Economic Risks of Climate Change

MEMORANDUM

From: Senator Sheldon Whitehouse
To: Members and staff on the Senate Budget Committee
Date: February 1, 2023
RE: Economic Risks of Climate Change

Economic Risks of Climate Change

1. Numerous experts are warning of the risk of a carbon bubble:
   - Mark Carney, Governor of the Bank of England: "The exposure of UK investors, including insurance companies, to [stranded assets] is ***potentially huge***." (Page 8)
   - Mark Carney: "The combination of the weight of scientific evidence and the dynamics of the financial system suggest that, in the fullness of time, ***climate change will threaten financial resilience and longer term prosperity***." (Page 11)
   - Paul Fisher, Deputy Head of the Prudential Regulation Authority and Executive Director, Insurance Supervision for the Bank of England: "As the world increasingly limits carbon emissions, and moves to alternative energy sources, ***investments in fossil fuels and related technologies […] may take a huge hit***." (Page 5)
   - 34 central bank presidents, Network for Greening the Financial System First Comprehensive Report: "Estimates of losses […] are large and range from $1 trillion to $4 trillion when considering the energy sector alone, or ***up to $20 trillion*** when looking at the economy more broadly." (Page 17)
   - Christopher McGlade & Paul Elkins, University College London, writing in *Nature*: "Our results suggest that, globally, ***a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves*** should remain unused from 2010 to 2050 in order to meet the target of 2 degrees Celsius." (Page 1)
   - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*: "Our conclusions support the existence of a carbon bubble that, if not deflated early, could lead to a discounted global wealth loss of US$1 – 4 trillion, ***a loss comparable to the 2008 financial crisis***." (Page 1)

2. The effects of a carbon bubble on the U.S. economy could be particularly severe:
   - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*:
      i. The U.S. economy could experience **more than $3 trillion (2016 dollars) in losses** (Page 4, Figure 3a)
      ii. U.S. GDP could **shrink by more than 5 percent** (Page 4, Figure 3b)
      iii. The U.S. could **lose millions of jobs** (Page 4, Figure 3c)
      iv. "Regions with higher marginal costs experience a steep decline in production (for example, Russia), or lose almost their entire oil and gas industry (for example, Canada, the United States)." (Page 4)

3. The sooner policy makers act to decarbonize the economy, the less risk from a carbon bubble:
    - Mark Carney: "**Risks to financial stability will be minimized if the transition begins early** and follows a predictable path, thereby helping the market anticipate the transition to a 2 degree world." (Page 4)
    - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*: "[E]conomic damage from a potential bubble burst could be avoided by decarbonizing early." (Page 1)
    - Jean-François Mercure, *et al.*, Cambridge University, writing in *Nature Climate Change*: "[T]he United States is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them." (Page 5)
    - Battiston, *et al.*, University of Zurich, writing in *Nature Climate Change*: "The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk." (Page 5)
    - Joseph Stiglitz, Expert Report, *Juliana v. United States of America*: "**[T]he more time that passes, the more expensive it becomes to address climate change**." (Page 19)

4. Numerous experts are warning of the risk of a coastal real estate crash:
    - Freddie Mac, *Life's a Beach*: "While technical solutions may stave off some of the worst effects of climate change, rising sea levels and spreading flood plains nonetheless appear likely to destroy billions of dollars in property and to displace millions of people. The economic losses and social disruption may happen gradually, but they are **likely to be greater in total than those experienced in the housing crisis and Great Recession**."
    - Union of Concerned Scientists, *Underwater* (2018): "In the coming decades, the consequences of rising seas will strain many coastal real estate markets – abruptly or gradually, but some eventually ***to the point of collapse – with potential reverberations throughout the national economy***." (Page 2)
    - *Risk & Insurance*: "These bellwether locations [Miami, Atlantic City, and Norfolk] signify a growing and alarming threat; that continually rising seas will damage coastal residential and commercial property values to the point that property owners will flee those markets in droves, thus ***precipitating a mortgage value collapse that could equal or exceed the mortgage crisis that rocked the global economy in 2008***."

5. A coastal real estate crash would have profound economic implications:
    - Freddie Mac, *Life's a Beach*: Between **$238 and $507 billion worth of real estate** will be below sea level by 2100.

- Union of Concerned Scientists, *Underwater* (2018): "[B]y the end of the 21st century ***nearly 2.5 million residential and commercial properties, collectively valued at $1.07 trillion today***, will be at risk of chronic flooding." (Page 2)
- *Risk & Insurance*: "In the housing crisis of 2008, a significant percentage of borrowers continued to make their mortgage payments even though the value of their homes was less than their mortgages. It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater. As a result, ***lenders, servicers and mortgage insurers are likely to suffer large losses***."
- First Street Foundation: Coastal residential real estate along the East Coast has already lost more than $15 billion in value since 2005 because of sea level rise.
- Moody's: "The growing effects of climate change, including climbing global temperatures, and rising sea levels, are forecast to have an increasing economic impact on US state and local issuers. This will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies."
- Ouazad & Kahn: "In particular, bank lenders may have an incentive to sell their worse flood risk to the two main agency securitizers, […] Fannie Mae and […] Freddie Mac." (Page 1)

6. The aggregate economic effects of climate change are systemic and could result in severe economic repercussions:
    - Bank of International Settlements, *The Green Swan*: "[C]limate change is a source of ***major systemic financial risks***." (Page 65); "[C]limate catastrophes are ***even more serious than most systemic financial crises***." (Page 3) "Exceeding climate tipping points could lead to ***catastrophic and irreversible*** impacts that would make quantifying financial damages impossible." (Page 1)
    - Deloitte: "[U]nchecked climate change could **cost the global economy $178 trillion** in net present value terms from 2021–2070. […Achieving net-zero emissions by mid-century] could **increase the size of the world economy by $43 trillion** in net present value terms from 2021–2070." (Page 4)
    - Deloitte: "In 2070 alone, **global GDP could be 7.6% lower** compared to a baseline that does not account for climate change." (Page 10)
    - McKinsey: Climate change could "make long-duration borrowing unavailable, impact insurance cost and availability, and **reduce terminal values**." It could "trigger ***capital reallocation and asset repricing***." (Page viii)
    - Fourth National Climate Assessment: "With continued growth in emissions at historic rates, ***annual losses in some economic sectors are projected to reach hundreds of billions of dollars by the end of the century***—more than the current gross domestic product (GDP) of many U.S. states."
    - Standard & Poor's: "***Global warming of 3 degrees Celsius is likely to cost us 2% of global output.*** [… W]e might even be underestimating the costs of climate change. [… T]he higher the temperature, the more damaging climate change will be – and in a nonlinear way."

- 34 central bank presidents, Network for Greening the Financial System First Comprehensive Report: "Estimates suggest that absent action to reduce emissions, the physical impact of climate change on the global economy in the second half of the century will be substantial. The more sophisticated studies suggest ***average global incomes may be reduced by up to a quarter by the end of the century***." (Page 13)
- Blackrock: "***Some 58% of U.S. metro areas would see likely [annual] GDP losses of up to 1% or more***, with less than 1% set to enjoy gains of similar magnitude. Florida tops the danger zones, with Naples, Panama City and Key West seeing likely annual GDP losses of up to 15% or more." (Page 9)
- Tom Kompas, *et al.*, University of Melbourne, writing in *Earth's Future* journal published by the American Geophysical Union: "***The approximate global potential loss is estimated to be US$ 9,593.71 billion or roughly 3% of the 2100 world GDP for 3ºC global warming.*** At 4ºC, losses from global warming increase significantly to US$ 23,149.18 billion." (Page 1160) ***Climate change-related economic losses in the U.S. are estimated to be approximately $224 billion per year in the U.S. in 2100 under a 3ºC scenario*** and $700 billion per year under a 4ºC scenario. (Page 1169)

This is a tab page.
Please title tab
“Carney”

Mark Carney: Breaking the tragedy of the horizon – climate change and financial stability

Speech by Mr Mark Carney, Governor of the Bank of England and Chairman of the Financial Stability Board, at Lloyd's of London, London, 29 September 2015.

* * *

I am grateful to Rhys Phillips and Iain de Weymarn for their assistance in preparing these remarks, and to Michael Sheren, Clare Ashton, Matthew Scott and Professor Myles Allen for their comments.

I'm grateful to Lloyd's for the invitation to speak tonight on the occasion of the first City Dinner held in this magnificent, eponymous "Room".

Lloyd's is the bedrock of the UK insurance industry.

An industry whose direct contribution to the UK economy is impressive: 300,000 high-paying jobs and £25bn in annual GDP.

Its economic contribution goes much deeper.

Insurance supports households, companies and investors, safeguarding them from perils they could not otherwise shoulder.

It matches long-term savings and investment, financing the infrastructure essential to productivity.

With its unique perspective and skill set, insurance diversifies the financial system and reinforces its resilience.

Since 1688 Lloyd's has, in the great tradition of the City, served both the UK and the world, providing protection against the perils of the age; helping enterprise and trade to thrive.

From its origins in marine insurance, the Lloyd's market has evolved constantly to meet the needs of a rapidly changing world.

The first excess of loss reinsurance was created here.

Modern catastrophe cover was born with your decision to stand by policyholders after the San Francisco earthquake.

And Lloyd's pioneered aviation insurance.[1]

With eyes constantly on the horizon, Lloyd's has remained at the forefront of global insurance.

Today, you are insuring new classes of risk in new parts of the world – from cyber to climate, from space to specie, from Curitiba to Chengdu.

And you are doing so in market conditions as challenging as any in the last 20 years.

The need to manage emerging, mega risks is as important as ever.

Alongside major technological, demographic and political shifts, our very world is changing. Shifts in our climate bring potentially profound implications for insurers, financial stability and the economy.

I will focus on those risks from climate change this evening.

---

[1] The first aviation policy was written in 1911, followed in 1919 by the founding of the British Aviation Insurance Association. That venture closed in 1921, with underwriters concluding that *"there seems to be no immediate future in aviation insurance…"* www.lloyds.com/lloyds/about-us/history/innovation-and-unusual-risks/pioneers-of-travel.

The tragedy of the horizon

There is a growing international consensus that climate change is unequivocal.[2]

Many of the changes in our world since the 1950s are without precedent: not merely over decades but over millennia.

Research tells us with a high degree of confidence that:

- In the Northern Hemisphere the last 30 years have been the warmest since Anglo-Saxon times; indeed, eight of the ten warmest years on record in the UK have occurred since 2002;[3]
- Atmospheric concentrations of greenhouse gases are at levels not seen in 800,000 years; and
- The rate of sea level rise is quicker now than at any time over the last 2 millennia.[4]

Evidence is mounting of man's role in climate change. Human drivers are judged extremely likely to have been the dominant cause of global warming since the mid-20th century.[5] While natural fluctuations may mask it temporarily, the underlying human-induced warming trend of two-tenths of a degree per decade has continued unabated since the 1970s.[6]

While there is always room for scientific disagreement about climate change (as there is with any scientific issue) I have found that insurers are amongst the most determined advocates for tackling it sooner rather than later. And little wonder. While others have been debating the theory, you have been dealing with the reality:

- Since the 1980s the number of registered weather-related loss events has tripled; and
- Inflation-adjusted insurance losses from these events have increased from an annual average of around $10bn in the 1980s to around $50bn over the past decade.[7]

The challenges currently posed by climate change pale in significance compared with what might come. The far-sighted amongst you are anticipating broader global impacts on property, migration and political stability, as well as food and water security.[8]

So why isn't more being done to address it?

A classic problem in environmental economics is the tragedy of the commons. The solution to it lies in property rights and supply management.

---

[2] For instance, the IPCC has stated "*Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia*". See IPCC - Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (2014).

[3] See www.metoffice.gov.uk/news/releases/archive/2015/Record-UK-temps-2014.

[4] See IPCC (2014).

[5] See IPCC (2014) which notes that the effects of anthropogenic greenhouse gas emissions, together with other anthropogenic drivers are "*extremely likely to have been the dominant cause of observed [global] warming since the mid-20th Century*".

[6] See, for example, Otto et al (2015).

[7] See Munich Re, NatCatSERVICE (2015).

[8] The report "*Risky Business – the economic risks of climate change in the United States*" (2014) suggests that in the USA $238-507bn worth of coastal property could be below sea level by 2100. Research by Lloyd's identifies climate change as an important supply-side issue for food security. See www.lloyds.com/~/media/lloyds/reports/emerging%20risk%20reports/food%20report.pdf. This is consistent with the views expressed by Lloyd's market participants surveyed by the PRA for its report to Defra.

Climate change is the Tragedy of the *Horizon*.

We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

That means beyond:

- the ***business cycle***;[9]
- the ***political cycle***; and
- the ***horizon of technocratic authorities***, like central banks, who are bound by their mandates.

The horizon for monetary policy extends out to 2-3 years. For financial stability it is a bit longer, but typically only to the outer boundaries of the credit cycle – about a decade.[10]

In other words, once climate change becomes a defining issue for financial stability, it may already be too late.

This paradox is deeper, as Lord Stern and others have amply demonstrated. As risks are a function of cumulative emissions, earlier action will mean less costly adjustment.[11]

The desirability of restricting climate change to 2 degrees above pre-industrial levels[12] leads to the notion of a carbon "budget", an assessment of the amount of emissions the world can "afford".

Such a budget - like the one produced by the IPCC[13] – highlights the consequences of inaction today for the scale of reaction required tomorrow.

These actions will be influenced by policy choices that are rightly the responsibility of elected governments, advised by scientific experts. In ten weeks representatives of 196 countries will gather in Paris at the COP21 summit to consider the world's response to climate change. It is governments who must choose whether, and how, to pursue that 2 degree world.

And the role of finance? Earlier this year, G20 Finance Ministers asked the Financial Stability Board to consider how the financial sector could take account of the risks climate change poses to our financial system.

As Chair of the FSB I hosted a meeting last week where the private and public sectors discussed the current and prospective financial stability risks from climate change and what might be done to mitigate them.

I want to share some thoughts on the way forward after providing some context beginning with lessons from the insurance sector.

---

[9] Few business leaders list climate change as a near-term pressing risk. See, for instance, PWC's annual survey of CEOs (www.pwc.com/gx/en/ceo-agenda/ceo-survey.html) and the Bank of England's Systemic Risk Survey (www.bankofengland.co.uk/publications/Documents/other/srs/srs2015h1.pdf).

[10] Even credit ratings typically only look out to 3-5 years.

[11] For instance, IPCC (2014) Conclusion SPM 2.1 notes that "*cumulative emissions of CO2 largely determine global mean surface warming by the late 21st century and beyond*". The Stern review observes that "*many greenhouse gases, including carbon dioxide, stay in the atmosphere for more than a century*" (See The Stern Review of the Economic Effects of Climate Change (2006)).

[12] The Cancun Agreement in 2010 committed governments to "*hold the increase in global average temperature below two degrees*". Discussion of this level has been attributed to Nordhaus (1975). Others, including the UNEP Advisory Group on Greenhouse Gasses (1990) have suggested that two degrees could be a point beyond which the damage caused by climate change may become non-linear.

[13] See IPCC (2014).

Climate change and financial stability

There are three broad channels through which climate change can affect financial stability:

- First, ***physical risks***: the impacts today on insurance liabilities and the value of financial assets that arise from climate- and weather-related events, such as floods and storms that damage property or disrupt trade;
- Second, ***liability risks***: the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible. Such claims could come decades in the future, but have the potential to hit carbon extractors and emitters – and, if they have liability cover, their insurers – the hardest;
- Finally, ***transition risks***: the financial risks which could result from the process of adjustment towards a lower-carbon economy. Changes in policy, technology and physical risks could prompt a reassessment of the value of a large range of assets as costs and opportunities become apparent.

The speed at which such re-pricing occurs is uncertain and could be decisive for financial stability. There have already been a few high profile examples of jump-to-distress pricing because of shifts in environmental policy or performance.

Risks to financial stability will be minimised if the transition begins early and follows a predictable path, thereby helping the market anticipate the transition to a 2 degree world.

To draw out these crucial points consider the Bank of England's current approach to the insurance sector.

As regulator of the world's third largest insurance industry, the PRA is responsible for protecting policyholders and ensuring the safety and soundness of insurers.

Our supervision is forward-looking and judgement-based. It is risk-based and proportionate – tailored to different business models around the sector – and considers both business-as-usual and whether a firm can fail safely – recognising that "zero failure" is neither desirable nor realistic.

Our supervisors take a view of your business plans, risk management, governance, and capital models. Where the PRA judges that it is necessary to intervene it does so sooner rather than later.

While our mandate is to protect policyholders – many of whom are local – we are conscious that international competition needs robust and internationally-consistent regulatory standards.

Solvency II is a good example. It is a prudent but proportionate Directive, that embodies the core principles of our domestic standards and embeds them more consistently across Europe while replacing a patchwork of local regimes.

Another example of how best practice is converging globally is the FSB agreement last week on HLA for global systemic insurers, as well as its support for the IASB completing its new insurance contracts standard. The UK insurance industry is well-prepared for such developments.

Forward-looking regulators consider not just the here and now, but emerging vulnerabilities and their impact on business models.

That is why the PRA has worked with regulated firms, many of them represented here tonight, to produce for the Department for Environment, Food and Rural Affairs a review – published today – into the impact of climate change on British insurers.

The Report concludes that insurers stand exposed to each of the three types of risk climate change poses to finance; and while the sector is well-placed to respond in the near-term you should not assume your ability to manage risks today means the future is secure. Longer term risks could have severe impacts on you and your policyholders.

The insurance response to climate change

It stands to reason that general insurers are the most directly exposed to such losses.

Potential increases in the frequency or severity of extreme weather events driven by climate change could mean longer and stronger heat waves; the intensification of droughts; and a greater number of severe storms.

Despite winter 2014 being England's wettest since the time of King George III; forecasts suggest we can expect at least a further 10% increase in rainfall during future winters.[14]

A prospect guaranteed to dampen the spirits and shoes of those who equate climate change with global warming.

While the attribution of increases in claims to specific factors is complex, the ***direct costs*** of climate change are already affecting insurers' underwriting strategies and accounts.

For example, work done here at Lloyd's of London estimated that the 20cm rise in sea-level at the tip of Manhattan since the 1950s, when all other factors are held constant, increased insured losses from Superstorm Sandy by 30% in New York alone.[15]

Beyond these direct costs, there is an upward trend in losses that arise indirectly through second-order events like the disruption of global supply chains.

Insurers are therefore amongst those with the greatest incentives to understand and tackle climate change in the short term. Your motives are sharpened by commercial concern as capitalists and by moral considerations as global citizens. And your response is at the cutting edge of the understanding and management of risks arising from climate change.

Lloyd's underwriters were the first to use storm records to mesh natural science with finance in order to analyse changing weather patterns. Events like Hurricanes Andrew, Katrina and Ike have helped advance catastrophe risk modelling and provisioning.[16] Today Lloyd's underwriters are required to consider climate change explicitly in their business plans and underwriting models.

Your genius has been to recognise that past is not prologue and that the catastrophic norms of the future can be seen in the tail risks of today.

For example, by holding capital at a one in 200 year risk appetite, UK insurers withstood the events of 2011, one of the worst years on record for insurance losses. Your models were validated, claims were paid, and solvency was maintained.

The combination of your forecasting models, a forward-looking capital regime and business models built around short-term policies means general insurers are well-placed to manage physical risks in the near term.

---

[14] See Met Office research into climate observations, projections and impacts – http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf.

[15] A Lloyd's report ("*Catastrophe Modelling and Climate Change*" - 2014) looks at factors that influence the impact of hurricanes. It notes the importance of sea-level changes – in addition to wind speed and tides – in the impact of Sandy on New York. See www.lloyds.com/~/media/Lloyds/Reports/Emerging%20Risk%20Reports/CC%20and%20modelling%20template%20V6.pdf.

[16] As the PRA's report to Defra notes, major catastrophe events have often driven innovations in risk management. For example, following Hurricane Andrew (1992, $15.5 billion uninflated insured losses) and the associated insolvency of eight insurance companies, the industry developed a more sophisticated approach to assessing catastrophe risk, and became more resilient to similar events.

But further ahead, increasing levels of physical risk due to climate change could present significant challenges to general insurance business models.

Improvements in risk modelling must be unrelenting as loss frequency and severity shifts with:

- Insurance extending into new markets not covered by existing models;
- Previously unanticipated risks coming to the fore; and
- Increasingly volatile weather trends and hydrological cycles making the future ever-harder to predict.

For example, the extent to which European windstorms occur in clusters[17] could increase the frequency of catastrophes and reduce diversification benefits.

Indeed, there are some estimates that currently modelled losses could be undervalued by as much as 50% if recent weather trends were to prove representative of the new normal.[18] In addition, climate change could prompt increased morbidity and mortality from disease or pandemics.

Such developments have the potential to shift the balance between premiums and claims significantly, and render currently lucrative business non-viable.

Absent actions to mitigate climate change, policyholders will also feel the impact as pricing adjusts and cover is withdrawn.[19]

Insurers' rational responses to physical risks can have very real consequences and pose acute public policy problems.

In some extreme cases, householders in the Caribbean have found storm patterns render them unable to get private cover, prompting mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned.

Thankfully these cases are rare. But the recognition of the potential impact of such risks has prompted a publicly-backed scheme in the UK – Flood Re – to ensure access to affordable flood insurance for half a million homes now considered to be at the highest risk of devastating flooding.

This example underlines a wider point. While the insurance industry is well placed to adapt to a changing climate in the short-term, their response could pose wider issues for society, including whether to nationalise risk.

The passage of time may also reveal risks that even the most advanced models are not able to predict, such as third party liability risks.

Participants in the Lloyd's market know all too well that what appear to be low probability risks can evolve into large and unforeseen costs over a longer timescale.

Claims on third-party liability insurance – in classes like public liability, directors' and officers' and professional indemnity - could be brought if those who have suffered losses show that insured parties have failed to mitigate risks to the climate; failed to account for the damage they cause to the environment; or failed to comply with regulations.

---

[17] Discussions on correlation are not new. For example, a current issue is the extent to which European windstorms occur in clusters, such as windstorms Daria, Vivian, Wiebke and Herta in 1990 and Lothar, Martin, and Anatol in 1999.

[18] See Standard and Poor's – "*Climate Change Could Sting Reinsurers That Underestimate Its Impact"* (2014).

[19] In 1992 after Hurricanes Andrew and Iniki hit the US, the price of reinsuring weather risks spiked and several carriers left the market, leading to a rise of up to 40% in premiums in some parts of Florida. A series of hurricanes affecting the Bahamas has prompted several insurers to withdraw flood cover for low-lying areas.

Asbestos alone is expected to cost insurers $85bn on a net ultimate claims basis in the United States – equivalent to almost three Superstorm Sandy-sized loss events.[20]

It would be premature to draw too close an analogy with climate risks, and it is true that court cases have, so far, largely been unsuccessful.

Cases like Arch Coal and Peabody Energy – where it is alleged that the directors of corporate pension schemes failed in their fiduciary duties by not considering financial risks driven at least in part by climate change[21] – illustrate the potential for long-tail risks to be significant, uncertain and non-linear.

And "Loss and Damage" from climate change – and what to do about it – is now formally on the agenda of the United Nations Framework Convention on Climate Change, with some talking openly about the case for compensation.[22]

These risks will only increase as the science and evidence of climate change hardens.

Physical risks from climate change will also become increasingly relevant to the ***asset side*** of insurer's balance sheets.[23]

While the ability to re-price or withdraw cover mitigates some risk to an insurer, as climate change progresses, insurers need to be wary of cognitive dissonance within their organisations whereby prudent decisions by underwriters lead to falls in the value of properties held by the firm's asset managers. This highlights the transition risk from climate change.

Transition risks

The UK insurance sector manages almost £2tn in assets to match liabilities that often span decades.

While a given physical manifestation of climate change – a flood or storm – may not directly affect a corporate bond's value, policy action to promote the transition towards a low-carbon economy could spark a fundamental reassessment.

Take, for example, the IPCC's estimate of a carbon budget that would likely limit global temperature rises to 2 degrees above pre-industrial levels.

That budget amounts to between 1/5th and 1/3rd world's proven reserves of oil, gas and coal.[24]

---

[20] See AM Best – *Special Report: Asbestos Losses Fueled by Rising Number of Lung Cancer Cases* (2013) www.ambest.com/ambv/bestnews/presscontent.aspx?altsrc=0&refnum=20451.

[21] See *Roe v Arch Coal Inc et al*, Case: 4:15-cv-00910-NAB, United States District Court, Eastern District of Missouri, 9 June 2015 and *Lynn v Peabody Energy Corporation et al*, Case: 4:15-cv-00916-AGF, United States District Court, Eastern District of Missouri, 11 June 2015. Note that as at 1 September 2015 the defences to these claims were yet to be filed.

[22] Loss and damage refers to impact of climate change not mitigated by reductions in emissions. The UNFCCC Warsaw agreement in 2013 discussed support for measures to address loss and damage. See http://unfccc.int/resource/docs/2013/cop19/eng/10a01.pdf.

[23] The largest UK insurers hold or manage in excess of £40bn of CRE and infrastructure assets, and have committed to further such investments in future. For instance, six major insurers pledged to invest £25bn into UK domestic infrastructure in 2013 as part of the Government's national infrastructure plan (see http://www.ft.com/cms/s/0/1f74e176-5c41-11e3-b4f3-00144feabdc0.html).

[24] The IPCC gives a range of budgets for future emissions which depends on assumptions about other climate drivers and the level of risk of temperatures going >2 degrees that society is willing to accept. It sets these in the context of existing fossil fuel reserves. See table 2.2 in IPCC (2014).

If that estimate is even approximately correct it would render the vast majority of reserves "stranded" – oil, gas and coal that will be literally unburnable without expensive carbon capture technology, which itself alters fossil fuel economics.[25]

The exposure of UK investors, including insurance companies, to these shifts is potentially huge.

19% of FTSE 100 companies are in natural resource and extraction sectors; and a further 11% by value are in power utilities, chemicals, construction and industrial goods sectors. Globally, these two tiers of companies between them account for around one third of equity and fixed income assets.

On the other hand, financing the de-carbonisation of our economy is a major opportunity for insurers as long-term investors. It implies a sweeping reallocation of resources and a technological revolution, with investment in long-term infrastructure assets at roughly quadruple the present rate.[26]

For this to happen, "green" finance cannot conceivably remain a niche interest over the medium term.

There are a number of factors which could influence the speed of transition to a low carbon economy including public policy, technology, investor preferences and physical events.

From a regulator's perspective the point is not that a reassessment of values is inherently unwelcome. It is not. Capital should be allocated to reflect fundamentals, including externalities.

But a wholesale reassessment of prospects, especially if it were to occur suddenly, could potentially destabilise markets, spark a pro-cyclical crystallisation of losses and a persistent tightening of financial conditions.

In other words, an abrupt resolution of the tragedy of horizons is in itself a financial stability risk.

The more we invest with foresight; the less we will regret in hindsight.

And there are ways to make that more likely.

Financial policy implications

Financial policymakers will not drive the transition to a low-carbon economy. It is not for a central banker to advocate for one policy response over another. That is for governments to decide.

But the risks that I have outlined mean financial policymakers do, however, have a clear interest in ensuring the financial system is resilient to any transition hastened by those decisions, and that it can finance the transition efficiently.

Some have suggested we ought to accelerate the financing of a low carbon economy by adjusting the capital regime for banks and insurers. That is flawed. History shows the danger

---

[25] The IPCC makes clear that, without this critical technology, the cost of meeting the two degree goal more than doubles – if it can be achieved at all. Canada is home to the world's first *commercial*-scale CCS plant at Boundary Dam. Other projects rely on government subsidies which can prove unreliable. If companies are relying on CCS to achieve net zero carbon emissions, investors will want to assess how they plan to get there – and who they expect to pay for it.

[26] The IPCC estimates that additional investment of US$ 190-900bn is required annually in the energy sector alone if the rise in average global temperature is to be capped at 2C. www.ipcc.ch/report/ar5/ Mercer estimates that additional cumulative investment in efficiency improvements, renewable energy, biofuels and nuclear, and carbon capture and storage could be in the range of US$3-5trn by 2030. www.mercer.com/insights/point/2014/climate-change-scenarios-implications-for-strategic-asset-allocation.html

of attempting to use such changes in prudential rules – designed to protect financial stability – for other ends.

More properly our role can be in developing the frameworks that help the market itself to adjust efficiently.

Any efficient market reaction to climate change risks as well as the technologies and policies to address them must be founded on transparency of information.

A "market" in the transition to a 2 degree world can be built. It has the potential to pull forward adjustment – but only if information is available and *crucially* if the policy responses of governments and the technological breakthroughs of the private sector are credible.

That is why, following our discussions at the FSB last week, we are considering recommending to the G20 summit that more be done to develop consistent, comparable, reliable and clear disclosure around the carbon intensity of different assets.

Better information to allow investors to take a view

An old adage is that which is measured can be managed.

Information about the carbon intensity of investments allows investors to assess risks to companies' business models and to express their views in the market.

A well-known dictum of macroeconomics is Say's Law: that supply creates demand.

This means that the act of producing new products creates income and profits that ultimately finance the demand for them.

By analogy, a framework for firms to publish information about their climate change footprint, and how they manage their risks and prepare (or not) for a 2 degree world, could encourage a virtuous circle of analyst demand and greater use by investors in their decision making. It would also improve policymaker understanding of the sources of CO2 and corporate preparedness.

A carbon budget – like the one produced by the IPCC – is hugely valuable, but can only really be brought to life by disclosure, giving policymakers the context they need to make choices, and firms and investors the ability to anticipate and respond to those choices.

Given the uncertainties around climate, not everyone will agree. Some might dispute the IPCC's calculations. Others might despair that there will never be financial consequences of burning fossil fuels. Still others could take a view that the stakes make political action inevitable.

The right information allows sceptics and evangelists alike to back their convictions with their capital.

It will reveal how the valuations of companies that produce and use fossil fuels might change over time.

It will expose the likely future cost of doing business, paying for emissions, changing processes to avoid those charges, and tighter regulation.

It will help smooth price adjustments as opinions change, rather than concentrating them at a single climate "Minsky moment".

Crucially, it would also allow feedback between the market and policymaking, making climate policy a bit more like monetary policy.

Policymakers could learn from markets' reactions and refine their stance, with better information allowing more informed reactions, and supporting better policy decisions including on targets and instruments.

A climate disclosure task force

That better information – about the costs, opportunities and risks created by climate change – can promote timely responses is not a new idea.

Much the opposite: there are already nearly 400 initiatives to provide such information.

Existing schemes vary in their status (from laws to voluntary guidance); scope (from greenhouse gas emissions to broader environmental risks); and ambition (from simple disclosure to full explanations of mitigation and divestment strategies).[27]

In aggregate over 90% of FTSE 100 firms and 80% of Fortune Global 500 firms participate in these various initiatives. For instance, the Carbon Disclosure Project makes available disclosure from 5,000 companies to investment managers responsible for over $90 trillion of assets.

The existing surfeit of existing schemes and fragmented disclosures means a risk of getting "lost in the right direction".

In any field, financial, scientific or other, the most effective disclosures are:

- ***Consistent*** – in scope and objective across the relevant industries and sectors;
- ***Comparable*** – to allow investors to assess peers and aggregate risks;
- ***Reliable*** – to ensure users can trust data;
- ***Clear*** – presented in a way that makes complex information understandable; and
- ***Efficient*** – minimising costs and burdens while maximising benefits.

Meeting these standards requires coordination, something the G20 and FSB are uniquely placed to provide.

The logical starting point is a co-ordinated assessment of what constitutes effective disclosure, by those who understand what is valuable and feasible.

One idea is to establish an industry-led group, a ***Climate Disclosure Task Force***, to design and deliver a voluntary standard for disclosure by those companies that produce or emit carbon.

Companies would disclose not only what they are emitting today, but how they plan their transition to the net-zero world of the future. The G20 – whose member states account for around 85% of global emissions[28] – has a unique ability to make this possible.

This kind of proposal takes its lead from the FSB's successful catalysing of improved disclosure by the world's largest banks following the financial crisis, via the Enhanced Disclosure Task Force.

The EDTF's recommendations, published in October 2012, were the product of collaboration between banks, analysts and investors. This has given the providers of capital the disclosures they need – specifically how banks manage risks and make profits – in a format that the banks can readily supply.

That shows that private industry can improve disclosure and build market discipline without the need for detailed or costly regulatory interventions.

---

[27] A non-exhaustive list of some of the more prominent initiatives in this space includes the Carbon Standards Disclosure Board, Integrated Reporting, the Carbon Disclosure Project, and the UN Principles for Responsible Investment.

[28] See www.pwc.co.uk/assets/pdf/low-carbon-economy-index-2014.pdf

Like the EDTF, a CDTF could be comprised of private providers of capital, major issuers, accounting firms and rating agencies.

Complementing static disclosures

Static disclosure is a necessary first step. There are two ways its impact could be amplified.

First, governments, potentially sparked by COP21, could complement disclosure by giving guidance on possible carbon price paths.

Such a carbon price *corridor* involves an indicative minimum and maximum price for carbon, calibrated to reflect both price and non-price policy actions, and increasing over time until the price converges towards the level required to offset fully the externality. [29]

Even if the initial indicative price is set far below the "true" cost of carbon, the price signal itself holds great power. It would link climate exposures to a monetary value and provide a perspective on the potential impacts of future policy changes on asset values and business models.

Second, stress testing could be used to profile the size of the skews from climate change to the returns of various businesses.[30]

This is another area where insurers are at the cutting edge.

Your capital requirements are based on evaluating the impact of severe but plausible scenarios. You peer into the future, building your defences against a world where extreme events become the norm.

This stress-testing technology is well-suited to analysing tail risks likely to grow fatter with time, casting light on the future implications of environmental exposures embedded in a wide range of firms and investments.

Stress testing, built off better disclosure and a price corridor, could act as a time machine, shining a light not just on today's risks, but on those that may otherwise lurk in the darkness for years to come.

Conclusion

Our societies face a series of profound environmental and social challenges.

The combination of the weight of scientific evidence and the dynamics of the financial system suggest that, in the fullness of time, climate change will threaten financial resilience and longer-term prosperity.

While there is still time to act, the window of opportunity is finite and shrinking.[31]

Others will need to learn from Lloyd's example in combining data, technology and expert judgment to measure and manage risks.

The December meetings in Paris will work towards plans to curb carbon emissions and encourage the funding of new technologies.

---

[29] For instance, the report of the Canfin-Grandjean Commission (2015) discusses the merits of an indicative price corridor with a maximum and minimum price that can be increased over time. See www.elysee.fr/assets/Report-Commission-Canfin-Grandjean-ENG.pdf

[30] These skews could be upside or downside, depending on business model and the point in the transition path.

[31] Already our failure to act since 2010 has increased the task – since emissions persist – and the pace of de-carbonisation required – for instance see http://site.thomsonreuters.com/corporate/pdf/global-500-greenhouse-gases-performance-trends-2010-2013.pdf

We will need the market to work alongside in order to maximise their impact.

With better information as a foundation, we can build a virtuous circle of better understanding of tomorrow's risks, better pricing for investors, better decisions by policymakers, and a smoother transition to a lower-carbon economy.

By managing what gets measured, we can break the Tragedy of the Horizon.

This is a tab page.
Please title tab “Fisher”

BANK OF ENGLAND

Speech

Confronting the challenges of tomorrow's world

Speech given by
Paul Fisher, Deputy Head of the Prudential Regulation Authority and Executive Director,
Insurance Supervision

Economist's Insurance Summit 2015, London
Tuesday 3 March 2015

Thank you for inviting me to speak to you today. As many of you will know I have been covering as Executive Director of Insurance, in addition to my responsibilities as Deputy Head of the PRA, since August last year whilst a search was made for a permanent appointment. At long last I will be passing the baton over to Sam Woods at Easter. So this is likely to be my final speech made as Insurance Director.

I would like to take the opportunity to offer up some personal observations about the current and prospective state of the insurance industry, as well as comment more generally on the role regulation will play in 'confronting the challenges of tomorrow'.

The insurance sector, by absorbing and laying off risk, plays a fundamental role in fostering a stable economy. A successful industry is therefore key to achieving the Bank of England's financial and monetary stability objectives. And as society and its economy evolve, it is vital that the insurance sector also responds to that changing environment.

Tomorrow's world inevitably brings change. Some changes can be forecast, or guessed by extrapolating from what we know today. But there are, inevitably, the unknown unknowns which will help shape the future. That means that a successful industry needs to be both dynamic and robust.

Uncertainty generates challenges but also represents opportunity. I want to discuss these risk/reward trade-offs and the importance of understanding the potential for new exposures that changing risk profiles can bring.

Insurance fulfils important social functions: the provision of income security in retirement; income protection whilst in work; funding for health care services and preserving the continuity of businesses subject to unexpected shocks. Indeed, in some areas, insurance is compulsory such as with motor insurance and employers' liability. Disruption to these functions is unlikely to be tolerated by wider society, not only because of the social benefits, but because risk transfer and pooling are crucial for sustainable economic growth and development. It is for this reason that the need to protect the interests of policy holders and to preserve long-term critical cover is so important.

Although one cannot be sure what the future may bring, we can learn from past mistakes to avoid their repetition. That is particularly apposite given that the residual effects of the great financial crisis are still being felt across the global economy. One of the things we appreciate very well at the PRA is that insurance business is very different to banking, and I have seen that at first hand over the past six months or so. I have also seen that there are lessons to be learnt from the banking crisis that <u>can</u> directly read across to the world of insurance.

Let me express a clear personal opinion; financial crises of the past were often, in large part, created by the people at the top making poor decisions – people not possessing the right information; not having due regard for risk; not being properly incentivised. Significant failures have often had their roots in poor governance with insufficient checks and balances to the decisions of powerful individuals. Strong, effective systems of oversight and risk management are paramount in meeting the PRA's objectives for the safety and soundness of firms and insurance policyholder protection. Not surprisingly, governance issues are consistently at, or near the top, of the PRA's agenda whether for banks or insurers. I can safely predict that this focus is not about to lessen any time soon. Firms in tomorrow's world need to aim for governance best practice.

The recent banking crises further illustrated that one of the most obvious ways in which financial stability can be undermined is through disorderly firm failure and the consequent disruption of financial services. The PRA's stance is that unsuccessful business models need to be allowed to fail, but that failure should be in an orderly manner so as not to disrupt the provision of core financial services. And I think we would all agree that the taxpayer should not be asked to bail out a failed firm.

One difference from banking is that failing insurers usually do exit in an orderly manner. Actually, about a third of the PRA's authorised firms are in run-off. But that is in part a testament to the successful regulatory regime that the UK has been running for the insurance sector. And, whatever the regime, we cannot be certain this will be the case in every conceivable circumstance. For this reason, the PRA continues to place the resolution arrangements for insurers on both the domestic and international agendas.

The banking crisis further taught us all that we need to be looking at potential storms ahead and not to be misled by periods of fair weather. For the PRA this means it will assess firms not just against current risks, but also against those that could plausibly arise in the future, carrying out increased business model analysis. For insurers, this involves monitoring emerging risks and taking preparatory steps to deal with what may result, with firms holding capital commensurate to their evolving risk profile. This approach is embedded as part of Solvency II, for example with the requirement for each undertaking to conduct a forward looking assessment of its own risk and solvency needs.

The fallout from the global financial crisis has accentuated the need for an open, two-way dialogue between regulator and regulated. This is especially true in times of change or stress. To ensure policyholder protection, regulators need to be alert to emerging risks and this is best achieved through a 'cards on the table' approach. Indeed, where the PRA judges it is necessary to intervene, we will seek to do so at an early stage. Firms should be open and straightforward in their dealings with the PRA and we in turn will take a risk-based and proportionate approach.

This is being put into practice. For example, enhanced communication is particularly pertinent as we transition to the Solvency II world. From April, firms will be able to make formal applications and we don't need a crystal ball to predict a very busy year for both regulator and regulated. The PRA has had an extensive on-going dialogue with firms, giving detailed feedback on, for example, their internal model developments or their matching adjustment applications. Just over a week ago we issued guidance on how equity release mortgages might be structured for use in the matching adjustment. Right now, the PRA is aiming to provide both general and individual firm feedback, recognising the importance of timely communication allowing firms to prepare thoroughly.

As a consequence of the financial crisis, financial regulation in all its forms has been through a major transition. In the UK we have seen the split of prudential and conduct regulation, the establishment of a single Insurance Directorate at the PRA with an insurance specific secondary objective, and we have moved forward in our application of 'judgement-based regulation'. The next few years will be about embedding this new approach through Solvency II.

I would like to move on now from regulation to a number of other developments and challenges that are currently on the horizon and to discuss the possible impacts these could have on insurers' business models.

The nature of insurance and the risk transfer role it provides means that insurance cuts across all aspects of society; whether providing at retirement solutions to pensioners to insuring the latest iPhone. It is for this reason that insurers find themselves innovating in step with wider society. As insurers are directly exposed to social changes, the changing world is the very stuff on which they should thrive. There are a number of such societal, regulatory or environmental changes currently at play such as global warming, globalisation, digitisation, demographic changes and cyber risk to name but a few.

Societal and Environmental Changes

A topical environmental change that is quickly moving up the agenda for insurers is that of climate change.

Climate change impacts insurers on both sides of their balance sheets. Insurers may be impacted by increased claims experience - particularly so given the London Market's prominence in areas like catastrophe risk. But it appears that the asset side may also give rise to unexpected risks.

Let's take these in turn.

We are seeing evermore frequent "record" weather events; storms; floods; hotter summers; intense rainfall; not to mention global concerns such as higher sea levels. Insurers are having to respond to these shifts. However, increases in catastrophic risk events can provide both an opportunity and a threat to insurers. There is an opportunity for growth in underwriting new products. But the combination of concentrated exposures to large catastrophe losses, inadequate risk management and/or the potential for mis-pricing could undermine the sustainability of businesses.

The insurance industry is already taking steps to stay ahead of the climate curve on the liability side with the establishment of Flood Re; ClimateWise forums; more sophisticated underwriting techniques; the development of climate change products and carbon offsets. However, it is worth bearing in mind that, even though the full impacts of climate change often may not be visible in the short term, it is well worth insurers being alert to the emerging risks, including those emanating from policy makers.

But insurers, as long term investors, are also exposed to changes in public policy as this affects the investment side. One live risk right now is of insurers investing in assets that could be left ‘stranded’ by policy changes which limit the use of fossil fuels. As the world increasingly limits carbon emissions, and moves to alternative energy sources, investments in fossil fuels and related technologies – a growing financial market in recent decades – may take a huge hit. There are already a few specific examples of this having happened.

The Bank of England has been carrying out analysis to better understand these risks. The Bank of England voluntarily accepted DEFRA’s invitation to compile a Climate Change Adaptation Report, due for delivery later this year. A project team was established to inquire into the topics of climate change and stranded assets. We are seeking to understand how these changes may impact upon the PRA’s objectives and how that could shape our role going forward.

We have noted that change to an insurers’ business model can be driven from many sources – which include changing consumer expectations.

Today the consumer demands more control, flexibility and automatism having become accustomed to interactive, accessible and digitised services. Increasingly consumers – that’s you and I in our personal lives – expect the same digitised experience for all their buying needs, including insurance.

Digitisation and the prominence of 'smart tech' cannot be ignored and already innovation in technology is leading insurers to do business differently. This shift can be felt across the value-chain, whether it be changes in distribution channels and use of cloud-based infrastructure, to enhanced underwriting processes and use of ‘black boxes’.

For the most part, digital includes putting the customer experience at the centre of insurers’ strategies. Whilst positive, as with any shift in business model and strategy, business developments need to be carefully managed and monitored to ensure the core objectives of enhancing the customer experience are indeed achieved. And new IT systems don’t come cheap, nor are they riskless.

Digitisation and enhanced technology can be a double-edged sword. Technological enhancements bring new opportunities to businesses but the pace of innovation must be met by the pace of corresponding safeguards to deal with the risks. In particular, the risk of cyber-attack is a great concern. The pace here is really changing very rapidly.

As with the other risks, insurers are affected for both good and ill: with ever more frequent and increasingly sophisticated cyber-attacks on businesses and individuals, insurers are being relied upon more and more for protection. A new business opportunity for sure. But, unlike most other insured risks, insurance firms could themselves be significant victims.

It is difficult to predict how cyber-crime – or even cyber accidents – will evolve, and it is very challenging to obtain data for losses that arise out of cyber-events. This makes it all the more difficult to quantify reserves, models and prices as well as develop operational safeguards internally.

An Insurer wishing to expand into any new business area needs to demonstrate to the PRA that new risk exposures are well understood and that the required capital for an altered risk profile has been fully considered. As stated previously, business model analysis forms an important part of the PRA's supervisory approach and a focus for its supervisory activity. Insurers will need to deal with the PRA in an open, co-operative and constructive manner to allow us to understand whether the business model is sustainable and to identify key vulnerabilities. This will ensure a more informed, focussed and proportionate supervisory approach.

Into the unknown

Over the past 25 years we have seen: the introduction of the Euro; break-up of the Soviet Union; a shift from West to East; the introduction of the world wide web to ordinary life; and smart technology – so what will happen over the next 25 years?

As an ex-forecaster I can tell you confidently that the only thing we can be certain of is that there will be changes that no one will predict.

I did not think, some six years ago, when sat at the table of the Monetary Policy Committee for my first meeting, that Bank Rate would continue to be 0.5% this far down the line. One can never be sure what tomorrow will bring and interest rates is a case in point.

The low level of real interest rates today is, in large part, a product of spare capacity in the real economy and low levels of growth and productivity across the developed world. This presents a number of issues for insurers who rely on interest income from their assets as part of their basic business model, especially where these returns back contractual guarantees. Without making any implied comment about monetary policy, just looking at today's yield curve, it is not plausible for insurers to expect high nominal or real rates of return in the near future from low-risk assets. Firms relying on high income streams from their assets may find themselves taking ever greater risks to their balance sheets.

Earlier on I mentioned the importance of governance in the work of the PRA. It is one thing that can help generate robustness in the face of these uncertain developments. Good governance should lie at the heart of every organisation. It is not just about the role of the board but includes management, controls, oversight and management information. Good governance encourages better business practices and outcomes. Of course, well intentioned people can make sub-optimal structures work – just as good structures can be run poorly. But a better structure gives a firm a better chance of avoiding a big business mistake and of surviving an unexpected shock.

Insurance retains highly talented and competent individuals. However, I have observed that the sector can be a bit of a ‘closed field’. I hear some firms – not all – talk of the difficulty in being able to appoint successful executives and even more difficulty in finding qualified, independent non-executives. Insurers also talk about the challenges of attracting young and ambitious individuals to supply the talent of the future. These people issues become particularly relevant in an environment under the Solvency II regime when the system of governance will be given even more prominence. I hope that the new Senior Insurance Managers Regime will be seen as both appropriate and proportionate to the needs of the industry and policy holders alike. To be clear, the Senior Insurance Managers Regime should not be operated in such a way so as to put good people off. The desired outcome is that of effective governance, not enforcement.

Insurance innovation and regulation

Preparedness for what tomorrow’s world may bring will likely involve a degree of change – greater risk-awareness, ensuring good governance, collaboration with the regulator – but is the insurance industry capable of that change?

The insurance industry has been founded upon taking the long term view. This is a concept that perhaps evokes a perception of consistency rather than innovation. However, the UK industry has traditionally not shied away from changing with the times, with the London market being a particular example.

Already, in response to changes on the horizon, we are seeing shifts in business models. Insurers are refreshing their product offerings, altering operational structures and enhancing distribution channels. The PRA has an important role to play in this so let me return to the subject of regulation.

To be clear, regulators have no intrinsic reason to stifle innovation. Far better to supervise a successful, profitable, innovating enterprise than a declining out-dated one. Underpinning that view, I would say that there should not be a prohibitive trade-off between insurers’ ability to innovate versus their ability to manage risks.

Instead, the PRA will need to work with its regulated entities closely and early in the process of innovation. Let's be clear that the business model and the risk are owned by the firm – the PRA's job is make sure that a firm's approach to risk management is sound and that their policy holders are adequately protected.

I believe Solvency II will help to do this. It will introduce greater risk-sensitivity; co-operation across jurisdictions; and consistency in approach. Being a risk-based regime means that insurers should be able to evolve and adapt to capture all risks they are exposed to and the qualitative risk assessment introduced under Pillar II will further support this move towards a more responsive, reflective and adaptable solvency regime. This in turn will mean that insurers will need to think carefully about the risks they are exposed to and how this is captured and managed. This does not mean that Solvency II should dictate firms' business models. Rather, market forces and expectations of policy holders will inform insurers' pricing and strategies.

As referred to earlier, there is much we can do to prepare for the future by learning from mistakes of the past. One such area where this should be borne in mind is in the use of risk models which will play a huge role in Solvency II for the larger, more complicated firms. Firms need to be able to understand their models and their limitations, and be able to challenge them. As the Governor said last year: "*The dangers of using poorly designed models were made all too clear in the banking sector. So the Bank won't hesitate to withhold approval of inadequate or opaque models*".

There are many things I could say about Solvency II, but I want to concentrate on what it means for the future. One particular aspect is that it sensibly allows for a smooth transition, over a period of 16 years in some cases. It is recognised that for insurers (particularly life insurers), Solvency II with the introduction of a 'going concern' regime, is a considerable shift. In particular, firms will have to hold a risk margin to ensure that the insurance liabilities reflect the value for which they could be transferred to a third party. To allow for the gradual introduction of the risk margin, firms will be able to make a transitional deduction from their technical provisions. Together, the various transitional measures within Solvency II should ensure a smooth progression, avoiding the market dislocation, volatility and increased costs that could result should a number of firms have to augment their capital base at the same time. They rightly recognise that the underlying risks have not changed overnight, even if the regime has.

Firms making use of transitional measures will be afforded time to reach the level of financial resources required by the full Solvency II regime. In the meantime we can be sure that the transitional deduction from technical provisions will not result in a firm's resources falling below those required under the existing UK regime. This is because Solvency II caps the amount of transitional benefit a firm may derive. Bearing in mind this cap, and the benefits to be gained from a smooth transition, the take-up of transitional measures should be seen as a viable option for firms to take to assist with their capital planning, and are a feature that the UK authorities strongly supported during the development of Solvency II. They are there to be used where appropriate.

As we shift to a Solvency II world, I think it is worth bearing in mind that, like a smartphone, regulation tends to get new “updates” and “apps” in response to changes in the external environment. Indeed, the path of the future is in global policy development, including the insurance capital standard (ICS) under the aegis of the International Association of Insurance Supervisors (IAIS) which will look to develop risk-based global standards.

Insurance business is fast becoming globalised and interlinked. It naturally follows that so too should regulation. Introducing global capital standards would enhance global cooperation, ensure a level playing field and limit regulatory arbitrage.

For this reason, the PRA supports the development of global capital standards and the establishment of a long term vision in order to achieve a single insurance capital standard predicated on a single valuation basis which is genuinely comparable across jurisdictions.

Concluding remarks

Insurance sits at frontline of innovation and, as seen with climate change and digitisation, insurers can be directly exposed to changes in regulation, public policy and other shifts in society. This is because insurance forms one of the foundations to our daily lives, providing a risk transfer role for all facets of human activity. Risk transfer allows society as we know it to function effectively and as such, insurers oil the wheels for the engine of the economy to function. On the basis of what I have seen since last August, the UK insurance industry is one of the most advanced and successful in the world. The key to meeting the challenges of tomorrow’s world is for the industry and regulator to continue to develop and work together.

This is a tab page.

Please title tab “Central Banks”

Network for Greening the Financial System

First comprehensive report

A call for action
Climate change as a source of financial risk

April 2019

NGFS

Central Banks and Supervisors
Network for Greening the Financial System

Foreword by Frank Elderson, Chair of the NGFS

We collectively face the effects of climate change, as it reaches beyond economies, borders, cultures, and languages. In 2017, air pollution was a cause of almost 5 million deaths worldwide while 62 million people in 2018 were affected by natural hazards, with 2 million needing to move elsewhere due to climate events. A transition to a green and low-carbon economy is not a niche nor is it a "nice to have" for the happy few. It is crucial for our own survival. There is no alternative. Therefore, we need to come together and take action to create a bright, sustainable future.

Understanding what the magnitude of climate change heralds for financial stability, at the initiative of Banque de France, eight central banks and supervisors established a Network of Central Banks and Supervisors for Greening the Financial System (NGFS) at the Paris "One Planet Summit" in December 2017. Since then, the NGFS has grown to 34 Members and 5 Observers from all over the globe.

Climate-related risks are a source of financial risk and it therefore falls squarely within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks. This significant breakthrough was already acknowledged in the NGFS progress report, published in October 2018. With this first NGFS comprehensive report, we build upon this insight to issue six recommendations: the first four apply to the work of central banks and supervisors while the last two address policymakers. However, all six call for collective action and draw a focus to integrating and implementing previously identified needs and best practices for a smooth transition towards a low-carbon economy. These recommendations are aimed at inspiring central banks and supervisors– NGFS members and non-members – to take the necessary measures to foster a greener financial system. We need to take action and we cannot and will not do this alone. We will globally cooperate with policy makers, the financial sector, academia and other stakeholders to distill best practices in addressing climate-related risks.

The achievements of the NGFS and the rapid expansion of its membership within a year have exceeded my expectations. However, we are not there yet. These recommendations represent only the Network's beginnings, as there is much work to be done in order to equip these aforementioned actors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. Future deliverables include a handbook on climate and environmental risk management, voluntary guidelines on scenario-based risk analysis and best practices for incorporating sustainability criteria into central banks' portfolio management. Going forward, the NGFS also expects to dedicate more resources to the analysis of environmental risks.

I am confident that the brain trust of the NGFS will continue to grow and evolve, keeping in mind the aim of having the financial sector worldwide contribute toward a greener future. As chair, I am very proud of what the NGFS has accomplished in only 16 months since its creation, and I look forward to consolidating our work during the coming years.

Finally, I would like to extend my thanks to the tremendous amount of work done by everyone involved in this endeavour, the chairs and members of the three working groups and my team at De Nederlandsche Bank. In particular I would like to thank the secretariat at the Banque de France, without whom we would not have stood where we stand today.

Contents

Boxes

Executive summary

In the October 2018 progress report, NGFS members acknowledged that ***"climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks."*** The legal mandates of central banks and financial supervisors vary throughout the NGFS membership, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions. Even though the prime responsibility for ensuring the success of the Paris Agreement rests with governments, it is up to central banks and supervisors to shape and deliver on their substantial role in addressing climate-related risks within the remit of their mandates. Understanding how structural changes affect the financial system and the economy is core to fulfilling these responsibilities.

Climate change is one of many sources of structural change affecting the financial system.[1] However, it has distinctive characteristics that mean it needs to be considered and managed differently. These include:

- **Far-reaching impact in breadth and magnitude:** climate change will affect all agents in the economy (households, businesses, governments), across all sectors and geographies. The risks will likely be correlated with and potentially aggravated by tipping points, in a non-linear fashion. This means the impacts could be much larger, and more widespread and diverse than those of other structural changes.
- **Foreseeable nature:** while the exact outcomes, time horizon and future pathway are uncertain, there is a high degree of certainty that some combination of physical and transition risks will materialise in the future.
- **Irreversibility:** the impact of climate change is determined by the concentration of greenhouse gas (GHG) emissions in the atmosphere and there is currently no mature technology to reverse the process. Above a certain threshold, scientists have shown with a high degree of confidence that climate change will have irreversible consequences on our planet, though uncertainty remains about the exact severity and time horizon.
- **Dependency on short-term actions:** the magnitude and nature of the future impacts will be determined by actions taken today, which thus need to follow a credible and forward-looking policy path. This includes actions by governments, central banks and supervisors, financial market participants, firms and households.

While today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change, climate science leaves little doubt: action to mitigate and adapt to climate change is needed now. The NGFS recognises that there is **a strong risk that climate-related financial risks are not fully reflected in asset valuations**. There is **a need for collective leadership and globally coordinated action** and, therefore, the role of international organisations and platforms is critical.

The NGFS, as a coalition of the willing and a voluntary, consensus-based forum provides **six recommendations** for central banks, supervisors, policymakers and financial institutions to enhance their role in the greening of the financial system and the managing of environment and climate-related risks. The recommendations are not binding and reflect the best practices identified by NGFS members to facilitate the role of the financial sector in achieving the objectives of the Paris Agreement.

Recommendations n°1 to 4 *are aimed at inspiring central banks and supervisors – NGFS members and non-members – to take these best practices on board when it fits within their mandate. Parts of these recommendations may also be applicable to financial institutions.*

Recommendation n°1: Integrating climate-related risks into financial stability monitoring and micro-supervision.

Important steps in this regard include:

a) Assessing climate-related financial risks in the financial system by:

- mapping physical and transition risk transmission channels within the financial system and adopting key risk indicators to monitor these risks;

---

[1] The report focuses on climate-related risks rather than environment-related risks.

- conducting quantitative climate-related risk analysis to size the risks across the financial system, using a consistent and comparable set of data-driven scenarios encompassing a range of different plausible future states of the world;
- considering how the physical and transition impact of climate change can be included in macroeconomic forecasting and financial stability monitoring.

b) Integrating climate-related risks into prudential supervision, including:

- Engaging with financial firms:
  - to ensure that climate-related risks are understood and discussed at board level, considered in risk management and investment decisions and embedded into firms' strategy;
  - to ensure the identification, analysis, and, as applicable, management and reporting of climate-related financial risks.
- Setting supervisory expectations to provide guidance to financial firms as understanding evolves.

Recommendation n°2: Integrating sustainability factors into own-portfolio management.

Acknowledging the different institutional arrangements in each jurisdiction, the NGFS encourages central banks to lead by example in their own operations. Without prejudice to their mandates and status, this includes integrating sustainability factors into the management of some of the portfolios at hand (own funds, pension funds and reserves to the extent possible).

Notwithstanding that the focus of central banks incorporating environmental, social and governance (ESG) aspects into their portfolio management has been on own funds and pension portfolios, some voices have called for an extension of this approach to monetary policy. Going forward, the NGFS considers exploring the interaction between climate change and central banks' mandates (beyond financial stability) and the effects of climate-related risks on the monetary policy frameworks, paying due regard to their respective legal mandates.

Recommendation n°3: Bridging the data gaps.

The NGFS recommends that the appropriate public authorities share data of relevance to Climate Risk Assessment (CRA) and, whenever possible, make them publicly available in a data repository. In that respect, the NGFS sees merit in setting up a joint working group with interested parties to bridge the existing data gaps.

Recommendation n°4: Building awareness and intellectual capacity and encouraging technical assistance and knowledge sharing.

The NGFS encourages central banks, supervisors and financial institutions to build in-house capacity and to collaborate within their institutions, with each other and with wider stakeholders to improve their understanding of how climate-related factors translate into financial risks and opportunities. The NGFS also encourages relevant parties to offer technical assistance to raise awareness and build capacity in emerging and developing economies.

Recommendations n°5 and 6 *do not fall directly within the remit of central banks and supervisors but point to actions that can be taken by policymakers to facilitate the work of central banks and supervisors. Parts of these recommendations may also be applicable to the private sector.*

Recommendation n°5: Achieving robust and internationally consistent climate and environment-related disclosure.

The NGFS emphasises the importance of a robust and internationally consistent climate and environmental disclosure framework. NGFS members collectively pledge their support for the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD). The NGFS encourages all companies issuing public debt or equity as well as financial sector institutions to disclose in line with the TCFD recommendations. The NGFS recommends that policymakers and supervisors consider further actions to foster a broader adoption of the TCFD recommendations and the development of an internationally consistent environmental disclosure framework.

Recommendation n°6: Supporting the development of a taxonomy of economic activities.

The NGFS encourages policymakers to bring together the relevant stakeholders and experts to develop a taxonomy that enhances the transparency around which economic activities (i) contribute to the transition to a green and low-carbon economy and (ii) are more exposed to climate and environment-related risks (both physical and transition). Such a taxonomy would:

- facilitate financial institutions' identification, assessment and management of climate and environment-related risks;
- help gain a better understanding of potential risk differentials between different types of assets;
- mobilise capital for green and low-carbon investments consistent with the Paris Agreement.

To some extent, recommendations n°1-4 require the implementation of recommendations n°5-6, but this does not preclude central banks and supervisors from acting now.

Going forward, the NGFS will continue its work as long as its members deem it necessary and useful. The lesson drawn from the first sixteen months of NGFS activity is that climate change presents significant financial risks that are best mitigated through an early and orderly transition.

To ensure such a smooth transition, there is still a significant amount of analytical work to be done in order to equip central banks and supervisors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. This calls for a close and specific dialogue with academia and for further technical work to translate the NGFS recommendations or observations into operational policies and processes.

More precisely, the NGFS is planning to develop:
(i) a handbook on climate and environment-related risk management for supervisory authorities and financial institutions;
(ii) voluntary guidelines on scenario-based risk analysis;
(iii) best practices for incorporating sustainability criteria into central banks' portfolio management (particularly with regard to climate-friendly investments).

This report has been coordinated by the NGFS Secretariat/Banque de France.
For more details, go to *https://www.banque-france.fr*
or contact the NGFS Secretariat *sec.ngfs@banque-france.fr*

BANQUE DE FRANCE
EUROSYSTÈME

NGFS
Secretariat

1 Climate change as a source of economic and financial risks

The Intergovernmental Panel on Climate Change (IPCC) has concluded that anthropogenic emissions have increased since the pre-industrial era, driven largely by economic and population growth. This has led to increased concentrations of GHGs which are unprecedented in at least 800,000 years.[3] This is extremely likely to have been the dominant cause of the observed warming since the mid-20th century. Temperatures are now at least 1°C above pre-industrial levels.

Climate scientists have concluded that continued emissions in line with historical rates would lead to warming of 1.5°C between 2030 and 2052.[4] This would cause long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems.

BOX 1

Distinguishing between climate and environment-related risks

The NGFS aims to contribute to the development of environment and climate-related risk management in the financial sector. By **environment-related risks**, this report refers to risks (credit, market, operational and legal risks, etc.) posed by the exposure of financial firms and/or the financial sector to activities that may potentially cause or be affected by environmental degradation (such as air pollution, water pollution and scarcity of fresh water, land contamination, reduced biodiversity and deforestation). By **climate-related risks**, the report refers to risks posed by the exposure of financial firms and/or the financial sector to physical or transition risks caused by or related to climate change (such as damage caused by extreme weather events or a decline of asset value in carbon-intensive sectors).

This report focuses on climate-related risks rather than environmental risks for two main reasons: first, the transition to a low-carbon economy consistent with the objectives of the Paris Agreement requires a radical shift of resource allocation and, thus, a seminal response by the financial sector. It was first against this background that the NGFS was founded. Second, climate change itself poses a major challenge – if not the major challenge – of our time and its impact will be felt globally, thus demanding a strong international response and multilateral cooperation, particularly given that the impacts of climate change may only be felt many years into the future, and yet are determined by the actions we take today.

Nevertheless, there are compelling reasons why the NGFS should also look at environmental risks relevant to the financial system. For instance, environmental degradation could cascade to risks for financial institutions, as reduced availability of fresh water or a lack of biodiversity could limit the operations of businesses in a specific region. These could turn into drivers of financial risks and affect financial institutions' exposures to those businesses.[1] Also, it is important to be aware of potential greater impacts due to the combined effects of climate and environmental risks. Against this background, the NGFS expects to dedicate more resources to the analysis of environmental risks going forward.

[1] Schellekens, Van Toor (DNB), *Values at risk? Sustainability risks and goals in the Dutch financial sector*, 2019.

---

[3] IPCC, *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014.

[4] IPCC, *Global Warming of 1.5°C, Summary for Policymakers*, 2018.

1.1 Climate change is a source of structural change in the economy and financial system and therefore falls within the mandate of central banks and supervisors

The legal mandates of central banks and financial supervisors vary throughout the NGFS membership, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions. Understanding structural changes to the financial system and the economy is core to fulfilling these responsibilities. Climate change is one source of structural change.[5] As highlighted by the NGFS October 2018 progress report, climate change may result in physical and transition risks that can have system-wide impacts on financial stability and might adversely affect macroeconomic conditions.

Physical impacts include the economic costs and financial losses resulting from the increasing severity and frequency of extreme climate change-related weather events (such as heat waves, landslides, floods, wildfires and storms) as well as longer term progressive shifts of the climate (such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures).

Transition impacts relate to the process of adjustment towards a low-carbon economy.[6] Emissions must eventually reach "net zero" to prevent further climate change. The process of reducing emissions is likely to have significant impact on all sectors of the economy affecting financial assets values. While urgent action is desirable, an abrupt transition could also have an impact on financial stability and the economy more broadly.

These risks might have persistent impacts on macroeconomic and financial variables (for instance, growth, productivity, food and energy prices, inflation expectations and insurance costs) **that are fundamental to achieving central banks' monetary policy mandates**.[7]

Nevertheless, the prime responsibility for ensuring the success of the Paris Agreement rests with governments. Yet, it is up to the central banks and supervisors to shape and deliver on their substantial role in addressing climate-related risks, although the NGFS remains mindful that not all its member-central banks have the same mandates for action. An understanding of the links between broader climate policy and the mandates of central banks and supervisors is therefore necessary.

1.2 Climate change is different from other sources of structural change

Climate change is one of many sources of structural change. However, it has distinctive characteristics that mean it needs to be considered and managed differently.

These include:

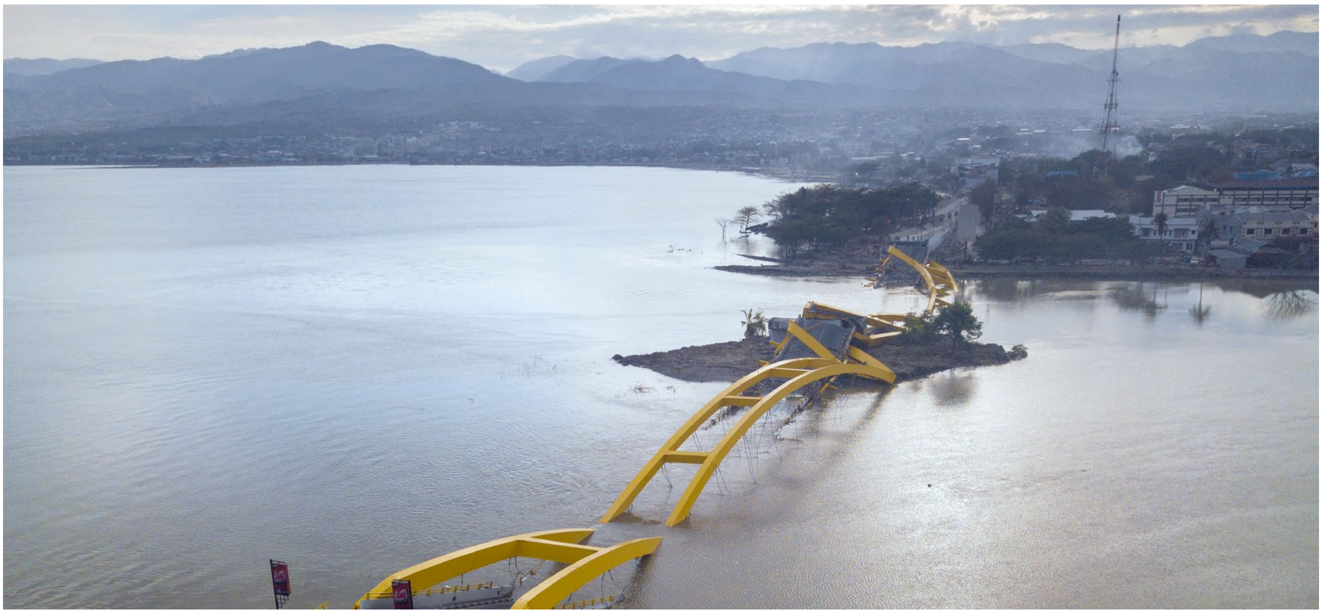
- **Far-reaching impact in breadth and magnitude:** climate change will affect all agents in the economy (households, businesses, governments), across all sectors and geographies. The risks will likely be correlated and, potentially aggravated by tipping points, in a non-linear fashion. This means the impacts could be much larger, and more widespread and diverse than those of other structural changes.
- **Foreseeable nature:** while the exact outcomes, time horizon and future pathway are uncertain, there is a high degree of certainty that some combination of increasing physical and transition risks will materialise in the future.
- **Irreversibility:** the impact of climate change is determined by the concentration of greenhouse gas (GHG) emissions in the atmosphere and there is currently no mature technology to reverse the process. Above a certain threshold, scientists have shown with a high degree of confidence that climate change will have irreversible consequences on our planet, though uncertainty remains about the exact severity and time horizon.
- **Dependency on short-term actions:** the magnitude and nature of the future impacts will be determined by

---

[5] Some NGFS members have extended this analysis to broader environmental risks, which are also considered within supervisory and financial stability mandates.

[6] In its work, the NGFS has incorporated the risk associated with emerging legal cases related to climate change for governments, firms and investors, e.g. liability risks, as a subset of physical and transition risks.

[7] See, for instance, the speech by Benoît Cœuré, Member of the Executive Board of the European Central Bank, at a conference on "Scaling up Green Finance: The Role of Central Banks", organised by the Network for Greening the Financial System, the Deutsche Bundesbank and the Council on Economic Policies, Berlin, 8 November 2018.



actions taken today which thus need to follow a credible and forward-looking policy path. This includes actions by governments, central banks and supervisors, financial market participants, firms and households.

1.3 How climate change might affect the economy and financial stability

1.3.1 Understanding the possible impacts of physical risks

Extreme weather events impact health and damage infrastructure and private property, reducing wealth and decreasing productivity. These events can disrupt economic activity and trade, creating resource shortages and diverting capital from more productive uses (e.g. technology and innovation) to reconstruction and replacement. Uncertainty about future losses could also lead to higher precautionary savings and lower investment.

Physical impacts are not just risks for the future; they are already impacting the economy and financial system today. Overall, worldwide economic costs from natural disasters have exceeded the 30-year average of USD 140 billion per annum in 7 of the last 10 years.[8] Since the 1980s, the number of extreme weather events has more than tripled.[9]

Over a longer time horizon, progressive changes in the natural environment will impact the liveability of different regions, particularly if mean temperatures rise by more than 1.5 to 2°C compared to pre-industrial levels. This is due to the significant risks related to human health, food security, water resources, heat exposure and sea level rise.[10]

Estimates suggest that absent action to reduce emissions, the physical impact of climate change on the global economy in the second half of the century will be substantial. The more sophisticated studies suggest average global incomes may be reduced by up to a quarter by the end of the century.[11] In addition, the increased probability of disruptive events such as mass migration, political instability and conflict in these scenarios means that economic estimates are likely to understate the size and timing of the associated risks.

---

[8] Munich Reinsurance Company (2019), "Natural Catastrophe Review 2018" *Geo Risks Research*, NatCatSERVICE.

[9] Munich Reinsurance Company (2018), "A stormy year: Natural catastrophe 2017" *Geo Risks Research*, NatCatSERVICE.

[10] IPCC (2018), Chapter 3.

[11] See, for example, Burke, Hsiang and Miguel, "Global Non-Linear Effect of Temperature on Economic Production", *Nature* Vol. 527, pp. 235-239 (12 November 2015).

There have been fewer attempts to quantify the physical risks to financial stability rather than for the economy as a whole, but again losses are likely to be significant. Studies estimate that the financial value at risk could be up to 17% depending on the mean average temperature rise.[12]

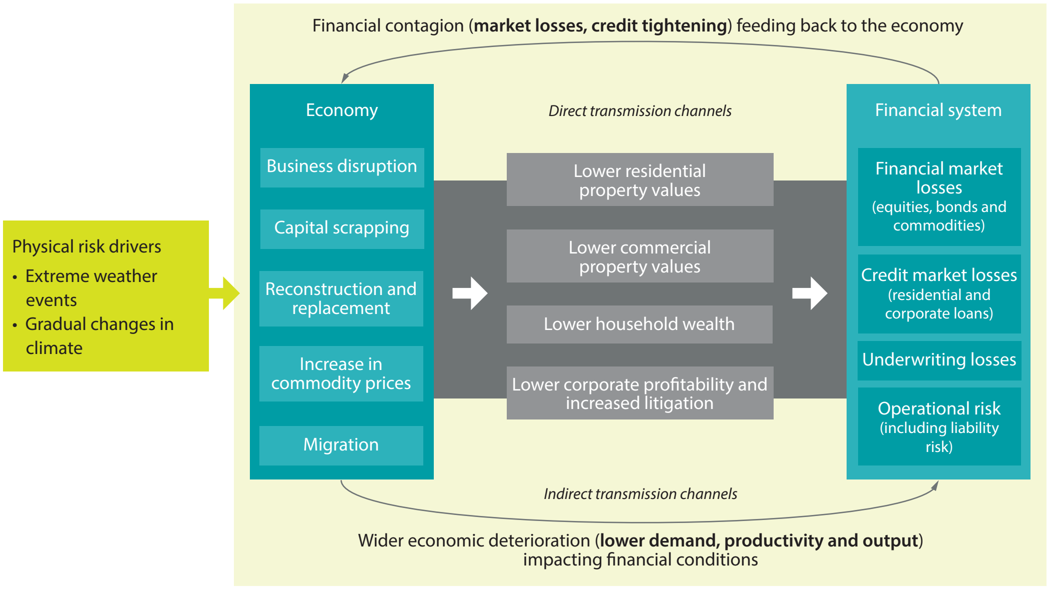
If losses are insured, more frequent and severe weather events affect insurance firms directly through higher claims and their customers indirectly via higher premiums. If losses are uninsured, the burden falls on households, companies and ultimately governments' budgets. A change in the debt repayment capacity of borrowers or a fall in collateral values can increase credit risks for banks and other lenders. A change in lenders' projected earnings would also be reflected in financial markets, impacting investors and asset owners.

Feedback loops between the financial system and the macroeconomy could further exacerbate these impacts and risks. For example, damage to assets serving as collateral could create losses that prompt banks to restrict their lending in certain regions, reducing the financing available for reconstruction in affected areas. At the same time, these losses weaken household wealth and could in turn reduce consumption.

The broad, global averages referenced above mask significant differences in the distribution of economic impacts and financial risks across regions and sectors. This variation is driven not only by differences in the gross exposure to physical risks, but also by the level of resilience and adaptation (action taken to prevent or minimise damage). Countries with less economic diversification, less climate resilient public infrastructure, less capital market flexibility and lower capacity to adapt will be at greater risk. Particular sectors could be at greater risk too, depending on their regional footprint.

These estimates represent a lower bound. Currently, physical impact models for both the economy and financial stability are partial. They typically cover only a handful of the possible transmission channels in order to make them tractable and neglect wider socio-economic impacts. Non-modelled impacts are also often estimated separately. A more holistic approach is needed to understand the relationship between different levels of risks, resilience and adaptation. The non-linearities stemming from the increasing risk of tipping points, and the potential for these to accelerate in the near term, are a core part of climate modelling that need to be better captured in economic and financial risk models.

Figure 1 **From physical risk to financial stability risks**



---

[12] One study found that almost 2% of the world's financial assets are at risk if the global mean surface temperature rises by 2.5°C compared to pre-industrial levels (Dietz, Bowen, Dixon and Gradwell "Climate value at risk' of global financial assets" *Nature Climate Change*, 2016). Warming of 5°C could result in losses equal to 5% of the global stock of manageable assets ("The cost of inaction: Recognising the value at risk from climate change", *The Economist Intelligence Unit*, 2015).

1.3.2 Understanding the possible impacts of transition risks

The potential severity of the physical impacts of climate change and the direct correlation with the concentration of greenhouse gases (GHG) motivated the international community to commit to reducing emissions in Paris in December 2015. The Paris Agreement aims to limit the rise in global average temperatures to well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5°C. Signatories agreed to reach global peaking of GHG emissions as soon as possible and to undertake rapid reductions thereafter, so as to achieve net zero emissions in the second half of this century.

The transition to a low GHG economy requires rapid and far-reaching transitions in energy, land, urban, infrastructure and industrial systems. **The scale of the economic and financial transformation related to this transition is significant, bringing both risks and opportunities for the economy and the financial system.** The Intergovernmental Panel on Climate Change (IPCC) projects the necessary additional energy-related investments compatible with a 1.5°C scenario for the period 2016-2050 to reach USD 830 billion annually.[13] The European Union alone has identified an annual investment gap amounting to almost EUR 180 billion to achieve its climate and energy targets.[14] Although the incremental change in total investment is not large, it would require a significant redirection of capital toward green finance.[15] For example, the OECD estimates that to achieve the 2°C target, bonds financing and refinancing in the renewable energy, energy efficiency and low-emission vehicle sectors have the potential to reach USD 620 billion to USD 720 billion in annual issuance and USD 4.7 trillion to USD 5.6 trillion in outstanding securities by 2035.[16]

Despite its rapid growth in the last few years, this is well beyond what the green bond market amounts to nowadays, namely an issuance volume of about USD 168 billion in 2018 after USD 162 billion in 2017 and USD 85 billion in 2016.[17] Although the green bond market does not account for all green investments, it provides a signal of the scaling up of green finance. The increase in volume has spurred the development of new green financial assets: for example, in addition to the already dynamic green bond market, new products have emerged such as green covered bonds and green securities.

This shift in investment would result in significant structural changes in the economy compared to today and some studies have sought to quantify the impacts of such a transition. Summarising the results of 31 models, the IPCC (2014) concluded that the costs of limiting warming to 2°C (with a 66% probability) would be between 1-4% of global aggregate consumption by 2030 compared to current economic forecasts.

Intuitively, the economic costs of the transition would stem from a disruptive transition and the need to switch to – initially more expensive – low-carbon technologies in some sectors, for instance, aviation or cement and steel production. However, these costs and the precise transition pathways will vary from country to country depending on the existing capital stock and may be more or less likely due to different political, technological and socioeconomic conditions. Moreover the costs and pathway for the transition can change over time depending on future choices made (e.g. infrastructure investment, a sudden decision by policy makers to cut subsidies for renewables energy or a sudden shift of consumers towards greener choices). **Nevertheless, the estimated costs are likely to be small compared to the costs of no climate action.**

In addition, these cost estimates are not universally accepted and **some argue that the economic costs of the transition to a low-carbon economy would be offset by a positive "green growth" effect.** According to this theory, ambitious climate policies aimed at achieving structural reforms would boost innovation and job creation and lower production costs.[18]

---

[13] IPCC, *Global Warming of 1.5°C, Summary for Policymakers* 2018.

[14] European Commission, *Action Plan: Financing Sustainable Growth*, 2018.

[15] The G20 Green Finance Study Group (GFSG, 2016) defines "green finance" as "financing of investments that provide [climate and] environmental benefits in the broader context of environmentally sustainable development".

[16] OECD, *Mobilising Bond Markets for a Low-Carbon Transition*, Paris, 2017.

[17] Sustainable Banking Network, *Creating green bond markets-insight, innovations and tools from the emerging markets*, October 2018. Green bond issuances have been stable in 2018, but the sustainable bond universe grew steadily (Climate Bonds Initiative, *Green bonds: The state of the market 2018*, 2019).

[18] ESRB, *Too late, too sudden: Transition to a low-carbon economy and systemic risk*, 2016; Finansinspektionen, *Climate change and financial stability*, 2016.

This would benefit the global economy in the short and medium term in aggregate.[19] This notion is called the **"Porter Hypothesis"**.[20] However, empirical evidence of this effect, focusing on smaller scale case studies, is mixed.[21]

What the literature does show is that, firstly, while the transition would result in a significant structural change in the economy – and some regions and sectors will fare better than others – the overall costs of the transition would be much lower than those that would arise absent action, i.e. in a "hot house world". Secondly, infrastructure decisions today affect choices in the future. Delaying the transition to a low-carbon stock means that sharper (and more costly) emissions cuts would be required in the future to meet a given policy target. The speed and timing of the transition is crucial: an orderly scenario, with clear policy signalling, would allow adequate time for existing infrastructure to be replaced and for technological progress to keep energy costs at a reasonable level.[22] In contrast, a disorderly, sudden, uncoordinated, unanticipated or discontinuous transition would be disruptive and costly, particularly for those sectors and regions that are more vulnerable to structural change.

Comparing economic estimates is, however, difficult because the models define a wide range of possible values for employment, investment, population, productivity and growth. Further research is needed to narrow the range of plausible values to be incorporated into economic models, particularly taking into account country and sectoral differences.

The potential risks to the financial system from the transition are greatest in scenarios where the redirection of capital and policy measures such as the introduction of a carbon tax occur in an unexpected or otherwise disorderly way. So far, scenarios have largely focussed on the potential for assets to become stranded when infrastructure has to be retired before the end of its useful life in order to meet emissions reduction targets. Stranded assets will fall in value leading to losses of both capital and

---

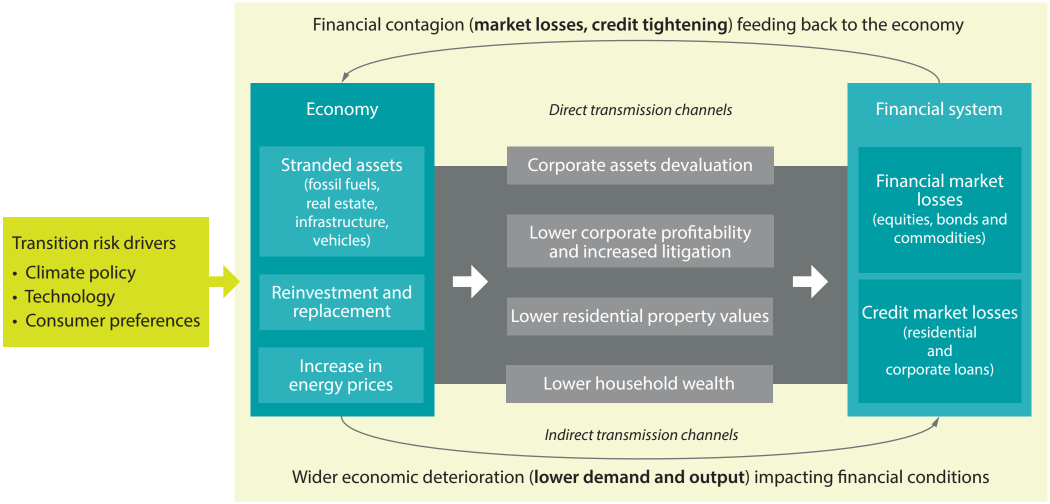
[19] OECD, *Investing in Climate, Investing in Growth*, 2017.

[20] Porter and van der Linde, "Toward a New Conception of the Environment-Competitiveness Relationship" *Journal of Economic Perspectives*, Vol. 9 (4): pp. 97-118, 1995.

[21] Jaffe, Newell and Stavins, "Technological Change and the Environment", *Working Paper* No. 7970, National Bureau of Economic Research, 2000; Berman and Bui, "Environmental Regulation and Productivity: Evidence from Oil Refineries", *NBER Working Paper* No. 6776, November 1998; Gray and Shadbegian, "Environmental Regulation, Investment Timing, and Technology Choice", *Working Paper* No. 6036, National Bureau of Economic Research, May 1997.

[22] ESRB, *Too late, too sudden: Transition to a low-carbon economy and systemic risk*, 2016; Finansinspektionen, *Climate change and financial stability*, 2016.

Figure 2 **From transition risk to financial stability risks**



income for owners but also to increased market and credit risks for lenders and investors.

Many of these studies on the transition risks of climate change are partial and often focus on the energy sector. A smaller number of studies are broader in scope, covering transition impacts to entire economic segments. **Estimates of losses in these studies are large and range from USD 1 trillion to USD 4 trillion when considering the energy sector alone,[23] or up to USD 20 trillion when looking at the economy more broadly.[24]** More research is needed to understand how these impacts translate into systemic risks for financial markets, particularly taking second order effects into account. A wholesale reassessment could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions, which would constitute a climate Minsky moment.[25]

Translating economic transition loss estimates into financial risks is challenging because often the macroeconomic models used were developed for a different purpose, such as calculating the social cost of carbon or the cost of meeting a particular emissions target. Linking these macroeconomic models to financial portfolios requires granular and holistic outputs at a firm, regional and sectoral level to better support bottom-up analysis.

1.4 The future impacts provide a loud wake-up call

If we continue along our current global emissions trajectory, the physical risks from climate change are likely to significantly change where and how we live in the second half of the century. Even though considerable effects of climate change on the economy are widely expected, due to various limitations in our economic models, quantitative estimates today can only give an indication of how big the impacts on the economy and the financial system might be.

Measures to smooth the climate-related structural changes towards a low GHG economy would minimise these risks. As mentioned before, the overall costs of the transition would be much lower than those in a "hot-house world". The size and nature of the risks will therefore be dependent on actions today.

---

[23] See IEA and IRENA, *Perspectives for the Energy Transition*, 2017.

[24] See IEA and IRENA (2017). There is also a difference in the methodology used. The IEA estimates stranded *capital* while IRENA estimates stranded *value*. For instance, in the upstream oil and gas sector, the IEA considers investments that oil & gas firms have made into exploration, which may not be recouped. IRENA, on the other hand, considers the potential priced-in market value of explored reserves, which, as one might expect, is higher than the cost of exploration.

[25] Bank of England Prudential Regulation Authority (2018), *Transition in Thinking: The impact of climate change on the UK banking sector*.

2 A call for action: what central banks and supervisors can do and how policymakers can facilitate our work

While today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change, **climate science leaves little doubt: action to mitigate and adapt to climate change is needed now**. At the country level, governments and agencies should step up their efforts to implement effective policies that incentivise sustainable practices, while firms should develop business strategies and risk management controls that achieve sustainability in the long term.

There is a need for global collective leadership and coordinated action and, therefore, the role of international organisations and fora is critical. The NGFS, as a coalition of the willing and a voluntary, consensus-based forum, acknowledges this fact. **It is within this context that we set out a number of recommendations for central banks, supervisors and policymakers to do more.**

The following six non-binding recommendations reflect the best practices identified so far by NGFS members to facilitate the role of the financial sector in achieving the objectives of the Paris Agreement.

- **Recommendations n°1 to 4 are aimed at inspiring central banks and supervisors** – NGFS members and non-members – to take these best practices on board as it fits within their mandate. Parts of these recommendations may also be applicable to financial institutions.

- **Recommendations n°5 and 6 do not fall directly within the remit of central banks and supervisors** but point to actions that can be taken by policymakers to facilitate the work of central banks and supervisors. Parts of these recommendations may also be applicable to the private sector.

2.1 Recommendation n°1
Integrating climate-related risks into financial stability monitoring and micro-supervision

The NGFS acknowledges that climate-related risks are a source of financial risk and therefore calls on central banks and supervisors to start integrating climate-related risks into micro-supervision and financial stability monitoring. Important steps in this regard include:

1) Assessing climate-related financial risks in the financial system by:
- **mapping physical and transition risk transmission channels within the financial system and adopting key risk indicators to monitor these risks;**
- **conducting quantitative climate-related risk analysis to size the risks across the financial system, using a consistent and comparable set of data-driven scenarios encompassing a range of different plausible future states of the world;**
- **considering how the physical and transition impact of climate change can be included in macroeconomic forecasting and financial stability monitoring.**

2) Integrating climate-related risks into prudential supervision, including:
- **engaging with financial firms:**
  - **to ensure that climate-related risks are understood and discussed at board level, considered in risk management and investment decisions and embedded into firms' strategy;**
  - **to ensure the identification, analysis, and, as applicable, management and reporting of climate-related financial risks.**
- **setting supervisory expectations to provide guidance to financial firms, as understanding evolves.**

2.1.1 Assessing climate-related financial risks in the financial system

Scenario analysis is an important tool to help central banks and supervisors assess how climate change will impact the macroeconomy, financial system and safety and soundness of financial firms. The NGFS has therefore been considering how it could be implemented into authorities' toolkits.

There are several challenges that need to be highlighted in the development of workable scenarios for the financial impact of climate change. Assessing the impacts of climate change can be challenging because of the uncertainties around the course of climate change itself, the breadth and complexity of transmission channels, the primary and secondary impacts and the need to consider, in aggregate, some combination of both physical and transition risks. Even if all these challenges were addressed, over long time horizons, estimates will be highly dependent on the assumptions made about how climate policy and technology will evolve.

The future of climate policy is highly uncertain especially given the extended time horizons and political economy considerations. Policies must be initiated far in advance of the benefits being realised, while costs typically occur more immediately. Furthermore, the rate of progress in low-carbon technologies will be instrumental in determining the emissions reductions that are technically and economically feasible. It will also determine the extent of disruption to current business models in various sectors. Scenario analysis requires assumptions about whether emissions targets are met and when and how policymakers choose to act. These decisions may of course not be uniform in every region.

Given the sensitivity of results to these underlying assumptions, **hypothetical transition scenarios can be used to explore the direction and broad scale of outcomes**.

BOX 2

Designing a scenario analysis framework for central banks and supervisors

To contribute to central banks' and supervisors' ongoing work in this area, **the NGFS is developing an analytical framework for assessing climate-related risks, in order to size the impact of climate-related risks on the economy and the financial stability**. This includes looking at the different possible outcomes for climate change and the policies to mitigate it, assessing the financial impact and determining the timeframes during which risks could materialise.

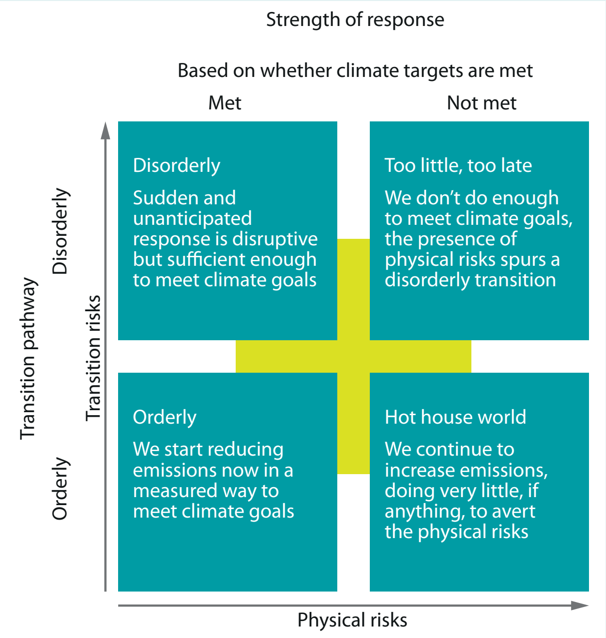
In its work so far, the NGFS has undertaken a **literature review** of existing scenarios to consider the most important design decisions when sizing macrofinancial risks. The NGFS has concluded that there are two important dimensions to consider when assessing the impact of physical risks and transition risks on the economy and the financial system.

- The total level of mitigation or, in other words, **how much action is taken** to reduce greenhouse gas emissions (leading to a particular climate outcome).
- Whether the transition occurs in an orderly or disorderly way, i.e. **how smoothly and foreseeably the actions are taken**.

Across these two dimensions there is a continuum of different outcomes and transition pathways to achieve them. However, to simplify the analytical exercise, four representative **high-level scenarios** have been developed that take both these dimensions into consideration.

The bottom-right scenario can help central banks and supervisors consider the long-term physical risks to the economy and financial system if we continue on our current "hot house world" pathway. The bottom-left orderly scenario can help us understand how climate policy (such as a carbon price) and other shifts in technology and sentiment to reduce emissions would affect the economy and the financial system.

The two scenarios at the top can help central banks and supervisors consider how physical and transition risks could crystallise in the economy and the financial system over a short time period (for example, in response to extreme weather events or a shift in climate policy leading to a sudden reassessment of future developments).



	Met	Not met
Disorderly	Disorderly Sudden and unanticipated response is disruptive but sufficient enough to meet climate goals	Too little, too late We don't do enough to meet climate goals, the presence of physical risks spurs a disorderly transition
Orderly	Orderly We start reducing emissions now in a measured way to meet climate goals	Hot house world We continue to increase emissions, doing very little, if anything, to avert the physical risks

In the next phase, **the NGFS will develop a more detailed data-driven narrative and quantitative parameters as a foundation to these scenarios** and enable central banks and supervisors to explore some of these questions in their own jurisdictions. This will include proposing key assumptions for policy and technological change. During this design phase, the NGFS will work with academic experts, scenario designers and financial firms to ensure the scenarios are fit for purpose.

Looking ahead, NGFS members may incorporate these scenarios into their domestic work programmes. This would provide a case study for other central banks and supervisors that are considering running similar exercises and provide some feedback for the calibration of the scenarios.

Although these scenarios are primarily being developed by central banks and supervisors in support of their own work and objectives, these scenarios may provide a useful input for other stakeholders, such as financial and non-financial firms, in considering how they may be impacted by climate change.

These scenarios should have a clear, plausible, qualitative narrative but also be data-driven and provide quantitative parameters to help anchor assessments of economic costs and financial risks. They can help identify sectors or geographies which are particularly vulnerable either to physical or transition risks or a combination thereof. Ultimately, they should be suitable to help explore materially different plausible future states of the world over different time horizons.

The different states of the world that feature prominently in the existing literature on scenario analysis (and are key determinants of risk) include those where international climate targets are either met or not, and those where the transition to a low-carbon economy occurs in an orderly or disorderly way.

Using a consistent set of transition scenarios can help to enhance the comparability of different analyses. Work to standardise some of the macroeconomic assumptions in transition scenarios is already underway and could be developed further.[26] However, it is vital that common scenarios do not unduly constrain or narrow the analysis and results.

Further work is also required to translate these economic scenarios into financial risk parameters for financial stability analysis. This would help supervisors assess the financial stability risks across the system. Key risk indicators allow us to track which future scenarios are most likely to materialise and whether the economy and financial system need to adjust to minimise the potential risks.

Common scenarios should only provide a starting point for supervisors and firms to carry out bespoke analyses on the risks to their balance sheet. Financial firms should not wait for central banks or supervisors (or others) to deliver some kind of universal, perfect model. Rather, they should initiate their own structured analytical work to identify risks and vulnerabilities, which, successively, can become more and more quantified and sophisticated.

2.1.2 Integrating climate-related risks into prudential supervision

The NGFS stock-taking exercise on national supervisory frameworks and practices concluded that **the integration of climate-related factors into prudential supervision is at an early stage.** However, it also shows that over the last few years, many authorities have made significant progress within this area, and methods and tools to assess the financial risks of climate change from both physical and transition risks are gradually developing.

To contribute to central banks' and supervisors' ongoing work to integrate these issues into their operations, and based on the experiences and best practices identified within its membership, the NGFS proposes a high-level framework summarised in Figure 3.

Raising awareness and building capacity

The first step is for national and supra-national competent authorities **to build in-house capacity and to collaborate within their institutions**.

This in-house capacity building needs to happen concurrently with integration of climate change into risk assessment to ensure engagement with firms is effective. Initiatives to achieve this include:

- **Increasing awareness of climate issues within institutions** through outreach presentations and bringing together expertise from multiple departments.
- **Providing training courses for frontline supervisors** and financial stability experts. Training can provide an understanding of both the financial risks stemming from climate change, as well as the distinct characteristics of climate issues, e.g. regarding the timing mismatch between action and impact.

Collaboration with other supervisors and with wider stakeholders (think-tanks, NGOs, government departments, environment and climate science experts, and industry bodies from the financial sector) is also important.

---

[26] See the Shared Socioeconomic Pathways (SSPs) project by the International Institute for Applied Systems Analysis (IIASA).

Figure 3 **High-level framework for the integration of climate-related factors into prudential supervision**

Courses of action	Possible measures by supervisors
Raising awareness and building capacity among firms	• Raise awareness of the relevance of climate-related risks publicly and during bilateral meetings; survey firms on the impact of these risks; lay out a strategic roadmap for the handling of climate-related risks. • Build capacity by convening events to progress the translation of scientific findings to financial analysis; set up working groups with firms, for example, on incorporating climate issues into risk management or scenario analysis.
Assessing climate-related risks	• Develop analytical tools and methods for assessing physical and transition risks related to climate change both at a micro- (financial institutions) and macro-level (i.e. the financial system). • Conduct and publish an assessment of these risks at a macro- and micro-level. • Analyse potential underlying risk differentials of "green" and "brown" assets. This pre-supposes that the supervisor and/or jurisdiction have agreed on definitions and classifications for "green" and "brown" activities.
Setting supervisory expectations	• Issue guidance on the appropriate governance, strategy and risk management of climate-related risks by regulated firms. • Train supervisors to assess firms' management of these risks.
Requiring transparency to promote market discipline	• Set out expectations for firms' climate-related disclosures in line with the TCFD recommendations. • Consider integrating climate-related disclosures into Pillar 3.
Mitigating risk through financial resources	• Consider applying capital measures in Pillar 2 for firms that do not meet supervisory expectations or with concentrated exposures. • Based on the risk assessment outlined above, possibly consider integrating it into Pillar 1 capital requirements.

As a next step, most authorities are focusing on engaging with firms to raise awareness and foster capacity building and discussing how the governance structure and strategy of the firm ensures a proper identification, assessment, management and reporting of climate and environment-related risks. In this regard, some central banks and supervisors have undertaken formal information gathering by sending out surveys to regulated firms.[27] Such a survey process can prompt firms to consider the risks more fully and then feed into an analysis of the approaches to address climate-related risks across the industry.[28]

---

[27] See Appendix A of *The impact of climate change on the UK insurance sector A Climate Change Adaptation* Report by the Bank of England Prudential Regulation Authority (PRA), September 2015 and Section 4 of *Transition in thinking: The impact of climate change on the UK banking sector*, PRA, September 2018.

[28] See e.g. Bank of England PRA, *Transition in thinking: The impact of climate change on the UK banking sector*, September 2018 and Finansinspektionen, *Integration of Sustainability into Corporate Governance, A survey of financial firms' public sustainability information*, 7 November 2018.

Developing tools and methods to identify and assess climate-related financial risks

Climate Risk Assessment

Climate Risk Assessment (CRA) refers to the methods and practices used to size the financial impact of climate-related risks to micro-prudential objectives, including:

- **Qualitative CRA** explores the longer-term impacts of different scenarios and provides a descriptive assessment, for example of risk transmission channels to the financial sector. Most member supervisors have undertaken some form of qualitative analysis.
- **Quantitative CRA** represents a numerical approach to sizing the financial risks. It is most effective at assessing the shorter-term financial exposures to physical and transition risks. Fewer authorities have performed quantitative analysis and in general, these studies have been partial, focusing on narrow channels of impact although wider methodologies are being developed.

Over the last few years, there has been significant progress on attempts to size the financial risks from both physical and transition risks. When combined, qualitative and quantitative assessments can provide a fuller picture of the risks the financial sector faces. The list below provides some examples of quantitative CRA.

On the transition risk side:

- Assessing financial institutions' exposures to high-carbon sectors.[29]
- Estimating the impact of a bank's exposure at risk to energy inefficient homes against the background of tightening energy efficiency regulation.
- Incorporating climate-related stresses into sector – or even market – wide stress tests.[30,31]

On the physical risk side:

- Developing climate scenarios based on specific temperature rises and estimating the climate-related claims burden for insurers (see the case studies in Box 3).
- Analysing the consequences of flood scenarios by linking estimated damage to residential and commercial buildings to financial institutions' exposures.
- Calculating a vulnerability index for firms' assets based on their geographical distribution.[32]

---

[29] Regelink, Reinders, Vleeschhouwer, van de Wiel (DNB), *Waterproof? An exploration of climate-related risks for the Dutch financial sector*, 2017.

[30] According to a stress test conducted by DNB, transition risk could lead to substantial losses for banks, leading to a reduction in the banks' CET-1 capital ratios of up to 4.3 percentage points. Vermeulen, Schets, Lohuis, Kölbl, Jansen, Heeringa, *An energy transition risk stress test for the financial system of the Netherlands*, 2018.

[31] Bank of England PRA, *General Insurance Stress Test 2017, Scenario Specification, Guidelines and Instructions*, 11 April 2017.

[32] Regelink, Reinders, Vleeschhouwer, van de Wiel (DNB), *Waterproof? An exploration of climate-related risks for the Dutch financial sector*, 2017.

BOX 3

Case study of quantitative analysis – DNB physical risk CRA tool

Dutch non-life insurers cover most of the economic damage caused by storms, hail and rain. Therefore, changing weather patterns are an important consideration for the insurance sector. In the Netherlands, more than 95% of all non-life insurance policies cover objects within domestic borders. Hence, insurers' claims are heavily related to regional climate change.

The 2017 Waterproof report explored the potential of a changing climate on climate-related claims. Based on scenarios from the Intergovernmental Panel on Climate Change (IPCC), the Dutch Meteorological Institute (KNMI) developed climate scenarios for the Netherlands for a 1.5°C and 3.5°C temperature rise in 2085. These scenarios include more frequent and severe hail and thunder, an increase in the intensity of rainfall and sea level rise. Based on these scenarios, the De Nederlandsche Bank (DNB) calculated the climate-related claims burden in 2085. Lower and higher estimates reflect the substantial uncertainty about the impact of changes in frequency and intensity of weather.

.../...

All scenarios showed an increase in climate-related claims as a result of climate change.

Since products of non-life insurance companies are typically on a one-year horizon, the sector might be able to adapt to the new circumstances on a relatively short notice. However, this would lead to additional pressure on premiums. Supervisors can use these scenario analyses to challenge insurance firms' risk model and climate strategies.

Other institutions have performed CRA exercises as well. According to an internal study by the Deutsche Bundesbank, in early 2018, **German banks' credit exposure to a limited set of carbon intensive industries was relatively small** (with an aggregated exposure of around EUR 157 billion or 4.7% of total loans to domestic households and non-financial corporations). According to a study by the ACPR, **in France, 13% of banks' total net credit was exposed to sectors vulnerable to transition risks** in 2016.[1]

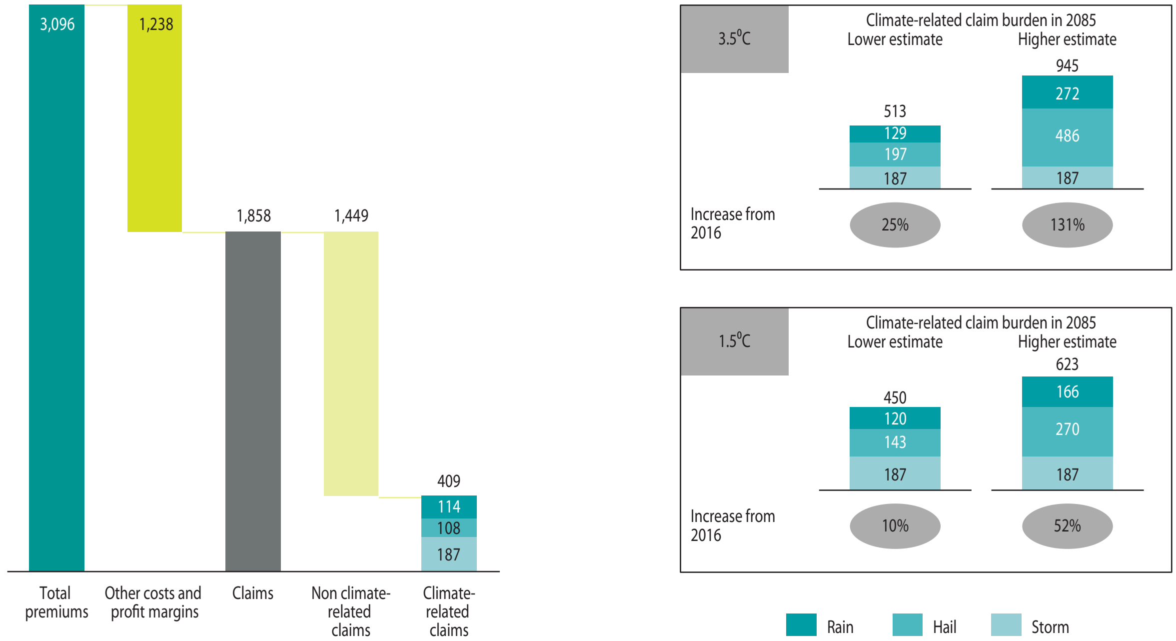
Increase in climate-related claims in 1.5°C and 3.5°C scenarios

C1 **Estimated climate-related claims burden as a proportion of premiums in 2016**

Homeowner's insurance policies *(in EUR millions)*

C2 **Estimated climate-related claims burden in 2085**

Homeowner's insurance policies *(in EUR millions)*



Source: DNB, 2017 Waterproof Report.

Source: DNB, 2017 Waterproof Report.

---

1 French Treasury, ACPR, Banque de France, *Evaluating Climate Change Risks in the Banking Sector*, April 2017.

Analysis of the potential risk differentials between profiles of green, non-green, brown and non-brown assets

From a supervisory perspective, there is a need to understand the potential risk differentials between green, non-green, brown and non-brown assets. If risk differentials are detected, further analysis needs to be performed to assess if the differentials can be attributed to (non-) green or (non-) brown characteristics, or if they are driven by other factors. Important prerequisites for this are clear definitions of which assets can be considered green or brown. Owing to the lack of taxonomies elsewhere, the default rates of these types of assets have not been evaluated in any jurisdiction, except for China.

BOX 4

The China Banking and Insurance Regulatory Commission analysis of default rates of green loans compared to the overall loan portfolio[1]

Data from the China Banking and Insurance Regulatory Commission (CBIRC, formerly the CBRC)[2] showed that, for the **21 largest banks in China as of June 2017, green loans had a non-performing loan (NPL) ratio that is 1.32 percentage points lower on average (at 0.37%) than that of all loans**. CBIRC data also showed that the NPL ratios of green loans were consistently lower than those of all loans for each of the previous four years (2013-16). However, further work is needed to assess whether the differences in performance can be attributed purely to the green/brown characteristics of the related loans.[3]

China was able to conduct this study following the introduction of official definitions for green loans in 2012, and official definitions for green bonds in 2015.[4] Other than China, Brazil is the only other G20 country to have adopted a green loan definition, but no data has been collected in Brazil.

[1] This simple statistical analysis does provide first insights about the relative performances of green and brown assets, but it does not allow inferring broader conclusions about their relative intrinsic riskiness. The study does not indeed control for other factors which influence NPL ratios (different states of the sectoral cycle, average characteristics of counterparties or the loan, etc.). Further data analysis is therefore warranted.

[2] *www.cbrc.gov.cn/*

[3] As an example, borrowers with high profitability and cash flow (i.e. low PD) may be the same borrowers who have the means to invest in modern, "green" production capacity.

[4] In China, the definition of green loans could be traced back to July 2007 in the *Opinions on Implementing Environmental Protection Policies and Regulations to Prevent Credit Risks* (MEP Document No. 108 2007) issued by the Ministry of Environment Protection (MEP), CBRC (the banking regulator) and the PBC, and has been further improved in the *Guidelines on Green Loans* (CBRC Document No. 4 2012) issued in February 2012.

Under prudential frameworks, risk weights are allocated to different asset classes or each individual exposure based on the riskiness of the underlying asset(s), in accordance with local supervisory requirements, usually based on BCBS and IAIS standards.[33] **No jurisdiction, however, has thus far explicitly taken into account the (non-) green or (non-) brown nature of the underlying assets when computing their perceived riskiness.**

The NGFS has performed a preliminary stock-take of studies conducted by market participants on credit risk differentials between green and non-green assets. These studies used either international or local definitions of "green". The preliminary finding of the stock-take is that **it is currently impossible to draw general conclusions on potential risk differentials.** Some studies, based on national and sectoral data found that green loans had lower default and non-performing[34] ratios than non-green loans while others did not.

The studies have covered several types of assets:

- Several studies point to a lower arrears frequency for **residential mortgages** on energy-efficient properties, although borrowers' financial ability and thus repayment capacity is only one of the factors controlled for.[35,36]
- There are fewer studies on **corporate loans**. The China Green Finance Committee (CGFC) found lower NPL ratios for green corporate loans across most corporate industry portfolios. Moody´s carried out a study in 2018 on infrastructure transactions from 1983 to 2016 in both

---

[33] The definition of "non-performing" in these studies is based only on arrears, which differs from other definitions such as in the EU, where the NPL definition includes loans where the borrower has been assessed as "unlikely to pay" by the lender.

[34] The Basel Committee on Banking Supervision (BCBS) is the primary global standard setter for the prudential regulation of banks. The International Association of Insurance Supervisors (IAIS) is responsible for the regulatory cooperation regarding the supervision of the insurance sector.

[35] "Home Energy Efficiency and Mortgage Risks" (2013), by the Institute for Market Transformation (IMT).

[36] E.g. "Impact of energy use and price variations on default risk in commercial mortgages: Case studies" (2017) by Mathew et al., "Insulated from risk? The relationship between energy efficiency of properties and mortgage defaults" (2018), by Guin and Korhonen and *Transition in Thinking: The impact of climate change on the UK banking sector*, case study 1: "Tightening energy efficiency standards and the UK buy-to-let market" (2018), by the Bank of England.

advanced and developing economies.[37] It found that green use-of-proceeds projects exhibit lower cumulative default risk (5.7%) than non-green use-of-proceeds projects (8.5%) in advanced economies. However, Moody´s suggests that the difference is likely to be due to subsample characteristics other than greenness.

- Some studies assess the default implications **from the perspective of loan/bond pricing**, on the basis that companies with lower default probabilities tend to enjoy lower funding costs. One study, based on data of 5,600 loans from the Thomson Reuters DealScan Database, finds that borrowers with better green management have more stable income streams. This makes them less likely to default on loans, violate covenants or file bankruptcy. As a result, the borrowing costs for "greener" companies tend to be lower than those of other companies.[38]
- Two studies found that a premium (ranging from 1 to 7 basis points) exists for **green bonds**. However, the study that found a larger premium has not isolated the "green factor".[39] Another study found no systematic evidence that green bonds would be issued or traded at lower yields than comparable non-green bonds. It highlighted the excess of demand for green bonds as the main driver behind the perceived premium of 1-2 basis points, rather than the explicit "greenness".[40]

However, the number of these studies is small and they typically have three types of limitations:

- most do not fully take into account other variables on borrower characteristics that may affect the default probability;
- country and sectoral coverage is limited;
- the definitions of green/non-green and brown/non-brown assets are not harmonised across the studies, therefore it is not possible to draw a general conclusion on their risk profiles.

The stock-take points to the need for a more thorough examination of existing studies as well as further fact-gathering and analyses. This should pay due regard to non-climate variables that might affect the default rates and performance of green assets. The NGFS intends to perform an exploratory data collection from selected banks in 2019. The objective is to analyse the collected data and assess if there is a risk differential between green and non-green assets (loans and bonds), taking into account the above mentioned constraints. The NGFS is aware that historical data is not always a good indicator of future performances, in particular given the likelihood of unprecedented disruptions to the economy caused by climate change. Therefore, as a possible next step after the collection and analysis of historical data, it may be expedient to introduce a more forward-looking perspective into the analysis, for example, through scenario analysis and/or stress tests.

Setting supervisory expectations

Some central banks and supervisors have further integrated climate-related risks into the supervisory framework by adjusting and communicating their supervisory expectations.[41] These expectations can set out how financial institutions should monitor and manage the financial risks associated with their climate exposures, anchored in the qualitative aspects of Pillar 2. This includes ensuring that consideration of these risks is integrated into governance, strategy and risk management assessments. The majority of authorities plan to assess climate-related financial risks through established financial risk categories, rather than to introduce new policy or frameworks.

Promoting transparency to enhance market discipline

In addition, authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues. Through the promotion of climate-related disclosure via Pillar 3, for example in line with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations (see recommendation n°5); authorities can contribute to an improvement of the pricing mechanisms for climate-related risks and a more efficient allocation of capital.

---

[37] "Default and recovery rates for project finance bank loans, 1983-2016: Green projects demonstrate lower default risk" (2018).

[38] Dawei Jin, Jun Ma, Liuling Liu, Haizhi Wang, Desheng Yin. "Are green companies less risky and getting lower cost bank loans? A stakeholder-management perspective." *Working Paper*, 2018.

[39] "Is there a Green Bond Premium?" (2018), by O D Zerbib and "The Pricing and Ownership of U.S. Green Bonds" (2018), by Baker et al.

[40] UBS Wealth Management Sustainable Investing – Green Bonds (2018).

[41] See e.g. *https://www.bankofengland.co.uk/*

Mitigating climate-related risks through financial resources

Climate-related risks could be integrated further via the quantitative aspects of the prudential framework. In particular, the Pillar 2 framework could be enhanced to assess the adequateness of firms' governance and risk management processes for dealing with climate and environment-related risks, or with concentrated exposures. If a risk differential and causation is established, it might be appropriate to include it in Pillar 1 capital requirements.

2.2 Recommendation n°2

Integrating sustainability factors into own-portfolio management

Acknowledging the different institutional arrangements in each jurisdiction, the NGFS encourages central banks to lead by example in their own operations. Without prejudice to their mandates and status, this includes integrating sustainability factors into the management of some of the portfolios at hand (own funds, pension funds and reserves to the extent possible).

NGFS members may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates.[42] **This approach could have several benefits:**

- The assessment of sustainability factors, in addition to traditional financial factors, can **improve investors' understanding of long-term risks and opportunities** and thereby enhance the risk-return profile of long-term investments. To the extent that sustainability factors, such as the exposure of a security to climate change, can pose financial risks, it is natural for investors to seek to capture them.

- **Central banks can reduce reputational risks** by acknowledging financial risks related to the transition towards a carbon-neutral economy and by addressing these risks proactively in their own (risk) frameworks. Against this backdrop, central banks could be scrutinised for not "walking the talk" if they fail to appropriately address climate-related risks in their own (risk) frameworks. Reputational risk could also arise when central banks invest in companies that are exposed to these risks.

- Central banks may decide to employ part of their investments to pursue non-financial sustainability goals in order to **generate positive (societal) impacts**, in addition to traditional financial return goals. In this way, central banks can also actively support the development of the market for green and sustainable assets.

Many NGFS members are, however, limited by their mandates and/or investment objectives, such that, overall, sustainability criteria currently still play a minor role in most central banks' portfolio management. **Nevertheless, a number of central banks have established themselves as frontrunners** in this field and have adopted sustainability strategies for all or at least part of their investments.

If other central banks were to follow, it seems expedient for them to first establish their fundamental strategy based on their motivation and rationale, then to establish sustainability policies for their different given portfolios and finally decide on the necessary implementation measures and how to evaluate and report on their progress towards achieving their set objectives. As central banks are not a homogeneous group of investors with one shared doctrine, it is up to each central bank to set the appropriate goals and scope for their respective sustainable investment approach.

---

[42] NGFS members' efforts to work towards mainstreaming green finance also include various steps they take as corporates to green their core business activities and to reduce their environmental impact. There is broad consensus among NGFS members that leadership also requires dedicated environmental strategies, well-defined sustainability targets – such as reducing resource, water and energy use as well as waste production – and transparency regarding the measures taken and the degree to which these targets have been met.

BOX 5

Sustainable investment at the Banque de France

In March 2018, the Banque de France (BdF) released its responsible investment charter for its portfolios backed to own funds and to the pension liability. This investment charter is in line with the BdF's corporate social responsibility (CSR) charter and its fiduciary duty as a long-term investor.

One year later, **the BdF released its first responsible investment report** based on the provisions of Article 173 of the French Law on the energy transition for green growth (LTECV) and recommendations from the Task Force on Climate-related Financial Disclosures (TCFD).[1] It describes the extra-financial performance of its portfolios and sets up the objectives of the BdF responsible investment strategy. The BdF committed to harmonise its investments with France's climate targets by getting aligned with a 2°C trajectory and by financing the energy and ecological transition through green bonds and dedicated funds. Moreover, the BdF will include environmental, social and governance (ESG) criteria in its asset management and a best-in-class approach based on firms' ESG score and climate performance will be applied. Lastly, the BdF will adopt a voting policy that includes provisions on non-financial transparency and will increase its general meeting attendance rate.

[1] *https://www.banque-france.fr/sites/*

Notwithstanding that the focus of central banks incorporating ESG aspects into their portfolio management has been on own funds and pension liability portfolios, **some voices have called for an extension of this approach to monetary policy.** Among NGFS members, so far only one central bank, the People's Bank of China, has a dedicated policy to promote green finance via monetary policy.

Going forward, the NGFS will consider exploring the interaction between climate change and central banks' mandates (other than financial stability) and the effects of climate-related risks on the monetary policy frameworks, paying due respect to their respective legal mandates.

2.3 Recommendation n°3 Bridging the data gaps

Building on the G20 GFSG/UNEP initiatives, the NGFS recommends that the appropriate public authorities share data of relevance to Climate Risk Assessment (CRA) and, whenever possible, make them publicly available in a data repository.

In that respect, the NGFS sees merit in setting up a joint working group with interested parties to bridge existing data gaps. The deliverable of this group would be a detailed list of data items that are currently lacking but which are needed by authorities and financial institutions to enhance the assessment of climate-related risks and opportunities – for example, physical asset level data, physical and transition risk data or financial assets data.

In the course of its work, the NGFS observed, like other institutions and academic papers before, that **data scarcity and inconsistency are substantial obstacles to the development of analytical work on climate risk**. The associated challenges include:

- **Data availability**: data covering the exposure to climate-related risks, risk-return profiles of green financial products as well as "brown" assets (loans, bonds and equity instruments) are critical to undertaking risk assessment and carrying out climate disclosure. Granular data is also needed to conduct bottom-up, quantitative analysis of the macrofinancial impacts of climate-related risks. Finally, such data is also needed to assess and quantify the development of green asset markets, which is of particular interest in a portfolio management context.
- **Time horizon**: the period covered by available data is currently too short. Risk-weighted assets, for example, are calculated on a one-year forward-looking basis only.
- **Lack of expertise**: there is a need to bring together the relevant expertise to gain a complete and integrated understanding of data needs, covering climate, environmental and financial data.

In order to move from observation to action, the NGFS is ready to initiate work with interested parties on setting out a detailed list of currently lacking data items, which authorities and financial institutions would need to enhance the assessment of climate-related risks and opportunities such as physical asset level data, physical and transition risk data and financial assets data. The aim of this initiative is to allow data providers to mine the relevant data and progressively bridge the gaps.

2.4 Recommendation n°4
Building awareness and intellectual capacity and encouraging technical assistance and knowledge sharing

The NGFS encourages central banks, supervisors and financial institutions to build in-house capacity and to collaborate within their institutions, with each other and with wider stakeholders to improve their understanding of how climate-related factors translate into financial risks and opportunities.

The NGFS therefore encourages central banks, supervisors and financial institutions to:
- **allocate sufficient internal resources to address climate-related risks and opportunities;**
- **develop training to equip employees with the necessary skills and knowledge;**
- **work closely together with academics and think-tanks to inform thinking;**
- **raise awareness by sharing knowledge within the financial system.**

The NGFS also encourages relevant parties to offer technical assistance to raise awareness and build capacity in emerging and developing economies when possible.

A key element to achieving effective consideration of climate risks across the financial system is to support internal and external collaboration. Internally, the distinct cross-cutting nature of climate-related risks has led to innovative ways of working across supervisory institutions. Central banks and supervisors have typically formed internal "hubs" or "networks" to bring together the relevant expertise within their organisations.

Externally, there are examples of collaboration with academia, think-tanks, NGOs, government departments, other local supervisors, climate science experts, and financial industry bodies. Examples of international collaboration include:
- ESRB – European Systemic Risk Board and the Analysis Working Group (AWG) Project Team on Sustainable Finance;
- G20 – the G20 Sustainable Finance Study Group;
- IOSCO – Sustainable Finance Network;
- OECD – Centre on Green Finance and Investment, including its annual Forum on Green Finance and Investment;
- SBN – Sustainable Banking Network supported by the IFC;
- SIF – Sustainable Insurance Forum;
- TCFD – Task Force on Climate-related Financial Disclosures.

NGFS members also promote market growth as facilitators between the financial industry and legislators. Many are involved in various national and/or international private sector or public-private initiatives such as the Network of Financial Centres for Sustainability, the Prudential Regulation Authority (PRA)-Financial Conduct Authority (FCA) Climate Financial Risk Forum, Finance for Tomorrow in Paris, the DNB's sustainable finance platform, and the Chinese Green Finance Committee. Participating in such initiatives allows for continuous dialogue with market participants and enables central banks and supervisors to contribute to the improvement of existing green market infrastructure and the development of new green financial instruments.

To foster international exchange on the topic, the NGFS organised an industry dialogue in Singapore in June 2018 which was instrumental in understanding the expectations of the private sector with regards to the role of the NGFS and its members in scaling up green finance. Some participants called for policymakers to set minimum transparency standards regarding the methodologies of second opinion providers for green assets, to provide guidelines (for example, for green bonds) or to simplify approval processes (facilitating green issuances).

Furthermore, the NGFS hosted a conference at the Bank of England in January 2019 bringing together academia, think-tanks, central banks and supervisors and financial institutions to better understand how to size the risks.

Going forward, NGFS members will scale up their efforts for capacity building and technical assistance in emerging economies. Emerging economies are often disproportionately affected by the effects of climate change and they often lack the resources to assess the associated risks. During its work, the NGFS has therefore initiated a dialogue with authorities in developing and emerging countries outside of its membership, and will continue to do so. The NGFS also encourages other relevant parties, such as multilateral institutions, to offer technical assistance to raise awareness and build capacity in emerging and developing economies when possible.

2.5 Recommendation n°5

Achieving robust and internationally consistent climate and environment-related disclosure

The NGFS emphasises the importance of a robust and internationally consistent climate and environmental disclosure framework.

NGFS members collectively pledge their support for the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD). The TCFD recommendations provide a framework for consistent, comparable and decision-useful disclosure of firms' exposures to climate-related risks and opportunities. The NGFS encourages all companies issuing public debt or equity as well as financial sector institutions to disclose in line with the TCFD recommendations.

The NGFS recommends that policymakers and supervisors consider further actions to foster a broader adoption of the TCFD recommendations and the development of an internationally consistent environment disclosure framework. This includes authorities engaging with financial institutions on the topic of environment and climate-related information disclosures, aligning expectations regarding the type of information to be disclosed and sharing good disclosure practices.

As stated in the NGFS October 2018 progress report, **robust disclosure of climate-related information by financial institutions has a number of important benefits:**

- It is integral to an efficient, well-functioning capital market, as it can improve the pricing mechanisms for climate-related risks. It also facilitates the surveillance of the financial system.
- Better disclosure can lead to better risk management. The discipline of public disclosure requires financial institutions to establish the necessary data collection and procedures to better identify and manage their risks.
- It enables market players and policymakers to quickly identify and capitalise on sustainable opportunities, thereby contributing to the continued growth of the green finance ecosystem.

Climate-related disclosure practices differ across jurisdictions, both in terms of what and how to disclose.

The majority of jurisdictions surveyed by the NGFS already have in place, or are planning to implement, some form of climate-related disclosure requirements for their entities. **There are various approaches to encourage disclosure**, including:

- **Non-mandatory approaches**: supporting industry-led or non-binding disclosure guidelines, including cross-border collaboration[43] and surveying disclosure practices. This approach can help financial institutions comply with broader disclosure requirements applied to listed entities and/or entities considered to be of significant public relevance within the jurisdiction.
- **A "comply or explain" approach**: a firm would be considered non-compliant if it does not disclose and fails to provide an adequate explanation.[44] This approach provides firms with clarity and guidance on disclosure requirements but with greater flexibility and possibly reduced compliance costs compared to a one-size-fits-all disclosure rule. Additional non-binding recommendations can support the standardisation of firms' disclosure.[45]
- **A mandatory approach**, specifying a catalogue of data items detailing the quantitative and qualitative data that need to be disclosed.

Most jurisdictions with disclosure requirements set out the type of information that entities must disclose, but allow flexibility on how to comply with the requirements. While the scope and extent of information disclosed varies across entities and jurisdictions, the reporting components broadly include:

- the firm's policies and practices in relation to climate matters;
- climate targets, metrics and performance (including the impact of their activities on the environment);
- material climate risk exposures as well as measures taken to mitigate such risks. In some entities and jurisdictions, this may include the entity's environmental impacts, and how it seeks to identify, prevent and mitigate those impacts.

The absence of a global standardised framework for disclosures results in two main drawbacks:

- the lack of comparability and consistency across jurisdictions, especially on the level of granularity and transparency;
- the lack of a level playing field across jurisdictions, which may lead to increased and skewed compliance costs.

This impedes the proper and globally consistent assessment of climate risks at a firm level as well as the analysis of financial stability risks.

A common international standard on climate information disclosure would foster comparable high-quality disclosures and provide greater clarity to the industry on how to align their reporting internationally. **The recommendations provided by the TCFD with support from the Financial Stability Board (FSB) are an obvious avenue of convergence for a global standardised framework on climate disclosures.** Unlike existing disclosure requirements, the TCFD proposal mainly focuses on climate rather than more broadly on sustainability.

There is a significant level of awareness amongst central banks, supervisors and regulated entities of the TCFD

---

[43] Led by the China Green Finance Committee and the City of London Green Finance Initiative, and in collaboration with the Principles for Responsible Investment, the China-UK Pilot TCFD group, comprising ten Chinese and UK financial institutions, launched a pilot TCFD reporting programme and developed templates for disclosure by banks. The three-year action plan of this pilot exercise was published in November 2018.

[44] An example of this is Article 173 of the French Energy Transition Law.

[45] EU law requires large companies to disclose certain information on the way they operate and manage social and environmental challenges. While Directive 2014/95/EU, as implemented into national law, is mandatory, the EU Commission issues non-binding guidelines on non-financial reporting which refine the disclosure obligation set out in the Directive.

recommendations, and support from the private sector has grown rapidly, particularly considering that the recommendations were only released in mid-2017. As of February 2019, the TCFD had the support of over 580 firms, with market capitalisations of over USD 7.9 trillion, and including financial firms responsible for assets of nearly USD 100 trillion. The most recent status report, from September 2018, highlighted that many firms are already disclosing in line with the recommendations, but there is still a need for progress in key areas, including scenario analysis and disclosing the financial impacts of climate change on the firms' operations. Increasing awareness and sharing best practices can help encourage wider implementation of the recommendations. For example, the United Nations Environment Programme Finance Initiative (UNEP FI)/TCFD pilot project involves 16 global banks working to assess how they can best adopt key elements of the recommendations.

Supervisors could support the development of a disclosure framework by proposing additional standardised metrics for the financial sector. This includes:

- engaging with financial institutions on the topic of environment and climate-related information disclosures to align expectations regarding the type of information to be disclosed and share good disclosure practices;
- issuing additional guidance on materiality assessment for their respective financial institutions and jurisdictions in order to help firms' comprehensively capture the climate-related risk factors to be considered and disclosed.

In jurisdictions where prudential and market supervision are conducted by different authorities, collaboration on disclosure is also very important.

The NGFS considers that disclosure of climate-related information and enhanced market discipline cannot emerge rapidly enough without action by policymakers or supervisory authorities. While acknowledging the need to move forward on this issue, the NGFS is also mindful of the remaining challenges, including the current lack of data, the scope of reporting, and methodological issues.

2.6 Recommendation n°6
Supporting the development of a taxonomy of economic activities

The NGFS encourages policymakers to bring together the relevant stakeholders and experts to develop a taxonomy that enhances the transparency around which economic activities (i) contribute to the transition to a green and low-carbon economy and (ii) are more exposed to climate and environment-related risks (both physical and transition). Such a taxonomy would:

- **facilitate financial institutions' identification, assessment and management of climate and environment-related risks;**
- **help gain a better understanding of potential risk differentials between different types of assets;**
- **mobilise capital for green and low-carbon investments consistent with the Paris Agreement.**

Policymakers would thus need to:

- **ensure that the taxonomy is robust and detailed enough to (i) prevent green washing, (ii) allow for the certification of green assets and investments projects and (iii) facilitate risk analysis;**
- **leverage existing taxonomies available in other jurisdictions and in the market and ensure that the taxonomy is dynamic and reviewed regularly to account for technological changes and international policy developments;**
- **make the taxonomy publicly available and underline the commonalities with other available taxonomies. Eventually, it should strengthen global harmonisation to ensure a level playing field and prevent the dilution of green labelling.**

BOX 6

Green taxonomies and the cases of China and Europe

Green finance taxonomies provide the basis for defining and classifying green financial assets (e.g., green loans, green bonds and green funds). **In China, the definition of green loans was introduced as early as 2013 by the China Banking and Insurance Regulatory Commission** (CBIRC, formerly CBRC) **in the *Guidance on Green Loans***. This green loan definition included 12 categories, such as renewable energy, green transportation, green building, etc. Since then, the CBIRC has requested all major banks to report on a semi-annual basis the balance of green loans and the environmental benefits these loans delivered. Green loan default data are also collected by the CBIRC. As of end-2018, the outstanding amount of green loans held by the 21 largest commercial banks in China reached RMB 8.23 trillion, accounting for about 10% of their total aggregate loan balance.

In 2015, China introduced the world's first national-level green bond taxonomy, the Green Bond Endorsed Project Catalogue (2015), which was published by the Green Finance Committee of China Society for Finance and Banking, an institution under the People's Bank of China (PBoC). The Catalogue defined six main categories and 31 sub-categories of projects as eligible for green bond financing. The six main categories included (i) energy saving, (ii) pollution prevention and control, (iii) resource conservation and recycling, (iv) clean transport, (v) clean energy, and (vi) ecological protection and climate change adaptation. The Catalogue was used by virtually all issuers, investors and verifiers in China, even though it was not intended to be "mandatory". Based on the green bond taxonomy, Chinese regulators have also introduced rules and guidelines on green bond verification, as well as environmental information disclosure by green bond issuers. The Catalogue is now under revision and a new version is expected to be released in 2019. Thanks in part to the green taxonomies and the green bond eco-system developed on the basis of the taxonomy, Chinese institutions have issued over USD 100 billion in green bonds from 2016 to 2018, becoming one of the largest green bond markets in the world.

In Europe, the European Commission has tabled a legislative proposal to develop a unified EU classification system – or taxonomy – to determine which economic activities can be regarded as environmentally sustainable for investment purposes. Such a list of environmentally sustainable economic activities would be a useful tool to help financial market participants identify sustainable companies and assets. The proposal identifies six environmental objectives. For an economic activity to be environmentally sustainable, it needs to (i) substantially contribute to at least one of the environmental objectives, (ii) do no significant harm to any of these objectives, (iii) comply with minimum safeguards, and (iv) comply with technical screening criteria. These criteria are meant to determine when an activity can be considered to "substantially contribute" to the objectives, while doing "no significant harm". The Commission has set-up a Technical Expert Group on Sustainable Finance to advise the Commission on the technical screening criteria. The taxonomy will be instrumental to many other actions that the Commission plans to take to move towards more sustainable growth. For example, the Technical Expert Group is also working on a potential EU Green Bond Standard, which will build on the EU Sustainability Taxonomy.

It is important to exploit potential synergies between taxonomies in different jurisdictions. For example, the China Green Finance Committee and the European Investment Bank (EIB) have already made such an attempt by publishing a White Paper called "The Need for a Common Language in Green Finance" in November 2017, followed by a second edition in December 2018. The White Papers compared and mapped the differences and similarities between different green bond taxonomies and highlighted the need for and a potential pathway towards harmonisation of green taxonomies.

The NGFS identified a clear taxonomy around green, non-green, brown and non-brown products as a prerequisite for deepening its analytical work.

- **A taxonomy of "brown" assets** based on clearly defined criteria is important to identify **which assets will be impacted by the Paris Agreement** and the low-carbon and climate-resilient transition. It is a preliminary step to better assess the risk profile of "brown" assets and ensure that disclosures by financial institutions are consistent and comprehensive.
- **A taxonomy of "green" assets** enables policymakers and supervisors to **assess their risk** profile. Like any other investor, central banks will benefit from these taxonomies when implementing sustainable investment strategies.
- **A taxonomy of "green" assets is also of particular use for scaling up green finance**, as it provides financial markets with more transparency, consistency and uniformity and, therefore, confidence in green characteristics. It provides the basis for labelling green financial assets and verifying the "green" feature of the underlying activities, for collecting statistics in green financial flows and stocks, such as green loans or bonds extended or issued during a certain period of time as well as the outstanding volume of green loans and green bonds at any point in time.

The practical challenge is for all affected stakeholders to come together and implement this taxonomy. This calls for policymakers to bring together the relevant stakeholders and experts and to structure and facilitate the debate.

Until now, no regulatory taxonomy has been implemented globally, except market-driven taxonomies which are, by definition, not binding. The NGFS acknowledges the trade-off between, on the one hand, the fragmentation of regional or national approaches, diversity of jurisdictions' collective preference and differing stages of development and, on the other hand, harmonisation in order to avoid level-playing-field problems and to facilitate global assessment of risk profiles. **Although the space for a global taxonomy is limited, the NGFS is supportive of ensuring comparability and consistency across different taxonomies.**

3 Looking forward: operationalising the work and strengthening the dialogue

The NGFS is an open-ended initiative and will continue its work as long as its members deem it necessary and useful. The lesson drawn from the first sixteen months of NGFS activity is that climate change presents significant financial risks that can only be mitigated through an early and orderly transition.

To ensure such a smooth transition, there is still a significant amount of analytical work to be done in order to equip central banks and supervisors with appropriate tools and methodologies to identify, quantify and mitigate climate risks in the financial system. This calls for a close and specific dialogue with academia and for further technical work to translate the NGFS recommendations or observations into operational policies and processes.

The NGFS will continue to leverage the best practices identified within its membership to help central banks and supervisors to better assess and mitigate climate-related risks.

More precisely, in terms of concrete deliverables, the NGFS is planning to develop:

- **A handbook on climate and environmental risk management for supervisory authorities and financial institutions:** this document would set out some detailed and concrete steps to be taken by supervisors and financial institutions to better understand, measure and mitigate exposures to climate and environmental risks. The handbook will build on the recommendations of this report. It would also provide some detailed case studies of climate/environmental risk analyses carried out by financial institutions and/or supervisory authorities. The focus will be primarily on climate-related risks but will also cover environmental risks.
- **Voluntary guidelines on scenario-based risk analysis:** scenario-based risk analysis is complex, requiring further research and analytical input. The NGFS is working to develop data-driven scenarios for use by central banks and supervisors in assessing climate-related risks. The next step will consist in providing practical advice and guidelines for authorities willing to conduct their own analyses.
- **Best practices for incorporating sustainability criteria into central banks' portfolio management (particularly with regard to climate-friendly investments):** building on some concrete case studies, NGFS members will further delve into the topic and develop a hands-on practical guide for central banks to integrate sustainability principles into their portfolio management.

The NGFS is also aware that addressing climate-related risks calls for a collective response with the relevant stakeholders, namely:

- **With non-NGFS central banks or supervisors, regional and/or international supervisory authorities and standard setting bodies and international organisations, governments and policymakers** in order to contribute to developing the appropriate policy framework. International standard setting bodies could consider how the NGFS recommendations could feed into their work and assess their current set of standards/best practices with respect to the relevance of climate-related risks. To this end, the NGFS will present this report to the BCBS in 2019. Specific regional outreach exercises, following the example of the Mexico Green Finance Conference in January 2019, will be arranged to strengthen the global reach of the NGFS.
- **With academia** in order to identify analytical blind spots and gaps in our collective knowledge. In 2019, the NGFS will set up a specific dialogue with academia and hold periodic academic events to discuss the most pressing research questions.
- **With the financial industry and NGOs** in order to ensure a mutually beneficial exchange of experience and information. To that end, the NGFS has entered into a close dialogue with a number of stakeholders relevant to its work.

Conclusion

Over barely sixteen months of existence, the NGFS has grown from eight founding members to more than thirty members from five continents including emerging and developed countries alike. **As time is running out to ensure a smooth transition to a low-carbon economy, and to mitigate climate change impacts on the world's economy and the global financial system, the momentum among the central bank and supervisory community to respond to this challenge is growing rapidly.** This first comprehensive report lays the foundations for the more technical deliverables the NGFS is going to produce in the coming months. The NGFS membership is collectively determined to develop practical tools and methodologies for its membership and beyond, while continuing to raise awareness and to reach out to the various stakeholders relevant to its work.

List of acronyms

BCBS	The Basel Committee on Banking Supervision is the primary global standard setter for the prudential regulation of banks.
CRA	Climate Risk Assessment refers to the methods and practices used to size the financial impact of climate-related risks to micro-prudential objectives, including qualitative and quantitative analysis.
CSR	Corporate social responsibility.
ESG	Environmental, social and governance criteria are used by responsible investors and can be financially material.
GFSG/SFSG	The G20 Green/Sustainable Finance Study Group was launched under China's Presidency of the G20 in 2016. The Study Group is co-chaired by China and the United Kingdom and has published three reports in 2016, 2017 and 2018.
GHG	According to the IPCC[1] the greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds.
IAIS	The International Association of Insurance Supervisors is responsible for regulatory cooperation regarding the supervision of the insurance sector.
IPCC	The Intergovernmental Panel on Climate Change is the United Nations body for assessing the science related to climate change.
NGFS	Network for Greening the Financial System.
NPL	A non-performing loan is a loan for which the debtor has not met the scheduled payments for a defined period.
PD	The probability of default refers to the likelihood of default on a financial asset over a defined time horizon.
SFN	The Sustainable Finance Network is an initiative of the International Organization of Securities Commissions (IOSCO) bringing together securities and markets authorities. The Network is currently chaired by Erik Thedéen, Director General, Finansinspektionen (Swedish Financial Supervisory Authority).
TCFD	The Task Force on Climate-related Financial Disclosures is a private-sector led task force, chaired by Michael R. Bloomberg with support from the Financial Stability Board, which provides a global standardised framework on climate disclosures.
UNEP FI	The United Nations Environment Programme – Finance Initiative is a partnership between UNEP and the global financial sector created in the wake of the 1992 Earth Summit with a mission to promote sustainable finance.

---

[1] IPCC, Special Report: Global Warming of 1.5°C, Glossary, 2018.

This is a tab page.
Please title tab
“McGlade”

doi:10.1038/nature14016

The geographical distribution of fossil fuels unused when limiting global warming to 2 °C

Christophe McGlade[1] & Paul Ekins[1]

Policy makers have generally agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above the average global temperature of pre-industrial times[1]. It has been estimated that to have at least a 50 per cent chance of keeping warming below 2 °C throughout the twenty-first century, the cumulative carbon emissions between 2011 and 2050 need to be limited to around 1,100 gigatonnes of carbon dioxide (Gt CO_2)[2,3]. However, the greenhouse gas emissions contained in present estimates of global fossil fuel reserves are around three times higher than this[2,4], and so the unabated use of all current fossil fuel reserves is incompatible with a warming limit of 2 °C. Here we use a single integrated assessment model that contains estimates of the quantities, locations and nature of the world's oil, gas and coal reserves and resources, and which is shown to be consistent with a wide variety of modelling approaches with different assumptions[5], to explore the implications of this emissions limit for fossil fuel production in different regions. Our results suggest that, globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C. We show that development of resources in the Arctic and any increase in unconventional oil production are incommensurate with efforts to limit average global warming to 2 °C. Our results show that policy makers' instincts to exploit rapidly and completely their territorial fossil fuels are, in aggregate, inconsistent with their commitments to this temperature limit. Implementation of this policy commitment would also render unnecessary continued substantial expenditure on fossil fuel exploration, because any new discoveries could not lead to increased aggregate production.

Recent climate studies have demonstrated that average global temperature rises are closely related to cumulative emissions of greenhouse gases emitted over a given timeframe[2,6,7]. This has resulted in the concept of the remaining global 'carbon budget' associated with the probability of successfully keeping the global temperature rise below a certain level[4,8,9]. The Intergovernmental Panel on Climate Change (IPCC)[3] recently suggested that to have a better-than-even chance of avoiding more than a 2 °C temperature rise, the carbon budget between 2011 and 2050 is around 870–1,240 Gt CO_2.

Such a carbon budget will have profound implications for the future utilization of oil, gas and coal. However, to understand the quantities that are required, and are not required, under different scenarios, we first

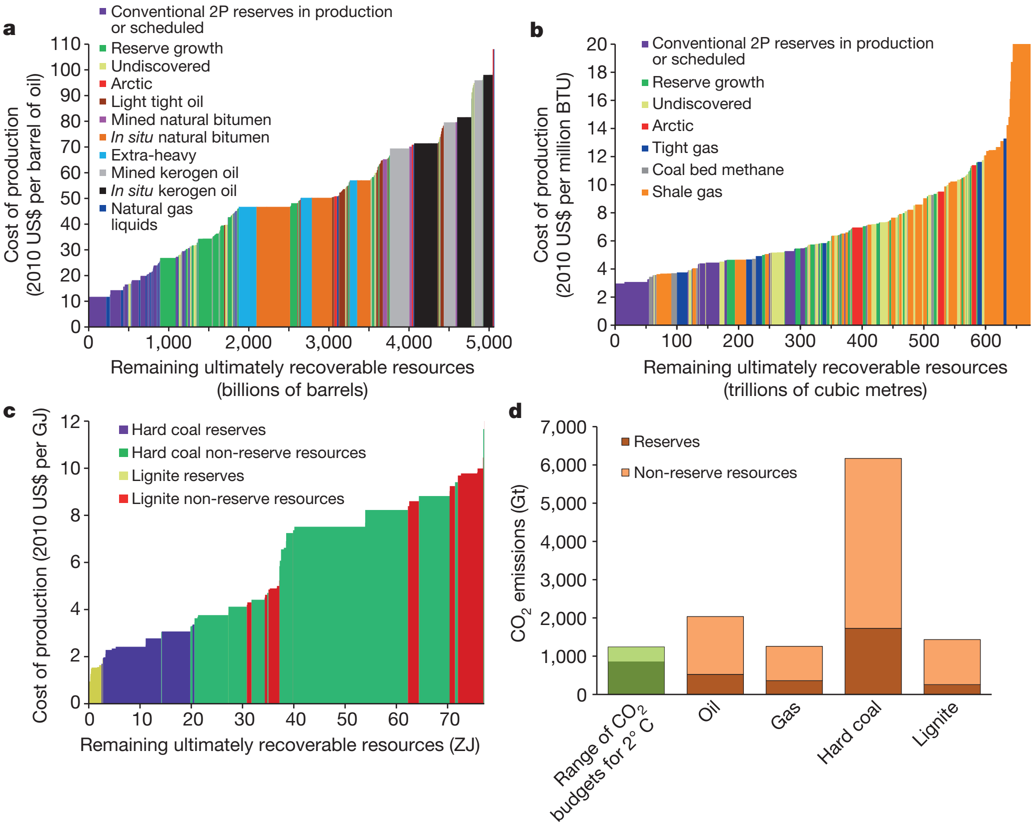


Figure 1 | Supply cost curves for oil, gas and coal and the combustion CO_2 emissions for these resources. a–c, Supply cost curves for oil (**a**), gas (**b**) and coal (**c**). **d**, The combustion CO_2 emissions for these resources. Within these resource estimates, 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 Gt of hard coal, and 276 Gt of lignite are classified as reserves globally. These reserves would result in 2,900 Gt of CO_2 if combusted unabated. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting the temperature rise to 2 °C (870–1,240 Gt of CO_2) is also shown. 2P, 'proved plus probable' reserves; BTU, British thermal units (one BTU is equal to 1,055 J). One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules. Annual global primary energy production is approximately 0.5 ZJ.

---

[1] University College London (UCL), Institute for Sustainable Resources, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK.

need to establish the quantities and location of those currently estimated to exist. A variety of metrics with disparate nomenclature are relied upon to report the availability of fossil fuels[10,11], but the two most common are 'resources' and 'reserves'. In this work 'resources' are taken to be the remaining ultimately recoverable resources (RURR)—the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of current economic conditions. 'Reserves' are a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced[11]. Our best estimates of the reserves and resources are presented in Fig. 1 and, at the regional level, in Extended Data Table 1.

Figure 1 also compares the above carbon budget with the CO_2 emissions that would result from the combustion of our estimate of remaining fossil fuel resources (nearly 11,000 Gt CO_2). With the combustion emissions of the remaining reserves alone totalling nearly 2,900 Gt CO_2, the disparity between what resources and reserves exist and what can be emitted while avoiding a temperature rise greater than the agreed 2 °C limit is therefore stark.

Although previous research[12] has examined the implications that emissions mitigation might have on the rents collected by fossil fuel resource owners, more pertinent to policy and industry are the quantities of fossil fuel that are not used before 2050 in scenarios that limit the average global surface temperature rise to 2 °C. Such geographically disaggregated estimates of 'unburnable' reserves and resources are provided here using the linear optimization, integrated assessment model TIAM-UCL[13].

To provide context to the issue of unburnable fossil fuels and our results, it is useful to examine scenarios provided by other models that quantify separately the volumes of oil, gas and coal produced globally under a range of future emissions trajectories[5]. Cumulative production between 2010 and 2050 from these are presented in Fig. 2. Since they have very different future greenhouse gas emissions profiles, we have converted them to approximate temperature rise trajectories. These have been calculated using the climate model MAGICC[14], which generates a probability distribution over temperature rise trajectories for a given emissions profile. We use the 60th percentile temperature trajectory (to correspond with assumptions within TIAM-UCL) and then group the scenarios by the final temperature rise in 2100: below 2 °C, between 2 °C and 3 °C, or exceeding 3 °C.

In this work we have constructed three core scenarios that are constrained to limit the average surface temperature rise in all time periods to 2 °C, to 3 °C, and to 5 °C. Cumulative production of each fossil fuel between 2010 and 2050 in each of these scenarios can be identified within each of the three temperature groupings in Fig. 2.

The global reserves of oil, gas and coal included in Fig. 1 total approximately 7.4 ZJ, 7.1 ZJ and 20 ZJ, respectively. With narrow inter-quartile ranges, relative to the level of reserves available, Fig. 2 shows good agreement on the levels of fossil fuels produced within the temperature groups, despite the range of modelling methodologies and assumptions included.

Since assumptions in modelling the energy system are subject to wide bands of uncertainty[15], we further constructed a number of sensitivity scenarios using TIAM-UCL that remain within a 2 °C temperature rise. These span a broad range of assumptions on production costs, the availability of bio-energy, oil and gas, demand projections, and technology availability (one with no negative emissions technologies, and one with no carbon capture and storage (CCS)) (Extended Data Table 2). The availability of CCS has the largest effect on cumulative production levels (Extended Data Fig. 1); however, there is little variability in the total production of fossil fuels if the world is to have a good chance of staying within the agreed 2 °C limit.

Global production of oil, gas and coal over time in our main 2 °C scenario is given in Fig. 3. This separates production by category, that is, by the individual kinds of oil and gas that make up the global resource base, and compares total production with the projections from the 2 °C scenarios in Fig. 2. The results generated using TIAM-UCL are a product of the economically-optimal solution, and other regional distributions of unburnable reserves are possible while still remaining within the 2 °C limit (even though these would have a lower social welfare). A future multi-model analysis could therefore usefully build on and extend the work that is presented here, but results at the aggregate level can be seen to lie within range of the ensemble of models and scenarios that also give no more than a 2 °C temperature rise.

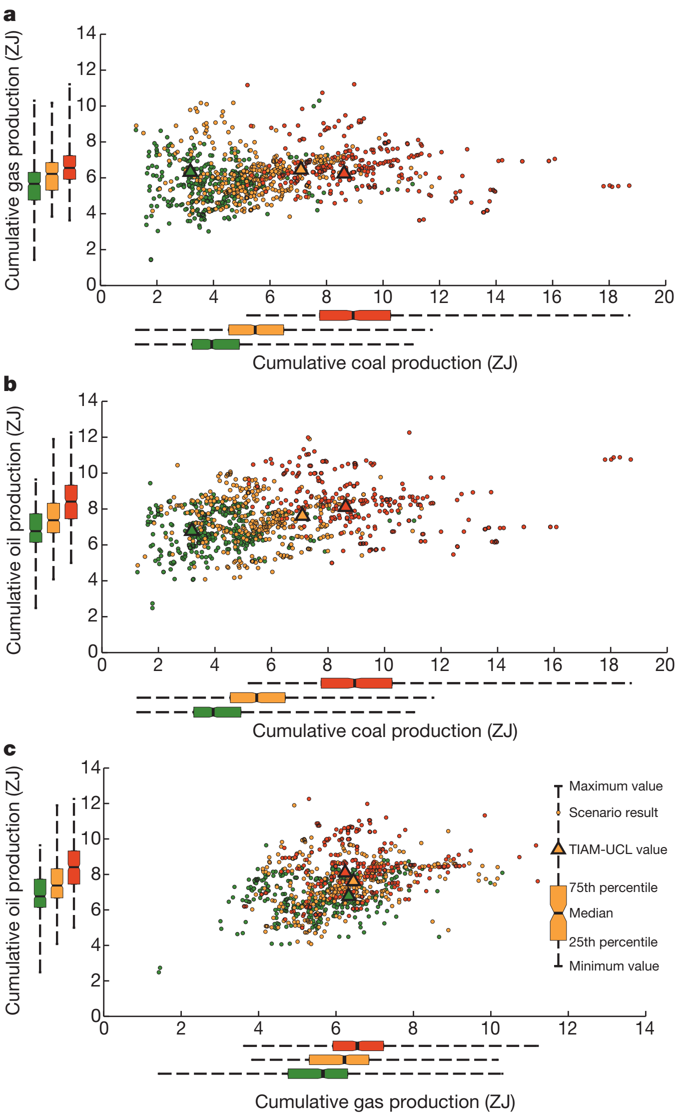


Figure 2 | Cumulative production between 2010 and 2050 from a range of long-term energy scenarios. Panels refer to coal and gas (**a**), coal and oil (**b**), and gas and oil (**c**). Scenarios[5] are coloured according to their approximate resultant 2100 temperature rise above pre-industrial levels. 379 individual scenarios result in a temperature rise of less than 2 °C (green), 366 of between 2 °C and 3 °C (orange), and 284 of more than 3 °C (red). Triangles are the values from the 2 °C (with CCS), 3 °C and 5 °C TIAM-UCL scenarios. Ranges and symbols are as shown in the key in **c**.

In the TIAM-UCL scenarios, production of reserves and non-reserve resources occurs contemporaneously. It is therefore important to recognize that it would be inappropriate simply to compare the cumulative production figures in Fig. 2 with the reserve estimates from Fig. 1 and declare any reserves not used as 'unburnable'. Although there may be sufficient reserves to cover cumulative production between 2010 and 2050, it does not follow that only reserves should be developed and all other resources should remain unused. For oil and gas, resources that are not currently reserves may turn out to be cheaper to produce than some reserves, while new resources will also be developed to maintain

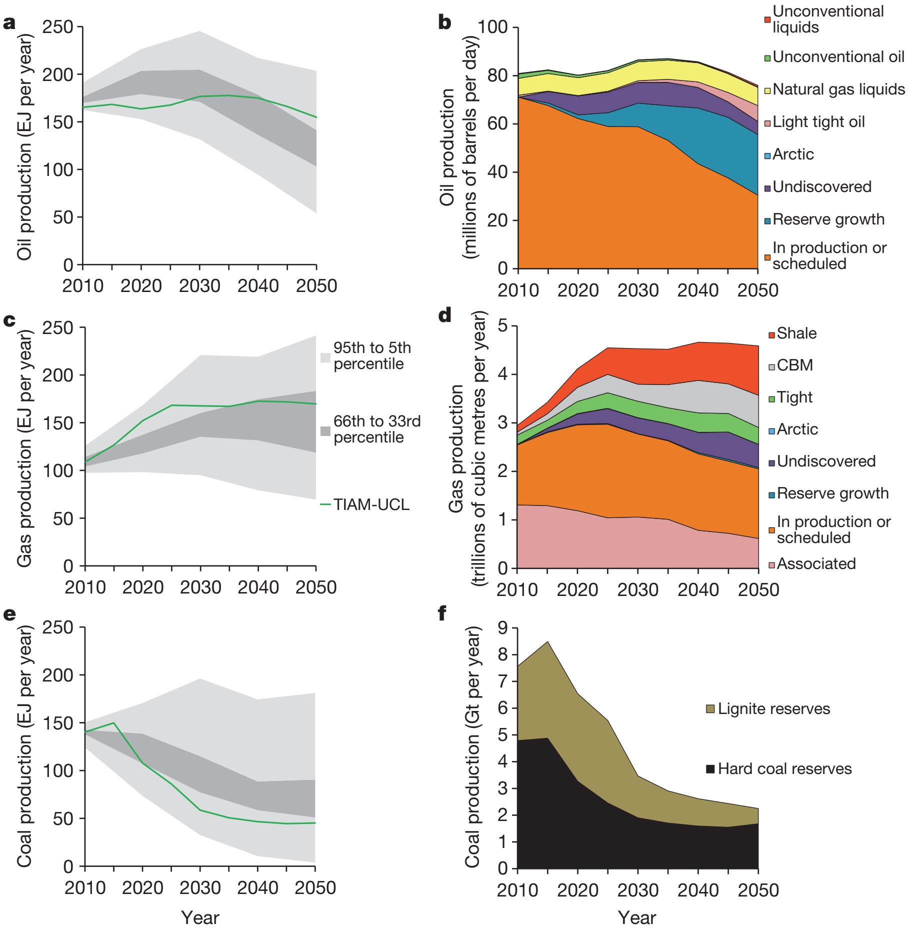


Figure 3 | Oil, gas and coal production in the TIAM-UCL 2 °C scenario (with CCS) and comparison with all other 2 °C scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) database[5]. **a**, **c** and **e** compare total production by oil, gas and coal with the AR5 database; **b**, **d** and **f** provide a disaggregated view of production for the TIAM-UCL 2 °C scenario separated by category. Associated gas is gas produced alongside crude oil from oil fields. One exajoule (EJ) is equal to one quintillion (10^{18}) joules.

the flow rates demanded by end-use sectors. However, if resources that are currently non-reserves are produced, a greater proportion of reserves must not be produced to stay within the carbon budget.

The reserves of oil, gas and coal that should be classified as unburnable within each region, and the percentage of current reserves that remain unused, are set out in Table 1. Since total production is most sensitive to assumptions on CCS, and since it has been suggested that the deployment of CCS will permit wider exploitation of the fossil fuel resource base[16], Table 1 includes the unburnable reserves from two alternative 2 °C scenarios. One scenario permits the widespread deployment of CCS from 2025 onwards, and the other assumes that CCS is unavailable in any time period.

Globally, when CCS is permitted, over 430 billion barrels of oil and 95 trillion cubic metres of gas currently classified as reserves should remain unburned by 2050. The Middle East, although using over 60% of its oil reserves, carries over half of the unburnable oil globally, leaving over 260 billions of barrels in the ground. Canada has the lowest utilization of its oil reserves (25%), as its natural bitumen[17] deposits remain largely undeveloped (see below) while the United States has the highest, given the proximity of supply and demand centres. The Middle East also holds half of unburnable global gas reserves, with Former Soviet Union countries accounting for another third, meaning that they can use only half their current reserves.

Coal reserves are by far the least-used fossil fuel, with a global total of 82% remaining unburned before 2050. The United States and the Former Soviet Union countries each use less than 10% of their current reserves, meaning that they should leave over 200 billion tonnes (Gt) coal (both hard and lignite) reserves unburned. Coal reserve utilization

Table 1 | Regional distribution of reserves unburnable before 2050 for the 2 °C scenarios with and without CCS

	2 °C with CCS						2 °C without CCS					
	Oil		Gas		Coal		Oil		Gas		Coal	
Country or region	Billions of barrels	%	Trillions of cubic metres	%	Gt	%	Billions of barrels	%	Trillions of cubic metres	%	Gt	%
Africa	23	21%	4.4	33%	28	85%	28	26%	4.4	34%	30	90%
Canada	39	74%	0.3	24%	5.0	75%	40	75%	0.3	24%	5.4	82%
China and India	9	25%	2.9	63%	180	66%	9	25%	2.5	53%	207	77%
FSU	27	18%	31	50%	203	94%	28	19%	36	59%	209	97%
CSA	58	39%	4.8	53%	8	51%	63	42%	5.0	56%	11	73%
Europe	5.0	20%	0.6	11%	65	78%	5.3	21%	0.3	6%	74	89%
Middle East	263	38%	46	61%	3.4	99%	264	38%	47	61%	3.4	99%
OECD Pacific	2.1	37%	2.2	56%	83	93%	2.7	46%	2.0	51%	85	95%
ODA	2.0	9%	2.2	24%	10	34%	2.8	12%	2.1	22%	17	60%
United States of America	2.8	6%	0.3	4%	235	92%	4.6	9%	0.5	6%	245	95%
Global	431	33%	95	49%	819	82%	449	35%	100	52%	887	88%

FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3; %, Reserves unburnable before 2050 as a percentage of current reserves.

is twenty-five percentage points higher in China and India, but still they should also leave nearly 200 Gt of their current coal reserves unburned.

The utilization of current reserves is lower in nearly all regions for all of the fossil fuels when CCS is not available, although there is a slight increase in gas production in some regions to offset some of the larger drop in coal production. Nevertheless, Table 1 demonstrates that the reserves of coal that can be burned are only six percentage points higher when CCS is allowed, with the utilization of gas and oil increasing by an even smaller fraction (around two percentage points). Because of the expense of CCS, its relatively late date of introduction (2025), and the assumed maximum rate at which it can be built, CCS has a relatively modest effect on the overall levels of fossil fuel that can be produced before 2050 in a 2 °C scenario.

As shown in Fig. 3, there is substantial production of many of the non-reserve resource categories of oil and gas. Extended Data Table 3 sets out the regional unburnable resources of all coal, gas and oil in the scenario that allows CCS by comparing cumulative production of all fossil fuel resources with the resource estimates in Fig. 1.

The RURR of both types of coal and unconventional oil vastly exceed cumulative production between 2010 and 2050, with the overwhelming majority remaining unburned. Resources of conventional oil are used to the greatest extent, with just under 350 billion barrels of non-reserve resources produced over the model timeframe. The Middle East again holds the largest share of the unburnable resources of conventional oil, but there is a much wider geographical distribution of these unburnable resources than was the case for oil reserves.

Regarding the production of unconventional oil, open-pit mining of natural bitumen in Canada soon drops to negligible levels after 2020 in all scenarios because it is considerably less economic than other methods of production. Production by *in situ* technologies continues in the 2 °C scenario that allows CCS, but this is accompanied by a rapid and total decarbonization of the auxiliary energy inputs required (Extended Data Fig. 2). Although such a decarbonization would be extremely challenging in reality, cumulative production of Canadian bitumen between 2010 and 2050 is still only 7.5 billion barrels. 85% of its 48 billion of barrels of bitumen reserves thus remain unburnable if the 2 °C limit is not to be exceeded. When CCS is not available, all bitumen production ceases by 2040. In both cases, the RURR of Canadian bitumen dwarfs cumulative production, so that around 99% of our estimate of its resources (640 billion barrels), remains unburnable. Similar results are seen for extra-heavy oil in Venezuela. Cumulative production is 3 billion barrels, meaning that almost 95% of its extra-heavy reserves and 99% of the RURR are unburnable, even when CCS is available.

The utilization of unconventional gas resources is considerably higher than unconventional oil. Under the 2 °C scenario, gas plays an important part in displacing coal from the electrical and industrial sectors and so there is over 50 trillion cubic metres unconventional gas production globally, over half of which occurs in North America. Nevertheless, there is a low level of utilization of the large potential unconventional gas resources held by China and India, Africa and the Middle East, and so over 80% of unconventional gas resources (247 trillion cubic metres) are unburnable before 2050. Production of these unconventional gas resources is, however, only possible if the levels of coal reserves identified in Table 1 are not developed: that is, it is not possible for unconventional gas to be additional to current levels of coal production.

Finally, we estimate there to be 100 billion barrels of oil (including natural gas liquids) and 35 trillion cubic metres of gas in fields within the Arctic Circle that are not being produced as of 2010. However, none is produced in any region in either of the 2 °C scenarios before 2050. These results indicate to us that all Arctic resources should be classified as unburnable.

To conclude, these results demonstrate that a stark transformation in our understanding of fossil fuel availability is necessary. Although there have previously been fears over the scarcity of fossil fuels[18], in a climate-constrained world this is no longer a relevant concern: large portions of the reserve base and an even greater proportion of the resource base should not be produced if the temperature rise is to remain below 2 °C.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 18 February; accepted 27 October 2014.

1. United Nations Framework Convention on Climate Change (UNFCC). *Report of the Conference of the Parties on its Fifteenth Session, held in Copenhagen from 7 to 19 December 2009. Part Two: Action taken by the Conference of the Parties at its Fifteenth Session.* United Nations Climate Change Conf. Report 43 http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf (UNFCC, 2009).
2. Meinshausen, M. *et al.* Greenhouse gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
3. Clarke, L. *et al.* in *Climate Change 2014: Mitigation of Climate Change* (Edenhofer, O. *et al.*) Ch. 6 (Cambridge Univ. Press, 2014).
4. Raupach, M. R. *et al.* Sharing a quota on cumulative carbon emissions. *Nature Clim. Chang.* **4,** 873–879 (2014).
5. IPCC Working Group III. *Integrated Assessment Modelling Consortium (IAMC) AR5 Scenario Database* https://secure.iiasa.ac.at/web-apps/ene/AR5DB/ (International Institute for Applied Systems Analysis, 2014).
6. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
7. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459,** 829–832 (2009).
8. Friedlingstein, P. *et al.* Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geosci.* **7,** 709–715 (2014).
9. Leaton, J. *Unburnable Carbon—Are the World's Financial Markets Carrying a Carbon Bubble?* http://www.carbontracker.org/wp-content/uploads/2014/09/Unburnable-Carbon-Full-rev2-1.pdf (Investor Watch, 2011).
10. McGlade, C. E. A review of the uncertainties in estimates of global oil resources. *Energy* **47,** 262–270 (2012).
11. Society of Petroleum Engineers (SPE). *Petroleum Resources Management System.* www.spe.org/industry/docs/Petroleum_Resources_Management_System_2007.pdf (SPE, 2008).
12. Bauer, N. *et al.* Global fossil energy markets and climate change mitigation—an analysis with REMIND. *Clim. Change* http://dx.doi.org/10.1007/s10584-013-0901-6 (2013).
13. Anandarajah, G., Pye, S., Usher, W., Kesicki, F. & McGlade, C. E. *TIAM-UCL Global Model Documentation.* http://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual (University College London, 2011).
14. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating atmosphere–ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).
15. Usher, W. & Strachan, N. Critical mid-term uncertainties in long-term decarbonisation pathways. *Energy Policy* **41,** 433–444 (2012).
16. IEA. *Resources to Reserves* Ch. 8 (International Energy Agency, 2013).
17. Alberta Energy Regulator (AER). *Alberta's Energy Reserves 2013 and Supply/Demand Outlook 2014–2023.* www.aer.ca/documents/sts/ST98/ST98-2014.pdf (AER, 2014).
18. Yergin, D. *The Prize: the Epic Quest for Oil, Money and Power* Epilogue (Simon and Schuster, 2009).

Acknowledgements We thank I. Keppo at the UCL Energy Institute, E. Trutnevyte at ETH Zurich, and A.-M. Lyne at the UCL Department of Statistical Science. This research formed part of the programme of the UK Energy Research Centre and was supported by the UK Research Councils under Natural Environment Research Council award NE/G007748/1.

Author Contributions Both authors contributed equally to this work.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to C.M. (christophe.mcglade@ucl.ac.uk).

METHODS

Fossil fuel definitions. A 'McKelvey' box[19] is often used to provide an overview of the relationship between different resource and reserve estimates[20]. The best estimates of current oil and gas reserves in Extended Data Table 1 were of the 'proved plus probable' or '2P' quantities. Since 2P reserve estimates are rare for coal and none are in the public domain, the best estimates shown for coal were of the 'proved' or '1P' reserves. Broadly speaking, 1P estimates are more conservative, often corresponding to an estimate with a 90% probability of being exceeded, while 2P estimates are the median estimate of the reserves for a given field or region[11].

Oil and gas can be further separated into 'conventional' and 'unconventional' reserves and resources. Again, there is no single definition of these terms, but here we define oil with density greater than water (often standardized as '10° API') to be unconventional and all other quantities as conventional. We therefore categorize the 'light tight oil' extracted from impermeable shale formations using hydraulic fracturing as conventional oil.

For gas, tight gas (gas trapped in relatively impermeable hard rock, limestone or sandstone), coal-bed methane (gas trapped in coal seams that is adsorbed in the solid matrix of the coal), and shale gas (gas trapped in fine-grained shale) are considered as the three 'unconventional gases'; all other quantities are considered to be conventional.

Coal is distinguished by its energy density following the definitions used by the Federal Institute for Geosciences and Natural Resources (BGR)[21]. Hard coal has an energy density greater than 16.5 $\mathrm{MJ\,kg^{-1}}$; any quantities with energy density less than this are classified as lignite.

Derivation of reserve and resource estimates. The estimated oil and gas reserves and resources shown in Extended Data Table 1 were derived in the following manner[22]. We first identified the individual elements or categories of oil and gas that make up the global resource base. For oil these are: current conventional 2P reserves in fields that are in production or are scheduled to be developed, reserve growth, undiscovered oil, Arctic oil, light tight oil, natural gas liquids, natural bitumen, extra-heavy oil, and kerogen oil. The latter three of these are the unconventional oil categories.

Reserve growth is defined to be 'the commonly observed increase in recoverable resources in previously discovered fields through time'[23]. Quantities in this category here include any contributions from reserves in fields that have been discovered but are not scheduled to be developed ('fallow fields'), the new implementation of advanced production technologies such as enhanced oil recovery, changes in geological understanding, and changes in regional definitions.

There are eight categories of conventional and unconventional gas: current conventional 2P reserves that are in fields in production or are scheduled to be developed, reserve growth, undiscovered gas, Arctic gas, associated gas, tight gas, coal-bed methane, and shale gas. As noted above, the latter three of these are collectively referred to as unconventional gas.

We then selected the most robust data sources that provide estimates of the resource potential of each individual category within each country; these sources are set out in Extended Data Table 4. Taken together, differences between these sources provide a spread of discrete quantitative resource estimates for each category within each country. We also differentiated between the quantities of conventional oil that are natural gas liquids, and the quantities of natural gas that are associated with oil fields; these distinctions are important for modelling purposes but are rarely made in the literature.

For unconventional oil, we first generated a range of estimates for the in-place resources of natural bitumen, extra-heavy oil, and kerogen oil, and a range of potential recovery factors for different extraction technologies. We separately characterized the natural bitumen and kerogen oil resources that are extractable using mining technologies and those resources that are extractable using *in situ* technologies because the resource potential, costs, and energy requirements of these technologies are very different.

Continuous distributions were next constructed across these data ranges. Since there is no empirical basis for the choice of a suitable shape or form for such distributions, we used both the triangular and the beta distributions, chosen because they can be skewed both positively and negatively, and because they allow identical distributions to be used across all of the ranges derived. With equal weighting for each distribution, we combined these into a single individual resource distribution for each category within each country.

We then estimated the production costs of each of the oil and gas resource categories. Taking account of the resource uncertainty, these were used to develop supply cost curves for each category of oil and gas within each country.

We finally used a Monte Carlo selection process to combine these country-level supply cost curves. Regional supply cost curves were thus formed from aggregated supply cost curves for individual countries, and similarly supply cost curves formed for multiple categories of oil or gas within one or more countries. Data in Fig. 1 are the median values from these aggregate distributions with Extended Data Table 4 giving high (95th percentile), median, and low (5th percentile) estimates for each category at the global level.

In most industry databases of oil and gas reserves (for example, the database produced by the consultancy IHS CERA[24,25]), some of the quantities classified as reserves lie in fields that were discovered over ten years ago, yet these fields have not been developed and there are no plans at present to do so. These are sometimes referred to as 'fallow fields'. For gas these quantities can also be called 'stranded gas', and they can be quite substantial; for example ref. 24 suggests that 50% gas reserves outside of North America are in stranded fields. Strictly, oil and gas in such fields should not be classified as reserves (for example, ref. 11 states that reserve quantities must have a 'reasonable timetable for development'). However, in this work, to ensure that the reserve estimates provided in Table 1 are not substantially different from the global totals provided by these industry databases, we follow their convention of classifying these quantities as reserves.

There are fewer independent estimates of reserves for coal and so we simply relied upon the estimates provided by the BGR[21] for the reserve figures in Extended Data Table 1. The RURR of coal are more problematic to characterize, however. The 'resource' estimates provided by the BGR are not estimates of the quantities that can actually be extracted but are the in-place quantities; large portions of these are unlikely ever to be technically recoverable.

We therefore used the proved, probable and possible reserve estimates for hard coal and lignite provided by the World Energy Council[26] for a selection of countries. The sum of these three figures gives an estimate of the 'tonnage within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future' (the definition provided by the World Energy Council). Since the sum of these three figures takes account of technical recoverability, we consider that, while imperfect, they provide a better estimate of the ultimately recoverable resources of coal than either the (narrower) proved reserve or the (broader) in-place resource estimates.

There are a number of countries that are estimated by the BGR to hold large quantities of coal in place but for which no probable and possible reserve estimates are provided by the World Energy Council. The ratio of the World Energy Council resource estimate to the BGR in-place estimate in countries that have estimates provided by both sources can vary substantially, but the average ratio is 16% for hard coal and 31% for lignite. We therefore assumed this ratio to generate resource estimates for all countries for which only BGR in-place estimates are provided. The proved reserve estimates of coal are so large themselves that the resource estimates are less important than is the case for oil and gas resource estimates.

There are few other sources providing a comprehensive overview of fossil fuel availability. Further, these often do not provide their sources or the methods used to generate estimates, do not define fully what categories or elements are included or excluded, and do not indicate sufficient conversion factors that would allow a like-with-like comparison. Some exceptions, however, are the IEA[27,28], the IIASA Global Energy Assessment (GEA)[29], and the BGR[21]. Their estimates are shown together with our aggregated reserve and resource estimates in Extended Data Table 5.

A number of factors contribute to the large variation between these estimates. A key reason is that the definitions of 'reserves' and 'resources' differ among sources, and so it is problematic to seek to compare them directly. For example, as noted above, the BGR, whose estimates are followed closely by the other sources, gives the total coal in place rather than an estimate of the resources that can be recovered, as in our study. Other reasons for the differences seen include: (1) the exclusion or inclusion of certain categories of fossil fuels such as light tight oil, aquifer gas, and methane hydrates; (2) whether proved (1P) or proved plus probable (2P) reserves are reported, and the methods used to generate the 1P reserve estimates; (3) the potential inflation of reserve estimates for political reasons, and whether they should consequently be increased or reduced[30]; (4) the inclusion of stranded gas volumes in gas reserve estimates; (5) differences in the functional form used to estimate volumes of reserve growth (if reserve growth is included at all); (6) the difficulty in estimating current recovery factors (the ratio of recoverable resources to total resources in place), and how these may increase in the future; (7) differences between the methods used to estimate undiscovered oil and gas volumes; (8) the scarcity of reports providing reliable estimates of the potential resources of Arctic oil and gas, light tight oil, tight gas and coal bed methane, and the frequent consequent reliance upon expert judgement; (9) variation in what unconventional oil production technologies, which vary considerably in their recovery factors, will be used in the future; and (10) the chosen cut-off 'yield' (the volume of synthetic oil produced from a given weight of shale rock) for kerogen oil.

The estimates considered in our model are the result of careful and explicit consideration of all these issues, with our choices justified in the light of available knowledge. It can be seen in Extended Data Table 5, however, that our median figures are generally lower than the estimates provided by the other sources shown there. Therefore, although we consider our median resource estimates to be more robust than the figures used by these other sources, if in fact these other estimates were found to be closer to being correct, then the unburnable resources given in Extended Data Table 3 would also be larger. For example, if total gas resources are actually at the GEA high estimate, then the percentage that should be classified as unburnable before 2050 under the 2 °C scenario would increase to 99% rather than our estimate of 75%.

The cut-off date after which quantities that have not been produced should be considered 'unburnable' is also an important assumption. While there are no specific timeframes attached to the definition of reserves, quantities are usually required to be developed within, for example, a 'reasonable timeframe'[11]. It is doubtful whether any reserves not produced by 2050 would fulfil this criterion. We therefore take cumulative production of reserves between 2010 and 2050 as the reserve 'utilization', and classify any quantities not used within this time as those that should be 'unburnable' if a certain temperature rise is not to be exceeded. Similarly, if none, or only a minor proportion, of a certain non-reserve resource is produced before 2050, then any current interest in developing it would be questionable. We thus also rely on 2050 as the cut-off date for classifying resources that should be considered as unburnable.

Description and key assumptions in TIAM-UCL. The TIMES Integrated Assessment Model in University College London ('TIAM-UCL') is a technology-rich, bottom-up, whole-system model that maximizes social welfare under a number of imposed constraints. It models all primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from resource production through to their conversion, infrastructure requirements, and finally to sectoral end-use. An extended explanation of input assumptions, approaches and data sources can be found in ref. 13. The base year of TIAM-UCL is 2005, the model is run in full to 2100, and thereafter the climate module is run to 2200. Results are presented here only between 2010 and 2050 (and are reported in five-year increments). All scenarios in this paper are run with the assumption of perfect foresight.

Resources and costs of all primary energy production are specified separately within 16 regions covering the world, and separately within the regions that contain members of the Organisation of Petroleum Exporting Countries (OPEC); the names of these are presented in Extended Data Table 6. For clarity in the main text, we have aggregated some of these regions into ten more-encompassing groups.

The climate module of TIAM-UCL is calibrated to the MAGICC model[14]. This module can be used to project the effects of greenhouse gas emissions on: atmospheric concentrations of greenhouse gas, radiative forcing, and average global temperature rises. It can also be used to constrain the model to certain bounds on these variables. In this work, the climate module is used to restrict the temperature rise to certain levels (as explained below). For the calibration to MAGICC, values from the probability distributions of climate parameters in MAGICC were selected so that there is a 60% chance that the temperature rise will remain below any level reported. Any constraints imposed using the TIAM-UCL climate module thus also correspond to this probability.

The emissions profiles[5] used in Fig. 2 were converted to temperature rises using MAGICC. To ensure consistency with TIAM-UCL, we use the 60th percentile temperature trajectory from MAGICC and then group by the final temperature rise in 2100; there is therefore also a 60% chance that the temperature rise will be below the level indicated.

For each of the scenarios run in this paper using TIAM-UCL, a 'base case' is first formed that incorporates no greenhouse gas abatement policies. This base case uses the standard version of the model that relies upon minimizing the discounted system cost. This is used to generate base prices for each commodity in the model. TIAM-UCL is then re-run using the elastic-demand version with the greenhouse gas abatement policies introduced. This version of the model maximizes social welfare (the sum of consumer and producer surplus) and allows the energy-service demands to respond to changes in the endogenously determined prices resulting from these new constraints.

Fossil fuel modelling in TIAM-UCL. Oil and gas are both modelled in a similar manner in TIAM-UCL. The nine categories of conventional and unconventional oil and eight categories of conventional and unconventional gas identified above are all modelled separately. Coal production in TIAM-UCL is modelled more collectively, with only two categories, reserves and resources, for hard coal and lignite.

Natural bitumen and kerogen oil resources can be produced using either mining or *in situ* means, the technologies for which have different costs, efficiencies, and energy inputs. Although natural gas is predominantly used at present for the energy inputs to these unconventional resources, the model is free to choose any source of heat, electricity and hydrogen to allow greater flexibility. The costs of the auxiliary energy inputs required to extract and upgrade the native unconventional oils are determined endogenously by the model.

Each of the coal, gas and oil categories are modelled separately within the regions listed in Extended Data Table 6, with each resource category within each region split into three cost steps. As discussed above, the supply cost curves given in Fig. 1 comprise the data input to TIAM-UCL.

After processing, oil is next refined into products (gasoline, diesel, naphtha and so on), whereas processed gas and coal can be used directly. Fuel switching to and from all of the fossil fuels is possible. Trade of hard coal, crude oil, refined products, natural gas, both in pipelines and as liquefied natural gas, is allowed. Lignite cannot be traded between the regions.

Refined oil products can also be produced directly using Fischer–Tropsch processes with possible feedstocks of coal, gas, or biomass; these technologies can also be employed either with or without carbon capture and storage. Regional coal, oil and gas prices are generated endogenously within the model. These incorporate the marginal cost of production, scarcity rents, rents arising from other imposed constraints, and transportation costs.

A new key aspect of TIAM-UCL is the imposition of asymmetric constraints on the rate of production of oil and gas given a certain resource availability; these are intended to represent 'depletion rate constraints'. In TIAM-UCL, these constraints are modelled through introducing maximum annual production growth and maximum 'decline rate' restrictions. These are imposed on each cost step of each category of both oil and gas in each region, and ensure that the production follows a more realistic profile over time.

Data for these constraints are available at the field level from the bottom-up economic and geological oil field production model ('BUEGO')[31]. BUEGO contains a data-rich representation of 7,000 producing 'undiscovered' and discovered but undeveloped oil fields. These data include each field's 2P reserves, potential production capacity increases, water depth, capital and operating costs, and natural decline rate (the rate at which production would decline in the absence of any additional capital investment).

We used production-weighted averages (as of 2010) of the individual fields within each region to give average regional natural decline rates, which were imposed as maximum decline constraints in TIAM-UCL in the form of equal maximum annual percentage reductions. Although data on gas natural decline rates are much more sparse, some are available at a regional level[32], which can be compared with similar results for oil natural decline rates[25]. This comparison suggests that gas natural decline rates are on average 1% per year greater than for oil, with similar distributions for location (onshore/offshore) and size. The constraints placed on the maximum annual reductions in natural gas production were thus assumed to be 1% higher than those derived for oil.

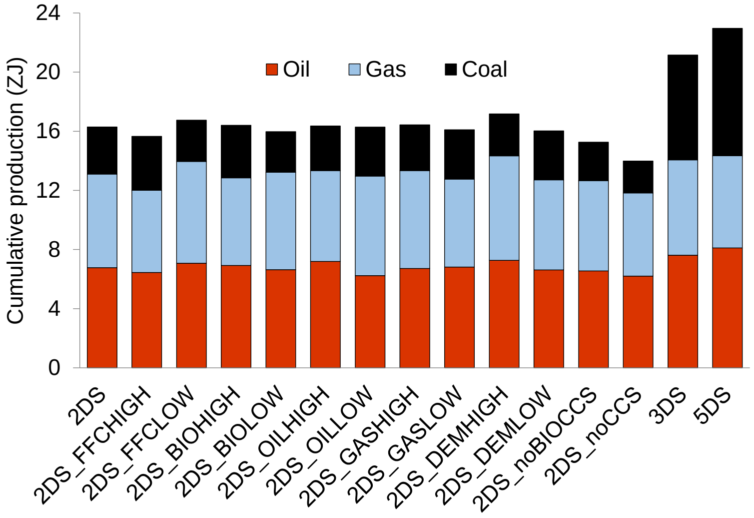
As identified in the main text, to understand the quantities of reserves of oil and gas that are unburnable, production of reserve sources only should be compared with reserve estimates, while cumulative production of all sources should be compared with the resource estimates. For coal, the reserves are so much greater than cumulative production under any scenario that this distinction is not as important.

The base year of TIAM-UCL is 2005, but the base year of this study is 2010. Since reserves have grown, and oil and gas have been discovered in the intervening five years, some quantities that were classified as reserve growth and undiscovered oil and gas in 2005 should be classified as reserves in 2010. Within each region, the cumulative production figures to which the reserve estimates in Extended Data Table 1 are compared therefore contain production from the conventional 2P reserves in the 'fields in production or scheduled to be developed' category, as well as some portions of production from the 'reserve growth' and 'undiscovered' categories. In addition, since, for example, reserves of natural bitumen are included in the reserves figures of Canada and unconventional gas reserves are included in the reserves figures of the United States, production of some of the unconventional categories are also included in these cumulative production figures. To ensure consistency within each region, the maximum production potentials over the modelling period from the categories included in the cumulative production figures are equal to the reserve estimates given in Extended Data Table 1.

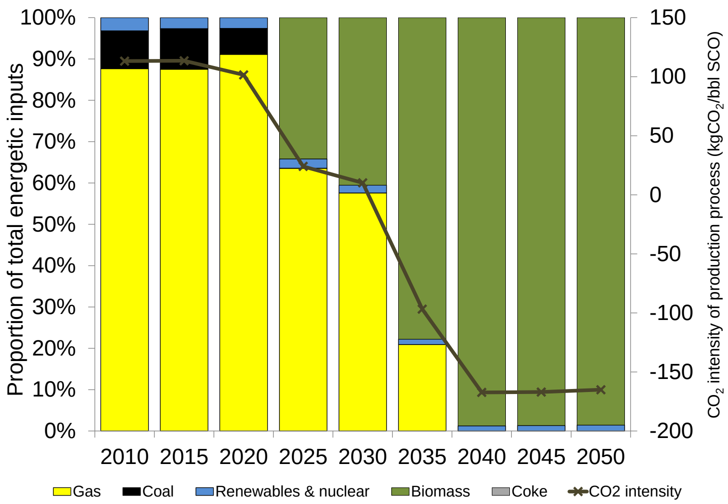
Overview of scenarios implemented. A brief overview of the main assumptions within the four scenarios run as part of this work is provided in Extended Data Table 7. For the emissions mitigation scenarios (those that limit the temperature rise to 3 °C and 2 °C), we assume that there are only relatively modest efforts to limit emissions in early periods as explained. The assumptions within the 2 °C sensitivity scenarios used to construct Extended Data Fig. 1 are provided in Extended Data Table 2.

19. McKelvey, V. E. Mineral resource estimates and public policy. *Am. Sci.* **60,** 32–40 (1972).
20. McGlade, C. E., Speirs, J. & Sorrell, S. Unconventional gas—a review of regional and global resource estimates. *Energy* **55,** 571–584 (2013).
21. Federal Institute for Geosciences and Natural Resources (BGR). *Energy Study 2012. Reserves, Resources and Availability of Energy Resources.* http://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-15e.pdf?__blob=publicationFile&v=3 (BGR, 2012).
22. McGlade, C. E. *Uncertainties in the outlook for oil and gas.* PhD thesis, UCL, http://discovery.ucl.ac.uk/1418473/2/131106%20Christophe%20McGlade_PhD%20Thesis.pdf (2013).

23. Klett, T. & Schmoker, J. in *Giant Oil and Gas fields of the Decade 1990–1999* (ed. Halbouty, M. T.) 107–122 (The American Association of Petroleum Geologists, 2003).
24. Attanasi, E. D. & Freeman, P. A. Survey of Stranded Gas and Delivered Costs to Europe of Selected Gas Resources. *SPE Econ. Manag.* **3,** 149–162 (2011).
25. International Energy Agency (IEA). *World Energy Outlook.* http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2008.pdf (IEA, 2008).
26. Trinnaman, J. & Clarke, A. *Survey of Energy Resources* http://www.worldenergy.org/wp-content/uploads/2012/09/ser_2010_report_1.pdf (World Energy Council, 2010).
27. International Energy Agency (IEA). *World Energy Outlook.* http://www.worldenergyoutlook.org/publications/weo-2013/ (IEA, 2013).
28. International Energy Agency (IEA). *World Energy Outlook.* http://www.iea.org/publications/freepublications/publication/weo2011_web.pdf (IEA, 2011).
29. Rogner, H.-H. *et al.* in *Global Energy Assessment—Towards a Sustainable Future* Ch. 7, 423–512 (Cambridge University Press, 2012).
30. Owen, N. A., Inderwildi, O. R. & King, D. A. The status of conventional world oil reserves—hype or cause for concern? *Energy Policy* **38,** 4743–4749 (2010).
31. McGlade, C. & Ekins, P. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. *Energy Policy* **64,** 102–112 (2014).
32. International Energy Agency (IEA). *World Energy Outlook.* http://www.worldenergyoutlook.org/media/weowebsite/2009/WEO2009.pdf (IEA, 2009).
33. Leatherdale, A. *et al. Bioenergy Review: Technical Paper 2—Global and UK Bioenergy Supply Scenarios.* http://archive.theccc.org.uk/aws2/Bioenergy/1463%20CCC_Bio-TP2_supply-scen_FINALwithBkMks.pdf (Committee on Climate Change, 2011).
34. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122,** 387–400 (2014).
35. Campbell, C. J. *Atlas of Oil and Gas Depletion* (Springer, 2013).
36. Herrmann, L. *et al. Oil and Gas for Beginners* 270–413 (Deutsche Bank, 2013).
37. Klett, T. R. *et al.* An Assessment of Potential Additions to Conventional Oil and Gas Resources of the World (outside the United States) from Reserve Growth. http://pubs.usgs.gov/fs/2012/3052/fs2012-3052.pdf (USGS, 2012).
38. Klett, T. R. *et al. Potential Additions to Conventional Oil and Gas Resources in Discovered Fields of the United States from Reserve Growth, 2012*. http://pubs.usgs.gov/fs/2012/3108/ (USGS, 2012).
39. Ahlbrandt, T., Charpentier, R., Klett, T., Schmoker, J. & Schenk, C. *USGS World Petroleum Assessment 2000.* http://pubs.usgs.gov/dds/dds-060/ (USGS, 2000).
40. Bentley, R., Miller, R., Wheeler, S. & Boyle, G. *UKERC Review of Evidence on Global Oil Depletion: Annex 1—Models of global oil supply for the period 2008-2030.* http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=292 (UKERC, 2009).
41. Brownfield, M., Charpentier, R. R., Cook, T., Gautier, D. L. & Higley, D. K. *An Estimate of Undiscovered Conventional Oil and Gas Resources of the World, 2012.* http://pubs.usgs.gov/fs/2012/3042/fs2012-3042.pdf (USGS, 2012).
42. Gautier, D. L. *et al.* Assessment of undiscovered oil and gas in the Arctic. *Science* **324,** 1175–1179 (2009).
43. Smith, T. Arctic dreams—a reality check. Geo ExPro **4,** 16–24 (2007).
44. Shah, A. *et al.* A review of novel techniques for heavy oil and bitumen extraction and upgrading. *Energy Environ. Sci.* **3,** 700–714 (2010).
45. Clarke, B. *NPC Global Oil and Gas Study: Topic Paper 22—Heavy Oil.* www.npc.org/study_topic_papers/22-ttg-heavy-oil.pdf (National Petroleum Council, 2007).
46. Schenk, C. *et al. An Estimate of Recoverable Heavy Oil Resources of the Orinoco Oil Belt, Venezuela.* http://pubs.usgs.gov/fs/2009/3028/pdf/FS09-3028.pdf (USGS, 2009).
47. Attanasi, E. D. & Meyer, R. F. in *2010 Survey of Energy Resources* 123–150 (World Energy Council, 2010).
48. Johnson, R. C., Mercier, T. J. & Brownfield, M. Assessment of in-place oil shale resources of the Green River Formation, Greater Green River Basin in Wyoming, Colorado, and Utah. http://pubs.usgs.gov/fs/2011/3063/pdf/FS11-3063.pdf (USGS, 2011).
49. Dyni, J. *Geology and Resources of Some World Oil-Shale Deposits.* http://pubs.usgs.gov/sir/2005/5294/pdf/sir5294_508.pdf (USGS, 2006).
50. Biglarbigi, K., Mohan, H. & Carolus, M. *Potential for Oil Shale Development in the United States.* http://www.inteki.com/reports.html (INTEK, 2009).
51. CEDIGAZ. *Natural Gas in the World, End of July 2008* (Centre International d'Information sur le Gaz Naturel et tous Hydrocarbures Gazeux (CEDIGAZ), 2009).



Extended Data Figure 1 | Cumulative fossil fuel production under a range of sensitivity scenarios run using TIAM-UCL. Scenario names and characteristics are given in Extended Data Table 2.



Extended Data Figure 2 | The auxiliary energy inputs for natural bitumen production in Canada by *in situ* technologies in the 2 °C scenario and the CO_2 intensity of these. bbl SCO, a barrel of synthetic crude oil, the oil that results after upgrading the natural bitumen.

Extended Data Table 1 | Best estimates of remaining reserves and remaining ultimately recoverable resources from 2010

	Oil (Gb)			Gas (Tcm)			Hard coal (Gt)		Lignite (Gt)	
Country or region	Res	Con RURR	Uncon RURR	Res	Con RURR	Uncon RURR	Res	RURR	Res	RURR
Africa	111	280	70	13	45	35	31	45	2	5
Canada	53	60	640	1	5	25	4	35	2	40
China and India	38	90	110	5	10	40	255	1,080	16	120
FSU	152	370	360	61	95	30	123	580	94	490
CSA	148	360	450	9	30	55	10	25	5	10
Europe	25	110	30	6	25	20	17	70	66	160
Middle East	689	1,050	10	76	105	20	2	10	2	5
OECD Pacific	6	30	130	4	10	20	45	120	44	200
ODA	23	75	5	9	25	15	15	40	14	155
United States	50	190	650	8	25	40	226	560	31	335
Global	1,294	2,615	2,455	192	375	300	728	2,565	276	1,520

'Con' and 'Uncon' stand for conventional and unconventional sources, respectively. Coal is specified in billions of tonnes (Gt), gas in trillions of cubic metres (Tcm) and oil in billions of barrels (Gb). Res, reserves.

Extended Data Table 2 | Labels and description of the sensitivity scenarios modelled in this project

Sensitivity Name	Description
2DS_FFCHIGH	Production costs of all fossil fuel technologies are 50% larger in 2015 and 100% larger in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_FFCLOW	Production costs of all fossil fuel technologies are 33% lower in 2015 and 50% lower in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_BIOHIGH	The maximum annual production of solid biomass and bio-crops in 2050 is assumed to be 350 EJ. This is close to the highest level of production of bio-energy in any of the scenarios from the AR5 scenario database[5] and is around three times the equivalent figure in 2DS (119 EJ).
2DS_BIOLOW	The maximum annual production of solid biomass and bio-crop in 2050 is assumed to be 38 EJ. This is similar to the figure given in the central scenario from [33] and is around a third of the equivalent figure in 2DS (119 EJ).
2DS_OILHIGH	Uses the high values of each category of oil in each region from the aggregate resource distributions described in the methods section (Extended Data Table 4)
2DS_OILLOW	Uses the low values of each category of oil in each region (Extended Data Table 4)
2DS_GASHIGH	Uses the high values of each category of gas in each region (Extended Data Table 4)
2DS_GASLOW	Uses the low values of each category of gas in each region (Extended Data Table 4)
2DS_DEMHIGH	The major drivers of energy service demands in TIAM-UCL are growth in GDP, population, and GDP/capita. Future regional growth in GDP and population are therefore modified to the values given in Shared Socioeconomic Pathway (SSP) number 5[34] the SSP with the highest GDP and GDP/capita growth by 2050 (a 240% increase in the global average; cf. a 120% increase in 2DS). All other energy service demands (not relying on GDP or population) are also modified commensurately.
2DS_DEMLOW	Future regional growth in GDP and population are modified to the values given in Shared Socioeconomic Pathway (SSP) number 3:[34] the SSP with the lowest GDP and GDP/capita growth by 2050 (a 50% increase in the global average).
2DS_NOBIOCCS	No negative emissions technologies are permitted i.e. carbon capture and storage (CCS) cannot be applied to any electrical or industrial process that uses biomass or bio-energy as feedstock in any period.
2DS_NOCCS	CCS is not permitted to be applied to any electrical or industrial process in any period.

Data for bio-energy sensitivities from refs 5 and 33, and for demand sensitivities from ref. 34.

Extended Data Table 3 | Regional distribution of resources unburnable before 2050 in absolute terms and as a percentage of current resources under the 2 °C scenario that allows CCS

	Conven oil		Unconven oil		Conven Gas		Unconven Gas		Hard Coal		Lignite	
Country or region	Gb	%	Gb	%	Tcm	%	Tcm	%	Gt	%	Gt	%
Africa	141	50%	70	100%	28	61%	35	100%	42	94%	2.8	56%
Canada	43	72%	633	99%	3.6	73%	18	71%	34	98%	39	97%
China and India	54	60%	110	100%	8.0	80%	35	88%	1,003	93%	106	88%
FSU	201	54%	360	100%	63	67%	27	89%	576	99%	480	98%
CSA	198	55%	447	99%	23	76%	51	92%	21	85%	6.3	63%
Europe	64	58%	30	100%	18	72%	16	78%	69	99%	142	89%
Middle East	554	53%	10	100%	72	68%	20	100%	10	100%	5.0	99%
OECD Pacific	23	77%	130	100%	9.0	90%	15	74%	116	97%	198	99%
ODA	38	51%	5.0	100%	14	55%	12	78%	34	84%	142	92%
United States	99	52%	650	100%	19	75%	20	50%	556	99%	317	95%
Global	1,417	54%	2,445	100%	257	69%	247	82%	2,462	96%	1,438	95%

'Conven' and 'Unconven' stand for conventional and unconventional resources, respectively.

Extended Data Table 4 | Principal data sources used to derive reserve and resource estimates and estimates at the global level for each category of production

Category	Data sources used to provide country-level estimates of resources	Aggregated high estimate	Aggregated median estimate	Aggregated low estimate
Oil		(in Gb)	(in Gb)	(in Gb)
Current conventional 2P reserves in fields in production or scheduled to be developed	[21,31,35,36]	950	820	620
Reserve growth	[37,38]	1,200	850	610
Undiscovered oil	Fact sheets since USGS World Petroleum Assessment [39] and [35,40,41]	580	300	180
Arctic oil	[42,43]	80	65	40
Light tight oil	[10]	470	300	150
Natural gas liquids (NGL)	[26] Ancillary data associated with [39]	380	280	170
Natural bitumen	Oil in place estimates [17,26] Extraction technologies [44–46]	Mined RURR 130 *In situ* RURR 1290	Mined RURR 100 *In situ* RURR 840	Mined RURR 70 *In situ* RURR 520
Extra-heavy oil	Oil in place estimates [47,48] Extraction technologies [47] and refs for bitumen	750	440	230
Kerogen oil	Oil in place estimates [49,50] Extraction technologies [51]	Mined RURR 740 *In situ* RURR 1,080	Mined RURR 485 *In situ* RURR 590	Mined RURR 270 *In situ* RURR 190
Total		7,650	5,070	3,050
Gas		(in tcm)	(in tcm)	(in tcm)
Current conventional 2P reserves in fields in production or scheduled to be developed	[35,52]	140	130	110
Reserve growth	[24,37,38]	125	90	60
Undiscovered gas	Fact sheets since USGS World Petroleum Assessment [39] and [35,41]	180	120	80
Arctic gas	[42,43]	40	35	25
Tight gas	[20]	60	60	60
Coal-bed methane	[20]	45	40	20
Shale gas	[20]	310	200	120
Associated gas	[36,37,44]	Included in the above		
Total		900	675	475

High and low values are the aggregated 95th and 5th percentile estimates, respectively. 'tcm', trillions of cubic metres. Data are from references 10, 17, 20, 21, 31, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50 and 51.

Extended Data Table 5 | Global aggregated oil, gas and coal reserve and resource estimates from a selection of data sources

	Oil (Gb)		Gas (Tcm)		Coal (Gt)	
Organisation	Reserves	Resources	Reserves	Resources	Reserves	Resources
BGR	1,600	4,750	195	825	1,000	23,500
IEA	1,700	5,950	190	810	1,000	21,000
GEA	1,500 - 2,300	4,200 - 6,000	670 - 2,000	2,000 - 12,500	850 - 1,000	14,000 - 20,000
This study's median figures	1,300	5,070	190	675	1,000	4,085

BGR, Federal Institute for Geosciences and Natural Resources[21]; IEA, International Energy Agency[27,28]; GEA, Global Energy Assessment[29].

Extended Data Table 6 | Regions included in TIAM-UCL and their aggregation to the regions given in the main text

Region	Aggregated region in main text
Non-OPEC Africa	Africa
OPEC Africa	Africa
Australia	OECD Pacific
Canada	Canada
Non-OPEC Central and South America	Central and South America (CSA)
OPEC Central and South America	Central and South America (CSA)
China	China and India
Eastern Europe	Europe
Former Soviet Union	Former Soviet Union (FSU)
India	China and India
Japan	OECD Pacific
Non-OPEC Middle	Middle East
OPEC Middle East	Middle East
Mexico	Central and South America (CSA)
Other Developing Asia	Other Developing Asia (ODA)
South Korea	OECD Pacific
United Kingdom	Europe
United States	United States
Western Europe	Europe

Extended Data Table 7 | Labels and description of the four core scenarios modelled in this project

Scenario Name	Description
5DS	The model is constrained to keep the average global surface temperature rise to less than 5°C in all years to 2200. No other emissions constraints are imposed, and since allowed emissions under this scenario are so high (i.e. the constraint is very lax), no real emissions mitigation is required. These constraints result in 2050 GHG emissions of 71 Gt CO_2-eq (up from around 48 Gt CO_2-eq in 2010).
3DS	From 2005 to 2010, the model is fixed to the solution given in the 5°C temperature i.e. we assume that no emissions reductions are required. From 2010-2015, it is assumed that the model must be on track to achieve the emissions reduction pledges set out in the Copenhagen Accord[1], but no other emissions reductions are required. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 3°C in all years to 2200. These constraints result in 2050 GHG emissions of 54 Gt CO_2-eq
2DS	The constraints between 2005 and 2015 in this scenario are identical to the 3DS. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 2°C in all years to 2200. These constraints result in 2050 GHG emissions of 21 Gt CO_2-eq
2DS-noCCS	Emissions reduction requirements are identical to 2DS. Carbon capture and storage (CCS) is not permitted to be applied to any electricity or industrial process in any period.

GHG, greenhouse gas measured in tonnes of CO_2 equivalent (CO_2-eq). Data from ref. 1.

This is a tab page.
Please title tab
“Mercure”

nature climate change

LETTERS
https://doi.org/10.1038/s41558-018-0182-1

Macroeconomic impact of stranded fossil fuel assets

J.-F. Mercure[1,2,3*], H. Pollitt[3,2], J. E. Viñuales[2], N. R. Edwards[2,4], P. B. Holden[4], U. Chewpreecha[3], P. Salas[2], I. Sognnaes[2], A. Lam[2,5] and F. Knobloch[1,2]

Several major economies rely heavily on fossil fuel production and exports, yet current low-carbon technology diffusion, energy efficiency and climate policy may be substantially reducing global demand for fossil fuels[1-4]. This trend is inconsistent with observed investment in new fossil fuel ventures[1,2], which could become stranded as a result. Here, we use an integrated global economy–environment simulation model to study the macroeconomic impact of stranded fossil fuel assets (SFFA). Our analysis suggests that part of the SFFA would occur as a result of an already ongoing technological trajectory, irrespective of whether or not new climate policies are adopted; the loss would be amplified if new climate policies to reach the 2 °C target of the Paris Agreement are adopted and/or if low-cost producers (some OPEC countries) maintain their level of production ('sell out') despite declining demand; the magnitude of the loss from SFFA may amount to a discounted global wealth loss of US$1–4 trillion; and there are clear distributional impacts, with winners (for example, net importers such as China or the EU) and losers (for example, Russia, the United States or Canada, which could see their fossil fuel industries nearly shut down), although the two effects would largely offset each other at the level of aggregate global GDP.

The Paris Agreement aims to limit the increase in global average temperature to "well below 2 °C above pre-industrial levels"[5]. This requires that a fraction of existing reserves of fossil fuels and production capacity remain unused, hence becoming SFFA[6–10]. Where investors assume that these reserves will be commercialized, the stocks of listed fossil fuel companies may be overvalued. This gives rise to a 'carbon bubble', which has been emphasized or downplayed by reference to the credibility of climate policy[8,9,11–14]. Here, we show that climate policy is not the only driver of stranding. Stranding results from an ongoing technological transition, which remains robust even if major fossil fuel producers (for example, the United States) refrain from adopting climate mitigation policies. Such refusal would only aggravate the macroeconomic impact on producers because of their increased exposure to stranding as global demand decreases, potentially amplified by a likely asset sell-out by lower-cost fossil fuel producers and new climate policies. For importing countries, a scenario that leads to stranding has moderate positive effects on GDP (gross domestic product) and employment levels. Our conclusions support the existence of a carbon bubble that, if not deflated early, could lead to a discounted global wealth loss of US$1–4 trillion, a loss comparable to the 2008 financial crisis. Further economic damage from a potential bubble burst could be avoided by decarbonizing early.

The existence of a carbon bubble has been questioned on grounds of credibility or timing of climate policies[11,12]. That would explain investors' relative confidence in fossil fuel stocks[11,12] and the projected increase in fossil fuel prices until 2040[2]. Yet, there is evidence that climate mitigation policies may intensify in the future. A report covering 99 countries concludes that over 75% of global emissions are subject to an economy-wide emissions-reduction or climate policy scheme[15]. Moreover, the ratification of the Paris Agreement and its reaffirmation at COP22 (the 22nd Conference of the Parties) have added momentum to climate action despite the position of the new US administration[16]. Furthermore, low fossil fuel prices may reflect the intention of producer countries to sell out their assets, that is, to maintain or increase their level of production despite declining demand for fossil fuel assets[17]. But that is not all.

Irrespective of whether or not new climate policies are adopted, global demand growth for fossil fuels is already slowing in the current technological transition[1,2]. The question then is whether, under the current pace of low-carbon technology diffusion, fossil fuel assets are bound to become stranded due to the trajectories in renewable-energy deployment, transport fuel efficiency and transport electrification. Indeed, the technological transition currently underway has major implications for the value of fossil fuels, due to investment and policy decisions made in the past. Faced with SFFA of potentially massive proportions, the financial sector's response to the low-carbon transition will largely determine whether the carbon bubble burst will prompt a 2008-like crisis[11,12,14,18].

We use a simulation-based integrated energy–economy–carbon-cycle–climate model, E3ME-FTT-GENIE (Energy-Environment-Economy Macroeconomic–Future Technology Transformations–Grid Enabled Integrated Earth) (see Methods and Supplementary Table 1), to calculate the macroeconomic implications of future SFFA. Integrated assessment models generally rely on general-equilibrium methods and systems optimization[19–21]. Such models struggle to represent the effects of imperfect information and foresight for real-world agents and investors. By contrast, a dynamic simulation-based model relying on empirical data on socio-economic and technology diffusion trajectories can better serve this purpose (see Supplementary Note 1). In this method, investments in new technology and the interactional effects of changing social preferences generate momentum for technology diffusion that can be quantitatively estimated for specific policy sets. Our model, E3ME-FTT-GENIE, is currently the only such

---

[1]Department of Environmental Science, Radboud University, Nijmegen, The Netherlands. [2]Cambridge Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, Cambridge, UK. [3]Cambridge Econometrics Ltd, Covent Garden, Cambridge, UK. [4]Environment, Earth and Ecosystems, The Open University, Milton Keynes, UK. [5]Department of Economics, Faculty of Social Sciences, University of Macao, Taipa, Macau. *e-mail: J.Mercure@science.ru.nl

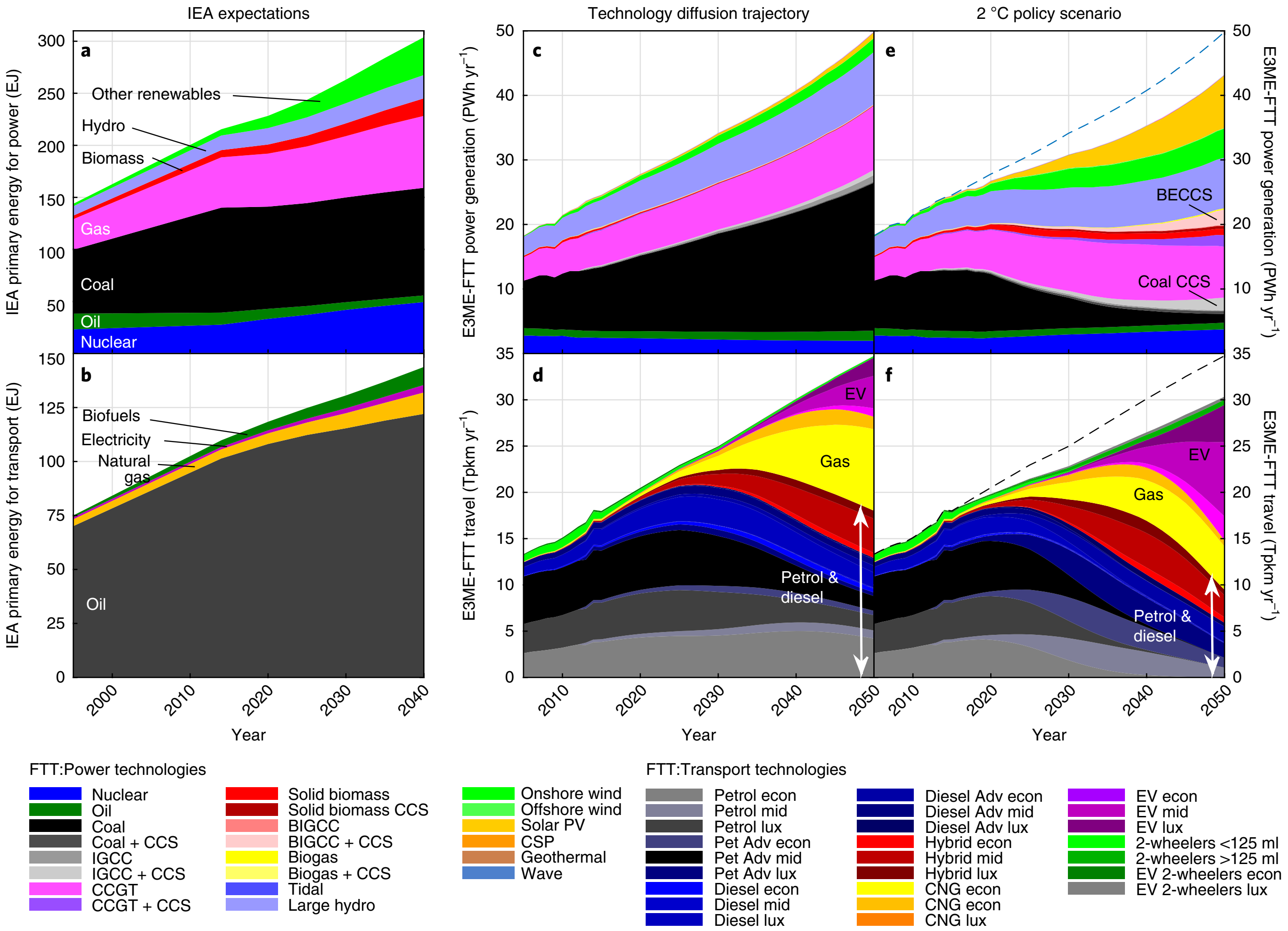


Fig. 1 | Projections of future energy use for power generation and transport. a,**b**, Global IEA fuel demand in the IEA expectations scenario. **c**–**f**, Technology composition in electricity generation (**c**,**e**) and road transport (in terms of trillion passenger kilometres travelled, Tpkm; **d**,**f**) in our Technology Diffusion Trajectory (**c**,**d**) and 2 °C (**e**,**f**) scenarios. IEA fuel demand is taken from ref. [2]. Dashed lines refer to our Technology Diffusion Trajectory scenario for comparison. CCS, carbon capture and storage; CC, combined cycle; IGCC, integrated gasification CC; CCGT, CC gas turbine; BIGCC, biomass IGCC; PV, photovoltaic; CSP, concentrated solar power; CNG, compressed natural gas; EV, electric vehicle; Adv, higher-efficiency combustion; Econ, engine size < 1,400 cc; Mid, 1,400cc ≤ engine size < 3,000 cc; Lux, engine size ≥ 3,000 cc.

Table 1 | Scenarios and models

Sector			Power generation	Road transport	Household heating	Other transport	Industry	Rest
Model			**FiT**	**FT**	**FT**	**E3ME**	**E3ME**	**E3ME**
Scenario	IEA expectations		Energy sector not modelled; replaced by fuel use data taken from IEA					
	Technology Diffusion Trajectory	No sell-out	CO_2P, FiT, Reg	Implicit in data	Implicit in data	Implicit in data	Implicit in data	Implicit in data
		Sell-out	Same, with exogenous assumptions over fossil fuel production (production/reserve ratio)					
	2 °C	No sell-out	CO_2P, Sub, FiT, Reg, K-S	FiT, RT, BioM, Reg, K-S	FiT, Sub	CO_2P, Reg	CO_2P, Reg	CO_2P, Reg
		Sell-out	Same, with exogenous assumptions over fossil fuel production (production/reserve ratio)					

Abbreviations: CO_2P, carbon price; FiT, feed-in tariff; Sub, capital cost subsidies; RT, registration carbon tax; Reg, regulations; K-S, kick-start programme; BioM, biofuel mandates; FT, fuel tax. Policy details available in the Methods. For carbon prices, sell-out assumptions and a sell-out sensitivity analysis, see Supplementary Figs. 5 and 6. For key model characteristics, see Methods, Supplementary Table 1 and Supplementary Note 1. For sensitivity analyses on key technology parameters, see Supplementary Note 2, Supplementary Tables 3 and 4 and Supplementary Fig. 8. Supplementary Table 5 and Supplementary Figs. 7–11 compare our scenarios with others in the literature. Supplementary Table 6 compares GENIE outputs with other models. For fossil fuel prices, see Supplementary Table 7. For sectoral impacts, see Supplementary Note 5 and Supplementary Table 8. The IEA expectations scenario corresponds to the IEA's new policies scenario[2]. Detailed policies can be obtained from the Supplementary Information.

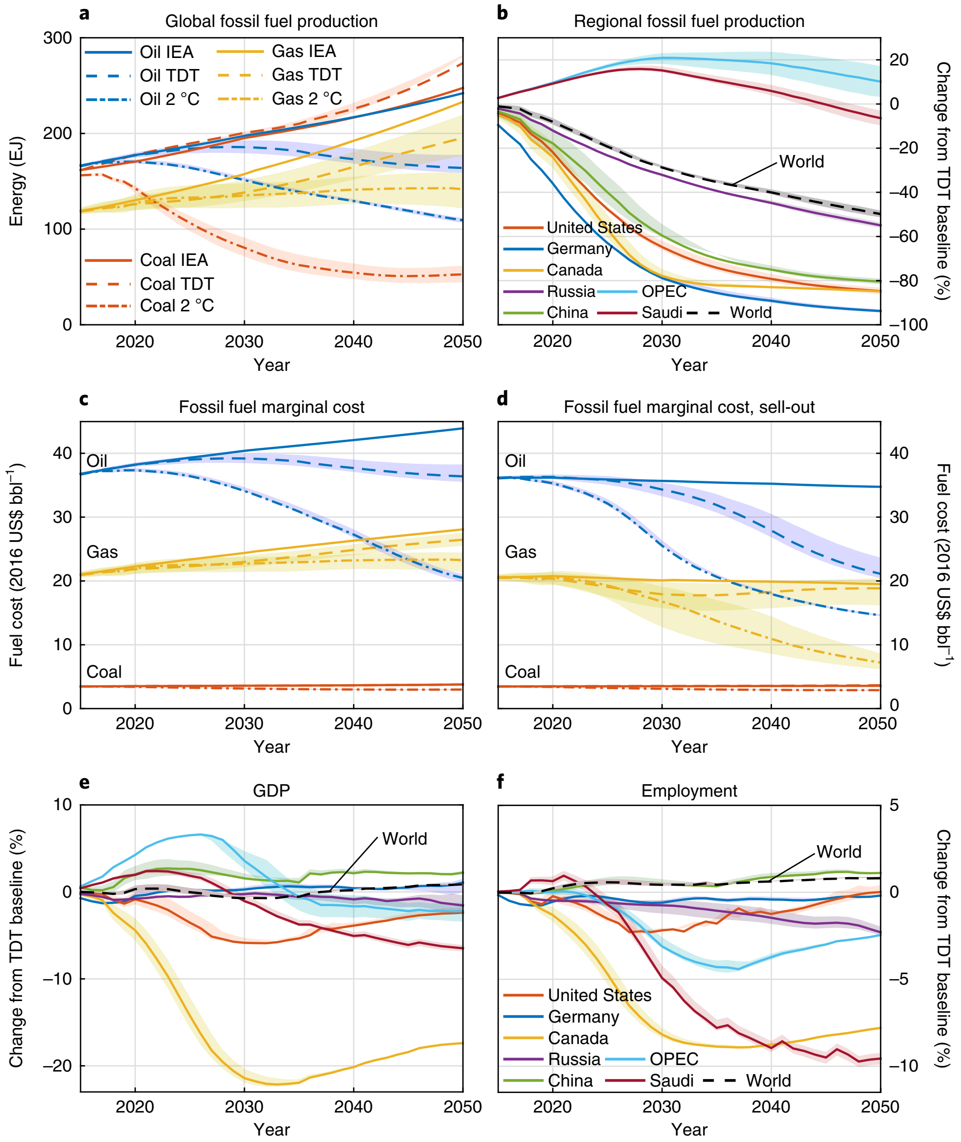


Fig. 2 | Change in fossil fuel asset value and production across countries, and in macroeconomic indicators. **a**, Global production of fossil fuels, for the IEA expectations (IEA) scenario, our Technology Diffusion Trajectory scenario (TDT) and our 2 °C policies scenario. **b**, Change in total fossil fuel production between the 2 °C policies scenario and TDT. **c**,**d**, Marginal costs of fossil fuels in the same three scenarios, without sell-out (**c**) and with sell-out (**d**). **e**,**f**, Changes in GDP and employment between the 2 °C policies sell-out scenario and TDT without sell-out (negative means a loss). The width of traces represents maximum uncertainty generated by varying technology parameters (see Supplementary Table 3 and Supplementary Note 2). OPEC excludes Saudi Arabia for higher detail. Macro impacts for Canada feature higher levels of economic uncertainty (not shown), because such high impacts could be mitigated in reality by various policies such as deficit spending by the government; however, we exclude studying deficit spending here for simplicity of interpretation (we assume balanced budgets).

simulation-based integrated assessment model that couples the macroeconomy, energy and the environment covering the entire global energy and transport systems with detailed sectoral and geographical resolution[22–24].

We study and compare three main scenarios (see Table 1 and Methods for details): fuel use from the International Energy Agency's (IEA) 'new policies scenario', which we call 'IEA expectations' to reflect the influence of the IEA's projections on the formation of investor and policymaker expectations as to future demand (see Fig. 1a,b for electricity generation and transport); our own E3ME-FTT 'Technology Diffusion Trajectory' projection with energy demand derived from our technology diffusion modelling in the power[25], road transport[26], buildings and other sectors under the ongoing technological trajectory (Fig. 1c,d); and a projection, which we call the '2 °C' scenario, under a chosen set of policies that achieve 75% probability of remaining below 2 °C (Fig. 1e,f; see Supplementary Fig. 1 for climate modelling), while keeping the use of bioenergy below 95 EJ yr^{-1} and thereby limiting excessive land-use change[27]. Only the Technology Diffusion Trajectory and 2 °C scenarios rely on FTT technology diffusion modelling.

Unlike the IEA expectations scenario, our Technology Diffusion Trajectory scenario captures technology diffusion phenomena by relying on historical data and projecting these data into the future. Importantly, historical data implicitly include the effects of past policies and investment decisions. On that basis, the Technology Diffusion Trajectory scenario reflects higher energy efficiency and leads to lower demand. Liquid fossil fuel use in transport peaks

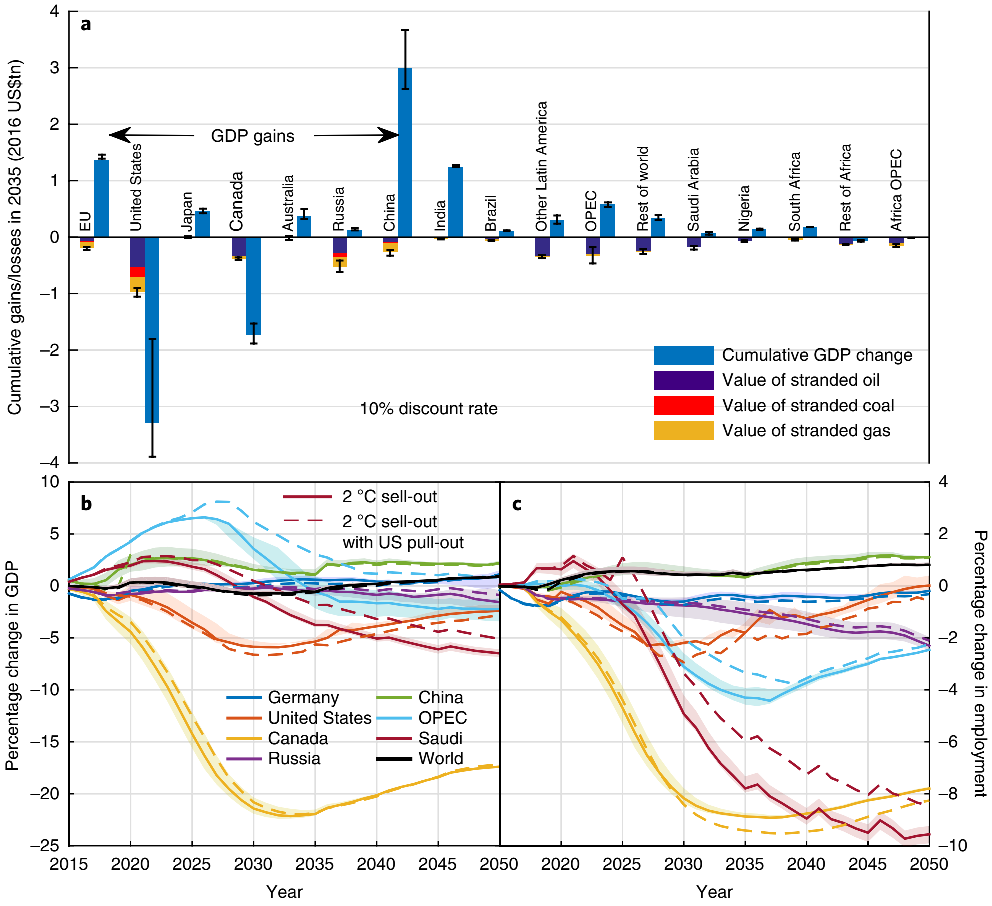


Fig. 3 | SFFA losses and impacts across countries. a, Discounted cumulated fossil fuel value loss to 2035 for oil, gas and coal, and GDP changes up to 2035, between the 2 °C sell-out scenario and the IEA expectations scenario (see Supplementary Table 2 and Supplementary Fig. 4 for other scenarios and aggregation methods). Negative bars indicate losses. Error bars represent maximum uncertainty on total SFFA generated by varying technology parameters (see Supplementary Table 3 and Supplementary Note 2; Supplementary Table 4 provides a breakdown for individual fuels). **b**,**c** Percent change in GDP (**b**) and labour force employment (**c**) between the 2 °C sell-out scenario and our Technology Diffusion Trajectory non-sell-out scenario (solid lines), and between the 2 °C sell-out scenario with a US withdrawal from climate policy and our Technology Diffusion Trajectory non-sell-out scenario (dashed lines).

in both the Technology Diffusion Trajectory and 2 °C scenarios before 2050 (Figs. 1 and 2a; for sectoral fuel use and emissions, see Supplementary Fig. 2). Solar energy partially displaces the use of coal and natural gas for power generation. On the basis of recent diffusion data (see Methods and Supplementary Table 1), our model suggests that a low-carbon transition is already underway in both sectors. Our sensitivity analysis (Supplementary Note 2 and Supplementary Table 3) confirms that these results are robust and driven by historical data rather than by exogenous modelling assumptions.

Importantly, the lower demand for fossil fuels leads to substantial SFFA, whether or not 2 °C policies are adopted (Fig. 2a). For individual countries, the effects vary depending on regional marginal costs of fossil fuel production, with concentration of production in OPEC (Organization of the Petroleum Exporting Countries) members where costs are lower (Fig. 2b). Regions with higher marginal costs experience a steep decline in production (for example, Russia), or lose almost their entire oil and gas industry (for example, Canada, the United States).

The magnitude of the loss depends on a variety of factors. Our analysis suggests that the behaviour of low-cost producers and/or the adoption of 2 °C policies can lead to an amplification of the loss (see Table 1 and Supplementary Table 2). The magnitude of the loss may indeed be amplified if low-cost producers decide to increase their ratio of production relative to reserves to outplay other asset owners and minimize their losses ('selling out': a detailed definition is given in Methods and Supplementary Note 3) (Fig. 2c,d). Slowing or peaking demand leads to fossil fuel prices peaking (without sell-out) or immediately declining (with sell-out). In the 2 °C scenario, fossil fuel markets substantially shrink and the prices fall abruptly between 2020 and 2030, a potentially disastrous scenario with substantial wealth losses to asset owners (investors, companies) but not to consumer countries. This result highlights the important strategic implications of decarbonization for the EU (European Union), China and India (consumers) compared with the United States, Canada or Russia (producers).

At the global level, it is possible to quantify the potential loss in value of fossil fuel assets (see Supplementary Note 4). If we assume that investment in fossil fuels in the present day continues on the basis of questioning commitments to policy, the return expectations derived from the IEA expectations projection and the assets' rigid lifespan with expected returns until 2035, and then if, contrary to investors' expectations, policies to achieve the 2 °C target are adopted, and low-cost producers sell-out their assets, then approximately US$12 trillion (in 2016 US dollars, which amounts to US$4 trillion present value when discounted with a 10% corporate rate) of financial value could vanish off their balance sheets globally in the form of stranded assets (see Supplementary Table 2). This is over 15% of global GDP in 2016 (US$75 trillion). This quantification arises from pairing the IEA expectations scenario with the 2 °C scenario with sell-out. If instead of the IEA expectations, we pair our own baseline (the Technology Diffusion Trajectory scenario) with the 2 °C scenario under the sell-out assumption, the total value loss from SFFA is approximately US$9 trillion (in 2016 US dollars; US$3 trillion with 10% discount rate; see Supplementary Table 2). Our quantification is broadly consistent with recent financial exposure estimates calculated at a regional and country level for the EU and the United States[14] (detailed explanation in Supplementary Note 4). Note that a 10% discount rate represents an investment horizon of about 10–15 years, and that fossil fuel ventures have lifetimes ranging between 2 (shale oil) and 50 (pipelines) years (oil wells: 15–30 years; oil tankers: 20–30 years; coal mines: >50 years). For reference, the subprime mortgage market value loss that took place following the 2008 financial crisis was around US$0.25 trillion, leading to global stock market capitalization decline of about US$25 trillion[18].

Regarding the impact of SFFA on GDP and employment, Fig. 2e,f show the change in GDP and employment between the Technology Diffusion Trajectory scenario without sell-out and the 2 °C scenario with sell-out, for several major economies/groups. The low-carbon transition generates a modest GDP and employment increase in regions with limited exposure to fossil fuel production (for example, Germany and most EU countries, and Japan). This is due to a reduction of the trade imbalance arising from fossil fuel imports, and higher employment arising from new investment in low-carbon technologies. The improvement occurs despite the general increase of energy prices and hence costs for energy-intensive industries[23,24]. Meanwhile, fossil fuel exporters experience a steep decline in their output and employment due to the near shutdown of their fossil fuel industry. These patterns emerge alongside a <1% overall impact of the transition on global GDP (<1% GDP change), indicating that impacts are primarily distributional, with clear winners (for example, the EU and China) and losers (for example, the United States and Canada, but also Russia and OPEC countries).

In both the Technology Diffusion Trajectory and 2 °C scenarios, a substantial fraction of the global fossil fuel industry eventually becomes stranded. In reality, these impacts should be felt in two independent ways (see Supplementary Note 4): through wealth losses and value of fossil fuel companies and their shareholders, and through macroeconomic change (GDP and employment losses in the fossil fuel industry, structural change), leaving winners and losers. Figure 3a compares cumulative GDP changes with the cumulative 2016 value of SFFA between the present and 2035. Due to different country reliance on the fossil fuel industry, impacts have different magnitudes and directions (see Supplementary Note 5).

Reducing fossil fuel demand generates an overall positive effect for the EU and China and a negative one for Canada and the United States. Figure 3b,c shows, however, that since impacts on the Canadian and US economies primarily depend on decisions taken in the rest of the world, the United States is worse off if it continues to promote fossil fuel production and consumption than if it moves away from them. This is due to the way global fossil fuel prices are formed. If the rest of the world reduces fossil fuel consumption and there is a sell-out, then lower fuel prices will make much US production non-viable, regardless of its own policy, meaning that its assets become stranded. If the United States promotes a fossil fuel-intensive economy, then the situation becomes worse, as it ends up importing this fuel from low-cost producers in the Middle East, while it forgoes the benefits of investment in low-carbon technology (for other countries, see Supplementary Fig. 3, Supplementary Table 8 and Supplementary Note 5).

Importantly, the macroeconomic impacts of SFFA on producer countries are primarily determined by climate mitigation decisions taken by the sum of consuming countries (for example, China or the EU), and thus a single country, however large, cannot alter this trajectory on its own. Also, critically, this finding contradicts the conventional assumption that global climate action is accurately described by the prisoner's dilemma game, which would allow a country to free-ride. But an exposed country can mitigate the impact of stranding, by divesting from fossil fuels as an insurance policy against what the rest of the world does. What remains to be known, however, is the degree to which SFFAs impose a risk to regional and global financial stability.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available at https://doi.org/10.1038/s41558-018-0182-1.

Received: 25 August 2017; Accepted: 3 May 2018;

References

1. *World Energy Investment* (OECD/IEA, 2017).
2. *World Energy Outlook* (OECD/IEA, 2016).
3. *Global Trends in Renewable Energy Investment* (UNEP, 2016).
4. *Global EV Outlook* (OECD/IEA, 2017).
5. *Paris Agreement* Article 2(1)(a) (UNFCCC, 2015); http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf
6. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517**, 187–190 (2015).
7. McGlade, C. & Ekins, P. Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system. *Energy Policy* **64**, 102–112 (2014).
8. Sussams, L. & Leaton, J. *Expect the Unexpected: The Disruptive Power of Low-Carbon Technology* (Carbon Tracker and Grantham Institute, 2017); https://www.carbontracker.org/reports/expect-the-unexpected-the-disruptive-power-of-low-carbon-technology
9. Leaton, J. & Sussams, L. *Unburnable Carbon: Are the World's Financial Markets Carrying a Carbon Bubble?* (Carbon Tracker, 2011); https://www.carbontracker.org/reports/carbon-bubble/
10. Heede, R. & Oreskes, N. Potential emissions of CO_2 and methane from proved reserves of fossil fuels: an alternative analysis. *Glob. Environ. Change* **36**, 12–20 (2016).
11. Carney, M. *Breaking the Tragedy of the Horizon—Climate Change and Financial Stability—Speech by Mark Carney* (Bank of England, 2015); http://www.bankofengland.co.uk/publications/Pages/speeches/2015/844.aspx
12. *The Impact of Climate Change on the UK Insurance Sector* (Bank of England Prudential Regulation Authority, 2015); https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/publication/impact-of-climate-change-on-the-uk-insurance-sector.pdf
13. *Recommendations of the Task Force on Climate-Related Financial Disclosures* (TCFD, 2017); https://www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Report-062817.pdf
14. Battiston, S., Mandel, A., Monasterolo, I., Schütze, F. & Visentin, G. A climate stress-test of the financial system. *Nat. Clim. Change* **7**, 283–288 (2017).
15. Nachmany, M. et al. *The Global Climate Legislation Study—2016 Update* (LSE and Grantham Institute, 2016); http://www.lse.ac.uk/GranthamInstitute/publication/2015-global-climate-legislation-study/
16. *Marrakech Action Proclamation for Our Climate and Sustainable Development* (UNFCCC, 2016); https://unfccc.int/files/meetings/marrakech_nov_2016/application/pdf/marrakech_action_proclamation.pdf
17. Sinn, H.-W. Public policies against global warming: a supply side approach. *Int. Tax Public Finance* **15**, 360–394 (2008).
18. Blanchard, O. J. *The Crisis: Basic Mechanisms, and Appropriate Policies* Working Paper WP/09/80 (IMF, 2008); https://www.imf.org/external/pubs/ft/wp/2009/wp0980.pdf
19. Clarke, L. et al. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. et al.) Ch. 6 (IPCC, Cambridge Univ. Press, 2014).
20. McCollum, D. L. et al. Quantifying uncertainties influencing the long-term impacts of oil prices on energy markets and carbon emissions. *Nat. Energy* **1**, 16077 (2016).
21. Bauer, N. et al. CO_2 emission mitigation and fossil fuel markets: dynamic and international aspects of climate policies. *Technol. Forecast. Social Change* **90**, 243–256 (2015).
22. Mercure, J.-F. et al. Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews* **20,** 195–208(2018).
23. Mercure, J.-F., Pollitt, H., Bassi, A. M., Viñuales, J. E. & Edwards, N. R. Modelling complex systems of heterogeneous agents to better design sustainability transitions policy. *Glob. Environ. Change* **37**, 102–115 (2016).

24. Mercure, J. et al. *Policy-induced Energy Technological Innovation and Finance for Low-carbon Economic Growth. Study on the Macroeconomics of Energy and Climate Policies* (European Commission, 2016); https://ec.europa.eu/energy/sites/ener/files/documents/ENER%20Macro-Energy_Innovation_D2%20Final%20(Ares%20registered).pdf
25. Mercure, J.-F. et al. The dynamics of technology diffusion and the impacts of climate policy instruments in the decarbonisation of the global electricity sector. *Energy Policy* **73**, 686–700 (2014).
26. Mercure, J.-F., Lam, A., Billington, S. & Pollitt, H. Integrated assessment modelling as a positive science: private passenger road transport policies to meet a climate target well below 2 degrees C. Preprint at https://arxiv.org/abs/1702.04133 (2018).
27. Fuss, S. et al. Betting on negative emissions. *Nat. Clim. Change* **4**, 850–853 (2014).

Acknowledgements

The authors acknowledge C-EERNG and Cambridge Econometrics for support, and funding from EPSRC (J.-F.M., fellowship no. EP/K007254/1), the Newton Fund (J.-F.M., P.S., J.E.V., H.P., U.C., EPSRC grant no. EP/N002504/1 and ESRC grant no. ES/N013174/1), NERC (N.R.E., P.B.H., H.P., U.C., grant no. NE/P015093/1), CONICYT (P.S.), the Philomathia Foundation (J.E.V.), the Cambridge Humanities Research Grants Scheme (J.E.V.), Horizon 2020 (J.-F.M., F.K., Sim4Nexus project no. 689150) and the European Commission (J.-F.M., H.P., F.K., U.C., DG ENERGY contract no. ENER/A4/2015-436/SER/S12.716128). J.-F.M. acknowledges the support of L. J. Turner during extended critical medical treatment, and H. de Coninck and M. Grubb for discussions. We are grateful to N. Bauer for sharing data from his study.

Author contributions

J.-F.M. designed and coordinated the research. J.-F.M., J.E.V., N.R.E., H.P. and I.S. wrote the article. J.-F.M., H.P. and U.C. ran simulations. U.C. and H.P. managed E3ME. J.-F.M. and A.L. developed FTT:Transport. J.-F.M. and P.S. developed FTT:Power and the resource depletion model. F.K. and J.-F.M. developed FTT:Heat. P.B.H. and N.R.E. ran GENIE simulations and provided scientific support on climate change. J.E.V. contributed geopolitical expertise.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-018-0182-1.

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence and requests for materials should be addressed to J.-F.M.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Methods

Detailed scenario definitions. *IEA expectations.* In the IEA expectations scenario, we replace our energy model (FTT and E3ME estimations) by exogenous fuel use data from the IEA's new policies scenario[2]. We derive macroeconomic variables from the evolution of a fixed energy system (FTT is turned off). We use our fossil fuel resource depletion model to estimate changes in the marginal cost of production of fossil fuels. This enables us to calculate fossil fuel asset values. Given that this scenario does not make use of our technology projections with FTT, we use this scenario with the interpretation that it represents the expectations of investors who do not fully realize the state of change of technology, in particular electric vehicles and renewables, that, as we argue in the text, is taking place.

Technology Diffusion Trajectory. In the Technology Diffusion Trajectory scenario, we use the three FTT diffusion models and our own E3ME energy sector model (see Supplementary Table 1) to estimate changes in fuel use due to the diffusion of new technologies. This is the baseline of the E3ME-FTT-GENIE model, which differs substantially from the IEA's. We interpret this scenario as that which, we argue, is likely to be realized instead of the IEA expectations scenario, according to the current technological trajectory observed in historical data that parameterize our models, if no climate policies are adopted. Policies are not specified explicitly, but instead are implicitly taken into consideration through the data.

In the 2 °C scenario, we choose a set of policies that achieve 75% chance of not exceeding 2 °C of peak warming, according to the GENIE model, itself validated with respect to Coupled Model Intercomparison Project Phase 5 models (see Supplementary Fig. 1). We estimate the diffusion of new low-carbon technologies and evolution of the energy sector under these policies using E3ME-FTT. Policies (for example, subsidies, taxes, regulations) are specified explicitly.

Sell-out versions of all scenarios. In both the Technology Diffusion Trajectory and 2 °C scenarios, the issue of the sell-out of fossil fuel resources by low-cost producers is a real but not inevitable possibility. We therefore present both sell-out and non-sell-out versions for each scenario. The sell-out is defined by increasing production-to-reserve ratios of producer countries, which concentrates production to OPEC and other low-cost production areas. Meanwhile, in the non-sell-out scenarios, these ratios are constant, as they have been until recently[28]. These assumptions are exogenous (see Supplementary Note 3). SFFAs are given for all combinations in Supplementary Table 2.

Policy assumptions for achieving a 2 °C target. The set of policies that we use to reach the Paris targets constitutes one of many possible sets that could theoretically reach the targets. They achieve emissions reductions consistent with a 75% probability of reaching the 2 °C target, and include the following.

Multiple sectors. CO_2 pricing is used to incentivize technological change across sectors in E3ME-FTT. One price/tax is defined exogenously, in nominal US dollars, at every year for every country, shown in Supplementary Fig. 5a. This policy applies to power generation and all heavy industry sectors (oil and gas, metals, cement, paper and so on). It is not applied to households or to road transport.

Electricity generation. Combinations of policies are used to efficiently decarbonize electricity generation, following earlier work[25]. These involve CO_2 pricing (see above) to incentivize technological change away from fossil fuel generators, subsidies to some renewables (biomass, geothermal, carbon capture and storage) and nuclear to level the playing field, feed-in tariffs for wind and solar-based technologies, and regulations to phase out the use of coal-based generators (none newly built). In some countries (foremost the United States, China, India), a kick-start programme for carbon capture and storage and bioenergy with carbon capture and storage is implemented to accelerate its uptake. All new policies are introduced in or after 2020.

Road transport. Combinations of policies are used to incentivize the adoption of vehicles with lower emissions, following earlier work[26]. These include (1) fuel efficiency regulations for new liquid-fuel vehicles; (2) a phase-out of older models with lower efficiency; (3) kick-start procurement programmes for electric vehicles where they are not available (by public authorities or private institutions, for example, municipality vehicles and taxis); (4) a tax starting at US\$50 per gCO_2 per km (2012 values) to incentivize vehicle choice; (5) a fuel tax (increasing from US\$0.10 per litre of fuel in 2018 to US\$1.00 in 2050; 2012 prices) to curb the total amount of driving; (6) biofuel mandates that increase from current values to between 10% and 30% (40% in Brazil) in 2050, different for every country, extrapolating IEA projections[29].

Industrial sectors. Fuel efficiency policy and regulations are used, requiring firms to invest in more recent, higher-efficiency production capital and processes, beyond what is delivered by the carbon price. These measures are publicly funded, following the IEA's 450 ppm scenario assumptions[29]. Further regulations are used that ban newly built coal-based processes (for example, boilers) in all sectors.

Buildings. For households, we assume a tax on the residential use of fossil fuels (starting at US\$60 per tCO_2 in 2020, linearly increasing by US\$6 per tCO_2 per year; 2016 prices), and subsidies on modern renewable heating technologies (starting at −25% in 2020, gradual phase-out after 2030). Commercial buildings increase energy efficiency rates, following the assumptions in the IEA's 450 ppm scenario[29].

The simulation-based integrated assessment model. E3ME-FTT-GENIE is an integrated assessment simulation model that comprises a model of the global economy and energy sector (E3ME), three subcomponents for modelling technological change with higher detail than E3ME (the FTT family), a global model of fossil fuel supply and an integrated model of the carbon cycle and climate system (GENIE). E3ME, FTT and the fossil fuel supply model are hard-linked in the same computer simulation, while GENIE is run separately, connected to the former group by soft coupling (transferring data). A peer-reviewed description of the model with fully detailed equations is available with open access[22]; key model codes and datasets can be obtained from the authors upon request.

The E3ME model. E3ME is a highly disaggregated demand-led global macroeconometric model[30–33] based on post-Keynesian foundations[24,33,34], which implies a non-equilibrium simulation framework (see Supplementary Table 1). It assumes that commercial banks lend according to bank reserves, which are created on demand by the central bank[34–36]. This means that increased demand for technologies and intermediate products in the process of decarbonization is financed (at least in part) by bank loans, and that spare production capacity in the economy and existing unemployment lead to possible output boosts during major building periods and to slumps during debt repayment periods[24]. In the jargon of the field, whereas computable general-equilibrium models normally 'crowd out' finance (additional investment in a given asset class implies a compensating reduction in investment in other asset classes), E3ME assumes a full availability of finance through credit creation by banks (additional investment in one sector does not require cancelling investment elsewhere; see ref. [24] for a discussion). E3ME does not feature an explicit representation of the sectoral detail of the financial sector (it is not stock-flow consistent) or model financial contagion; however, it does feature endogenous money through its investment equations, which is necessary and sufficient for this paper.

E3ME has 43 sectors of production, 22 users of fuels, 12 fuels and 59 regions. It uses a chosen set of 28 econometric relationships (including employment, trade, prices, investment, household consumption, energy demand) regressed over a corresponding high-dimension dataset covering the past 45 years, and extrapolates these econometric relationships self-consistently up to 2050. E3ME includes endogenous technological change in the form of technology progress indicators in each industrial sector and fuel user, providing the source of endogenous growth. It is not an equilibrium model; it is path-dependent and demand-led in the Keynesian sense. E3ME has been used in numerous policy analyses and impact assessments for the European Commission and elsewhere internationally (for example, see refs [37–39]). Recent discussions of the implications for results of the choice of an economic model for assessing the impacts of energy and climate policies are given in refs [24,33]. Previously, such debates have often concerned simpler types of integrated assessment models (for example, the Dynamic Integrated Climate–Economy model)[40–42], while newer debates are emerging that address issues of framing and philosophy of science[43,44]. Recent empirical studies appear to find no evidence for crowding-out in the finance of innovation, from the perspective of access to finance[45,46]. E3ME has been validated against historical data by reproducing history between 1972 and 2006, on the basis of the normal regression parameters[47].

The FTT model. Technology diffusion is not well described by time-series econometrics, as it involves nonlinear diffusion dynamics (S-shaped diffusion[48]). To improve our resolution of technological change in the fossil fuel-intensive sectors of electricity and transport, we use the FTT family of sectoral evolutionary bottom-up models of technological change dynamically integrated to E3ME[22,25,26,49]. FTT projects existing low-carbon technology diffusion trajectories on the basis of observationally determined preferences of heterogeneous consumers and investors, using a diffusion algorithm.

FTT models market share exchanges between competing technologies in the power, road transport and household heating sectors on the basis of technology 'fitness' to consumer/investor preferences. Agents have probabilistically distributed preferences calibrated on cross-sectional market datasets[26,49,50]. Choices are evaluated using chains of binary logits, weighted by their market share. The diffusion patterns of technologies are functions of their own market share and those of others, which reproduce standard observed S-shaped diffusion profiles (a so-called evolutionary replicator dynamics equation, or Lotka–Volterra competition equation[51–53]). FTT does not use optimization algorithms, and it is a time-step path-dependent simulation model (see Supplementary Table 1).

It is crucial to note that FTT projects the evolution of technology in the future by extending the current technological trajectory with a diffusion algorithm calibrated on recent history. The key property of FTT, strong path-dependence (or strong autocorrelation in time), typically found in technology transitions[48,54,55], is given to the model by two features. (1) Technologies with larger market shares have a proportionally greater propensity to increase their market share, until they reach market domination. This is a key stylized feature of the diffusion of innovations[48,55,56]. (2) Continuity of the technological trajectory at the transition year from historical data to the projection (2013 ± 3–5 years) is obtained by empirically determining cost factors (denoted γ; see below and Supplementary Fig. 8). Since the diffusion of innovations typically evolves continuously, there should not be a change of trajectory at the transition from history to projection. By ensuring that this is so, we obtain a baseline trajectory in which some new low-carbon technologies (for example, hybrid and electric vehicles, solar photovoltaics) already diffuse to non-negligible or substantial market shares, and some traditional vehicle types decline (for example, small motorcycles in China). This baseline (the Technology Diffusion Trajectory scenario) includes current policies implicitly in the data; that is, they are not specified explicitly. The introduction of additional policy, in later years, results in further gradual changes to the technological trajectory, typically after 2025, differences that become further from the baseline along the simulation time span. Sensitivity analysis (Supplementary Table 3) shows that these trajectories are robust under substantial changes of all relevant technological parameters.

The γ factors are determined in the following way. Historical databases were carefully constructed by the authors by combining various data sources (transport and household heating; see Supplementary Table 1) or taken from IEA statistics (power generation). The γ values are added to the respective levelized cost that is compared among options by hypothetical (heterogeneous) agents in the model[26,50]. One and only one set of γ values ensures that the first 3–5 years of projected diffusion features the same trajectory (time-derivative of market shares) as the last 3–5 years of historical data from the start date of the various simulations (2012 for transport, 2013 for power, 2015 for heat; see Supplementary Fig. 8 for an example). This is the sole purpose of γ. The interpretation of γ is a sum of all pecuniary or non-pecuniary cost factors not explicitly defined in the model, which includes agent preferences and existing incentives from current policy frameworks, as well as implicit valuations of non-pecuniary factors such as (for vehicles) engine power, comfort and status. While the heterogeneity of agents is explicitly specified in FTT cost data and handled by the model (through empirical cost distributions; see for example ref. [50]), γ are constant scalar values (not distributed or time-dependent). As is the case for any parameter determined with historical data, the further we model in the future, the less reliable the γ values are, but, just as with regression parameters, they do represent our best current knowledge as inferred from history.

The fossil fuel supply model. The supply of oil, coal and gas, in primary form, is modelled using a dynamical resource depletion algorithm[28]. It is equivalent in function and theory to that recently used by McGlade and Ekins[6]. Cost distributions of non-renewable resources are used, on the basis of an extensive survey of global fossil fuel reserves and resources[28]. The algorithm is then used to evaluate how resources are depleted, and how their marginal cost changes as the demand changes (that is, which is the most costly extraction venture, given extraction rates for all other extraction sites in production, supplying demand). As reserves are consumed and/or demand increases, fossil fuel resources previously considered to be uneconomic come online, requesting price increases. Meanwhile, when demand slumps, the most costly extraction ventures are first to shut down production (for example, deep offshore, oil sands). The data are disaggregated geographically following the E3ME regional classification.

The model assumes that the marginal cost sets the price, thus excluding effects on the price by events such as armed conflicts, processing bottlenecks (for example, refineries coming online and offline) and time delays associated with new projects coming online. While fossil fuel price changes may not always immediately follow changes in the marginal cost in reality, differences are cyclical (due to the ability of firms to cross-subsidize and produce at a loss for a limited time), and the long-term trend is robust. Taxes and duties on fuels, which differ in every region of the world, are not included in Fig. 2 or in the calculation of SFFA. E3ME includes end-user fuel prices from the IEA database, including taxes. The source for energy price data is the IEA. In the scenarios, we do not explicitly include the phase-out of fossil fuel subsidies, but the carbon price, when applied to fuels, effectively turns the subsidies into taxes. It is noted that some of the largest fuel subsidies are in countries that are energy exporters and that reducing or removing the subsidies would help to support public budgets (although doing so increases pressure on households). End-user prices are updated during the simulation to reflect changes in fossil fuel marginal costs from the fossil fuel supply model; however, end-user prices are not used in the calculation of SFFA. Behavioural assumptions over production decisions have important impacts in this submodel, described further below.

The GENIE model. GENIE is a global climate–carbon-cycle model, applied in the configuration of ref. [57], comprising the GOLDSTEIN (Global Ocean Linear Drag Salt and Temperature Equation INtegrator) three-dimensional ocean coupled to a two-dimensional energy–moisture-balance atmosphere, with models of sea ice, the ENTSML (Efficient Numerical Terrestrial Scheme with Managed Land) terrestrial carbon storage and land-use change, BIOGEM (BIOGEochemistry Model) ocean biogeochemistry, weathering and SEDGEM (SEDiment GEochemistry Model) sediment modules[57–61]. Resolution is 10° × 5° on average with 16 depth levels in the ocean. To provide probabilistic projections, we perform ensembles of simulations using an 86-member set that varies 28 model parameters and is constrained to give plausible post-industrial climate and CO_2 concentrations[62]. Simulations are continued from AD 850 to 2005 historical transients[63]. Post-2005 CO_2 emissions are from E3ME, scaled by 9.82/8.62, to match estimated total emissions[64], accounting for sources not represented in E3ME, and extrapolated to zero at 2079. For the 2 °C scenario, non-CO_2 trace gas radiative forcing and land-use-change maps are taken from Representative Concentration Pathway 2.6 (ref. [65]). For the purposes of validation, the GENIE ensemble has been forced with the Representative Concentration Pathway scenarios, and these simulations are compared with the CMIP5 (Coupled Model Intercomparison Project Phase 5) and AR5 (IPCC Fifth Assessment Report) EMIC (Earth system Model of Intermediate Complexity) ensembles in Supplementary Table 6.

In the 2 °C scenario, median peak warming relative to 2005 is 1.00 °C, with 10% and 90% percentiles of 0.74 °C and 1.45 °C, respectively. Corresponding values for peak CO_2 concentration are 457, 437 and 479 ppm, respectively. Total warming from 1850–1900 to 2003–2012 is estimated as 0.78 ± 0.06 °C (ref. [66]), giving median peak warming relative to pre-industrial levels of 1.78 °C. Ensemble distributions of warming and CO_2 are plotted in Supplementary Fig. 1. Oscillations are associated with reorganizations of ocean circulation or snow-albedo feedbacks rendered visible by the lack of chaotic variability in the simplified atmosphere.

It could be questioned why such a detailed climate model is needed in this analysis. One key aspect of our analysis is the quantification of additional SFFA that arise due to climate policy. For this quantification to be meaningful, it is also necessary to quantify the climate and carbon-cycle uncertainties that are associated with these policies (here, a 75% probability of avoiding 2 °C warming). Rapid decarbonization pathways lie outside the Representative Concentration Pathways framework, so that our physically based climate–carbon-cycle model is a more appropriate and robust tool than, for example, an emulator under extrapolation.

Data availability. The data that support the findings of this study are available from Cambridge Econometrics, but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are, however, available from the authors upon reasonable request and with the permission of Cambridge Econometrics.

References

28. Mercure, J.-F. & Salas, P. On the global economic potentials and marginal costs of non-renewable resources and the price of energy commodities. *Energy Policy* **63**, 469–483 (2013).
29. *World Energy Outlook* (OECD/IEA, 2014).
30. *The E3ME Model* (Cambridge Econometrics, 2017); http://www.e3me.com
31. Barker, T., Alexandri, E., Mercure, J.-F., Ogawa, Y. & Pollitt, H. GDP and employment effects of policies to close the 2020 emissions gap. *Clim. Policy* **16**, 393–414 (2016).
32. Pollitt, H., Alexandri, E., Chewpreecha, U. & Klaassen, G. Macroeconomic analysis of the employment impacts of future EU climate policies. *Clim. Policy* **15**, 604–625 (2015).
33. Pollitt, H. & Mercure, J.-F. The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Clim. Policy* **18**, 184–197 (2017).
34. Lavoie, M. *Post-Keynesian Economics: New Foundations* (Edward Elgar, Cheltenham, 2014).
35. McLeay, M., Radia, A. & Thomas, R. *Money in the Modern Economy: An Introduction* (Bank of England, 2014); http://www.bankofengland.co.uk/publications/Pages/quarterlybulletin/2014/qb14q1.aspx
36. McLeay, M., Radia, A. & Thomas, R. *Money Creation in the Modern Economy* (Bank of England, 2014); http://www.bankofengland.co.uk/publications/Pages/quarterlybulletin/2014/qb14q1.aspx
37. *Employment Effects of Selected Scenarios from the Energy Roadmap 2050* (Cambridge Econometrics, 2013); http://ec.europa.eu/energy/sites/ener/files/documents/2013_report_employment_effects_roadmap_2050_2.pdf
38. *Assessing the Employment and Social Impact of Energy Efficiency* (Cambridge Econometrics, 2015); https://ec.europa.eu/energy/sites/ener/files/documents/CE_EE_Jobs_main%2018Nov2015.pdf
39. Lee, S., Pollitt, H. & Park, S.-J. (eds) *Low-Carbon, Sustainable Future in East Asia: Improving Energy Systems, Taxation and Policy Cooperation* (Routledge, London, 2015).
40. Ackerman, F., DeCanio, S. J., Howarth, R. B. & Sheeran, K. Limitations of integrated assessment models of climate change. *Clim. Change* **95**, 297–315 (2009).
41. Pindyck, R. S. Climate change policy: what do the models tell us? *J. Econ. Lit.* **51**, 860–872 (2013).
42. Weyant, J. P. A perspective on integrated assessment. *Clim. Change* **95**, 317–323 (2009).
43. Geels, F. W., Berkhout, F. & van Vuuren, D. P. Bridging analytical approaches for low-carbon transitions. *Nat. Clim. Change* **6**, 576–583 (2016).

44. Turnheim, B. et al. Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges. *Glob. Environ. Change* **35**, 239–253 (2015).
45. Popp, D. & Newell, R. Where does energy R&D come from? Examining crowding out from energy R&D. *Energy Econ.* **34**, 980–991 (2012).
46. Hottenrott, H. & Rexhäuser, S. Policy-induced environmental technology and inventive efforts: is there a crowding out? *Ind. Innov.* **22**, 375–401 (2015).
47. Barker, T. & Crawford-Brown, D. (eds) *Decarbonising the World's Economy: Assessing the Feasibility of Policies to Reduce Greenhouse Gas Emissions* (Imperial College Press, London, 2014).
48. Grübler, A., Nakićenović, N. & Victor, D. G. Dynamics of energy technologies and global change. *Energy Policy* **27**, 247–280 (1999).
49. Mercure, J.-F. FTT:Power: a global model of the power sector with induced technological change and natural resource depletion. *Energy Policy* **48**, 799–811 (2012).
50. Mercure, J.-F. & Lam, A. The effectiveness of policy on consumer choices for private road passenger transport emissions reductions in six major economies. *Environ. Res. Lett.* **10**, 064008 (2015).
51. Hofbauer, J. & Sigmund, K. *Evolutionary Games and Population Dynamics* (Cambridge Univ. Press, Cambridge, 1998).
52. Mercure, J.-F. Fashion, fads and the popularity of choices: micro-foundations for diffusion consumer theory. Preprint at https://arxiv.org/abs/1607.04155 (2018).
53. Mercure, J.-F. An age structured demographic theory of technological change. *J. Evolut. Econ.* **25**, 787–820 (2015).
54. Geels, F. W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* **31**, 1257–1274 (2002).
55. Wilson, C. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy* **50**, 81–94 (2012).
56. Rogers, E. M. *Diffusion of Innovations* (Simon and Schuster, New York, NY, 2010).
57. Holden, P. B., Edwards, N. R., Gerten, D. & Schaphoff, S. A model-based constraint on CO_2 fertilisation. *Biogeosciences* **10**, 339–355 (2013).
58. Marsh, R., Müller, S., Yool, A. & Edwards, N. Incorporation of the C-GOLDSTEIN efficient climate model into the GENIE framework: "eb_go_gs" configurations of GENIE. *Geosci. Model Dev.* **4**, 957–992 (2011).
59. Ridgwell, A. & Hargreaves, J. Regulation of atmospheric CO2 by deep-sea sediments in an Earth system model. *Glob. Biogeochem. Cycles* **21**, GB2008 (2007).
60. Ridgwell, A. et al. Marine geochemical data assimilation in an efficient Earth System Model of global biogeochemical cycling. *Biogeosciences* **4**, 87–104 (2007).
61. Williamson, M., Lenton, T., Shepherd, J. & Edwards, N. An efficient numerical terrestrial scheme (ENTS) for Earth system modelling. *Ecol. Model.* **198**, 362–374 (2006).
62. Foley, A. Climate model emulation in an integrated assessment framework: a case study for mitigation policies in the electricity sector. *Earth Syst. Dynam.* **7**, 119–132 (2016).
63. Eby, M. et al. Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity. *Clim. Past* **9**, 1111–1140 (2013).
64. Jackson, R. B. et al. Reaching peak emissions. *Nat. Clim. Change* **6**, 7–10 (2016).
65. Vuuren, D. P. et al. RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C. *Clim. Change* **109**, 95–116 (2011).
66. IPCC: Summary for Policymakers. In *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. et al.) (Cambridge Univ. Press, 2013).

This is a tab page.
Please title tab
“Battiston”

nature climate change

ARTICLES

PUBLISHED ONLINE: 27 MARCH 2017 | DOI: 10.1038/NCLIMATE3255

A climate stress-test of the financial system

Stefano Battiston[1]*, Antoine Mandel[2], Irene Monasterolo[3], Franziska Schütze[4] and Gabriele Visentin[1]

The urgency of estimating the impact of climate risks on the financial system is increasingly recognized among scholars and practitioners. By adopting a network approach to financial dependencies, we look at how climate policy risk might propagate through the financial system. We develop a network-based climate stress-test methodology and apply it to large Euro Area banks in a 'green' and a 'brown' scenario. We find that direct and indirect exposures to climate-policy-relevant sectors represent a large portion of investors' equity portfolios, especially for investment and pension funds. Additionally, the portion of banks' loan portfolios exposed to these sectors is comparable to banks' capital. Our results suggest that climate policy timing matters. An early and stable policy framework would allow for smooth asset value adjustments and lead to potential net winners and losers. In contrast, a late and abrupt policy framework could have adverse systemic consequences.

Assessing the impact of climate risks and climate policies on the financial system is currently seen as one of the most urgent and prominent policy issues[1,2]. In particular, there is a debate on whether the implementation of climate policies to meet the 2 °C target generates systemic risk or, instead, opportunities for low-carbon investments and economic growth. However, data are scarce and there is no consensus on the appropriate methodologies to use to address this issue. The magnitude of so-called stranded assets of fossil-fuel companies (in a 2 °C economy) has been estimated to be around 82% of global coal reserves, 49% of global gas reserves and 33% of global oil reserves[3]. Moreover, several studies have investigated the role of stranded assets in specific sectors and countries[4–9]. By investing in fossil-fuel companies, financial institutions hold direct 'high-carbon exposures', which for European actors have been estimated to be, relative to their total assets, about 1.3% for banks, 5% for pension funds and 4.4% for insurances[10]. One can compute the value at risk (VaR) associated with climate shocks[11] in the context of integrated assessment models[12] in which aggregate financial losses are derived top-down from estimated GDP (gross domestic product) losses due to physical risks resulting from climate change. Yet, assessing the financial risk of climate policies (often referred to as transition risks) requires estimations of the likelihood of the introduction of a specific policy. However, the likelihood that a climate policy is introduced depends on the expectations of the agents on that very likelihood. Thus, the intrinsic uncertainty of the policy cycle undermines the reliability of the probability distributions of asset returns, also due to the presence of fat tails[13]. Further, it is now understood that interlinkages among financial institutions can amplify both positive and negative shocks[14–16] and significantly decrease the accuracy of our estimation of default probabilities in an interconnected financial system[17]. As a result, calculations of expected losses/gains from climate policies carried out with traditional risk analysis methodologies have to be taken with caution. Here, we develop a complementary approach, rooted in complex systems science, and consisting of a network analysis of the exposures of financial actors[18,19] to all climate-policy-relevant sectors of the economy, as well as the exposures among financial actors themselves, across several types of financial instruments. This analysis is meant as a tool to support further investigations of the potential impact and the political feasibility of specific climate policies[20,21]. To go beyond the mere exposure to the fossil-fuels extraction sector, we remap an existing standard classification of economic sectors (NACE Rev2) according to their relevance to climate mitigation policies, and we analyse empirical microeconomic data for shareholders of listed firms in the European Union and in the United States. We find (see Supplementary Table 6) that while direct exposures via equity holdings to the fossil-fuel sector are small (4–13% across financial actor types), the combined exposures to climate-policy-relevant sectors are large (36–48%) and heterogeneous. In addition, financial actors hold equity exposures to the financial sector (13–25%), implying indirect exposures to climate-policy-relevant sectors.

Results

By targeting the reduction of greenhouse gas (GHG) emissions, climate policies can affect (positively or negatively) revenues and costs of various sectors in the real economy with indirect effects on financial actors holding securities of firms in those sectors. However, the existing classifications of economic sectors such as NACE Rev2 (ref. 22) or NAICS (ref. 23) were not designed to estimate financial exposures to climate-policy-relevant sectors. Therefore, we define a correspondence between sectors of economic activities at NACE Rev2 4-digit level and five newly defined climate-policy-relevant sectors (fossil fuel, utilities, energy-intensive, transport and housing) based on their GHG emissions, their role in the energy supply chain, and the existence in most countries of related climate policy institutions (see Methods and Fig. 1).

The exposures of financial actors (classified according to the standard European Systems of Accounts, ESA (ref. 24)) can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). By combining the breakdown of exposures across instruments with the reclassification

---

[1]Department of Banking and Finance, University of Zurich, Andreasstr. 15, 8050 Zürich, Switzerland. [2]Université Paris 1 Panthéon-Sorbonne, Centre d'économie de la Sorbonne, Maison des sciences économiques, 106-112 Boulevard de l'hôpital, 75647 Paris Cedex 13, France. [3]Frederick S. Pardee Center for the Study of the Longer Range Future, Boston University, 67 Bay State Road, Boston, Massachusetts 02215, USA. [4]Global Climate Forum, Neue Promenade 6, 10178 Berlin, Germany. *e-mail: stefano.battiston@uzh.ch

Table 1 | Absolute (first row, in US$ billions) and relative (second row, percentage of aggregate equity portfolio) exposure of each financial actor type to each sector.

	OCIs (955)	GOV (125)	Individuals (33,733)	Banks (798)	IPFs (6,392)	OFSs (3,081)	NFCs (14,851)	IFs (5,124)
Fossil-fuel	31.17	66.17	98.17	173.29	230.21	185.15	377.30	549.85
(767)	6.02%	11.43%	3.77%	6.34%	7.09%	5.33%	8.06%	6.05%
Utilities	19.32	63.58	21.16	77.02	55.53	65.46	93.09	249.32
(216)	3.73%	10.99%	0.81%	2.82%	1.71%	1.88%	1.99%	2.74%
Energy-intensive	172.84	147.53	766.33	708.30	865.87	1,019.84	1,408.65	2,701.69
(3,956)	33.40%	25.49%	29.47%	25.92%	26.68%	29.36%	30.08%	29.71%
Housing	13.26	15.88	100.57	59.07	85.28	76.60	146.72	189.36
(797)	2.56%	2.74%	3.87%	2.16%	2.63%	2.21%	3.13%	2.08%
Transport	11.43	18.48	55.38	47.67	54.48	69.96	106.67	173.02
(224)	2.21%	3.19%	2.13%	1.74%	1.68%	2.01%	2.28%	1.90%
Finance	127.01	95.33	419.63	684.72	609.11	669.82	702.44	1,532.08
(2,659)	24.54%	16.47%	16.14%	25.06%	18.77%	19.29%	15.00%	16.85%
Other	142.44	171.80	1,139.53	982.46	1,345.08	1,386.27	1,847.40	3,698.41
(6,259)	27.53%	29.68%	43.82%	35.95%	41.44%	39.91%	39.46%	40.67%

Numbers in brackets indicate the number of firms in this group of actors or sectors. OCIs, Other Credit Institutions; GOV, Government; IPFs, Insurance and Pension Funds; OFSs, Other Financial Services; NFCs, Non-Financial Corporations; IFs, Investment Funds.

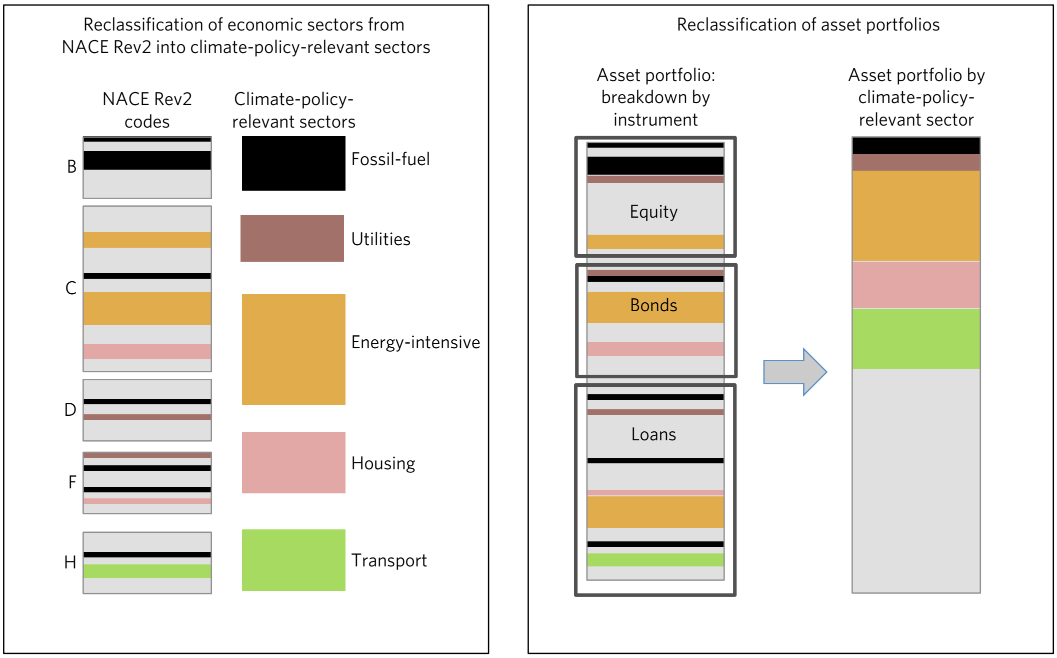


Figure 1 | Diagram illustrating the reclassification of sectors from NACE Rev2 codes into climate-policy-relevant sectors. For more information see the Methods and Supplementary Table 3.

of securities, we compute the total direct exposure of a given financial actor to each climate-policy-relevant sector (see Methods).

Direct financial exposure through equity holdings

To provide empirical estimates of exposures to climate-policy-relevant sectors, we apply our methodology to recent available data sets. Despite their relevance for policy purposes, data about securities holdings of financial institutions, in particular to climate-policy-relevant sectors, is generally scarce, inconsistent or even undisclosed. Along the three main instrument types mentioned above (equity, bonds and loans), at the level of individual institutions only some data of equity holdings are publicly available.

We thus first analyse a sample obtained from the Bureau Van Dijk Orbis database covering all EU and US listed companies and their disclosed shareholders (14,878 companies and 65,059 shareholders) at the last available year, that is, 2015. On the basis of our methodology, we construct the portfolio of each shareholder and we compute its exposure to each climate-policy-relevant sector. To gain insights into the magnitude of indirect exposures we further classify equity holdings in companies belonging to the financial sector. We group shareholders by financial actor type to include, besides the institutional financial sectors from the ESA classification (that is, Banks, Investment Funds, Insurance and Pension Funds) also Individuals, Governments, Non-Financial Companies, Other Credit Institutions and Other Financial Services (Table 1).

Figure 2a shows the result of the aggregated exposures in terms of equity holdings in listed companies for each financial actor type. The combined shares of equity holdings held by the financial sector (that is, Investment Funds, Insurance and Pension Funds, Banks, Other Credit Institutions, and Other Financial Services) amount to about 32.4 trillion US dollars, equivalent to 58.7% of total market capitalization.

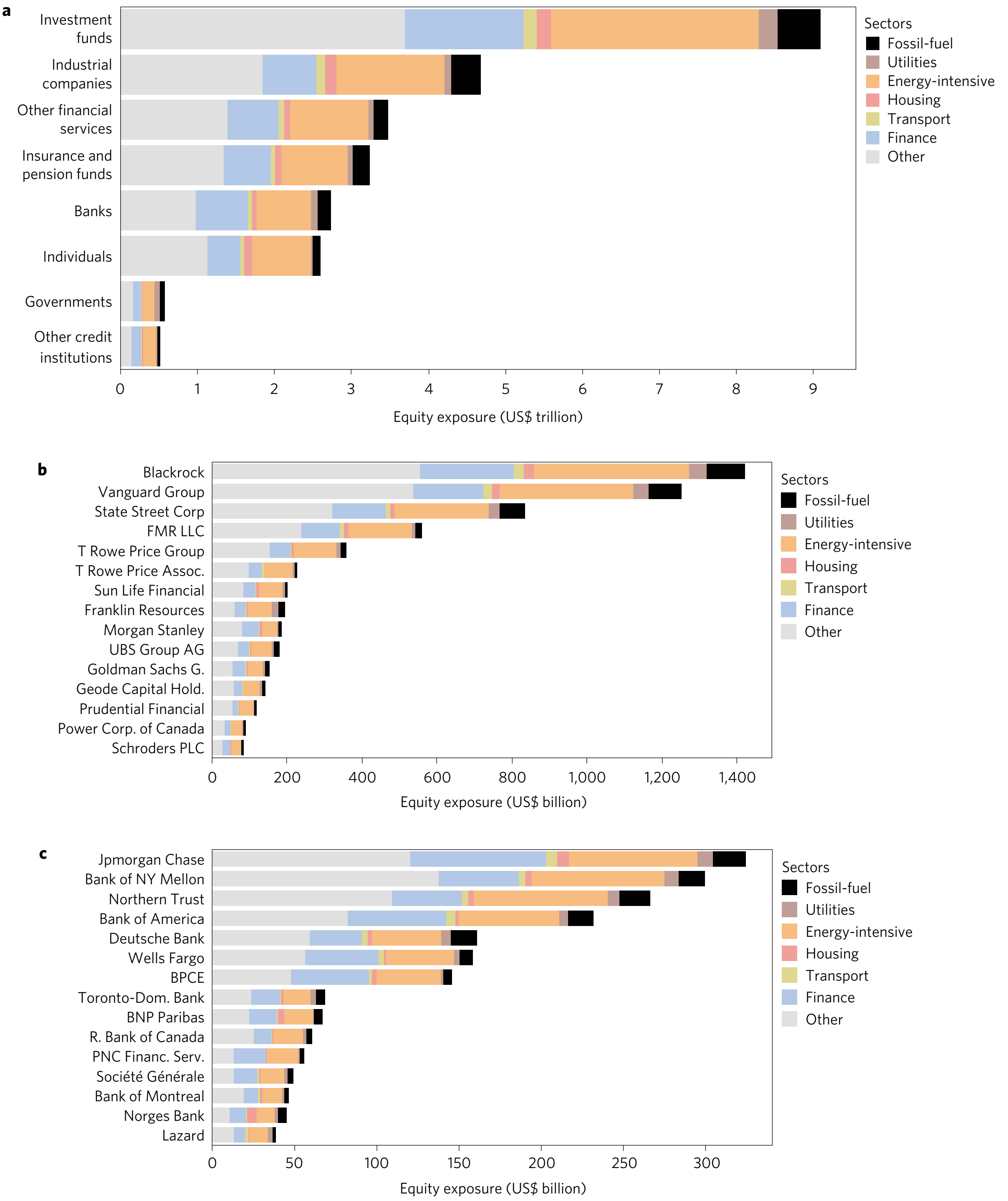


Figure 2 | Equity holdings in EU and US listed companies in 2015 (data from Bureau Van Dijk Orbis). a, Exposures to climate-policy-relevant sectors of aggregate financial actors worldwide. **b**, Exposures to climate-policy-relevant sectors of selected investment funds worldwide (top 15 by size of equity portfolio in the data). **c**, Exposures to climate-policy-relevant sectors of selected banks worldwide (top 15 by size of equity portfolio in the data).

The following findings emerge. First, the relative equity portfolio exposures of all financial actors types to the fossil-fuel sector are limited (that is, ranging from 4.4% for Individuals to 12.9% for Governments) (see Supplementary Table 6). Second, their relative equity portfolio exposures to all climate-policy-relevant sectors are large (that is, ranging from 45.2% for Insurance and Pension Funds, to 47.7% for Governments), and mostly accounted for by the energy-intensive sector. Third, since financial actors' exposures to the financial sector itself range from 13% for Industrial Companies up to 25.8% for Other Credit Institutions, they bear additional indirect exposures to climate-policy-relevant sectors. Within each financial actor type, the standard deviation of exposures across individuals (see Supplementary Table 6) reflects the level of heterogeneity across individuals' portfolio compositions. Examples of individual equity holdings' compositions are shown in Fig. 2b,c for the twenty largest players among investment funds and banks.

Climate stress-testing EU largest banks

Several quantitative estimates exist for the macroeconomic impacts of climate change and climate policies[25,26], as well as for the value

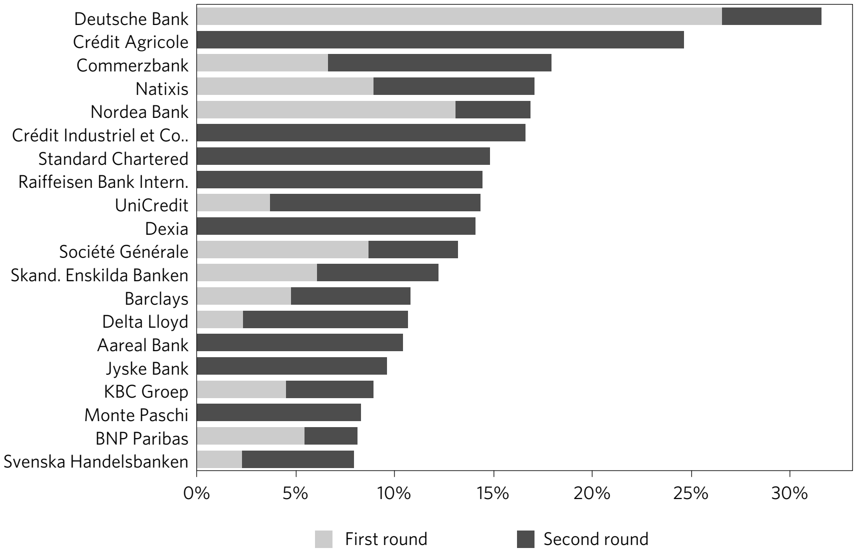


Figure 3 | First- and second-round losses in banks' equity for the 20 most-severely affected EU listed banks, under the Fossil fuel + Utilities 100% shock. Subsidiaries have not been taken into account.

of stranded assets[6]. Accordingly, probabilistic estimates of the climate VaR can be carried out from an aggregate perspective[11]. However, these estimates are too broad to define shock scenarios for individual institutions. At a more granular level, estimates of the value of stranded assets are available in the literature but their sectoral coverage is currently too narrow to inform an analysis of systemic impacts.

To overcome these limitations, we extend the stress-test methodology developed in refs 27,28, which allows one to disentangle the two main contributions to systemic losses. First-round losses are defined as losses in banks' equity due to direct exposures to shocks. Second-round losses are defined as indirect losses in banks' equity due to the devaluation of counterparties' debt obligations on the interbank credit market. The magnitude of second-round effects can vary significantly. Traditional methods (based on ref. 29), yielding small second-round effects, are appropriate only under specific market conditions (that is, full recovery from counterparties' asset liquidation and no mark-to-market valuation of debt obligations). In general, instead, second-round effects can be comparable in magnitude to first-round effects[15,27,28,30].

We illustrate how our methodology can be used to conduct a climate stress-test of the banking system based on microeconomic data at the level of individual banks, by carrying out two exercises on the set of the top 50 listed European banks by total assets (see Methods).

In the first exercise we aim to determine an upper bound on the magnitude of the losses induced by climate policies by considering a set of scenarios in which the whole equity value of the firms in the shocked sector would be lost. We can then compute for each bank the ratio of the exposures to climate-policy-relevant sectors over the banks' capital (that is, banks' equity on the liability side of their balance sheets). Different scenarios consist of different combinations of sectors as indicated in Supplementary Table 8, by increasing levels of shocks' severity. For instance, in the second scenario, 100% of the market capitalization of listed firms both in the fossil-fuel sector and in the utilities sector is lost. Figure 3 shows the losses as a percentage of the banks' capital across the 20 most affected banks as a result of the second scenario from Supplementary Table 8. Light (dark) grey bars indicate the losses from the first- (second-) round shocks. Notice that some banks have no first-round losses but have important losses at the second round. None of the largest banks could default solely due to their exposures to climate-policy-relevant sectors on the equity market. This result implies that even in a severe scenario, there is no systemic impact when considering only the equity holdings channel.

More refined scenarios, allowing one to compute a VaR for each bank, require one to have distributions of shocks across climate-policy-relevant sectors, which are not available in the literature at this stage. As a first step in this direction, in our second exercise, we construct distributions of shocks for the fossil-fuel and utility sectors based on the economic impact assessment of climate policies provided by the LIMITS database[26] and we consider several scenarios of banks' exposures to climate-policy-relevant sectors (see Methods).

In particular, we interpret scenarios (2) and (4) in terms of distributions of losses suffered by a 'representative' (average) bank adopting one of two different investment strategies:

- (2) a 'green' bank having all its equity holdings in utilities invested in renewables-based utilities and having no equity holdings in the fossil-fuel sector,
- (4) a 'brown' bank having all its equity holdings in utilities invested in fossil-fuel-based utilities and keeping its equity holdings in the fossil-fuel sector.

Supplementary Table 10 reports the main statistics on the global relative equity loss in the banking system. The results of the two exercises are consistent: the system's VaR in the brown scenario is less than 1% of the total banks' capital. Supplementary Table 3 reports the statistics for the 'representative' brown and green bank: depending on whether their exposure to utilities is mainly concentrated on renewables-based utilities or on fossil-fuel ones and if they are exposed to the fossil-fuel sector, banks might face very different impacts from climate policies. Further, Supplementary Fig. 6 shows the distribution of first-round losses: the brown bank incurs more losses than the green one, but these losses are small in comparison with the equity of the average bank (that is, US$32 billion) and with its total asset (that is, US$604 billion). Finally, Fig. 4a,b reports the VaR for the 20 most affected banks both in the brown and in the green scenario.

The limited magnitude of banks' losses in this exercise is due to the fact that Euro Area banks bear little equity holdings compared with their balance sheet (about 1.2T EUR, that is, 3.8% of total assets and 48% of capital), probably due to higher capital requirements for equity holdings[31]. However, banks bear larger exposures on loans to non-financial corporations (about 4.8T EUR = 13.8% of total assets and 192% of their capital). Unfortunately, Euro Area banks' loans are only available at 1-digit NACE Rev2 aggregation[32]. At this stage,

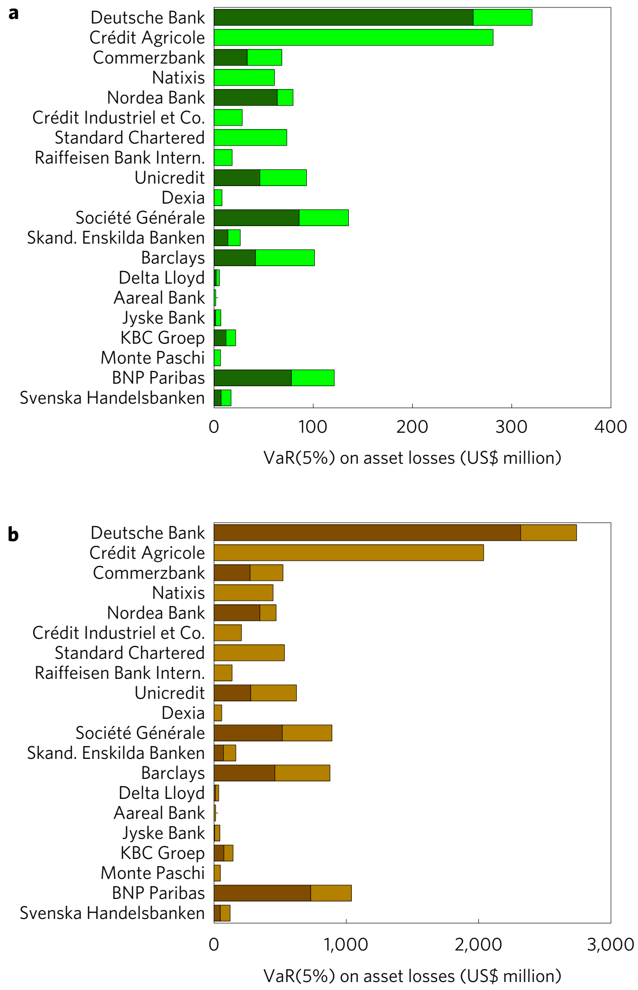


Figure 4 | Individual banks' value at risk under green and brown investment strategies. Value-at-risk at the 5% significance level of the 20 most-severely affected EU listed banks in the data set, under the scenario that they follow the green investment strategy (**a**) or the brown investment strategy (**b**). Darker colour refers to VaR(5%) computed on the distribution of first-round losses only, while lighter colour refers to VaR(5%) computed on the sum of first- and second-round losses.

we cannot compute individual exposures of banks to climate-policy-relevant sectors via their loans. Sector level data for 2014 from the ECB Data Warehouse provide the following aggregate estimations for the banks' exposures on loans as a fraction of banks' capital: 11.4% for fossil and utilities; 28% for energy-intensive; 16% for transportation; 73% for housing. We also need to consider banks' loans to households (presumably mostly granted for mortgages), which add a further 208% of exposures in the housing sector as a fraction of capital.

Better disclosure of climate-related financial exposures[33] would allow one to improve calculations for individual banks. The above considerations suggest that banks would not default solely due to their loan exposures to firms in the fossil-fuel and utilities sectors. However, if climate policies imply higher volatility of loans' values in the energy-intensive and transport sector or in the housing sector and for mortgages, this would translate into volatility of large portions of banks' assets, relative to their capital (16% + 28% = 44% and 73% + 208% = 281%, respectively).

Indirect exposures of European financial actors

By cross-matching aggregate balance sheet information for financial actors (from ECB Data Warehouse) with equity holdings (from Orbis), the following findings emerge for the Euro Area. First, the major direct exposures to climate-policy-relevant sectors of investment funds and pension funds are concentrated in equity holdings, while for banks they are concentrated on loans. Interestingly, bond holdings are only a minor channel of direct exposure to climate-policy-relevant sectors because outstanding bonds issued by non-financial firms in the Euro Area amount to about 1 trillion Euro, that is, about only one-fifth of the values of equity shares issued by the same type of firms. Indeed, only less than 7% of bonds are issued by firms in the real sectors, with roughly 40% issued by governments and another 45% issued by financial institutions.

Second, financial actors bear also indirect exposures to climate-policy-relevant sectors. For instance, pension funds hold an exposure of about 25% of their total assets in equity shares of investment funds, which in turn have an estimated exposure of about 25% of total assets in equity holdings of climate-policy-relevant sectors. Pension funds also hold an exposure of 15% of their total assets in bonds and loans to banks, which, on the basis of the previous section, hold an estimated exposure of about 14% of total assets to climate-policy-relevant sectors. In contrast, the direct exposure of pension funds to climate-policy-relevant sectors through equity holdings is about 8% of total assets. These findings imply that shocks on the fossil sector and increased volatility on asset values in the other climate-policy-relevant sectors could affect non-negligible portions of pension funds' assets through both direct (8.3%) as well as indirect exposures (about 8%).

Conclusions

By remapping the existing classification of economic activities (NACE Rev2) into newly defined climate-policy-relevant sectors, we find that direct and indirect exposures to such sectors represent a large portion of financial actors' equity holdings portfolios (in particular for investment funds and pension funds). Moreover, exposures represent a portion of banks' loan portfolios comparable to banks' capital. Further, we develop a network-based climate stress-test methodology that can be used to derive statistics of losses for individual financial actors, including VaR. We illustrate the methodology on a sample of the top 50 largest EU banks taking into account first- and second-round effects of shocks to their equity portfolios.

Our findings suggest that the implementation of climate mitigation policies is key, both in terms of timing and expectations. The extent to which financial exposures will translate into shocks depends on the ability of market participants to anticipate climate policy measures. If climate policies are implemented early on and in a stable and credible framework, market participants are able to smoothly anticipate the effects. In this case there would not be any large shock in asset prices and there would be no systemic risk. In contrast, in a scenario in which the implementation of climate policies is uncertain, delayed and sudden[2,10] (for example, as a reaction to increased frequency of extreme weather events and to align with the COP21 agreement), market participants would not be able to fully anticipate the impact of policies. In this case, given the large direct and indirect exposures of financial actors to climate-policy-relevant sectors, this might entail a systemic risk because price adjustments are abrupt and portfolio losses from the fossil-fuel sector and fossil-based utilities do not have the time to be compensated by the increase in value of renewable-based utilities. These two scenarios and their corresponding VaR are illustrated by the loss distributions for a 'green' and a 'brown' investing strategy in our climate stress-test on EU banks.

Moreover, the fact that financial actors bear large exposures to climate-policy-relevant sectors implies that climate mitigation policies could increase volatility on large portions of their portfolios. Climate mitigation policies are commonly thought to have an adverse effect on the value of assets in the fossil-fuel sector[5], as well as an adverse effect on the whole economy (see Ch. 6 of ref. 25). However, a transition to a low-carbon economy could also have net positive aggregate effects[34]. Overall, the effects of climate policies are likely to vary across firms and sectors: for example, the renewable energy and the energy efficiency sectors are expected to increase massively in market share (see ref. 35, IEA report 2015; IRENA Annual Review 2016), while real-estate assets can increase or decrease in value, depending on their energy performance (see Supplementary Table 6.7 in ref. 25). Further, stock price volatility in climate-policy-relevant sectors can increase as a result of: technological innovation[36,37], increased competition[38] and policy uncertainty[39]. Therefore, climate policy could lead to winners and losers (in absolute terms) across financial actors, depending on the composition of their portfolios.

Overall, our network analysis of financial exposures highlights that financial actors' portfolios are both interdependent and largely exposed to the outcome of the climate policy cycle. This implies the possibility of multiple equilibria without a clear way to assign *ex ante* probabilities for each equilibrium to occur. Therefore, while climate-related financial information disclosure is crucial for risk evaluation, a stable policy framework is necessary to resolve the multiplicity of possible outcomes. To this end, a network-based, conditional VaR approach represents an advancement in the analysis of climate-policy risks and their implications for the financial sector.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

Received 13 July 2016; accepted 24 February 2017;
published online 27 March 2017

References

1. Carney, M. Breaking the tragedy of the horizon–climate change and financial stability *Lloyd's* (29 September 2015); http://www.bankofengland.co.uk/publications/Pages/speeches/2015/844.aspx
2. *Too Late, Too Sudden: Transition to a Low-Carbon Economy and Systemic Risk* (ESRB Advisory Scientific Committee, 2016).
3. McGlade, C. & Ekins, P. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* **517,** 187–190 (2015).
4. Meinshausen, M. *et al*. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
5. Leaton, J. *Unburnable Carbon—are the World's Financial Markets Carrying a Carbon Bubble* 1–36 (Carbon Tracker Initiative, 2012).
6. Robins, N., Keen, A. & Night, Z. *Coal and Carbon Stranded Assets: Assessing the Risk* (HSBC, 2012).
7. Fleischman, L., Cleetus, R., Deyette, J., Clemmer, S. & Frenkel, S. Ripe for retirement: an economic analysis of the US coal fleet. *Electr. J.* **26,** 51–63 (2013).
8. Caldecott, B. & Robins, N. *Greening China's Financial Markets: The Risks and Opportunities of Stranded Assets* Briefing Paper 1–29 (Smith School et Enquête du PNUE, 2014).
9. World Resource Institute and UNEP-FI *Carbon Asset Risk Discussion Framework* Tech. Rep. 1–67 (2015).
10. Weyzig, F., Kuepper, B., van Gelder, J. W. & Van Tilburg, R. *The Price of Doing Too Little Too Late* Tech. Rep. 1–69 (Green European Foundation, 2014).
11. Dietz, S., Bower, A., Dixon, C. & Gradwell, P. Climate value at risk of global financial assets. *Nat. Clim. Change* **6,** 676–679 (2016).
12. Nordhaus, W. D. Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. *Resour. Energy Econ.* **15,** 27–50 (1993).
13. Nordhaus, W. D. The economics of tail events with an application to climate change. *Rev. Environ. Econ. Policy* **5,** 240–257 (2011).
14. Battiston, S., Caldarelli, G., Georg, C.-P., May, R. & Stiglitz, J. Complex derivatives. *Nat. Phys.* **9,** 123–125 (2013).
15. Battiston, S. *et al*. Complexity theory and financial regulation. *Science* **351,** 818–819 (2016).
16. Battiston, S., D'Errico, M. & Gurciullo, S. DebtRank and the network of leverage. *J. Altern. Invest.* **18,** 68–81 (2016).
17. Battiston, S., Roukny, T., Stiglitz, J., Caldarelli, G. & May, R. The price of complexity. *Proc. Natl Acad. Sci. USA* **113,** 10031–10036 (2016).
18. May, R. M., Levin, S. A. & Sugihara, G. Complex systems: ecology for bankers. *Nature* **451,** 893–895 (2008).
19. Haldane, A. G. & May, R. M. Systemic risk in banking ecosystems. *Nature* **469,** 351–355 (2011).
20. Rogelj, J. *et al*. Emission pathways consistent with a 2 °C global temperature limit. *Nat. Clim. Change* **1,** 413–418 (2011).
21. Peters, G. P. The 'best available science' to inform 1.5 °C policy choices. *Nat. Clim. Change* **6,** 646–649 (2016).
22. *NACE Rev. 2—Statistical Classification of Economic Activities* (Eurostat, 2008); http://ec.europa.eu/eurostat/web/nace-rev2
23. *North American Industry Classification System* (United States Census Bureau, 2017); http://www.census.gov/eos/www/naics
24. *European System of National and Regional Accounts* (Eurostat, 2010); http://ec.europa.eu/eurostat/web/esa-2010
25. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al.*) (Cambridge Univ. Press, 2015).
26. Kriegler, E. *et al*. What does the 2 °C target imply for a global climate agreement in 2020? The LIMITS study on Durban Platform scenarios. *Clim. Change Econ.* **4,** 1340008 (2013).
27. Battiston, S., Puliga, M., Kaushik, R., Tasca, P. & Caldarelli, G. DebtRank: too central to fail? Financial networks, the FED and systemic risk. *Sci. Rep.* **2,** 541 (2012).
28. Battiston, S., Caldarelli, G., D'errico, M. & Gurciullo, S. Leveraging the network: a stress-test framework based on DebtRank. *Stat. Risk Model.* **33,** 1–33 (2016).
29. Eisenberg, L. & Noe, T. H. Systemic risk in financial systems. *Manage. Sci.* **47,** 236–249 (2001).
30. Battiston, S., D'Errico, M. & Visentin, G. *Rethinking Financial Contagion* Working paper series no. 2831143 (2016).
31. *Basel Committee on Banking Supervision: Capital Requirements for Banks' Equity Investments in Funds* (Bank for International Settlements, 2013); http://www.bis.org/publ/bcbs266.pdf
32. *Statistical Data Warehouse* (European Central Bank, 2017); http://sdw.ecb.europa.eu
33. *Recommendations of the Task-Force on Climate-Related Financial Disclosure* (Financial Stability Board, 2016); https://www.fsb-tcfd.org/publications/recommendations-report/
34. Wolf, S., Schütze, F. & Jaeger, C. C. Balance or synergies between environment and economy a note on model structures. *Sustainability* **8,** 761 (2016).
35. *Towards Green Growth* (OECD, 2011).
36. Shiller, R. J. *Market Volatility* (MIT, 1992).
37. Mazzucato, M. & Semmler, W. *Economic Evolution Learning, and Complexity* (Springer, 2002); http://doi.org/fckmx3
38. Irvine, P. J. & Pontiff, J. Idiosyncratic return volatility, cash flows, and product market competition. *Rev. Financ. Stud.* **22,** 1149–1177 (2009).
39. Brogaard, J. & Detzel, A. The asset-pricing implications of government economic policy uncertainty. *Manage. Sci.* **61,** 3–18 (2015).

Acknowledgements

The authors would like to thank J. E. Stiglitz and A. C. Janetos for fruitful comments on an early version of the paper, M. D'Errico for precious suggestions on macro-network data from the ECB Data Warehouse, and J. Glattfelder for help on equity holdings data extraction from Orbis. We also would like to thank A. Barkawi, P. Monnin and M. Tanaka for their comments during the Bank of England conference on Climate Change and Central Banking. S.B. acknowledges financial support from the Swiss National Fund Professorship grant no. PP00P1-144689. All the authors acknowledge the support of the European Projects Future and Emerging Technologies (FET) SIMPOL (grant no. 610704) and DOLFINS (grant no. 640772), and the European Project SEI Metrics (grant no. 649982).

Author contributions

All authors contributed to the writing of the manuscript, as well as material and analysis tools. G.V. and S.B. also performed the data analysis.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to S.B.

Competing financial interests

The authors declare no competing financial interests.

Methods

Identifying climate-policy-relevant sectors in the real economy. Many climate policies target the reduction of GHG emissions (in particular in non-carbon neutral processes). To identify the climate-policy-relevant sectors we group economic activities with the following logic. We start from the top sectors by direct GHG emissions according to Eurostat (scope 1 CO_2 equivalent), which includes activities across sectors such as utilities, transports, agriculture, manufacturing and households. We also include the mining sector, although it has small direct emissions according to the scope 1 classification, because all the emissions of the three above sectors derive directly or indirectly from the fossil-fuel extraction when accounting from the supply side[40]. We then take into account the so-called carbon leakage risk classification, which according to the EC Directive 2014[41] identifies activities (mostly within manufacturing) for which either costs or competitiveness is heavily affected by introduction of a carbon price. It can be easily verified that the traditional NACE Rev2 (but the same holds for NAICS) classification of economic activities is not well-suited for a climate-policy analysis. For instance, some activities classified under B-Mining and quarrying, such as 'B7.1-Mining of iron ores', are not so relevant for climate policies. In contrast, some activities classified under C-Manufacturing, such as 'C19.2-Manufacture of refined petroleum products' or transport 'H49.5-Transport via pipeline', are more relevant to the fossil-fuel sector from the criterion of economic scenarios resulting from climate policies. Furthermore, some activities that pertain to the housing sector from a policy perspective fall into different NACE Rev2 sectors such as F—Construction and L—Real estate.

All the considered economic activities can be divided into three categories: (1) suppliers of fossil fuels, (2) suppliers of electricity (3) users of either fossil fuels or electricity. We can further divide the third category according to the traditional policy areas: transport, housing and manufacturing. While suppliers of fossil fuels are mostly negatively affected by GHG emission reduction policies, the other categories can be affected positively or negatively depending on the energy source utilized (fossil fuel versus renewable). On the basis of all the above information, we can finally remap all the economic activities from the 4-digit NACE Rev2 classification into the following climate-policy-relevant sectors: fossil, utilities, transport, energy-intensive, housing. The complete mapping from NACE Rev2 4-digits codes is provided in Supplementary Information.

Assessing direct exposures of financial actors. Since our goal is to assess the exposure of financial actors to the climate-policy-relevant sectors in the real economy, we group financial actors into financial institutional sectors according to the standard ESA classification: banks, investment funds, insurance and pension funds. The exposures of each financial actor can be decomposed along the main types of financial instruments: equity holdings (for example, ownership shares including both those tradable on the stock market and those non-tradable), bond holdings (for example, tradable debt securities) and loans (for example, non-tradable debt securities). More formally, denoting by A_i the total assets of financial actor i, and by $\mathbb{S}$ the set of climate-policy-relevant sectors, we can write

$$A_i=\left(\sum_{S\in\mathbb{S}}\sum_{j\in S}\alpha_{ij}^{\text{Equity}}+\alpha_{ij}^{\text{Bond}}+\alpha_{ij}^{\text{Loan}}\right)+R_i \tag{1}$$

where the terms α_{ij} denote the monetary values of the exposures of i in the securities associated with economic actors j for the different types of instruments and R_i is a residual accounting for the exposure to other sectors and instruments not considered in our analysis.

Although instrument types have different risk profiles, it is informative to look at the total exposure of financial actors to a given sector across all instruments. For instance, we can compute in this way the full exposure of a given bank to the fossil sector, by summing up all of its equity holdings, bonds and loans exposures to this sector. If we denote by α_{iS} the total exposure of actor i to sector S, we can write $\alpha_{iS}=\sum_{j\in S}\alpha_{ij}^{\text{Equity}}+\alpha_{ij}^{\text{Bond}}+\alpha_{ij}^{\text{Loan}}$.

In addition to the exposures of individual financial actors, we are also interested in the aggregate exposure of an entire financial institutional sector F to a given climate-policy-relevant sector, $A_{FS}=\sum_{i\in F}\alpha_{iS}$. Finally, the total direct exposure of the financial system in the totality of climate-policy-relevant sectors is $A_{\mathcal{F}\mathcal{S}}=\sum_{F\in\mathcal{F}}\sum_{i\in F}\alpha_{iS}$, where $\mathcal{F}$ denotes the set of institutional financial actors.

Assessing indirect exposures of financial actors. A large portion of total assets held by financial institutions are in fact securities issued by other financial institutions (for example, about 40% for banks in the Euro Area). Moreover, about 25% of total market capitalization is invested in equity issued by companies in the financial sectors, and about 40% of the bond market is represented by outstanding obligations issued by financial institutions.

As a result, there is a potential systemic risk that can materialize through the so-called second-round effects[16,17]. For instance, first-round effects may induce directly the bankruptcy of a financial institution that then defaults on its obligations towards its financial counterparties. Second-round effects refer to financial contagion effects including, but not necessarily, further defaults. More generally, the accounting practice of mark-to-market implies that the deterioration of the balance sheet of a financial institution has a negative impact on the market value of its obligations held by its counterparties. Mark-to-market and, in particular, credit valuation adjustment, is recognized as a major mechanism of financial distress propagation; during the 2007/2008 financial crisis, it accounted for two-thirds of losses among many financial institutions (see ref. 42). More formally, in the breakdown of total assets, we can distinguish the securities issued by firms in the financial sectors (whose values depend on their own assets' values) from those issued by firms in the climate-policy-relevant sectors to obtain

$$\begin{aligned}A_i={}&\left(\sum_{j\in\mathcal{F}}\alpha_{ij}^{\text{Equity}}(A_j)+\alpha_{ij}^{\text{Bond}}(A_j)+\alpha_{ij}^{\text{Loan}}(A_j)\right)\\&+\left(\sum_{k\in\mathcal{A}/\mathcal{F}}\alpha_{ik}^{\text{Equity}}+\alpha_{ik}^{\text{Bond}}+\alpha_{ik}^{\text{Loan}}\right)+R_i\end{aligned} \tag{2}$$

where $\mathcal{A}$ denotes the set of all actors and, again, $\mathcal{F}$ denotes the set of institutional financial actors. When we consider the above equation for many financial actors simultaneously, equation (2) becomes a system of coupled equations in the asset values. In the spirit of analysing the short-term effects of a deviation in the values from an initial face value of the securities, the terms $\alpha_{ij}^{\text{Instrument}}(A_j)$ can be written as the product $\alpha_{ij}^0 f_{ij}(A_j)$, where α_{ij}^0 represents the face value of the security at the initial time and $f_{ij}(A_j)$ represents the valuation of the security with respect to its face value. While the exact functional form of f_{ij} depends on the instrument type and the pricing model used for the valuation of the security, it is possible nevertheless to infer certain useful properties. Consider for instance a chain of exposure in which the financial actor i holds bond securities issued by the financial actor j, who in turn holds securities issued by a firm k in the climate-policy-relevant sector. From the equations above it follows that

$$\frac{\partial A_i(A_j(A_k))}{\partial A_k}=\frac{\partial A_i(A_j)}{\partial A_j}\,\frac{\partial(A_j)}{\partial A_k}=\alpha_{ij}^0\alpha_{jk}^0\,\frac{\partial f_{ij}}{\partial A_j}\,\frac{\partial f_{jk}}{\partial A_k} \tag{3}$$

Without loss of generality, in line with widely used pricing models such as those based on the Merton model for the value of debt obligations, the functions f_{ij} are non-decreasing in the value of the assets of the issuer j, that is, $df_{ij}/dA_j\geq 0$, because the ability of the issuer to pay either dividends or interest rates to its creditor generally increases with the issuer's total assets, everything else the same.

It follows that, as long as the terms df_{ij}/dA_j are not too small and comparable across instruments, the indirect exposure to a climate-policy-relevant sector along chains of financial actors is determined by the product of the face value of the exposures along the chain, $\alpha_{ij}^0\alpha_{jk}^0$, where each exposure corresponds to the strength of the link between the two nodes. The result can be generalized to longer chains, although we focus on length two in this work. Therefore, the problem of identifying the largest indirect exposure of a given path length is mathematically equivalent to the graph-theoretical problem of finding the path(s) with the largest product of link weights along the path in a weighted graph.

Distribution of shocks. To infer a distribution of shocks on the fossil-fuel and utilities sector we use the LIMITS database[26], which provides economic impact assessments of climate policies using a set of economic models and several scenarios that take into account the stringency of climate policy and the timing of its implementation. Results are reported as time series of forecasted production level for each sub-sector with a five-year interval up to 2050. In particular we analyse the estimated time series of the share of fossil fuels and renewables in primary and secondary (electricity) energy consumption. Out of the time series, one can infer a distribution of shocks by considering each change in market share from one period to the next as corresponding to an observation of a shock for the respective sub-sector. Hence, one obtains one shock per period per scenario and per model, for a total of 5,421 shocks. From an economic viewpoint, interpreting these shocks on market shares as shocks on equities amounts to make the following simplifying assumptions. First, the share of nominal expenses on energy is constant (that is, the demand elasticity of substitution is 1). Second, the value of equity in a sub-sector is proportional to total income. Third, market valuation is based on one-period (five years) ahead expectations. The shocks can then be interpreted as the impact on market valuation of a previously unanticipated policy measure. The extent to which these shocks will materialize depends on the ability of agents to anticipate policy measures. The shock scenario we describe in the paper corresponds to a setting in which informational imperfections prevent agents from smoothly adjusting their expectations. The alternative scenario emphasized in the conclusion corresponds to a situation where a stable policy framework would allow financial actors to smoothly adjust their expectations. In this case, climate-induced systemic risk would not materialize. Supplementary Fig. 6 shows the resulting distribution of the variation in asset value for a brown bank (investing in fossil-fuel primary sector and fossil-fuel-based utilities) and a green bank (investing in the renewable utilities sector only).

Data. Data on equity holding were obtained through the Bureau Van Dijk Orbis database. We collected a sample covering all EU and US listed companies and their disclosed shareholders with voting rights as of the end of the last available year, that is, 2014. After some consistency checks, we end up with 14,878 companies and 65,059 shareholders. By grouping the exposures by investor we thus reconstruct portions of their equity holding portfolios, within the limitations of the available data. Further details on the data set and the methodology are provided in the Supplementary Information. Data on the balance sheets of the top 50 listed European banks are obtained from the Bureau Van Dijk Bankscope database. Data include for each bank its total lending and borrowing to other banks. Exposures of a bank to individual other banks are not publicly available and have been estimated on the basis of existing methodologies (see literature in ref. 28). Data on GHG and CO_2 emissions of sectors have been obtained from Eurostat statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics). Data on financial exposures at the sectoral level have been obtained from the ECB Data Warehouse (http://sdw.ecb.europa.eu).

Data availability. The data that support the findings of this study are available from Bureau Van Dijk (Orbis database) but restrictions apply to the availability of these data, which were used under licence for the current study, and so are not publicly available. Data are however available from the authors on reasonable request and with permission of Bureau Van Dijk.

References

40. Erickson, P. & Lazarus, M. *Accounting for Greenhouse Gas Emissions Associated with the Supply of Fossil Fuels* Tech. Rep. 1–4 (2013).
41. European Commission: Decision of 27 October 2014 determining, pursuant to Directive 2003/87/EC of the European Parliament and of the Council, a list of sectors and subsectors which are deemed to be exposed to a significant risk of carbon leakage, for the period 2015 to 2019 (notified under document C(2014) 7809); http://data.europa.eu/eli/dec/2014/746/oj
42. FSA *The Prudential Regime for Trading Activities* Tech. Rep. (Financial Services Authority, 2010).

This is a tab page.
Please title tab
“Stiglitz”

EXPERT REPORT
OF
JOSEPH E. STIGLITZ, PH.D.

University Professor, Columbia University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

Prepared for Plaintiffs and Attorneys for Plaintiffs:

Julia A. Olson	Philip L. Gregory
JuliaAOlson@gmail.com	pgregory@gregorylawgroup.com
Wild Earth Advocates	Gregory Law Group
1216 Lincoln Street	1250 Godetia Drive
Eugene, OR 97401	Redwood City, CA 94062
Tel: (415) 786-4825	Tel: (650) 278-2957

TABLE OF CONTENTS

TABLE OF ACRONYMS AND ABBREVIATIONS

C:	Celsius
CAFE:	Corporate Average Fuel Economy
CAD:	Canadian Dollar
CBO:	Congressional Budget Office
CO_2:	carbon dioxide
CPI:	consumer price index
EPA:	U.S. Environmental Protection Agency
GDP:	gross domestic product
GHGs:	greenhouse gases
IMF:	International Monetary Fund
IPCC:	Intergovernmental Panel on Climate Change
NASA:	National Aeronautics and Space Administration
NOAA:	National Oceanic and Atmospheric Administration
OECD:	Organisation for Economic Co-operation and Development
OMB:	Office of Management and Budget
ppm:	parts per million
R&D:	research and development
USGCRP:	U.S. Global Change Research Program

I. QUALIFICATIONS AND PROFESSIONAL BACKGROUND

1. I am one of sixteen University Professors at Columbia University with joint appointments in the Faculty of Arts and Sciences (Department of Economics), the Graduate School of Business (Department of Finance), and the School of International and Public Affairs. Prior to assuming this position, I held professorships at Stanford University, Yale University, Princeton University, and the University of Oxford, where I taught a wide variety of graduate and undergraduate courses in economics and finance. I received my Ph.D. in Economics from MIT in 1967.

2. Over the course of my career I have published hundreds of peer-reviewed articles, written or edited more than 50 academic and popular books, testified several times before Congress, and written numerous opinion pieces for newspapers and magazines. My publications and research have extended into many different areas, including macroeconomics and monetary theory, development economics and trade theory, public and corporate finance, industrial organization and rural organization, welfare economics, and income and wealth distribution, many of which are germane to this case. Oxford University Press is in the process of publishing a six-volume set based on my research, *Selected Works of Joseph E. Stiglitz*. The first two volumes have been published and are entitled *Information and Economic Analysis: Basic Principles and Information and Economic Analysis: Applications to Capital, Labor, and Products Markets*.

3. Public economics and public finance, which study how governments raise funds and make expenditures, have been major pillars of my academic work. I served as a co-editor of the *Journal of Public Economics*, the leading economics journal dealing with matters of taxation and public economics, and have published broadly in this area. My textbook, *Economics of the Public Sector*, is a leading text first published in 1986 with the most-recent version released in 2015. Another of my books, *Lectures on Public Economics*, published in 1980 and reprinted in 2015 with a new introduction, has been widely translated. Many of my popular texts, including my recent books *The Great Divide* and *The Price of Inequality*, published in 2015 and 2012, respectively, critically examine our public institutions, and comment on public finance and public economics generally.

4. Environmental economics and economic policy around natural resources has been another focus of my academic and professional work. I was one of the lead authors of the 1995 Report of the Intergovernmental Panel on Climate Change, which shared the 2007 Nobel Peace Prize with former Vice President Gore. I was co-chair of the High-Level Commission on Carbon Prices (we released our report in May 2017). I was also involved in environmental economic policy during my time on the Council of Economic Advisors, where one of my responsibilities was evaluating, designing, and implementing public policies that affect the environment, and while Chief Economist of the World Bank, where one of my responsibilities was evaluating and designing environmentally sustainable economic policies. I have also published many peer-reviewed articles that examine how we treat externalities (e.g., pollution) and public goods (e.g., the environment).

5. I have received numerous fellowships and honors over my career. In 2001, I was awarded the Nobel Memorial Prize in Economics for my work on Information Economics. This work includes the study of how information asymmetries affect economic behavior, the determination of the conditions under which efficient sharing of risk occurs, and the economics of financial markets, which are directly relevant to this case. In 1979, I was awarded the John Bates Clark Medal by the American Economic Association, given biennially to the economist under 40 who has made the most significant contribution to economics.[1]

6. I was the founding editor of the *Journal of Economic Perspectives*. I have served (or am currently serving) on the Editorial Board of numerous journals, including *The Economists' Voice*, the *Journal of Globalization and Development,* the *World Bank Economic Review*, the *Journal of Public Economics*, the *American Economic Review*, the *Journal of Economic Theory*, *The Review of Industrial Organization*, *Managerial and Decision Economics*, *Energy Economics*, the *Review of Economic Design*, and the *Review of Economic Studies*.

---

[1] The John Bates Clark Medal has been given annually since 2009.

7. I served as President of the International Economic Association from 2011–2014 and as President of the Eastern Economic Association in 2008. I also served as Vice President of the American Economic Association in 1985.

8. I have received more than 40 honorary degrees, and have received awards from foreign governments, including the Legion of Honor from France. I have also been elected to numerous academic and scientific societies in the United States and abroad, including the National Academy of Sciences, the Royal Society, the American Academy of Arts and Sciences, the American Philosophical Society, and the British Academy. In 2011, *Time* magazine named me to their *Time 100* list as one of the 100 most influential people in the world.

9. From 1993 to 1997, I served as a member of President Clinton's Council of Economic Advisers, and from 1995 to 1997, as Chairman of the Council and a member of the President's Cabinet. As Chairman and Cabinet Member, I was heavily involved in formulating fiscal policy, sustainable economic policies (including environmental economic policies), financial sector regulation and banking policy, and coordinating policy with the U.S. Treasury.

10. From 1997 to 2000, I served as Chief Economist and Senior Vice President of the World Bank, in which capacity I had the responsibility of advising countries around the world on the design of fiscal, tax, and monetary policies, competition policies, sustainable economic policies (including those regarding natural resources and the environment), intellectual property regimes, financial regulations, and trade policy.

11. I have served or am serving currently on many commissions and advisory committees addressing a myriad of economic policy issues, both in the U.S. and abroad, including the Joint CFTC-SEC Advisory Committee on Emerging Regulatory Issues, the United Nations' International Labour Organization World Commission on the Social Dimensions of Globalization, the High Level Panel of the African Development Bank, and the Economic Advisory Panel in South Africa.

12. At the behest of the President of the General Assembly of the United Nations, I served as Chair of the Commission of Experts on Reforms of the International Monetary and Financial System, to review the workings of the global financial system in the wake of

the 2008 economic crisis and suggest steps for U.N. member states to secure a sustainable economic future. Our final report was published in September 2009. In addition, I was appointed President of the Commission on the Measurement of Economic Performance and Social Progress by President Sarkozy of France, in 2008. This commission was formed to consider flaws in traditional macroeconomic indicators measuring economic performance and social progress and consider what might be the more relevant metrics, which are relevant to this case. Our final report was released in September 2009.

13. In 2000, I founded the Initiative for Policy Dialogue, for which I continue to serve as co-President. The Initiative for Policy Dialogue is a global network of academics and practitioners to enhance democratic processes for decision-making in developing countries. I am also Co-Chair of the High-Level Expert Group on the Measurement of Economic Performance and Social Progress, Organisation for Economic Co-operation and Development (OECD) and the Chief Economist of, and a Senior Fellow at, the Roosevelt Institute.

14. Previously, I served as Chair of the Management Board at the Brooks World Poverty Institute at the University of Manchester, on the Board of Trustees of Amherst College, my undergraduate *alma mater*, and as Co-Chair of Columbia University's Committee on Global Thought.

15. I have provided expert testimony in various fora throughout the United States, and before foreign courts and international tribunals. I have submitted *amicus curiae* briefs before the Supreme Court of the United States and before U.S. Circuit Courts of Appeal. My expert testimonies have related broadly to financial markets and derivatives, taxes, antitrust and competition, patent enforcement, and public interest generally (e.g., promotion of efficiency and/or minimization of welfare costs). I have also offered testimony regarding environmental economics, specifically, around offshore drilling.

16. My curriculum vitae, which provides more details of my qualifications, including a list of my publications, is attached as **Exhibit A**. **Exhibit B** contains a list of my previous expert testimony within the last five years. The materials that I, and volunteers supporting me at my direction, considered in preparing this report are cited in the footnotes and listed in **Exhibit C**.

17. I am working *pro bono* to prepare this expert report. My usual rate for work in litigation matters is $2,000 per hour, which is the rate I will charge if another party seeks discovery under Federal Rule 26(b). I have no present or intended financial interest in the outcome of this matter. My work in this matter is ongoing, and I reserve the right to revise or augment the opinions set forth in this report should additional relevant information become available to me, or as I perform further analysis.

II. ASSIGNMENT AND SUMMARY OF CONCLUSIONS

18. Julia Olson and Philip Gregory, counsel for Plaintiffs in this matter, have asked me to provide my expert opinion on the economics of transitioning to a non-fossil fuel economy.[2] In particular, I have been asked: (a) to analyze from an economic perspective how climate change will harm the Youth Plaintiffs (and Affected Children) if Defendants continue to pursue policies that perpetuate a fossil-fuel-based energy system and defer action to mitigate climate change; and (b) to assess the economic benefits of transitioning to a non-fossil-fuel economy now rather than later. The opinions expressed in this report are my own. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated.

19. I have formed four primary conclusions in this case, the bases for which are set forth more fully below:

    a. Scientific evidence shows further incremental increases in global temperature will lead to disproportionately greater costs imposed on our society. This has important consequences for how Defendants' actions harm the Youth Plaintiffs and Affected Children more generally. Continuation of the national fossil fuel-based energy system by Defendants is causing imminent, significant, and irreparable harm to the Youth Plaintiffs and Affected Children more generally. This kind of environmental harm, by its nature, cannot be adequately remedied by money damages and is often permanent or at least of long duration, i.e., irreparable. There is a point at which, once this harm occurs, it cannot be undone at any reasonable cost or in any reasonable period of time. Based on the best available science, our country is close to approaching that point.[3]

---

[2] I understand that the plaintiffs in this litigation are young people, who I will refer to as the "Youth Plaintiffs." However, my analysis also looks at the impact on other young people who are not named plaintiffs (and as-yet-unborn youth, the so-called future generations), but are just as (or even more) affected, whom I collectively refer to as "Affected Children."

[3] This is a global problem. However, as I discuss below in Section V.B, the U.S. is a significant contributor to GHG emissions, and so actions by the U.S., have a significant impact on these global outcomes.

b. Defendants' continuing support and perpetuation of a national fossil fuel-based energy system and continuing delay in addressing climate change is saddling and will continue to saddle Youth Plaintiffs with an enormous cost burden, as well as tremendous risks, which is causing substantial harm to the economic and personal well-being and security of Youth Plaintiffs. These costs and risks will be borne over each ensuing year that progress towards remediation is not undertaken by Defendants. Such costs and risks arise both from damage caused by accumulated greenhouse gas emissions and from the required outlays on future remediation and adaptation efforts, which grow more expensive as the accumulation of greenhouse gases in the atmosphere increases. There are particularly consequential risks arising from the potentially catastrophic impacts of climate change, which increase each year that Defendants defer action on greenhouse-gas mitigation efforts.

c. Moving the U.S. economy away from fossil fuels is both feasible and beneficial, especially over the next 30 years (as technological and scientific evidence discussed below makes clear). Defendants could facilitate this transition with standard economic tools for dealing with externalities, for example a tax or levy on carbon (a price on the externality) and the elimination of subsidies on fossil-fuel production. Relatedly, decisions concerning the transition off of fossil fuels can be reached more systematically and efficiently by revising current government discounting practices, the methodology by which future costs are compared to present costs. Current and historical government decision making practices based on incorrect discount rates lead to inefficient and inequitable outcomes that impose undue burdens on Youth Plaintiffs and future generations. Basing decisions (policies, programs, and actions) on appropriate discount rates would help minimize the burdens that Defendants' current policies place on Youth Plaintiffs and future generations. That is to say, if Defendants' discounting policies and practices more accurately reflected the expected changes in relative prices over time (and their distribution, implicitly putting a lower discount rate on climate change benefits), the basis for Defendants' policy-making decisions would more closely align with economic principles and yield more efficient outcomes.

d. Based on this reasoning, I conclude that Defendants can and should take meaningful actions to reduce GHG emissions from fossil fuels and mitigate climate change impacts now rather than defer action to some future date. Acting now will yield benefits for both Defendants and Youth Plaintiffs and reduce harm to Youth Plaintiffs, and the costs of mitigating climate change now are manageable. Defendants could make meaningful progress on climate change mitigation by acting today in accordance with the best available science. Moreover, Defendants meeting their constitutional and public trust obligations to redress climate change would improve societal well-being by any reasonable economic standard. In fact, some of the actions that Defendants could take to meet these obligations would actually have a negative cost. That is to say, in the long run, the net present value of benefits to society would exceed the net present value of costs that society would have to incur.[4] This is referred to as Kaldor–Hicks efficiency in standard economic analysis, typically a hallmark of sound policymaking, from an economic perspective, whereby the net benefits of a policy change outweigh the net costs of such policy change. Thus, if Defendants were to make such changes as are argued for by other of Plaintiffs' experts, the net societal gain would more than outweigh the net societal loss. In contrast, Defendants' current policies of perpetuating the fossil fuel-based energy system impose unacceptably high costs and risks on the Youth Plaintiffs specifically and Affected Children more generally, and will continue to do so, well out of portion to the amounts that Defendants save currently by avoiding taking the appropriate actions.

20. The body of my report sets out the factual and analytical bases for my conclusions and opinions. The balance of my report proceeds as follows: Section III summarizes the scientific evidence on increasing greenhouse gases affecting global temperatures and why the time to act is now; Section IV discusses the costs that Youth Plaintiffs will face if Defendants continue to promote and permit a fossil-fuel-based energy system and no

---

[4] This is not to say that each party is better off (which would be a Pareto improvement); but those parties who are better off by the policy change (e.g.., non-polluters) are made better off by more than the parties made worse off by the policy change (e.g.., polluters) are made worse off.

actions (or insufficient actions) are taken to wean society off fossil fuels; Section V analyzes how the transition away from fossil fuels is feasible and can be facilitated with standard economic tools; and, finally, Section VI concludes.

III. BACKGROUND ON THE RELATIONSHIP BETWEEN ATMOSPHERIC CONCENTRATIONS OF GREENHOUSE GASES AND CLIMATE CHANGE

21. The climate change young people are experiencing today is caused by the historic emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs), primarily from burning fossil fuels and other anthropogenic activities, including deforestation and agricultural practices.[5] It is scientifically established that human activities produce GHG emissions, which accumulate in the atmosphere and the oceans, resulting in warming of Earth's surface and the oceans[6], acidification of the oceans,[7] increased variability of climate, with a higher incidence of extreme weather events, and other changes in the climate.

22. Dangerous impacts are already occurring from the current level of global warming of around 1°C above preindustrial temperatures. Climate scientists have established through the paleo record that warming of 1.5°C or 2°C above pre-industrial levels would be well outside the Holocene range of global temperatures within which humans have lived and

---

[5] See, for example, Intergovernmental Panel on Climate Change, "Climate Change 2014: Synthesis Report Summary for Policymakers," pp. 4-5. Other Greenhouse Gases, like Methane, also trap heat within the earth. They differ in key technical properties, like the rate of dissipation. Throughout this report, I use the terms GHG and CO_2 emissions interchangeably.

There is a popular but misguided debate among so-called climate "skeptics" about the extent to which the observed increase in temperature is a result of the emissions of CO_2 and other GHGs. The scientific literature is clear (and has been clear for a long time): the increase in atmospheric concentration of GHGs predictably increases the Earth's temperature in the manner observed. This has been most recently reaffirmed by "Climate Science Special Report: Fourth National Climate Assessment, Volume I" U.S. Global Change Research Program, November 2017, pp. 96-97 https://science2017.globalchange.gov/downloads/CSSR2017_FullReport.pdf. (Hereinafter USGCRP Climate Science Special Report).

But even if there were other factors contributing to climate change, the analysis here is unchanged: Defendants could, with mild costs, take actions now that would avoid imposing the undue and excessive burdens and risks imposed on the Youth Plaintiffs in this case.

[6] USGCRP Climate Science Special Report, p. 364.

[7] USGCRP Climate Science Special Report, pp. 371-372.

societies developed.[8] Moreover, leading experts believe that there is already more than enough excess heat in the climate system to do severe damage and that 2°C of warming would have very significant adverse effects, including resulting in multi-meter sea level rise.[9] NOAA projects up to 0.63 m (2.1 feet) of sea level rise by 2050, 1.2 m (3.9 feet) by 2070, 2.5 m (8.2 feet) by 2100, 5.5 m (18 feet) by 2150, and 9.7 m (31.8 feet) by 2200.[10] A 2-3 foot sea level rise would inundate and render uninhabitable large portions of the world's barrier islands and deltas and place major pressures on the infrastructure of low-lying coastal zones like South Florida, and 3 feet of seal level rise would "permanently inundate 2 million American's homes and communities."[11] Sea level rise of this magnitude would impose irreversible harm and an immense financial burden on young people in coastal areas, along with significant indirect costs on young people elsewhere.

23. Experts have identified a number of known "feedback loops" in the climate system. These feedback loops cause warming to catalyze still further warming. For example, warmer arctic temperatures result in melting permafrost that releases methane, a GHG that further warms the planet. These feedbacks, in conjunction with the fact that CO_2 persists in the atmosphere for centuries, mean that the longer we delay action, the greater the risk that warming will trigger tipping points in the climate system and become irreversible, or reversible only at much increased cost. Given the self-reinforcing nature

---

[8] J. Hansen et al., "Assessing ''Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature," *PLOS One*, 8:12, e81648, 2013, p. 9.

[9] J. Hansen, et al., "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2C global warming is highly dangerous," *Atmospheric Chemistry and Physics Discussions*, 15, 20059-179, 2015, http://faculty.sites.uci.edu/erignot/files/2017/06/Ice-melt-sea-level-rise-and-superstorms-evidence-from-paleoclimate-data-climate-modeling-and-modern-observations-that-2C-global-warming-is-highly-dangerous.pdf.

[10] "Global and regional sea level rise scenarios for the United States," NOAA Technical Report NOS CO-OPS 083, January 2017, p. 23, https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

[11] H. Wanless, "Declaration of Dr. Harold R. Wanless in Support of Answer of Real Parties in Interest to Petition for Writ of Mandamus", *in United States of America et al. v. United States District Court for the District of Oregon et al.*, Case No. 17-71692, Doc. No. 14-3, paras. 31-32, *citing* "Global and regional sea level rise scenarios for the United States," NOAA Technical Report NOS CO-OPS 083, January 2017.

of climate change, prompt action is needed to both minimize future emissions and reduce the effects of historic emissions.

24. Experts have observed an increased incidence of climate-related extreme weather events, including increased frequency and intensity of extreme heat and heavy precipitation events and more severe droughts and associated heatwaves. Experts have also observed an increased incidence of large forest fires; and reduced snowpack affecting water resources in the western U.S. The most recent National Climate Assessment projects these climate impacts will continue to worsen in the future as global temperatures increase.[12]

25. Although the scale of the problems and risks that we face are immense, it is possible to reduce these risks by acting now to avoid irreversible harm to essential natural systems with its catastrophic consequences such as sea level rise, increased ocean temperatures, ocean acidification, heat waves, increased drought, and the associated impacts on water quality and availability, human health, and agriculture. Such impacts would harm our economy directly and introduce much increased risk in the form of variability in and uncertainty around climate outcomes.

26. Dr. Hansen and other experts in this case have provided a prescription for an emissions reduction and carbon sequestration pathway back to CO_2 levels below 350 ppm by 2100, which they say would substantially lessen the risk of catastrophic sea level rise and other climate harms.[13] Returning to temperatures and atmospheric CO_2 levels that avoid dangerous anthropogenic climate change has a limited window (because of tipping points in the climate system), which is still open but is closing rapidly. Defendants must take action now to reduce these risks.

---

[12] USGCRP Climate Science Special Report, pp. 19-22.

[13] James Hansen et al., "Assessing ''Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature," *PLOS One*, 8:12, e81648, 2013.

IV. DEFENDANTS' ACTIONS THAT PERPETUATE A FOSSIL FUEL ENERGY SYSTEM AND INSUFFICIENT ACTION ON CLIMATE CHANGE ARE IMPOSING AND WILL CONTINUE TO IMPOSE ENORMOUS COSTS ON YOUTH PLAINTIFFS

27. The current national energy system, in which approximately 80 percent of energy comes from fossil fuels, is a direct result of decisions and actions taken by Defendants.[14] Defendants control and dictate the U.S. national energy policy in a myriad of ways. For example, they provide billions of dollars annually in subsidies to the fossil fuel industry;[15] control the fuel economy of cars and trucks through the Corporate Average Fuel Economy ("CAFE") standard; set efficiency standards for appliances; permit the extraction, transportation, import, export, and combustion of fossil fuels; and provide funding for research and development.[16] The fact that the U.S. national energy system is so predominately fossil fuel-based is not an inevitable consequence of history. With the oil crises of the 1970s, recognition of the risks of dependence on oil was developed (though these risks were markedly different from those with which we are concerned today). Even then, it was clear that there were viable alternatives, and with the appropriate allocation of further resources to R&D, it is likely that these alternatives would have been even more competitive. Thus, the current level of dependence of our energy system on fossil fuels is a result of intentional actions taken by Defendants over many years (including subsidization of fossil fuels and *inactions* in the form of not providing adequate support for alternatives).[17] Cumulatively, these actions promote the use of fossil fuels, contribute to dangerous levels of CO_2 emissions, and cause climate change. The economic impacts of these actions are deleterious to Youth Plaintiffs and the nation as a whole. In other words, Defendants' actions promoting a fossil fuel based

---

[14] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, August 2017 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

[15] See, Section V, below.

[16] "Direct Federal Financial Interventions and Subsidies in Energy in Fiscal Year 2013", U.S. Energy Information Administration, March 2015, https://www.eia.gov/analysis/requests/subsidy/pdf/subsidy.pdf.

[17] I would note that inactions in this sense are affirmative decisions by Defendants not to act.

energy system are serving to undermine the legitimate government interests of national security and economic prosperity that they purport to advance.[18]

28. When conducting an economic analysis of the effects of climate change and appropriate responses thereto, Defendants must take into account a number of salient aspects of climate change. I have already noted some of these aspects: not just global warming in the sense of on-average increases in temperature, but also an increase in extreme (and damaging) weather events, rising sea levels, the public health consequences, and many other direct and indirect impacts of climate change. Still another aspect of climate change that is crucial in framing an appropriate response are the long lag times inherent in the climate system, implying that the full climate impact of any given accumulation of GHGs may not be apparent for many years.[19] Moreover, critical to the effects (as already noted) is the increase in concentration of GHGs. The fact that GHGs dissipate very slowly from the atmosphere (particularly in the case of CO_2[20]) and that the costs of taking

---

[18] Daniel R. Coats, Director of National Intelligence, "Statement for the Record: Worldwide Threat Assessment of the US Intelligence Community," *Office of the Director of National Intelligence*, February 13, 2018, https://www.intelligence.senate.gov/sites/default/files/documents/os-dcoats-021318.PDF (at page 16: "The impacts of the long-term trends toward a warming climate, more air pollution, biodiversity loss, and water scarcity are likely to fuel economic and social discontent—and possibly upheaval….").

[19] Because of these lags, we have not yet seen the full rise in temperature that will occur as a result of the CO_2 that has already been emitted. As noted above, the Earth's average surface temperature has already risen by approximately 1°C since the Industrial Revolution. The concentration of CO_2 in the atmosphere is increasing at the rate of 2-3 ppm per year. Scientists tell us that even if CO_2 were stabilized at current levels, there would be at least another 0.5°C "in the pipeline." The delayed response is known as climate lag. The reason the planet takes several decades to respond to increased CO_2 is the thermal inertia of the oceans. Consider a saucepan of water placed on a gas stove. Although the flame has a temperature measured in hundreds of degrees C, the water takes a few minutes to reach boiling point. This simple analogy explains climate lag. The mass of the oceans is around 500 times that of the atmosphere. The time that it takes to warm up is measured in decades. For example, a paper by Dr. Hansen (and others) estimates the time required for 60 percent of global warming to take place in response to increased emissions to be in the range of 25 to 50 years. See, Hansen, J.E. et al., "Earth's Energy Imbalance: Confirmation and Implications," *Sciencexpress*, April 28, 2004, http://science.sciencemag.org/content/early/2005/04/28/science.1110252.

[20] Accumulations of CO_2 are particularly problematic because they dissipate so slowly. See, e.g., "Carbon is forever," *Nature Reports Climate Change,* November 20, 2008. This article discusses results from Dr. Hansen's research, stating: "Several long-term climate models, though their details differ, all agree that anthropogenic CO_2 takes an enormously long time to dissipate. If all recoverable fossil fuels were burnt up using today's technologies, after 1,000 years the air would still hold around

Continued on next page

CO_2 out of the atmosphere through non-biological carbon capture and storage are very high[21] means that the consequences of GHG emissions should be viewed as effectively irreversible. Accordingly, if Defendants do not take serious action to mitigate climate change now, Youth Plaintiffs and Affected Children will largely shoulder the costs caused by Defendants' actions that contribute to the further accumulation of GHGs and Defendants' failure to act to redress the harm. We can expect these burdens to manifest themselves in at least four ways.

29. ***First***, despite their relative lack of economic power in society today, Youth Plaintiffs themselves will suffer the disproportionate, increased financial burdens of climate change as the impacts of climate change propagate throughout the economy. For example, rising sea levels will lead to massive reductions in property value (indeed, the value of land that is underwater will fall to zero). Some Youth Plaintiffs, such as Levi D., and Affected Children will (with high probability) be deprived of the use of submerged lands, and many of them will almost surely experience large capital losses, as markets eventually fully reflect the realities of climate change. In addition, Youth Plaintiffs and Affected Children will, as future taxpayers, help bear the enormous cost of relocating the people and infrastructure that are now on this land to higher ground. Youth Plaintiffs and Affected Children will also bear the cost of instituting temporary stopgap measures, such as dikes to hold back rising sea levels, and some of them will have to bear directly themselves relocation costs.

Continued from previous page

a third to a half of the CO_2 emissions. 'For practical purposes, 500 to 1000 years is 'forever,'' as Hansen and colleagues put it. In this time, civilizations can rise and fall, and the Greenland and West Antarctic ice sheets could melt substantially, raising sea levels enough to transform the face of the planet."

[21] See, for example, House, K.Z., et al., "Economic and energetic analysis of capturing CO_2 from ambient air," *Proceedings of the National Academy of Sciences,* 108(51) (December 2011): 20428-20433, http://www.pnas.org/content/108/51/20428.full.pdf. The authors concluded: "Our empirical analysis of energetic and capital costs of existing, mature, gas separation systems indicates that air capture processes will be significantly more expensive than mitigation technologies aimed at decarbonizing the electricity sector. Unless a technological breakthrough that departs from humankind's accumulated experience with dilute gas separation can be shown to "break" the Sherwood plot and the second-law efficiency plot—and the burden of proof for such a process will lie with the inventor—direct air capture is unlikely to be cost competitive with CO_2 capture at power plants and other large point sources."

30. ***Second***, Youth Plaintiffs and Affected Children will face increased burdens as taxpayers because, as Defendants and climate scientists project, climate change will increase future losses related to climate variability, sometimes of a catastrophic nature.[22] In previous cases of catastrophic loss, society as a whole has borne much of the cost in the form of disaster relief payments from the public sector.[23] Recent examples of catastrophes in which a large proportion of the losses were borne by the public sector include Hurricane Katrina, Hurricane Sandy, Hurricane Harvey, Hurricane Irma, and Hurricane Maria. Each of these disasters has (or will) cost the public sector billions of dollars in disaster relief. For instance, Hurricane Sandy cost the U.S. government over $50 billion, which is three times larger than the $18.7 billion of insured losses from that disaster, and over 70

---

[22] "The Impact of Climate Change on Natural Disasters," NASA, https://earthobservatory.nasa.gov/Features/RisingCost/rising_cost5.php. "Global Warming and Hurricanes," National Oceanic and Atmospheric Association, https://www.gfdl.noaa.gov/global-warming-and-hurricanes/. "Climate Change Indicators: Weather and Climate," EPA, https://www.epa.gov/climate-indicators/weather-climate. See also, K. Trenberth et al., "Attribution of climate extreme events," *Nature Climate Change* 5 (2015): 725-730.

[23] "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget", Congressional Budget Office (CBO), June 2016, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

Public sector relief is needed in these cases because private risk-pooling solutions, such as property and casualty insurers, do not and cannot cover even a majority of the realized losses. This is true for three primary reasons. *First*, a significant portion of the population is uninsured or underinsured for certain types of losses such as the risk of flood, especially in areas that have not been historically prone to flooding. *Second*, public property may not be insured at all. *Third*, property and casualty insurers are sometimes insufficiently capitalized to cover the enormous losses that such events can potentially cause, and their insolvency forces policyholders to turn to the government for assistance.

This point is illustrated by Hurricane Harvey in 2017, where some estimates of the costs run to nearly $200 billion, which represents about 1 percent of gross national product. See, e.g., Doyle Rice, "Harvey to be costliest natural disaster in U.S. history, estimated cost of $190 billion," *USA Today*, August 31, 2017, https://www.usatoday.com/story/weather/2017/08/30/harvey-costliest-natural-disaster-u-s-history-estimated-cost-160-billion/615708001/ and Reuters, "Hurricane Harvey Damages Could Cost up to $180 Billion," *Fortune*, September 3, 2017, http://fortune.com/2017/09/03/hurricane-harvey-damages-cost/. The Treasury Secretary went so far as to speculate that the Federal government's debt limit would have to be raised to free up spending for disaster recovery, and the Governor of Texas estimated that such relief could require $180 billion. *Id.*

Estimates for Hurricane Maria have been on the order of $100 billion. See, Jill Disis, "Hurricane Maria could be a $95 billion storm for Puerto Rico," *CNN*, September 28, 2017, http://money.cnn.com/2017/09/28/news/economy/puerto-rico-hurricane-maria-damage-estimate/index.html.

percent of the total economic damage of the disaster as estimated by the CBO.[24] Hurricane Katrina cost the U.S. government over $110 billion, 75 percent of the total economic damages of the disaster.[25] With increased catastrophic losses due to climate change, we can expect that the U.S. government's role as a safety net will expand.[26] As this trend continues, taxpayers of the future, including Youth Plaintiffs, will have to make whole the losses of property owners. The continuation, let alone the expansion, of the public sector's role as a safety net will be enormously costly, impose an increased burden and economic disadvantage on Youth Plaintiffs and Affected Children compared to older generations, and result in fewer government resources to be spent on public services.[27]

31. The National Centers for Environmental Information tracks the impact of weather events on the United States. As they report, from 1980 to 2017 the U.S. has experienced "219 weather and climate disasters since 1980 where overall damages/costs reached or exceeded $1 billion (including CPI adjustment to 2017). **The total cost of these 219 events exceeds $1.5 trillion.**"[28] (Emphasis in original.) In describing the impact on the U.S. in 2017 (the last full year):[29]

---

[24] "Catastrophes: U.S.," Insurance Information Institute, http://www.iii.org/fact-statistic/catastrophes-us. "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget", Congressional Budget Office (CBO), June 2016, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[25] "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget," Congressional Budget Office (CBO), p. 17, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[26] "Underinsurance of Property Risks: Closing the Gap," Swiss Re, No. 5/2015, http://institute.swissre.com/research/overview/sigma/5_2015.html.

[27] The CBO estimates that, by 2075, hurricane losses alone will total 0.22 percent of GDP, or $39 billion in 2016 dollars, an increase of 40 percent from today's annual levels, and over half of that loss will be borne by the U.S. government. "Potential Increases in Hurricane Damage in the United States: Implications for the Federal Budget," Congressional Budget Office, https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/reports/51518-hurricane-damage.pdf.

[28] "Billion-Dollar Weather and Climate Disasters: Overview," National Centers for Environmental Information, 2018, https://www.ncdc.noaa.gov/billions/.

[29] *Id.*

> In 2017, there were 16 weather and climate disaster events with losses exceeding $1 billion each across the United States. These events included 1 drought event, 2 flooding events, 1 freeze event, 8 severe storm events, 3 tropical cyclone events, and 1 wildfire event. Overall, these events resulted in the deaths of 362 people and had significant economic effects on the areas impacted.

32. As the above makes clear, it is not just hurricanes that can cause such costly events. The 2017 wildfire season in California was particularly harsh. Insurance claims at the end of 2017 were approximately $9.4 billion (with many properties being underinsured or not insured, the total damage is higher),[30] and estimates of the total impact on economic activity were $180 billion (including damages, closures, costs to fight fires, lost sales, etc.).[31] In 2016, Canada had a similar experience in Fort McMurray, Alberta; insurance payments were the costliest in Canadian history at CAD 3.58 billion,[32] and this covered only 70 percent of the total economic loss.[33] Particularly insidious with forest fires is that they also lead to massive injections of CO_2 into the atmosphere. As the Climate Science Special Report (a compilation by the U.S. Global Change Research Program, spanning multiple government agencies) noted about the Alberta wild fires specifically: “They can also radically increase emissions of greenhouse gases, as demonstrated by the amount of carbon dioxide produced by the Fort McMurray fires of May 2016—more than 10% of Canada’s annual emissions.”[34] The federal government expends significant financial

---

[30] W. Richter, “We may never be able to know the true cost of California’s massive wildfires,” *Business Insider*, December 7, 2017, http://www.businessinsider.com/santa-rosa-california-fires-cost-damage-2017-12.

[31] “AccuWeather predicts 2017 California wildfire season cost to rise to $180 billion,” *AccuWeather*, December 8, 2017, https://www.accuweather.com/en/weather-news/accuweather-predicts-2017-california-wildfire-season-cost-to-rise-to-180-billion/70003495.

[32] “Northern Alberta Wildfire Costliest Insured Natural Disaster in Canadian History – Estimate of insured losses: $3.58 billion,” Insurance Bureau of Canada, July 7, 2016, http://www.ibc.ca/ab/resources/media-centre/media-releases/northern-alberta-wildfire-costliest-insured-natural-disaster-in-canadian-history.

[33] W. Koblensky, “Fort McMurray in top 10 worst insured losses globally,” Insurance Business Canada, March 29, 2017, http://www.insurancebusinessmag.com/ca/news/environmental/fort-mcmurray-in-top-10-worst-insured-losses-globally-63960.aspx.

[34] USGCRP Climate Science Special Report, p. 415.

resources each year on both fire suppression efforts and in the aftermath of wildfires, and while costs do vary from year to year, in general, they are rising.[35]

33. Other potential examples include agricultural losses. Whether or not insurance reimburses farmers for their crops, there can be food shortages that lead to higher food prices (that will be borne by consumers, that is, Youth Plaintiffs and Affected Children). There is a further risk that as our climate and land use pattern changes, disease vectors may also move (e.g., diseases formerly only in tropical climates move northward).[36] This could lead to material increases in public health costs in terms of vaccinations and treatments, at least some portion of which will be borne by future taxpayers, i.e., Youth Plaintiffs and Affected Children. Moreover, the Youth Plaintiffs and Affected Children will be at risk of experiencing directly one or more of these increased health hazards, only a portion of the costs of which will be picked up by insurance or public assistance. There is a risk too that the increased health costs will be reflected in increased insurance premiums, affecting all those relying on private insurance, including some or all of the Youth Plaintiffs and Affected Children.

34. All of these factors will also lead to increasing inequality, as those with financial means are more able to privately bear the costs of these disasters, while those without financial means will not. Those with means will also be able to relocate, perhaps avoiding (for themselves) the burdens of rising sea levels. This will impose a greater burden on those less able to pay for the direct, local consequences of climate change. Such increasing inequality is bad not only for those made worse off, but also for society as a whole, as a more unequal society is one with poorer economic performance.[37] This will impose

---

[35] See, e.g., K. Hoover & B. Lindsay, "Wildfire Suppression Spending: Background, Issues, and Legislation in the 115th Congress," Congressional Research Service, October 5, 2017, https://fas.org/sgp/crs/misc/R44966.pdf.

[36] See, e.g., G. Mercer, "The Link Between Zika and Climate Change," *The Atlantic*, February 24, 2016, https://www.theatlantic.com/health/archive/2016/02/zika-and-climate-change/470643/.

[37] See, e.g., OECD, "Inequality hurts economic growth, finds OECD research," September 12, 2014, http://www.oecd.org/newsroom/inequality-hurts-economic-growth.htm and Prakash Loungani and Jonathan D. Ostry, "The IMF's Work on Inequality: Bridging Research and Reality," IMF, February 22, 2017, https://blogs.imf.org/2017/02/22/the-imfs-work-on-inequality-bridging-research-and-reality/ ("Another important conclusion of IMF research: rising inequality poses risks to durable

Continued on next page

further costs on the Youth Plaintiffs and Affected Children as they have to adapt to a structurally weaker economy due to increasing inequality (as elaborated on below, inequality is also exacerbated by Defendants' subsidy system that takes from taxpayers and gives to fossil-fuel corporations).

35. ***Third,*** Youth Plaintiffs will face increased burdens because the more time that passes, the more expensive it becomes to address climate change.[38] It is highly likely that, as the consequences and magnitude of climate change become manifest, there will finally be a global consensus for a globally equitable and efficient response.[39] At that juncture, the only way to prevent the accumulation of greenhouse gases beyond a tolerable level will be "negative emissions," i.e. taking carbon out of the atmosphere, effectively attempting to undo the damage that is currently being done.[40] That will be enormously expensive relative to what it would have cost to begin curtailing emissions today.[41] Further, there is no guarantee that Youth Plaintiffs will be able to timely and effectively repair this

---

Continued from previous page

economic growth. This puts addressing inequality squarely within the IMF's mandate to help countries improve economic performance.").

[38] See, e.g., "Climate change in the United States: Benefits of Global Action", EPA. Beccherle, Julien and Tirole, Jean, "Regional Initiatives and the Cost of Delaying Binding Climate Change Agreements", *Journal of Public Economics* 95 (December 2011): 1339-1348. Jakob, Michael and Tavoni, Massimo, "Time to act now? Assessing the costs of delaying climate measures and benefits of early action", *Climate Change* 114 (2012): 79-99.

[39] See, for example, Climate change in the United States: Benefits of Global Action, EPA, https://www.epa.gov/sites/production/files/2015-06/documents/cirareport.pdf.

[40] See, for example, "The cost of delaying action to stem climate change," Executive Office of the President of the United States, July 2014, p. 13, https://obamawhitehouse.archives.gov/sites/default/files/docs/the_cost_of_delaying_action_to_stem_climate_change.pdf.

[41] Even as these costly actions to undo the damage are undertaken, the effects of failing to act now will likely be felt, in ways described earlier in this report. Each and every one of the Youth Plaintiffs will face a risk of being personally affected, e.g., by increased taxes, increased direct losses, and increased exposure to health risks and to climate variability itself.

A recent estimate pegged the costs of CO_2 extraction to be on the order of \$8 to \$18.5 trillion, or over \$100 billion per year over 80 years, to return to a 350 ppm target by 2100. These costs are much higher with continued high emissions (i.e., if we do not cease fossil fuel use and rely only on carbon capture and storage), being on the order of \$100 *trillion* or more. See, J. Hansen et al., "Young People's Burden: Requirement of Negative CO_2 Emissions," *Earth System Dynamics*, vol. 8, 2017, pp. 577-616, at 591-592.

damage. In other words, the actions of Defendants in promoting and perpetuating a fossil fuel-based energy system impose a disproportionately higher financial burden and economic disadvantage on Youth Plaintiffs and Affected Children, undermining their economic security and depriving them of the stronger economy that they would have had in the absence of unmitigated climate change.

36. ***Fourth**,* in the absence of mitigation efforts, there is a significant risk of catastrophic impacts of climate change; indeed, there is overwhelming evidence that such catastrophic impacts are likely to result. Defendants' failure to invest in climate change mitigation and thereby insure against that outcome imposes an enormous degree of risk on Youth Plaintiffs, not experienced by older generations. Events such as the rapid melting of ice sheets and consequent increases in global sea levels or temperature increases on the higher end of the range of scientific forecasts have the potential to entail severe, perhaps even irreparable, consequences.[42] To confront properly the possibility of climate catastrophes, Defendants must take prudent steps now to reduce the chance of the most severe consequences of climate change. The longer Defendants postpone such action, the greater will be the atmospheric concentration of GHGs and the risk (due to the self-reinforcing and path-dependent[43] nature of climate systems and long lags between actions and results, as discussed above). Just as businesses and individuals guard against severe financial risks by purchasing various forms of insurance, Defendants can take actions now that reduce the chances of triggering the most severe climate events. There is no third party from which Defendants could purchase insurance to protect Youth Plaintiffs from the damages that are consequent to Defendants' actions. The only alternative for Defendants is to take actions without delay to reduce the atmospheric concentration of CO_2 in order to restore Earth's energy balance and avert catastrophic and irreversible

---

[42] See, Section III, above.

[43] By path dependence, I mean that prior actions affect the future trajectory of the economy in ways that are not irreversible, or reversible only at high costs. Accordingly, what is a prudent strategy today depends on decisions made yesterday (and many years ago). Put differently, prior decisions are not something that we can now just walk away from; those prior decisions directly affect the world we live in today and affect the analysis of what is a prudent strategy going forward.

climate change impacts.[44] Unlike conventional insurance policies, climate and energy policy that serves the purpose of climate insurance also results in cleaner air, improved energy security, and other benefits, many of which are difficult to monetize, like biological diversity or preserving culturally important places, but are nonetheless significant.

37. The benefits of undertaking such actions are disproportionate to the costs, even without taking account of the huge benefits that arise from the reduction of risk itself. This has been documented, for example, in the High-Level Commission on Carbon Prices.[45] Due to feedback loops, the magnitude of climate change may change much more than the proportionate increase in atmospheric concentrations of GHGs. Likewise, the increases in atmospheric concentrations of GHGs may increase disproportionately relative to emissions,[46] and the cost of damage wrought by climate change can increase much faster still.[47] More is being learned about the behavior of the climate system, including the potential timing and likelihood of these worst-case scenarios. However, the paleo-climate record gives scientists at least one good indication of the consequences of different levels of atmospheric CO_2. The last time in the geologic record that CO_2 levels were over 400 ppm, the seas were 70-90 feet higher than sea level today.[48] The experience of the last

---

[44] J. Hansen, "Exhibit A: Declaration of Dr. James E. Hansen in Support of Plaintiffs' Complaint for Declaratory and Injunctive Relief," in *Juliana et al. v. United States et al.*, Case No. 6:15-cv-01517-TC, Doc. No. 7-1., 2015, paras. 39, 67, 85.

[45] The Commission showed that even a modest tax on carbon combined with the elimination of subsidies and certain other regulatory measures and modest public investments would be able to prevent a rise of temperature beyond the 1.5°C to 2°C.

[46] See, for example, "The study of Earth as an integrated system," NASA, https://climate.nasa.gov/nasa_science/science/ and National Research Council of the National Academies, "Climate Change: Evidence, Impacts, and Choices," *The National Academies of Sciences, Engineering, and Medicine*, 2012, http://nas-sites.org/americasclimatechoices/files/2012/06/19014_cvtx_R1.pdf.

[47] This is discussed in the Stern Review. See, for example, Figure 6.6 showing the exponential increase in reduced GDP per capita as global mean temperature increases. Nicholas Stern, "Stern Review: The Economics of Climate Change", p. 159, http://unionsforenergydemocracy.org/wp-content/uploads/2015/08/sternreview_report_complete.pdf.

[48] H. Wanless, "Declaration of Dr. Harold R. Wanless in Support of Answer of Real Parties in Interest to Petition for Writ of Mandamus", *in United States of America et al. v. United States District Court for the District of Oregon et al.*, Case No. 17-71692, Doc. No. 14-3, para. 52.

quarter century is that there have been many surprises of underestimating adverse climate impacts (e.g., early estimates of sea level rise had not taken into account the effect of the melting of the arctic icecap or the release of methane gases from the tundra).[49]

38. Fair treatment of Youth Plaintiffs by Defendants requires taking due account of some of the worst, but still plausibly possible, cases. In such cases, national income will be lower because of the adverse effects of climate change,[50] imposing doubly an increased financial burden and economic disadvantage on Youth Plaintiffs and Affected Children: they will face the costs of remediation and adaptation with fewer resources with which to do so. Even if national incomes continue to rise in real terms, the costs of taking remedial climate action are an ever-increasing burden on Youth Plaintiffs and Affected Children as well. Moreover, as discussed in the climate science summary above, we are quickly approaching (or some argue we may have already passed) certain "tipping points" that will dramatically increase costs in a non-linear fashion.[51] Thus, it is not a practical solution to say Youth Plaintiffs and future generations may be more wealthy in the future (in fact, GDP may be lower in the future because of climate effects) and can bear the costs more efficiently than Defendants today (because those costs continue to increase disproportionately and have long-lasting adverse effects). The assumption of ever-increasing national income has significant implications for Defendants' cost-benefit

---

[49] See, for example, Schneider, Stephen H. and Root, Terry L. Ecological implications of climate change will include surprises, *Biodiversity and Conservation* 5 (1996): 1109-1119.

[50] In one recent study, researchers found that temperature change due to unmitigated global warming will leave global GDP per capita 23 percent lower in 2100 than it would be without any warming. See Burke, M., Hsiang, S. M., & Miguel, E., (2015) "Global non-linear effect of temperature on economic production," *Nature*, 527 (7577): 235-239.

A per capita 23 percent lowering of GDP is the on-average result, which understates the full potential impact in two ways (much as the on-average temperature increases understate the increase in catastrophic events, as I discussed above). *First*, a 23 percent on-average result includes many states of the world where the average may be much worse. *Second*, a 23 percent on-average result will not affect all persons or all regions equally; those near the bottom of the income distribution that have no savings will suffer from lack of ability to consume, and almost surely these effects will be felt more in coastal regions, from which those near the bottom of the income distribution will lack the financial resources to relocate, further exacerbating their financial difficulties.

[51] See also, "The study of Earth as an integrated system," NASA, https://climate.nasa.gov/nasa_science/science/.

analysis and development of discount rates and the social cost of carbon, as described in more detail in Section V.C, below.

39. Moreover, it will be necessary to devote a significant proportion of national income to dealing with the consequences of climate change; the standard term is that there will be high costs of adaptation.[52] Especially disturbing are the impacts on developing countries, many of which are in tropical zones, which will be particularly hard hit. In the U.S., Youth Plaintiffs will not be able to insulate themselves from the global repercussions. The costs of adaptation to climate change by developing countries are well beyond anything that those countries can afford (or will be able to afford in the future). Youth Plaintiffs may recognize that they have a moral responsibility to global citizens elsewhere in the world because of the actions of the U.S., including Defendants, and thus they will bear a burden because of the failure of Defendants to take appropriate actions.[53] However, even were they not to do so, the markedly lower incomes in developing countries will set off large migration pressures, which we are already seeing today.[54]

---

[52] According to the United Nations Environment (UNEP) report, the cost of adapting to climate change in developing countries could rise to between $280 and $500 billion per year by 2050. There will be a significant financing gap unless new and additional finance for adaptation is made available. See UNEP 2016. The Adaptation Finance Gap Report 2016. United Nations Environment Programme (UNEP), Nairobi, Kenya

[53] Of course, Defendants do not control global climate emissions. The U.S. is the second-largest current emitter of CO_2 at 15 percent of global emissions (behind only China), and by far the largest historical emitter of CO_2 and GHGs. See, EPA, "Global Greenhouse Gas Emissions Data," *United States Environmental Protection Agency*, data as of 2014, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Country and J. Gillis and N. Popovich, "The U.S. Is the Biggest Carbon Polluter in History. It Just Walked Away From the Paris Climate Deal," *The New York Times*, June 1, 2017, https://www.nytimes.com/interactive/2017/06/01/climate/us-biggest-carbon-polluter-in-history-will-it-walk-away-from-the-paris-climate-deal.html.

However, action by the world's largest historical contributor of GHGs and the world's largest economy (the U.S.) would help further the goals of the Paris agreement and other countries' efforts to reduce GHG emissions. Moreover, it could reduce the incentive for other countries to shirk their climate change efforts by attempting to gain a competitive edge by not addressing climate change (a race to the bottom, so to speak). In any event, however, the fact that other countries, particularly developing countries, may not take as strong as action as is needed is not justification for Defendants using out-dated economic models and analysis to foist high costs on Youth Plaintiffs and Affected Children more generally.

[54] See, for example, Coral Davenport and Campbell Robertson, "Resettling the First American 'Climate Refugees,'" *The New York Times*, May 3, 2016, https://www.nytimes.com/2016/05/03/us/resettling-

Continued on next page

Managing this migration (including possibly putting up hard-and costly-to-enforce barriers to it) will impose large costs on Youth Plaintiffs, undermining their economic security.[55] Moreover, in a globally interconnected system, lower incomes abroad will adversely affect the demand for American goods and services, thereby reducing U.S. GDP from what it otherwise would be, with consequent risks for Youth Plaintiffs and Affected Children.

40. I understand that Defendants argue their policies were necessary for the economic and national security of the U.S.[56] Such arguments do not withstand economic scrutiny. Whatever benefits might have existed in the middle of the 20th century, it has been decades since such policies were rational. This has been recognized by leading security experts. For example, since at least 2007, members of the U.S. military have recognized that "serious consequences to our national security … are likely from unmitigated climate

---

Continued from previous page

the-first-american-climate-refugees.html and Aryn Baker, "How Climate Change is Behind the Surge of Migrants to Europe," *Time*, September 7, 2015, http://time.com/4024210/climate-change-migrants/.

[55] As discussed in the Stern Review, some estimates suggested up to 200 million people may become permanently displaced by climate change by the middle of this century, noting that almost as many people leave their homes because of environmental disasters as flee political oppression. See, Nicholas Stern, "Stern Review: The Economics of Climate Change", p. 77, http://unionsforenergydemocracy.org/wp-content/uploads/2015/08/sternreview_report_complete.pdf. See also, K. Burrows & P. Kinney, "Exploring the Climate Change, Migration and Conflict Nexus," *International Journal of Environmental Research and Public Health* 13(4) (2016): 443, noting that the number of people displaced by climate change by 2050 is estimated to be between 50 million, on the low end, and 1 billion, on the high end.

[56] See, e.g., "Office of Fossil Energy FY 2019 Budget," U.S. Department of Energy, https://www.energy.gov/fe/about-us/our-budget ("The Office of Fossil Energy (FE) programs are focused on activities related to the reliable, efficient, affordable, and environmentally sound use of fossil fuels that are essential to our Nation's security and economic prosperity.").

See also, Jason Furman and Gene Sperling, "Reducing America's Dependence on Foreign Oil As a Strategy to Increase Economic Growth and Reduce Economic Vulnerability," Obama White House Archives, August 29, 2013, https://obamawhitehouse.archives.gov/blog/2013/08/29/reducing-america-s-dependence-foreign-oil-strategy-increase-economic-growth-and-redu ("...the President's focus on increasing America's energy independence is not just a critical national security strategy, it is also part of an economic plan to create jobs, expand growth and cut the trade deficit." The first element of President's Obama plan was "Increasing domestic production of oil.").

change."[57] In a report released in 2007, eleven retired military generals and admirals detailed the variety of threats to America's national and economic security that climate change poses:[58]

> In already-weakened states, extreme weather events, drought, flooding, sea level rise, retreating glaciers, and the rapid spread of life-threatening diseases will themselves have likely effects: increased migrations, further weakened and failed states, expanded ungoverned spaces, exacerbated underlying conditions that terrorist groups seek to exploit, and increased internal conflicts. In developed countries, these conditions threaten to disrupt economic trade and introduce new security challenges, such as increased spread of infectious disease and increased immigration. Overall, climate change has the potential to disrupt our way of life and force changes in how we keep ourselves safe and secure by adding a new hostile and stressing factor into the national and international security environment.

41. From an economic perspective, one of the key insights is that, just at the time when money is scarce (and our economy is weak) because of climate change, there will be greater need for funds. Thus, government will be less able to provide the requisite finance for key public services, depriving Youth Plaintiffs and Affected Children of the economic benefits enjoyed by older generations. This makes it even more compelling for Defendants to take all the precautionary measures today that they can.

42. As noted by the High-Level Commission on Carbon Prices (the "High-Level Commission"), which I co-chaired, the estimated economic costs of climate change in many of the standard models, and in particular Defendants' estimates of the social cost of carbon (under the Obama administration), are:[59]

---

[57] "National Security and the Threat of Climate Change," The CNA Corporation, 2007, p. 44, https://www.cna.org/cna_files/pdf/national%20security%20and%20the%20threat%20of%20climate%20change.pdf.

[58] "National Security and the Threat of Climate Change," The CNA Corporation, 2007, pp. 44-45, https://www.cna.org/cna_files/pdf/national%20security%20and%20the%20threat%20of%20climate%20change.pdf.

[59] High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices", 2017, Washington, DC: World Bank, Appendix A.

> …biased downward because they fail to consider many vitally important risks and costs associated with climate change—particularly the widespread biodiversity losses, long-term impacts on labor productivity and economic growth, impacts on the poorest and most vulnerable, rising political instability and the spread of violent conflicts, ocean acidification, large migration movements, as well as the possibility of extreme and irreversible changes.

43. Thus, it is prudent for Defendants to take precautionary actions, not based on the "average" estimate of what the damage might be, but rather based on estimates of realistically plausibly possible "worst cases." Because, as detailed below, Defendants could take actions at modest costs, and it would be reckless not to undertake those actions; it would be needlessly endangering the future prospects and the economic and personal security of Youth Plaintiffs and Affected Children.

V. TRANSITIONING THE U.S. ECONOMY OFF OF FOSSIL FUELS IS NOT ONLY FEASIBLE BUT WILL BENEFIT THE ECONOMY

A. TRANSITIONING OFF OF FOSSIL FUELS IS FEASIBLE

44. There is broad consensus among economists, and the High-Level Commission concluded, that limiting temperature increase to "well below 2°C" is achievable with reasonable and modest measures, and that the costs of those measures are far smaller than the costs of the damage that climate change could inflict.[60]

45. The High-Level Commission estimated that the costs of curtailing emissions to a level to achieve the goals set forth by the Paris Agreement ("well below 2°C") would be modest.[61] The High-Level Commission noted that the carbon tax, that they explained could induce the requisite change in emissions, could substitute for other more distortionary taxes. If governments made such a substitution, the aggregate cost of curtailing carbon emissions could even be less than zero, providing net benefits to the economy. Furthermore, at a time when so much discussion focuses on the Federal government's deficit spending (and our national debt), the elimination of billions of dollars of often-hidden subsidies to the fossil fuel industry would improve the country's fiscal situation and economic performance generally. As discussed below in Section V.B, the full amount of post-tax subsidies in the U.S. has been estimated at nearly $700 billion a year, more than half of the Federal government's forecasted deficit for the next fiscal year.[62] Eliminating all fossil fuel subsidies (implicit and explicit, many of which

---

[60] High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices", 2017, Washington, DC: World Bank, p. 1.

[61] When I use the term "costs" here, I refer to the net effect of undertaking such policy changes—that is, such costs can be negative (when the benefits outweigh the costs). As is standard in economic analysis, I analyze the *marginal* effects, that is, the marginal (i.e., additional as compared to the *status quo*) net outlays that will be required for effectuating a given policy choice. Because certain policy choices can have long-term benefits that outweigh long-term costs, negative costs are a distinct possibility.

[62] Coady et al., "How Large Are Global Energy Subsidies?", IMF Working Paper, Fiscal Affairs Department, 2015, paper and underlying data available at: https://www.imf.org/en/News/Articles/2015/09/28/04/53/sonew070215a.

Continued on next page

go to large corporations) could, therefore, both curtail fossil-fuel production, through forcing companies to bear more of the true costs of fossil-fuel production, and substantially reduce our national deficit in one fell swoop. Equity would also be improved with corporations paying more and individuals, such as the Youth Plaintiffs and Affected Children, benefiting.

46. There are many reasons to be optimistic that emissions could be curtailed further than previously thought. These benefits are a result of continued technological development in the renewables sector. Because of technological improvements, the costs of renewables and storage are decreasing. The price of solar panels has dropped by more than half in recent years (80 percent reduction from 2008 to 2016).[63] In 2016 alone, the average dollar capital expenditure per megawatt for solar photovoltaics and wind dropped by over 10 percent.[64] As these technologies continue to improve and the efficiency increases, while manufacturing costs drop, these technologies will more easily substitute for existing fossil fuel infrastructure.

47. Transitioning to a non-fossil-fuel-based economy will require additional investment in our energy sector. Such sectoral shifts in our economy are not uncommon. In fact, a hallmark of a well-functioning market economy is its ability to shift between sectors as

---

Continued from previous page

See also a report published by the Overseas Development Institute and Oil Change International, which found that as of 2014, the U.S. government provides approximately $20 billion annually in producer side subsidies through various tax exceptions/deductions.

Doukas, Alex, "G20 subsidies to oil, gas and coal production: United States", Overseas Development Institute, 2015, https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9979.pdf).

With the recent tax cuts, the deficit is currently forecasted to be about $1 trillion in the next fiscal year. See, Associated Press in Washington, "US deficit to approach $1tn after Trump tax cuts and spending bill, CBO says," *The Guardian*, April 9, 2018, https://www.theguardian.com/us-news/2018/apr/09/us-deficit-trump-tax-cuts-trillion-cbo-projection.

[63] See, e.g., Ryan Whitman, "We could be headed for a solar power renaissance as costs keep dropping," *ExtremeTech*, December 19, 2016, https://www.extremetech.com/extreme/241300-headed-solar-power-renaissance-costs-keep-dropping.

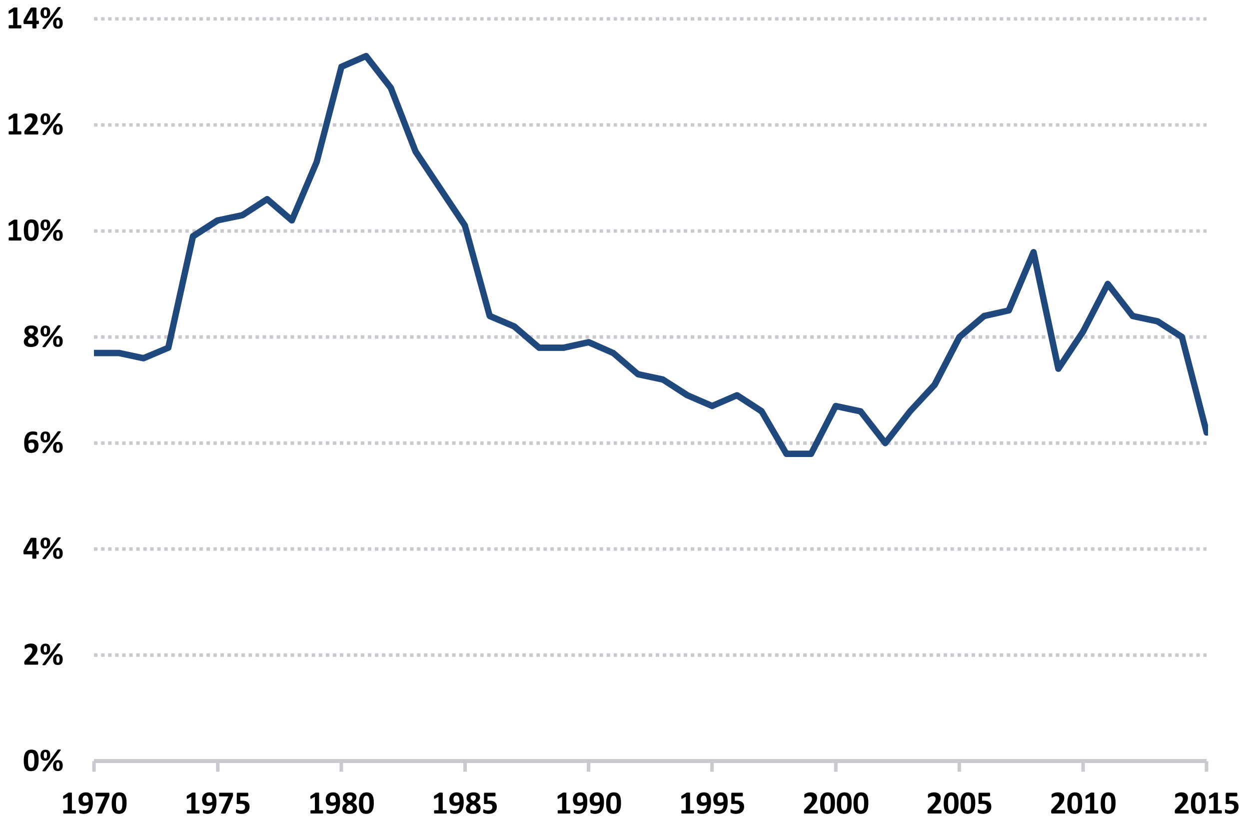
[64] Frankfurt School-UNEP Centre/BNEF, "Global Trends in Renewable Energy Investment 2017," 2017, http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

technology changes and demand fluctuates. For example, we have seen shifts from agriculture to manufacturing to services over the course of the twentieth century, and we saw a shift towards the financial sector (from less than 3 percent to over 8 percent of GDP) from the 1950s to its peak in 2006 (immediately before the financial crisis).[65] Our spending on our energy sector has also fluctuated, as the chart below shows energy expenditures as a percent of GDP from 1970 to 2015. While the high levels of spending in the early 1980s (over 10 percent) were during periods of economic turbulence with high inflation and an energy crisis, there have been other periods, such as the 2000s and the early 1970s where there was economic growth and high spending on our energy system. Moreover, our economy has endured sudden, unplanned disruptions in the past (again, for example, the financial crisis); moving our economy to one without fossil fuels would come with a slight cost, but would be an event we can plan for to minimize disruptions (and would bring net benefits in the form of risk reduction).

---

[65] See, e.g., Robin Greenwood and David Scharfstein, "The Growth of Finance," *Journal of Economic Perspectives*, 27(2) (Spring 2013): 3-28.

Figure 1: Energy Expenditures as Share of GDP (Percent)



Source: U.S. Energy Information Administration, March 2018 Monthly Energy Review, Table 1.7 Primary Energy Consumption, Energy Expenditures, and Carbon Dioxide Emissions Indicators.

48. There are a number of important new "energy smart" technologies that can play a role in reducing dependence on energy, making our existing energy infrastructure more efficient.[66] Smart grids, for example, can turn on appliances when renewable electricity is plentiful—and ramp down electric loads when renewable power wanes. Advanced energy storage technologies are increasingly diverse and many, like ice energy storage, are simpler and can be more cost effective than chemical batteries. Electric vehicles can also be considered "energy smart" technology, as their charging and discharging of batteries can be flexible, creating great potential to improve the efficiency of our national energy infrastructure. These technologies reduce overall energy consumption, so that even without the introduction of less carbon intensive energy sources, they can reduce

---

[66] Frankfurt School, UNEP Centre, "Global Trends In Renewable Energy Investment 2017," http://fs-unep-centre.org/sites/default/files/publications/globaltrendsinrenewableenergyinvestment2017.pdf.

carbon emissions. Many energy efficiency technologies actually have a negative cost to implement, especially if one includes in the costs the implicit costs associated with GHG emissions (costs to society that are currently externalized).[67]

49. The major U.S. corporations that have committed themselves to dramatic emissions reductions—as well as state and local governments that have committed to emissions reductions—support the feasibility of a swift transition.[68] Creating predictability is of significant economic value in aggressively seeking to reduce emissions; i.e., it makes clear to players in the future economy that they can plan accordingly with very high confidence. In addition, this greater certainty facilitates the production of goods and services at lower costs. For instance, the Chief Executive Officers of Apple, BHP Billiton, BP, DuPont, General Mills, Google, Intel, Microsoft, National Grid, Novartis Corporation, Rio Tinto, Schneider Electric, Shell, Unilever, and Walmart all called on the President to stay the course with respect to United States' participation in the Paris Agreement.[69] So too, were the Defendants to adopt a high and reliable price of carbon, households and firms would know that it paid economically to adopt low- or zero-emission technologies and products.

50. In pursuing clean-energy technology, there is also the potential for increasing overall economic production and stimulating aggregate demand and economic growth. As I

---

[67] See, e.g., European Commission, "The Macroeconomic and Other Benefits of Energy Efficiency", https://ec.europa.eu/energy/sites/ener/files/documents/final_report_v4_final.pdf.

[68] In 2017, for example, nine states making up the Regional Greenhouse Gas Initiative consortium agreed to a cap-and-trade program that seeks a 30 percent reduction in carbon pollution from energy plants by 2030. See, Colin Young, "9 states, including Mass., Agree to Accelerate Emission Reductions in Next Decade," *WBUR*, August 23, 2017, http://www.wbur.org/news/2017/08/23/9-states-including-mass-agree-to-extend-carbon-reduction-goals-to-2030.

Other state-driven strategies include California's January 2018 announcement to have 5 million zero-emission vehicles in use by 2030; Hawaii mandating that all of the state's electricity come from renewable sources by the mid-21st century; and Vermont's commitment to reduce emissions to 80-95 percent below 1990 levels by 2050. See, "U.S. Leads in Greenhouse Gas Reductions, but Some States are Falling Behind," Environmental and Energy Study Institute, March 27, 2018, http://www.eesi.org/articles/view/u.s.-leads-in-greenhouse-gas-reductions-but-some-states-are-falling-behind.

[69] See, e.g., Center for Climate and Energy Solutions, "Top companies urge White House to stay in the Paris Agreement," Center for Climate and Energy Solutions Press Release, April 2017, https://www.c2es.org/newsroom/releases/major-companies-urge-white-house-stay-paris.

wrote a few years ago in *The Guardian*, "retrofitting the global economy for climate change would help to restore aggregate demand and growth."[70] Consistent with this, the High-Level Commission, which I co-chaired with Lord Stern,[71] found that "climate policies, if well designed and implemented, are consistent with growth, development, and poverty reduction. The transition to a low-carbon economy is potentially a powerful, attractive, and sustainable growth story, marked by higher resilience, more innovation, more livable cities, robust agriculture, and stronger ecosystems."[72]

51. However, instead of supporting existing clean energy technology that would benefit the economy and create jobs, Defendants are acting in ways to suppress and hinder clean energy, which also leads to job losses and harms the economy. For example, in January 2018, President Trump approved tariffs on imported solar cells that start at 30 percent. The tariffs are unlikely to benefit American solar manufacturing jobs, but, according to the Solar Energy Industries Association, are likely to result in the loss of 23,000 American jobs this year and the delay or cancelation of billions in solar investments. The tariffs are also expected to lead to a net reduction in solar installations by roughly 11 percent between 2018 and 2022, a 7.6-gigawatt reduction in solar PV capacity, which means approximately 1.2 million homes will not be powered by renewable solar energy. Such tariffs are both harmful for the environment and the economy.[73]

52. Not promptly undertaking actions to pursue clean-energy technology continues to expose Youth Plaintiffs and Affected Children to the risk of extreme costs and damages, not just from climate change itself, but from the required outlays on future remediation and adaptation efforts and a weaker, less efficient, and more expensive U.S. economy.

---

[70] Stiglitz, J., "Climate Change and Poverty Have Not Gone Away," *The Guardian*, January 7, 2013, https://www.theguardian.com/business/2013/jan/07/climate-change-poverty-inequality

[71] Lord Stern succeeded me as Chief Economist of the World Bank and subsequently was a leading economic advisor to the UK Treasury, as Second Permanent Secretary and head of the Government Economic Service.

[72] High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices," 2017, Washington, DC: World Bank, p. 1.

[73] Julia Pyper, "New Tariffs to Curb US Solar Installations by 11% Through 2022," *Greentech Media,* January 23, 2018, https://www.greentechmedia.com/articles/read/tariffs-to-curb-solar-installations-by-11-through-2022#gs.YNyvdYQ

B. POLLUTION IS A CLASSIC EXTERNALITY THAT CAN BE COMBATED WITH STANDARD ECONOMIC TOOLS THAT PROMOTE SOCIAL WELFARE

53. Currently, around 80 percent of the energy consumed in the U.S. comes from fossil fuels.[74] In contrast, renewable energy sources comprise 11 percent of total energy consumption. That percentage has only risen by 2 percent (9 to 11 percent) from 1949 to 2017.[75]

54. The burning of fossil fuels generates large amounts of pollution. Pollution is the archetypal negative externality. In economics, an externality arises when the cost or benefit of an activity of one party imposes a cost or benefit on another. In the pollution example, the polluter makes a good (its primary activity), but in the course of doing so generates pollution that imposes a cost or burden on another (e.g., a fisherman who fishes in the waters that become polluted will catch fewer fish). A positive externality example might be a technological development that benefits more than the inventor alone (e.g., the developer of the worldwide web who made it freely available).

55. The issue that arises with a negative externality is that the producer of the externality (e.g., the polluter) considers only their private costs when making production decisions and not the total costs of their activity (the costs borne by the polluter and the fisherman). Standard economic theory argues that private markets can be relied on to make efficient decisions, if, and only if, the (marginal private) costs confronting individuals equal the (marginal) social costs, and the (marginal private) benefits confronting them equal the (marginal) social benefits. When there is an externality, social and private costs and/or benefits are not aligned. A classic way to intervene in this situation is for government to tax the causes of negative externalities (thereby raising the effective private cost closer to

---

[74] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, March 2018 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

[75] U.S. Energy Information Administration, Table 1.3 Primary Energy Consumption by Source, March 2018 Monthly Energy Review, https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.03&freq=m.

the social cost and forcing the producer to bear the full cost of their actions).[76] Having a well-functioning price system—where price setters take into account all costs—is important for economic efficiency and overall social welfare.

56. At present, the U.S. lacks a comprehensive carbon-pricing regime that accounts for the negative externalities of burning fossil fuels such that private markets can be relied on to make efficient decisions. Thus, producers and sellers of fossil fuels consider only their private costs and benefits, and the costs that their activities are imposing on society through, among other factors, increased GHG emissions and long-term climate effects of the sort I discussed earlier are not considered or internalized as part of the price.

57. Beyond the lack of a comprehensive carbon-pricing regime, a faulty system that is full of hidden subsidies for fossil fuels, as noted above, hinders the transition towards a less carbon-intensive economy. These subsidies also accelerate and exacerbate the costs to Youth Plaintiffs from climate change.

58. These subsidies take many forms. For instance, upstream oil and gas exploration and production companies in the U.S. receive several tax breaks that go beyond those afforded to businesses generally, such as deducting intangible drilling costs as a current business expense (not capitalized over the life of the well), depletion allowances,[77] and offshore drilling tax royalty relief (which permits the claiming of foreign royalties as taxes (and makes them creditable against U.S. taxes) for taxpayers taxed in two countries). When companies make an investment, it is natural that they be allowed to depreciate the cost of the capital as a tax-deductible expense over the lifetime of the asset.

---

[76] Sometimes, governments have to rely on "second best" interventions. Thus, government can subsidize alternatives (or positive-externality activities), which lowers the effective price of substitute products. Lowering the price of a substitute product can have the effect of increasing demand for the substitute (e.g., clean energy) and reducing the demand for the original product (e.g., fossil fuel-based energy). But leaving the negative externality-generating activity without a "charge" for its external effects leaves a distortion in place.

[77] I have studied the economics of depletion allowances, together with Sir Partha Dasgupta, in my academic work. See, J.E. Stiglitz, "Monopoly and the Rate of Extraction of Exhaustible Resources," *The American Economic Review* 66(4) (September 1976): 655-661 and P. Dasgupta and J.E. Stiglitz, "Uncertainty and the Rate of Extraction Under Alternative Arrangements," *Institute Mathematical Studies in the Social Sciences*, tech. rep. no. 179 (September 1975).

But with depletion allowances, an oil company can deduct 15 percent of the revenue as a "depletion allowance," regardless of the amount of investment it made to find the oil.[78] The company receives the depletion allowance—as if it invested money—even if it makes no investment. The value of this provision itself is enormous; some estimates say it could save the U.S. Treasury over $11 billion in 10 years if it were eliminated.[79] (Money not received by Treasury is, in effect, money given to the fossil fuel industry.) Coal companies can receive similar corporate tax reductions, and are able to purchase or lease land from Defendants at below market rates.[80] These tax breaks artificially reduce the private cost of fossil fuels to producers and consumers (but not the social cost), which makes renewable sources of energy appear less competitive to consumers.[81] In the U.S., these tax breaks for fossil fuel companies have resulted in an economy heavily dependent on fossil fuels and infrastructure designed around fossil fuels.

59. Similarly, at various times, oil, gas, and coal leases have been conducted in ways in which fossil fuel companies are able to obtain leases at prices far below what the competitive equilibrium price would be, depriving taxpayers of money they need for a variety of public purposes, while distorting the market to make participation in oil, gas, and coal more economically attractive.[82] The efficient auctions that have been used in

---

[78] This provision dates to 1913. See, e.g., Rebecca Leber, "Happy 100th Birthday, Big Oil Tax Breaks," *Think Progress*, March 1, 2013, https://thinkprogress.org/happy-100th-birthday-big-oil-tax-breaks-3c9731c4bc85/. See also, Seth Hanlon, "Big Oil's Misbegotten Tax Gusher," *Center for American Progress*, May 5, 2011, https://www.americanprogress.org/issues/economy/news/2011/05/05/9663/big-oils-misbegotten-tax-gusher/.

[79] See, Seth Hanlon, "Big Oil's Misbegotten Tax Gusher," *Center for American Progress*, May 5, 2011, https://www.americanprogress.org/issues/economy/news/2011/05/05/9663/big-oils-misbegotten-tax-gusher/.

[80] Doukas, Alex, "G20 subsidies to oil, gas and coal production: United States", Overseas Development Institute, 2015, https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/9979.pdf.

[81] Bridle, Richard, Kitson, Lucy, "The Impact of Fossil-Fuel Subsidies on Renewable Electricity Generation", International Institute for Sustainable Development, December 2014, http://www.iisd.org/sites/default/files/publications/impact-fossil-fuel-subsidies-renewable-electricity-generation.pdf.

[82] This was the case, for instance, in the early 1980s, when large numbers of tracts were simultaneously put up for auctions, so many that the average tract had less than two bidders. I discussed some of the

Continued on next page

other areas (e.g., for the auctioning of the electro-magnetic spectrum) were typically never used. A 2016 report from the President's Council of Economic Advisors regarding coal leases recognized several of these points explicitly, noting, for example, that the coal leasing program "has been widely criticized in recent years by economic and environmental experts for providing a poor return to the taxpayer and for not adequately addressing the environmental costs of coal extraction, processing, and combustion."[83] The report also found that previous and then-current policies of Defendants had misaligned incentives: "the program has been structured in a way that misaligns incentives going back decades, resulting in a distorted coal market with an artificially low price for most Federal coal and unnecessarily low government revenue from the leasing program."[84] The report suggests that to fully reflect the social costs of coal extraction—i.e., price the externality completely—the costs are so high that the resulting royalty rate may be "well-over 100 percent."[85]

Continued from previous page

research in this instance in my Nobel lecture. See, J.E. Stiglitz, "Information and the Change in the Paradigm in Economics," Prize Lecture, December 8, 2001, pp. 489-490, https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/2001/stiglitz-lecture.pdf.

See also, J.J. Leitzinger and J.E. Stiglitz, "Information Externalities in Oil and Gas Leasing," *Contemporary Policy Issues* 5 (March 1984): 44-57 and J.E. Stiglitz, "What is the Role of the State?" Chapter 2 in M. Humphreys, J.D. Sachs, and J.E. Stiglitz (eds.) "Escaping the Resource Curse," 2007, Columbia University Press, pp. 23-52 at p. 31: "When competition for the resources is limited—and especially when it is known that it is limited—then the prices that prevail will be lower. There are three ways of limiting competition. The first is suddenly to put up for lease a large number of tracts—increase the supply so that the bidding on each tract is limited. This is what President Reagan did in the early 1980s. It was like a fire sale—as if the government had to get rid of its holdings immediately. But in fact, there was no reason for it; it was not as if the oil was going to disappear, or as if the United States needed to raise cash quickly. On a very large fraction of tracts, there was only one bidder (and, of course, the oil companies knew this). In a study I conducted with Jeff Leitzinger (1984) we quantified the impact on the price the government received. The government got a fraction of what it would have earned had the tracts been put up in a more orderly process, and the extra profits went into the coffers of the oil companies."

[83] "The Economics of Coal Leasing on Federal Lands: Ensuring a Fair Return to Taxpayers," Executive Office of the President of the United States, June 2016, at p. 2, https://obamawhitehouse.archives.gov/sites/default/files/page/files/20160622_cea_coal_leasing.pdf.

[84] *Id.*

[85] *Id*. at p. 29.

60. An important source of protection against global warming is carbon-sequestration—holding carbon in trees, plants, wetlands, or soils. Carbon molecules that are thus held are carbon molecules that are not in the atmosphere.[86] There are large amounts of public land holding millions of acres of trees, but the government has an industry-driven policy framework in which (a) the timber industry, which acquires the right to cut down the timber, does not pay for the carbon costs of their activities; (b) the timber industry is typically subsidized through roads constructed by the Department of Agriculture, which manages these public forests; (c) the timber industry, like the fossil fuel industry, receives favorable tax benefits; and (d) the timber industry acquires these assets at prices that are below prices that would prevail in a competitive market that accounted for all private and public costs of logging.[87]

61. The provision of these tax benefits and the sale and/or lease of these public assets at below competitive market prices by Defendants harms the U.S. today, and these Youth Plaintiffs and Affected Children, in multiple ways. The harm to the U.S. arises because improper pricing that ignores the externalities of logging leads to inefficient uses of forests, logs, and wood products that would not materialize if the price of logs reflected the carbon costs of cutting down the trees and releasing CO_2 into the atmosphere. These actions by Defendants support the destruction of forests, which are needed to sequester CO_2 (not to mention all the critical ecosystem benefits forests provide). The poorly functioning price mechanism deprives our society of governmental revenues that could be used for multiple purposes, including investment in emission reductions and investments in R&D that would facilitate the transition towards a green economy; and forces taxes to be imposed elsewhere, with distortionary costs—so that total costs to society are well in excess of the losses of tax revenues. The resulting weaker economy

---

[86] For a more thorough articulation of this framework, see J.E. Stiglitz, “Sharing the Burden of Saving the Planet: Global Social Justice for Sustainable Development: Lessons from the Theory of Public Finance,” Columbia University Academic Commons, https://doi.org/10.7916/D8KD24MX and Mary Kaldor and Joseph E. Stiglitz, eds., *The Quest for Security: Protection without Protectionism and the Challenge of Global Governance*, New York: Columbia University Press, pp. 161-190.

[87] See, e.g., “Congressional Subsidies for Private Logging,” Taxpayers for Common Sense, December 13, 2001, http://www.taxpayer.net/library/article/congressional-subsidies-for-private-logging.

means that Youth Plaintiffs are inheriting an economy that is not only dirtier than it otherwise would have been, but also weaker.

62. There are also indirect explicit subsidies that contribute to the continued reliance on fossil fuels, such as government investments and policies that promote emission producing methods of transportation or manufacturing.

63. Another implicit subsidy granted by governments is to not charge the fossil fuel industry for the negative externalities they create, such as carbon emissions. As discussed above, carbon emissions, and pollution in general, are negative externalities that can affect society and the economy, yet the vast majority of negative-externality carbon emissions across the globe are not priced.[88] Pricing CO_2 emissions and emissions of other GHGs would greatly enhance revenues available to government to address a variety of societal needs, as I discussed in Section IV above. A basic principle of taxation is that it is better to tax bad things like pollution than good things like savings and work. Again, the resulting weaker economy means that Youth Plaintiffs are inheriting an economy that is not only dirtier than it otherwise would have been, but also weaker. In this instance, not only are Defendants not raising revenue in an efficient way (subsidizing rather than taxing carbon emissions), Youth Plaintiffs are burdened with the socioeconomic costs that arise with pollution, such as additional healthcare costs.

64. Defendants have recognized for at least 40 years that these direct and indirect subsidies to fossil fuel producers hinder the adoption of renewable energy and improvements in

---

[88] See, e.g., High-Level Commission on Carbon Prices, "Report of the High-Level Commission on Carbon Prices," 2017, Washington, DC: World Bank, at p. 35: "The carbon prices observed span from less than US$1/tCO2e to US$126/tCO2e, 85 percent of global emissions are not priced today…"

Because all emissions generate externalities, for an efficient economy, all emissions should be taxed. In a few instances, the adverse effects of not taxing the emissions can be mitigated by the imposition of regulations.

renewable energy technologies. For example, a 1978 memo to President Carter regarding solar power found that:[89]

> Widespread use of solar energy is also hindered by Federal and state policies and market imperfections that effectively subsidize competing energy sources. These policies include Federal price controls on oil and gas, a wide variety of direct and indirect subsidies, and utility rate structures that are based on average, rather than marginal costs. Also, the market system fails to reflect the full social benefits and costs of competing energy sources, such as the costs of air and water pollution.

65. If Defendants stopped providing subsidies and/or implemented carbon pricing policies that allow the U.S. government to further fund research and development of green technologies to decarbonize the economy, such measures would have a large positive impact in the long term. These positive effects are not limited to mitigating the environmental effects; there are monetary gains, too. Some estimates of the financial benefit to the U.S. economy of accelerating technological developments for lowering carbon emissions suggest that they would amount to $1 trillion by 2050.[90]

66. This monetary estimate does not take into account possible spillover effects from advancing technology that could provide further value to the economy (e.g., in the same way that the space race or developments in the world wars brought us many advancements in basic science that made their way into consumer and industrial products). Even without technological change, the net financial costs to the economy may be negative, taking into account the financial benefits of eliminating carbon subsidies and replacing them with carbon taxes and the consequent development of a more efficient low-carbon energy system.

67. A short-term measure Defendants can readily implement is to cease approvals for any new fossil fuel infrastructure, pending completion of a national climate recovery plan. Any new coal projects or coal extraction harms Youth Plaintiffs. For example, it

---

[89] Attachment to Memorandum from Jim Schlesinger to The President, "Domestic Policy Review of Solar Energy: A Response Memorandum to The President of the United States," December 5, 1978, at p. iv.

[90] Richard G. Richels, Geoffrey J. Blanford, "The value of technological advance in decarbonizing the U.S. economy," *Energy Economics* 30(6) (2008): 2930-2946, ISSN 0140-988.3.

increases GHG emissions locking in higher concentrations of GHGs in the atmosphere as Youth Plaintiffs grow up and live their lives, with all the attendant costs and impacts that I have described thus far. Enabling investments in long-lasting "fossil" infrastructure (like coal-burning power plants and oil and natural gas pipelines) means that for decades going forward, there will continue to be incentives to engage in costly carbon emissions. Once the plants are built, the owners have an incentive to continue using it to recover their investment (and in so doing, generate GHG emissions). Furthermore, should a fossil-fuel plant be shut down before the natural end of its economic life, there will be allegations of lost economic value (the owners' private loss on their investment). Such allegations will become a political argument against taking further actions curbing emissions. (These arguments will almost surely be put forward even though the public benefits of shutting down the coal fired plants may be enormous—as I have noted—and even though a standard argument in economics is that bygones-are-bygones. Mistaken investments in the past should not continue to justify distorted power generation. Elsewhere, however, the "politics" of stranded assets has played an important role—that is to say; private owners of large, sunk investments have (successfully) argued for preferential treatment for them to recoup their private investments, despite the attendant social costs.)

68. I should also respond to an expected argument from Defendants that, even if the U.S. were to lower its GHG emissions, other countries would increase their production of goods that create GHGs. This might be referred to as a "substitution" argument. There are two rejoinders to this:

a. First, I turn to standard economic theory. That is, that in any given equilibrium the lowest-cost providers are providing any given resources. Thus, if the U.S. is providing GHG-dependent products today, it is because the marginal cost of the U.S. providing such products is below the next-cheapest alternative. If the U.S. were to cease producing, say, 100 "units" of GHGs, the next-cheapest alternative would increase its production by less than 100 "units" (because if it made economic sense for the next-cheapest alternative to produce more than 100 "units" they would already be doing so). As such, any substitution will be less than perfect and reductions in

U.S. emissions will be offset less than one-to-one by alternative supplies (i.e., there will be a net reduction).

b. Second, specific to GHG emissions, recent technical studies have shown that U.S. emissions will not be perfectly offset.[91] This is consistent with the general theory I mentioned above. While climate change is a global problem, the U.S. is a significant contributor to GHG emissions, and so actions by the U.S., both directly, and by the leadership which such actions provide, has a significant impact on these global outcomes. Indeed, the U.S. stands out as the sole country announcing that it is not committed to the reduction of carbon emissions, having announced that it will leave the Paris Agreement. Despite the U.S.'s actions, other countries remain committed. Thus, if the U.S. were to recommit itself to climate action, there is no significant risk of other countries polluting more, so as to offset the benefits of U.S. reductions in carbon emissions.

69. The government has recognized since the 1980s that the U.S. will need to take a leadership role in climate change. For example, a government memorandum from 1989 discusses the desire for the U.S. to have a leadership role in addressing climate change. The memorandum also makes clear that when it comes to addressing climate change the U.S. "simply cannot wait -- the costs of inaction will be too high."[92]

C. DEFENDANTS' USE OF DISCOUNTING IN DECISION-MAKING UNDERESTIMATES THE COSTS OF CLIMATE CHANGE ON YOUTH PLAINTIFFS AND FUTURE GENERATIONS AND THE BENEFITS OF MITIGATION, WITH DELETERIOUS CONSEQUENCES

70. In running the government, Defendants must repeatedly make decisions about projects and policies. They must evaluate alternative choices with which they are confronted. In this section, I explain that the way Defendants do this systematically undermines the

---

[91] See, e.g., P. Erickson and M. Lazarus, "Would constraining US fossil fuel production affect global CO2 emissions? A case study of US leasing policy," *Climatic Change*, 2018, https://doi.org/10.1007/s10584-018-2152-z.

[92] Memorandum from Frederick M. Bernthal to Richard T. McCormack, Department of State, February 9, 1989, attachment "Environment, Health and Natural Resources Issues," and responses to "Question #1."

interests of Youth Plaintiffs in a way which cannot be justified. Indeed, economic science provides sound alternative methodologies for the evaluation of policies and projects which systemically lead to better outcomes for society in general, and would not systematically discriminate against Youth Plaintiffs in the way that existing policies do.

71. While there are a number of longstanding and well-established perspectives in economics which recognize that delaying the kinds of precautionary actions suggested above is deleterious to societal welfare, government practices and procedures underlying important decision-making systematically undervalue the costs to be borne by future generations (including Youth Plaintiffs and Affected Children).

72. The issue devolves around how governments should value benefits and costs that arise at some future date relative to those that occur today. Typically, less value is given to future effects than to current effects. The question is, how much less. Since the most catastrophic effects of climate change may not be felt for years (see paragraph 27 and footnote 19, above), saying that what happens in the future does not matter much biases public decision making against taking actions to protect Youth Plaintiffs.

73. The standard methodology for making such assessments is called cost-benefit analysis. In a cost-benefit analysis, using a discount rate is commonplace; however, that discount rate must be appropriate. As I have noted, issues around discounting are especially important in the context of climate change because the full benefits may not accrue for many years after society incurs costs to limit the emissions of GHGs.[93]

74. Formal intertemporal analysis on which so much of modern economics is based originated with the path breaking work of Frank Ramsey, who argued that there was no ethically defensible justification for discounting the well-being (utility) of future

---

[93] There is also a problem with how discounting is often applied when we consider future costs compared to future benefits. Standard economic theory says that risky future benefits (e.g., uncertainty regarding an investment's return) are discounted to account for that risk. That is, risky benefits are worth less than riskless benefits. When we consider costs, however, analysts often *reduce* risky costs: uncertainty regarding future costs should decrease the value of a project (i.e., increase its costs), not increase the value of a project.

generations.[94] In the almost one century since his work, no one has developed a persuasive argument to the contrary.[95]

75. There is an argument that future consumption should be discounted, since future incomes are assumed to be higher, and standard arguments of diminishing marginal utility imply that if that is the case, the value of consumption will be lower. But the high discount rates used by Defendants can only be justified by the assumption of high future increases in standards of living. Since 2008, there is overwhelming evidence that the pace of productivity has declined markedly, implying that we cannot count on past rates of increases prevailing in the future. There is one school of thought (studied and advocated by Prof. Robert Gordon at Northwestern) that argues even the current pace of

---

[94] Clearly, if one thought that the world would end, say in 50 years, as a consequence of a nuclear war, unrelated to climate change, one would not need to take into account events beyond the 50-year extension. We rule out such possibilities, or assume that they are of sufficiently low probability as not to affect our analysis.

For mathematical tractability, many analyses assume a small, positive pure intergenerational discount rate. While ethically indefensible for our purposes, the results are not much different from those obtained with a zero discount rate.

[95] In the middle of the twentieth century, two teams of researchers, each with a prominent Nobel Prize winner, formulated "guides" to cost benefit analysis. See Dasgupta, Sen, and Marglin, prepared for UNIDO (the United Nations Industrial Development Organization) (P. Dasgupta, S.A. Marglin, A. Sen, *Guidelines for project evaluation*, United Nations Industrial Development Organization, Vienna (1972) (United Nations publication sales no.: E.72.II.B.11)) and Little and Mirrlees, prepared for OECD Development Center (I.M.D. Little and J.A. Mirrlees, *Manual of Industrial Project Analysis in Developing Countries vols. 1 and 2*, OECD, Paris (1968, 1969). Amartya Sen received the Nobel prize in 1998, Partha Dasgupta was knighted in 2002, Ian Little was the Deputy Director of the Economic Section at the U.K. Treasury and a distinguished Oxford development economist, and Sir James Mirrlees received the Nobel Prize in 1996.

In the 1970s, discounting became important as the country thought through how to respond to the oil price shocks: what were the requisite changes to its energy system? Though this was done in an era before the costs of carbon emissions were widely understood, the principles are still relevant. See J.E. Stiglitz, "The Rate of Discount for Cost-Benefit Analysis and the Theory of the Second Best," *Discounting for Time and Risk in Energy Policy*, R. Lind (ed.), Baltimore: The Johns Hopkins University Press, 1982, pp. 151-204.

There have been various guidelines published on this topic for internal government use, see, for example: OMB Circular No. A-94, "Discount Rates to be Used in Evaluating Time-Distributed Costs and Benefits" (Mar. 27, 1972) and OMB Circular No. A-94, "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs", Oct. 1992.

productivity—far lower even than in the recent past—may decline still more.[96] Whether one agrees with Gordon's assessment or not, this recent discussion has brought out four key points:

a. There is considerable uncertainty about the pace of increase in living standards.

b. The pace of increase in living standards is endogenous—it depends on what actions we take.

c. If there is significant climate change, and if we continue on our current path, there is a significant risk of a decrease in standards of living.

d. The marginal value of consumption is likely to be high in those states of nature where climate change is greater, and where the adverse effects of climate change are large. That is to say, the value of additional consumption—the ability to build or consume more—and therefore its price will be higher when the effects of climate change are greater. Thus, in those places where the effects of climate change are most pronounced—where damage is the greatest and remediation need and costs are the highest—the *social cost* of such remediation will also be at its highest, exacerbating the damages to Youth Plaintiffs (both because when damages are high, the cost of remediation is also high, and because levels of consumption—what is left over after paying for remediation costs, and taking into account the damage done by climate change—are low).

76. It would be foolhardy—and wrong—for public policy to proceed as if there were no risk, either of a decrease in living standards, and especially of a lowering of those standards as a result of a failure to appropriately curtail emissions.

77. Standard economics over the past half century has emphasized the importance of risk aversion, and that risk affects our actions. Common usage of discounting in public finance fails to take account of risk appropriately. When individuals are risk averse, they

---

[96] See, R.J. Gordon, *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War*, Princeton University Press, 2016. See also, R.J. Gordon, "Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds," *NBER Working Paper*, No. 18315, August 2012, http://www.nber.org/papers/w18315.pdf.

are willing to buy insurance against a risk—to pay a considerable risk premium. This is also true for the business sector and society in general. This is especially important when we assess the appropriate response to the threat of climate change. The planet Earth cannot buy insurance from another planet against the risk of climate change here, but we can take precautionary actions. At the very least, this implies that the discount rate used for assessing climate change actions should be markedly different from that used for conventional short-term projects. As Chairman of the Council of Economic Advisers, I headed a review committee for the Office of Management and Budget (OMB) reviewing the guidelines for discounting, and that was the conclusion we reached in the late 1990s—that one must account for changes in relative price over time, and when our environment becomes more valuable in the future (i.e., as the value of preserving it becomes higher) that must be reflected in the economic analysis.[97] This was consistent with the position taken in the 2nd assessment of the IPCC, and in a paper I co-authored with the late Nobel laureate Kenneth Arrow and others.[98]

78. More than half a century ago, President Johnson sent a message to Congress that we faced two paths: the cheaper option, in the short-term, of carrying down the path of pollution, or the more expensive option (at the time), of restoring the country and its natural heritage to the people.[99]

> We are able to see the magnitude of the choice before us, and its consequences for every child born on our continent from this day forward. Economists estimate that this generation has already suffered losses from pollution that run into billions of dollars each year. But the ultimate cost of

---

[97] Our report was issued in 1996: "Economic Analysis of Federal Regulations Under Executive Order 12866," The White House, January 11, 1996, https://obamawhitehouse.archives.gov/omb/inforeg_riaguide/.

[98] K. Arrow, W.R. Cline, K-G. Maler, M. Munasinghe, J. E. Stiglitz, and R. Squitieri, "Intertemporal Equity and Discounting," in *Global Climate Change: Economic and Policy Issues,* M. Munasinghe (ed.), World Bank Environment Paper 12, Washington, D.C. 1995, pp. 1-32. Reprinted in an abbreviated format as "Intertemporal Equity, Discounting, and Economic Efficiency," *Climate Change 1995: Economic and Social Dimensions of Climate Change,* J. Bruce, H. Lee, and E. Haites (eds.), Cambridge: Cambridge University Press, 1996, pp. 125-144.

[99] "Preserving Our Natural Heritage," Message from the President of the United States, transmitting "Programs for Controlling Pollution and Preserving our Natural and Historical Heritage," February 23, 1966.

> pollution is incalculable. We see that we can corrupt and destroy our lands, our rivers, our forests, and the atmosphere itself all in the name of progress and necessity. Such a course leads to a barren America, bereft of its beauty, and shorn of its sustenance. We see that there is another course more expensive today, more demanding. Down this course lies a natural America restored to her people. The promise is clear rivers, tall forests, and clean air – a sane environment for man.

79. For the last 50 years, Defendants have shirked from the "more demanding" course of restoring "America … to her people." Defendants' policies that discount the future of Youth Plaintiffs and Affected Children at inappropriately high rates continue to steer America on the path of incalculable losses and away from that more demanding and sane course. The costs of fixing the damage today are much higher than they would have been in 1966 when President Johnson sent his message; but, the costs today are much lower than what they will be after another 50 years of fossil fuel pollution and inaction.

VI. CONCLUSION

80. The choice between incurring manageable costs now and the incalculable, perhaps even irreparable, burden Youth Plaintiffs and Affected Children will face if Defendants fail to rapidly transition to a non-fossil fuel economy is clear. While the full costs of the climate damages that would result from maintaining a fossil fuel-based economy may be incalculable, there is already ample evidence concerning the lower bound of such costs, and with these minimum estimates, it is already clear that the cost of transitioning to a low/no carbon economy are far less than the benefits of such a transition. No rational calculus could come to an alternative conclusion. Defendants must act with all deliberate speed and immediately cease the subsidization of fossil fuels and any new fossil fuel projects, and implement policies to rapidly transition the U.S. economy away from fossil fuels.

81. This urgent action is not only feasible, the relief requested will benefit the economy. More importantly, this action is necessary if Defendants are to prevent the extreme cost and damages Youth Plaintiffs and Affected Children are facing and will face to an even greater extent if Defendants continue on a path that does not account for what is scientifically necessary to protect the climate system they depend on for their future well-being and their personal and economic security.

Joseph E. Stiglitz, Ph.D.
April 13, 2018

This is a tab page.
Please title tab
“Freddie Mac”

Economic & Housing Research **Insight**

APRIL 2016

Life's A Beach

So you've always dreamed of living at the beach, but you're discouraged by the high price of beachfront property? Not to worry. We've found just the place for you. Three bedrooms, two baths, just under 2,000 square feet. Zillow®'s estimate of the value of the home is $105,398, but the listed price was recently reduced to $54,900. Oh, one more thing. According to the information on Zillow, the property is "Located very close to `Wash Away Beach,' home…will have to be moved off the property soon due to the land eroding away."

Washaway Beach is located on Cape Shoalwater in Washington State. Underwater sand bars near the entrance to Willapa Bay create a circular current that has been eroding the beach front at an average rate of 100 feet per year for the last century. The original location of the town of North Cove—homes, cannery, lighthouse, Coast Guard station, cemetery, school and post office—is now a mile off shore. State Highway 105 had to be moved inland and is threatened again in its new location.

None of this has scared away buyers. In the six years leading up to 2007, 65 parcels changed hands. The lure of living at the seashore apparently outweighs the knowledge that it's only for a short time. Pricing reflects the unusual nature of the area. Beachfront property may sell for $500, but it might not survive the winter. A quarter-mile inland, property with a longer "life expectancy" may sell for $100,000.

Washaway Beach represents a unique and isolated natural hazard. However, the current trend of climate change—with the associated rising seas, changing weather patterns, and increasing temperatures—presents a more serious challenge to millions of people. Great uncertainty surrounds the pace and magnitude of climate change, but sea levels already are rising measurably, threatening coastal cities around the globe. Worldwide, it's estimated that a hundred million people live within three feet of mean high tide and another hundred million or so live within six feet of it.[1]

---

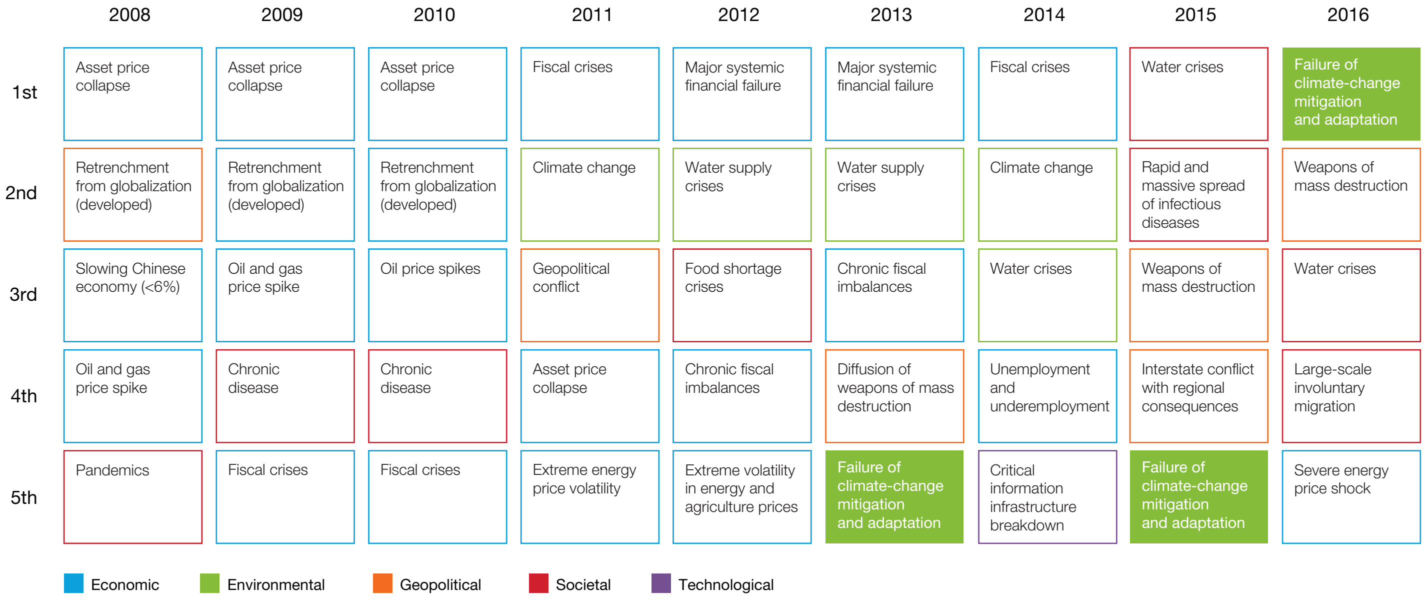
[1] Elizabeth Kolbert, "The Siege of Miami," The New Yorker, Dec. 21 & 28, pp. 42-50.

In the United States, South Florida is one of the more-vulnerable areas. Daily high-water levels in the Miami area have been increasing almost an inch a year, much faster than the average rate of global sea-level rise.[2] The city of Miami Beach already has spent around $100 million to combat recurrent flooding. Other cities on the Eastern seaboard of the U.S. also are experiencing a 10-fold increase in the frequency of flooding. These floods may produce only a foot or two of standing saltwater, but they kill lawns and trees, block streets, clog storm drains, and threaten freshwater resources.

Insurance is an essential component of real estate transactions, and flood insurance currently makes it possible to obtain loans for homes in areas of identified flood risk. However, some of the varied impacts of climate change—rising sea levels, changing rainfall and flooding patterns, increasing temperatures—may not be insurable. As a result, some important features of housing finance may have to change. The potential impact of these systemic changes on the financial system is difficult to visualize today.

To clarify our thinking about this challenge, we focus on the risk of flooding. In the next section, we discuss the current system in the United States for dealing with flood risk. Finally, we pose some of the questions that will have to be addressed if climate change raises sea levels significantly.

Top 5 Global Risks in Terms of Impact



	2008	2009	2010	2011	2012	2013	2014	2015	2016
1st	🟦 Asset price collapse	🟦 Asset price collapse	🟦 Asset price collapse	🟦 Fiscal crises	🟦 Major systemic financial failure	🟦 Major systemic financial failure	🟦 Fiscal crises	🟥 Water crises	🟩 Failure of climate-change mitigation and adaptation
2nd	🟧 Retrenchment from globalization (developed)	🟦 Retrenchment from globalization (developed)	🟦 Retrenchment from globalization (developed)	🟩 Climate change	🟩 Water supply crises	🟩 Water supply crises	🟩 Climate change	🟥 Rapid and massive spread of infectious diseases	🟧 Weapons of mass destruction
3rd	🟦 Slowing Chinese economy (<6%)	🟦 Oil and gas price spike	🟦 Oil price spikes	🟧 Geopolitical conflict	🟥 Food shortage crises	🟦 Chronic fiscal imbalances	🟩 Water crises	🟧 Weapons of mass destruction	🟥 Water crises
4th	🟦 Oil and gas price spike	🟥 Chronic disease	🟥 Chronic disease	🟦 Asset price collapse	🟦 Chronic fiscal imbalances	🟧 Diffusion of weapons of mass destruction	🟦 Unemployment and underemployment	🟧 Interstate conflict with regional consequences	🟥 Large-scale involuntary migration
5th	🟥 Pandemics	🟦 Fiscal crises	🟦 Fiscal crises	🟦 Extreme energy price volatility	🟦 Extreme volatility in energy and agriculture prices	🟩 Failure of climate-change mitigation and adaptation	🟪 Critical information infrastructure breakdown	🟩 Failure of climate-change mitigation and adaptation	🟦 Severe energy price shock

🟦 Economic 🟩 Environmental 🟧 Geopolitical 🟥 Societal 🟪 Technological

Source: World Economic Forum, (2016) *The Global Risks Report 2016*. p11

---

[2] Elizabeth Kolbert, "The Siege of Miami," The New Yorker, Dec. 21 & 28, pp. 42-50.

How do we handle flood risk today?

Lenders require borrowers to take out and maintain insurance against risks that might compromise the value of the home that collateralizes a mortgage. For example, title insurance protects the borrower and the lender against the risk of a defect in the title that might prevent the borrower from selling the property or the bank from foreclosing in the event of a default. And homeowners insurance protects against a variety of risks such as fire and hail damage. However, most homeowners policies do not cover flood damage.

When a prospective home buyer applies for a mortgage, the lender consults the Flood Insurance Rate Maps (FIRMs) maintained by the Federal Emergency Management Agency (FEMA). If the home is in a high-risk area—as defined by FEMA—the borrower must obtain a flood insurance policy. In addition to maintaining the FIRMs, FEMA also administers the National Flood Insurance Program (NFIP), which offers policies through a network of over 80 private insurance companies. FEMA sets national rates that do not vary across insurance companies or agents. Private, non-NFIP insurance also is available. In fact, NFIP policies are available only in communities that participate in NFIP. FEMA scores participating communities according to their floodplain management activities. Flood insurance premiums can be reduced fby as much as 45 percent in communities that adopt management standards that exceed the NFIP minimum.

WHERE IS THE FLOOD RISK?

To produce a flood risk map for a community, FEMA conducts a Flood Insurance Study. These studies include statistical data on river flow, storm tides, hydrologic/hydraulic analyses, and rainfall and topographic surveys. The study divides the community into areas defined by the level of flood risk. An important risk measure is the **base flood** which is defined as the flood having a one percent chance of being equaled or exceeded in any given year. The base flood often is called the **100-year flood**; however, this term can be confusing. So-called 100-year floods can occur two years in a row, and the probability of a 100-year flood occurring during the term of a 30-year mortgage is 26 percent.
In addition, the magnitude of a 100-year flood can change over time as weather patterns change or there are changes to the terrain.

DO YOU LIVE IN A HIGH-RISK AREA?

FEMA provides access to its Flood Insurance Rate Maps (FIRMs) on its website. You can check the risk of your home by going to this site, and typing in your address.
As an example, here is the map that covers Freddie Mac's headquarters on Jones Branch Drive in McLean, VA. The gray shaded areas indicate Special Flood Hazard Areas (SFHAs) along the creeks in the area. Fortunately, our headquarters do not lie within an SFHA.

On the other hand, this map shows one panel of the FIRM for Miami Beach. The entire area is an SFHA.

FEMA identifies the **base flood elevation** (BFE), as the elevation that would be reached by the base flood. Areas at elevations lower than the base flood elevation are defined by FEMA as Special Flood Hazard Areas (SFHAs). FEMA further divides the SFHAs into eight different flood insurance rate zones based on the magnitude of the flood hazard. FEMA also identifies a lower-risk zone—the 500-year flood zone—defined as the area with a 0.2 percent probability in any given year that a flood exceeds the BFE.

Under federal law, flood insurance is mandatory for all federal or federally-related financial assistance for the acquisition and/or construction of buildings in SFHAs. In addition, the GSEs require flood insurance before they will purchase a loan for a property in an SFHA. Typically, a lender will require flood insurance on a house in an SFHA even if the loan will be held in its portfolio. In addition, lenders often require flood insurance for houses outside of SFHAs which nonetheless are exposed to some level of flood risk.[3] Approximately 20 percent of flood insurance claims come from outside of SFHAs.

COASTAL RISK

In coastal areas, FEMA takes wave effects into account in determining the BFE and subdivides the SFHA zones further. For example, **Zone A** is defined as an area with shallow flooding only due to rising water, where potential for breaking waves and erosion is low, while Coastal Zone A is defined as an area with potential for breaking waves and erosion during a base flood. In addition, the Coastal Barrier Resources Act (CBRA) of 1982 defines a Coastal Barrier Resources System (CBRS)—ocean front and land around the Great Lakes and other protected areas—that serves as a buffer between coastal storms and inland areas. Properties within the CBRS are eligible for federally-regulated flood insurance only if the properties were built prior to 1982 and the community participates in the National Flood Insurance Program (NFIP) administered by FEMA.

The impact of rising sea levels—and some potential responses

The impact of rising sea levels depends on the pace and the magnitude of the change—two factors about which there is great uncertainty. For instance, a recent study which updates the estimates on the amount of ice melting in Antarctica concluded that the increase in sea level may be twice the level that was previously estimated.

An additional source of uncertainty in the forecasts is the willingness and ability of the world's nations to change the trajectory of climate change. At the Paris climate conference in December 2015, 195 countries adopted a global action plan to hold climate change to well below 2° Centigrade above pre-industrial levels. The success of this and future agreements hold the potential to mitigate some of the projected impacts of climate change.

---

[3] The requirement to obtain flood insurance applies only to purchases with mortgages and not to cash purchases. The GSE requirement for flood insurance in SFHAs is a legal obligation of the GSEs and not simply a GSE policy. More broadly, federal regulators must require their regulated lenders to insure that borrowers obtain flood insurance for mortgages on properties within SFHAs.

ESTIMATES OF THE IMPACT

One measure of the impact of climate change is the estimated increase in the areas identified by FEMA as SFHAs, that is, areas where flood insurance is required. A 2013 study prepared for FEMA by AECOM and Deloitte Consulting LLP estimated that the area of the SFHAs will increase by 45 percent nationally on average by the end of this century. In coastal areas, SFHAs will increase by 55 percent, assuming no change in the shoreline. Under the more-likely assumption that shorelines recede, there will be no change in SFHAs; new SFHAs will simply replace the SFHAs that become submerged.

Any growth in SFHAs represents an increased burden on taxpayers. According to GAO estimates, the premiums set by FEMA on NFIP flood insurance policies do not cover the risk. GAO gauged the subsidy for the years 2002 through 2013 at somewhere between $16 billion and $25 billion. Depending on assumptions about climate change and the amount of shoreline erosion, the AECOM study projects an increase between 20 and 90 percent in expected losses.

The climate risk assessment published by the Risky Business Project—an organization co-chaired by Michael Bloomberg, Henry Paulson, and Thomas Steyer—estimates that three-to-four percent of the US population will live in coastal SFHAs by 2100 and 11 percent of the US population will live in riverine (that is, inland) SFHAs. In addition, between $66 billion and $160 billion worth of real estate is expected to be below sea level by 2050. By the end of the century, the range is $238 billion to $507 billion.

The loss estimates above refer to insured properties with a high risk of flooding. However other areas will become permanently submerged, generating even larger losses. The Risky Business Project estimates the cost of all structures likely to be destroyed by the end of the century due to shoreline movement at two to four percent of the cumulative insurance premiums paid through 2100. In Florida alone, this study estimates a 1-in-20 chance that more than $346 billion in current property will be underwater by 2100.

POTENTIAL RESPONSES

Even with significant and coordinated global action like that outlined at the Paris climate conference, some of the projected impacts of climate change appear to be unavoidable. Governments and private organizations are working on plans to mitigate impacts where possible and to adapt to changes that are inevitable. Many are taking notes from the experience of the Netherlands, which has prospered for centuries despite lying below sea level.

However, the dikes and sea walls used by the Dutch may not solve the problems of South Florida. Florida sits on a substrate of porous limestone that holds Florida's supply of fresh water. As the sea level rises, it infiltrates the limestone underground and contaminates the freshwater supply. A sea wall might stop storm water surges on the surface, but it can't prevent the underground incursion of salt water.

While technical solutions may stave off some of the worst effects of climate change, rising sea levels and spreading flood plains nonetheless appear likely to destroy billions of dollars in property and to displace millions of people. The economic losses and social disruption may happen gradually, but they are likely to be greater in total than those experienced in the housing crisis and Great Recession. That recent experience illustrated the difficulty of allocating losses between homeowners, lenders, servicers, insurers, investors, and taxpayers in general. The delays in resolving these differences at times exacerbated the losses. Similar challenges will face the nation in dealing with the impact of climate change.

Some thorny issues to ponder:

- The government-supported NFIP currently incorporates a subsidy for homeowners. Suggestions to raise premiums to reduce or eliminate the subsidy so far have met with resistance from homeowners in SFHAs. However, taxpayers may balk at covering escalating losses as sea levels rise in light of the predictability of the losses. Taxpayers may feel that the affected homeowners ignored decades-long warnings of the risks they were bearing.
- A large share of homeowners' wealth is locked up in their equity in their homes. If those homes become uninsurable and unmarketable, the values of the homes will plummet, perhaps to zero. Unlike the recent experience, homeowners will have no expectation that the values of their homes will ever recover.
- In the housing crisis, a significant share of borrowers continued to make their mortgage payments even though the values of their homes were less than the balances of their mortgages. It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater. As a result, lenders, servicers and mortgage insurers are likely to suffer large losses.
- Some homeowners outside the impacted areas will nonetheless suffer losses as businesses are forced to relocate, taking employment opportunities with them. Companies that sell services to these relocating businesses also will suffer losses.
- Additionally, the effects on homeowners not in the impacted areas, but are nearby, will be complicated by the fact that there may be increased demand for their homes.
- Non-economic losses may be substantial as some communities disappear or unravel. Social unrest may increase in the affected areas.

One challenge for housing economists is predicting the time path of house prices in areas likely to be impacted by climate change. Consider an expensive beachfront house that is highly likely to be submerged eventually, although "eventually" is difficult to pin down and may be a long way off. Will the value of the house decline gradually as the expected life of the house becomes shorter? Or, alternatively, will the value of the house—and all the houses around it—plunge the first time a lender refuses to make a mortgage on a nearby house or an insurer refuses to issue a homeowner's policy? Or will the trigger be one or two homeowners who decide to sell defensively?

As the market shakes out in the affected areas, perhaps we'll be left with a host of Washaway Beaches. Some residents will cash out early and suffer minimal losses. Others will not be so lucky. And newcomers may appear, finally able to live out their dreams of living at the seashore, if only for a short time.

Sean Becketti, Chief Economist
Brock Lacy, Economic & Finance Modeling Professional

This is a tab page.
Please title tab
“UCS”

Underwater

Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate

Union of Concerned Scientists

Introduction

Along nearly 13,000 miles of coastline of the contiguous United States, hundreds of thousands of buildings lie in the path of rising seas: schools, hospitals, churches, factories, homes, and businesses. Long before these properties and infrastructure are permanently underwater, millions of Americans living in coastal communities will face more frequent flooding, as the tides inch higher and reach farther inland. As sea levels rise, persistent high-tide flooding of homes, yards, roads, and business districts will begin to render properties effectively unlivable, and neighborhoods—even whole communities—financially unattractive and potentially unviable.

Yet property values in most coastal real estate markets do not currently reflect this risk. And most homeowners, communities, and investors are not aware of the financial losses they may soon face.

BILLIONS OF DOLLARS OF PROPERTY AT RISK IN THE COMING DECADES

In the coming decades, the consequences of rising seas will strain many coastal real estate markets—abruptly or gradually, but some eventually to the point of collapse—with potential reverberations throughout the national economy. And with the inevitability of ever-higher seas, these are not devaluations from which damaged real estate markets will recover.

This analysis estimates the number of homes and commercial properties throughout the coastal United States that will be put at risk from chronic, disruptive flooding—defined as flooding that occurs 26 times per year or more (Dahl et al. 2017; Spanger-Siegfried et al. 2017)—in the coming decades. It brings together data on coastal regions that are projected to experience this type of flooding, and data on existing properties provided by Zillow*, the online real estate company. Our findings indicate that sea level rise, driven primarily by climate change and even absent heavy rains or storms, puts more than 300,000 of today's homes and commercial properties in the contiguous United States at risk of chronic, disruptive flooding within the next 30 years. The cumulative current value of the properties that will be at risk by 2045 is roughly $136 billion. In those 30 years—encompassing the terms of a typical mortgage taken out today—what will the properties be worth if they are flooding on a chronic basis? And how will the broader coastal real estate market fare in the long term? Our analysis finds that by the end of the 21st century nearly 2.5 million residential and commercial properties, collectively valued at $1.07 trillion today, will be at risk of chronic flooding.

[***By the end of the 21st century, nearly 2.5 million properties will be at risk of chronic flooding.***]

Many experts in risk assessment, credit ratings, real estate markets, insurance markets, and flood policy (dozens of whom were consulted for this report), recognize that the risk of sea level rise to coastal real estate is significant and growing—and that for the most part, financial markets do not currently account for these risks.

RISKS BELOW THE RADAR

In many cases, the risks are masked by short-sighted government policies, market incentives, and public and private investments that prop up business-as-usual choices and fail to account for sea level rise (McNamara et al. 2015). Even in places such as Miami-Dade County, which is already experiencing disruptive tidal flooding, the real estate market is only just beginning to adjust (Tampa Bay Times 2017; Corum 2016; Urbina 2016; Spanger-Siegfried, Fitzpatrick, and Dahl 2014). This disconnect can be attributed to a lack of information about risks; subsidized, myopic development choices; and the continued attraction of seaside property and vibrant coastal economies (Keenan, Hill, and Gumber 2018). Other smaller, less in-demand locations, such as in coastal Louisiana and the eastern shore of Maryland, are already facing a chronic flooding reckoning (Spanger-Siegfried et al. 2017).

Properties will not be the only things to flood. Roads, bridges, power plants, airports, ports, public buildings, military bases, and other critical infrastructure along the coast also face the risk of chronic inundation. The direct costs of replacing, repairing, strengthening, or relocating infrastructure are not captured in our analysis, nor do we account for the indirect costs of flooded infrastructure, including disruptions to commerce and daily life (Neumann, Price, and Chinowsky 2015; NCA 2014; Ayyub and Kearney 2012). Taken together, these costs of chronic flooding of our coastal built environment—both property and infrastructure—could have staggering economic impacts.

---

* *Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at* http://www.zillow.com/ztrax. *The results and opinions are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.*

Cover photo: David Harp

Will Brown

Homes and businesses in hundreds of US communities will face an unprecedented challenge as sea levels rise. Many of those communities, such as the barrier island town of Hampton Beach, New Hampshire, pictured here, developed over time for greatest-possible proximity to the ocean—but today the ocean is on the move, and the cost of that proximity is becoming evident. Although constructing seawalls and installing storm water pumps, for example, can serve to buy time in some places, most defensive measures are expensive to build, are not currently designed to fend off rising seas, and cannot prevent losses uniformly or indefinitely.

A NARROWING WINDOW OF OPPORTUNITY TO MAKE BETTER CHOICES

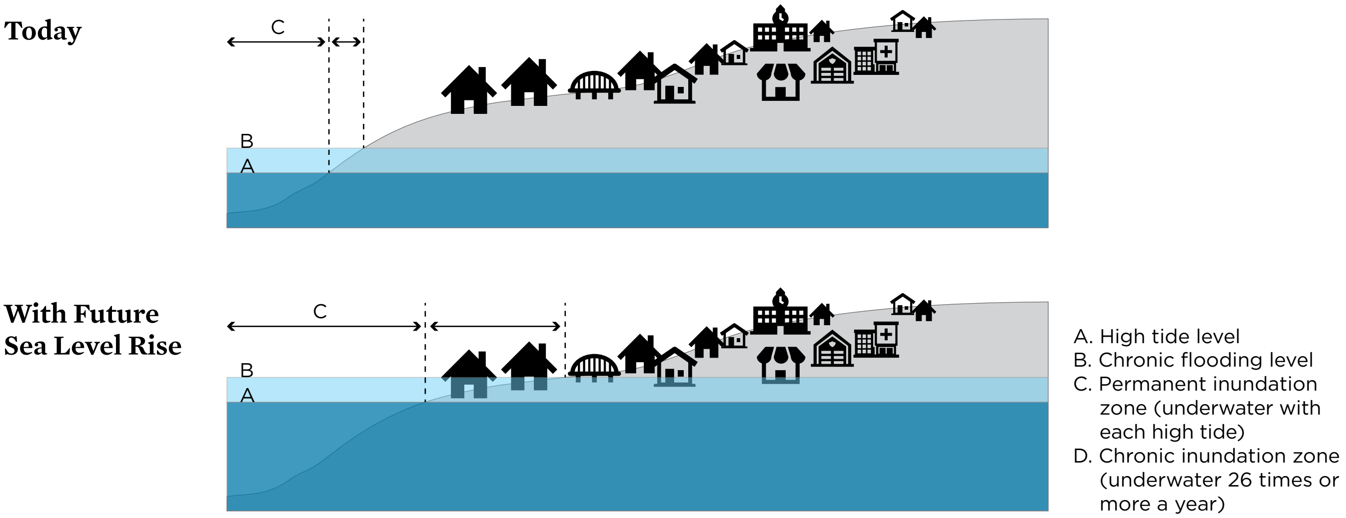
Even when these risks are understood, there are seldom easy solutions. As chronic flooding increases in coastal communities, a tricky cycle begins: investments in adaptation measures could be made to potentially forestall the flooding of properties and the subsequent decline in the tax base. But for communities to maintain credit-worthiness and access to the capital needed for these investments, they would increasingly need to show that they have already made smart decisions and investments to adapt and build resilience (Moody's Investors Services 2017; Walsh 2017; S&P 2016). Falling behind in this cycle, or lacking the means to invest in the first place, could have grave fiscal consequences.

There are many stakeholders in the coastal real estate market, from individual homeowners and business owners, to lenders, taxpayers, developers, insurers, and investors. Whether a property market crashes, or property values steadily decline in response to worsening flooding, these stakeholders are poised to sustain large collective losses. Many coastal residents, whether they own homes or not, will be affected as shrinking property tax bases prevent cities and towns from fully funding schools, emergency services, and infrastructure repairs, or as property tax rates rise for all residents to compensate for those properties devalued by flood risks.

As a nation, we have a narrowing window of opportunity to make better choices and ameliorate risks. The actual physical risks from sea level rise are growing and risk perceptions in the marketplace can shift abruptly, both of which leave communities vulnerable to economic hardships that many will not be able to cope with on their own. This creates a national imperative to prepare individuals and brace our communities and economies for an irreversible decline in the value of many coastal homes and commercial properties, even as we create pathways to new beginnings in safer locations. Given the scale of this challenge, action from the local to the national level will be required, engaging many sectors of the economy. The federal government has a unique and critical leadership role to help provide the tools, funding, resources, and policies that can guide more resilient choices and equitable outcomes along our imperiled coasts.

There will be no simple solution. But continued inaction is unacceptable; we must use the remaining response time wisely to meet this serious threat and protect coastal communities as effectively as we can.

FIGURE 1. What is Chronic Inundation?



With higher sea levels come higher high tides, which can reach onto normally dry land. As sea level rises further, this occasional flooding can become chronic, as even less extreme tides begin to cause flooding. The top panel shows the current reach of high tide (C) and the current extended reach of extreme tides, which defines a current chronic inundation zone where flooding occurs at least 26 times per year (D). The bottom panel shows how sea level rise expands the reach of not just extreme tides but also more typical tides such that some more land is permanently inundated and a portion of the community becomes chronically flooded.

Findings

In this analysis, we identified residential and commercial properties at risk of chronic inundation as sea levels rise, defined as experiencing at least 26 floods per year (Figure 1) (Dahl et al. 2017; Spanger-Siegfried et al. 2017). Using data provided by Zillow (Zillow 2017)*, we determined these properties' current collective value and contribution to community tax bases. We looked at outcomes for the entire coastline of the contiguous United States at multiple points in time through the end of the century, based on localized projections of three different sea level rise scenarios developed for the 2014 National Climate Assessment (Huber and White 2015; Walsh et al. 2014; Parris et al. 2012). In addition, we examined basic demographics of at-risk communities, including the number of people currently housed in these properties and at risk of being displaced, as well as factors such as race, age, and income that could make some populations more vulnerable than others to the physical and financial risks of flooding (Cleetus, Bueno, and Dahl 2015; US Census Bureau 2010; Cutter, Boruff, and Shirley 2003). For more information see Appendix: About this Analysis, p. 22.

Given the importance of individual properties to those who own or live in them, and the broader importance of the coastal real estate market to many market actors invested therein, the following results are based on the high sea level rise scenario, a scenario that results in 6.6 feet of global sea level rise by 2100 and should be used to inform decision-making where there is a low tolerance for risk (Parris et al. 2012).[1] Our results through the end of the century are generated based on today's existing property numbers, property values, and related data (Zillow 2017), and today's demographic statistics (US Census Bureau 2015; US Census Bureau 2010). Aside from rising sea levels and their direct threat to property, our results do not reflect what the future will bring in terms of additional coastal development, adaptation measures, the impact of major storms, population growth, other changes in property values, or other relevant factors. As a result, our findings may under- or overestimate the future number of properties, people, and value that will be affected over time (Hardy and Hauer 2018; Hauer 2017; Lentz et al. 2016).

---

* *Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at* http://www.zillow.com/ztrax. *The results and opinions are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.*

THE COAST-WIDE PICTURE

With this high sea level rise scenario, we found that within the next 15 years roughly 147,000 existing homes and 7,000 commercial properties—currently worth $63 billion—are at risk of being inundated an average of 26 times per year, or more. About 280,000 people are estimated to live in these homes today; in this time frame many will need to either adapt to regular floods or relocate.

By 2045—near the end of the lifetime of a 30-year home mortgage issued today—sea levels are projected to have risen such that nearly 311,000 of today's residential properties, currently home to more than half a million people, would be at risk of flooding chronically, representing a doubling of at-risk homes in the 15 years between 2030 and 2045. Not only are the mortgage loans on these homes at growing risk of default if the value of the properties drops, but each successful sale of one of these homes represents the potential transfer of a major latent financial liability. Eventually, the final unlucky homeowners will hold deeds to significantly devalued properties (Conti 2018). Our calculations show that in about 120 communities along US coasts, the properties that would be at-risk in 2045 currently represent a full 20 percent or more of the local property tax base, a crucial source of funding for schools, fire departments, law enforcement, infrastructure, and other public services. For about 30 communities, properties accounting for more than half of the local property tax base today would be at risk by 2045.

By the end of the century, as many as 2.4 million of today's residential properties and 107,000 commercial properties, worth $1.07 trillion today—roughly equivalent to the entire gross domestic product of Florida—would be at risk of chronic flooding (BEA 2018). Those properties are estimated to currently house about 4.7 million people, the equivalent of the entire population of Louisiana.

Together with previous studies of property at risk from rising seas, our findings illustrate a clear, rapidly growing risk to both coastal communities and the nation as a whole, given the deep financial stakes that both the private sector and the US taxpayer have in our coasts (Figure 2, p. 6) (Center for the Blue Economy 2018; Bretz 2017).

> ***In Florida, the number of today's homes that are at risk from sea level rise balloons to more than 1 million by 2100.***

COMMON THEMES AND STATE-LEVEL FINDINGS

As sea levels rise, each of the 23 coastal states in the contiguous US faces the loss of residential and commercial properties and frequent flooding of populated areas, posing new challenges for all communities and adding particular stressors for communities of color and low-income and working-class communities. The following is a selection of common themes that arise across many states. While our discussion of states and locations highlights areas of high risk, this does not mean that other locales face only minimal risk.

MOST TO LOSE? FLORIDA AND NEW JERSEY

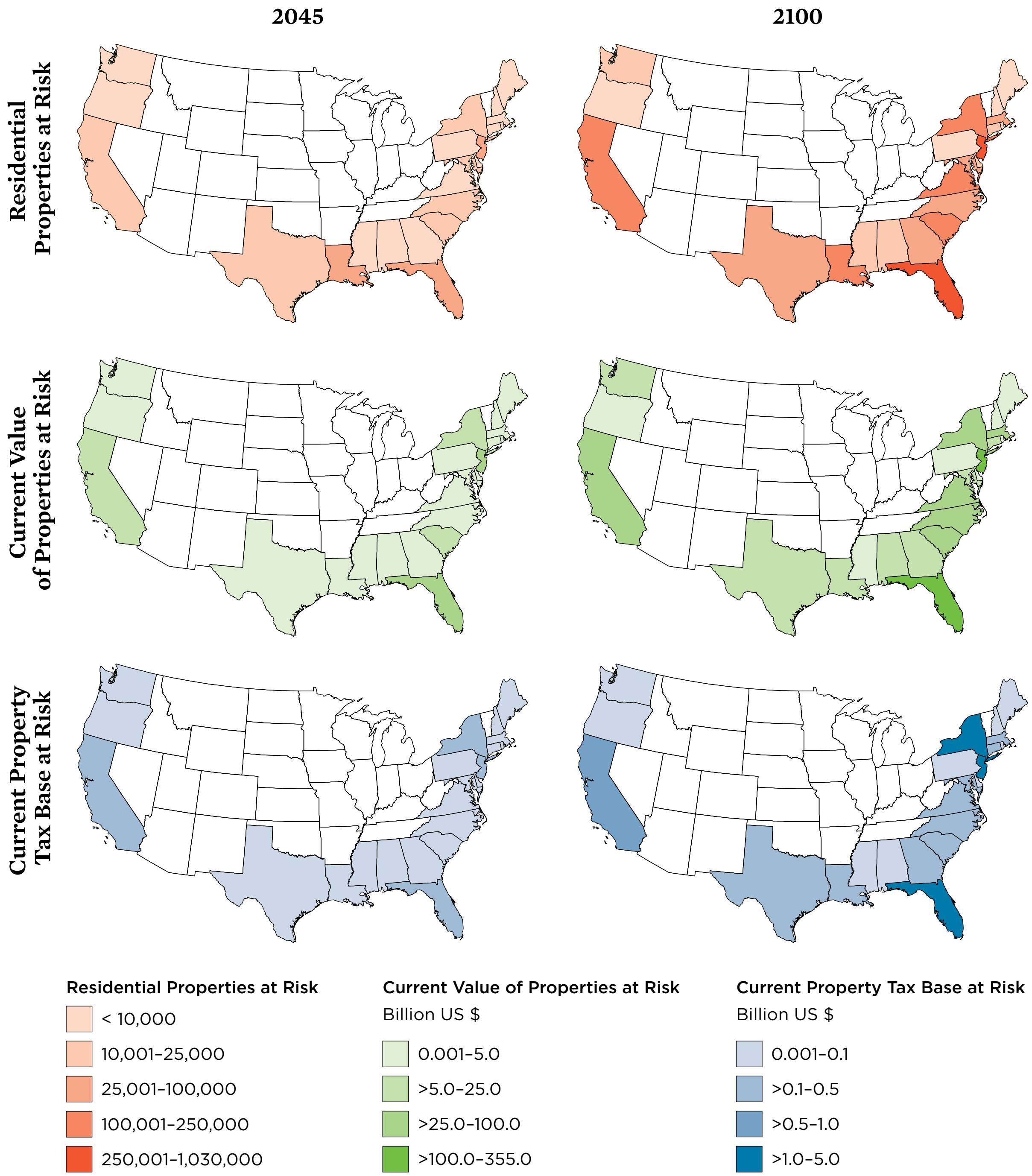
On the east coast of the United States, generations of people have made homes and set up shop close to the water, making this coast some of the most developed land in the country. Often this development has taken place within fragile environments such as barrier islands and filled wetlands; some of the gravest consequences of this overdevelopment will be along the New Jersey and Florida coasts.

Within the next 30 years, roughly 64,000 homes in Florida and 62,000 in New Jersey will be at risk of chronic flooding. Along the Florida coast, Miami Beach alone, with its iconic high rises located within steps of the beach, accounts for more than 12,000 of those homes.[2] Of New Jersey's beach towns, 10 are projected to have at least 1,500 at-risk homes by 2045. Ocean City tops the list with more than 7,200 at-risk homes.

Emily Michot/The Miami Herald via AP

Development in at-risk areas such as the coast of Florida has continued despite the increasingly apparent risks of sea level rise. Indeed, with the allure of its weather and beaches, Florida's housing market has remained strong, even as sunny-day flooding has become a familiar and disruptive reality. Measures to reduce tidal flood risks are hampered in Florida by factors including the porous limestone bedrock underlying much of the state's coastal regions and the large quantity of housing built on extremely low-lying barrier islands (such as Miami Beach, pictured here) and filled land.

FIGURE 2. Residential Properties at Risk in 2045 and 2100

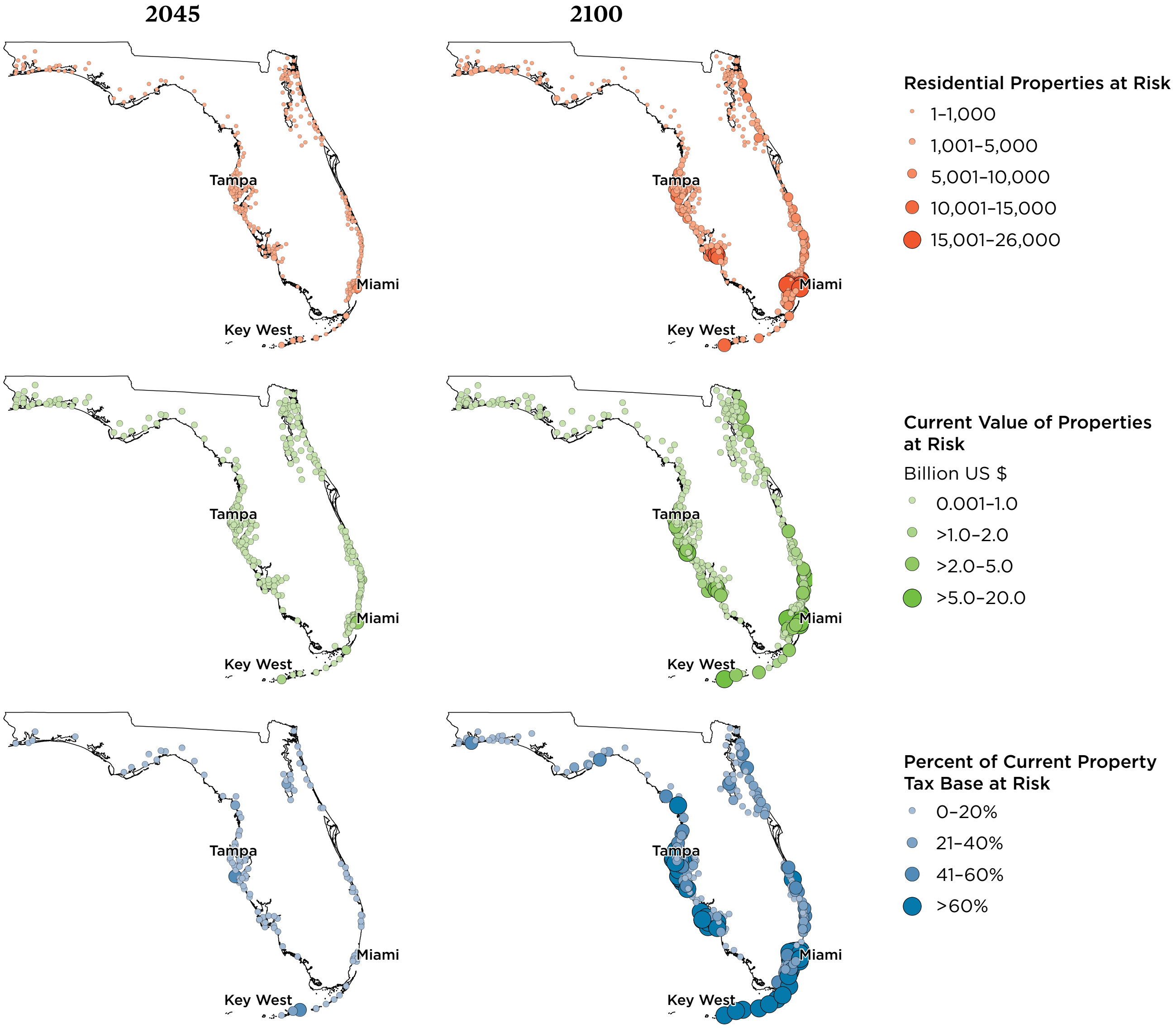


In the contiguous US, more than 310,000 existing homes are projected to be at risk of chronic inundation by 2045, a number that grows to nearly 2.4 million by the end of the century. Within the 30-year time frame represented in the 2045 maps shown here, the states with the most existing homes at risk are (in order) Florida, New Jersey, Louisiana, and California. Florida, New Jersey, and California also all rank in the top three in terms of current value of properties that would be at risk in 2045, and the current contribution of those properties to the local tax base. Note that in California, we have used assessed home values in place of market values, which makes our property value estimates for California conservative (see Appendix: About this Analysis on p. 22 for more details). Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

In Florida, the number of today's homes that are at risk from sea level rise balloons to more than 1 million by 2100, reflecting the scale of existing development in Florida's low-lying inland regions. By the end of the century, Florida alone would account for more than 40 percent of the nation's at-risk homes. In New Jersey, in the same time frame, more than 250,000 homes would be at risk.

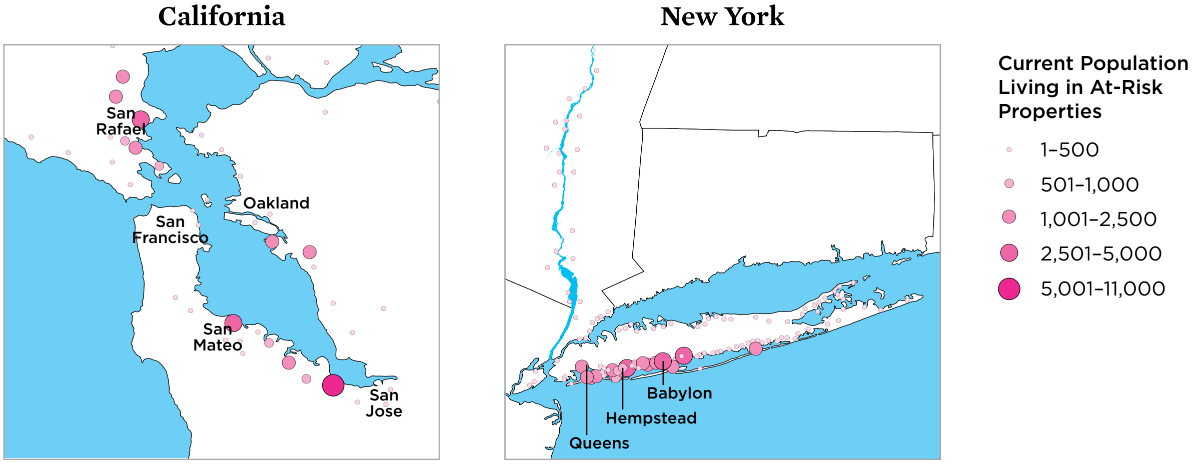
Even as the reality of sea level rise has become clearer, development in flood-prone locations has burgeoned. Fifteen to 20 percent of the at-risk homes in 2045 and 2100 in both Florida and New Jersey were built after the year 2000. Roughly 2,600 of the coastal New Jersey homes at risk by 2045 were built or rebuilt after Hurricane Sandy devastated the region in 2012.

FIGURE 3. Acute Exposure in Florida



Florida leads the nation in the number of homes—along with property value and tax base (based on current values for each)—at risk of chronic inundation through the end of the century. At the ZIP code level, shown here with symbols located at the center of each ZIP code area, the Miami area, the Florida Keys, and Tampa-St. Petersburg stand out as being the most highly exposed within the next 30 years. By the end of the century, nearly 100 ZIP code areas in Florida could see properties chronically flooded that today represent 40 percent or more of their property tax base. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

FIGURE 4. Communities at Risk: Snapshots from California and New York



The San Francisco Bay area, in California, and Long Island, in New York, are both densely populated areas that face significant exposure to chronic inundation by 2045. Within the nine Bay Area counties, roughly 13,000 homes that currently house 33,000 people are at risk of chronic inundation in the next 30 years. On Long Island, roughly 40,000 people currently live in about 15,000 existing homes at risk in this time frame. Housing at risk is shown at the ZIP code level, with symbols located at the center of each ZIP code area. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

HOUSING RISK HOTSPOTS: CALIFORNIA AND NEW YORK

Along the southern shore of Long Island, New York, and around the San Francisco Bay, proximity to major metropolitan areas has spurred development for decades (Figure 4). In both regions, some suburban communities may find themselves facing considerably more risk than the nearby urban centers of Manhattan and San Francisco. By 2045, the three counties that make up most of Long Island—Suffolk, Nassau, and Queens—could encompass nearly 15,000 homes at risk of chronic inundation. Today, there are roughly 40,000 people living in those homes, which are collectively valued at $7.7 billion. In contrast, Manhattan has no at-risk homes in this time frame. Similarly, while San Francisco itself has just 270 at-risk homes in 2045, in the nine counties surrounding the San Francisco Bay roughly 13,000 properties—home to more than 33,000 people and valued at $8.6 billion today—are at risk.[3, 4]

Within each of these regions, some communities are more exposed to chronic inundation than others. On Long Island, for example, Hempstead, Babylon, and Queens are projected to have more than 2,500 homes at risk by 2045, whereas there are only a few homes at risk in other towns. In the Bay Area, San Rafael, San Mateo, and San Jose are each projected to have more than 2,000 at-risk homes by 2045. Future impacts could also vary substantially within a metropolitan region, as some towns may invest in protective infrastructure, while others may choose not to, or may not be able to.

POVERTY, RACIAL INEQUITIES, AND TIDES CREATE HOTSPOTS OF RISK: LOUISIANA, MARYLAND, NORTH CAROLINA, AND NEW JERSEY

Communities with fewer resources to start with, or that are otherwise disadvantaged, will likely be most heavily affected by chronic flooding and its accompanying financial losses (Deas et al. 2017; Mearns and Norton 2010; Fothergill and Peek 2004). We used two metrics to identify communities that may have fewer resources to cope with chronic flooding: poverty rate and the percentage of the community composed of traditionally underserved groups—African Americans, Hispanic Americans, and tribal communities (US Census Bureau 2010).

> ***In communities where the poverty level is above the national average, the erosion of the property tax base could have severe consequences for local residents.***

Nearly 175 communities nationwide can expect significant chronic flooding by 2045, with 10 percent or more of their housing stock at risk. Of those, nearly 40 percent—or 67 communities—currently have poverty levels above the national average. The largest share of these is in Louisiana, where there are 25 communities with above-average poverty rates and with 10 percent or more of the homes at risk by 2045.[5] In several Terrebonne Parish communities such as Houma and Bayou Cane, between one in five and one in three residents lives in poverty. These and many other Louisiana regions are also home to large African American and tribal populations as well as other communities of color, where decades of systematic bias have limited personal and community-level financial resources (DHS 2018). In Terrebonne Parish communities, where up to one-third of the residents are living in poverty and half or more are African American, the projected chronic flooding of hundreds of homes and erosion of up to one-quarter of the property tax base could have severe consequences for local residents.

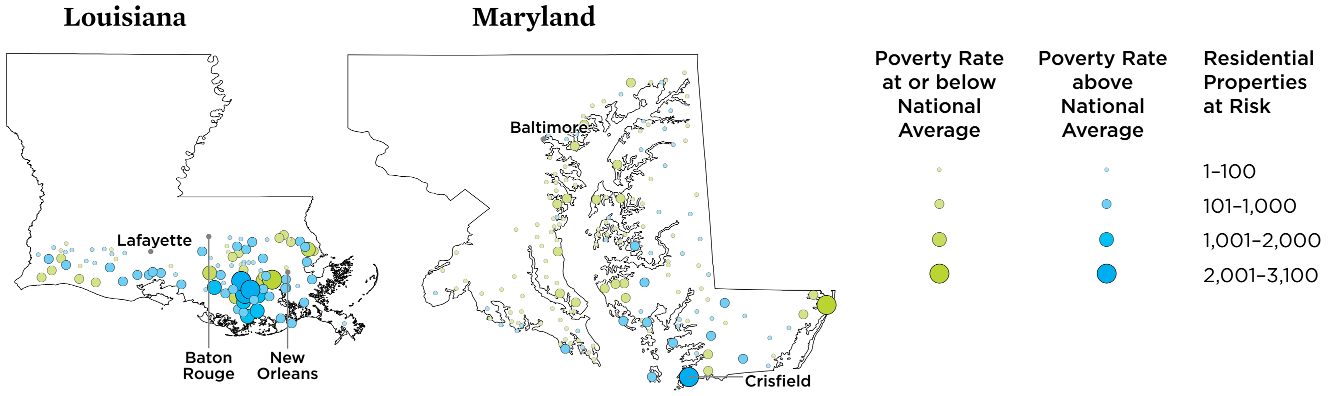
Louisiana is not the only state where poverty and exposure to chronic inundation intersect to create a hotspot of heightened risk. North Carolina, New Jersey, and Maryland also have significant numbers of highly exposed communities with above-average rates of poverty. Within the next 30 years, about a dozen communities along Maryland's eastern shore are projected to have one-third or more of their property tax base at risk. People living in these doubly vulnerable communities stand to lose the most, yet have fewer resources to adapt to flooding or relocate to safer areas.

GENERATIONAL WEALTH AT STAKE: NEW JERSEY, MARYLAND, AND TEXAS

Elderly homeowners tend to live on fixed incomes, own their homes outright, and/or have a relatively large share of personal wealth tied up in their property (Kaul and Goodman 2017; Butrica and Mudrazija 2016). When their property—or even just their neighborhood—is chronically flooded and the value of their home drops, they stand to lose a larger share of their personal wealth, without means of recouping it through future income. People living on fixed incomes can also be hurt financially as taxes rise on non-inundated properties to compensate for municipal budget shortfalls or when services they depend on (such as public transportation) are cut as those budgets shrink.

Of the roughly 400 US communities with at least 50 homes at risk of chronic inundation in 2030, about 60 percent (roughly 240 communities) currently have large populations of elderly people—far above the national average of 14.5 percent of the total population. In towns such as Beach Haven and Tuckerton, New Jersey; Madison, Maryland; and Croatan, North Carolina; each of which has high elderly populations, more than 20 percent of homes, value, and tax base are at risk within the next 15 years. Similarly, in several communities along the Texas coast, including the Bolivar Peninsula, Rockport, and Fulton, where hundreds of properties are at risk of chronic inundation by 2030, between one in five and one in three residents is currently over the age of 65.

FIGURE 5. Communities at Risk: Snapshots from Louisiana and Maryland



Chronic inundation is poised to add new challenges to communities already struggling with high rates of poverty. Of the nearly 120 Louisiana communities with at least one home at risk of chronic inundation by 2045, 60 percent currently have poverty rates above the national average of 12.7 percent. In Maryland, 30 of the roughly 105 communities that contain at-risk properties in 2045 (shown at the ZIP code level, with symbols located at the center of each ZIP code area) have above average poverty rates. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

BLUE COLLAR AMERICA AT RISK: MASSACHUSETTS, DELAWARE, PENNSYLVANIA, MARYLAND, VIRGINIA, MISSISSIPPI, OREGON, AND WASHINGTON

Hundreds of blue collar towns dot the US coastline. To assess the impact of chronic inundation on low- to moderate-income homeowners, we assessed the number of properties that are at risk of chronic inundation in each state and are valued below that state's median home value, as defined by the Zillow Home Value Index (Zillow 2018; Zillow Research 2014).

In eight states—Massachusetts, Delaware, Pennsylvania, Maryland, Virginia, Mississippi, Oregon, and Washington—60 percent or more of the homes at risk of chronic inundation within the next 30 years are valued below the state median.[6] In Delaware and Oregon, nearly all (90 percent or more) of the chronic inundation risk is borne by residents of these lower-value properties. In Oregon, these properties are clustered around Coos Bay and Astoria, two working-class towns. Likewise, in Massachusetts, in 2045, there are large clusters of at-risk homes in Revere, Saugus, and Winthrop—all working-class suburbs of Boston.

> ***Of the roughly 14,000 commercial properties at risk on US coasts within the next 30 years, more than one-third are in Florida and New Jersey.***

BUSINESS AS USUAL? FLORIDA AND NEW JERSEY

Our nation's coasts are defined not just by homes and neighborhoods, but by commercial districts. From corner cafés to high-rise office buildings, these properties and the businesses they house are critical components of the coastal economy. The low-lying and highly developed coastlines of Florida and New Jersey make the commercial sector in both states particularly exposed to chronic flooding as sea levels rise. Of the

Maureen Drennan

For many Americans, to own a home on the coast is to claim a prized lifestyle and aesthetic—a "little slice of heaven." And in areas where they could afford to, many working-class communities have taken root there over the years. Unlike wealthier areas with larger homes and lots, smaller, lower-value homes cluster closely together in blue collar towns of Massachusetts, Delaware, Mississippi, New Jersey, and Oregon, to name a few. Many such clusters are in low-lying areas that rising tides will soon reach. For these residents, the loss of these properties could mean the loss of a large share of their personal wealth, as well as the loss of ways of life that have been shared over generations.

roughly 14,000 commercial properties at risk on US coasts within the next 30 years, more than one-third are in Florida and New Jersey. Those same two states are home to 45 percent of the commercial properties, coastwide, that would be at risk by end of the century.

The kinds of properties at risk are quite different in each state. In New Jersey, nearly all (96 percent) of the roughly 2,600 commercial properties that would be at risk in 2045, as well as the 11,000 at risk in 2100, are retail establishments: hotels, restaurants, gas stations, convenience stores, and pharmacies. In contrast, in Florida, 30 percent of the 2,300 commercial properties at risk in 2045 and 50 percent of the 38,000 at risk in 2100 are commercial office buildings, which include medical and financial offices, as well as more general offices and mixed-use buildings.

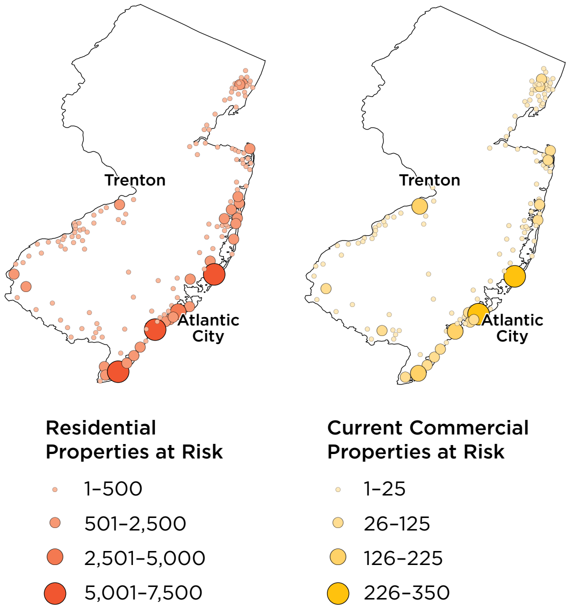
TOURISM REVENUE AT STAKE IN VACATION STATES: NEW JERSEY, NORTH CAROLINA, SOUTH CAROLINA, AND TEXAS

For many people, the coast is synonymous with beach vacations. Homes in coastal vacation destinations may be second homes or primary residences, rental properties, or beloved family homes passed down from generation to generation. The property taxes paid on these homes is often an important source of steady revenue in locations where tourism revenues are highly seasonal and weather-dependent. When a home in a beach town is at risk of chronic flooding, not only is the homeowner affected, but so is a larger network of people, from the vacationer who rents it for a week every summer to the year-round residents who benefit from the revenues generated by tourism. If a significant number of homes in the area are regularly flooded, the popularity of the town as a vacation destination could decline (Flavelle 2017a).

Tens of thousands of homes (if not more) in well-known coastal vacation destinations are projected to be at risk of chronic inundation in the next 30 years. Along the Texas coast, roughly 3,200 residential properties in Galveston and another 1,500 in Brazosport would be at risk, homes that currently represent 17 and 10 percent of the local property tax base, respectively. In South Carolina, nearly 1,500 homes on Kiawah Island would be at risk, and more than 2,700 on Hilton Head. On Kiawah Island, those homes represent nearly one-quarter of the local property tax base today. In North Carolina, the Outer Banks communities of Nags Head and Hatteras together would have nearly 2,000 at-risk homes in this timeframe. On the Jersey Shore, Ocean City alone would have more than 7,200 at risk homes by 2045, which today represents nearly 40 percent of the town's homes and nearly one-third of the local property tax base.

In many seaside communities, such as Galveston and Nags Head, homes are physically elevated. However, even if living spaces stay dry, if the access roads, surrounding land, and key infrastructure are flooded, home values and tourism would be adversely affected.

FIGURE 6. Communities at Risk: Snapshot of New Jersey



New Jersey leads the nation in the number of commercial properties at risk of chronic inundation in 2045 (right) and is second only to Florida in the number of residential properties at risk in that time frame (left). Results are shown at the ZIP code level, with symbols located at the center of each ZIP code area. Properties along the highly developed and much beloved Jersey Shore are particularly at risk. Nearly all of the commercial properties at risk in New Jersey are retail establishments including, but not limited to, shops, hotels and restaurants. Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX).

A LOW SEA LEVEL RISE SCENARIO: RISKS TO REAL ESTATE DRASTICALLY REDUCED

The difference in impacts to real estate between high and low sea level rise scenarios is stark. A rapid decrease in carbon emissions coupled with slow melting of land-based ice could lead to substantially slower rates of sea level rise. With this low sea level rise scenario, by the year 2060, our analysis finds that the number of homes at risk of chronic inundation would be reduced by nearly 80 percent, from 625,000 with the high scenario to 138,000 with the low scenario. And by the end of the century, only 340,000 homes would be at risk with the low scenario, compared to 2.4 million with the high scenario.

If the global community adheres to the primary goal of the Paris Agreement of capping warming below 2°C

> ***A rapid decrease in global carbon emissions coupled with slow melting of land-based ice could reduce the number of homes at risk of chronic inundation by 2060 by nearly 80 percent.***

(UNFCCC 2018), and with limited loss of land-based ice, the United States could avoid losing residential properties that are currently valued at $780 billion, contribute $10 billion annually in property tax revenue, and house 4.1 million people.

Unfortunately, the low, or best-case, scenario is not the track we are on, given current emissions and the vulnerability of the Antarctic ice sheet to warming temperatures, as indicated by the latest research. (Mengel et al. 2018; DeConto and Pollard 2016). The low emissions scenario is one we should work toward but not count on—and decisionmakers must plan for the likely need to manage greater risks.

FIGURE 7. The Potential Economic Reverberations of Chronically Inundated Properties

With chronic inundation, homeowners and owners of commercial properties are directly at risk of significant financial losses as the value of their properties declines. Such losses have ramifications for the local community, which could see its property tax base eroded and its ability to fund local services compromised. There will also be implications for the wider economy, including for banks with outstanding mortgage loans on properties at risk of inundation, coastal property developers, investors and insurers, business owners whose places of business may face flooding, and US taxpayers, broadly, who may face increased taxes to pay for measures to cope with flooding and to reduce flood risk.

Implications

The declining value and increasingly unlivable condition of coastal homes will be damaging, even devastating, to individual homeowners. It will also have more widespread consequences, including for affected communities, lenders, investors, and taxpayers. Unlike housing market crashes of the past, where property values eventually rebounded in most markets, properties chronically inundated by rising seas will only go further underwater, raising the urgent need for more proactive long-term solutions.

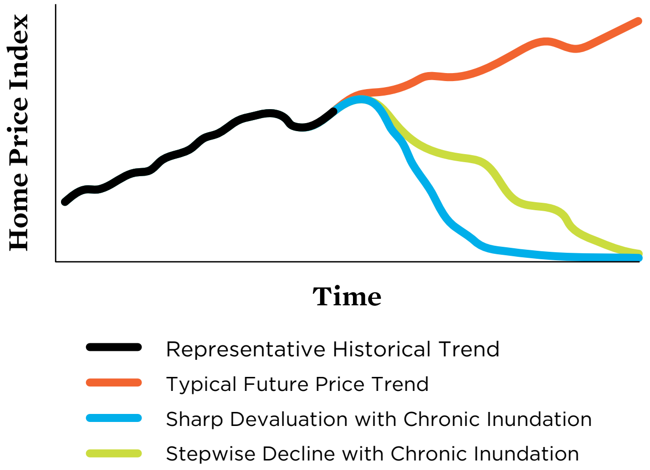
RISKS TO HOMEOWNERS AND BUSINESS OWNERS

With chronic inundation, average homeowners will risk being unable to capitalize on their greatest asset as their homes become undesirable on the real estate market and eventually unsellable. Flood insurance for chronically inundated coastal properties could become increasingly expensive—or not available at all (FEMA 2018; Dixon et al. 2017; Lieberman 2017; GAO 2017). A rash of coastal foreclosures and abandoned homes could ensue, causing neighborhood blight and millions of dollars in lost wealth, even as new real estate wealth is potentially created further inland. In some neighborhoods, even if many individual homes remain out of the chronic inundation zone, the large numbers of homes at risk could cause the neighborhood to collectively experience significant property value declines (Dixon et al. 2017).

Renters, too, could find themselves looking for new homes or putting up with flood-damaged properties—and perhaps facing a scarce local rental market and rising rents. In Miami, for example, developers are increasingly considering buying land in lower-income neighborhoods located farther inland and at higher elevations (Bolstad 2017). But without regulation and policy around these market-driven reactions to sea level rise, this practice can perpetuate racial and social inequities, as lower-income communities see their property values rise to unaffordable levels, creating climate gentrification (Keenan, Hill, and Gumber 2018; Beeler 2017).

Business owners are similarly at risk: flooded streets mean loss of traffic and in-person sales; flooded properties can mean loss of inventory and expensive clean-up; and flooded roads and parking lots can prevent workers from reaching and doing their jobs. Moreover, many business owners invest in the communities that host them, a revenue source that could dry up if those businesses are harmed by chronic flooding. Some commercial property owners will also see the value of their investments erode and may find it increasingly hard to secure long-term leases for properties that are at risk of inundation.

FIGURE 8: Loss in Home Value with Chronic Inundation



These curves depict illustrative trends in home prices with and without chronic inundation. The black line represents a typical historical trend. Going forward, home values in healthy real estate markets would typically trend upward over time (orange line). However, with chronic inundation some coastal real estate markets could face sharp devaluations if their risk is high or they do not have the resources to adapt (blue line); other communities with a longer time horizon to respond or the ability to invest in adaptation measures could face a slower, stepwise decline in property values (green line).

RISKS TO THE LOCAL TAX BASE: A VICIOUS CYCLE BEGINS

Falling property values mean reduced local tax revenue from those properties. In communities where a small share of homes is initially affected, local leaders may opt to raise the tax rate across all properties to mitigate the budget shortfall. However, when many homes are affected, the property tax base will be eroded more quickly, reducing municipal budgets (LILP/MCFE 2018).

Local tax revenues help fund the maintenance and new construction of infrastructure—including critical adaptation measures that could help protect homes, businesses, and infrastructure itself from chronic flooding. Access to additional capital for such projects depends on a municipality's credit rating; its credit rating depends on its financial health and degree of risk exposure, both of which are compromised as chronic flooding worsens. Ironically, communities may find it harder to raise funds for increasing their resilience to floods—through the bond market, for instance—if their credit rating is lowered because of flood risks. Turning again to the relatively wealthy city of Miami, in 2017 the city's residents voted in favor of a $400 million "Miami Forever" bond, which included $192 million for measures to help protect the city from sea level rise–induced flooding (Smiley 2017). But many smaller municipalities will not be able to drum up similar resources or act quickly enough while they are still credit-worthy, highlighting the need for marshaling a national response to help ensure that there is equitable, timely access to adaptation measures for all communities.

RISKS TO THE WIDER ECONOMY: LENDERS, TAXPAYERS, DEVELOPERS, AND INVESTORS

Mortgages on homes that could be chronically flooded during the term of the loan are inherently riskier. As chronic inundation worsens, homeowners will begin to find themselves with mortgages that exceed the value of their homes, and with homes that grow unlivable or difficult to insure. With no obvious option for reversing that trend, some might choose to abandon their homes and allow banks to foreclose on their mortgages. Lenders who provide mortgages, however, rely on the surety that the value of the property will be maintained, or even appreciate, so that their financial position is secure even in the event of foreclosure. That may cease to be the case for many coastal properties, many of which today carry these risky mortgages with neither homeowner nor lender realizing it (Federal Reserve 2018). Mortgage-backed securities and

> ***Mortgages on homes that could be chronically flooded are inherently riskier, potentially with neither homeowner nor lender realizing it.***

Paul Zoeller/The Post And Courier via AP

Some communities and individuals are better positioned to absorb economic blows than others. And while wealthier homeowners, business owners, and communities may risk losing more value cumulatively, people who are less well-off risk losing a greater percentage of their wealth. Chronic flooding will place tremendous strain on low-income homeowners and renters, pressuring them, for example, to weigh costly flood-proofing investments against losing their homes. This mounting flood risk may spell deep losses for many, and without policies in place to help, will spell ruin for some.

bonds (essentially, investment vehicles created by bundling individual mortgages) tied into these riskier coastal real estate mortgages will thus also be at risk of losing value.

Real estate developers and investors risk sinking millions into properties that will shrink in value as chronic flooding increases. Insurers covering residential and commercial properties risk unsustainable payouts.

When enough major market actors become aware of and begin to act on these risks, it could potentially trigger a regional housing market crisis, or even a more widespread economic crisis.

Our Challenge–and Our Choices

The development along our nation's coasts today is the result of choices made over centuries. We've made our living from the sea; we've bought and built homes with ocean views; we've visited and vacationed in seaside towns, leaving behind money and taking away memories; we've toiled and built lives in coastal cities and small towns. Investors and developers have found ways to profit from this timeless pull to the seaside. Hundreds of years of history, personal and shared, painful and triumphant, are held in the homes, businesses, schools, roads, and treasured places that line our coasts. And much of it is at risk from sea level rise.

Despite long-available scientific information on observed and projected sea level, and the actual experience of flooding in some coastal communities, most coastal housing markets are a long way from reflecting the growing flood risks.

Imperfect information about localized risks and flawed policies have created a strong bias toward business-as-usual choices, greatly impeding science-based decisionmaking (Wing et al. 2018; Schwartz 2018). In the absence of adequate resources, or the wherewithal to invest in protective measures, many communities struggle to make more resilient choices. There are also significant questions about the accountability of local zoning regulators, developers, credit rating agencies, insurers, banks that proffer mortgages, and others who are effectively worsening the problem by ignoring or minimizing it (Allen 2017). In the near term, these policy and market incentives are serving to artificially prop up coastal real estate values (Becketti 2016).

But some experts and coastal residents are beginning to raise questions about the future of coastal real estate markets (Bernstein, Gustafson and Lewis 2018; Keenan, Hill, and Gumber 2018). Some real estate investors are also taking note (Coffee 2018; McConkey 2017). Zillow and Freddie Mac, two influential giants in the real estate sector, have both released reports in the last two years examining the impact of future sea level rise on coastal real estate (Rao 2017; Becketti 2016). Freddie Mac finds that sea level rise could "destroy billions of dollars in property and displace millions of people," with the resulting social and economic impacts "greater in total than those experienced in the housing crisis and Great Recession."

The prospect of these future losses compels action today. We must reorient policy and market forces toward solutions that work for people, ecosystems, coastal heritage, and the economy: by employing the best available science and information; by aligning existing policy and market incentives with the realities of sea level rise; and by investing in bold, transformative changes that limit harms and foster new frontiers of opportunity on safer ground.

KNOWING OUR RISK

To begin with, many homeowners and prospective home buyers are simply not sufficiently aware of the risks of sea level rise to their properties, whether present-day or future risks, and whether confined to major storms or chronic tidal flooding. This information is inadequately reflected in the Federal Emergency Management Agency's (FEMA) flood risk maps, for example, which only account for present-day flood risks (Schwartz 2018; Wing et al. 2018; Joyce 2017; Cleetus 2013). Although some individual states and localities have standards requiring real estate agents and home sellers to disclose flood risks at the time of a home sale, there are no uniform robust national requirements (Lightbody 2017).[7] Lenders and investors, especially those at a distance from the specific location, are also either largely unaware of growing tidal flood risks to properties or not adequately accounting for it in their business decisions (Farzad 2018; Allen 2017).

To address this gap in awareness, federal, state, and local policymakers, as well as members of the private sector, have important, complementary roles to play. These actions must be supplemented with resources and options for adaptation measures because greater awareness of flood risks will also bring challenges, especially to communities whose risks are revealed to be high. Actions should include the following:

1. The federal government must play a lead role in communicating risks to the public and incorporating those risks into its own policies and actions. Recent authoritative reports from the US Global Change Research Program and the National Oceanic and Atmospheric Administration (NOAA), together with online tools from federal government agencies such as the Environmental Protection Agency and NOAA, can serve a critical purpose in helping communities, policymakers, investors, and the broader public understand the risks of sea level rise (Sweet et al. 2018; EPA 2017; NOAA 2017a; USGCRP 2017). FEMA flood risk

maps—which help set flood insurance rates, guide local land-use policies, and inform infrastructure design standards—must be updated coast-wide to reflect sea level rise projections (TMAC 2016). This will help communicate the threat and encourage communities to take protective steps. Congress needs to increase funding beyond current levels and provide an explicit directive to FEMA to make this possible (ASFPM 2013).

2. State and local policymakers must help disseminate flood risk information to communities, and set local zoning and building regulations in line with these risks.
3. Flood-risk disclosure in the marketplace is vital to help individuals and businesses understand the risks to their investments and drive more resilient outcomes. National standards for flood-risk disclosure, including floods from sea level rise—for all real estate transactions—would go a long way toward making risks clear and transparent in coastal real estate markets. Mortgage underwriters and home appraisers can also play important roles in assessing and disclosing information about these risks to lenders and buyers.

Widespread adoption of industry standards and best practices for disclosing flood and other climate-related risks is needed. Financial institutions have begun taking steps to internalize climate risks, albeit slowly (Bonanno and Teras 2018). In the wake of the 2015 Paris Agreement, the Financial Stability Board—an international body that monitors and makes recommendations about the global financial system—launched the Taskforce on Climate-Related Financial Disclosures. The taskforce has released a set of recommendations on governance, strategy, risk management, and metrics and targets for financial-sector companies to support more accurate pricing of climate-related risks and thereby more informed investment decisions (TCFD 2017). These recommendations and the taskforce's five-year climate disclosure implementation pathway have the support of more than 250 major corporations, including banks, insurers, and investors.

Credit rating bodies also must start reflecting risks to coastal property, while rewarding proactive adaptation measures to limit those risks. For example, the credit rating agencies Moody's and Standard & Poor's have begun to evaluate and communicate how to account for climate risks in their credit ratings of municipal bonds (Bonanno and Teras 2018; Moody's Investors Services 2017; Walsh 2017; S&P 2016).

Cris Benton

The historic attractiveness and market value of coastal property have long driven coastal development, like this pulse of new home construction in Richmond, California, some 20 years ago. Though the risks of sea level rise have been evident for some time in cities like Miami, Florida; Charleston, South Carolina; Norfolk, Virginia; and Annapolis, Maryland; in many such places a brisk pace of new home construction continues.

REALIGNING POLICIES AND MARKET INCENTIVES TO REFLECT GROWING FLOOD RISKS

Well-intentioned but short-sighted federal, state, and local policies can mask risk and create incentives that reinforce the status quo, or even expose *more* people and property to risk. The market's bias toward short-term decisionmaking and profits can also perpetuate risky investment choices. Identifying and reorienting the principal policies and market drivers of risky coastal development is a necessary and powerful way to move the nation toward greater resilience.

Here we identify several existing federal and state policies that play a de facto role in how communities—and financial markets—perceive and respond to coastal risks. Each of these policies can be improved to better incentivize and enhance resilience:

1. Federal disaster aid, when not accompanied by explicit incentives to reduce residents' and businesses' exposure to risks, has led states and municipalities to rebuild in a business-as-usual way and underinvest in risk-reduction measures (Kousky and Shabnam 2017; Moore 2017). Post-disaster investments should instead be made with a view to reducing future risks through a range of protective measures, including home buyouts and investments in flood-proofing measures as appropriate, and a requirement for adequate insurance coverage. For now, communities and financial sector actors rely on the assumption that federal aid will continue in its current form. Credit rating agencies have cited this assumption of continued federal aid for rebuilding as a reason to avoid downgrading the credit rating of municipalities that are exposed to risks of sea level rise.

BOX 1.

Can’t We Just Keep the Water Out?

As homeowners become more aware of the threat that chronic flooding poses to what is likely their most significant financial asset, interest in adaptation options—in particular, defensive measures that allow life to go on as usual—is likely to spike. And while adaptation is essential, there is cause for caution in embracing defensive measures as the sole or even primary solution.

Most community-level defensive measures are designed to help minimize wave action, reduce erosion, and protect against storm surge (NRC 2014). But keeping out normal, but higher, high tides is a different challenge. To defend large areas against chronic inundation, impervious seawalls (for example) would need to extend along large stretches of shoreline and avoid channeling incoming seas toward other exposed areas (NRC 2014). Or levees would need to be constructed, potentially requiring the use of large tracts of land and encouraging new development behind them (GAO 2016; Kousky 2014). As sea level rises, however, hard structures can aggravate coastal erosion, with natural habitat and beach loss, even as the walls fail to protect against infiltration of saltwater from below ground (Boda 2018; Vitousek et al. 2017; Moser et al. 2014; NRC 2014; Mazi, Koussis, and Destouni 2013; Barlow and Reichard 2010).

USACE

A seawall is constructed in New Jersey by the US Army Corps of Engineers. The hard defensive measures that are widely deployed today were typically built to dampen storm surge and limit erosion, not keep out normal but higher tides.

Such measures also come with an expiration date: either the defensive infrastructure reaches retirement age, or sea level rise catches up and necessitates further upgrades, at additional cost, lest it be overwhelmed.

Defensive measures can require investment—both initially and for ongoing maintenance and operation—on a scale that many communities will be unable to muster with diminished tax bases, particularly if they had fewer resources to start with. Individual property-level measures such as elevating buildings and installing doorway flood gates also require funding, and do not address the inundation of the roadways, commercial districts, septic systems, schools, etc. that those households and businesses rely on. Investing in defensive measures may help forestall chronic flooding in many locations, but for some home- and business owners there will be no practical or affordable way to keep the tide out of their property; for some communities, it will be similarly impractical or unaffordable to defend whole flooded areas. Options such as retreat and relocation will need to be part of the conversation.

2. Existing federal, state, and local policies could be effectively deployed for investments in measures that will both reduce risks ahead of time and help rebuild in a more resilient way (Kousky 2014). We should recognize coastal flood risk for the predictable, slow-moving disaster it is, rather than respond only episodically, i.e., in the aftermath of major storms. One way this can be done is by ramping up investments in FEMA’s pre-disaster hazard mitigation grant program and the flood mitigation assistance program, and the community development block grant program administered by the US Department of Housing and Urban Development (HUD). A recent analysis by the National Institute of Building Sciences of almost a quarter century’s worth of data found that for these types of flood risk mitigation programs, every $1 invested can save the nation $6 in future disaster costs (MMC 2017).

[***Reforming short-sighted policy and market drivers of risky coastal development is a necessary and powerful way to move the nation toward greater resilience.***]

3. The taxpayer-backed National Flood Insurance Program—while a vital program—has long been recognized as subsidizing some homeowners in flood-prone areas and inaccurately portraying flood risks because, in too many cases, insurance premiums and the flood risk maps that underlie them do not reflect true risks (Schwartz 2018; Joyce 2017; Kousky and Michel-Kerjan 2015). The most egregious examples are so-called repetitive loss properties that have received repeated payouts from the program despite being in places that are clearly too risky to insure (Moore 2017).[8] With sea level rise, the maps used by the National Flood Insurance Program are increasingly out of sync with the actual risks to coastal properties. Commonsense reforms to the program can ensure that it more effectively communicates flood risks, protects communities, and promotes better floodplain management.

4. A robust federal flood risk management standard should be restored and mandate that all federal investments take

---

BOX 2.

Insights from Market Experts on the Financial Risks of Sea Level Rise: Excerpts from the Matrix of Voices

To better understand the financial implications of the risks of sea level rise to coastal property markets and the wider economy, we gathered perspectives from market experts—including representatives from credit rating agencies, insurers, real estate investors, bond investment advisors, and mortgage and real estate industry experts—and municipal officials. Taken together, a picture emerges that highlights the likely impact of sea level rise on coastal property values, the property tax base, and the many inextricably connected market sectors, and reinforces the need for broad-based action to limit harmful consequences for people and the economy.

The **six main insights** that emerged from the experts consulted were (see the full Matrix of Voices at *www.ucsusa.org/underwater* for more details):

1. **The financial risks of sea level rise are real and significant—and they are largely unaccounted for in the current market.**

   "Sea level rise is an extremely serious issue with direct implications for municipal credit ratings, which will in turn affect the value of their bonds. Also, if the tax base contracts substantially, that will affect the ability of municipalities to pay back bond investors."
   — *Andrew Teras, vice president and senior analyst, Breckinridge Capital Advisors*

   "The impacts to coastal real estate markets, coastal businesses, and property tax bases will be geographically concentrated in the near term, but will become more widespread over time. Many of today's financial decisions do not consider sea level rise, but as the evidence evolves, market signals (insurance rates, community credit scores) may increasingly reflect a heightened risk."
   — *Roger Grenier, senior vice president, global resilience practice leader, AIR Worldwide, Consulting and Client Services*

   "As risks increase, insurers will pull out of markets and limit coverages, increase deductibles, or raise rates. When significant volumes of property value decline and mortgage delinquencies increase, there are major ramifications for our entire financial system, as we experienced in the 2008 financial collapse caused by the mortgage-market meltdown."
   — *Cynthia L. McHale, director, Ceres*

   "There is no risk, it's a guaranteed total loss. The only uncertainty is the timeline."
   — *Mayor Philip Stoddard, South Miami*

2. **Some initial steps are underway to try to incorporate these risks, but there are barriers to doing so.**

   "The challenge to incorporating climate risks like sea level rise into market-based decisions today is that there is no uniform way to communicate future risk conditions, nor consensus on the timeframe to consider in communication, or which model results/scenarios should form the basis of any outreach."
   — *Carolyn Kousky, PhD, director for policy research and engagement, Wharton Risk Management and Decision Processes Center, University of Pennsylvania*

   "As an investment manager, one of the biggest challenges is the disconnect between time horizons for our clients' investments in bonds—usually three to five years—and the time frame for significant tipping points when, say, 50 to 70 percent of the tax base is at risk of flooding."
   — *Andrew Teras, vice president and senior analyst, Breckinridge Capital Advisors*

into account future flood risks in order to help protect vital federally funded infrastructure, ensure wise use of taxpayer dollars, and also set a valuable guidepost for communities. State and local building and zoning regulations that are solely focused on near-term economic outcomes, and thereby allow questionable coastal development, are essentially building new exposure to risk when they could and should be reducing such exposure (IBHS 2018). Additional important opportunities include more protective building standards and coastal zone management regulations to help encourage flood-resilience measures in floodplains, including the protection of wetlands and barrier islands and other natural flood-risk reduction methods.

5. Increased funding for voluntary home buyout programs administered by FEMA and the HUD can also help homeowners move to safer locations. Communities in high-risk areas may also increasingly need relocation grants and technical assistance, and, correspondingly,

---

"Our first infrastructure challenge is going to be loss of septic tank function. Installing municipal sewer systems after a neighborhood is built-out is very expensive. We are looking at the costs and cringing. Nobody is going to help, not the feds, not the state, not the county. So, cost is the biggest barrier."
— Mayor Philip Stoddard, South Miami

3. **Some federal and local policies, in their current form—particularly those related to disaster risk response, flood insurance, and zoning regulations—unintentionally serve to mask the risks to coastal communities.**

"Flood insurance creates risky behavior when it is extended to new development. Zoning regulations should be considering the 100-year outlook for the land, including the future cost of providing access and infrastructure to the land, incenting construction in areas without sea level rise risk, and 'charging' areas with [sea level risk] to cover the future public costs of mitigating those risks."
— Douglas M. Poutasse, executive vice president, head of strategy and research, Bentall Kennedy (US) LP

"The existing government-backed system effectively creates a program of subsidized insurance coverage for Americans to live at the coast... In addition, current spending is heavily weighted towards post-disaster mitigation, instead of investing in communities before disasters occur... Finally, the economic incentives of the real estate industry, construction industry, and local chambers of commerce are often not aligned with risk-informed policies and practices."
— Roger Grenier, senior vice president, global resilience practice leader, AIR Worldwide, Consulting and Client Services

4. **A coastal property market correction is inevitable, but the form and severity it will take in specific locations, and its timing, are still uncertain.**

"If policymakers confront the National Flood Insurance Program's moral hazards and reduce the scope of coverage it provides, or increase premiums in line with the underlying risk, development or redevelopment of coastal lands might be constrained as they become uninsurable."
— Kurt Forsgren, managing director, infrastructure sector lead, S&P Global Ratings

"Once the properties enter the 'decline' phase, the behavior of owners changes. They invest less new capital in maintaining and improving their properties, because the shortened time frame to receive a return on additional investment necessitates a higher rate of return. This becomes a self-reinforcing mechanism, as properties with lower reinvestment become less attractive to tenants and occupants."
— Douglas M. Poutasse, executive vice president and head of strategy and research, Bentall Kennedy (US) LP

5. **Some communities will be hit harder than others, especially if policy interventions are not made ahead of a steep downward adjustment in property values.**

"The concern I always have is that, ultimately, only some portions of the vast US coastline will be protected, i.e., major urban areas. Many, many other portions of the coast, along with their respective people and livelihoods, will remain in harms' way."
— Cynthia L. McHale, director, Ceres

6. **Standards and guidelines for risk disclosure are an important first step for market actors to be able to account for these risks in their business models.**

"S&P Global Ratings see the uniform and transparent disclosure by governments of the potential effects of gradual environmental change and extreme weather events as both an important input into our assessment of management's ability to respond to the risks, and one of the largest challenges to the market. Uniform risk disclosure is necessary for markets to price this risk accurately."
— Kurt Forsgren, managing director, infrastructure sector lead, S&P Global Ratings

communities that receive an influx of new residents may need financial resources. And as sea levels rise, federal, state, and local policies and resources should specifically target and address the needs of disadvantaged communities.

6. Banks, insurers, real estate investors, developers, and other major financial actors in coastal areas should establish guidelines and standards to incorporate the risks of sea level rise in their business models, thus better serving the long-term economic interests of their clients. A blinkered focus on near-term profits and market factors can obscure significant risks just beyond the horizon.

If there are changes in the perception of risk to coastal properties or if there is a growing political or social pressure to make changes, the marketplace or policymakers could make rapid changes to align incentives with risks. Potential examples of these types of shifts include changes in insurance premiums or criteria for insurability, changes in lending terms, and changes in credit ratings for communities. These types of tipping points could trigger very quick shifts in property values and the broader economic health of a coastal community.

Unfortunately, a rapid realignment of taxpayer and private-sector investments reflecting true risk could jeopardize the well-being of communities unless deliberate steps are taken to provide options for them ahead of time. The withdrawal of private-sector investment dollars, and even public dollars when places are deemed too costly to support, could bring disruptive local impacts and market speculation with inequitable outcomes, particularly for those communities with fewer resources. Rather than a wholesale rapid withdrawal of funding for these areas, a judicious scaling back of new investment in line with flood risks would be far preferable from a societal perspective, together with a redirection of those investments toward options to help communities cope and build resilience.

PLANNING FOR A RESILIENT FUTURE FOR ALL

As a nation, we must use wisely the diminishing response time that communities have to reduce their exposure to this threat, from the individual scale to the economy as a whole. For communities facing chronic flooding of properties in the near term, it is imperative to act quickly to phase out policies that perpetuate and increase risk, while considering options for retreat from the highest-risk places. For cities and towns where the effects of chronic inundation will become apparent by mid-century, a slightly longer time horizon might allow for more creative solutions and comprehensive policies and planning. Targeted resources must be made available for disadvantaged communities for whom any of these adaptive responses could pose steep challenges. Given the wide-scale nature of the risks to our nation, we need a holistic, timely response strategy.

> [***Decisionmakers still have choices that can help limit threats to coastal cities and towns, and ultimately, to the national economy.***]

Decisionmakers still have choices that can help limit—even if they cannot eliminate—threats to coastal cities and towns, and ultimately, to the national economy. Three main strategies exist for adapting to sea level rise on any coast: defend, accommodate, and retreat. Decisions about which combination of strategies to employ, and when and where, require expertise, stakeholder engagement, and ultimately the resources to implement the chosen options. Many cities and towns can expect adaptation to be costly, and that some financial losses will be inevitable. Homeowners and communities cannot be expected to absorb all of these potentially crippling costs on their own, especially those with fewer resources. A range of relevant actors—chiefly, the federal government—can implement policies that will help support adaptation and limit the extent of financial loss, ensuring that these taxpayer-funded resources are wisely and equitably deployed. The private sector also has an important role in driving innovative risk-reduction measures and creating new loci of economic opportunities in areas further inland.

Sea level rise is challenging us to reimagine our coasts in many ways. Hundreds of communities will face losses. Retreat may be necessary from some of the highest-risk places. But there are opportunities to be had too—especially if we plan and invest wisely. Inland communities may be revitalized by the influx of new residents and new businesses. New communities can emerge, new infrastructure be built, and new economic opportunities created. All of this will only be possible with visionary leadership from policymakers, the private sector, and communities themselves.

Critically, the United States must also work with other nations to slow the pace and limit the magnitude of sea level rise through aggressive reductions in heat-trapping emissions, in order to allow as many communities and homes as possible—both at home and abroad—to avoid chronic inundation in the years ahead.

RESEARCH AGENDA FOR MEETING THIS CHALLENGE

Developing a coherent, just, and forward-thinking approach to the challenges we face will require further research on several fronts.

First, the many stakeholder groups within the coastal real estate sector—from individual homeowners to insurers—need to examine their tidal flooding tolerance and explore thresholds beyond which a pull-back (physically or financially) from affected areas is required. Within the private sector, for example, a careful examination of the risks could trigger decisions—such as not granting loans, raising insurance premiums, or downgrading credit—which will in turn drive big, sometimes painful, changes that begin to align market outcomes with those risks. Local-scale, community-specific modeling under different climate projections is a key piece of this research that can be built out.

Patricia Lane Evans

This Hampton Beach, New Hampshire, home captures both our desire to be close to the ocean and the risks as seas rise. Homeowners and communities have a narrowing window of time to take action. They require support from local, state, and national elected officials to manage what lies ahead.

Second, communities will need more complete information on whether and how they can be made more resilient in place: for example, through what measures, at what cost, for how long? Third, further research is needed around successful models for retreat that could lead to positive outcomes for coastal and inland communities, particularly considering lessons learned following buyouts and individual homeowner retreat after Hurricane Sandy (Binder and Greer 2016). Critical areas in which we need to build our understanding are the necessary governance structures that will best support coastal retreat, legal implications of historically dry land going underwater, and the relationship between market downturns and climate-induced migration (Flavelle 2018; Kousky 2014). Additionally, as communities increasingly face the challenge of frequent, disruptive flooding, they will need to marshal resources to rise to that challenge—which inherently puts communities with fewer resources at a disadvantage (ERG 2013). We will therefore need to deepen our understanding of how policies can be made equitable and how best to enact them (Deas et al. 2017).

Conclusion

The cliff's edge of a real estate market deflation due to flooding and sea level rise is already visible for many communities if they choose to look. The trajectory of our current actions—continued building in vulnerable places and ever-increasing global warming emissions—is propelling us closer to that edge. There are thresholds for properties at risk of chronic flooding from sea level rise beyond which regular life becomes unmanageable and financial loss becomes a better bet than struggling to live with floodwater. There are thresholds for communities beyond which economic and financial viability, and crucial public services, are threatened. When enough of those households and communities falter, entire real estate markets may face a tipping point. Whether we react to this threat by implementing science-based, coordinated, and equitable solutions—or walk, eyes open, toward a crisis—is up to us right now.

__Kristina Dahl__ is a senior climate scientist in the UCS Climate and Energy program. __Rachel Cleetus__ is the policy director in the program. __Erika Spanger-Siegfried__ is the lead climate analyst in the program. __Shana Udvardy__ is the climate resilience analyst in the program. __Astrid Caldas__ is a senior climate scientist in the program. __Pamela Worth__ is the staff writer in the Communications department.

ACKNOWLEDGMENTS

This report was made possible by the generous support of the Barr Foundation, Energy Foundation, Fresh Sound Foundation, The Grantham Foundation for the Protection of the Environment, Leonardo DiCaprio Foundation, Louise Elving, The John D. and Catherine T. MacArthur Foundation, The Scherman Foundation, and members of the Union of Concerned Scientists. Underlying property data were generously provided by Zillow.

The report team would like to express thanks to the following individuals for their invaluable advice, technical guidance, and review of the report: Joyce Coffee, Climate Resilience Consulting; Jesse M. Keenan, Harvard University; Carolyn Kousky, Wharton Risk Center, University of Pennsylvania; and John Miller, University of Pennsylvania.

For indispensable technical guidance and input during the analytical process, the team is indebted to several advisers from the National Oceanic and Atmospheric Administration: Dave Carlton, Dkcarlton & Associates, PLLC; Doug Marcy and Billy Brooks, NOAA Office for Coastal Management.

The authors would like to express their gratitude to the following individuals for their unparalleled perspective and advice: Michael D. Berman, Michael Berman Consulting, LLC; Gunnar Branson, National Association of Real Estate Investors; Anne Canfield, Consumer Mortgage Coalition; Joyce Coffee, Climate Resilience Consulting; Jack Davis, ReTech Advisors; Simon Fischweicher, CDP; Roger Grenier, AIR Worldwide; Mathias and Michele Hansen, geocodio; Carolyn Kousky, Wharton Risk Center, University of Pennsylvania; Marion McFadden, Laurie Schoeman and Clay Kerchof, Enterprise Community Partners, LLC; Cynthia L. McHale, Ceres; Samantha Medlock and the Capital, Science & Policy Practice Team, Willis Towers Watson; Douglas Poutasse, Bentall Kennedy; Sara Singhas, Mortgage Bankers Association; and Andrew Teras, Breckinridge Capital Advisors. We would also like to thank the following individuals who generously provided quotes for this report: Kurt Forsgren, S&P Global Ratings; Roger Grenier, AIR Worldwide; Cynthia L. McHale, Ceres; Douglas Poutasse, Bentall Kennedy; Mayor Philip Stoddard, South Miami, FL; Carolyn Kousky, Wharton Risk Center, University of Pennsylvania; and Andrew Teras, Breckinridge Capital Advisors.

The opinions expressed herein do not necessarily reflect those of the organizations that funded the work or the individuals who provided advice to the authors, reviewed the report, or provided quotes. The Union of Concerned Scientists bears sole responsibility for the report's content.

DISCLOSURE

Data provided by third parties through the Zillow Transaction and Assessment Dataset (ZTRAX). More information on accessing the data can be found at http://www.zillow.com/ztrax. The results and opinions presented in this report are those of the Union of Concerned Scientists and do not reflect the position of Zillow Group.

DISCLAIMER

This research is intended to help individuals and communities appreciate when sea level rise may place existing coastal properties (aggregated by community) at risk of tidal flooding. It captures the current value and tax base contribution of those properties (also aggregated by community) and is not intended to project changes in those values, nor in the value of any specific property. The projections herein are made to the best of our scientific knowledge and comport with our scientific and peer review standards. They are limited by a range of factors, including but not limited to the quality of property-level data, the resolution of coastal elevation models, the potential installment of defensive measures not captured by those models, and uncertainty around the future pace of sea level rise. More information on caveats and limitations can be found at www.ucsusa.org/underwater. Neither the authors nor the Union of Concerned Scientists are responsible or liable for financial or reputational implications or damages to homeowners, insurers, investors, mortgage holders, municipalities, or other any entities. The content of this analysis should not be relied on to make business, real estate or other real world decisions without independent consultation with professional experts with relevant experience. The views expressed by individuals in the quoted text of this report do not represent an endorsement of the analysis or its results.

ENDNOTES

1. Complete results for the intermediate and low scenarios are available here at *www.ucsusa.org/underwater*. The high scenario used throughout this report is not now thought to be extreme, given recent observations and analysis of land-based ice melt (e.g., Kopp et al. 2017, Schroeder et al. 2017; DeConto and Pollard 2016). In addition, in 2017 the National Oceanic and Atmospheric Administration released new sea level rise scenarios that are comparable to these three and include an "extreme" scenario of a roughly eight-foot increase by 2100 (Sweet et al. 2017).
2. In southeast Florida, individual units in high-rise buildings (which have been constructed at a rapid pace on low-elevation land in recent years) account for many at-risk homes. In this analysis, ground-floor chronic flooding risk is applied to the entire building since the unit's access, functionality, and value are all impacted (see the full methodology at *www.ucsusa.org/underwater*.)
3. The shore line of the San Francisco Bay contains a vast network of locally controlled defensive structures such as seawalls and levees. This analysis explicitly accounts for only those structures identified by the Federal Emergency Management Agency as reducing flood risk—namely, those surrounding Foster City and the Oakland International Airport. As such, the statistics reported here likely do not reflect the varying levels of protection that other coastal defense structures could potentially provide to Bay Area communities.
4. California home values reflect assessed rather than market values, unlike all other coastal states in this analysis. See the full methodology at *www.ucsusa.org/underwater* for details.
5. Many Louisiana communities have locally controlled levees or other flood-control structures that were not explicitly included in this analysis. Federally controlled leveed areas as defined by the US Army Corps of Engineers were excluded from the analysis. See the full methodology at *www.ucsusa.org/underwater* for details.
6. If properties of all values were equally at risk, 50 percent of the at-risk homes would be valued below the state median.
7. In general, real estate agents and home sellers are required to disclose all material facts that could affect the price or desirability of a property. But in practice, unless they are shown to have actual knowledge of flood risks, there is no easy way to require agents and sellers to disclose projected sea level rise–related flood risk under current laws.
8. A recent study from the Natural Resources Defense Council, using data from FEMA, found that from 1978 through 2015 the agency paid $5.5 billion to repair or rebuild 30,000 severe repetitive loss properties that have been flooded an average five times or more. Texas, New Jersey, New York, and Florida ranked the highest in terms of both numbers of these properties and damage costs.

APPENDIX: ABOUT THIS ANALYSIS

Our basic methodology

This analysis intersects two existing datasets: 1) zones of chronic inundation along the US coastline, previously published by Dahl et al. 2017 and Spanger-Siegfried et al. 2017; and 2) the Zillow Transaction and Assessment Database (ZTRAX), which contains property data gathered by county assessors' offices and has been collated by the online real estate company Zillow. The chronic inundation zones are defined for a suite of future years and sea level rise projections, as described as follows. The overarching goal of the analysis is to evaluate the risks of chronic, disruptive flooding to the coastal real estate sector.

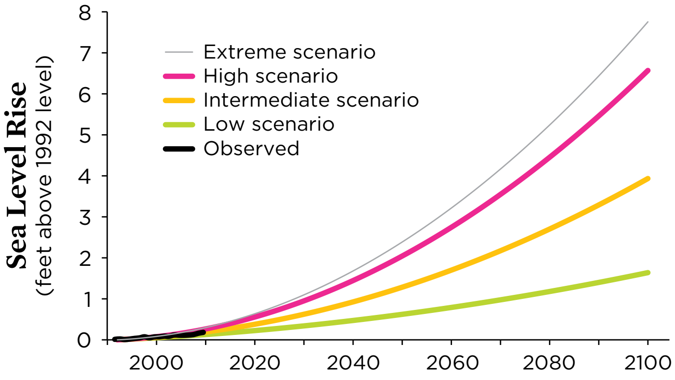
What is chronic inundation?

Building on prior research, this analysis defines a chronic inundation zone as any area where tidal flooding occurs 26 times per year (on average, twice a month) (Dahl et al. 2017). This frequency is based on previously published thresholds (e.g., Sweet and Park 2014), consultation with technical experts at universities and federal agencies, and perspective gained from local community experts. The flood tolerance of individual homeowners or homebuyers, however, will be highly subjective. Similarly, the willingness of private sector actors to bear financial exposure in flooded locations may change far earlier than the threshold used here. When it comes to real estate markets, it may take considerably less flooding to drive big choices and changes.

What sea level rise scenarios did we use and why?
We used three scenarios developed for the 2014 National Climate Assessment and localized for this analysis (Huber and White 2015; Walsh et al. 2014; Parris et al. 2012). We refer to our projections as the high, intermediate, and low scenarios (Figure A-1). The high scenario assumes rapid ice sheet loss and projects a global average sea level rise of 6.6 feet (2.0 m) above 1992 levels by the end of this century. The intermediate scenario assumes a moderate rate of ice sheet loss that increases over time for a rise of 4.0 feet (1.2 m) by the end of this century. The low scenario assumes curtailed warming and sea level rise that is driven primarily by ocean warming with very little contribution of ice loss, and projects a rise of 1.6 feet (0.5 m) by the end of this century. Because the total 21st-century warming in this scenario is in line with the Paris Agreement's goal of holding warming to less than 3.6°F (2°C) above preindustrial temperature levels, we use this scenario as a proxy for sea level rise under the Paris Agreement (Rasmussen et al. 2018).

We have made projections for at-risk properties under all three scenarios, but in this report, we lead with results of the high scenario. The high scenario is considered most applicable in situations with a low tolerance for risk. This makes it most suitable for estimating the scale of risk to residential properties, which typically represent a homeowner's greatest single asset. The full suite of results is available online at *www.ucsusa.org/underwater*.

FIGURE A-1. Projected 21st Century Sea Level Rise



How much the sea level rises this century depends on our past and future emissions of heat-trapping gases as well as how Earth responds to those emissions. We based our projections for sea level rise—our low, intermediate, and high scenarios—on the intermediate-low, intermediate-high, and highest scenarios from the Third National Climate Assessment (Parris et al. 2012). The Fourth National Climate Assessment includes an "extreme" sea level rise scenario predicated on our growing understanding of the sensitivity of Antarctic ice to warming temperatures (Sweet et al. 2017).

How were incomplete or inaccurate data in the ZTRAX dataset handled?
Within the ZTRAX dataset, issues such as missing values are common. We applied three broad corrections to the ZTRAX data. First, we removed properties that were duplicated in the database. Second, we re-geocoded each property using an external service (geocod.io) to ensure its positional accuracy. Finally, for properties missing a market value or a property tax value, we calculated the missing value based on the reported assessed value and county-specific information about the ratio between assessed and market values and/or effective tax rates. Missing market and property tax values were calculated only for residential properties. It is important to note that for California, where there is no simple ratio between assessed value, market value, and property tax value, we used assessed value in place of market value.

How were population and demographic statistics derived?
Estimates of the number of residents living in homes at risk of chronic inundation were derived using the housing unit method (Smith 1986) and 2010 census data on occupancy rate and number of people per household (US Census Bureau 2010). Population totals as well as racial demographics were also taken from the 2010 census. Community-level poverty rates were derived from the 2011–2015 American Community Survey.

What are the key caveats, assumptions, and limitations?

1. Our determination of the extent of chronic inundation is dependent upon the quality of the underlying elevation data, which were provided by the National Oceanic and Atmospheric Administration (Marcy et al. 2011; NOAA 2017b). These data vary in horizontal resolution and accuracy, and communities are encouraged to work with the highest resolution elevation data available to do more detailed mapping.
2. Even the highest-resolution elevation data used here do not fully capture many local coastal defenses, such as sea walls. Though most defenses are constructed to manage storm surge and erosion, not to keep out higher tides, areas with such structures in place may not experience as much flooding as suggested by our analysis.
3. Tidal dynamics vary greatly depending on local coastal morphology. Features such as bays, inlets, barrier islands, and wetlands can attenuate or amplify the tide relative to its level at the open ocean–facing tide gauges that were used to determine chronic inundation water levels.
4. This analysis makes no assumptions about adaptation measures that communities may implement in the future, such as building flood control structures or restoring wetlands. Several factors could affect whether and how communities implement adaption measures, including geography, resources, and the range of options available to any given community.
5. Population, demographics, number of properties, and associated property data are assumed to be constant at present-day levels. Studies incorporating future population growth into sea level rise studies tend to show greater population impacts, which suggests that our results may be conservative (Hauer, Evans, and Mishra 2016).

For more details on this analysis, see *www.ucsusa.org/underwater*.

Underwater

Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate

> ***In the coming decades, many coastal real estate markets will be strained by tidal flooding, with potential reverberations throughout the national economy.***

As sea levels rise, more and more American homes and businesses will experience frequent, disruptive flooding that makes everyday life impossible. More than 300,000 of today's coastal homes are at risk of this untenable flooding within the term of a 30-year mortgage.

Yet property values in most coastal real estate markets do not currently reflect this risk. And with short-sighted investments and policies at all levels of government concealing this growing problem, homeowners, businesses, communities, and investors are not aware of the financial losses they may soon face.

In the coming decades, many coastal real estate markets will be strained by flooding, some to the point of collapse, with potential reverberations throughout the national economy. Individual homeowners and businessowners, banks, lenders, investors, developers, insurers, and taxpayers are poised to sustain large collective losses. Shrinking property tax bases could spell decline for many coastal cities and towns.

We have scant time remaining to brace our communities, and our local and national economies, for this challenge. While there are no easy solutions, knowing our risk—and using that knowledge to create bold new policies and market incentives—will help protect coastal communities. Whether we react to this threat by implementing science-based, coordinated, and equitable solutions—or walk, eyes open, toward a crisis—is up to us right now.

Union of Concerned Scientists

FIND THIS DOCUMENT ONLINE: **www.ucsusa.org/underwater**

The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with people across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
Phone: (617) 547-5552
Fax: (617) 864-9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Suite 800
Washington, DC 20006-1232
Phone: (202) 223-6133
Fax: (202) 223-6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
Phone: (510) 843-1872
Fax: (510) 451-3785

MIDWEST OFFICE
One N. LaSalle St., Suite 1904
Chicago, IL 60602-4064
Phone: (312) 578-1750
Fax: (312) 578-1751

WEB: www.ucsusa.org

PRINTED ON RECYCLED PAPER USING VEGETABLE-BASED INKS

This is a tab page.
Please title tab
“Risk & Insurance”

2017 Most Dangerous Emerging Risks

Coastal Mortgage Value Collapse

As seas rise, so does the risk that buyers will become leery of taking on mortgages along our coasts.

By: | April 7, 2017

Topics: April 2017 Issue | Claims | Climate Change | Emerging Risks | Insurance Industry | Property | Underwriting

Rising seas encroach on our cities and towns at rates exponentially greater than before.

So-called King Tides, urged on by climate change and brought about by the close alignment of the sun, the moon and the earth are already producing flooding in Miami 10 days a year.

Debate the cause if you want to expend more hot air denying science. But it’s a fact that resale values of coastal homes in Miami, Atlantic City and Norfolk, Va. are already starting to erode.

These bellwether locations signify a growing and alarming threat; that continually rising seas will damage coastal residential and commercial property values to the point that property owners will flee those markets in droves, thus precipitating a mortgage value collapse that could equal or exceed the mortgage crisis that rocked the global economy in 2008.

“Insurance deals with extreme weather and billions of dollars of losses, but what we are talking about is uninsured loss of fair market value that is trillions of dollars in losses and I am not talking about in 2100, I’m talking about the next mortgage cycle,” said Albert Slap, president of Coastal Risk Consulting, a Florida firm that provides lot by lot modeling of flood risk.

Models created by Coastal Risk Consulting show flooding rates of Miami properties are going to rise substantially between now and 2050, within that 30–year mortgage cycle he refers to.

“The results of our modeling and that of NOAA and many others shows that the increase in flooding on people’s properties, due to astronomy and physics, not weather, is alarming and significant and in all likelihood is not backstopped by insurance,” Slap said.

Adding to the threat is that real estate agents and homeowners aren't incentivized or required to reveal how frequently properties flood, or how exposed they are to flooding.

"Forty percent of Americans live on the coast, which means you have trillions of dollars at risk for climate change that hasn't been modeled for default increases," Slap said.

The Pew Charitable Trusts, as part of its testimony to Congress as the National Flood Insurance Program undergoes review, is asking that all homeowners be required to report on that risk.

Many coastal homes are backstopped by the NFIP, which is still billions in debt from its losses in the Katrina-Wilma-Rita hurricane cycle of 2005.

Private sector insurers are eyeing ways to write more flood business. But if the NFIP suffers further losses, and private sector insurers retreat, what then?

"If you look at it systematically, if a broad number of insurance companies decide that they need to triple homeowners insurance rates, or they need to pull out of a local market, that would create a lot of problems in terms of the value of the properties that are in that locale," said Cynthia McHale, president of insurance for Ceres, a nonprofit that advocates for sustainable business practices.

In November, Sean Becketti, the chief economist for the economic and housing research group at Freddie Mac, the federally backed housing lender, co-authored a paper that documented this very risk.

The paper referenced the fact that daily high-water levels in Miami are increasing at a rate of an inch per year, much faster than the rate of global sea-level rise. Other cities along the Eastern seaboard are experiencing a 10-fold increase in the frequency of flooding, according to Freddie Mac.

"A large share of homeowners' wealth is locked up in the equity in their homes," Becketti wrote.

"If those homes become uninsurable and unmarketable, the values of the homes will plummet, perhaps to zero."

"Forty percent of Americans live on the coast, which means you have trillions of dollars at risk for climate change that hasn't been modeled for default increases." —Albert Slap, president, Coastal Risk Consulting

In the housing crisis of 2008, according to Becketti, a significant percentage of borrowers continued to make their mortgage payments even though the value of their homes was less than their mortgages.

“It is less likely that borrowers will continue to make mortgage payments if their homes are literally underwater,” Becketti said.

“As a result, lenders, servicers and mortgage insurers are likely to suffer large losses,” he said.

Insurers would suffer, according to Ceres’ McHale, and not just as backers of insurance policies.

“Insurance companies themselves are major commercial and residential mortgage holders,” she said.

“They assume that the property is going to hold its value and act as collateral if needed. If it doesn’t hold its value, where is the collateral?”

“Not only will their mortgages be metaphorically underwater, they are going to be literally underwater,” said Slap.

“And there is no coming back from it.”

“The New York Times” published a piece in November that detailed the case of Roy and Carol Baker of Sarasota, Fla. The Bakers tried for months to sell their home in Siesta Key, according to the story, but buyers kept backing out when they discovered the annual flood insurance premium was about $7,000.

“This experience will become more common, economists say, as the federal government shifts away from subsidizing flood insurance rates to get premiums closer to reflecting the true market cost of the risk,” reporter Ian Urbina wrote in his piece.

The Climate Race

What Becketti, Slap and others say is true, said Helen Thompson, a director, commercial marketing at Esri, the mapping and analytics company that works with insurers and property owners.

But she said there is a solution, the public and private sector working together to address the problem: That and about $4 trillion.

“The challenge for a lot of people is to understand the scope and the scale of this issue, and in some ways, like the mortgage bubble before, if you are ignorant of the problem, you can’t fix it,” she said.

“I think taking action means crafting a discussion of the problem and moderated expressions of what those solutions are, based on science and analysis and not hyperbole,” she said.

It’s well documented how dire the nation’s infrastructure needs are.

Thompson compares the current dilemma posed by climate change and sea rise in the U.S. and elsewhere to the cholera epidemic that ravaged London in the mid-19th century. What’s needed now, she said, is something akin to the massive public works projects that were undertaken to provide Londoners with cleaner drinking water.

“They realized the social and political cost of this,” Thompson said.

“We need to change our thinking to say this is not just about handing debt to our children, it’s about maintaining the same level of opportunity and quality of life for our children,” she said.

Thompson points to China, which she says is investing in climate change-resistant ports and additional infrastructure internationally to remain economically competitive.

“It’s in their best interests as a global manufacturing hub to mitigate the cost and the impact of climate change because of how much collateral damage it will do to their economies,” Thompson said.

She said the U.S. needs to go down the same path, and step on it.

“I call it the ‘climate race,’ like the space race,” she said.

“The infrastructure needs to be created to deal with this, and the United States is massively lagging.”

Slap envisions another solution, a “climate ready” mortgage program, similar to the federal government’s energy efficient mortgage program, which gives property owners federally guaranteed loans to make energy efficiency upgrades.

Such a program would provide loans for sewage backflow preventers, changing the grade on a driveway, or elevating a home on a platform

Thompson said the massive infrastructure projects she envisions could include moving the vital container operations at the Port of Miami inland and constructing a berm to defend against sea water.

Office building owners in Lower Manhattan, which was so damaged by Superstorm Sandy, are increasingly investing in flood prevention barricades and moving critical building components like HVAC and plumbing components to higher floors.

Americans just got a chilling reminder of the dangers presented by changing weather patterns and crumbling infrastructure. Fears that the Oroville Dam on California's Feather River would buckle under heavy rainfall got everyone's attention.

"People are looking at that and saying, 'We didn't realize what this change in weather patterns means in the long term,' " Thompson said, and they are relating the Oroville event to infrastructure in their own towns and the risks they present.

As the NFIP undergoes its annual review in Congress, Slap said administrators would do well to exclude King Tide events.

"If you were to go to NFIP and ask them if they cover King Tide flooding, they would say, 'If it meets our definition of flood then we must cover it.' This is a red flag, because what you are saying is the government and the taxpayers are covering sea level rise and that is not something we can afford," Slap said.

This is a tab page.
Please title tab
“First Street”

As the seas have been rising, home values have been sinking.

Scientists from the non-profit First Street Foundation find $7.4 billion has been lost in home value across 5 coastal states from 2005 to 2017 due to sea level rise flooding. These findings have been integrated into Flood iQ, a sea level rise flooding prediction tool from First Street Foundation, so individuals can find property-specific value loss and aggregated total city loss.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant, recently released an academic publication in the journal Population Research and Policy Review proving $465 million was lost in Miami-Dade County real-estate market value from 2005 to 2016 due to sea level rise flooding. This peer-reviewed analysis was expanded to cover all of Florida, South Carolina, North Carolina, Virginia and Georgia by analyzing over 5.5 million real estate transactions in these states and extrapolating the results to 12.2 million properties, to find a total home value loss of $7.4 billion since 2005. Lists of the top 250 most impacted cities and ZIP codes have been released.

Previous academic studies have forecasted the negative impact sea level rise will have on the value of coastal properties in the future but “Estimating Recent Local Impacts of Sea-Level Rise on Current Real-Estate Losses: A Housing Market Case Study in Miami-Dade, Florida” is the first to show that depreciation has already taken place. By identifying the predictors of home value, such as square footage or proximity to amenities, while controlling for economic trends like the 2008 housing recession, the scientists were able to isolate the impact frequent tidal flooding, caused by sea level rise, has had on home value.

“It is one thing to project what the future impacts of sea level rise could be, but it is quite another to know that the market has already responded negatively to this threat,” said McAlpine.

“We need to act now,” said Porter. “The ability to pay for solutions to sea level rise is directly related to our ability to finance them. We do not want to see the beginning of a domino effect, where lost property value lowers the tax base and cripples our ability to finance solutions.”

This is the first academic paper to demonstrate that sea level rise is directly to blame for a decrease in coastal home value and the first to identify the role nearby flooding plays in that decrease. Proximity to road flooding was proven to have as much of an impact on home value as direct, property-level, flooding--indicating that all members of a community should be concerned by any amount of flooding in the streets.

“Flooding does not have to be a way of life for coastal communities. Cities can take measures to mitigate the impact and protect property values,” said Matthew Eby, Executive Director at First Street Foundation. “But without action, the rate of home value loss will only accelerate.”

• • •

First Street Foundation, is a 501(c)(3) tech nonprofit that educates policymakers and the public about the risks, causes, and solutions to sea level rise.

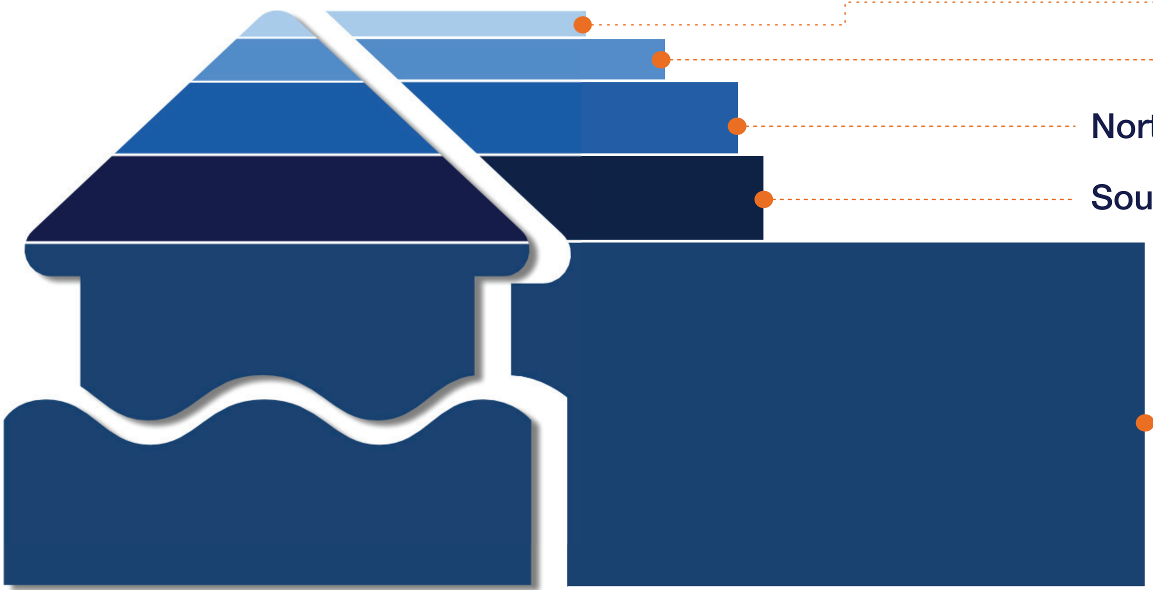
Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

For questions please reach out to pr@firststreet.org

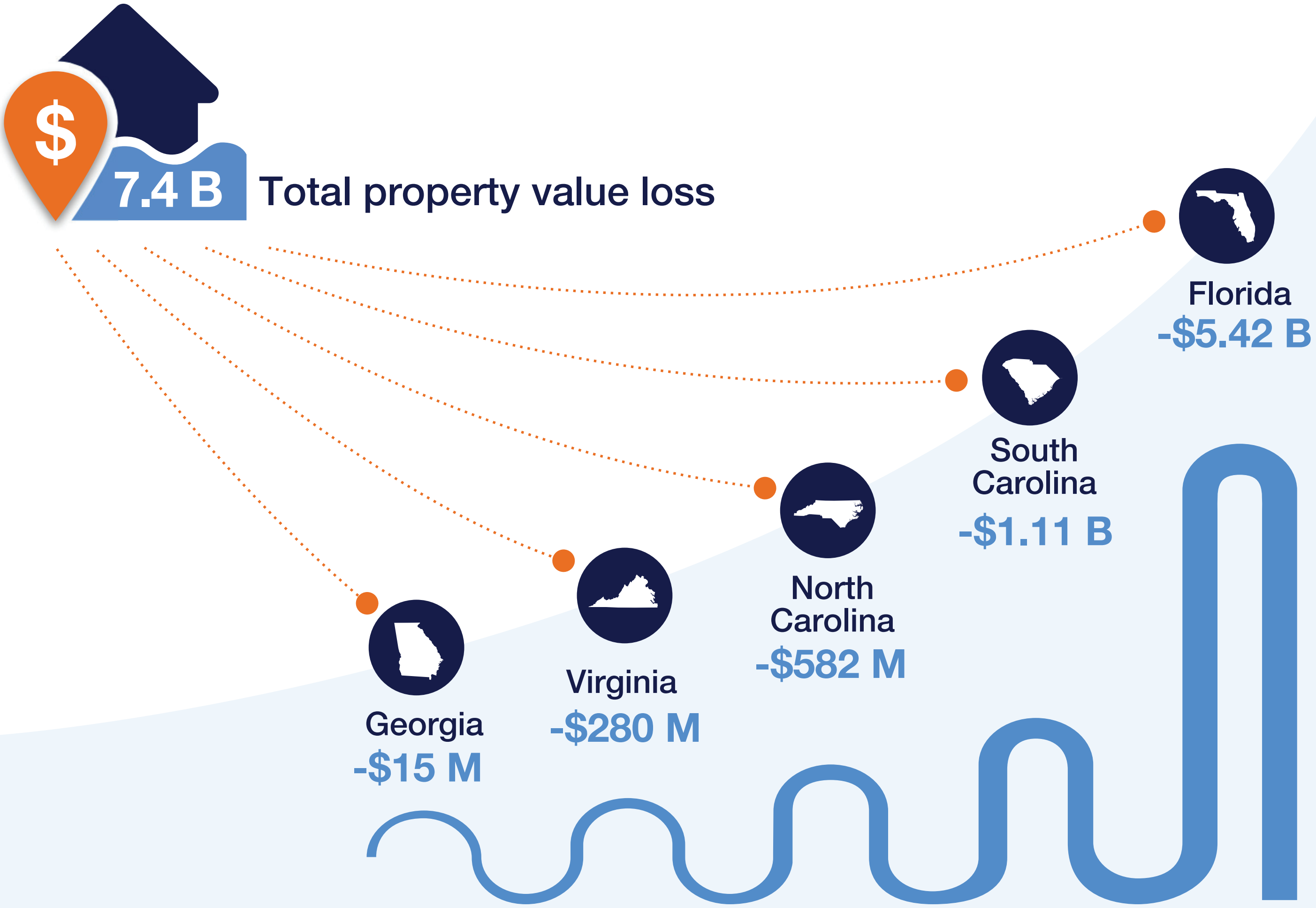
FIRST STREET
FOUNDATION
FirstStreet.org

A five state analysis of home value loss due to sea level rise and flooding

Total properties that lost value: 616,626



Georgia	11,360
Virginia	47,035
North Carolina	81,908
South Carolina	92,775
Florida	384,548



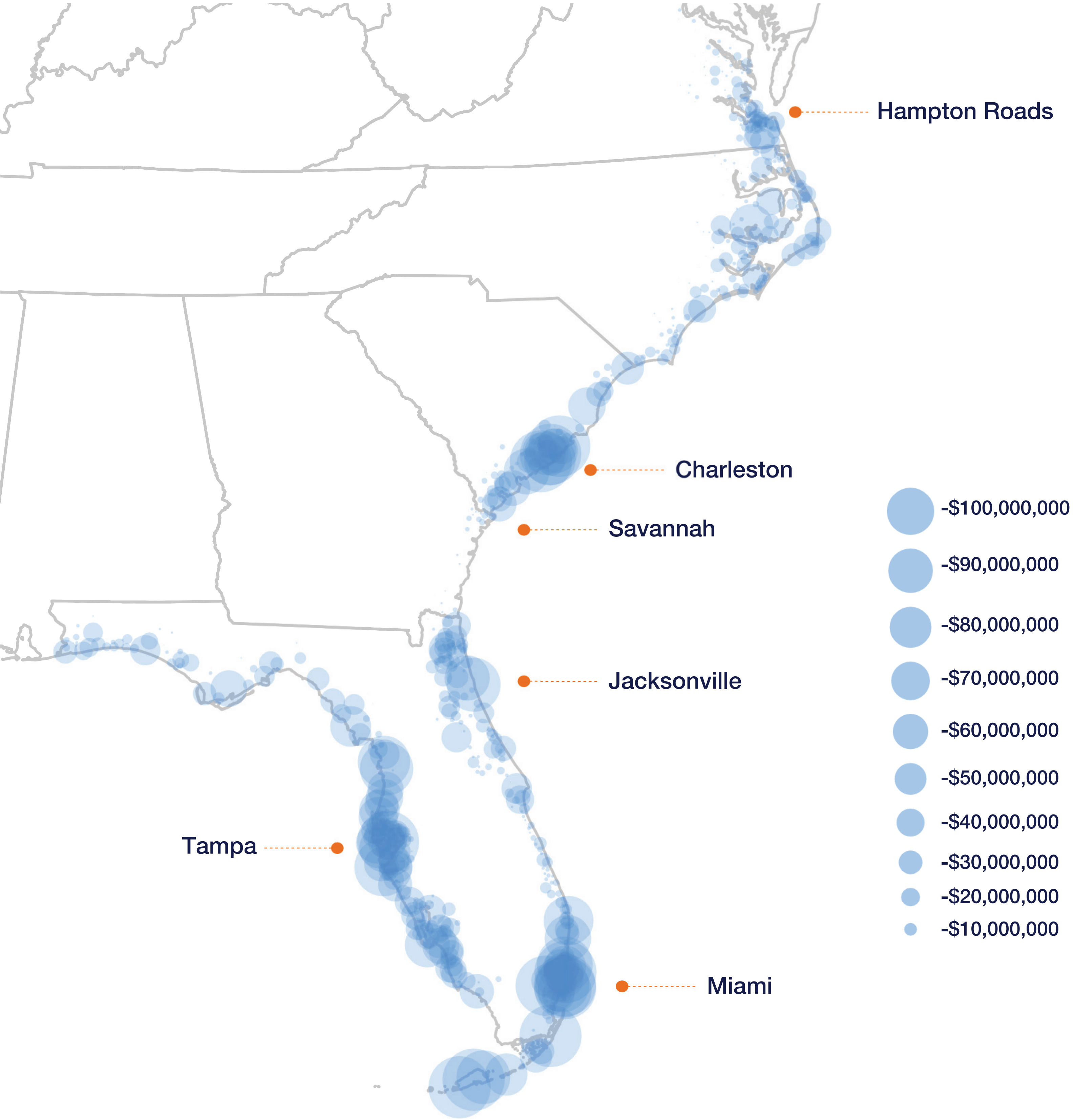
7.4 B Total property value loss

Florida	-$5.42 B
South Carolina	-$1.11 B
North Carolina	-$582 M
Virginia	-$280 M
Georgia	-$15 M

FIRST STREET
FOUNDATION

FirstStreet.org

Total property value lost from 2005 - 2017 (by zip code)



FIRST STREET FOUNDATION

FirstStreet.org

Top 20 cities by total property value lost from 2005 - 2017

Rank	City Name	Total Property Value Lost
1	Miami Beach, FL	-$337,167,466
2	Hollywood, FL	-$304,568,101
3	Charleston, SC	-$266,217,606
4	Saint Petersburg, FL	-$243,968,610
5	Fort Lauderdale, FL	-$193,885,367
6	Key Largo, FL	-$159,615,296
7	Mount Pleasant, SC	-$149,072,672
8	Jacksonville, FL	-$146,483,838
9	Key West, FL	-$133,015,501
10	Miami, FL	-$125,275,830
11	Kiawah Island, SC	-$90,490,822
12	Doral, FL	-$85,517,020
13	Saint Augustine, FL	-$79,809,123
14	Tampa, FL	-$76,084,992
15	Holmes Beach, FL	-$75,212,310
16	Chesapeake, VA	-$71,009,779
17	Homosassa, FL	-$66,584,367
18	Palm Beach, FL	-$62,445,556
19	Sanibel, FL	-$55,567,578
20	Norfolk, VA	-$55,515,241

Top 20 zip codes by total property value lost from 2005 - 2017

Rank	ZIP Code	State	Total Property Value Lost
1	33019	Florida	-$256,107,024
2	33040	Florida	-$194,923,568
3	29455	South Carolina	-$178,870,640
4	33037	Florida	-$176,269,824
5	33703	Florida	-$152,503,280
6	33140	Florida	-$147,746,416
7	33141	Florida	-$135,996,864
8	33042	Florida	-$106,351,368
9	29466	South Carolina	-$98,784,464
10	29401	South Carolina	-$97,694,512
11	33178	Florida	-$94,402,840
12	34217	Florida	-$88,288,480
13	33301	Florida	-$82,690,952
14	33138	Florida	-$78,050,480
15	32080	Florida	-$77,920,312
16	33139	Florida	-$77,767,328
17	33043	Florida	-$77,283,352
18	34448	Florida	-$76,522,504
19	34429	Florida	-$74,219,792
20	29412	South Carolina	-$72,215,928

FIRST STREET
FOUNDATION

August 23rd, 2018

As the seas have been rising, Tri-State home values have been sinking.

Scientists from the non-profit First Street Foundation analyzed recent housing market trends in New York, New Jersey, and Connecticut and found $6.7 billion has been lost in home value from 2005 to 2017 due to sea level rise flooding.

This builds on their previous research that found $7.4 billion in home value had been lost across 5 southeastern coastal states, bringing the total loss in the 8 states to $14.1 billion. These findings have been integrated into Flood iQ, a flood risk tool from First Street Foundation, which enables individuals to find their property-specific value loss and aggregated loss for their city.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant, recently released an academic publication in the journal *Population Research and Policy Review* showing $465 million was lost in Miami-Dade County's real-estate market from 2005 to 2016 due to sea level rise flooding. The peer-reviewed analysis has now been expanded to cover all of New York, New Jersey, Connecticut, Florida, Georgia, South Carolina, North Carolina, and Virginia by analyzing over 9.2 million real estate transactions, and extrapolating the results to 20 million properties. The expanded analysis has found a total home value loss of $14.1 billion across these eight coastal states since 2005.

Previous peer-reviewed academic studies have forecasted the negative impact sea level rise will have on the future value of coastal properties, but McAlpine and Porter's research is the first to demonstrate value loss has already occured. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value.

"This is the first market indicator that rising seas and related flooding have depressed home values," said McAlpine. "This is not just a Florida issue, but an issue the entire coastal United States needs to address."

"As we have expanded our study, the results have been incredibly consistent," said Porter. "Americans across 8 states have already lost $14.1 billion from increased flooding caused by sea level rise, and all signs are pointing to this being an accelerating trend."

The research is the first to find that in addition to direct, property-lot flooding, nearby road flooding also has a major impact on home value. This suggests that all residents in neighborhoods with flooding should be concerned by any flooding in their streets.

"We all knew that flooding issues were getting worse from sea level rise, but the home value loss associated with it is truly staggering." said Matthew Eby, Executive Director at First Street Foundation. "The time to act is now."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that educates policymakers and the public about the risks, causes, and solutions to sea level rise.

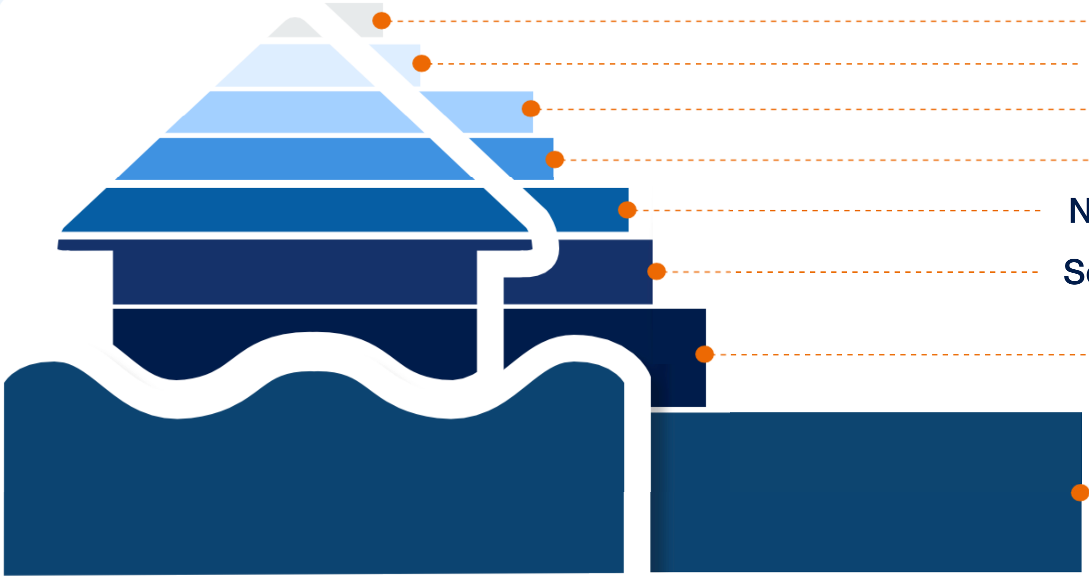
Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

For questions please reach out to pr@firststreet.org.

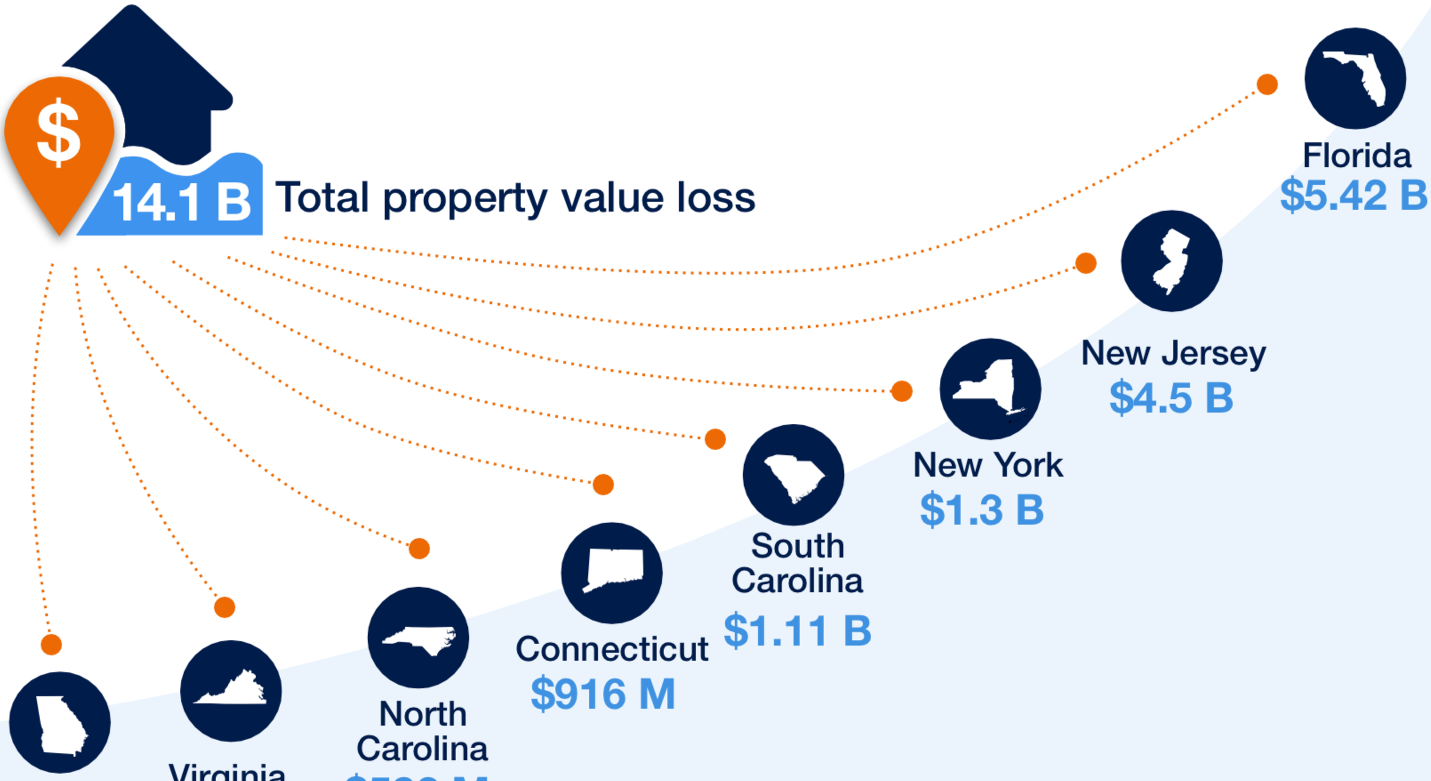
FIRST STREET FOUNDATION | FirstStreet.org

An eight-state analysis of home value loss due to sea level rise and flooding

Total properties that lost value: 819,526



Georgia	11,360
Connecticut	14,713
Virginia	47,035
New York	74,604
North Carolina	81,908
South Carolina	92,775
New Jersey	112,583
Florida	384,548



14.1 B Total property value loss

Florida	$5.42 B
New Jersey	$4.5 B
New York	$1.3 B
South Carolina	$1.11 B
Connecticut	$916 M
North Carolina	$582 M
Virginia	$280 M
Georgia	$15 M

FIRST STREET FOUNDATION

FirstStreet.org

Total property value lost from 2005 - 2017 (by zip code)

FIRST STREET
FOUNDATION

FirstStreet.org

Top 20 cities by total property value lost from 2005 - 2017

Rank	City Name	Total Property Value Lost
1	Ocean City, NJ	$530,439,399
2	Miami Beach, FL	$337,167,466
3	Hollywood, FL	$304,568,101
4	Charleston, SC	$266,217,606
5	Saint Petersburg, FL	$243,968,610
6	North Beach Haven, NJ	$216,899,215
7	Sea Isle City, NJ	$208,644,351
8	Fort Lauderdale, FL	$193,885,367
9	New York City, NY	$185,052,918
10	Atlantic City, NJ	$174,748,706
11	Avalon, NJ	$165,956,129
12	Key Largo, FL	$159,615,296
13	Brigantine, NJ	$158,874,047
14	Mount Pleasant, SC	$149,072,672
15	Jacksonville, FL	$146,483,838
16	North Wildwood, NJ	$138,435,750
17	Key West, FL	$133,015,501
18	Freeport, NY	$131,021,192
19	Milford City, CT	$126,947,753
20	Mystic Island, NJ	$125,508,045

Top 20 zip codes by total property value lost from 2005 - 2017

Rank	ZIP Code	State	Total Property Value Lost
1	08008	New Jersey	$541,193,136
2	08226	New Jersey	$531,806,217
3	08260	New Jersey	$314,508,114
4	33019	Florida	$256,107,024
5	08243	New Jersey	$207,078,907
6	33040	Florida	$194,923,568
7	08087	New Jersey	$188,439,710
8	29455	South Carolina	$178,870,640
9	33037	Florida	$176,269,824
10	08401	New Jersey	$174,857,998
11	08202	New Jersey	$172,525,022
12	08742	New Jersey	$169,124,952
13	08203	New Jersey	$158,766,736
14	33703	Florida	$152,503,280
15	33140	Florida	$147,746,416
16	08751	New Jersey	$137,627,358
17	33141	Florida	$135,996,864
18	11520	New York	$131,216,057
19	06460	Connecticut	$127,332,216
20	08735	New Jersey	$124,707,036

Media Contact:
Carolyn Costello
323.384.7098
carolyn@firststreet.org

Rising Seas Swallow $403 Million in New England Home Values

For Immediate Release: January 22, 2019

Data scientists from First Street Foundation and Columbia University have expanded their peer-reviewed housing market research to include 2.5 million coastal properties in Massachusetts, Maine, New Hampshire, and Rhode Island and found that increased tidal flooding caused by sea level rise has eroded $403.1 million in relative home values between 2005 and 2017. Coastal homes in Massachusetts were hit hardest, losing $273.4 million in relative appreciation. Homes in Maine saw $69.9 million in unrealized value, followed by Rhode Island at $44.7 million, and New Hampshire at $15.2 million. One of the region's hardest hit homes, a triplex located on Marginal Street in Boston, currently valued at $373,725, would be worth more than double at $799,054 if not for increased tidal flooding due to sea level rise.

Homeowners can learn how much relative value their personal property missed out on over the 12 year study period and how much value it is projected to lose over the next 15 years at FloodiQ.com. The interactive visualization tool also shows current inundation estimates for frequent and annual tidal floods as well as from hurricane storm surge, and how those levels are projected to increase over the next 15 years.

Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant first established their peer-reviewed methodology with an analysis of the Miami-Dade County real estate market. That study, published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 16 housing market-specific models. By analyzing approximately 11 million real estate transactions, and applying the results to 22.5 million properties, the researchers have found a $15 billion loss in home values across 14 states. The Foundation's previous research was reported by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor

"Each time we analyze a new state we see the same phenomenon," said Porter. "Increased tidal flooding leads to a loss in home value appreciation. As sea level rise accelerates, we expect the corresponding loss in relative home value to accelerate as well."

McAlpine and Porter's research is the first to quantify the observed negative impact of increasingly frequent flooding, driven by sea level rise, on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding caused by sea level rise has had on home value. While most of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding. The research is also the first to find that in addition to direct property-lot flooding nearby road flooding also has a major impact on home value.

“It’s not just property lot flooding that leads to home value loss, persistent flooding of nearby roads has a significant impact as well,” said McAlpine. “Road flooding affects commutes and school bus access, and because it’s on display for everyone to see, it can give an area a negative reputation. In New England, winter flooding can create sheets of ice on roadways, adding another, dangerous, consequence to street flooding.”

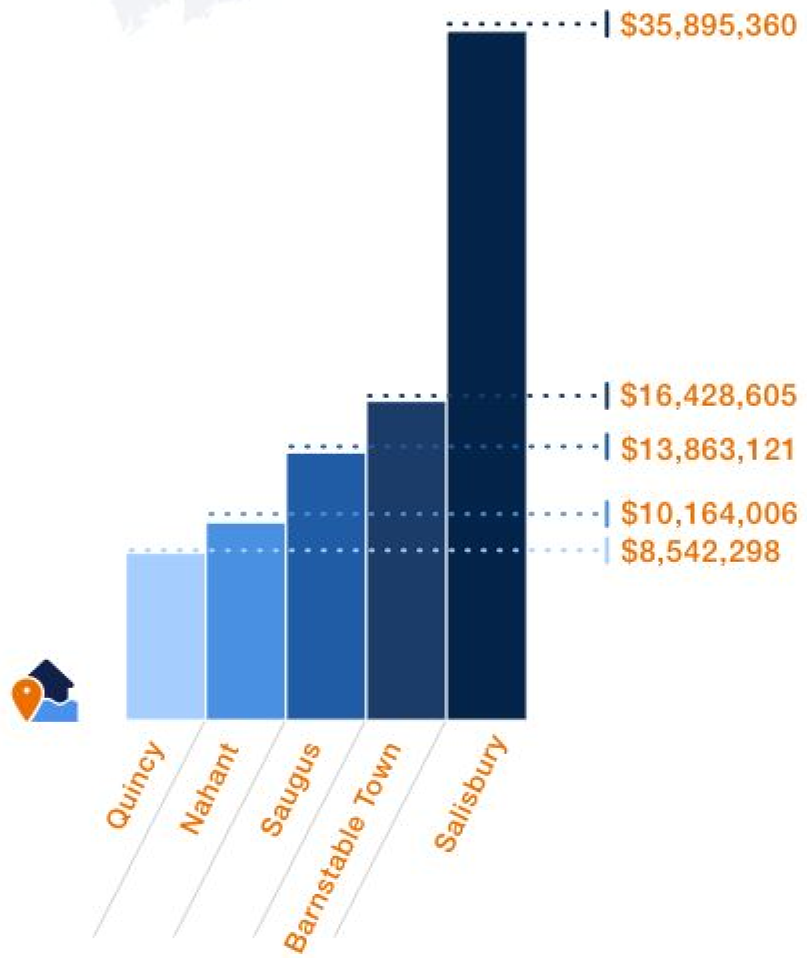
FloodiQ.com is the first publicly available database that gives coastal residents, homeowners, and prospective homebuyers access to comprehensive flood risk and property value loss information.

“This levels the playing field for average Americans looking to invest in real-estate by giving them access to the same information as institutional investors and the wealthy,” said Matthew Eby, Executive Director of First Street Foundation. “Knowing the direct impact of previous flood events on the value of your home and understanding how the risks of flooding will increase as sea levels rise is something the public deserves to know.”

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

FIRST STREET FOUNDATION FirstStreet.org

Massachusetts: Top 5 Hardest Hit Cities

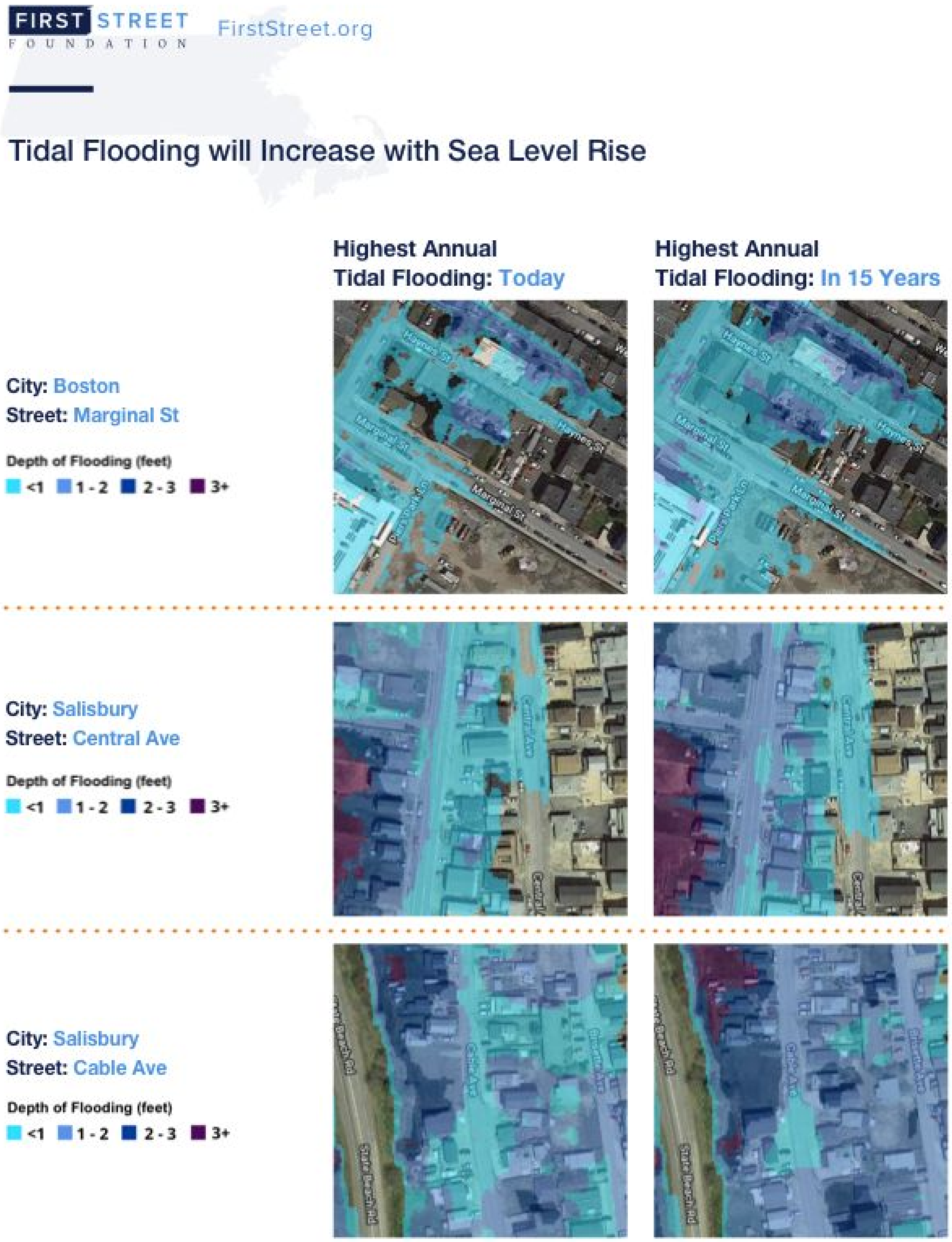


Massachusetts: Top 3 Hardest Hit Homes

City: Boston
Street: Marginal St
Tax Assessed Value: $373,725
Should be Worth: $799,054
Relative Value Loss: -$425,329

City: Salisbury
Street: Central Ave
Tax Assessed Value: $227,900
Should be Worth: $421,822
Relative Value Loss: -$193,922

City: Salisbury
Street: Cable Ave
Tax Assessed Value: $349,000
Should be Worth: $582,422
Relative Value Loss: -$233,422



FIRST STREET FOUNDATION FirstStreet.org

Tidal Flooding will Increase with Sea Level Rise

Highest Annual Tidal Flooding: Today

Highest Annual Tidal Flooding: In 15 Years

City: Boston
Street: Marginal St

Depth of Flooding (feet)
■ <1 ■ 1 - 2 ■ 2 - 3 ■ 3+

City: Salisbury
Street: Central Ave

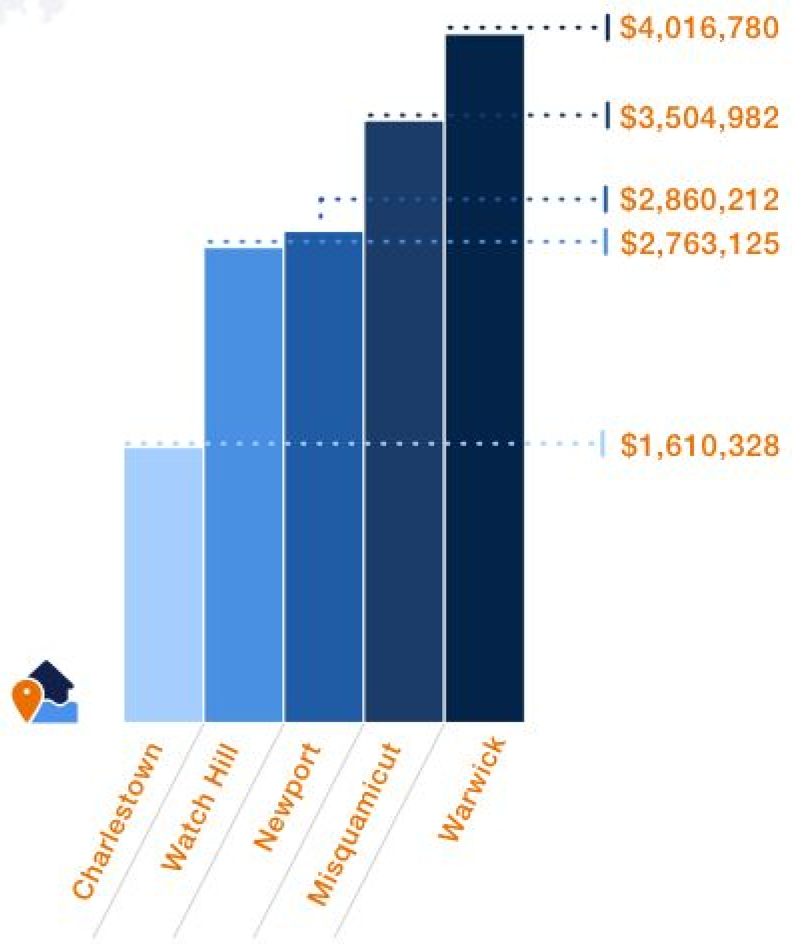
Depth of Flooding (feet)
■ <1 ■ 1 - 2 ■ 2 - 3 ■ 3+

City: Salisbury
Street: Cable Ave

Depth of Flooding (feet)
■ <1 ■ 1 - 2 ■ 2 - 3 ■ 3+

FIRST STREET FOUNDATION FirstStreet.org

Rhode Island: Top 5 Hardest Hit Cities



Rhode Island: Top 3 Hardest Hit Homes

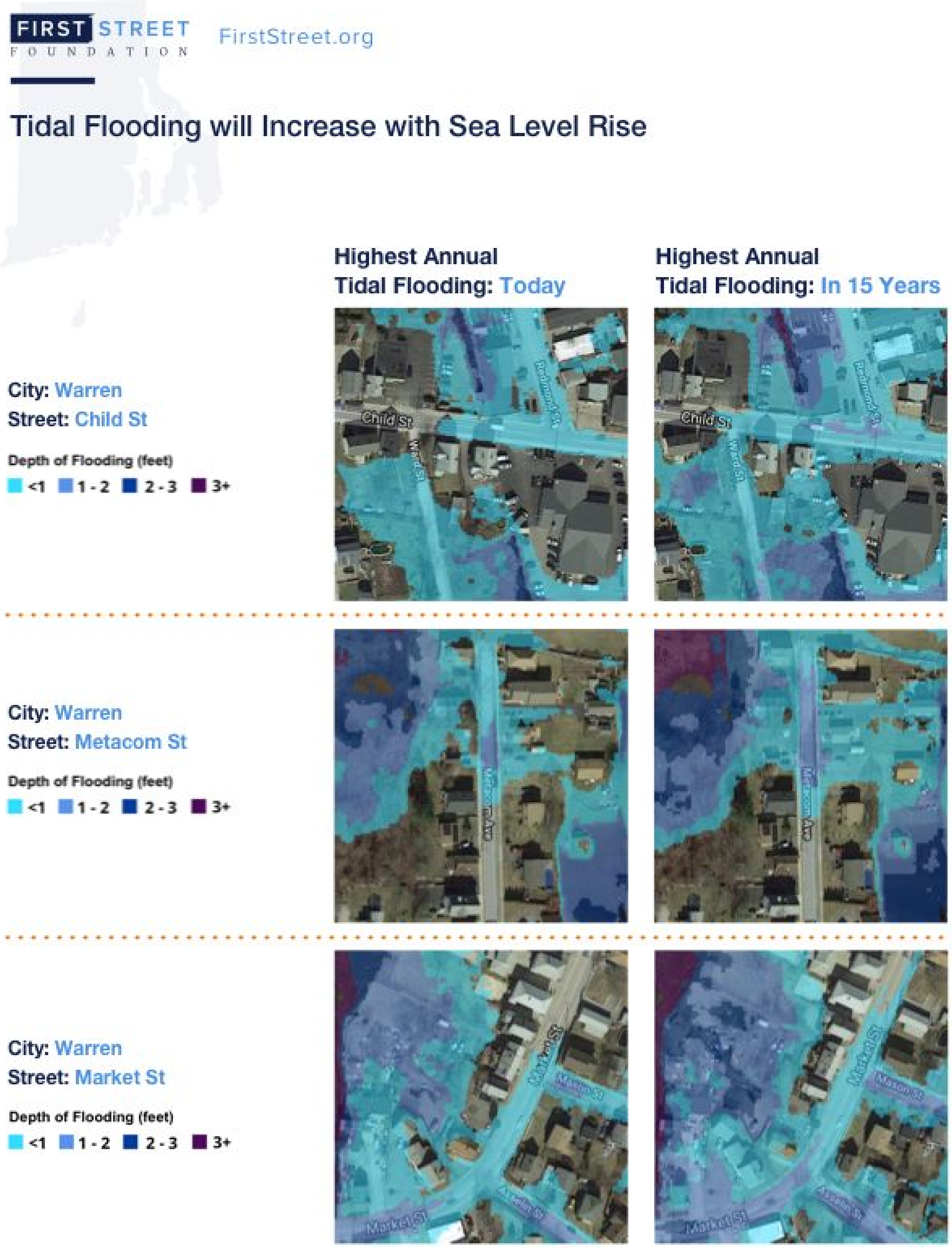
City: Warren
Street: Child St
Tax Assessed Value: $179,300
Should be Worth: $294,148
Relative Value Loss: -$114,848

City: Warren
Street: Metacom St
Tax Assessed Value: $130,700
Should be Worth: $213,373
Relative Value Loss: -$82,673

City: Warren
Street: Market St
Tax Assessed Value: $131,500
Should be Worth: $205,699
Relative Value Loss: -$74,199

FIRST STREET
FOUNDATION

Media Contact:
Carolyn Costello
323.384.7098
carolyn@firststreet.org



FIRST STREET FOUNDATION FirstStreet.org

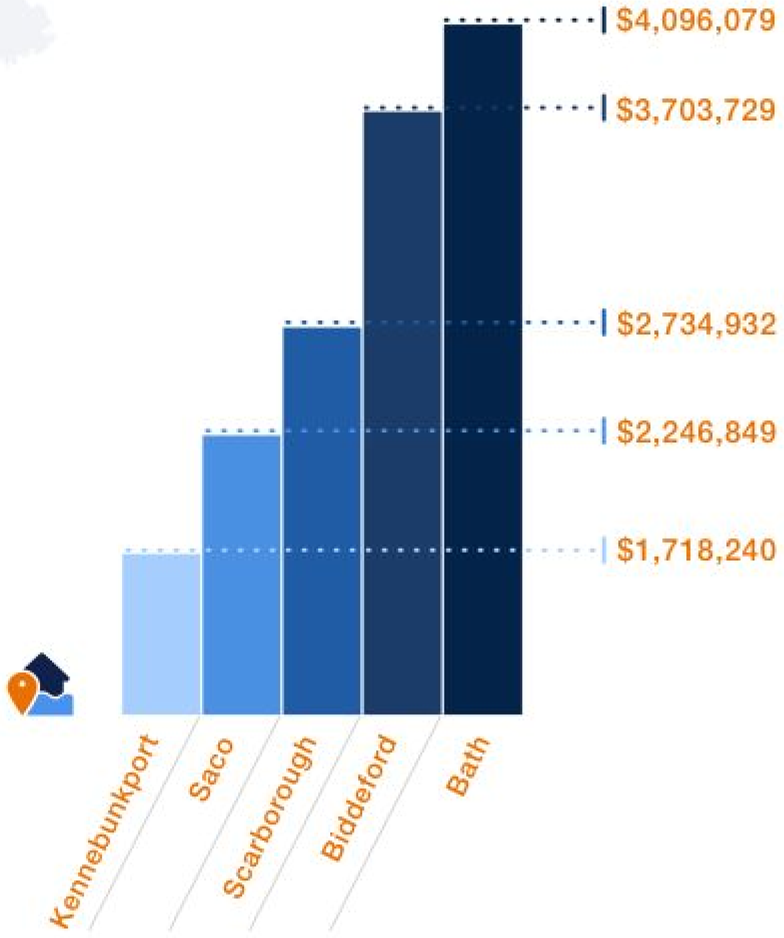
Tidal Flooding will Increase with Sea Level Rise

	Highest Annual Tidal Flooding: Today	Highest Annual Tidal Flooding: In 15 Years
City: Warren Street: Child St Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		
City: Warren Street: Metacom St Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		
City: Warren Street: Market St Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		

Media Contact:
Carolyn Costello
323.384.7098
carolyn@firststreet.org

FIRST STREET FOUNDATION FirstStreet.org

Maine: Top 5 Hardest Hit Cities



Maine: Top 3 Hardest Hit Homes

City: Scarborough
Street: E Grand Ave
Tax Assessed Value: $117,100
Should be Worth: $248,556
Relative Value Loss: -$131,456

City: Bath
Street: Varney Mill Rd
Taxed Assess Value: $92,900
Should be Worth: $150,674
Relative Value Loss: -$57,774

City: Bath
Street: Washington St
Taxed Assessed Value: $93,800
Should be Worth: $145,898
Relative Value Loss: -$52,098

FIRST STREET FOUNDATION

Media Contact:
Carolyn Costello
323.384.7098
carolyn@firststreet.org

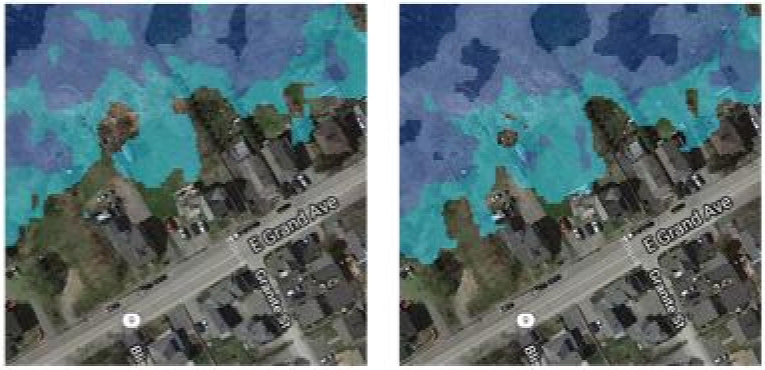
FIRST STREET FOUNDATION FirstStreet.org

Tidal Flooding will Increase with Sea Level Rise

Highest Annual Tidal Flooding: Today | **Highest Annual Tidal Flooding:** In 15 Years

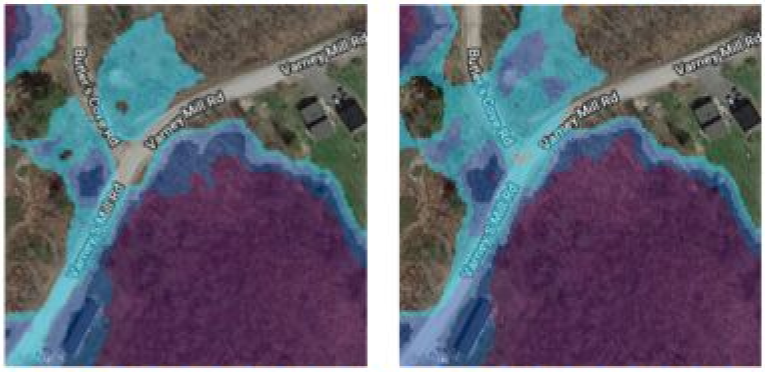
City: Scarborough
Street: E Grand Ave

Depth of Flooding (feet)
■ <1 ■ 1-2 ■ 2-3 ■ 3+



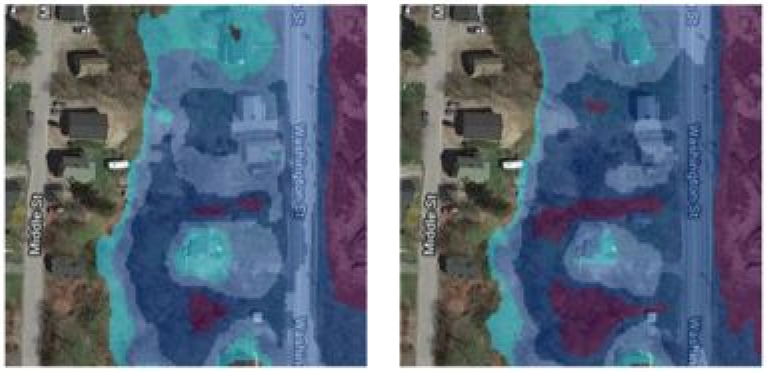
City: Bath
Street: Varney Mill Rd

Depth of Flooding (feet)
■ <1 ■ 1-2 ■ 2-3 ■ 3+



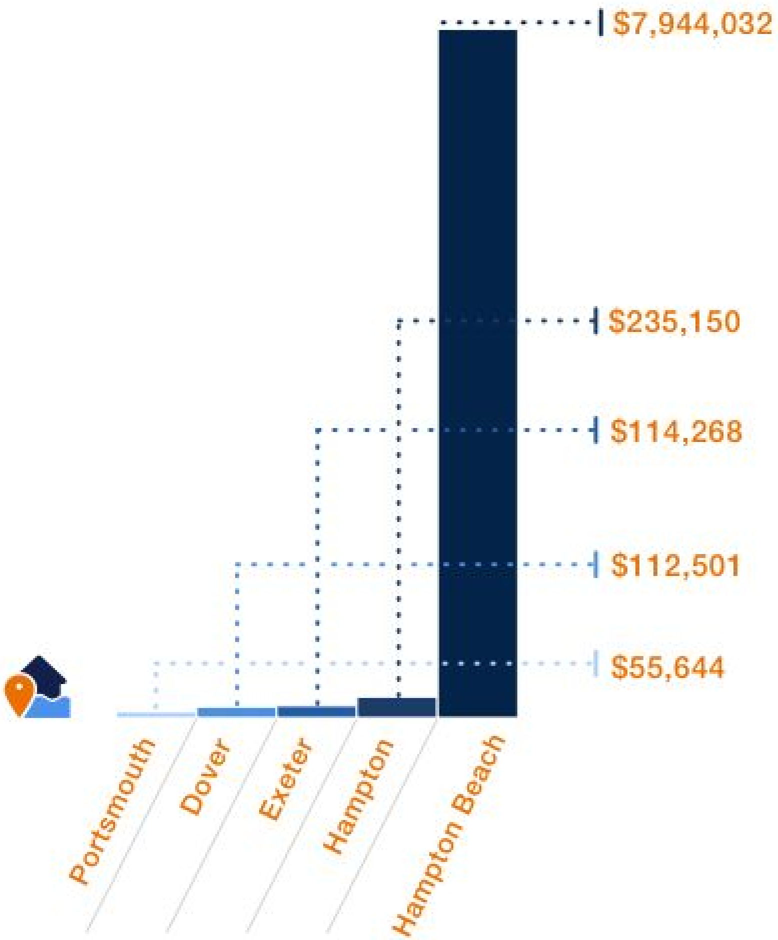
City: Bath
Street: Washington St

Depth of Flooding (feet)
■ <1 ■ 1-2 ■ 2-3 ■ 3+



FIRST STREET FOUNDATION FirstStreet.org

New Hampshire: Top 5 Hardest Hit Cities



New Hampshire: Top 3 Hardest Hit Homes

City: Hampton Beach
Street: Page Ln
Tax Assessed Value: $516,800
Should be Worth: $841,066
Relative Value Loss: -$324,266

City: Hampton Beach
Street: Perkins Ave
Tax Assessed Value: $560,700
Should be Worth: $840,406
Relative Value Loss: -$279,706

City: Hampton Beach
Street: Wall St
Tax Assessed Value: $236,800
Should be Worth: $425,731
Relative Value Loss: -$188,931

FIRST STREET
FOUNDATION

Media Contact:
Carolyn Costello
323.384.7098
carolyn@firststreet.org

FIRST STREET FOUNDATION FirstStreet.org

Tidal Flooding will Increase with Sea Level Rise

	Highest Annual Tidal Flooding: Today	**Highest Annual Tidal Flooding:** In 15 Years
City: Hampton Beach **Street:** Page Ln Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		
City: Hampton Beach **Street:** Perkins Ave Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		
City: Hampton Beach **Street:** Wall St Depth of Flooding (feet) 🟦 <1 🟦 1 - 2 🟦 2 - 3 🟪 3+		

FIRST STREET FOUNDATION

Media Contact
Carolyn Costello
323.384.7098
carolyn@firststreet.org

Sea Level Rise Sinks Mississippi Home Values by More Than $263 Million

For Immediate Release: December 3, 2018

Scientists from First Street Foundation and Columbia University analyzed recent housing market trends in Mississippi and found home values lost $263.8 million from 2005 to 2017 due to sea level rise flooding. Bay St. Louis showed the greatest property value loss, totaling $95.4 million. There, the average impacted home would be worth 49% more if tidal flooding were not a risk. Pass Christian had the second highest loss at $26.8 million, followed by Kiln at $24.9 million. Homeowners can use FloodiQ.com to look up their personal home value loss as well as the total loss for their city.

The Mississippi analysis expands on the Foundation's previous research on other states which has been widely covered by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor.

The research is based on peer reviewed methodology, established by Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant. Their original analysis of the Miami-Dade County real estate market, published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 15 housing market-specific models to cover Florida, Georgia, South Carolina, North Carolina, Virginia, as well as New York, New Jersey, Connecticut, Mississippi and Alabama. By analyzing approximately 10 million real estate transactions, and applying the results to 20 million properties, the researchers have found a $14.6 billion loss in home values across those ten states.

The Mississippi findings come from a study that also analyzed home values in Alabama. That state lost $157 million in home values due to sea level rise flooding. The Alabama results have also been integrated into First Street's Flood iQ tool.

McAlpine and Porter's research is the first to quantify the observed negative impact of sea level rise on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value. While some of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding.

"In Bay St. Louis the average impacted home would be worth 49% more if tidal flooding were not a risk, and in Kiln 41% more," said McAlpine. "These are the hardest hit neighborhoods in Mississippi because homes and roads are at low elevations and sea level rise is increasing the frequency of flooding along the Jourdan River."

The research is also the first to find that in addition to direct property-lot flooding, nearby road flooding also has a major impact on home value.

"As we have expanded our study, the results have been incredibly consistent," said Porter. "Americans across 10 states have already lost $14.6 billion from increased flooding caused by sea level rise, and all signs are pointing to this being an accelerating trend."

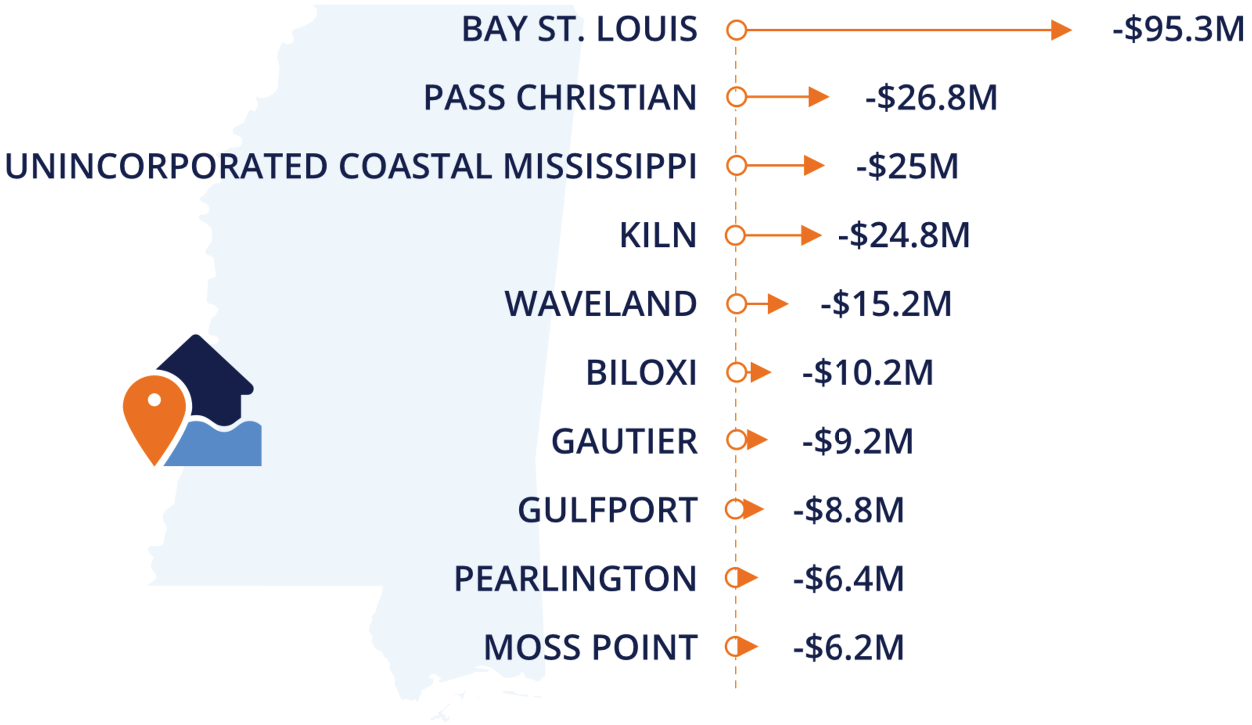
"What has made this research truly striking for people is its integration with Flood iQ," said Matthew Eby, Executive Director of First Street Foundation."People can look up their personal addresses and learn just how much value they have lost due to sea level rise flooding. It's powerful, and in some cases, devastating."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

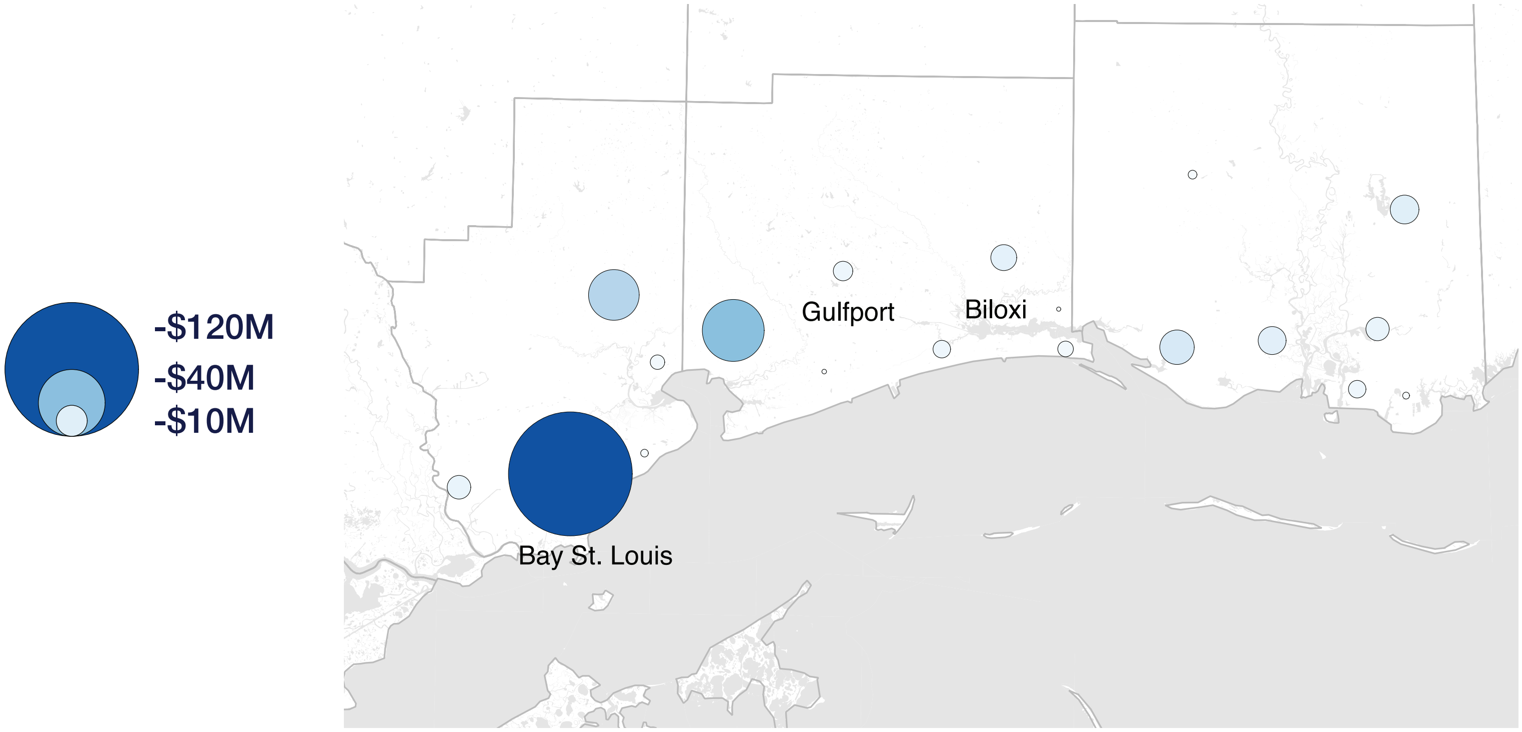
Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

Top Ten Impacted Mississippi Cities



• • •

Mississippi Property Loss by Zip Code



FIRST STREET FOUNDATION | FirstStreet.org

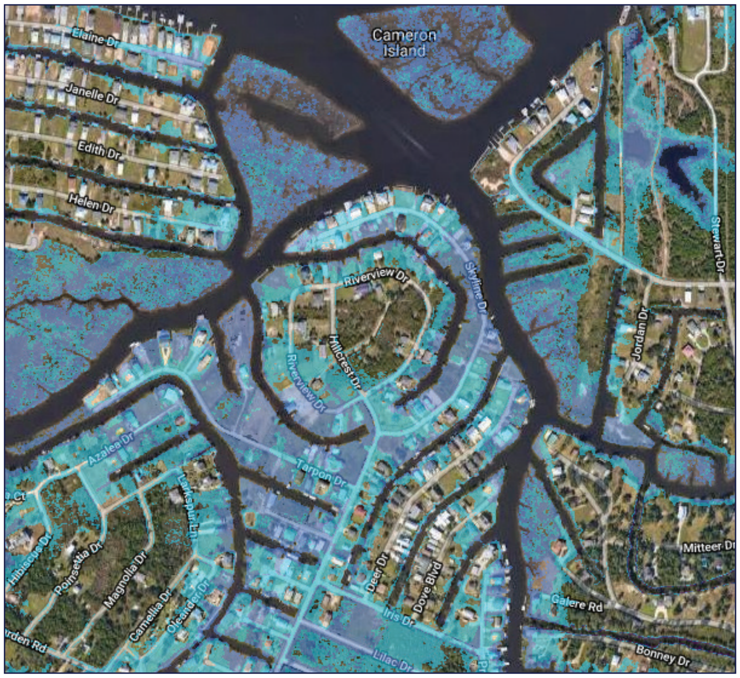
Bay St. Louis Tidal Flooding Today and in 15 Years

A:
Shoreline Park
Frequent Tidal Flooding Today

A:
Shoreline Park
Frequent Tidal Flooding in 15 Years

B:
Shoreline Park
Frequent Tidal Flooding Today

B:
Shoreline Park
Frequent Tidal Flooding in 15 Years



FIRST STREET
FOUNDATION

Media Contact
Carolyn Costello
323.384.7098
carolyn@firststreet.org

Sea Level Rise Sinks Alabama Home Values by More Than $157 Million

For Immediate Release: December 3, 2018

Scientists from First Street Foundation and Columbia University analyzed recent housing market trends in Alabama and found home values lost $157.9 million from 2005 to 2017 due to sea level rise flooding. The unincorporated area of Mobile Bay saw the greatest loss at $46.7 million, followed by Gulf Shores at $26.1 million, and Mobile at $25.9 million. Homeowners can use FloodiQ.com to look up their personal home value loss as well as the total loss for their city.

The Alabama analysis expands on the Foundation's previous research across other states which has been widely covered by The Wall Street Journal, Bloomberg, Axios, The Washington Post, and The Christian Science Monitor.

The research is based on peer reviewed methodology, established by Steven A. McAlpine, Head of Data Science at First Street Foundation, and Dr. Jeremy R. Porter, a Columbia University professor and First Street Foundation statistical consultant. Their original analysis of the Miami-Dade County real estate market, published in the journal *Population Research and Policy Review*, showed $465 million was lost from 2005 to 2016 due to sea level rise flooding. McAlpine and Porter have since created 15 housing market-specific models to cover Florida, Georgia, South Carolina, North Carolina, Virginia, as well as New York, New Jersey, Connecticut, Mississippi and Alabama. By analyzing approximately 10 million real estate transactions, and applying the results to 20 million properties, the researchers have found a $14.6 billion loss in home values across ten states.

The Alabama findings come from a study that also analyzed home values in Mississippi. That state lost more than $263 million in value due to sea level rise flooding. The Mississippi results have also been integrated into First Street's Flood iQ tool.

McAlpine and Porter's research is the first to quantify the observed negative impact of sea level rise on the housing market. Other models have forecasted the future impact of sea level rise flooding on coastal properties, but this is the first to demonstrate value loss that has already occurred. By taking into account characteristics associated with home value, such as square footage and proximity to amenities, and accounting for economic trends like the 2008 housing recession, the scientists were able to isolate the impact that increased frequent tidal flooding, caused by sea level rise, has had on home value. While some of the affected homes did appreciate over the studied period, they did so at a significantly lower rate than comparable homes unaffected by tidal flooding.

"People like living by the water," said McAlpine. "In Alabama many of the homes experiencing tidal flooding are beach homes built on stilts, so there is an expectation of flooding to some degree. Still, we are seeing value loss due to the increasing frequency and severity of flooding as people look to buy at higher elevations."

"All signs point to this being an accelerating trend," said Porter. "As we have expanded our study, the results have been incredibly consistent. Americans across 10 states have lost $14.6 billion from increased flooding caused by sea level rise."

The research is also the first to find that in addition to direct property-lot flooding nearby road flooding also has a major impact on home value.

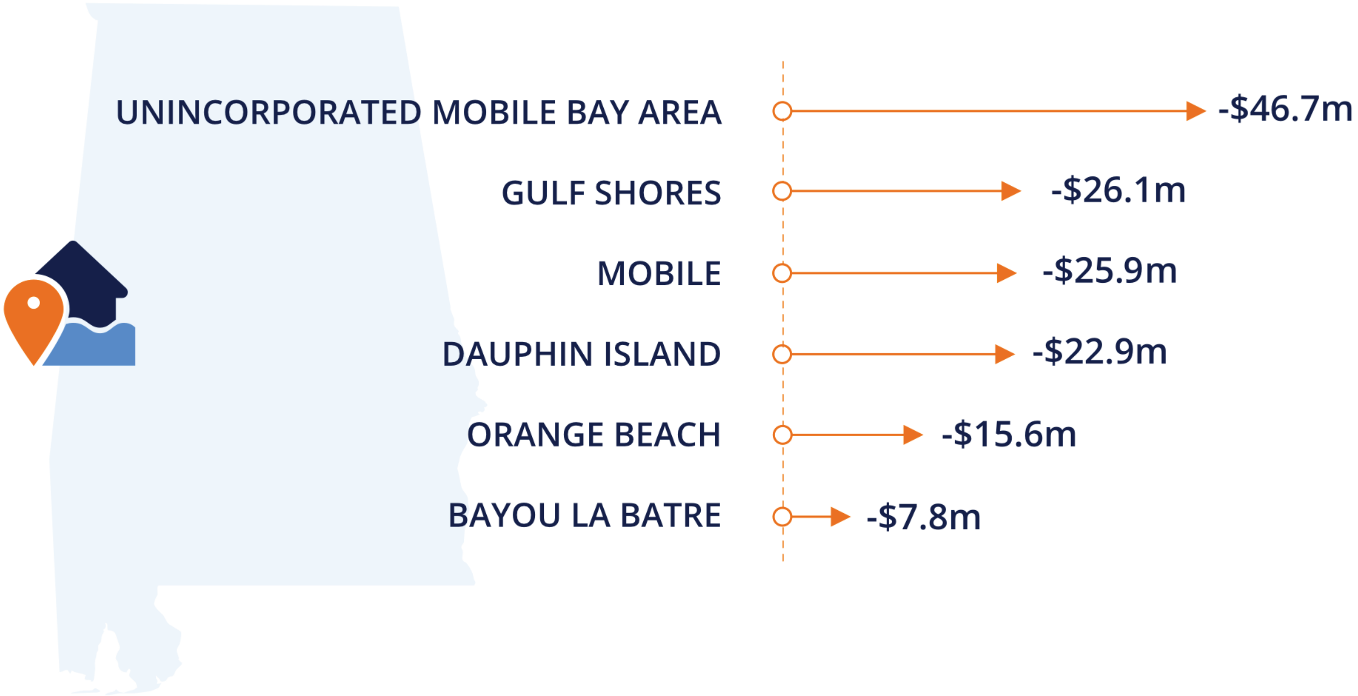
"What has made this research truly striking for people is its integration with Flood iQ," said Matthew Eby, Executive Director of First Street Foundation." People can look up their personal addresses and learn just how much value they have lost due to sea level rise flooding. It's powerful, and in some cases, devastating."

• • •

First Street Foundation is a 501(c)(3) tech nonprofit that quantifies and communicates the impacts of sea level rise and flooding.

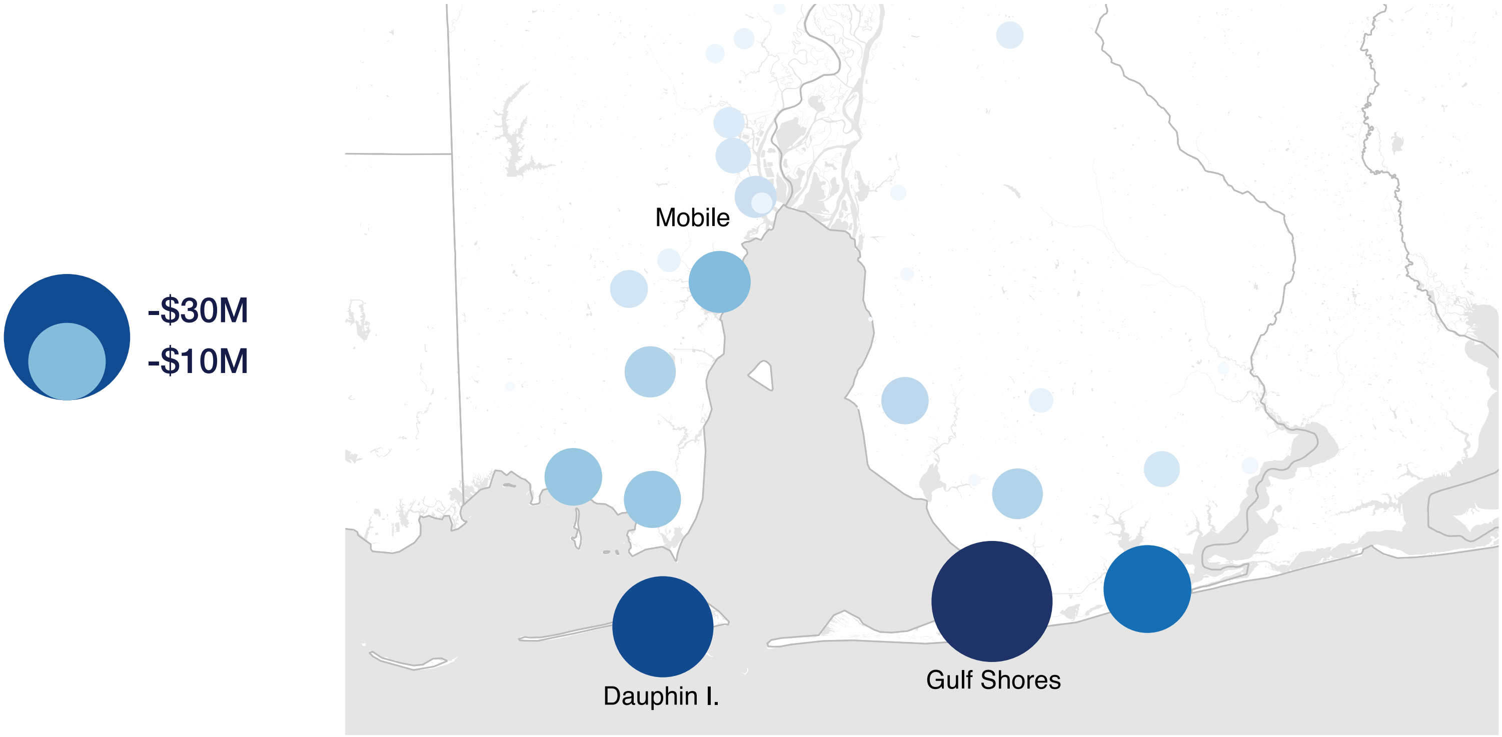
Flood iQ visualizes your risk of flooding today and up to 15 years in the future as sea levels rise.

Alabama Cities With Loss Above $5 Million



• • •

Alabama Property Loss by Zip Code

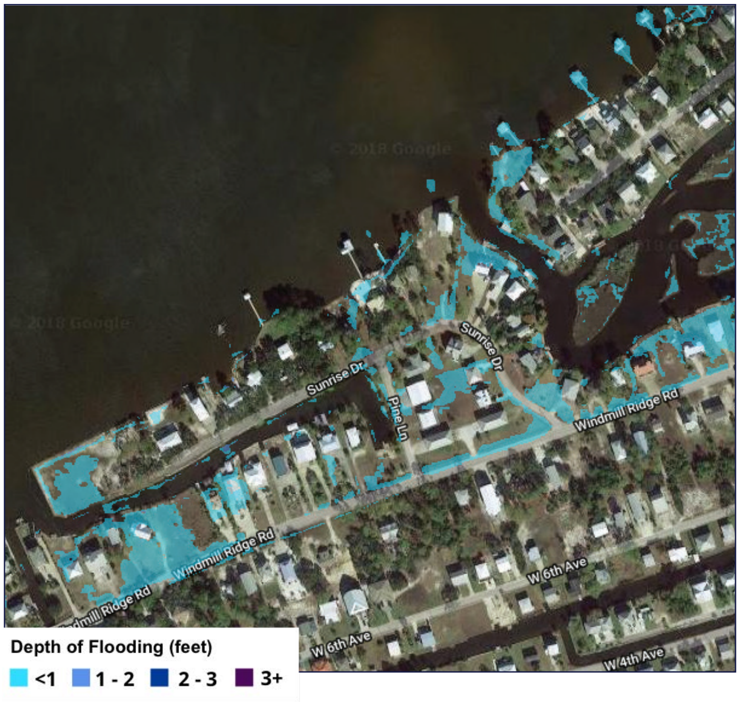


FIRST STREET
FOUNDATION

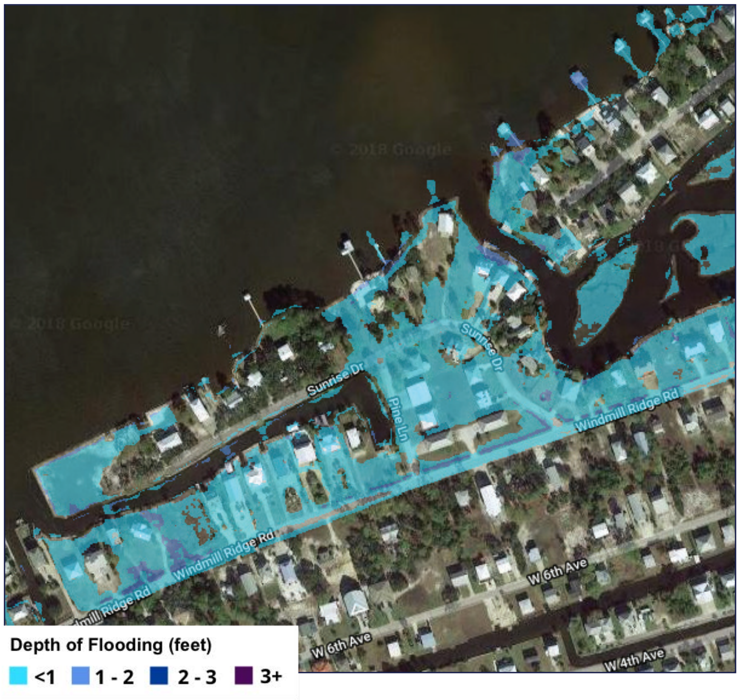
FirstStreet.org

Alabama Flooding Will Get Worse with Sea Level Rise

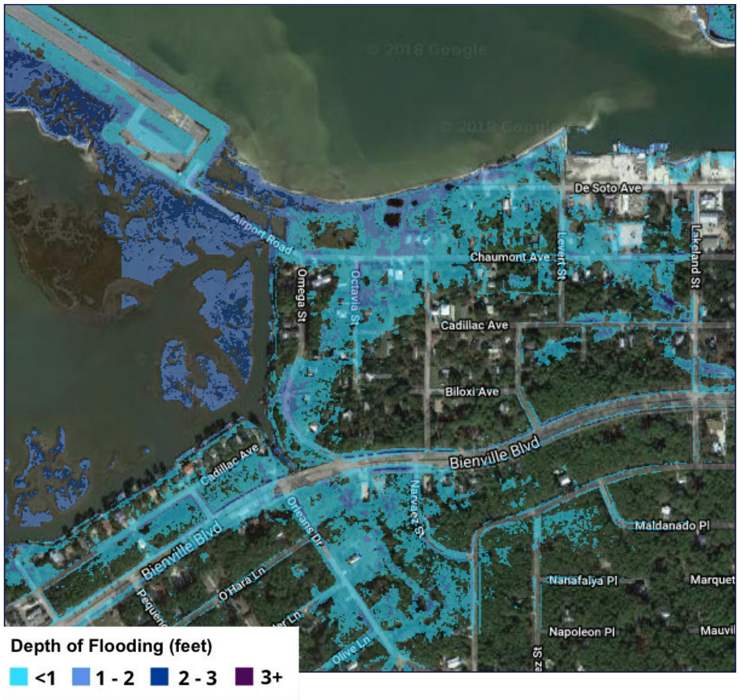
A:
Gulf Shores
Highest Annual Tidal Flooding Today



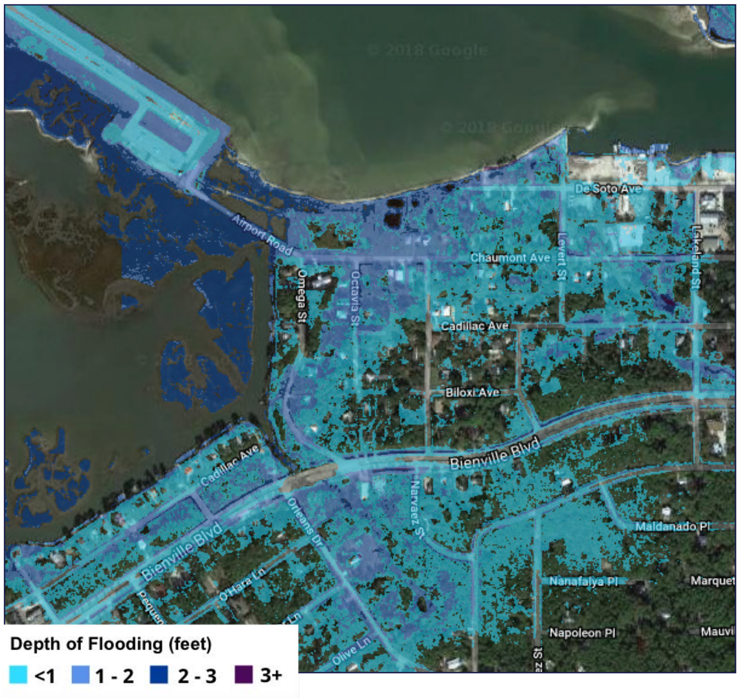
A:
Gulf Shores
Highest Annual Tidal Flooding in 15 Years



B:
Dauphin Island
Highest Annual Tidal Flooding Today



B:
Dauphin Island
Highest Annual Tidal Flooding in 15 Years



This is a tab page.
Please title tab
“Moody’s”

MOODY'S
INVESTORS SERVICE

Announcement: Moody's: Climate change is forecast to heighten US exposure to economic loss placing short- and long-term credit pressure on US states and local governments

28 Nov 2017

New York, November 28, 2017 -- The growing effects of climate change, including climbing global temperatures, and rising sea levels, are forecast to have an increasing economic impact on US state and local issuers. This will be a growing negative credit factor for issuers without sufficient adaptation and mitigation strategies, Moody's Investors Service says in a new report.

The report differentiates between climate trends, which are a longer-term shift in the climate over several decades, versus climate shock, defined as extreme weather events like natural disasters, floods, and droughts which are exacerbated by climate trends. Our credit analysis considers the effects of climate change when we believe a meaningful credit impact is highly likely to occur and not be mitigated by issuer actions, even if this is a number of years in the future.

Climate shocks or extreme weather events have sharp, immediate and observable impacts on an issuer's infrastructure, economy and revenue base, and environment. As such, we factor these impacts into our analysis of an issuer's economy, fiscal position and capital infrastructure, as well as management's ability to marshal resources and implement strategies to drive recovery.

Extreme weather patterns exacerbated by changing climate trends include higher rates of coastal storm damage, more frequent droughts, and severe heat waves. These events can also cause economic challenges like smaller crop yields, infrastructure damage, higher energy demands, and escalated recovery costs.

"While we anticipate states and municipalities will adopt mitigation strategies for these events, costs to employ them could also become an ongoing credit challenge," Michael Wertz, a Moody's Vice President says. "Our analysis of economic strength and diversity, access to liquidity and levers to raise additional revenue are also key to our assessment of climate risks as is evaluating asset management and governance."

One example of climate shock driving rating change was when Hurricane Katrina struck the City of New Orleans (A3 stable). In addition to widespread infrastructure damage, the city's revenue declined significantly and a large percentage of its population permanently left New Orleans.

"US issuer resilience to extreme climate events is enhanced by a variety of local, state and federal tools to improve immediate response and long-term recovery from climate shocks," Wertz says.

For issuers, the availability of state and federal resources is an important element that broadens the response capabilities of local governments and their ability to mitigate credit impacts. As well, all municipalities can benefit from the deployment of broader state and federal aid, particularly disaster aid from the Federal Emergency Management Agency (FEMA) to help with economic recovery.

Moody's analysts weigh the impact of climate risks with states and municipalities' preparedness and planning for these changes when we are analyzing credit ratings. Analysts for municipal issuers with higher exposure to climate risks will also focus on current and future mitigation steps and how these steps will impact the issuer's overall profile when assigning ratings.

The report "Environmental Risks -- Evaluating the impact of climate change on US state and local issuers," is available to Moody's subscribers at http://www.moodys.com/researchdocumentcontentpage.aspx?docid=PBM_1071949.

****

NOTE TO JOURNALISTS ONLY: For more information, please call one of our global press information hotlines: New York +1-212-553-0376, London +44-20-7772-5456, Tokyo +813-5408-4110, Hong Kong +852-3758-1350, Sydney +61-2-9270-8141, Mexico City 001-888-779-5833, São Paulo 0800-891-2518, or Buenos Aires 0800-666-3506. You can also email us at mediarelations@moodys.com or visit our web site at

This is a tab page.
Please title tab
“Ouazad”

Mortgage Finance in the Face of Rising Climate Risk[*]

Amine Ouazad[†] Matthew E. Kahn[‡]

September 2019

Released as NBER Working Paper 26322 on September 30, 2019

Abstract

Recent evidence suggests an increasing risk of natural disasters of the magnitude of hurricane Katrina and Sandy. Concurrently, the number and volume of flood insurance policies has been declining since 2008. Hence, households who have purchased a house in coastal areas may be at increasing risk of defaulting on their mortgage. Commercial banks have the ability to screen and price mortgages for flood risk. Banks also retain the option to securitize some of these loans. In particular, bank lenders may have an incentive to sell their worse flood risk to the two main agency securitizers, the Federal National Mortgage Association, commonly known as Fannie Mae, and the Federal Home Loan Mortgage Corporation, known as Freddie Mac. In contrast with commercial banks, Fannie and Freddie follow observable rules set by the FHFA for the purchase and the pricing of securitized mortgages. This paper uses the impact of one such sharp rule, the conforming loan limit, on securitization volumes. We estimate whether lenders' sales of mortgages with loan amounts right below the conforming loan limit increase significantly after a natural disaster that caused more than a billion dollar in damages. Results suggest a substantial increase in securitization activity in years following such a billion-dollar disaster. Such increase is larger in neighborhoods for which such a disaster is "new news", i.e. does not have a long history of hurricanes. Conforming loans are riskier in dimensions not observed in publicly available data sets: the borrowers have lower credit scores and they are more likely to become delinquent or default. A structurally estimated model of mortgage pricing with asymmetric information suggests that bunching at the conforming loan limit is an increasing function of perceived price volatility and declining price trends. A simulation of the impact of increasing climate risk on mortgage origination volumes with and without the GSEs suggests that the GSEs may act as an implicit insurer, i.e a substitute for the declining National Flood Insurance Program.

---

[*] We would like to thank Asaf Bernstein, Thomas Davidoff, Matthew Eby, Ambika Gandhi, Richard K. Green, Jesse M. Keenan, Michael Lacour-Little, Tsur Sommerville, Susan Wachter, for comments on early versions of our paper, as well as the audience of the 2018 annual meeting of the Urban Economics Association at Columbia University, Stanford University's Hoover Institution, the Urban Economics Conference in Montreal. The usual disclaimers apply.

[†] HEC Montreal, 3000 Chemin de la Côte Sainte Catherine, Montreal H2T 2A7. *amine.ouazad@hec.ca*

[‡] Johns Hopkins University, Carey School of Business. *mkahn10@jhu.edu.*

1 Introduction

Place-based asset purchases such as real estate are likely to be exposed to increasing risk in a world confronting ambiguous climate change. Standard financial arguments would argue that such risk, if idiosyncratic, can be diversified away. Yet a host of politically popular subsidies and institutions encourage households to invest in homes as their primary source of wealth. Lenders and government sponsored enterprises play a key role in providing the capital to allow households to bid and purchase such place-based wealth, totaling 27.5 trillion dollars in value and 10.9 trillion dollars of debt as of 2019Q1.[1] While the climate change economics literature has explored how real estate prices reflect emerging climate risk (Bakkensen & Barrage 2017, Ortega & Taşpınar 2018, Zhang & Leonard 2018, Bernstein, Gustafson & Lewis 2019), we know little about how the mortgage industry responds.

Recent evidence suggests an increasing risk of natural disasters along the east coast: the empirical analysis of Bender, Knutson, Tuleya, Sirutis, Vecchi, Garner & Held (2010) predicts a doubling of category 4 and 5 storms by the end of the 21st century in moderate scenarios. Lin, Kopp, Horton & Donnelly (2016) suggests that, in the New York area, the return period of Hurricane Sandy's flood height is estimated to decrease 4 to 5 times between 2000 and 2100.[2] Gallagher & Hartley's (2017) analysis of Hurricane Katrina suggests that insurance payments due to the federal government's National Flood Insurance Program (NFIP) led to *reductions* in debt. Yet, both the number of NFIP flood insurance policies and their total dollar amount have declined substantially since 2006 (Kousky 2018), leading to potentially greater losses for mortgage lenders. With the future of flood insurance in doubt, two key issues arise (i) whether mortgage lenders will transfer default risk due to floods to the two large securitizers Fannie Mae and Freddie Mac, and hence whether the two GSEs act as *de facto* insurers, and (ii) whether their role incentivizes households to borrow to locate in flood prone parcels.

Such natural disasters may cause losses to mortgage lenders either due to an increasing probability of household default, or, when households are insured, through an increasing probability of prepayment.[3] The impact of natural disasters varies substantially across neighborhoods at a local scale (Masozera, Bailey & Kerchner 2007, Vigdor 2008). Hence, the screening of mortgages for securitization may not fully take into

---

[1] Source: Quarterly Financial Accounts of the United States.

[2] Other key papers predict a similar increase in natural disaster risk over the course of the 21st century (Webster, Holland, Curry & Chang 2005, Elsner 2006, Mann & Emanuel 2006, Garner, Mann, Emanuel, Kopp, Lin, Alley, Horton, DeConto, Donnelly & Pollard 2017, Lin, Emanuel, Oppenheimer & Vanmarcke 2012, Grinsted, Moore & Jevrejeva 2013, Lin et al. 2016).

[3] While securitization insures the lender against the risk of default, prepayments are typically "passed through" back to the lender. The paper suggests that default risk is a significantly higher risk than prepayment risk.

account the risk of natural disasters attached to a particular house and a particular mortgage. As local lenders with access to better information relating to the local impact and occurrence of natural disasters may securitize mortgages that are unobservably worse risk, a '*market for lemons*' in climate risk could develop as a potential threat to the stability of financial institutions. In particular, the mispricing of disaster risk, either because of a mispricing of mortgage default or a mispricing of prepayment risk; and the correlation of such natural disaster risk across loans in a mortgage pool can together be a substantial source of aggregate risk for holders of mortgage backed securities.

This paper focuses on the impact of 15 "Billion-dollar events" on banks' securitization activity; and whether mortgages securitized in areas prone to natural disaster risk are worse risk for financial institutions that hold them in securitized mortgage pools. Billion-dollar events have caused at least a billion dollar of losses as estimated by the National Oceanic and Atmospheric Administration (Smith & Katz 2013). Two of the largest purchasers of securitized mortgages are the Government Sponsored Enterprises (GSEs) Fannie Mae and Freddie Mac: in 2008, they held or guaranteed about $5.2 trillion of home mortgage debt (Frame, Fuster, Tracy & Vickery 2015). The GSEs adopt specific sets of observable rules when screening mortgages for purchase. One such rule is based on the size of the loan: GSEs purchase conforming loans, whose loan amount does not exceed a limit set nationally. The conforming loan limit is a single limit set by the FHFA until 2008, and only two different limits set by Congress, the FHFA, and then the CFPB after 2008. As this national limit varies over time, this offers a unique opportunity to estimate lenders' response to shifts in their incentives to securitize mortgages. Previous literature suggests that the discontinuity in securitization costs at the limit causes a bunching in the number of originated mortgages right below the conforming loan limit (DeFusco & Paciorek 2017). Yet, it is not known whether (i) natural disaster risk leads to a shift in lenders' incentives to securitize, (ii) whether securitized loans right below the conforming loan limit are worse default or worse prepayment risk, (iii) whether securitization volumes will increase as we likely face rising disaster risk, and (iv) in the counterfactual scenario where the GSEs would withdraw from risky areas, whether lenders would bear the risk of default, adjust their interest rates and possibly lower their origination volumes. In particular, as local loan officers have discretion over the characteristics of the mortgages sold for securitization, the GSEs' guidelines for securitization do not rely on the on-the-ground information of loan officers and may not take into account local climate risk as accurately as the local loan officer with better knowledge of the future distribution of house prices, e.g. for houses near the bank's branch network. Lenders can securitize jumbo mortgages to other, non-GSE, securitizers called Private Label Securitizers (PLS). Yet evidence suggests that the private label securitization market is small and does not represent a significative alternative (Goodman 2016).

This paper's identification strategy combines a regression discontinuity design at the conforming loan limit with a difference-in-difference setup comparing the magnitude of the discontinuity in mortgage loan density at the limit before and after a billion dollar natural disaster. The discontinuity in density follows the intuition of McCrary's (2008) test and Keys, Mukherjee, Seru & Vig (2010) application to ad-hoc securitization rules. The difference-in-difference approach compares the change in the discontinuity in counties hit by a natural disaster, including Hurricane Sandy, Hurricane Irma, and Hurricane Katrina, with the change in the discontinuity in counties not affected by a natural disaster. The local natural disasters considered in this paper are the 15 largest "billion-dollar events" occuring between 2004 and 2012, and as presented in Smith & Katz (2013) and Weinkle, Landsea, Collins, Musulin, Crompton, Klotzbach & Pielke (2018).

The paper develops a structurally estimated model of monopolistic competition in mortgage pricing with asymmetric information about local default risk and the ability to securitize conforming loans. Such model enables two *out of sample* simulations of the impact of rising disaster risk; and of the impact of such risk in the counterfactual scenario where the GSEs would withdraw from the mortgage market. In the model, bunching and discontinuities at the conforming loan limit are increasing function of lenders' perceived price volatility and declining price trends. The model is estimated using observations at the discontinuity using Gourieroux, Monfort & Renault's (1993) method of indirect inference recently featured in Fu & Gregory (2019). Keeping household preferences and lenders' cost of capital constant, simulations of increasing price volatility and declining price trends provide the two out-of-sample predictions.

Two features of the conforming loan limit are key to the identification of the impact of securitization costs on lenders' activity. First, the conforming loan limit is time-varying. As the limits are set nationally either by the FHFA, by Congress (in 2008), and by the CFPB, they are less likely to be confounded by other regional discontinuities that would also affect the mortgage market for loans of similar amounts. Second, there are two limits starting in 2008: there is a higher limit for "high-cost", as opposed to "general" counties. As those two limits affect different *marginal* borrowers in counties whose house prices are either close or far from the limit, the estimate is more likely to capture an average effect across a large support of borrower and house characteristics.

The impact of billion dollar events on securitization activity is estimated using four different data sets: first, a national data set of all mortgage applications, originations, and securitization purchases between

1995 and 2017 inclusive collected according to the Home Mortgage Disclosure Act (HMDA); second, a loan-level payment history data set with approximately 65% of the mortgage market since 1989, including households' FICO scores, foreclosure events, delinquency, prepayment, and securitization. Third, such data can be matched to the neighborhood (Census tract) of each mortgaged house, and to the lender's identity from the Chicago Federal Reserve's Report of Income and Condition. Fourth, the treatment group of affected neighborhoods is estimated by using the path and impact of hurricanes (wind speed data every 6 hours for all major hurricanes), combined with USGS elevation and land use data that identify disaster-struck coastal areas. The combination of these four data sources enables a neighborhood-level analysis of the impact of 15 billion dollar events on securitization activity, lending standards, and household sorting. The fifth and last data set is the universe of banks' branch network throughout the United States. As bank branches are geolocalized, we can estimate the geographic coverage of a bank's branch network and assess which banks have a branch network that is mostly in counties hit by a billion dollar disaster.

Results suggest that after a billion-dollar event, lenders are significantly more likely to increase the share of mortgages originated and securitized below the conforming loan limit. After a billion-dollar event, the difference in denial rates for conforming loans and jumbo loans increases by 5 percentage points. This leads to a substantial increase in the volume of conforming loans post-billion dollar event. This could be driven by either a retreat to safer mortgages, if conforming loans are safer, or increasing adverse selection, if mortgages sold to the GSEs are riskier. Evidence from the national-level BlackKnight data set suggests that conforming loans are likely *riskier* than jumbo loans and that adverse selection into the conforming loan segment increases after a natural disaster: borrowers are more likely to experience foreclosure at any point post origination; they are more likely to be 60 or 120 delinquent; they have lower FICO scores. Banks that originate conforming loans hold typically less liquidity on their balance sheet, and lenders that originate conforming loans are less likely to be FDIC-insured commercial banks. Interestingly, while the GSEs' guarantee fee (paid by lenders) is a function of observable characteristics such as FICO scores and loan-to-value ratios, there is evidence of significant unpriced unobservable risk, suggesting a mispricing of the cost of securitization.

While analysis suggests no evidence of significant trends prior to a billion-dollar event, there is a statistically and economically significant increase in securitization volumes at the conforming loan limit in years following the event. A billion dollar event has a similar effect on securitization activity as 17% employment decline, which is about twice the standard deviation of employment growth.

The paper's quasi-experimental findings can be used to simulate the impact of future disaster risk on securitization volumes, with and without the GSEs' securitization activity. For this purpose, the paper develops a model of mortgage pricing with asymmetric information, household location choice, and the dynamics of mortgage default. The model is structurally estimated at the discontinuities, in the spirit of Fu & Gregory (2019). The model's out-of-sample simulations suggest that the GSEs' securitization activity, without increasing guarantee fees, stabilizes the mortgage market with little change in interest rates and location choice probabilities. In contrast, increasing disaster risk without the GSEs' securitization activity leads to substantial shifts in households' location choices, interest rates, and origination volumes. The model's findings thus suggest that the GSEs act as an implicit substitute for the National Flood Insurance Program, and do not provide significant incentives to either lenders or households to choose different locations and mortgage amounts when facing increasing climate risk.

This paper contributes to at least three literatures. First, the literature on adverse selection in the mortgage securitization market. As the GSEs' securitization rules rely on a finite vector of observable loan, borrower, and collateral characteristics, lenders may not have an incentive to collect the full range of private information prior to originating loans, including collecting local information about climate risk. If mortgage lenders couldn't securitize loans and sell them, then they would have strong incentives to use their scale and their human capital to assess what risks are entailed by lending funds for 30-year fixed rate mortgages. Such market discipline is especially valuable when there is ambiguous risk and heterogeneity among buyers in their risk assessments (Bakkensen & Barrage 2017). Results of this paper suggest the ability to securitize may weaken the discipline brought about by the mortgage finance industry in fostering climate change adaptation. In contrast with Keys et al. (2010), this paper focuses on defaults implied by the strongly correlated, arguably upward-trending climate risk that is likely harder to hedge than idiosyncratic household-specific income shocks. Systematic aggregate income risk is present in the real estate literature since at least Shiller (1995). Banking regulators may need to take into account the new kind of systemic financial risk caused by local natural disasters (Carney 2015).

This paper also contributes to the literature on financial risk propagation. This paper's results suggest that participants in financial markets should likely track the contagion of climate risk. As we show that such billion dollar events affects aggregate banks' balance sheets, this paper makes a link between the literature on local natural disasters and the literature on the transmission of risks in the financial sector through banks' balance sheets. A rapidly expanding literature (Elliott, Golub & Jackson 2014, Acemoglu, Ozdaglar & Tahbaz-Salehi 2015, Heipertz, Ouazad & Rancière 2019) uses microdata on security-level holdings of assets and the supply of liabilities to estimate whether and how networks amplify financial shocks on individual banks. In this paper, we find that natural disaster risk is a shock to expected mortgage returns that increases the return to securitization. As the suggestive evidence presented in this paper indicates that the risk of such newly-originated mortgages is higher, this suggests caution for securitizers and financial institutions connected to these exposed banks.

Finally, this paper presents another consequence of increasing local natural disaster risk. As an expanding literature studies the housing market's equilibrium pricing of natural disaster risk (Bakkensen & Barrage 2017, Ortega & Taṣpınar 2018, Zhang & Leonard 2018) this paper focuses on a potential *mispricing* of assets vulnerable to natural disaster risk: securitizers' guarantee fees may not be an accurate reflection of mortgage risk. While accurately-priced risk and returns are part of the typical formula for financial portfolio composition (Markowitz 1952), the mispricing of mortgage risk, carried onto securitizers' balance sheets, can be a source of unhedged and unanticipated systemic risk. The structural model presented in this paper simulates the evolution of a counterfactual endogenous GSE guarantee fee that reflects the increase in natural disaster risk.

The paper is organized as follows. Section 2 presents a simple conceptual framework that ties expected risk to securitization volumes. Section 3 describes the three sources of data used in this paper's analysis: a loan-level data set with monthly payment history information; a billion-dollar disaster dataset paired with blockgroup-level elevation, hurricane wind speeds, and land use information; and a bank-level data set with geocoded branch networks. Section 3 also presents evidence of negative selection into securitization at the conforming loan limit. Section 4 estimates the impact of natural disasters on securitization volumes using an identification strategy that combines time-varying discontinuities with a difference-in-difference approach. Section 5 suggests that results are driven by changes in lenders' beliefs about future risks. Section 6 presents and structurally estimates a model of mortgage pricing with asymmetric information and the ability to securitize mortgages. Such model then provides the main out-of-sample simulations: (i) increasing risk, (ii) withdrawal of the GSEs, (iii) endogenous guarantee fee. Section 7 concludes.

2 Basic Mechanism and Empirical Predictions

We present here the basic mechanisms of a model of mortgage pricing with asymmetric information about default risk. The key observation is that the government sponsored enterprises' rules for securitizing loans include a strict upper bound on securitizable loan amounts, called the conforming loan limit. This affects the lender's optimal menu of mortgage interest rates and thus also affects households' self-selection into mortgage options. Such a simple model yields empirical predictions.

First, the model implies that the lender's optimal menu of mortgage payments and loan amounts will induce bunching at the conforming loan limit.[4] The bunching of loans at the conforming loan limit is positively related to the value of the securitization option. The value of the securitization is the difference between the profit of originating and securitizing and the profit of originating and holding a mortgage. Second, under mild and fairly general assumptions, *increases* in bunching reveal increases in the value of the securitization option for *lenders*, even after accounting for the endogeneity of household sorting at the limit. Third, increases in *households'* perceived disaster risk leads to demand for higher loan amounts and *less* bunching. Such three observations are formalized below.

The Lender's Menu of Mortgage Options

A lender faces a heterogeneous set of households indexed by $\theta \in [\underline{\theta}, \overline{\theta}]$ with density $f(\theta)$. Household θ's default rate $d(\theta)$ is an increasing function of the household's type. The lender offers a menu of loan sizes and mortgage payments (L, m). The profit $\pi(L, m; \theta)$ of the lender depends on the loan amount L, the mortgage payment m and the household type θ. The household derives positive utility from a larger loan size (at given payment m) and incurs a disutility $v(m, \theta)$ of mortgage payments; such disutility is decreasing in the type: households with higher expected probability of default incur less disutility of mortgage payments, $\partial v/\partial\theta < 0$. Such disutility is increasing in the mortgage payment, $\partial v/\partial m > 0$. Finally the disutility is convex in the type $\partial^2 v/\partial\theta^2 > 0$. If the household does not take up any loan, she gets utility $\underline{V}$.

The lender's objective is to find the menu $\theta \mapsto (L(\theta), m(\theta))$ that maximizes profit given each household's participation constraint:

$$\max_{L(\cdot),m(\cdot)} \int_{\underline{\theta}}^{\overline{\theta}} [\pi(m(\theta); \theta) - L(\theta)]\, f(\theta) d\theta$$

$$\text{s.t.} \quad L(\theta) - v(m(\theta); \theta) \geq L(\hat{\theta}) - v(m(\hat{\theta}); \theta) \;\text{ for all } \hat{\theta}, \theta$$

$$L(\theta) - v(m(\theta); \theta) \geq \underline{\mathrm{V}}$$

---

[4] Bunching in mechanism design problems has been a subject of analysis at least since Myerson (1981).

This is a formulation of the monopoly pricing problem with unobservable type (Mirrlees 1971, Maskin & Riley 1984). This leads to a simple optimal menu of mortgage payments and loan sizes where the mortgage payment for each type maximizes the surplus:

$$m(\theta) = \operatorname{argmax} \pi(m(\theta); \theta) - v(m(\theta); \theta) + \frac{1 - F(\theta)}{f(\theta)} \frac{\partial v}{\partial \theta}(m, \theta). \tag{1}$$

The first two terms are the total surplus, the sum of the lender's profit and the household's disutility. The last term provides household θ with the incentive to choose the option designed for her/him. When the profit function is smooth, households with higher default probability self-select into loans with higher mortgage installments, $dm/d\theta > 0$ as in Rothschild & Stiglitz (1976). Households with a lower propensity to default θ take smaller loan amounts to signal their higher creditworthiness, $dL/d\theta > 0$.

Bunching at the Conforming Loan Limit

The key ingredient of this paper is the discontinuity in the lender's ability to securitize mortgage generated by the GSEs' conforming loan limit.[5] For loan amounts $L \leq \tilde{L}$ the lender's profit π is the maximum of π^h, the profit of holding the mortgage, and π^s, the profit of originating and securitizing the mortgage. For loan amounts L above the conforming loan limit $\tilde{L}$, the lender's profit π is equal to π^h. At $\tilde{L}$ the profit thus experiences a discontinuity $\max\left\{\pi^h, \pi^s\right\} - \pi^h$. No discontinuity occurs in at least two cases: (i) when households are fully insured, and thus $\pi^s = \pi^h$, and (ii) when the cost of securitization, called the guarantee fee, is at high levels such that $\max\left\{\pi^h, \pi^s\right\} = \pi^h$.

We abstract from the ability to sell to non-agency securitizers for the sake of clarity but without loss of generality.[6] Such discontinuity at $\tilde{L}$ in the profit of the seller generates bunching in the density of mortgages for which $L(\theta) = \tilde{L}$, as displayed in Figure 1. Noting $[\tilde{\theta}, \tilde{\tilde{\theta}}]$ the set of household types that are offered and choose a mortgage amount exactly equal to the conforming limit $\tilde{L}$, the lower bound of such segment satisfies:

$$\tilde{L} = v(m(\tilde{\theta}), \tilde{\theta}) + U(\tilde{\theta}), \quad U(\tilde{\theta}) = -\int_{\underline{\theta}}^{\theta} v_\theta(m(\theta), \theta) f(\theta) d\theta, \tag{2}$$

---

[5] While π is discontinuous at $L = \tilde{L}$, the loan amount $L(\theta)$, the mortgage payment $m(\theta)$ and utility $U(\theta)$ are smooth functions of θ.

[6] Of course, the lender still has the option to sell mortgages to private label (non-agency) securitizers and the results of this paper can be seen as differences in the value of agency securitization relative to either holding the mortgage or selling to private label securitizers.

and the upper bound satisfies:

$$\pi(m(\tilde{\tilde{\theta}}), \tilde{\tilde{\theta}}) = \pi^h(m(\tilde{\tilde{\theta}}), \tilde{\tilde{\theta}}) \tag{3}$$

and the amount of bunching is $F_\theta(\tilde{\tilde{\theta}}) - F_\theta(\tilde{\theta})$ or alternatively $f(\tilde{L})$ the point density of households choosing exactly $\tilde{L}$.

Hence bunching at the conforming loan limit reflects (i) the discontinuity in the lender's profit at such limit (equation (3)), i.e. depends positively on the difference $\pi^s - \pi^h$ of profits when securitizing and when holding the mortgage. Bunching at the conforming loan limit also reflects (ii) households' disutility of mortgage payments (equation (2)).

Proposition 1. *The amount of bunching at the conforming loan limit is positively related to the difference between the profit of securitizing mortgages and the profit of originating and holding mortgages. The amount of bunching is negatively related to borrowers' disutility of mortgage payments, and thus to average default rates.*

Bunching and Expected Default Risk

The second step is to derive the impact of an across-the-board increase in households' expected default rate on the amount of bunching at the conforming limit. Let the default rate $d(\theta, \zeta^b)$ depend on both the household's type θ and households' proxy for disaster risk ζ^b. Such increase in disaster risk has the following properties: (i) it lowers the disutility of mortgage payments as the house is paid off over a shorter period of time, hence $\partial v/\partial\zeta^b < 0$; (ii) it lowers the marginal impact of an increase in the household's propensity to default θ on the disutility of mortgage payments $\partial^2 v/\partial\theta\partial\zeta^b$. By lowering both v and U on the right-hand side of equation (2), it increases the value of the threshold $\tilde{\theta}$ and leads to *less* bunching.

An increase in *lenders*' expected disaster risk ζ^ℓ has a different effect. By lowering the value of holding a mortgage, while keeping constant the value π^s of securitizing a mortgage, it leads to an increase in the upper bound $\tilde{\tilde{\theta}}$ and therefore an *increase* in bunching $F_\theta(\tilde{\tilde{\theta}}) - F_\theta(\tilde{\theta}) = f(\tilde{L})$. We get the following proposition.

Proposition 2. *An increase in lenders' expectation of disaster risk ζ^ℓ leads to an* increase *in the number of loans originated at the conforming loan limit $\tilde{L}$. Formally, $d\tilde{\tilde{\theta}}/d\zeta^\ell > 0$. An increase in borrowers' expectation of disaster risk ζ^b leads a* decline *in the number of loans originated at the conforming loan limit $\tilde{L}$.*

This proposition forms the basis of this paper's identification strategy, which estimates the impact of natural disasters on the value of the securitization option by measuring the impact of natural disasters on the size of bunching at the conforming limit:

$$\Delta f(\tilde{L}) = f(\tilde{L})\big|_{Disaster} - f(\tilde{L})\big|_{No\ disaster} \tag{4}$$

In other words, the disaster provides "new news" to either households or lenders, which shift the expected disaster risks ζ^{ℓ} and ζ^{b} potentially upwards. Bunching provides a source of information on lenders' and borrowers' updated beliefs about future disaster risk. Importantly our analysis is based on *newly* originated mortgages rather than current mortgages, reflecting forward-looking expectations of default rather than an impact on the current stock of houses and loans.

The next section presents the natural disasters, the treatment and control groups, and the mortgage application and origination data used for the econometric analysis, performed in Section 4.

3 Data Set and Treatment Group

This paper focuses on the neighborhoods of the 18 Atlantic States. We combine information from four data sources: (i) mortgage and housing market data, including information from the universe of mortgage applications and originations, payment history, FICO score, rents and house prices, (ii) natural disaster data, using the universe of Atlantic hurricanes between 1851 and 2018, (iii) sea-level rise, elevation, land use data, which enables an identification of at-risk areas, (iv) banking data, on banks' branch network and balance-sheet information.

Natural Disasters: Billion Dollar Events and the Treatment Group

The paper focuses on disasters that have caused more than 1 billion dollars in estimated damages. The estimates come from Weinkle et al.'s (2018) computations for 1900 to now; we focus on events happening between 2004 and 2012. All of these events are hurricanes, and we extract their path from the Atlantic Hurricane Data set of NOAA's National Hurricane Center[7]. The events post 2004 provide wind radiuses by speed every 6 hours, enabling the computation of the set of neighborhoods within the 64 knot hurricane

---

[7] Accessed in 2018.

wind path. This wind speed maps naturally into the Saffir Simpson hurricane intensity scale. Examples of these paths are presented for four hurricanes in Figure 4. Damages to real estate property is however unevenly distributed within the hurricane's wind path. In particular, building-level data from Hurricane Sandy reveals that coastal and low-lying areas are significantly more likely to experience damages. Using the observed damages from Hurricane Sandy, we define a set of criteria to pinpoint treated areas for all of the 15 hurricanes: first, we focus on blockgroups, the smallest Census geographic area for which the Census long form and the American Community Survey are available. Second, blockgroups are hit if (i) they are within the 64kt wind path, (ii) their minimum elevation is below 3 meters, and (iii) they are within 1.5 kilometers of the coastline, or (iv) they are within 1.5 km of wetland. Such criteria yield a set of blockgroups that correlates well with observed damages from Hurricane Sandy and Katrina.[8] Elevation comes from the USGS's digital elevation model, at 1/3 of an arc second precision (about 10 meters). Wetlands come from the 2001 National Land Cover Database.

The set of treated blockgroups is displayed on Figure 2 for hurricane Katrina and on Figure 3 for hurricane Sandy. It is also estimated for the other 13 disasters. The dark grey area is the hurricane's 64kt wind path. The blue area is the set of coastal areas or areas close to wetland. The red boundaries correspond to blockgroups whose elevation is less than 3 meters.

Mortgage and Housing Market: HMDA, BlackKnight

The first data source is the universe of mortgage applications and originations from the Home Mortgage Disclosure Act, from 1995 to 2016 inclusive. The data is collected following the Community Reinvestment Act (CRA) of 1975, and includes information from between 6,700 and 8,800 reporting institutions, on between 12 and 42 million mortgage applications. The law mandates reporting by both depository and non-depository institutions. It mandates reporting by banks, credit unions, savings associations, whose total assets exceeded a threshold, set to 45 million USD in 2018,[9] with a home or branch office in a metropolitan statistical area; which originated at least one home purchase loan or refinancing of a home purchase loan secured by a first lien on a one-to-four-family dwelling; and if the institution is federally insured or regulated. The following non-depository institutions are required to report: for-profit institutions for which home purchase loan originations equal or exceed 10 percent of its total loan originations or 25 million USD or more; whose assets

---

[8] Sandy Damage Estimates Based on FEMA IA Registrant Inspection Data.

[9] The minimum asset size threshold is typically adjusted according to the CPI for urban wage earners (CPI-W), is currently set by the Consumer Financial Protection Bureau, and published in the Federal Register.

exceed 10 million dollars; or who originated 100 or more home purchase loans. HMDA data includes the identity of the lender, loan amount, the income, race, and ethnicity of the borrower, the census tract of the house, the property type (1-4 family, manufactured housing, multifamily), the purpose of the loan (home purchase, home improvement, refinancing), owner-occupancy status, preapproval status, and the outcome of the application (denied, approved but not accepted, approved and accepted, widthdrawn by the applicant). This paper focuses on 1-4 family housing, owner-occupied home purchase loans. The census tract of the loan enables a geographic match with the counties hit by the billion dollar events.

This first data source does not include the full range of proxies for borrowers' creditworthiness. We complement HMDA with the BlackKnight financial data files, which follow each loan's history from origination to either full payment, prepayment, foreclosure, or bankruptcy. The BlackKnight financial file follows about 65% of the market, and includes the borrower's FICO score, the structure of the mortgage ARM, FRM, Interest Only, the amortization schedule, the interest rate; and follows refinancings, securitizations, and delinquencies. In addition, BlackKnight financial data includes the home's 5-digit ZIP code, which is matched to natural disaster data.

BlackKnight financial data includes the house price and characteristics of the property. We obtain ZIP-level house price index data and rental data from Zillow, using two indices: the Zillow Home Value Index (ZHVI), a smoothed, seasonally adjusted measure of the median estimated home value;[10] and the Zillow Rent Index (ZRI): a similarly smoothed measure of the median estimated market rate rent.

The GSEs' Mandate and the Conforming Loan Limit

The Governement Sponsored Enterprises' mandate is set by the National Housing Act, Chapter 13 of the U.S. Code's Title 12 on Banks and Banking. In it, Congress establishes secondary market facilities for residential mortgages. Its stated purposes include providing "stability to the secondary market," providing "ongoing assisatnce to the secondary market for residential mortgages," as well as "manag[ing] and liquidat[ing] federally owned mortgage portfolios in an orderly manner, with a minimum of adverse effect upon the residential mortgage market and minimum loss to the Federal Government." Jaffee (2010) reports that such mandate has a very substantial influence over the mortgage market, as they cover over 50 percent of all U.S. single-family mortgages and close to 100 percent of all prime, conforming, mortgages.

This paper assesses the implications of such mandate in the case of climate risk. Section 1719 of such

---

[10] Zillow Research, accessed October 2018.

National Housing Act empowers the Government Sponsored Enterprises to set the standards that determine eligibility of mortgages for securitization. In particular, a set of observable loan characteristics is part of this assessment. This paper focuses on one such time-varying and county-specific observable, the conforming loan limit, set by the Federal Housing Finance Agency, by Congress, or by the Consumer Financial Protection Bureau (Weiss, Jones, Perl & Cowan 2017). Three interesting features enable an identification of the impact of such limit on market equilibrium: first, the limit is time-varying, thus enabling an estimation of the impact of the *change* in the limit on origination, securitization volumes. Second, the limit is also county-specific after 2007, implying that the limit bites at different margins of the distribution of borrower characteristics. Finally, the limit for second mortgages (last column) is high, allowing homeowners to combine a first, conforming mortgage, with a second mortgage to increase the Combined Loan-to-value ratio (CLTV), while maintaining a loan amount within the upper bound of the conforming loan limit.

The observable loan characteristics that the Government Sponsored Enterprises use also pin down the guarantee fee that is charged to primary lenders in exchange for purchasing the mortgage. The Loan Level Price Adjustment Matrix (LLPA) maps the applicant's credit score and loan-to-value ratio into a guarantee fee ranging in 2018[11] for fixed-rate mortgages (FRM) between 0% (for applicants with a FICO score above 660 and an LTV below 60%), and 3.75% (for applicants with a FICO score below 620 and an LTV above 97%). Specific guarantee fees also apply to Adjustable Rate Mortgages, manufactured homes, and investment property, where fees can reach 4.125% as of 2018.

The Impact of the Conforming Loan Limit: Originations and Adverse Selection

If guarantee fees were substantially above the maximum risk premium that lenders are ready to pay, securitization volumes would not affect origination volumes. Figure 5 presents evidence that the GSEs' mandate has an impact on application and on origination volumes. It uses data from the Home Mortgage Disclosure Act. In each year and each county, loans with an amount between 90 and 110% of the conforming loan limit are considered. Such loans are grouped into bins of 0.5%, and the number of applications is computed. The blue line is the curve fitted using a general additive model. The vertical axis is log scaled. Figure (a) suggests that there is a discontinuity in the volume of applications at the limit, with significant bunching exactly on the left side of the limit: the count of applications exactly at the limit is up to twice the volume of applications on the right side of the limit. Figure (b) suggests that the share of white applicants is substantially higher (between 5

---

[11] The BlackKnight data set used in this paper includes the loan-specific guarantee fee.

and 10 ppt higher) for applicants of conforming loans. When considering only the first mortgage, Figure (c) suggests that conforming loans have lower Loan-to-Income ratio, about 0.17 lower. Figure (d) matches the HMDA application and origination file to the balance sheet of the lender, when such information is available: it includes large, FDIC guaranteed depository institutions, and does not include non-bank lenders. The figure suggests that the liquidity on lenders' asset-side is 1.1 ppt lower for originators of conforming loans. This is consistent with evidence from Loutskina & Strahan (2009) suggesting that the ability to securitize loans led to the expansion of mortgage lending by banks with low levels of liquidity. In addition, the preferential capital treatment given to securitized products incentivize the securitization of mortgages.

The evidence presented in this figure also suggests that Private Label Securitizers (PLS) are an imperfect substitute for the GSEs. Indeed, while PLSs do take on the risk of non-conforming, i.e. jumbo, loans, the size of the market is smaller and fees are higher.

The discontinuity in the number of mortgages and in their characteristics can stem from a few different mechanisms; first, a household willing to purchase a house at a given price p_0 may choose a lower level of indebtedness, increasing his cash down and lowering the loan-to-value ratio. Second, the household can downscale its housing consumption to borrow an amount within the conforming loan limit. A third possibility is that the household borrows using two mortgages, one conforming mortgage that can be securitized by the lender, and a second mortgage to achieve the same combined Loan-to-Value ratio (CLTV) as a jumbo mortgage. Given an interest rate schedule, the choice of one of the three options will depend on the borrower's preferences, e.g. for (i) higher indebtedness, including the higher interest cost paid for larger mortgages, (ii) the household's preference for higher equity, (iii) and his/her expected risk of default. Thus an important goal of the analysis is to separate what is driven by the demand for debt from what is driven by the supply of credit.

Evidence of Negative Selection into Securitization

Evidence present in HMDA and in publicly available GSE loan files does not provide sufficient information to assess the welfare impact of the GSEs' securitization program. Indeed, different policy implications would follow from either positive or negative selection into securitization, i.e. self-selection of safer or riskier borrowers into securitization.

Figures 6 and 7 present evidence from BlackKnight's loan-level files. Such files provide data on the FICO credit score at origination, and on detailed payment history, which are typically absent from publicly available files. Figure (a) confirms the presence of bunching in loans at the conforming loan limit in this different dataset. The granularity of the data set enables a focus on a narrower window of 95 to 105% of the conforming loan limit. Figure (b) suggests that conforming loans have *lower* credit scores. The magnitude of the discontinuity is between 14 and 30 points unconditionally, and between 5 and 3.7 (significant at 1%) when controlling for zip code and year fixed effects, within a 0.5% window around the conforming loan limit. This is reflected in the pricing of such mortgages: Figure (c) suggests that interest rates on conforming loans are *higher*, with a discontinuity of about 0.8 ppt. This suggests that lenders are pricing delinquency and default risk. Similarly, Figure (d) presents evidence that conforming loan borrowers are significantly more likely to purchase private mortgage insurance (PMI), with a discontinuity of about 3 percentage points.

While intriguing, this evidence does not a priori suggest negative selection as GSEs observe FICO scores and PMI take-up. Figure 7 builds four indicators of ex-post mortgage performance. Indeed, BlackKnight reports monthly updates on each loan covered by its network of servicers. Loans are either current, delinquent (90, 120 days), in foreclosure, or the household is going through a bankruptcy process. Figure (a) suggests that conforming loans are more likely to foreclose at any point after origination. The difference is about 2 to 1.4 percentage points depending on the window (+-10% down to 0.5%). Figure (b) presents a larger discontinuity in hazard rates. Figure (c) suggests that conforming loans are more likely to be 60 days delinquent at any point. The visually most striking discontinuity is in voluntary prepayment: Figure (d) suggests that conforming loans are more likely to experience a voluntary payoff. Such prepayment is a risk for the lender, which forgoes interest payments.

Appendix Table B suggests that while jumbo loans seem riskier along observable dimensions, these loans are safer along unobservable dimensions (Appendix Table C): jumbo loans are less likely to be full documentation loans, terms are longer (4.3 months), they are more likely to be adjustable rate mortgages, have higher loan-to-value ratios, and have a higher share of second mortgages. Yet, Appendix Table C suggests that they are safer along every dimension of ex-post payment history.

Overall the evidence presented in Figure 7 is consistent with negative selection of borrowers into conforming loans along unobservable dimensions: while the GSEs' rules ensure positive selection along observable characteristics, residual variance in borrower quality is sufficient to offset the national selection criteria enforced by Federal regulators.

Banks' Branch Network and National Balance Sheet

The third data source is data on banks' reports of income and condition, collected by the Federal Financial Institutions and Examination Council (FFIEC). These data can be matched to the depository institutions that originate loans in HMDA data using a unique Replication Server System Database ID (RSSDID) and the identity of the lender's federal reporting agency. The reports of income and condition includes a range of balance sheet and income items, from which we build the following statistics: (a) the liquidity of the financial institution, defined as the ratio of cash and securities to total assets, as in Loutskina & Strahan (2009). (b) the volume of mortgages held by the financial institution. (c) the amount of recourse on mortgages sold by the institution. d) the volume of mortgage backed securities sold by the financial institution.

We match such data to the FFIEC's Summary of Deposits, Annual Survey of Branch Office Deposits. Reporting is required for all FDIC-insured financial institutions. The FFIEC collects information on the geographic location of bank branches as of June 30, the amount of deposits in each branch, the date the branch was established, and matches each branch with its corresponding national bank. The location of bank branches is then used to estimate the geographic coverage of a bank, and whether such coverage includes parts of counties hit by billion dollar event.

4 The Impact of Disasters on Agency Securitization

The paper's main specification estimates the impact of natural disasters on the discontinuity in mortgage numbers and characteristics at the conforming loan limit, conditional on neighborhood-specific and time-specific unobservables controls. This identification strategy is first described. The specification follows.

4.1 Identification Strategy

Historical data and statements by the National Oceanic and Atmospheric Administration suggest that a large share of the year-to-year variation in local hurricane risk is idiosyncratic. Indeed:

> *NOAA's Seasonal outlook, issued in May and updated in August, predicts the number of named tropical storms, hurricanes, and major hurricanes (Category 3 or higher on the Saffir-Simpson Wind Scale) expected over the entire Atlantic basin during the six-month season. But that's where the reliable long-range science stops. The ability to forecast the location and strength of*

> *a landfalling hurricane is based on a variety of factors, details that present themselves days, not months, ahead of the storm.*[12]

This paper identifies the impact of natural disasters conditional on the blockgroup-specific history of hurricanes across the atlantic coast. This implies that the neighborhood-level occurence of hurricanes is orthogonal to local unobservables conditional on history: [13]

$$Hurricane_{jt+1} \perp \varepsilon_{jt+1} | h_{jt}, h_{jt-1}, h_{jt-2}, \dots, h_{j0} \tag{5}$$

where $h_{jt}, h_{jt-1}, h_{jt-2}, \dots, h_{j0}$ is the history of hurricanes in location j in each time period $0, ..., t$. Section 4.2 provides a placebo test based on comparing pre-disaster outcomes.

4.2 The Impact of Natural Disasters on Securitization Volumes and Adverse Selection

The paper identifies the impact of natural disasters on GSE securitization activity by estimating the impact of natural disasters on the discontinuous bunching in loans at the conforming limit. Hence we combine the discontinuity estimate of Section 3 with an event-study design for each of the $d = 1, 2, \dots, 15$ natural disasters described in Table 1, from Hurricane Charley (August 2004) to Hurricane Sandy (October 2012).

The year of the disaster is noted $y_0(d)$, $y_0(d) \in \{2004, 2005, 2008, 2011, 2012\}$. For each disaster, the time t relative to the disaster year is $t \equiv y - y_0(d)$. The treatment group for each disaster is the set $\mathcal{J}(d)$ of neighborhoods hit by that disaster. The criteria for inclusion in this set are described in Section 3 and combine elevation, proximity to the coastline or wetland, and belonging to the 64kt hurricane wind path. The control group C is made of Atlantic neighborhoods of that are not hit by any one of the disasters in 2004–2012. By controlling for a local neighborhood fixed effect, and for a year fixed effect, we are controlling for two key confounders: (i) the historical propensity of local hurricane risk, described in the previous section, and (ii) for the intensity of each particular hurricane season.

---

[12] *https://www.noaa.gov/stories/what-are-chances-hurricane-will-hit-my-home*

[13] Seasonal outlook data stretching back to 1995 is available at the following link

The paper's main specification is:

$$\begin{aligned} Outcome_{it} = {} & \alpha \cdot \text{Below Conforming Limit}_{it} + \gamma \text{Below Conforming Limit}_{it} \times \text{Hit}_{id} \\ & + \sum_{t=-10}^{+10} \delta_t \cdot \text{Below Conforming Limit}_{it} \times \text{Hit}_{id} \times Time(t) + Time_{t=y-y_0} + Year_y \\ & + Disaster_d + Neighborhood_i + \varepsilon_{it}, \end{aligned} \tag{6}$$

where i is a mortgage, $j(i)$ is the ZIP code of mortgage i, $Below\,Conforming\,Limit_{it}$ is the time and county-specific conforming loan limit (Weiss et al. 2017). By controlling for both year fixed effects and for the disaster-specific time fixed effects, we can identify the identify of the disaster separately from time trends, e.g. the nationwide real estate cycle, which may be a concern for hurricanes occuring at the peak of the housing boom or a the trough of the housing bust. The $Outcome_{it}$ variables are: the denial rate for mortgage applications, the loan-to-income ratio, whether the borrower is white, African-American, or Hispanic, the log(Income) of the applicant, the credit score, the term, the probability of foreclosure, 30, 60, 90, 120-day delinquency at any point, and voluntary payoff.

The paper's coefficients of interest are the δ_t, where controls range between $t = -10$ and $t = +10$. In particular, the δ_t for $t \geq 0$ measure how the natural disaster causes an increase or a decline in denial rates for mortgages on the left side of the conforming loan limit. The δ_t for negative values of t provide a placebo test for the equality of pre-disaster trends. As we estimate the coefficients on a window around the conforming loan limit, the specification measures the impact of the disaster on the discontinuity in that location-specific and time-specific window.

Impact on Denial Rates of Conforming Loans

Results are presented in Tables 3, 4, and in Figure 9. They involve 4.3 million loans in the HMDA files, and 1.7 million loans in the BlackKnight files, with between 8,119 and 9,627 5-digit ZIP codes. Standard errors are two-way clustered at the 5-digit ZIP and year levels.

A natural disaster leads to a 2.8 ppt decline in the denial rate in the year following the event, and up to a 8.5ppt decline 3 years after the disaster. There are effects up to 7 years inclusive after the event. Importantly in 13 out of 14 regressions, the difference prior to the event is neither statistically nor economically significant. The loan-to-income ratio of conforming loan originations declines, the fraction of white applicants increases, the fraction of Black and Hispanic applicants goes down, the income of the applicants increases.

Impact of Disasters on Adverse Selection into Securitization

When turning to ex-post mortgage performance, in Table 4, the evidence suggests that conforming loans originated *after* the disaster tend to perform worse. The probability of foreclosure is higher by 3.6 percentage points in the year following the disaster, and up to 4.9 percentage points in the third year after the disaster. The probability of 30 day delinquency at any point for conforming loans originated after the event increases by 3.6 percentage points. Similar long-term changes appear for 60 day, 90 day, 120 day delinquency. Voluntary prepayment declines as well, by 3.1 ppt in the year following the disaster.

Tables 3 and 4 together suggest that post-disaster, banks increase positive selection in observable dimensions while increasing negative selection in unobservable dimensions.

Specification (6)'s results may be driven by observations away from the conforming loan limit. In particular, given the 90%-110% window, one question is whether bunching increases exactly at the 90% limit. Hence, we design an additional test. We running 20 separate estimations where the Below Conforming Limit$_{it}$ variable is replaced by an indicator for Below x% of the conforming limit$_{it}$, with x ranging from 92% to 108% of the conforming limit, on a grid of 20 equally spaced points. Figure (9) (a) reports the coefficients $\hat{\delta}_{t=+1}$ thus estimated. The figure suggests that the decline in denial rates post-disaster is specific to the conforming limit, as the treatment effect spikes exactly at the threshold. Figure (b) presents the coefficients $\hat{\delta}_{t=+1}$, $\hat{\delta}_{t=+2}$, $\hat{\delta}_{t=+3}$ of the treatment effects in years +1, +2, +3, suggesting that the magnitude of the treatment effect's spike increases over time.

5 Documenting the Mechanism: Learning About Future Risk

Section 2 suggested that the amount of bunching at the conforming loan limit depends on the lenders' perceived value of the securitization option and on households' perceived disutility of mortgage payments.

This section first suggests that natural disasters affect the market's subjective probability of natural disaster risk: prices and price-to-rent ratios decline. Then the section shows that hurricane risk is autocorrelated: being treated in a given year is correlated with treatment in the next year. Thus there is local "new news" contained in a natural disaster's path.

5.1 The Impact of Natural Disasters on Expected Price Trends

While it is typically hard to identify beliefs, empirical analysis of the price to rent ratio, in the spirit of Giglio, Maggiori & Stroebel (2014) and Giglio, Maggiori & Stroebel (2016), suggests that fluctuations in the price to rent ratio can capture changes in the market's expectation of future price trends. In this section we estimate the impact of billion dollar natural disasters on expected price trends.

We do so by estimating the impact of the post-2010 natural disasters on the price to rent ratio in a saturated specification. Fluctuations in the price to rent ratio reveals fluctuations in the market's expectations of future rents, future mortgage default, future maintenance costs, time discount factors (cost of capital), and fluctuations in taxation. The following formula abstracts from property tax, insurance payments, and assumes full depreciation of assets in case of disaster:

$$Price_{j(i)t} = \sum_{k=0}^{\infty} \frac{(1-\delta_{j(i)t+k})^k}{(1+r)^k} \left(Rent_{j(i)t+k} - Maintenance_{j(i)t+k} \right), \tag{7}$$

with $j(i)$ the ZIP code of mortgage i, and $\delta_{j(i)t+k}$ the probability of future of future disaster risk. While simple, this formula implies, with a constant rent, a constant expectation of climate risk $\mathbb{E}\delta_{j\cdot}$, and s the share of maintenance costs over rent, that the log price to rent ratio reflects future risk.

$$\log(Price/Rent)_{j(i)t} = \log\left[\frac{1-\mathbb{E}\delta_{j(i)\cdot}}{r+\mathbb{E}\delta_{j(i)\cdot}}\right] + \log(1-s) - \log(1-\tau) \tag{8}$$

The following regression estimates the impact of the natural disaster controlling for both time, year, neighborhood, and disaster fixed effects:

$$\begin{aligned} log(Price/Rent)_{j(i)} = {} & Constant + \sum_{t=-10}^{+10} \Delta_t \mathrm{Hit}_{id} \times Time(t) + Time_{t=y-y_0} \\ & + Year_y + Disaster_d + Neighborhood_{j(i)} + \varepsilon_{j(i)t} \end{aligned} \tag{9}$$

The year fixed effects capture the economy's cost of capital r. The year fixed effects control for the nation-wide's housing cycle. The neighborhood fixed effects capture unobservable differences in neighborhoods' price to rent ratios, e.g. driven by time-invariant differences in maintenance or state-level taxation differentials. Standard errors are two-way clustered at the neighborhood (zip code) and year levels.

Results are presented on Figure 10 for the price/rent ratio, rents, and prices. The time series come from

Zillow's rent and house price indices, available after 2010. Yet, even on this more limited set of natural disasters, the impacts of the disaster on the price/rent ratio and prices are both economically and statistically significant post-disaster; and the placebo coefficient in the year preceding the event is not statistically significant. The price-rent ratio declines by about 3% in the year following the disaster. Using equation 8 with constant taxes and maintenance costs, and with a discount factor $r \simeq 5\%$, we can estimate a that the expected risk probability increases by about 52.5%.

While rents either do not significantly change post disaster or slightly increase (in part due to the lower supply of rental units), prices and price/rent ratios decline significantly. Given the saturated set of controls of the specification, we interpret such result as evidence of a decline in the market's expectation of future price appreciation at the ZIP level.

5.2 Learning about Local Risk from Past Disasters

The impact of a natural disaster on the amount of bunching at the conforming loan limit depends on whether a natural disaster brings "new news" that shifts the probability distribution over *future* risk. Indeed, if the probability of a natural disaster was simply a constant throughout the period of analysis, the occurence of a disaster in a specific neighborhood would be the realization of a shock, with no change in the future probability of a disaster. This section suggests that: (i) hurricane risk is spatially autocorrelated, i.e. occurence of a hurricane is correlated with the future occurrence of hurricanes, even controlling for average historical levels and (ii) that lenders' increasing bunching at the conforming limit is greater in areas with little or no history of hurricanes, a fact consistent with belief updating.

We start with the first point. To test whether hurricanes bring such new news about the future occurence of disasters, we use the 168 years of history of geocoded hurricanes provided by the NOAA, between 1851 inclusive and 2018. For each of these events, NOAA provides the hurricane wind path and 64 knot radius as for the more recent hurricanes used as treatments. A 2018 ZIP code is in the hurricane's wind path if any point of its surface is contained in the hurricane's wind path. And we run the following regression:

$$\text{In wind path}_{jt} = \text{ZIP Code}_j + \text{Time}_t + \alpha \cdot \text{In wind path}_{jt-1} + \varepsilon_{jt} \tag{10}$$

where In wind path$_{jt}$ is equal to 1 if a ZIP is in the hurricane's wind path during decade $t = 1, 2, \ldots, 15$; ZIP Code$_j$ is a ZIP code fixed effect that captures the average neighborhood probability over the 168-year history, Time_t measures the average intensity of the hurricane season during the decade, and α is an autocorrelation coefficient. ε_{jt} represents idiosyncratic fluctuations. If there is no information contained in the history of hurricanes in a particular neighborhood, then $\alpha \equiv 0$, i.e. there is no autocorrelation in hurricane occurence.

Estimation of the regression requires care as the fixed effect panel estimate typically suffers from the classic Arellano & Bond (1991) dynamic panel data bias which implies that $\hat{\alpha}$ can be severely downward biased. Table 2 presents the estimation results.

Column (1) includes a set of ZIP code fixed effects, which capture 32% of the variance of the decennial probability. Column (2) includes both neighborhood and a decade fixed effect, suggesting that the neighborhood f.e. captures most of the variance of the probability. Column (3) includes a linear time trend instead of a series of decadal fixed effects, suggesting an increase in hurricane propensity over 168 years, by 0.06 percentage points per decade. Column (4) performs a similar analysis with a ZIP code fixed effect. The time trend is unchanged. Columns (5) and (6) include the lagged decennial probability (i.e. 1861–1870 for 1871-1880), where column (5) is the naive OLS coefficient and (6) is the Arellano-Bond coefficient. Bother columns present an autoregressive coefficient that is significant at 1%, implying that prior hurricane occurence is an informative predictor of future hurricane occurence: a 1 percentage point increase in prior decennial probability increases the next decade's probability by between 0.3 and 2.3 percentage points. This suggests that lenders and households learn about the specific location of future events from the windpath of past events.

We then turn to the second point by estimating this paper's main treatment effect interacted with the historical decennial probability of hurricane occurrence. If lenders do update their beliefs about local risk from the observation of the most recent natural disaster, we should expect that a high historical probability leads to *smaller* responses of bunching to natural disasters. Decennial probabilities range from 0% (never in a hurricane's wind path) to a maximum of 39%. In areas with low decennial probabilities, a natural disaster leads to a decline of the denial rate of conforming loans of 2.98% in the year following a disaster, as in the main baseline Figure 9. In contrast, the denial rate of conforming loans declines by only 1.4%, about half of the baseline effect, in areas with a historical probability in the 3rd quartile (15.6% decennial probability). There is no significant impact of natural disasters on denial rate discontinuity for areas with the highest historical probability (38.9%). Such evidence is consistent with the hypothesis that *current* natural disasters provide "new news" about *future* disaster risk.

5.3 The Impact of Natural Disasters on *Current* Mortgages' Default and Prepayment

A key empirical question is whether natural disasters affect households' payment behavior, and whether disaster trigger either defaults or prepayments. In both cases, increases in either defaults or prepayments affect the profit of a lender that held the mortgage. Expectations of default risk should lead to greater securitization probabilities, while expectations of prepayment are less likely to affect securitization behavior as an agency MBS typically "passes through" mortgage prepayments. In other words, the agency MBS insures the lender against default risk, but does not insure the lender against prepayment risk.

We estimate the impact of natural disasters on payment history by considering a dataset made of (i) the universe of individual loans in ZIPs affected by the billion dollar disasters of Table 1, regardless of the specific timing of the origination of these loans, and (ii) a 1% random sample of the universe of loans in the control group. The dataset has a total of 3.68 million loan-month observations.

The following specification controls for ZIP code, year fixed effects, and estimates the impact of a natural disaster relative to the specific year t_0 of that event:

$$\mathbf{1}(\text{Default})_{it} = \sum_{k=-K}^{+K} \delta_k \cdot \mathbf{1}\left[t = (t_0(i) + k)\right] + \text{ZIP}_{j(i)} + \text{Year}_t + \text{Residual}_{it} \tag{11}$$

where $\delta_0, \delta_1, \ldots$ are the coefficients of interest, which measure the impact of the disaster on default. $t_0(i)$ is the year of the natural disaster of mortgage loan i. $j(i)$ is the ZIP code of mortgage i at origination. The effect of a natural disaster is identified as disasters occur over a period a 8 years. Year and ZIP code fixed effects are identified by observations both in the treatment and the control groups. Residuals are two-way clustered at the ZIP code and year levels.

Results are presented graphically in Figure 11. The solid lines in each graph present the coefficients δ_{-2} to δ_{+5}. The dotted lines are the 95% confidence intervals. Results suggest that a natural disaster has a statistically significant negative impact on the probability that a loan is current, by about 4 percentage points. A natural disaster increases the probability that a loan is in foreclosure by 1.6 percentage points. In contrast, the impact on the probability of prepayment is marginally significant at 5%.

These results suggest that insurance payments and other transfers post-disaster may not mitigate the impact of natural disasters on delinquencies and foreclosures. This is consistent with recent work (Kousky 2018) suggesting a decline in the number and dollar amount of properties insured through the National Flood Insurance Program. The next section assesses whether lenders tend to bunch mortgages at the conforming loan limit in areas where Fannie and Freddie require flood insurance.

5.4 The Impact of Mandated Flood Insurance on Securitization Behavior

The availability, cost, and take-up of flood insurance affects both the option value $\pi^s - \pi^h$ of securitization. In particular, given that agency mortgage backed securities do not insure lenders against prepayment risk, full insurance would shift lenders' focus from default to prepayment risk, and substantially lower the value of securitizing mortgages.

We map the areas where flood insurance is mandated at the time of the billion dollar event, using past flood maps from the National Flood Hazard Layer. In particular, zones A, AE, A1-A30, AH, AO, AR, A99, V, VE, V1-V30 from the Flood Insurance Rate Maps are areas where homeowners are required to purchase flood insurance. We compute the share of a ZIP code that is in such a Special Flood Hazard Area (SFHA). In contrast, Zones D, X, C, X500, B, XFUT are areas where flood insurance can be purchased but is not required.

As a test of whether flood insurance mandates affect the level of bunching and the discontinuities at the conforming loan limit, we interact our treatment indicator variable with the share in the SFHA in the paper's main specification (equation 6). Results suggest no statistically significant impact of the share in an SFHA area on bunching and discontinuities. Such result may be consistent with the following recent evidence. First, average payouts were not exceeding $70,000 for the top 10 highest cost flood events (including Sandy), except for Katrina, where the average payout was close to $90,000. Second, Kousky (2018) documents a significant decline in the number and total volume of insurance policies purchased through the National Flood Insurance Program. Third, Kousky (2019) suggests that the impacts of insurance coverage on risk reduction and land use patterns may be modest.

6 The Impact of Disasters on Lenders' Perceptions of Local Risk: Identifying and Estimating the Mechanism Design Problem

Previous evidence documented an increasing bunching of mortgages at the conforming limit. To make a statement about *lenders' risk perceptions*, which are typically unobservable, we develop an estimated micro structural model that maps lenders' risk perceptions into bunching and discontinuities. The key intuition is that lenders' perception of greater risk lead to greater bunching, a mechanism described in proposition 2 of Section 2. The structural model estimates how lenders supply a menu of mortgage contracts based on their expectations of (i) price trends and price volatility, (ii) the sorting of households into each mortgage contract and location and hence how households' individual default drivers interact with local risk. The model replicates the "structure-free" discontinuity estimates established earlier in the paper and allows for their comparative statics with respect to lenders' risk perceptions.

6.1 A Structural Model of Mortgage Pricing with Asymmetric Information

There are $j = 1, 2, \dots, J$ neighborhoods, each with a vector of amenities $\mathbf{z}_j$ of size K. Each of the $i \in [0, N]$ households chooses a neighborhood j. Such a continuum of households differs by their observable vector $\mathbf{x}$ of size $\mathscr{k}$ and their unobservable scalar ε.

There are $\ell = 1, 2, \dots, L$ lenders. The lender's opportunity cost of capital is noted κ_ℓ. Each lender offers a fixed rate mortgage with loan amount L_j and maturity T in each location, and chooses an interest rate $r_{\ell j}$ in each location.[14] Lenders compete in interest rates in each segment defined by $\mathbf{x}$; each lender sets the interest rate $r_{\ell j}(\mathbf{x})$ in this segment given the menu of interest rates $\mathbf{r}_{-\ell j}(\mathbf{x})$ chosen by the $L-1$ other lenders.

After choosing a location-mortgage contract pair $(j, \ell) \in \{1, 2, \dots, J\} \times \{1, 2, \dots, L\}$, households start paying a mortgage with payment $m_{j\ell}(r_{j\ell}, T, L_j)$ and can default or prepay every year $t = 1, 2, \dots, T$. For the sake of clarity we abstract from prepayment but those can be introduced at no notational cost.

The annual default probability $\delta(\mathbf{x}, \varepsilon, B_{jt}, p_{jt}) \in [0, 1]$ is driven both by household fundamentals $(\mathbf{x}, \varepsilon)$, by the household's mortgage balance B_{jt}, and by the house price p_{jt} in year t after origination.

$$\text{Default}^*_{jt}(\mathbf{x}, \varepsilon) = \mathbf{x}\boldsymbol{\beta}_{default} + \varepsilon + \alpha^B_{default} B_{jt} + \alpha^p_{default} \log p_{jt} + \eta_{jt}(\mathbf{x}, \varepsilon) \tag{12}$$

where η is extreme-value distributed and $\delta = P(\text{Default}^*_{jt}(\mathbf{x}, \varepsilon) > 0)$. The balance follows the mechanical rule of mortgage amortization:

$$B_{jt+1} = r_j(\mathbf{x}) B_{jt} - m_{jt}(\mathbf{x}) \tag{13}$$

The last driver of mortgage default in equation (12) is the current house price. A household whose balance substantially exceeds the current value of its house is more likely to default. Each lender forecasts the path of future prices. At the time of origination, each lender ℓ expects that house prices follow a geometric brownian

---

[14] For the sake of clarity we present the structural approach with fixed rate mortgage (FRM) contracts, but the model is extended and estimated with other contracts such as ARMs and IO loans.

motion with constant drift α_ℓ and volatility σ_ℓ as is typical in the real estate literature (Bayer, Ellickson & Ellickson 2010):

$$dp_t = p_t \cdot (\alpha_\ell dt + \sigma_\ell dW_t) \tag{14}$$

where α_ℓ is lender ℓ's perception of house price log trends, σ_ℓ the lender's perception of price volatility.[15] W_t is a brownian motion, i.e. $W_t - W_s \sim N(0, t-s)$ for any pair (t, s).

If the household default, a foreclosure auction is run that yields a payoff $\min\left\{B_{jt}, p_{jt}\right\}$, which is at most equal to the current mortgage balance.

Lenders' Optimal Menus of Contracts Lender ℓ chooses a vector of interest rates $\mathbf{r}_\ell$ to maximize its total profit, coming from each of the J locations:

$$\Pi_\ell(r_{\ell 1}, r_{\ell 2}, \dots, r_{\ell J}; \mathbf{r}_{-\ell j}(\mathbf{x})) = \sum_{j=1}^{J} \Pi_{j\ell}(r_{\ell 1}, r_{\ell 2}, \dots, r_{\ell J}; \mathbf{r}_{-\ell j}(\mathbf{x})) \tag{15}$$

where the profit in location j is driven by the default probability, the mortgage payment, and the fraction of households choosing j:

$$\Pi_{j\ell} = \left\{E_{j\ell}\left[\xi\right] \cdot m(r^*_{\ell J}, T, L_j) - L_j + E_{j\ell}\left[\phi(\delta)\right]\right\} \cdot P(j, \ell) \tag{16}$$

where the discounting ξ of mortgage payments depends on the expected default rate, so that:

$$E_{j\ell}\left[\xi\right] \equiv E_{j\ell}\left[\sum_{t=1}^{T} \frac{\Pi_{s=1}^{t}(1 - \delta_{js}(\mathbf{x}, \varepsilon))}{1 + \kappa_\ell}\right] \tag{17}$$

In this expression the probability of default of households that choose location j and contract ℓ is driven by the location choices of households with characteristics $\mathbf{x}, \varepsilon$.

$$E_{j\ell}\left[\xi\right] = \int \xi(\mathbf{x}, \varepsilon) f(\mathbf{x}, \varepsilon | j) d\mathbf{x} d\varepsilon \tag{18}$$

In the lender's profit (16), the term $E_{j\ell}\left[\phi(\delta)\right]$ is the expected revenue generated by a foreclosure sale in case of default, equal to $\sum_{t=1}^{T} \Pi_{s=1}^{t}(1 - \delta_{js})/(1 + \kappa_\ell)\delta_{jt} \min\left\{B_{jt}, p_{jt}\right\}$.

---

[15] Such perceptions α_ℓ, σ_ℓ are identified by observing the lender's menu of mortgage interest rates, approval and securitization decisions.

At this point it is clear that households' location choices are a key input in lenders' optimal mortgage menu.

Households' Location and Contract Choices A household $(\mathbf{x}, \varepsilon)$ chooses its location and contract based on local amenities $\mathbf{z}_j$ and contract features $r_{j\ell}, L_j$. It maximizes the indirect utility:

$$U_{j\ell}(\mathbf{x}, \varepsilon) = \mathbf{z}_j \boldsymbol{\gamma} + \mathbf{z}_j \Omega \mathbf{x} - \alpha r_j + \beta \varepsilon \cdot r_j - \tau \log L_j + \tau_\epsilon \varepsilon \log L_j + Lender_\ell + Location_j + \eta_{j\ell} \tag{19}$$

where $\eta_{j\ell}$ is extreme-value distributed as is common in the discrete choice literature. $Lender_\ell$ and $Location_j$ are lender and location fixed effects respectively. Here the household's sensitivity to the interest rate and to the loan amount depends on its unobservable default driver ε. Noting $V_{j\ell}(\mathbf{x}, \varepsilon)$ the deterministic part of utility, the choice probability $f(j|\mathbf{x}, \varepsilon)$ is a logit functional form. Households have the outside option of not purchasing a house, which yields utility $U_0 \equiv 0$ by convention.

In turn the expected distribution of unobservable household characteristics ε in a given contract (j, ℓ) is given by inverting Bayes' rule:

$$f(\varepsilon|j, \ell, \mathbf{x}) = \frac{f(j, \ell|\mathbf{x}, \varepsilon) f(\mathbf{x}, \varepsilon)}{f(j, \ell)}, \tag{20}$$

which is a key ingredient in the lender's calculation of its discounting factor ξ described in equation 18. It is also a key ingredient of the lender's first-order condition as shifts in interest rates affect households' sorting in the unobservable dimension ε.

Monopolistic Competition and Sorting

Definition 1. *An equilibrium is a JL-vector $\mathbf{r}$ of interest rates for each location-contract pair (j, ℓ) such that (i) each lender ℓ chooses a menu $\mathbf{r}_\ell$ of interest rates in each location j to maximize its total profit given the other lenders' menu and given households' location choices; (ii) each household $i \in [0, 1]$ chooses a location-contract pair (j, ℓ) that maximizes its utility.*

The structure of this problem is in the class of problems first introduced by Mirrlees (1971) and developed in the case of monopoly pricing by Maskin & Riley (1984).[16]

---

[16] A recent structural model of business lending with asymmetric information is presented in Crawford, Pavanini & Schivardi (2018).

The Securitization Option The introduction of the securitization option is straightforward. For mortgages whose amount L_j is below the conforming limit $\tilde{L}$, the lender can sell the mortgage to the agency securitizers at a guaranty fee $\varphi(\mathbf{x})$ that depends on the borrower's FICO score and the LTV.[17] In such a case, the multiplier becomes $\xi(\varphi)$ and the lender does not earn the revenue $E_{j\ell}[\phi]$ of a foreclosure sale. As the lender picks loans for securitization after observing $(\mathbf{x}, \varepsilon)$, the lender securitizes mortgages for which the profit $\Pi^h_{j\ell}$ of originating and holding (equation (16)) is lower than the profit $\Pi^s_{j\ell}$ when originating and securitizing. Then:

$$\Pi_{j\ell} = \begin{cases} \max\left\{\Pi^h_{j\ell}, \Pi^s_{j\ell}\right\} & \text{for } L_j \leq \tilde{L} \\ \Pi^h_{j\ell} & \text{otherwise} \end{cases} \tag{21}$$

Identification using Discontinuities at the Conforming Loan Limit The structural parameters of interest are lenders' perceptions of price trends $\hat{\alpha}_j, \hat{\sigma}_j$ and their cost of capital $\hat{\kappa}_\ell$ that pin down their choice of interest rates and approval decisions. In turn these interest rate and approval decisions are driven by households' self-selection into mortgage options (their unobservable driver ε_i) and by their propensity to default.

The relationship between default rates δ, observables $\mathbf{x}$, unobservables ε, mortgage balance B_{jt}, and current house price p_{jt} is identified using a discrete choice estimation. The BlackKnight data set described in Section 3 has each borrower's payment history at monthly frequency, with the unpaid balance. Such data is merged at the ZIP level with Zillow's house price index.

Households' self-selection into mortgage options is estimated using a discrete choice model akin to Berry, Levinsohn & Pakes (1995) with JL options, one for each location and each lender. A simple contraction mapping yields base utilities, which regressed on interest rates $r_{j\ell}$, mortgage amounts $L_{j\ell}$, and house prices, provide the structural drivers of households' choices conditional on $\mathbf{x}$ and ε.

The expected price trend α_ℓ, volatility σ_ℓ, and the lender's cost of capital κ_ℓ are backed out using the discontinuities in mortgage characteristics at the conforming loan limit. The estimator $\hat{\alpha}_\ell, \hat{\sigma}_\ell$ of the lender's perception of house price dynamics is the quantity that minimizes the distance between the model-predicted discontinuity in approval rates, securitization rates, interest rates, default probabilities at the conforming loan limit and the observed discontinuity in each of these dimensions.

$$\left(\hat{\alpha}_\ell, \hat{\sigma}_\ell, \hat{\kappa}_\ell\right) \equiv \operatorname{argmin} \left(\mathbf{Disc.}^*_\ell - \widehat{\mathbf{Disc.}}_\ell\right)' \Psi_\ell \left(\mathbf{Disc.}^*_\ell - \widehat{\mathbf{Disc.}}_\ell\right) \tag{22}$$

---

[17] In the model's simulation upfront fees are converted into ongoing fees following standard formulas.

where $\mathbf{Disc.}^*_\ell$ is the vector of discontinuities generated by the model, $\hat{\mathbf{Disc}}._\ell$ is the vector of discontinuities estimated in the data (without structural assumptions); and Ψ_ℓ is the positive definite matrix that minimizes the variance of the estimator.

This method of *indirect inference* described by Gourieroux et al. (1993) and recently used in Fu & Gregory (2019) provides consistent estimators of lenders' beliefs about future prices as well as their opportunity cost of capital.

6.2 Estimation Results

Baseline Results and Model Predictions The model's baseline estimates of the average perception of price trends, price volatility, and cost of capital are:

$$\hat{\alpha} = +2.68\%, \quad \hat{\sigma} = 0.48\%, \quad \hat{\kappa} = 4.40\% \tag{23}$$

Figure 13 presents the model's predictions of discontinuities at the conforming loan limit given the structural parameters. On these graphs, the lender sets interest rates, makes approval and securitization decisions optimally. Each point is a neighborhood. Households make neighborhood and lender choices based on their multinomial discrete choice model; households can also choose not to borrow (choose the outside option). Households default based on their observables, unobservables, their balance and the neighborhood's price.

The model predicts a bunching of households at the conforming loan limit, where the probability that a household chooses a conforming loan is strictly higher than the probability of choosing a jumbo loan with similar amount. Similarly, the model predicts lower interest rates (at given household observables $\mathbf{x}$) for conforming loans. Importantly, the model also predicts significantly higher default rates for conforming loans than for jumbo loans with similar amounts. This is due to the self-selection of worse risk ε into the conforming loan segment. The model is thus able to jointly generate similar dynamics as in this paper's data from HMDA and BlackKnight financial.

6.3 Out-of-Sample Predictions

6.3.1 Increasing Disaster Risk

The model enables an out-of-sample estimation of the impact of declining price trends on securitization and origination volumes. Figure 14 compares the baseline scenarios generated by the estimated parameters (23), to a scenario with declining expected prices $\alpha_\ell = -1\%$ and similar volatility $\sigma_\ell = 0.48\%$. The cost of capital is kept constant.

As expected, the decline in prices causes a rise in expected default rates (subfigure (b)). The most salient fact from the simulation is the rise in the fraction of conforming mortgages that are securitized (subfigure (c)). While interest rates further from the conforming loan limit increase, interest rates at the limit remain stable (subfigure (a)). The increase in securitization coupled with the relative stability of the mortgage at the limit suggests that the GSEs' securitization activity acts as an insurance mechanism and that lenders transfer risk to the GSEs' balance sheet.

6.3.2 The Withdrawal of the GSEs

Finally, the structural approach also allows a simulation of the impact of the withdrawal of the GSEs with increasing disaster risk. In particular, the simulation can establish whether lenders would reduce lending volumes, increase interest rates, in the absence of the option to sell risky mortgages. Elenev, Landvoigt & Van Nieuwerburgh (2016) predicts that underpriced government mortgage guarantees lead to more and riskier mortgage originations. This paper's model predicts both aggregate shifts in default risk and local, neighborhood-level, shifts in mortgage originations, securitizations, as well as households' self-selection into the GSE-guaranteed segment.

This is what Figure 15 presents. The green points depict the equilibrium in the mortgage market when lenders do not have the option to securitize. The withdrawal of the GSEs causes a substantial decline in the overall fraction of households who choose to buy a home, and no bunching at the conforming loan limit (subfigure (a)). Without the securitization option, there is no evidence of adverse selection of households into lower mortgage volumes (subfigure (c)). Default rates for low mortgage amounts drop substantially, yet default rates for large mortgage amounts remain similar (subfigure (b)).

Finally, subfigure (d) combines the withdrawal of the GSEs with increasing risk, in the form of a decreasing price trend $\alpha = -1\%$. In the previous subsection, increasing risk translated into greater securitization volumes with no substantial shift in origination volumes. Without the GSEs however, increasing risk leads to a substantial decline in origination volumes, consistent with the hypothesis that the securitization option acts as an implicit insurance mechanism.[18]

---

[18] This is also consistent with Elenev et al.'s (2016) macro-level findings that "increasing the price of the mortgage guarantee reduces financial fragility, leads to fewer but safer mortgages."

7 Conclusion

Fannie Mae and Freddie Mac have an important public mission (Frame & Tracy 2018): to support liquidity in the secondary U.S. mortgage market, and thereby facilitate access to homeownership for millions of Americans. They also make possible the popular 30-year, fixed-rate mortgage. Households borrowing in 2020 using such a mortgage contract sign loans maturing in 2050. Thus, in a world of increasing disaster risk, Fannie Mae and Freddie Mac play a key role in guiding lenders and households through the climate change adaptation process.

This paper uses mortgage-level data merged with neighborhood-level natural disaster data to find that (i) after natural disasters, lenders have incentives to screen their loans for securitization, (ii) conforming loans, that are eligible for sale to Fannie Mae or Freddie Mac, are riskier than non-conforming loans at equal loan amount, (iii) after natural disasters, lenders increase their originations and securitization of conforming loans. Our out-of-sample simulations suggest that (iv) in the current status quo scenario (at constant agency guarantee fees), increasing disaster risk would not significantly affect origination volumes, at the cost of increasing securitization and default. This latter finding would not hold if the GSEs either withdrew or increased their guarantee fee: origination volumes and interest rates would then significantly respond to increasing risk.

Given that natural disasters cause correlated mortgage defaults,[19] such default may become difficult to diversify if the volume of at-risk loans increases. Hence this paper's conclusions should be of interest to stakeholders interested in monitoring the systemic climate risk held onto lenders' and GSEs' balance sheets.

References

Acemoglu, D., Ozdaglar, A. & Tahbaz-Salehi, A. (2015), 'Systemic risk and stability in financial networks', *American Economic Review* **105**(2), 564–608.

Arellano, M. & Bond, S. (1991), 'Some tests of specification for panel data: Monte carlo evidence and an application to employment equations', *The review of economic studies* **58**(2), 277–297.

---

[19] Phelan (2017) presents a financial model where one of the purposes of intermediaries (e.g. commercial banks) is to facilitate the monitoring of mortgage default correlation.

Bakkensen, L. A. & Barrage, L. (2017), Flood risk belief heterogeneity and coastal home price dynamics: Going under water?, Technical report, National Bureau of Economic Research.

Bartik, T. J. (1991), 'Who benefits from state and local economic development policies?', *WE Upjohn Institute for Employment Research* .

Bayer, P., Ellickson, B. & Ellickson, P. B. (2010), 'Dynamic asset pricing in a system of local housing markets', *American Economic Review* **100**(2), 368–72.

Bender, M. A., Knutson, T. R., Tuleya, R. E., Sirutis, J. J., Vecchi, G. A., Garner, S. T. & Held, I. M. (2010), 'Modeled impact of anthropogenic warming on the frequency of intense atlantic hurricanes', *Science* **327**(5964), 454–458.

Bernstein, A., Gustafson, M. T. & Lewis, R. (2019), 'Disaster on the horizon: The price effect of sea level rise', *Journal of Financial Economics* .

Berry, S., Levinsohn, J. & Pakes, A. (1995), 'Automobile prices in market equilibrium', *Econometrica: Journal of the Econometric Society* pp. 841–890.

Carney, M. (2015), 'Breaking the tragedy of the horizon–climate change and financial stability', *Speech given at Lloyd's of London* **29**, 220–230.

Center, H. F. P. (2019), 'Housing finance at a glance: a monthly chartbook'.

Crawford, G. S., Pavanini, N. & Schivardi, F. (2018), 'Asymmetric information and imperfect competition in lending markets', *American Economic Review* **108**(7), 1659–1701.

David, H., Dorn, D. & Hanson, G. H. (2013), 'The china syndrome: Local labor market effects of import competition in the united states', *American Economic Review* **103**(6), 2121–68.

DeFusco, A. A. & Paciorek, A. (2017), 'The interest rate elasticity of mortgage demand: Evidence from bunching at the conforming loan limit', *American Economic Journal: Economic Policy* **9**(1), 210–40.

Elenev, V., Landvoigt, T. & Van Nieuwerburgh, S. (2016), 'Phasing out the gses', *Journal of Monetary Economics* **81**, 111–132.

Elliott, M., Golub, B. & Jackson, M. O. (2014), 'Financial networks and contagion', *American Economic Review* **104**(10), 3115–53.

Elsner, J. B. (2006), 'Evidence in support of the climate change–atlantic hurricane hypothesis', *Geophysical Research Letters* **33**(16).

Frame, W. S., Fuster, A., Tracy, J. & Vickery, J. (2015), 'The rescue of fannie mae and freddie mac', *Journal of Economic Perspectives* **29**(2), 25–52.

Frame, W. S. & Tracy, J. (2018), 'Introduction to special issue: The appropriate role of government in us mortgage markets', *Economic Policy Review* **24**(3).

Fu, C. & Gregory, J. (2019), 'Estimation of an equilibrium model with externalities: Post-disaster neighborhood rebuilding', *Econometrica* **87**(2), 387–421.

Gallagher, J. & Hartley, D. (2017), 'Household finance after a natural disaster: The case of hurricane katrina', *American Economic Journal: Economic Policy* **9**(3), 199–228.

Garner, A. J., Mann, M. E., Emanuel, K. A., Kopp, R. E., Lin, N., Alley, R. B., Horton, B. P., DeConto, R. M., Donnelly, J. P. & Pollard, D. (2017), 'Impact of climate change on new york city's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 ce', *Proceedings of the National Academy of Sciences* **114**(45), 11861–11866.

Giglio, S., Maggiori, M. & Stroebel, J. (2014), 'Very long-run discount rates', *The Quarterly Journal of Economics* **130**(1), 1–53.

Giglio, S., Maggiori, M. & Stroebel, J. (2016), 'No-bubble condition: Model-free tests in housing markets', *Econometrica* **84**(3), 1047–1091.

Goodman, L. S. (2016), 'The rebirth of securitization: Where is the private-label mortgage market?', *The Journal of Structured Finance* **22**(1), 8–19.

Gourieroux, C., Monfort, A. & Renault, E. (1993), 'Indirect inference', *Journal of applied econometrics* **8**(S1), S85–S118.

Grinsted, A., Moore, J. C. & Jevrejeva, S. (2013), 'Projected atlantic hurricane surge threat from rising temperatures', *Proceedings of the National Academy of Sciences* **110**(14), 5369–5373.

Heipertz, J., Ouazad, A. & Rancière, R. (2019), The transmission of shocks in endogenous financial networks: A structural approach, Technical report, National Bureau of Economic Research.

Jaffee, D. M. (2010), 'The role of the gses and housing policy in the financial crisis', *Testimony before the Financial Crisis Inquiry Commission, February* **25**, 2010.

Keys, B. J., Mukherjee, T., Seru, A. & Vig, V. (2010), 'Did securitization lead to lax screening? evidence from subprime loans', *The Quarterly journal of economics* **125**(1), 307–362.

Kousky, C. (2018), 'Financing flood losses: A discussion of the national flood insurance program', *Risk Management and Insurance Review* **21**(1), 11–32.

Kousky, C. (2019), 'The role of natural disaster insurance in recovery and risk reduction', *Annual Review of Resource Economics* **11**.

Lin, N., Emanuel, K., Oppenheimer, M. & Vanmarcke, E. (2012), 'Physically based assessment of hurricane surge threat under climate change', *Nature Climate Change* **2**(6), 462.

Lin, N., Kopp, R. E., Horton, B. P. & Donnelly, J. P. (2016), 'Hurricane sandy's flood frequency increasing from year 1800 to 2100', *Proceedings of the National Academy of Sciences* **113**(43), 12071–12075.

Loutskina, E. & Strahan, P. E. (2009), 'Securitization and the declining impact of bank finance on loan supply: Evidence from mortgage originations', *The Journal of Finance* **64**(2), 861–889.

Mann, M. E. & Emanuel, K. A. (2006), 'Atlantic hurricane trends linked to climate change', *Eos, Transactions American Geophysical Union* **87**(24), 233–241.

Markowitz, H. (1952), 'Portfolio selection', *The journal of finance* **7**(1), 77–91.

Maskin, E. & Riley, J. (1984), 'Monopoly with incomplete information', *The RAND Journal of Economics* **15**(2), 171–196.

Masozera, M., Bailey, M. & Kerchner, C. (2007), 'Distribution of impacts of natural disasters across income groups: A case study of new orleans', *Ecological Economics* **63**(2-3), 299–306.

McCrary, J. (2008), 'Manipulation of the running variable in the regression discontinuity design: A density test', *Journal of econometrics* **142**(2), 698–714.

Mirrlees, J. A. (1971), 'An exploration in the theory of optimum income taxation', *The review of economic studies* **38**(2), 175–208.

Myerson, R. B. (1981), ‘Optimal auction design’, *Mathematics of operations research* **6**(1), 58–73.

Ortega, F. & Taşpınar, S. (2018), ‘Rising sea levels and sinking property values: Hurricane sandy and new york’s housing market’, *Journal of Urban Economics* .

Phelan, G. (2017), ‘Correlated default and financial intermediation’, *The Journal of Finance* **72**(3), 1253–1284.

Rothschild, M. & Stiglitz, J. (1976), ‘Equilibrium in competitive insurance markets: An essay on the economics of imperfect information’, *The Quarterly Journal of Economics* pp. 629–649.

Shiller, R. J. (1995), ‘Aggregate income risks and hedging mechanisms’, *The Quarterly Review of Economics and Finance* **35**(2), 119–152.

Smith, A. B. & Katz, R. W. (2013), ‘Us billion-dollar weather and climate disasters: data sources, trends, accuracy and biases’, *Natural hazards* **67**(2), 387–410.

Vigdor, J. (2008), ‘The economic aftermath of hurricane katrina’, *Journal of Economic Perspectives* **22**(4), 135–54.

Webster, P. J., Holland, G. J., Curry, J. A. & Chang, H.-R. (2005), ‘Changes in tropical cyclone number, duration, and intensity in a warming environment’, *Science* **309**(5742), 1844–1846.

Weinkle, J., Landsea, C., Collins, D., Musulin, R., Crompton, R. P., Klotzbach, P. J. & Pielke, R. (2018), ‘Normalized hurricane damage in the continental united states 1900–2017’, *Nature Sustainability* p. 1.

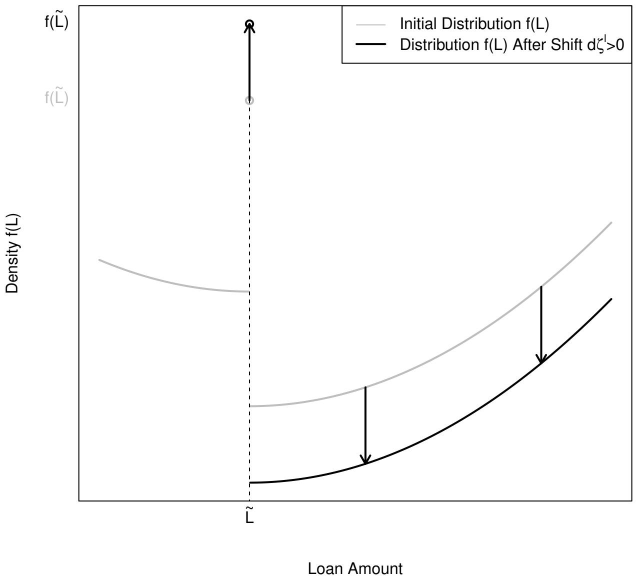
Weiss, N. E., Jones, K., Perl, L. & Cowan, T. (2017), The loan limits for government-backed mortgages, Technical report, Congressional Research Service, Washington, D.C.

Zhang, L. & Leonard, T. (2018), ‘Flood hazards impact on neighborhood house prices’, *The Journal of Real Estate Finance and Economics* pp. 1–19.

Figure 1: The Impact of Lender and Borrower's Risk Perceptions on Bunching at the Conforming Loan Limit – Theoretical Predictions from the Mechanism Design Model

These two figures present the predictions of the model of mortgage pricing with asymmetric information (Section 2) when either the lender's risk perception ζ^{ℓ} *increases (subfigure (a)) or the borrower's risk perception* ζ^{b} *increases (subfigure (b)). Subfigure (a) suggests that bunching at the conforming limit increases, while subfigure (b) suggests that bunching at the conforming loan limit declines. Such results are described in Proposition 2.*

(a) An Increase in the Lender's Perception of Risk



(b) An Increase in the Household's Perception of Risk

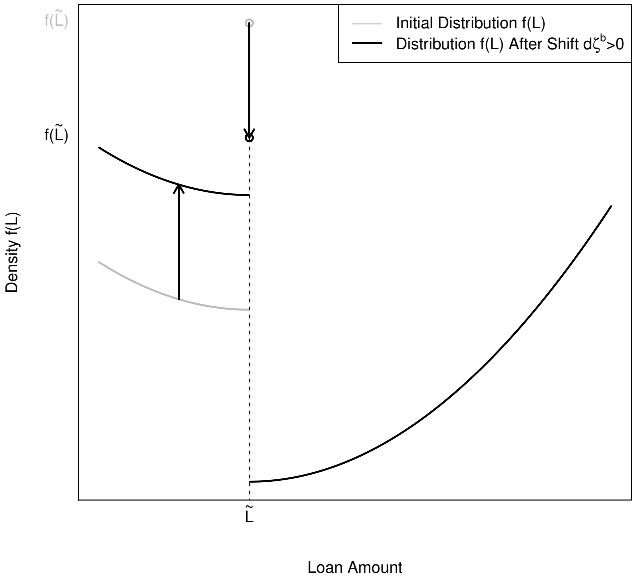


Figure 2: The treatment group for Hurricane Katrina

This figure highlights the boundaries of neighborhoods hit by Hurricane Katrina. A neighborhood is in the treatment group if: (i) its minimum elevation is less than 3 meters, (ii) its distance to the coastline or its distance to wetland is less than 2 km, and (iii) if it lies in the 64kt wind path. Elevation from USGS' digital elevation model. Distance to wetland from the Land Cover data set. Wind speed from the Atlantic Hurricane data of the National Hurricane Center. The treatment group is at the intersection of the red and blue areas.

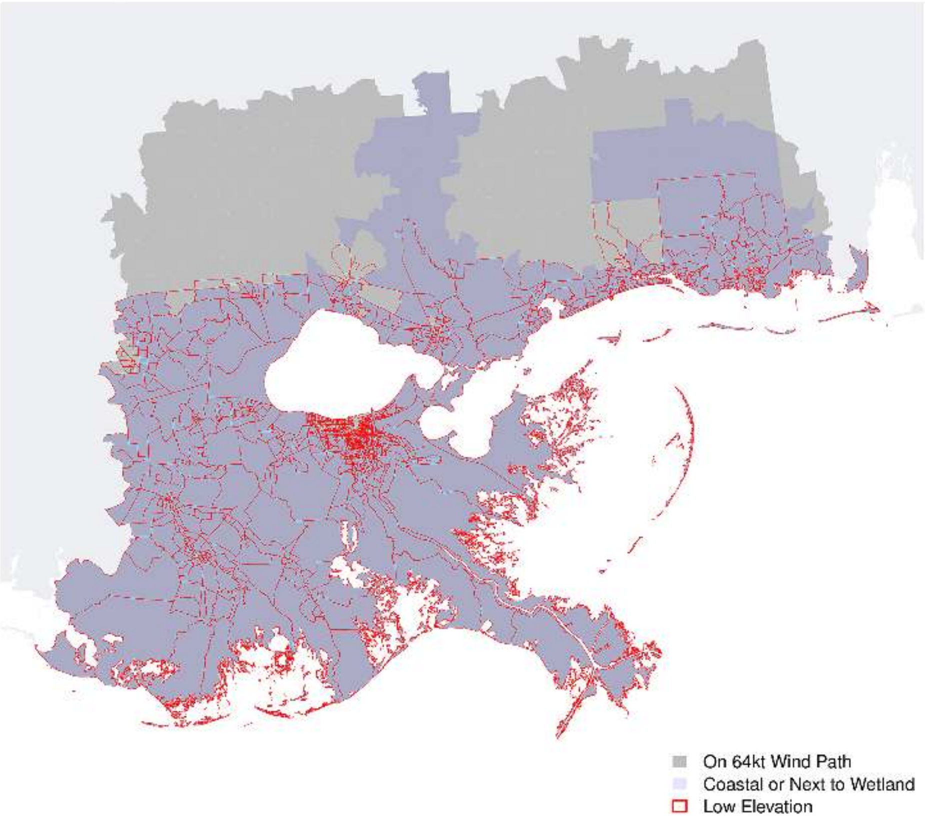


Figure 3: The treatment group for Hurricane Sandy

This figure highlights the boundaries of neighborhoods hit by Hurricane Sandy. A neighborhood is in the treatment group if: (i) its minimum elevation is less than 3 meters, (ii) its distance to the coastline or its distance to wetland is less than 2 km, and (iii) if it lies in the 64kt wind path. Elevation from USGS' digital elevation model. Distance to wetland from the Land Cover data set. Wind speed from the Atlantic Hurricane data of the National Hurricane Center. The treatment group is at the intersection of the red and blue areas.

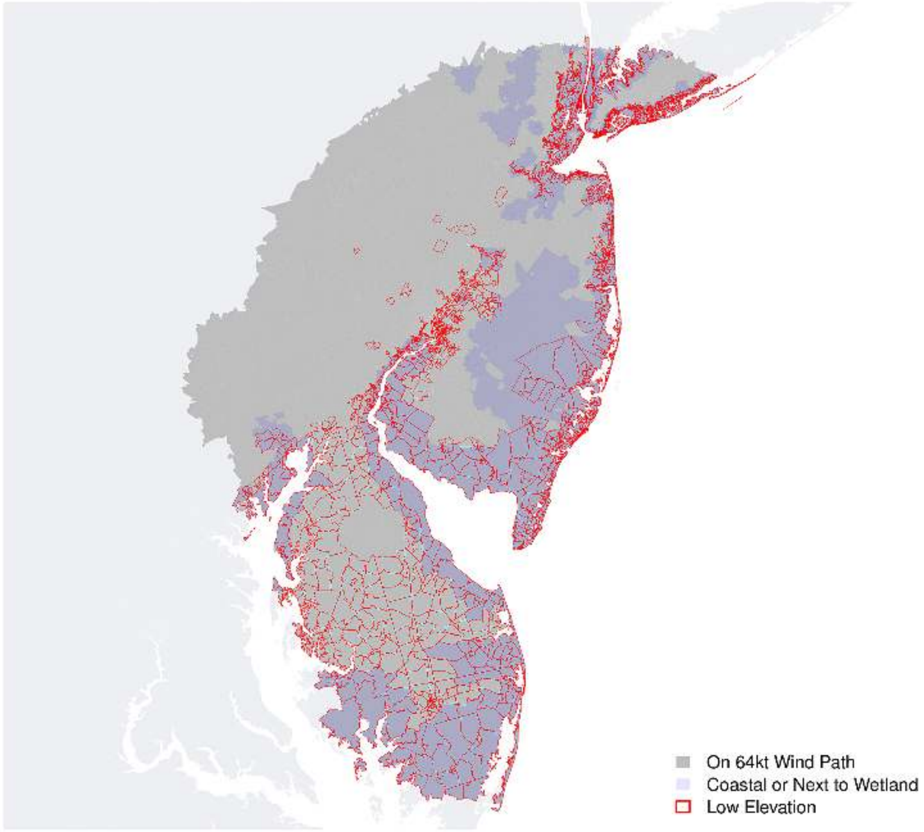
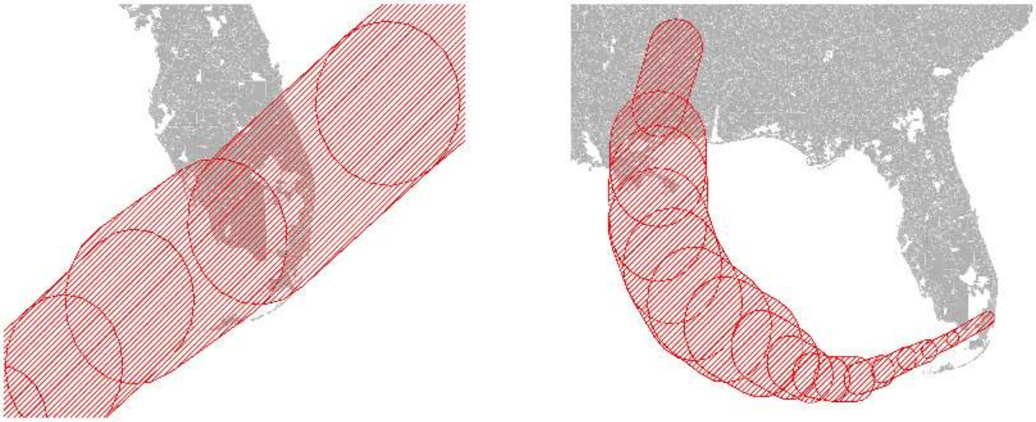


Figure 4: ZIP Codes in Hurricanes' Wind Path

These four maps illustrate the determination of 5-digit ZIP codes (ZCTA5) in the 64 knot wind radius of a hurricane path. These are ZCTAs in grey or red in the previous figure. We present here 4 hurricanes out of the 20. The red area is the radius of 64 knot winds around each hurricane's path. Hurricane paths are measured by NOAA National Hurricane Center's Atlantic Hurricane Data Set. The grey polygons are the boundaries of ZCTAs from the 2014 edition of Census maps.

(a) Wilma 2005

(b) Katrina 2005



(c) Ike 2008

(d) Sandy 2012

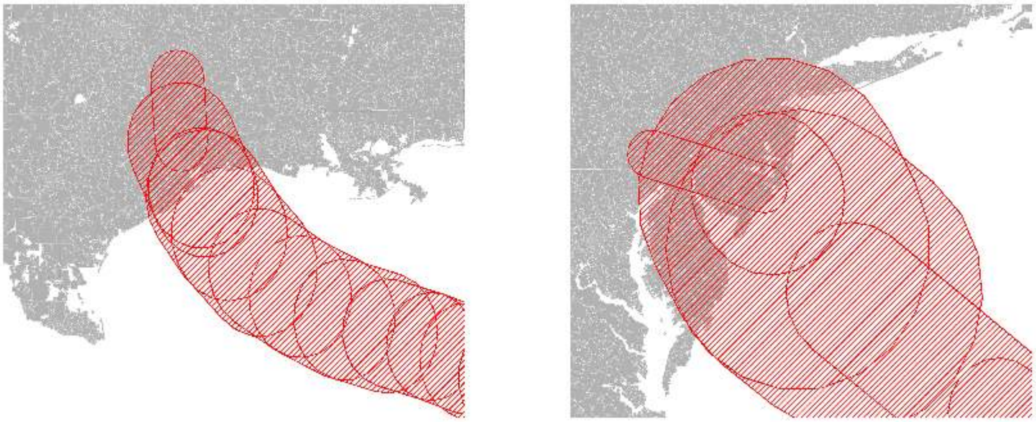
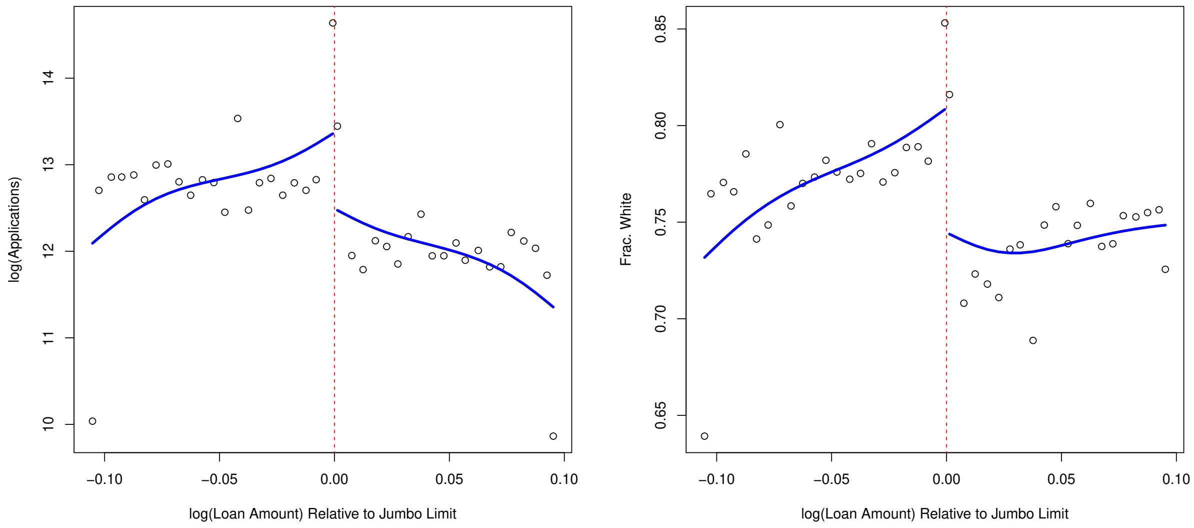


Figure 5: Baseline Discontinuities at the Conforming Loan Limit – HMDA Analysis

These figures present the estimates of the impact of the conforming loan limit on the log count of applications, borrowers' ethnicity, the loan-to-income ratio of originations, and the liquidity ratio of the lender. The black points are the value for each 1 ppt bin in the window around the conforming loan limit. The blue lines are the predictions from a generalized additive model. The red dotted line is the conforming loan limit. The horizontal axis is the difference between the log loan amount and the log conforming loan limit. The conforming loan limits are year- and county-specific .



(a) Counts of Applications

(b) White Applicants

(c) Loan-to-Income Ratio

(d) Lender's Balance-Sheet Liquidity

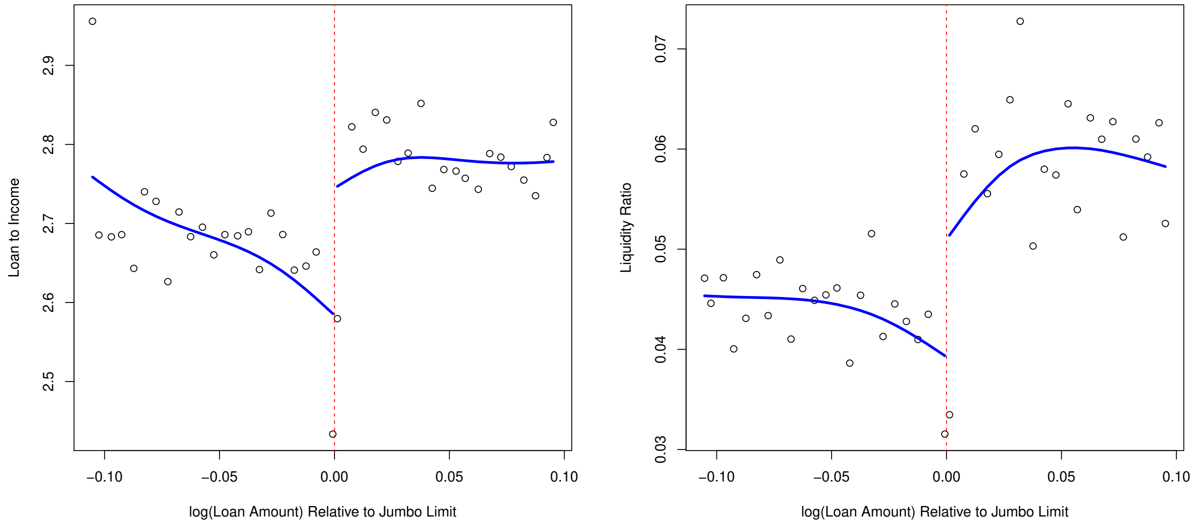
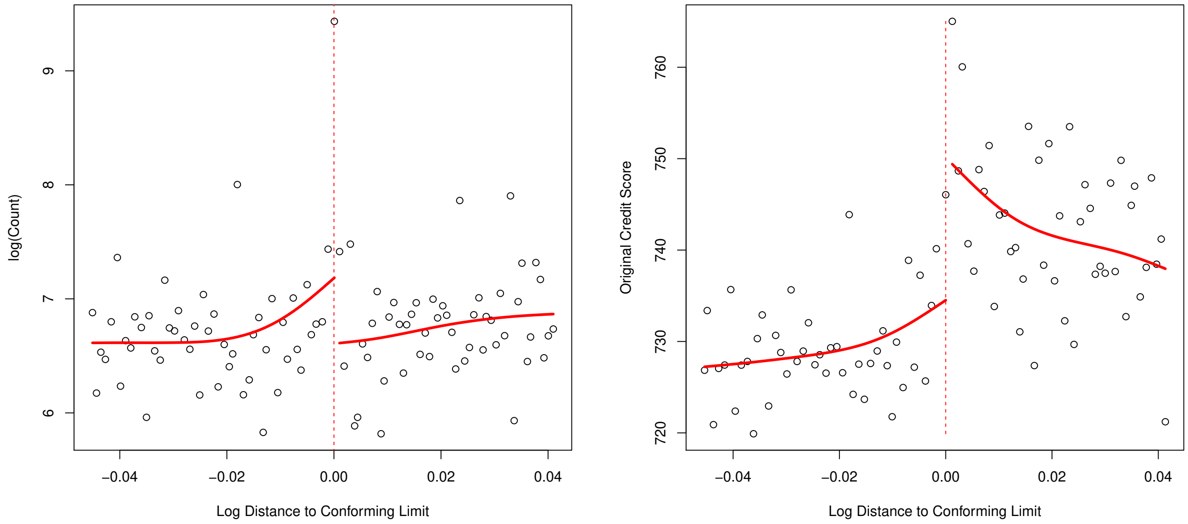


Figure 6: Baseline Discontinuities at the Conforming Loan Limit – BlackKnight Data Analysis

These figures present the estimates of the impact of the conforming loan limit on mortgage characteristics in the data set of property transactions for the New York metro area. The solid red lines are the predictions from a generalized additive model. The red dotted line is the conforming loan limit. The horizontal axis is the difference between the log loan amount and the log conforming loan limit. The values are year- and county-specific.

(a) Counts of Originations (First Mortgage)

(b) Credit Score at Origination



(c) Interest Rate

(d) Private Mortgage Insurance

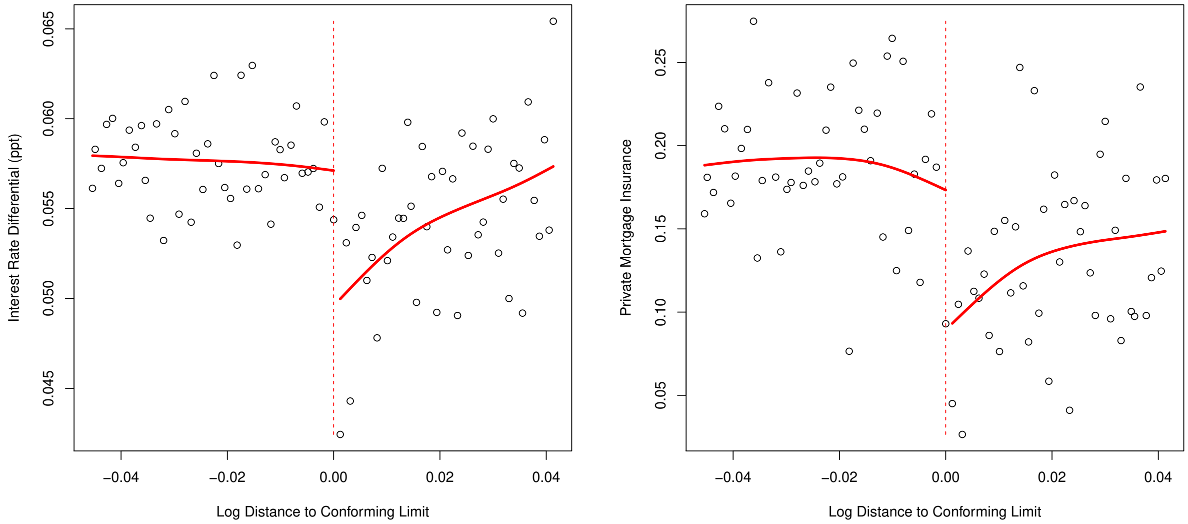
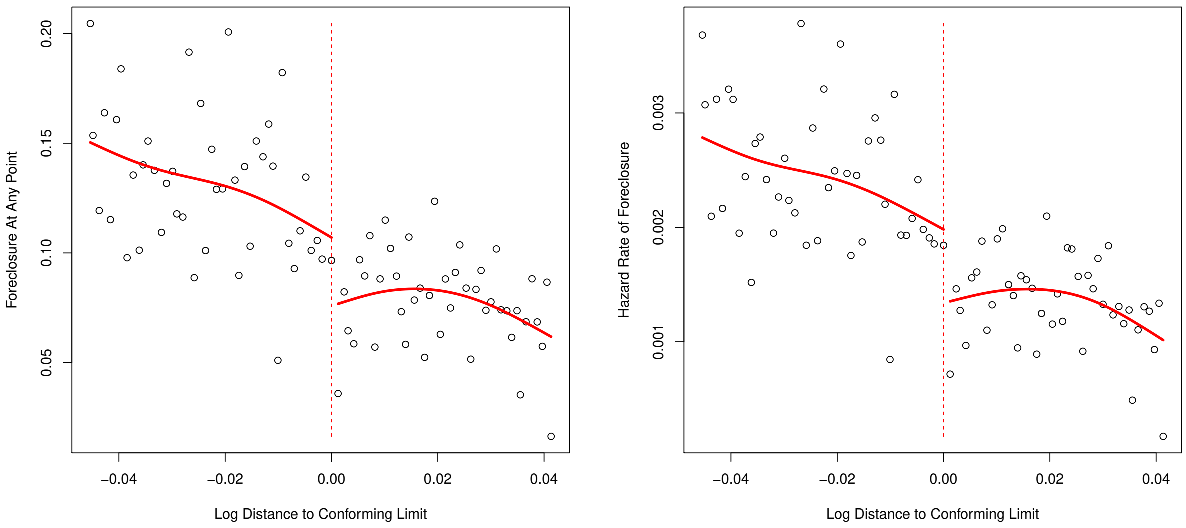


Figure 7: Default and Prepayment Around the Conforming Limit

These figures estimates delinquency, foreclosure, and bankruptcy probabilities around the conforming loan limits.

(a) Foreclosure at any point after origination

(b) Hazard Rate of a Payment Incident (Delinquency, Foreclosure)



(c) 60 Days Delinquent At Any Point

(d) Voluntary Payoff

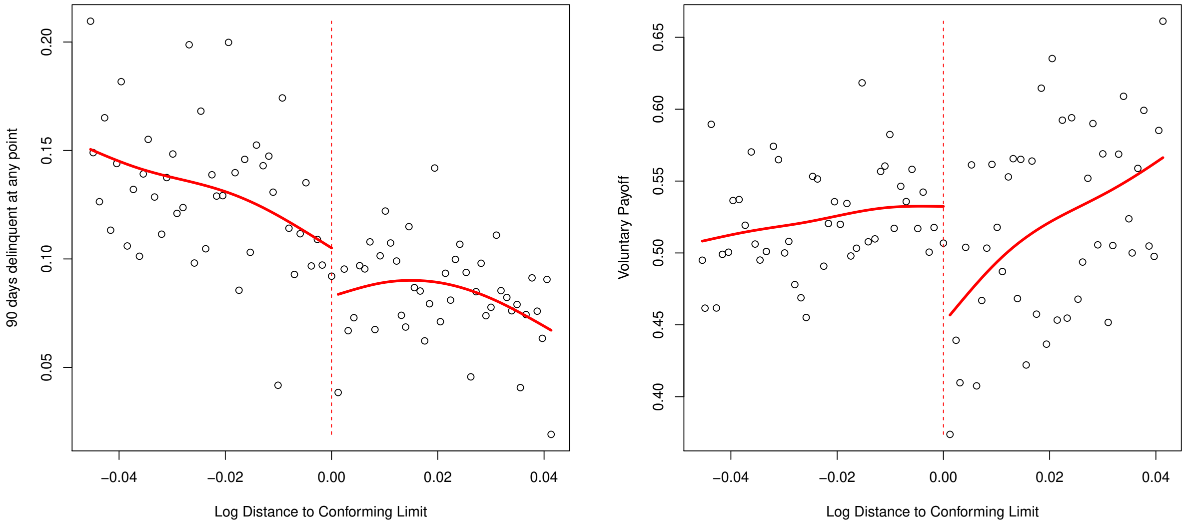
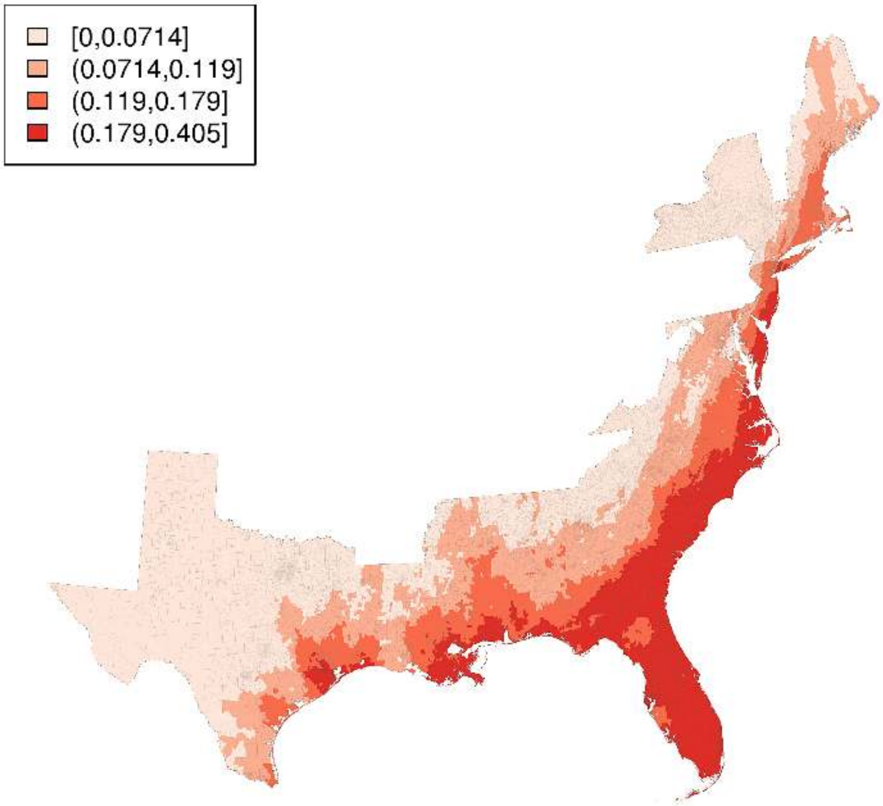


Figure 8: 168-Year Probability of Hurricane Occurence

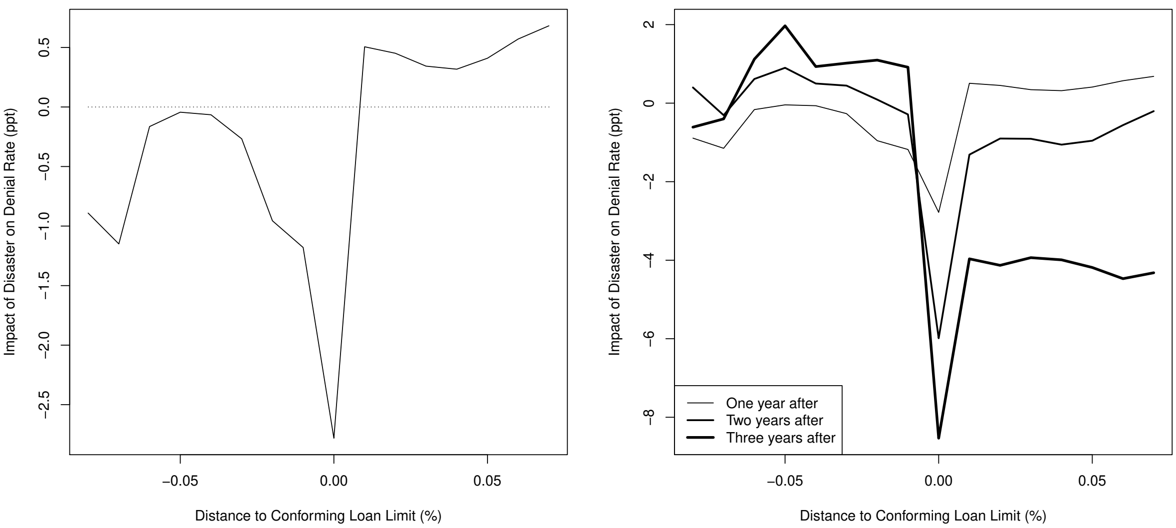
This map presents, for each of the 86,455 blockgroups in the Atlantic states, the number of hurricane paths intersecting the neighborhood divided by 167 years. The time period is 1851-2017. For instance, a probability of 0.10 implies that there were between 16 and 17 hurricanes going through the neighborhood over 168 years. The hurricane path is the 64kt wind speed path.



Source: NOAA's Atlantic Hurricane Data Base.

Figure 9: Main Figure – Impact of Billion Dollar Event on Originations at the Conforming Loan Limit

This figure describes the estimates of the impact of the 15 billion dollar events on the denial rate by loan volume relative to the conforming loan limit. The horizontal axis is the % distance of the loan volume to the conforming loan limit. The vertical axis is the impact of the billion dollar event on the probability of denial (in percentage points) for loan volumes at each level (horizontal axis).



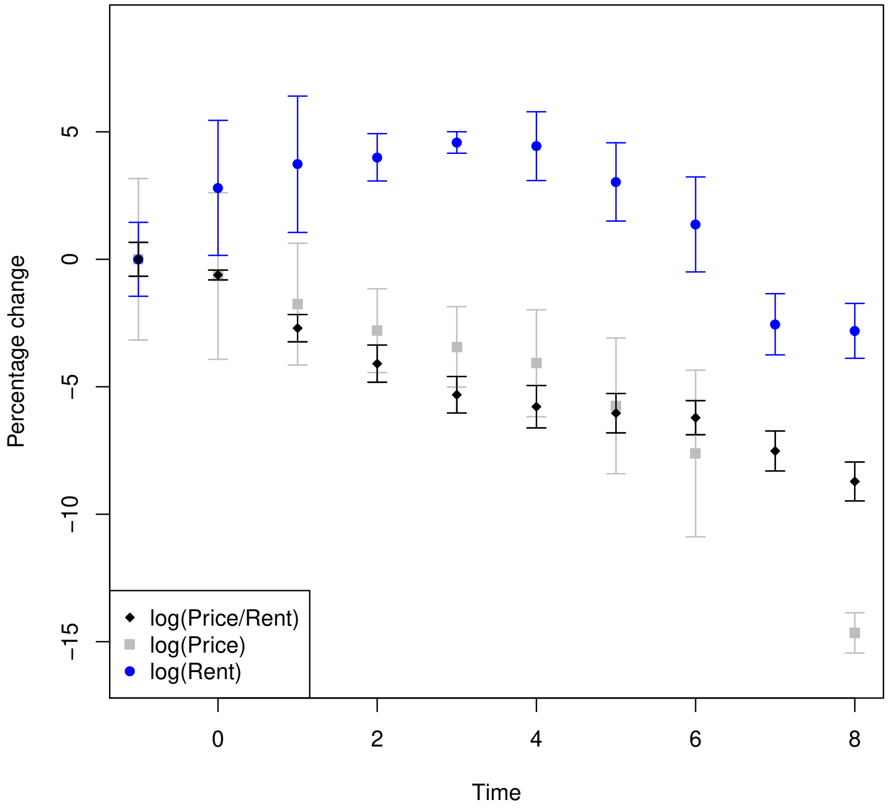
(a) In the year following the disaster

(b) In the three years after the disaster

The reported number on the vertical axis is the coefficient of a variable interacting the loan volume with a treatment dummy. The treatment dummy is equal to 1 if the zip is hit by a natural disaster in year $t-k$ *for* $k = 1, 2, 3$ *. The regression includes year, 5-digit Zip fixed effects, indicator variables for the number of years relative to each disaster. The sample is the set of mortgages with a loan amount between 90 and 110% of the year- and county-specific conforming loan limit.*

Figure 10: Impact of Billion Dollar Disasters on Prices, Rents, and the Price/Rent Ratio

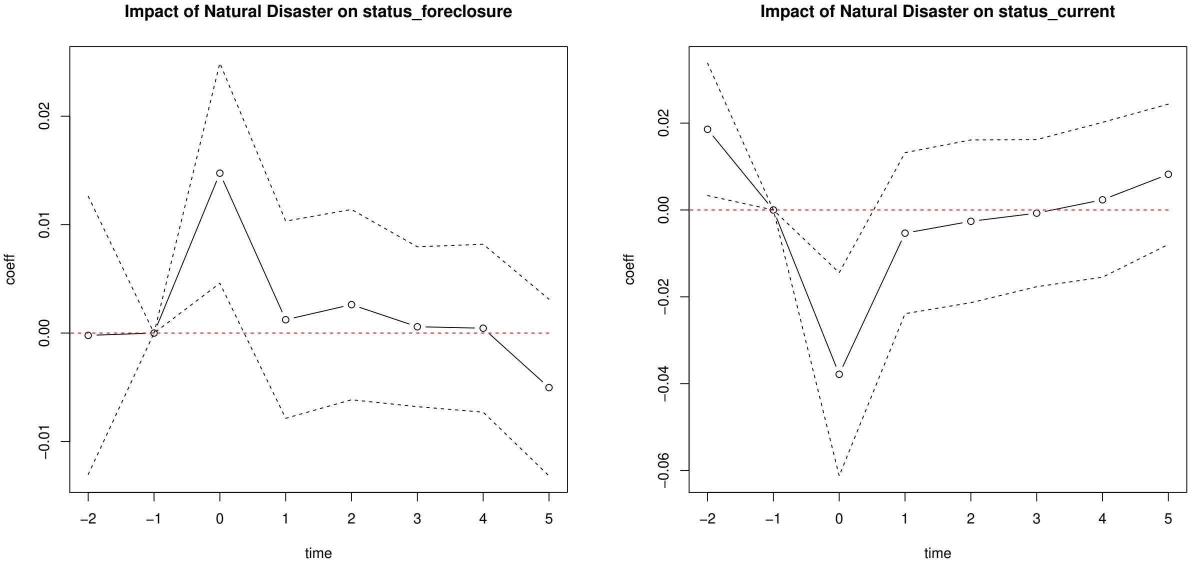
This figure presents the results of a regression of log price, log rent, and log price/rent ratio on a series of pre- and post-disaster indicator variables.



Source: Zillow House Price Index Single Family/Multifamily. Rental Price Index. Billion dollar events after 2010 (first year of data availability for Zillow's price indices) as in Table 1. Impacts on prices and price/rent ratios significant at 1% after the event. Standard errors clustered by Zip and by year.

Figure 11: The Impact of Billion Dollar Events on Default and Prepayment

These figures present the coefficients of a regression of payment history dummies on a set of pre- and post-natural disaster indicator variables. Regression control for both ZIP code and year fixed effects.



(a) Foreclosure

(b) Mortgage is Current

(c) Prepayment

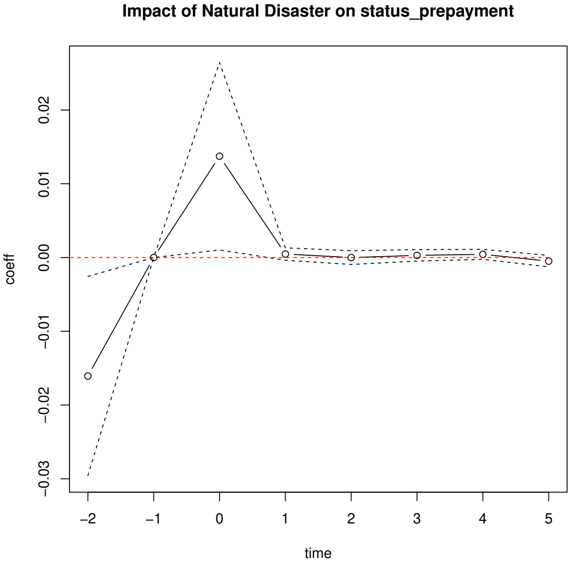
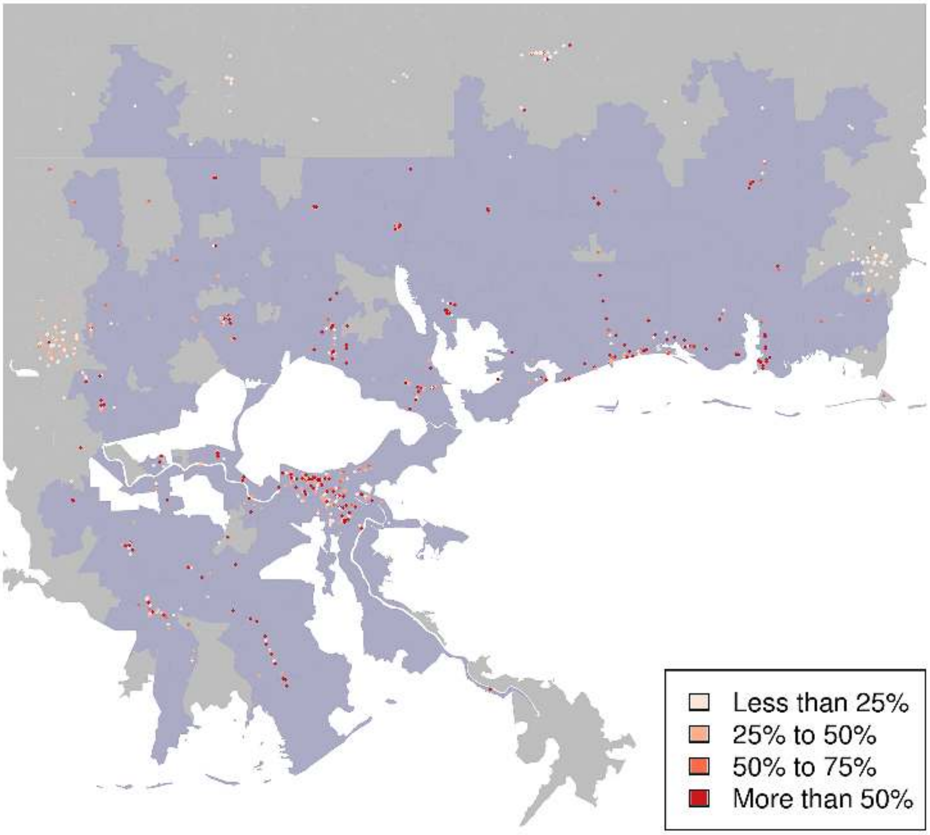


Figure 12: Bank Branches and Banks' Geographic Coverage of Billion Dollar Events

Each dot on this figure is a bank branch. The blue areas are 5-digit Zips hit by a billion dollar event. Bank branches are matched to their corresponding banks. Regression Table 5 uses two measures of a bank's geographic coverage: (i) the minimum distance of its branch network to the billion dollar event, and (ii) the share of a bank's network in zips hit. The upper panel presents a map, where the color indicates what share of a bank's branches are in the area hit by a billion dollar event, i.e. the extent to which a bank's branch network is geographically concentrated in this area. The lower panel presents descriptive statistics for the two measures. This data is built for the 15 billion dollar events described in Table 1.

(i) Share of a Bank's Network in Disaster-Struck Area: the Case of Hurricane Katrina (2005)

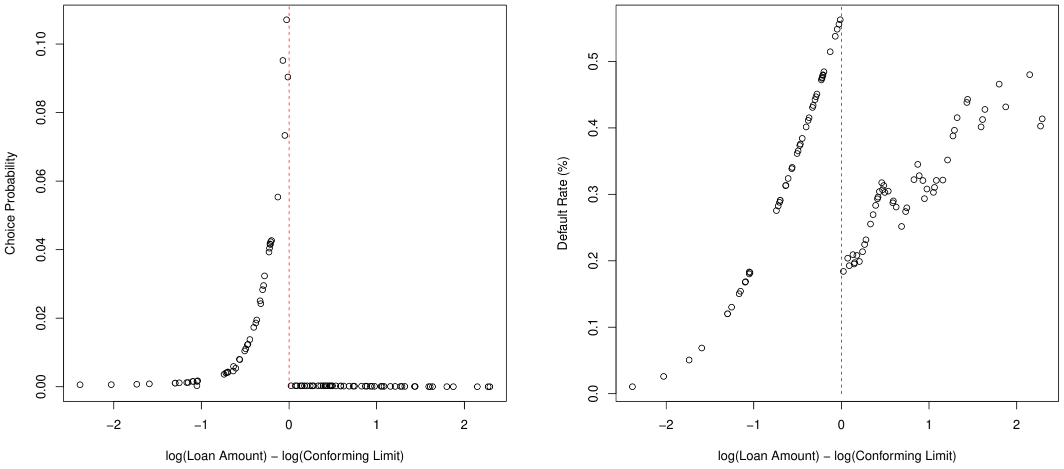


(ii) Descriptive statistics for the case of Hurricane Katrina

Measure	P25	Median	Mean	P75
log Minimum Distance of Branches to Area	0.00	5.20	4.98	6.55
Share of a Bank's Network in Area	0.00	3.90	22.86	31.80

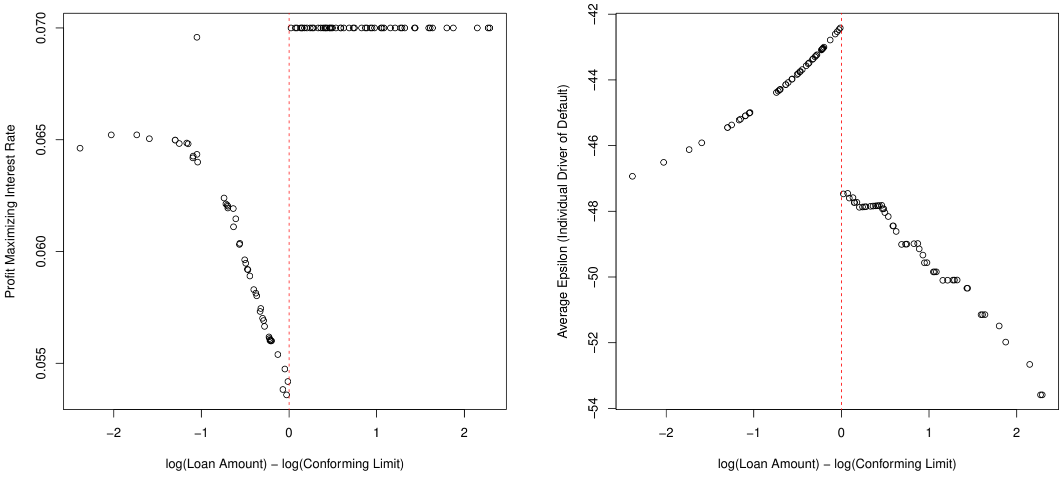
Figure 13: Model-Generated Discontinuities at the Conforming Loan Limit

This set of figures presents the predictions of Section 6's model of monopolistic competition with asymmetric information. Each lender chooses a menu of interest rates and approval rates optimally given households' self-selection and future default probabilities. In the graphs below each point is a neighborhood, with loan amounts displayed as a distance to the conforming loan limit.



(a) Probability of Neighborhood Choice

(b) Default Probability (%)



(c) Interest Rate Discontinuity

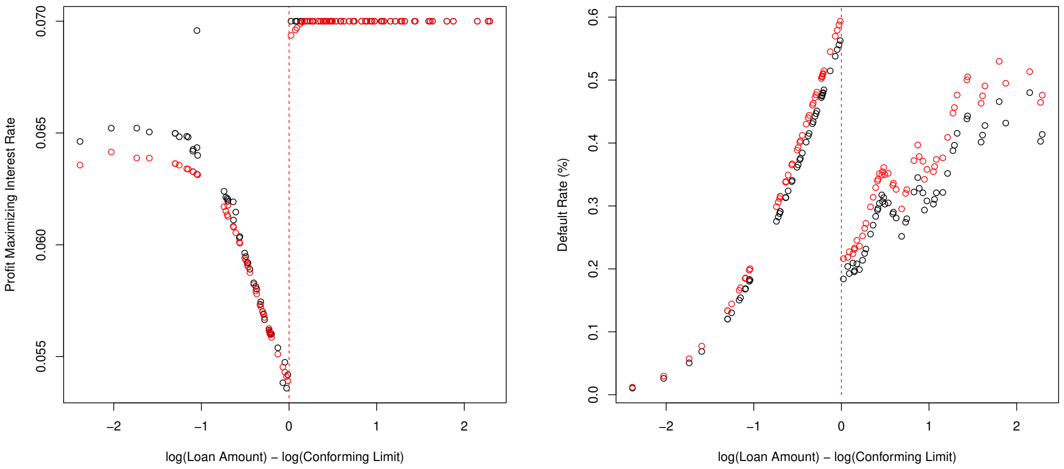
(d) Household Sorting by Unobservable Driver of Default

Figure 14: Impact of Increasing Risk on Mortgage Market Equilibrium

Keeping the cost of capital, neighborhood amenities, household preferences, and the dynamics of default constant, these figures present the simulation of a decline in expected price trends α, with a constant price volatility σ. This is described in Section 6.3.1. The red points are for the declining price trend.

(a) Evolution of Interest Rates

(b) Evolution of Default Probabilities



(c) Evolution of Securitization Probabilities

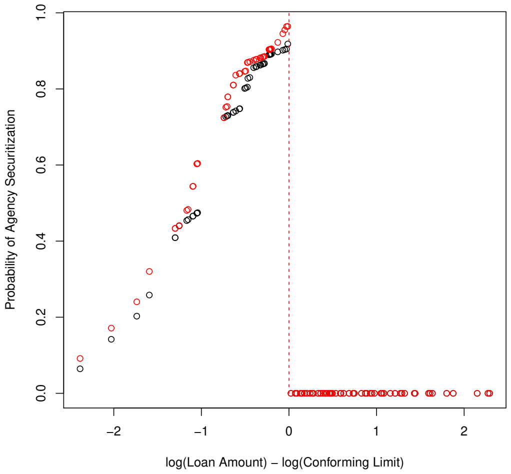
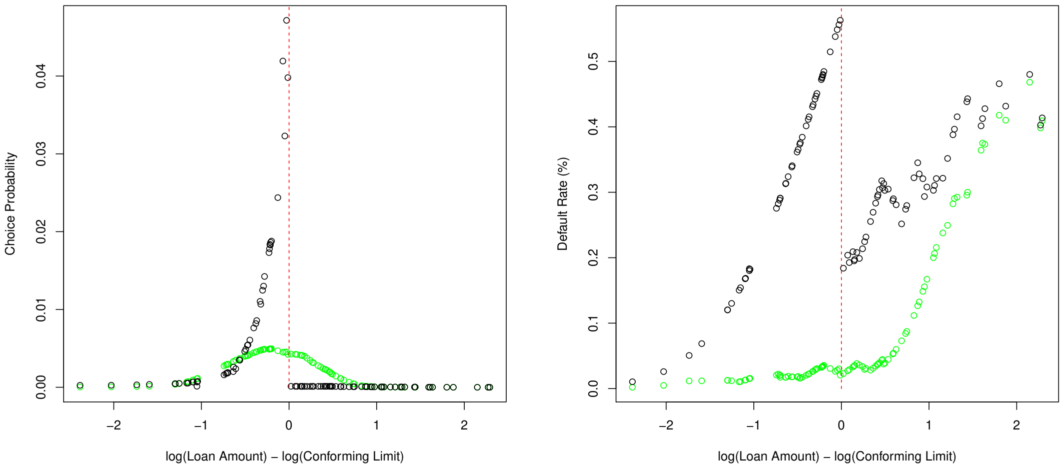


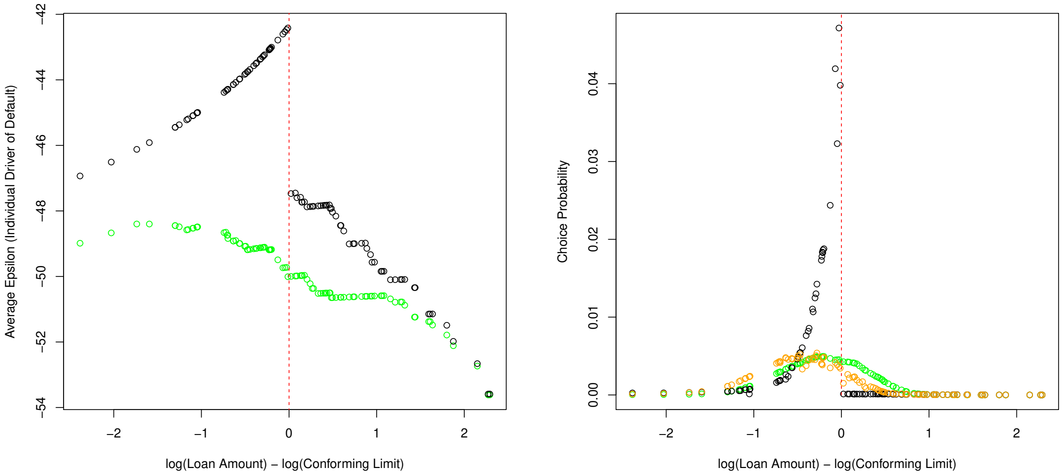
Figure 15: Simulating the Impact of the Widthdrawal of the GSEs

Keeping cost of capital, neighborhood amenities, household preferences, and the dynamics of default constant, these figures simulate the removal of the option to securitize on origination volumes and interest rates. This is described in Section 6.3.2. The green points correspond to the outcome without the option to securitize. Subfigure (d) combines the withdrawal of the GSEs with increasing risk in the form of declining prices (orange points).



(a) Probability of Neighborhood Choice

(b) Probability of Default



(c) Household Sorting in Unobservable Default Dimension

(d) Combining the Withdrawal with Increasing Risk

Table 1: Billion Dollar Events

This table describes the 15 ‘billion dollar’ natural disasters occuring between 2004 and 2012. These are used as a series of natural experiments. Damage calculations from Weinkle et al.’s (2018) data base. Events are ranked in decreasing order of their damages.

Year	Name	From	To	Category	States	Base Economic Damage (US $)	Normalized PL 2018	Normalized CL 2018
2005	Katrina	25-Aug	30-Aug	3	FL, LA, MS, AL	$82,200,000,000	$116,888,574,230	$118,825,443,322
2012	Sandy	30-Oct	31-Oct	1	NY	$60,280,000,000	$73,490,344,205	$72,819,173,227
2008	Ike	12-Sep	14-Sep	2	TX, LA	$25,000,000,000	$35,152,707,968	$34,686,138,787
2005	Wilma	24-Oct	24-Oct	3	FL	$20,600,000,000	$31,907,535,239	$31,922,162,521
2004	Charley	13-Aug	14-Aug	4	FL, SC	$14,000,000,000	$26,932,343,549	$27,460,765,919
2004	Ivan	12-Sep	21-Sep	3	AL, FL	$14,200,000,000	$25,893,348,510	$26,850,349,084
2004	Frances	03-Sep	09-Sep	2	FL	$9,000,000,000	$16,482,385,793	$16,476,581,358
2005	Rita	20-Sep	24-Sep	3	LA, TX	$11,254,000,000	$14,893,539,790	$14,798,423,194
2004	Jeanne	15-Sep	29-Sep	3	FL	$6,900,000,000	$13,570,831,322	$13,899,939,110
2011	Irene	26-Aug	28-Aug	1	NC	$8,600,000,000	$10,794,272,712	$10,928,324,331
2008	Gustav	31-Aug	03-Sep	2	LA	$4,300,000,000	$5,456,056,462	$5,422,320,570
2005	Dennis	04-Jul	18-Jul	3	FL, AL	$2,230,000,000	$3,542,320,160	$3,685,848,912
2005	Ophelia	09-Oct	18-Oct	1	NC	$1,600,000,000	$2,484,301,087	$2,521,769,392
2012	Isaac	21-Aug	03-Sep	1	LA	$1,940,000,000	$2,359,697,891	$2,344,120,103
2008	Dolly	20-Jul	27-Jul	1	TX	$1,050,000,000	$1,479,682,209	$1,411,245,880

PL: Pielke Landsea 2018 (PL18) methodology. CL: Collins Lowe 2018 (CL18) methodology.

Table 2: A 150-Year History of Hurricane Risk – Local Determinants, Time Trends, Idiosyncratic Risk, and Autocorrelation

The first column performs a regression of each of the 15 decennial probabilities for each of the neighborhoods on neighborhood fixed effects. It thus measures how much the "local" explains the probabilities vs. the idiosyncratic randomness. The local fixed effect explains 32% of the total variance of the probability. The second column includes in addition a fixed effect for which decade. The third column performs a regression on a linear trend, where the lhs is in decades. This predicts that over 150 years, the decennial probability of being hit has increased by 1 percentage point. The fourth column adds neighborhood fixed effects. The fifth column performs an autoregressive approach to estimate the amount of persistence, without a neighborhood fixed effect. The sixth column performs this autoregressive approach with a neighborhood fixed effect.

	(1) Decennial Probability (ppt)	(2) Decennial Probability (ppt)	(3) Decennial Probability (ppt)	(4) Decennial Probability (ppt)	(5) Decennial Probability (ppt)	(6) Decennial Probability (ppt)†
Secular Linear Trend	-	-	0.064*** (0.002)	0.064*** (0.002)	-	-
Lagged Probability	-	-	-	-	0.302*** (0.001)	2.317*** (0.112)
Fixed effect	Neighborhood	Neighborhood Decade	None	Neighborhood	None	Neighborhood
Observations	1296825	1296825	1296825	1296825	1296825	1296825
Neighborhood	86455	86455	86455	86455	86455	86455
Decades	15	15	15	15	15	15
R Squared	0.32	0.33	0.01	0.32	0.09	-†

†: this specification is a dynamic panel with fixed effects. The lagged probability is instrumented by the second lag following Arellano and Bond (1991).

Table 3: Impact of Billion Dollar Events on Denials and Mortgage Characteristics

This table presents the estimates of the impact of billion dollar events on the discontinuity in denials mortgages', applicants' and lenders' characteristics at the conforming loan limit. Mortgages with amounts between 90 and 110% of the conventional loan limit are considered in every year and every area between 1995 and 2016 inclusive. The conforming loan limit ('jumbo') is determined annually and differs between high cost and general counties. Standard errors 2-way clustered at the ZIP and year level. The unit of observation is the mortgage application. The control group is the set of mortgages in Zips of Atlantic states.

	Application Denied	Loan to Income	White	Black	Hispanic	log(Income)
Below Limit × Treated × Disaster −2	−0.007	−0.029*	0.003	0.000	−0.005	0.022
	(0.008)	(0.018)	(0.005)	(0.004)	(0.004)	(0.018)
Below Limit × Treated × Disaster Year	−0.009	−0.018	0.005	−0.000	−0.007	0.004
	(0.008)	(0.021)	(0.007)	(0.003)	(0.007)	(0.010)
Below Limit × Treated × Disaster +1	−0.028***	−0.044**	0.016**	−0.003	−0.017***	0.020
	(0.009)	(0.022)	(0.008)	(0.004)	(0.004)	(0.018)
Below Limit × Treated × Disaster +2	−0.060***	−0.091***	0.045***	−0.017***	−0.028***	0.056***
	(0.012)	(0.026)	(0.007)	(0.005)	(0.006)	(0.020)
Below Limit × Treated × Disaster +3	−0.085***	−0.137***	0.045***	−0.020*	−0.018***	0.099***
	(0.023)	(0.030)	(0.015)	(0.011)	(0.006)	(0.022)
Other Controls	Below Limit, Below Limit × Treated, 5-Digit ZIP f.e., Year and Time f.e.					
Clustering	2–way 5-Digit ZIP and Year					
Observations	3,993,461	3,688,118	3,342,372	3,342,372	3,342,372	4,297,918
5-digit ZIPs	8,205	8,119	8,136	8,136	8,136	8,179
R Squared	0.045	0.118	0.231	0.203	0.235	0.180
F Statistic	22.392	59.934	121.511	103.442	124.341	113.547

*p<0.1; **p<0.05; ***p<0.01

Table 4: Impact of Billion Dollar Events on Denials and Mortgage Characteristics

This table uses BlackKnight Financial's longitudinal mortgage file to estimate the impact of billion dollar events on borrowers' credit score, loan term, and subsequent default for conforming loans vs. jumbo loans. Descriptive statistics from Blackknight financial are presented in Appendix Table A(b).

	Credit Score	Term	Foreclosure	30 d. del.	60 d. del.	90 d. del.	120 d. del.	Vol. Payoff
Below Limit × Treated × Disaster −2	−2.110 → 2.110	−4.268	−0.004	−0.003	−0.001	0.000	−0.000	−0.018
	(1.493)	(3.537)	(0.009)	(0.008)	(0.009)	(0.010)	(0.008)	(0.011)
Below Limit × Treated × Disaster Year	−0.117	2.686	0.009	0.015***	0.012	0.010	−0.004	−0.012**
	(0.912)	(2.521)	(0.008)	(0.006)	(0.008)	(0.007)	(0.006)	(0.006)
Below Limit × Treated × Disaster +1	−3.371*	4.680	0.036**	0.036***	0.039***	0.032***	0.013	−0.031***
	(1.962)	(3.190)	(0.018)	(0.009)	(0.014)	(0.013)	(0.010)	(0.009)
Below Limit × Treated × Disaster +2	−3.745***	6.058**	0.057***	0.033***	0.046***	0.041***	0.032***	−0.026***
	(1.180)	(3.070)	(0.008)	(0.009)	(0.012)	(0.010)	(0.005)	(0.008)
Below Limit × Treated × Disaster +3	−3.403***	3.136	0.049***	0.006	0.022**	0.024***	0.013**	−0.023***
	(1.029)	(3.193)	(0.009)	(0.007)	(0.010)	(0.009)	(0.006)	(0.009)
Other Controls	Below Limit, Below Limit × Treated, 5-Digit ZIP f.e., Year and Time f.e.							
Clustering	2–way 5-Digit ZIP and Year							
Observations	1,072,465	1,696,513	1,697,650	1,697,650	1,697,650	1,697,650	1,697,650	1,697,650
5-digit ZIPs	8,084	9,627	9,627	9,627	9,627	9,627	9,627	9,627
R Squared	0.176	0.111	0.246	0.158	0.198	0.192	0.175	0.168
F Statistic	27.915	21.608	56.772	32.610	42.833	41.334	36.952	35.223

*p<0.1; **p<0.05; ***p<0.01

Table 5: Impact of Billion Dollar Events on Banks' Mortgage Credit Supply – Overall (Conforming and non-Conforming Loans)

This set of tables estimates the impact of billion dollar events on (i) the minimum distance of lenders' branch network to the location of the disaster, (ii) the supply of credit by lenders whose branch network is located in the disaster area, (iii) the supply of credit by banks regulated by the Federal Deposit Insurance Corporation (FDIC), (iv) the origination of conforming loans by such FDIC-insured banks.

	(1) log(Minimum Distance)	(2) % of Branches in Disaster	(3) FDIC Insured Lender†
Treated × Disaster −2	−0.858	−0.009	−0.021
	(0.768)	(0.010)	(0.015)
Treated × Disaster Year	+1.762**	−0.002	+0.003
	(0.814)	(0.009)	(0.013)
Treated × Disaster +1	+1.913***	−0.007	+0.001
	(0.756)	(0.008)	(0.012)
Treated × Disaster +2	+1.388*	−0.014**	+0.1198
	(0.755)	(0.007)	(0.019)
Treated × Disaster +3	+1.391*	−0.011	+0.0415*
	(0.729)	(0.009)	(0.021)
Other Controls	Treated, 5-Digit ZIP f.e., Year and Time f.e.		
Clustering	2–way 5-Digit ZIP and Year		
Observations	1,527,061†	1,527,061†	2,547,648†
5-digit ZIPs	7,721	7,721	8,213
R Squared	0.411	0.241	0.133
F Statistic	136.438	62.072	91.150

†: columns (1) and (2) focus on the set of loans originated by bank lenders. Column (3) includes observations from all bank and non-bank lenders. The sample is identical to the sample of the paper's baseline regressions: loans in the 90%-110% window around the conforming loan limit.

A Natural Disasters and the Securitization Activity of Regional and National Banks

Focusing on the impact of billion-dollar events on securitization and origination at the conforming limit arguably leads to more causal estimates than correlations using aggregate securitization and origination volumes. Yet, understanding the impact of billion dollar events on the composition of the pool of lenders in disaster-struck areas is key to understanding the mechanism.

The extent of a bank's involvement in a disaster-struck area is proxied by building two geographic measures based on their branch networks: (i) first, we measure the minimum distance of its bank branches to ZIP codes hit by billion dollar disasters; (ii) second, we compute the share of each bank's branches that are located within ZIP codes hit by the natural disaster. The first and the second measures differ: while the second measure captures the bank's specialization in the area, the first measure is a proxy for a physical presence of loan officers in areas hit by the natural disaster.

This is illustrated in the case of Hurricane Katrina in Figure 12. Each point is a bank branch from the Summary of Deposits. Points are colored according to the share of bank's branch network that is located in one of the treated ZIP codes. The lower-panel table suggests that in the case of Katrina, the median bank has 3.9% of its branches in the area, and the average is 22.86%, suggesting that banks that are more geographically specialized are also banks that originate a larger number of mortgages in the area.

The panel also shows that a share of mortgages are extended by banks whose brick-and-mortar branch network is far away from the event: the mean minimum log distance is about 4.98, or 90 miles (148 kilometers). There is thus a diversity of banks supplying loans prior to the billion dollar, and this section estimates the heterogeneous response of such banks to the event.

We perform a pre- post-natural disaster regression to estimate the impact of the billion-dollar event on the composition of the supply side:

$$\begin{aligned} Lender\,Characteristics_{\ell(i)} = Constant + \sum_{t=-10}^{+10} \Delta_t \mathrm{Hit}_{id} \times Time(t) + Time_{t=y-y_0} \\ + Year_y + Disaster_d + Neighborhood_i + \varepsilon_{it} \end{aligned} \tag{24}$$

where d indexes disasters, $\ell(i)$ is the lender of mortgage i, t indexes time, and y indexes years. Δ_t is the impact of the event on the outcome in time $t = y - y_0(d)$ relative to disaster year. $Year_t$ a year fixed effect, and ε_{it} a residual two-way clustered at the ZIP and year levels.

The regression is performed with three types of characteristics: each of the two branch network measures, and an indicator variable for FDIC insured bank lenders (Table 5). The first two regressions do not include observations of non-bank lenders. The last regression includes all observations, whether the mortgage was originated by a bank or a non-bank lender. In Table 5 Column (1), loans tend to be more likely to be originated by more distant banks. Column (2)'s results although non-significant in years +1 and +3, suggest a similar pattern: a lower share of branches in the area for the lenders of loans originated post-disaster. Column (3) presents evidence that the long-run share of bank lenders increases.

Section 5 presented evidence that increasing bunching at the conforming loan limit is consistent with lenders updating their beliefs about local disaster risk. This section's results further suggest that national lenders are more likely than regional banks to shift their securitization behavior following a natural disaster. Local lenders may have invested in the fixed cost of learning about local disaster.

B Comparing the Impact of Natural Disasters with the Impact of Income Shocks on Agency Securitization

This paper's results can be compared to the impacts of other types of predictable yet unpriced local shocks on securitization activity. Specifically, areas with a declining manufacturing sector should see more securitization activity as such predictable trends are not part of the GSEs' pricing of mortgage default rates: guaranty fees are not conditional on future income trends.

If the local industrial structure is, like natural disasters, better observed and/or predicted by local loan officers than by the national securitizers, a secular decline in economic activity should lead to an increase in securitization volumes as lenders transfer mortgage default risk onto the GSEs' balance sheets.

Using the Census's County Business Patterns, we build county-level predictors of local employment shocks as in David, Dorn & Hanson (2013). Specifically, the Bartik measure B_{jt} is the inner product of the share of each industry $i = 1, 2, \ldots, N$ in county j in 1998 with the national log growth of employment in each industry i between years t and $t-1$ for $t = 1998, \ldots, 2017$. We consider 1998 as this is the first year of a consistent time series for 2-digit NAICS industries, as prior years present employment statistics in SIC industry classification. We then proceed by interacting Bartik-predicted local employment shocks on the discontinuity at the conventional loan limit, in regressions with the number of mortgages (the *bunching*) and the characteristics of the mortgages (the *sorting*) as left-hand side variables. The following specification formalizes this idea:

$$\begin{aligned}\log n_{kjt} = {} & Constant + \delta \cdot \mathbf{1}(k \geq 0) + \alpha \cdot Bartik_{jt} \\ & + \delta_b \cdot \mathbf{1}(k \geq 0) \cdot Bartik_{jt} \\ & + f(L_{kt}) \cdot \mathbf{1}(k \geq 0) + g(L_{kt}) \cdot \mathbf{1}(k < 0) + County_j + Year_t + \varepsilon_{kjt},\end{aligned} \tag{25}$$

and the $Bartik_{jt} = \sum_i Share\ Industry\, i_{j,1998} \cdot \Delta \log L_{it}$; and similarly with characteristics $\mathbf{x}_{it}$ as left-hand side. Bins of width 0.25 percentage points are indexed by k. As long as the local 2-digit NAICS industry share in 1998 is exogenous to local unobservable shocks in following years, the estimate $\hat{\delta_b}$ will reflect the impact of employment shocks on bunching at the conventional loan limit. $\hat{\alpha}$ is the impact of local employment shocks on origination volumes.

Results are presented in Table D. As expected a downward Bartik employment shock leads to a decline of originations across the board around the conventional loan limit. It also leads to an increase in bunching at the conventional loan limit: a billion dollar event corresponds to the effect of a $0.423/2.531 = -17\%$ employment decline.

Appendix Table A: Descriptive Statistics for the BlackKnight and HMDA Samples

This table describes the two main samples used in this paper: (i) the BlackKnight mortgage data set, covering up to 65% of the mortgage market, and (ii) a national universe of mortgage files, built from Home Mortgage Disclosure Act data, merged with the Federal Reserve of Chicago's Report of Income and Condition. Each of these two data sets are merged with FEMA's Billion Dollar Events, and with the average number of storms per county from NOAA. Both samples consider mortgages between 90% and 110% of the year- and county-specific conforming loan limits.

(a) Home Mortgage Disclosure Act Sample, 1995-2016

Variable	Mean	P10	P25	P50	P75	P90	Observations
Application Denied	0.152	0.000	0.000	0.000	0.000	1.000	10,835,083
Loan Originated	0.512	0.000	0.000	1.000	1.000	1.000	13,446,510
log(Applicant Income)	11.767	7.032	9.061	13.181	14.532	14.532	990,712
Loan to Income	2.654	1.508	1.976	2.606	3.308	3.889	9,892,849
Asian Applicant	0.099	0.000	0.000	0.000	0.000	0.000	9,084,807
Black Applicant	0.040	0.000	0.000	0.000	0.000	0.000	9,084,807
Hispanic Applicant	0.070	0.000	0.000	0.000	0.000	0.000	9,084,807
White Applicant	0.781	0.000	1.000	1.000	1.000	1.000	9,084,807
Lender's Liquidity Ratio	0.044	0.001	0.008	0.032	0.032	0.129	1,139,292
Lender's Securitizability	0.710	0.601	0.638	0.638	0.795	0.883	1,133,724
Credit Union	0.017	0.000	0.000	0.000	0.000	0.000	13,446,510
Reg. by Federal Reserve	0.110	0.000	0.000	0.000	0.000	1.000	13,446,510

(b) BlackKnight McDash Data Set

Variable	Mean	P10	P25	P50	P75	P90	Observations
Below Conforming Limit	0.620	0.000	0.000	1.000	1.000	1.000	1,746,112
Credit Score	712.481	625.000	671.000	721.000	767.000	790.000	1,086,311
Term	345.996	300.000	360.000	360.000	360.000	360.000	1,744,975

Appendix Table B: Baseline Sorting Regressions – Observable Mortgage Characteristics

These regressions estimate the sorting of mortgage characteristics around the conforming loan limit, for windows of decreasing sizes around the limit. All regressions include ZCTA and year fixed effects.

	Window around conforming loan limit					
Variable	±10.0 pct	±4.0 pct	±3.0 pct	±2.0 pct	±1.0 pct	±0.5 pct
Jumbo Loan	0.871***	0.865***	0.833***	0.782***	0.680***	0.567***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.005)	(0.006)
Original Credit Score	4.723***	4.450***	4.464***	3.946***	3.727***	3.710***
	(0.374)	(0.391)	(0.449)	(0.544)	(0.755)	(0.946)
Interest Rate Differential (ppt)	0.000***	0.000***	0.000**	0.000	0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Loan-to-Value Ratio	0.007***	0.010***	0.012***	0.014***	0.003*	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Combined Loan-to-Value Ratio	1.448***	1.486***	1.437***	1.007***	0.376	-0.088
	(0.169)	(0.176)	(0.206)	(0.251)	(0.353)	(0.446)
Second Mortgage	0.018***	0.018***	0.017***	0.012***	0.007	0.003
	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)	(0.006)
Full Documentation	-0.021***	-0.021***	-0.021***	-0.023***	-0.030***	-0.033***
	(0.004)	(0.004)	(0.004)	(0.005)	(0.007)	(0.009)
Debt to Income Ratio	0.070	0.093	0.060	0.248	0.434*	0.312
	(0.133)	(0.139)	(0.157)	(0.189)	(0.262)	(0.340)
log(Property Value)	0.076***	0.065***	0.040***	0.015***	0.010***	0.007*
	(0.001)	(0.001)	(0.002)	(0.002)	(0.003)	(0.004)
Mortgage Term	4.311***	4.520***	4.612***	4.581***	3.711***	3.291***
	(0.308)	(0.321)	(0.369)	(0.462)	(0.651)	(0.878)
Fixed Rate Mortgage	-0.023***	-0.024***	-0.025***	-0.032***	-0.038***	-0.040***
	(0.003)	(0.003)	(0.004)	(0.004)	(0.006)	(0.008)
Private Mortgage Insurance	-0.030***	-0.029***	-0.030***	-0.032***	-0.043***	-0.048***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.004)	(0.005)

*p<0.1; **p<0.05; ***p<0.01. Standard errors clustered at the ZCTA-year level.

Appendix Table C: Baseline Sorting Regressions – Defaults

These regressions estimate the impact of the conforming loan limit on the mortgage's payment history for windows of decreasing sizes around the limit. All regressions include ZCTA and year fixed effects.

	Window around conforming loan limit					
Variable	±10.0 pct	±4.0 pct	±3.0 pct	±2.0 pct	±1.0 pct	±0.5 pct
Foreclosure at any point	-0.020*** (0.002)	-0.019*** (0.002)	-0.018*** (0.002)	-0.016*** (0.002)	-0.017*** (0.003)	-0.014*** (0.004)
30 days delinquent at any point	-0.009*** (0.002)	-0.008*** (0.002)	-0.007** (0.003)	-0.004 (0.003)	-0.005 (0.004)	-0.004 (0.005)
60 days delinquent at any point	-0.016*** (0.002)	-0.015*** (0.002)	-0.013*** (0.002)	-0.009*** (0.003)	-0.012*** (0.003)	-0.010** (0.004)
90 days delinquent at any point	-0.014*** (0.002)	-0.013*** (0.002)	-0.012*** (0.002)	-0.008*** (0.002)	-0.010*** (0.003)	-0.007* (0.004)
120 days delinquent at any point	-0.004** (0.002)	-0.003** (0.002)	-0.003* (0.002)	-0.001 (0.002)	-0.000 (0.003)	-0.004 (0.004)
Voluntary Payoff	0.053*** (0.003)	0.052*** (0.003)	0.043*** (0.003)	0.034*** (0.004)	0.026*** (0.006)	0.011 (0.007)

*p<0.1; **p<0.05; ***p<0.01. Standard errors clustered at the ZCTA-year level.

Appendix Table D: Impact of Bartik Shocks on the Bunching at the Conforming Loan Limit

This table estimates the impact of labor demand shocks on the bunching at the conforming loan limit. Labor demand shocks are predicted using a Bartik (1991) type predictor of employment growth $Bartik_{jt} = \sum_i Share\,Industry\,i_{j,1998} \cdot \Delta \log L_{it}$ *where* $Share\,Industry\,i_{j,1998}$ *is the share of industry i in the employment of county j in 1998, and* $\Delta \log L_{it}$ *is the national log employment growth in industry i.*

	Dependent variable (Counts):			
	(1) log(Applications)	(2) log(Originations)	(3) log(Denials)	(4) log(Securitizations)
Employment Growth Bartik Predictor	0.993***	1.065***	-0.395	2.091***
	(0.407)	(0.379)	(0.266)	(0.391)
Above Conforming Limit	-0.666***	-0.560***	-0.291***	-0.567***
	(0.009)	(0.009)	(0.006)	(0.008)
× Employment Growth Bartik Predictor	1.943***	2.531***	0.519***	-0.124
	(0.323)	(0.327)	(0.203)	(0.271)
Other Controls	Polynomial in log(*Loan*) − log(*Conforming Loan Limit*)			
R Squared	0.63	0.56	0.45	0.53
Observations	859679	859679	859679	859679
F Statistic	472.49	356.14	224.45	309.83

*p<0.1; **p<0.05; ***p<0.01

This is a tab page.
Please title tab
“BIS”

BIS

BANQUE DE FRANCE
EUROSYSTÈME

The green swan

Central banking and financial stability in the age of climate change

Patrick BOLTON - Morgan DESPRES - Luiz Awazu PEREIRA DA SILVA
Frédéric SAMAMA - Romain SVARTZMAN

January 2020

Abstract

Climate change poses new challenges to central banks, regulators and supervisors. This book reviews ways of addressing these new risks within central banks' financial stability mandate. However, integrating climate-related risk analysis into financial stability monitoring is particularly challenging because of the radical uncertainty associated with a physical, social and economic phenomenon that is constantly changing and involves complex dynamics and chain reactions. Traditional backward-looking risk assessments and existing climate-economic models cannot anticipate accurately enough the form that climate-related risks will take. These include what we call "green swan" risks: potentially extremely financially disruptive events that could be behind the next systemic financial crisis. Central banks have a role to play in avoiding such an outcome, including by seeking to improve their understanding of climate-related risks through the development of forward-looking scenario-based analysis. But central banks alone cannot mitigate climate change. This complex collective action problem requires coordinating actions among many players including governments, the private sector, civil society and the international community. Central banks can therefore have an additional role to play in helping coordinate the measures to fight climate change. Those include climate mitigation policies such as carbon pricing, the integration of sustainability into financial practices and accounting frameworks, the search for appropriate policy mixes, and the development of new financial mechanisms at the international level. All these actions will be complex to coordinate and could have significant redistributive consequences that should be adequately handled, yet they are essential to preserve long-term financial (and price) stability in the age of climate change.

Contents

Foreword by Agustín Carstens

A growing body of research by academics, central banks and international institutions including the BIS focuses on climate-related risks. These studies show that physical risks related to climate change can severely damage our economies, for example through the large cost of repairing infrastructure and coping with uninsured losses. There are also transition risks related to potentially disorderly mitigation strategies. Both physical and transition risks, in turn, can increase systemic financial risk. Thus their potential consequences have implications for central banks' financial stability mandate. All these considerations prompted central banks to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS), which the BIS has been part of since its inception.

This book helps to trace the links between the effects of climate change, or global warming, and the stability of our financial sectors. It includes a comprehensive survey of how climate change has been progressively integrated into macroeconomic models and how these have evolved to better assess financial stability risks stemming from climate change (eg stress testing models using global warming scenarios). But the book also recognises the limitations of our models, which may not be able to accurately predict the economic and financial impact of climate change because of the complexity of the links and the intrinsic non-linearity of the related phenomena. Nevertheless, despite the high level of uncertainty, the best scientific advice today suggests that action to mitigate and adapt to climate change is needed.

Naturally, the first-best solution to address climate change and reduce greenhouse gas emissions is Pigovian carbon taxation. This policy suggests that fundamental responsibility for addressing issues related to climate change lies with governments. But such an ambitious new tax policy requires consensus-building and is difficult to implement. Nor can central banks resolve this complex collective action problem by themselves. An effective response requires raising stakeholders' awareness and facilitating coordination among them. Central banks' financial stability mandate can contribute to this and should guide their appropriate involvement. For instance, central banks can coordinate their own actions with a broad set of measures to be implemented by other players (governments, the private sector, civil society and the international community). This is urgent since climate-related risks continue to build, and negative outcomes such as what this book calls "green swan" events could materialise.

Contributing to this coordinating role is not incompatible with central banks doing their share within their current mandates. In this sense there are many practical actions central banks can undertake (and, in some cases, are already undertaking). They include enhanced monitoring of climate-related risks through adequate stress tests; developing new methodologies to improve the assessment of climate-related risks; including environmental, social and governance (ESG) criteria in their pension funds; helping to develop and assess the proper taxonomy to define the carbon footprint of assets more precisely (eg "green" versus "brown" assets); working closely with the financial sector on disclosure of carbon-intensive exposure to assess potential financial stability risks; studying more precisely how prudential regulation could deal with risks to financial stability arising from climate change; and examining the adequate room to invest surplus FX reserves into green bonds.

The BIS has been collaborating with the central bank community on all these aspects. In addition, in September 2019 it launched its green bond BIS Investment Pool Fund, a new vehicle that facilitates central banks' investments in green bonds. And with this book it hopes to steer the debate and discussions further while recognising that all these actions will require more research and be challenging, but nevertheless essential to preserving long-term financial and price stability in the age of accelerated climate change.

Agustín Carstens
BIS General Manager

Foreword by François Villeroy de Galhau

In the speech he delivered when receiving the Nobel Prize in Literature in 1957, the French writer Albert Camus said: "Each generation doubtless feels called upon to reform the world. Mine knows that it will not reform it, but its task is perhaps even greater. It consists in preventing the world from destroying itself". Despite a different context, these inspiring words are definitely relevant today as mankind is facing a great threat: climate change.

Climate change poses unprecedented challenges to human societies, and our community of central banks and supervisors cannot consider itself immune to the risks ahead of us. The increase in the frequency and intensity of extreme weather events could trigger non-linear and irreversible financial losses. In turn, the immediate and system-wide transition required to fight climate change could have far-reaching effects potentially affecting every single agent in the economy and every single asset price. Climate-related risks could therefore threaten central banks' mandates of price and financial stability, but also our socio-economic systems at large. If I refer to our experience at the Banque de France and to the impressive success of the Network for Greening the Financial System (NGFS) we launched in December 2017, I would tend to affirm that our community is now moving in the right direction.

But despite this growing awareness, the stark reality is that we are all losing the fight against climate change. In such times, the role our community should play in this battle is questioned. It is then important to clearly state that we cannot be the only game in town, even if we should address climate-related risks within the remit of our mandates, which may include considering options relating to the way we conduct monetary policy. On monetary policy, I have two strong beliefs, and we will have the opportunity to discuss them against the backdrop of the ECB strategic review led by Christine Lagarde. First, we need to integrate climate change in all our economic and forecasting models; second we need, instead of opening a somewhat emotional debate on the merits of a green quantitative easing, which faces limitations, to do an overhaul of our collateral assessment framework to reflect climate-related risks.

In order to navigate these troubled waters, more holistic perspectives become essential to coordinate central banks', regulators' and supervisors' actions with those of other players, starting with governments. This is precisely what this book does. If central banks are to preserve financial and price stability in the age of climate change, it is in their interest to help mobilize all the forces needed to win this battle. This book is an ambitious, carefully thought-out and therefore necessary contribution toward this end.

François Villeroy de Galhau
Governor of the Banque de France

Scientific knowledge is as much an understanding of the diversity of situations for which a theory or its models are relevant as an understanding of its limits.

Elinor Ostrom (1990)

Executive Summary

This book reviews some of the main challenges that climate change poses to central banks, regulators and supervisors, and potential ways of addressing them. It begins with the growing realisation that climate change is a source of financial (and price) instability: it is likely to generate physical risks related to climate damages, and transition risks related to potentially disordered mitigation strategies. Climate change therefore falls under the remit of central banks, regulators and supervisors, who are responsible for monitoring and maintaining financial stability. Their desire to enhance the role of the financial system to manage risks and to mobilise capital for green and low-carbon investments in the broader context of environmentally sustainable development prompted them to create the Central Banks and Supervisors Network for Greening the Financial System (NGFS).

However, integrating climate-related risk analysis into financial stability monitoring and prudential supervision is particularly challenging because of the distinctive features of climate change impacts and mitigation strategies. These comprise physical and transition risks that interact with complex, far-reaching, nonlinear, chain reaction effects. Exceeding climate tipping points could lead to catastrophic and irreversible impacts that would make quantifying financial damages impossible. Avoiding this requires immediate and ambitious action towards a structural transformation of our economies, involving technological innovations that can be scaled but also major changes in regulations and social norms.

Climate change could therefore lead to "green swan" events (see Box A) and be the cause of the next systemic financial crisis. Climate-related physical and transition risks involve interacting, nonlinear and fundamentally unpredictable environmental, social, economic and geopolitical dynamics that are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere.

In this context of deep uncertainty, traditional backward-looking risk assessment models that merely extrapolate historical trends prevent full appreciation of the future systemic risk posed by climate change. An "epistemological break" (Bachelard (1938)) is beginning to take place in the financial community, with the development of forward-looking approaches grounded in scenario-based analyses. These new approaches have already begun to be included in the financial industry's risk framework agenda, and reflections on climate-related prudential regulation are also taking place in several jurisdictions.

While these developments are critical and should be pursued, this book presents two additional messages. First, scenario-based analysis is only a partial solution to apprehend the risks posed by climate change for financial stability. The deep uncertainties involved and the necessary structural transformation of our global socioeconomic system are such that no single model or scenario can provide a full picture of the potential macroeconomic, sectoral and firm-level impacts caused by climate change. Even more fundamentally, climate-related risks will remain largely unhedgeable as long as system-wide action is not undertaken.

Second, it follows from these limitations that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, if they sit still and wait for other government agencies to jump into action, they could be exposed to the real risk of not being able to deliver on their mandates of financial and price stability. Green swan events may force central banks to intervene as "climate rescuers of last resort" and buy large sets of devalued assets, to save the financial system once more. However, the biophysical foundations of such a crisis and its potentially irreversible impacts would quickly show the limits of this “wait and see” strategy. On the other hand, central banks cannot (and should not) simply replace governments and private actors to make up for their insufficient action, despite growing social pressures to do so. Their goodwill could even create some moral hazard. In short, central banks, regulators and supervisors can only do so much (and many of them are already taking action within their mandates), and their action can only be seen as enhancing other climate change mitigation policies.

To overcome this deadlock, a second epistemological break is needed: central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. We believe that they can best contribute to this task in a role that we dub the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the risk, time horizon and system resilience approaches (see Box B).

Contributing to this coordinating role is not incompatible with central banks, regulators and supervisors doing their own part within their current mandates. They can promote the integration of climate-related risks into prudential regulation and financial stability monitoring, including by relying on new modelling approaches and analytical tools that can better account for the uncertainty and complexity at stake. In addition, central banks can promote a longer-term view to help break the “tragedy of the horizon”, by integrating sustainability criteria into their own portfolios and by exploring their integration in the conduct of financial stability policies, when deemed compatible with existing mandates.

But more importantly, central banks need to coordinate their own actions with a broad set of measures to be implemented by other players (ie governments, the private sector, civil society and the international community). This coordination task is urgent since climate-related risks continue to build up and negative outcomes could become irreversible. There is an array of actions to be consistently implemented. The most obvious ones are the need for carbon pricing and for systematic disclosure of climate-related risks by the private sector.

Taking a transdisciplinary approach, this book calls for additional actions that no doubt will be difficult to take, yet will also be essential to preserve long-term financial (and price) stability in the age of climate change. These include: exploring new policy mixes (fiscal-monetary-prudential) that can better address the climate imperatives ahead and that should ultimately lead to societal debates regarding their desirability; considering climate stability as a global public good to be supported through measures and reforms in the international monetary and financial system; and integrating sustainability into accounting frameworks at the corporate and national level.

Moreover, climate change has important distributional effects both between and within countries. Risks and adaptation costs fall disproportionately on poor countries and low-income households in rich countries. Without a clear indication of how the costs and benefits of climate change mitigation strategies will be distributed fairly and with compensatory transfers, sociopolitical backlashes will increase. Thus, the needed broad social acceptance for combating climate change depends on studying, understanding and addressing its distributional consequences.

Financial and climate stability could be considered as two interconnected public goods, and this consideration can be extend to other human-caused environmental degradation such as the loss of biodiversity. These, in turn, require other deep transformations in the governance of our complex adaptive socioeconomic and financial systems. In the light of these immense challenges, a central contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all capabilities to combat climate change.

Box A: From black to green swans

The "green swan" concept used in this book finds its inspiration in the now famous concept of the "black swan" developed by Nassim Nicholas Taleb (2007). Black swan events have three characteristics: (i) they are unexpected and rare, thereby lying outside the realm of regular expectations; (ii) their impacts are wide-ranging or extreme; (iii) they can only be explained after the fact. Black swan events can take many shapes, from a terrorist attack to a disruptive technology or a natural catastrophe. These events typically fit fat tailed probability distributions, ie they exhibit a large skewness relative to that of normal distribution (but also relative to exponential distribution). As such, they cannot be predicted by relying on backward-looking probabilistic approaches assuming normal distributions (eg value-at-risk models).

The existence of black swans calls for alternative epistemologies of risk, grounded in the acknowledgment of uncertainty. For instance, relying on mathematician Benoît Mandelbrot (1924–2010), Taleb considers that fractals (mathematically precise patterns that can be found in complex systems, where small variations in exponent can cause large deviation) can provide more relevant statistical attributes of financial markets than both traditional rational expectations models and the standard framework of Gaussian-centred distributions (Taleb (2010)). The use of counterfactual reasoning is another avenue that can help hedge, at least partially, against black swan events. Counterfactuals are thoughts about alternatives to past events, "thoughts of what might have been" (Epstude and Roese (2008)). Such an epistemological position can provide some form of hedging against extreme risks (turning black swans into "grey" ones) but not make them disappear. From a systems perspective, fat tails in financial markets suggest a need for regulation in their operations (Bryan et al (2017), p 53).

Green swans, or "climate black swans", present many features of typical black swans. Climate-related risks typically fit fat-tailed distributions: both physical and transition risks are characterised by deep uncertainty and nonlinearity, their chances of occurrence are not reflected in past data, and the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). In this context, traditional approaches to risk management consisting in extrapolating historical data and on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. That is, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management, as discussed in this book.

However, green swans are different from black swans in three regards. First, although the impacts of climate change are highly uncertain, "there is a high degree of certainty that some combination of physical and transition risks will materialize in the future" (NGFS (2019a), p 4). That is, there is certainty about the need for ambitious actions despite prevailing uncertainty regarding the timing and nature of impacts of climate change. Second, climate catastrophes are even more serious than most systemic financial crises: they could pose an existential threat to humanity, as increasingly emphasized by climate scientists (eg Ripple et al (2019)). Third, the complexity related to climate change is of a higher order than for black swans: the complex chain reactions and cascade effects associated with both physical and transition risks could generate fundamentally unpredictable environmental, geopolitical, social and economic dynamics, as explored in Chapter 3.

Box B: The five Cs – contribute to coordination to combat climate change: the risk, time horizon and system resilience approaches

Responsibilities / **Paradigmatic approach to climate change**	**Measures to be considered[1] by central banks, regulators and supervisors**	**Measures to be implemented by other players[2] (government, private sector, civil society)**
Identification and management of climate-related risks **>> Focus on risks**	Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into: – Prudential regulation – Financial stability monitoring	Voluntary disclosure of climate-related risks by the private sector (Task Force on Climate-related Financial Disclosures) – Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)
Limitations: – Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels – Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken		
Internalisation of externalities **>> Focus on time horizon**	Promotion of long-termism as a tool to break the tragedy of the horizon, including by: – Integrating environmental, social and governance (ESG) considerations into central banks' own portfolios – Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates	– Carbon pricing – Systematisation of ESG practices in the private sector
Limitations: – Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences – Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system		
Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – Green monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures which are deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors' elaboration.

1. INTRODUCTION – "PLANET EARTH IS FACING A CLIMATE EMERGENCY"

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to "tell it like it is." On the basis of this obligation […] we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of global socioeconomic and financial systems. Our current production and consumption patterns cause unsustainable emissions of greenhouse gases (GHGs), especially carbon dioxide (CO_2): their accumulated concentration in the atmosphere above critical thresholds is increasingly recognised as being beyond our ecosystem's absorptive and recycling capabilities. The continued increase in temperatures has already started affecting ecosystems and socioeconomic systems across the world (IPCC (2018), Mora et al (2018)) but, alarmingly, climate science indicates that the worst impacts are yet to come. These include sea level rise, increases in weather extremes, droughts and floods, and soil erosion. Associated impacts could include a massive extinction of wildlife, as well as sharp increases in human migration, conflicts, poverty and inequality (Human Rights Council (2019), IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Ripple et al (2019)).

Scientists today recommend reducing GHG emissions, starting immediately (Lenton et al (2019), Ripple et al (2019)). In this regard, the 2015 United Nations Climate Change Conference (COP21) and resulting Paris Agreement among 196 countries to reduce GHG emissions on a global scale was a major political achievement. Under the Paris Agreement (UNFCCC (2015)) signatories agree to reduce greenhouse gas emissions "as soon as possible" and to do their best to keep global warming "to well below 2 degrees" Celsius (2°C), with the aim of limiting the increase to 1.5°C. Yet global emissions have kept rising since then (Figueres et al (2018)),[1] and nothing indicates that this trend is reverting.[2] Countries' already planned production of coal, oil and gas is inconsistent with limiting warming to 1.5°C or 2°C, thus creating a "production gap", a discrepancy between government plans and coherent decarbonisation pathways (SEI et al (2019)).

Changing our production and consumption patterns and our lifestyles to transition to a low-carbon economy is a tough collective action problem. There is still considerable uncertainty on the effects of climate change and on the most urgent priorities. There will be winners and losers from climate change mitigation, exacerbating free rider problems. And, perhaps even more problematically, there are large time lags before climate damages become apparent and irreversible (especially to climate change sceptics): the most damaging effects will be felt beyond the traditional time horizons of policymakers and other economic and financial decision-makers. This is what Mark Carney (2015) referred to as "the tragedy of the horizon": while the physical impacts of climate change will be felt over a long-term horizon, with massive costs and possible civilisational impacts on future generations, the time horizon in which financial, economic and political players plan and act is much shorter. For instance, the time horizon of rating

---

[1] Ominously, David Wallace-Wells recently observed in *The Uninhabitable Earth* (2019), "We have done as much damage to the fate of the planet and its ability to sustain human life and civilization since Al Gore published his first book on the climate than in all the centuries – all the millenniums – that came before."

[2] The Agreement itself is legally binding, but no enforcement mechanisms exist and the GHG reduction targets set by each country through their Nationally Determined Contributions (NDCs) are only voluntary.

agencies to assess credit risks, and of central banks to conduct stress tests, is typically around three to five years.

Our framing of the problem is that climate change represents a green swan (see Box A): it is a new type of systemic risk that involves interacting, nonlinear, fundamentally unpredictable, environmental, social, economic and geopolitical dynamics, which are irreversibly transformed by the growing concentration of greenhouse gases in the atmosphere. Climate-related risks are not simply black swans, ie tail risk events. With the complex chain reactions between degraded ecological conditions and unpredictable social, economic and political responses, with the risk of triggering tipping points,[3] climate change represents a colossal and potentially irreversible risk of staggering complexity.

Carbon pricing and beyond

Climate change is widely considered by economists as an externality that, as such, should be dealt with through publicly imposed Pigovian carbon taxes[4] in order to internalise the climate externalities. Indeed, according to basic welfare economics, a good policy to combat climate change requires such a "price" to act as an incentive to reduce GHG emissions. A carbon tax, for example, creates an incentive for economic agents to lower emissions by switching to more efficient production processes and consumption patterns. The amount of this tax needs to reflect what we already know about the medium- to long-term additional costs of climate change. From a mainstream economist's perspective, a carbon tax that reflects the social cost of carbon (SCC) would make explicit the "shadow cost" of carbon emissions and would be sufficient to induce economic actors to reduce emissions in a perfect Walrasian world.

By this analytical framing, central banks, regulators and supervisors have little to do in the process of decarbonising the economic system. Indeed, the needed transition would mostly be driven by non-financial firms and households, whose decentralised decisions would be geared towards low-carbon technologies thanks to carbon pricing. From a financial perspective, using a carbon tax to correctly price the negative externality would be sufficient to reallocate financial institutions' assets from carbon-intensive towards greener capital. At most, central banks and supervisors should carefully scrutinise financial market imperfections, in order to ensure financial stability along the transition towards a low-carbon economy.

Yet the view that carbon pricing is the sole answer to climate change, and its corollary in terms of monetary and prudential policies (ie that central banks, regulators and supervisors should not really be concerned by climate change) suffers from three significant limitations, which contribute to overlooking potential "green swan" events.

First, even though conceptually carbon pricing has been recognised as the first best option for decades, in practice it has not been implemented at a level sufficient to drive capital reallocation from "brown" (or carbon-intensive) to "green" (or low-carbon) assets. The reality is that governments have failed to act and will continue to do so unless much broader pressure from civil society and business induces significant policy change. Given the current deficiency in global policy responses, it only becomes more likely that the physical impacts of climate change will affect the socioeconomic system in a rapidly warming world. Given that rising temperatures will unleash complex dynamics with tipping points, the impact of

[3] A tipping point in the climate system is a threshold that, when exceeded, can lead to large changes in the state of the system. Climate tipping points are of particular interest in reference to concerns about global warming in the modern era. Possible tipping point behaviour has been identified for the global mean surface temperature by studying self-reinforcing feedbacks and the past behaviour of Earth's climate system. Self-reinforcing feedbacks in the carbon cycle and planetary reflectivity could trigger a cascading set of tipping points that lead the world into a hothouse climate state (source: Wikipedia).

[4] From Arthur C Pigou (1877–1959), who proposed the concept and the solution to externality problems by taxation, an idea that is key to modern welfare economics and to the economic analysis of environmental impacts. Other economic instruments aimed at pricing carbon exist, such as emission trading schemes (ETS), also known as cap-and-trade systems. Unlike a tax, where the price is determined ex ante, the price of CO_2 in a cap-and-trade mechanism is determined ex post, as a result of the supply and demand of quotas to emit CO_2.

global warming will affect our economies in a disorderly yet cumulative manner that, in turn, could trigger unforeseeable negative financial dynamics.

These so-called physical risks will have financial consequences that are naturally of concern to central bankers and supervisors. They can threaten financial stability by causing irreversible losses, as capital is affected by climate change and as financial agents may be unable to protect themselves from such climate shocks. These risks can also threaten price stability by triggering supply shocks on various commodities, which could in turn generate inflationary or even stagflationary effects (Villeroy de Galhau (2019a)). It should also be noted that traditional policy instruments may be less effective at smoothing these shocks, to the extent that these are more or less permanent biophysical shocks, rather than transitory economic shocks (Cœuré (2018)).

Second, climate change is not merely another market failure but presumably “the greatest market failure the world has ever seen”, as leading climate economist Lord Nicholas Stern puts it (Stern (2007)). Given the size of the challenge ahead, carbon prices may need to skyrocket in a very short time span towards much higher levels than currently prevail. Moreover, taking climate-related risks and uncertainty seriously (eg by including the possibility of tipping points leading to catastrophic and irreversible events) should lead to even sharper increases in the SCC (Ackerman et al (2009), Cai and Lontzek (2019), Daniel et al (2019), Weitzman (2009)). With this in mind, the transition may trigger a broad range of unintended consequences. For example, it is increasingly evident that mitigation measures such as carbon price adjustments could have dramatic distributional consequences, both within and across countries.

More to the point of actions by central bankers and supervisors, newly enforced and more stringent environmental regulations could produce or reinforce financial failures in credit markets (Campiglio (2016)) or abrupt reallocations of assets from brown to green activities motivated by market repricing of risks and/or attempts to limit reputational risks and litigations. All this could result in a “climate Minsky moment” (Carney (2018)), a severe financial tightening of financial conditions for companies that rely on carbon-intensive activities (so-called “stranded assets”; see Box 1), be it directly or indirectly through their value chains. These risks are categorised as transition risks; as with physical risks, they are of concern to central bankers and supervisors. Here, the “paradox is that success is failure” (Carney (2016)): extremely rapid and ambitious measures may be the most desirable from the point of view of climate mitigation, but not necessarily from the perspective of financial stability over a short-term horizon. Addressing this tension requires a broad range of measures, as extensively discussed in this book.

Third, the climate change market failure is of such magnitude that it would be prudent to approach it as more than just a market failure. It is a subject that combines, among other things, uncertainty, risk, potentially deep transformations in our lifestyles, prioritising long-term ethical choices over short-term economic considerations, and international coordination for the common good. With this in mind, recent and growing transdisciplinary work suggests that our collective inability to reverse expected climate catastrophes originates in interlocked, complex institutional arrangements, which could be described as a socio-technical system: “a cluster of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks” (Geels et al (2004), p 3).

Given this institutional or sociotechnical inertia, higher carbon prices alone may not suffice to drive individual behaviours and firms’ replacement of physical capital towards low-carbon alternatives, as economics textbooks suggest. For instance, proactive fiscal policy may be an essential first step to build adequate infrastructure (eg railroads), before carbon pricing can really lead agents to modify their behaviour (eg by switching from car to train). Tackling climate change may therefore require finding complex policy mixes combining monetary, prudential and fiscal instruments (Krogstrup and Oman (2019)) as well as many other societal innovations, as discussed in the last chapter. Going further, the fight against climate change is taking place at the same time when the post-World War II global institutional framework is under growing criticism. This means that the unprecedented level of international coordination required to address the difficult (international) political economy of climate change is seriously compromised.

Therefore, to guarantee a successful low-carbon transition, new technologies, new institutional arrangements and new cultural frameworks should emerge (Beddoe et al (2009)) towards a comprehensive reshaping of current productive structures and consumption patterns. The analogy one may use to envision the change ahead is that of engaging in a multidimensional combat against climate change (Stiglitz (2019)). Even for the sceptics who prefer a "wait and see" approach, a pure self-interested risk management strategy recommends buying the proper insurance of ambitious climate policies (Weitzman (2009)) as a kind of precautionary principle[5] (Aglietta and Espagne (2016)), "pari Pascalien"[6] or "enlightened doomsaying"[7] (Dupuy (2012)), ie as a hedging strategy against the possibility of green swan events.

For all these reasons, even if a significant increase in carbon pricing globally remains an essential step to fight climate change, other (second-, third- or fourth-best from a textbook perspective) options must be explored, including with regard to the financial system.

Revisiting financial stability in the age of climate change

The reflections on the relationship between climate change and the financial system are still in their early stages: despite rare warnings on the significant risks that climate change could pose to the financial system (Carbon Tracker (2013)), the subject was mostly seen as a fringe topic until a few years ago (Chenet (2019a)). But the situation has changed radically in recent times, as climate change's potentially disruptive impacts on the financial system have started to become more apparent, and the role of the financial system in mitigating climate change has been recognised.

This growing awareness of the financial risks posed by climate change can be related to three main developments. First, the Paris Agreement's (UNFCCC (2015)) Article 2.1(c) explicitly recognised the need to "mak[e] finance flows compatible with a pathway toward low greenhouse gas emissions and climate-resilient development", thereby paving the way to a radical reorientation of capital allocation. Second, as mentioned above, the Governor of the Bank of England, Mark Carney (2015), suggested the possibility of a systemic financial crisis caused by climate-related events. Third, in December 2017 the Central Banks and Supervisors Network for Greening the Financial System[8] (NGFS) was created by a group of central banks and supervisors willing to contribute to the development of environment and climate risk management in the financial sector, and to mobilise mainstream finance to support the transition toward a sustainable economy.

The NGFS quickly acknowledged that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).[9] The NGFS also acknowledged that these risks are tied to complex layers of interactions between the macroeconomic, financial and climate systems (NGFS (2019b)). As this book

---

[5] The precautionary principle is used to justify discretionary measures by policymakers in situations where there are plausible risks of harming the public through certain decisions, but extensive scientific knowledge on the matter is lacking.

[6] The French philosopher, mathematician and physicist Blaise Pascal (1623–62) used a game theory argument to justify faith as a "hedge": rational people should believe in God as a "pari" or bet. They would incur small losses of pleasure (by accepting to live a life without excessive pleasures), which would be more than offset by infinite gains (eternity in heaven) if God existed. In the same way, accepting some small inconveniences (adjusting one's lifestyle to climate imperatives) is compensated by a more sustainable earth ecosystem, if indeed global warming exists (from the climate change sceptic's perspective).

[7] The concept of "enlightened doomsaying" (catastrophisme éclairé) put forward by the French philosopher of science Jean-Pierre Dupuy (2012) involves imagining oneself in a catastrophic future to raise awareness and trigger immediate action so that this future does not take place.

[8] As of 12 December 2019, the NGFS is composed of 54 members and 12 observers. For more information, see www.ngfs.net.

[9] As acknowledged by the NGFS (2019a), the legal mandates of central banks and financial supervisors vary throughout the world, but they typically include responsibility for price stability, financial stability and the safety and soundness of financial institutions.

will extensively discuss, assessing climate-related risks involves dealing with multiple forces that interact with one another, causing dynamic, nonlinear and disruptive dynamics that can affect the solvency of financial and non-financial firms, as well as households' and sovereigns' creditworthiness.

In the worst case scenario, central banks may have to confront a situation where they are called upon by their local constituencies to intervene as climate rescuers of last resort For example, a new financial crisis caused by green swan events severely affecting the financial health of the banking and insurance sectors could force central banks to intervene and buy a large set of carbon-intensive assets and/or assets stricken by physical impacts.

But there is a key difference between green swan and black swan events: since the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, the biophysical causes of the crisis will be difficult, if not impossible, to undo at a later stage. Similarly, in the case of a crisis triggered by a rapid transition to a low-carbon economy, there would be little ground for central banks to rescue the holders of assets in carbon-intensive companies. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. Intervening as climate rescuers of last resort could therefore affect central bank's credibility and crudely expose the limited substitutability between financial and natural capital.

Given the severity of these risks, the uncertainty involved and the awareness of the interventions of central banks following the 2007–08 Great Financial Crisis, the sociopolitical pressure is already mounting to make central banks (perhaps again) the "only game in town" and to substitute for other if not all government interventions, this time to fight climate change. For instance, it has been suggested that central banks could engage in "green quantitative easing"[10] in order to solve the complex socioeconomic problems related to a low-carbon transition.

Relying too much on central banks would be misguided for many reasons (Villeroy de Galhau (2019a), Weidmann (2019)). First, it may distort markets further and create disincentives: the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are needed to transition to a global low-carbon economy. That includes fiscal, regulatory and standard-setting authorities in the real and financial world whose actions should reinforce each other. Second, and perhaps most importantly, it risks overburdening central banks' existing mandates. True, mandates can evolve, but these changes and institutional arrangements are very complex issues because they require building new sociopolitical equilibria, reputation and credibility. Although central banks' mandates have evolved from time to time, these changes have taken place along with broader sociopolitical adjustments, not to replace them.

Outline

These considerations suggest that central banks may inevitably be led into uncharted waters in the age of climate change. Whereas they cannot and should not replace policymakers, they also cannot sit still, since this could place them in the untenable situation of climate rescuer of last resort discussed above. This book sets out from this analytical premise and asks the following question: what, then, should be the role of central banks, regulators and supervisors in preserving financial stability[11] in the age of climate change? It is organised as follows.

Chapter 2 provides an overview of how climate-related risks are threatening socioeconomic activities, thereby affecting the future ability of central banks and supervisors to fulfil their mandates of monetary and financial stability. Following the old adage "that which is measured can be managed" (Carney (2015)), the obvious task in terms of financial regulation and supervision is therefore to ensure

---

[10] See De Grawe (2019) and the current debate about green quantitative easing in the United States and Europe.

[11] The question of price stability is also touched upon, although less extensively than financial stability.

that climate-related risks become integrated into financial stability monitoring and prudential supervision. However, such a task presents a significant challenge: traditional approaches to risk management consisting in extrapolating historical data based on assumptions of normal distributions are largely irrelevant to assess future climate-related risks. Indeed, both physical and transition risks are characterised by deep uncertainty, nonlinearity and fat-tailed distributions. As such, assessing climate-related risks requires an "epistemological break" (Bachelard (1938)) with regard to risk management. In fact, such a break has started to take place in the financial community, with the development of forward-looking, scenario-based risk management methodologies.

Chapter 3 assesses the methodological strengths and limitations of these methodologies. While their use by financial institutions and supervisors will become critical, it should be kept in mind that scenario-based analysis will not suffice to preserve financial stability in the age of climate change: the deep uncertainty at stake and the need for a structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers (although new modelling and analytical approaches will be critical to embrace the uncertain and non-equilibrium patterns involved). In particular, forward-looking approaches remain highly sensitive to a broad set of uncertain parameters involving: (i) the choice of a scenario regarding how technologies, policies, behaviours, macroeconomic variables and climate patterns will interact in the future; (ii) the translation of such scenarios into granular sector- and firm-level metrics in an evolving environment where all firms will be affected in unpredictable ways; and (iii) the task of matching the identification of a climate-related risk with the adequate mitigation action.

Chapter 4 therefore argues that the integration of climate-related risks into prudential regulation and (to the extent possible) into the relevant aspects of monetary policy will not suffice to shield the financial system against green swan events. In order to deal with this challenge, a second epistemological break is needed: there is an additional role for central banks to be more proactive in calling for broader changes. This needs not threaten existing mandates. On the contrary, calling for broader action by all players can only contribute to preserving existing mandates on price and financial stability. As such, and grounded in the transdisciplinary approach that is required to address climate change, this book makes four propositions (beyond the obvious need for carbon pricing) that are deemed essential to preserve financial stability in the age of climate change, related to: long-termism and sustainable finance; coordination between green fiscal policy, prudential regulation and monetary policy; international monetary and financial coordination and reforms; and integration of natural capital into national and corporate systems of accounting. Some potential obstacles related to each proposition are discussed.

Chapter 5 concludes by discussing how financial (and price) stability and climate stability can be considered as two public goods, the maintenance of which will increasingly depend on each other. Moreover, the need to ensure some form of long-term sustainability increasingly applies to prevent other human-caused environmental degradations such as biodiversity loss, and could require deep transformations in the governance of our socio-ecological systems. All this calls for new quantitative and qualitative approaches aimed at building system resilience (OECD (2019a), Schoon and van der Leeuw (2015)). At a time when policymakers are facing well known political economy challenges and when the private sector needs more incentives to transition to a low-carbon economy, an important contribution of central banks is to adequately frame the debate and thereby help promote the mobilisation of all efforts to combat climate change.

2. CLIMATE CHANGE IS A THREAT TO FINANCIAL AND PRICE STABILITY

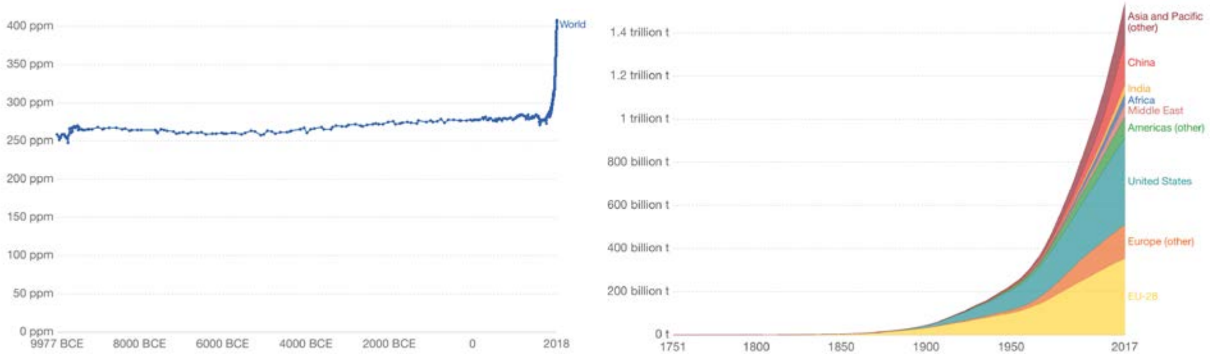
Climate change is the Tragedy of the Horizon. We don't need an army of actuaries to tell us that the catastrophic impacts of climate change will be felt beyond the traditional horizons of most actors – imposing a cost on future generations that the current generation has no direct incentive to fix.

Mark Carney (2015)

2.1 Climate change as a severe threat to ecosystems, societies and economies

At 415 parts per million (ppm),[12] Earth's concentration of CO_2 as of 11 May 2019 was higher than ever in human history, and far above the 270–280 ppm that had prevailed for millennia up to the Industrial Revolution (Graph 1, left-hand panel), guaranteeing stable climate conditions in which human societies were able to develop agriculture (Feynman and Ruzmaikin (2007)) and become more complex (Chaisson (2014)). The past decades, in particular, have shown a sharp increase in levels of atmospheric CO_2, from approximately 315 ppm in 1959 to 370 ppm in 1970 and 400 ppm in 2016 (right-hand panel).[12]

Evolution of atmospheric CO_2 concentration Graph 1



Atmospheric CO_2 concentration over the past 12 millennia, measured in parts per million (left-hand panel); and annual total CO_2 emissions by world region since 1751 (right-hand panel).

Sources: Bereiter et al. (2015), NOAA, www.esrl.noaa.gov/gmd/ccgg/trends/data.html; Carbon Dioxide Information Analysis Center, http://cdiac.ornl.gov; and Global Carbon Project (2018). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

These increasing levels of atmospheric CO_2 concentration, caused by human activity (IPCC (2018)), primarily the burning of fossil fuels (Hansen et al (2013)) but also deforestation and intensive agriculture (Ripple et al (2017)), prevent the Earth's natural cooling cycle from working and cause global warming. Global warming has already increased by close to 1.1°C since the mid-19th century. Temperatures are currently rising at 0.2°C per decade, and average yearly temperatures are increasingly

---

[12] Based on the daily record of global atmospheric carbon dioxide concentration measured at Mauna Loa Observatory in Hawaii, and reported by the Scripps Institution of Oceanography at UC San Diego. See https://scripps.ucsd.edu/programs/keelingcurve/.

among the hottest ever recorded (IPCC (2018), Masson-Delmotte and Moufouma-Okia (2019), Millar et al (2017), Ripple et al (2017)).

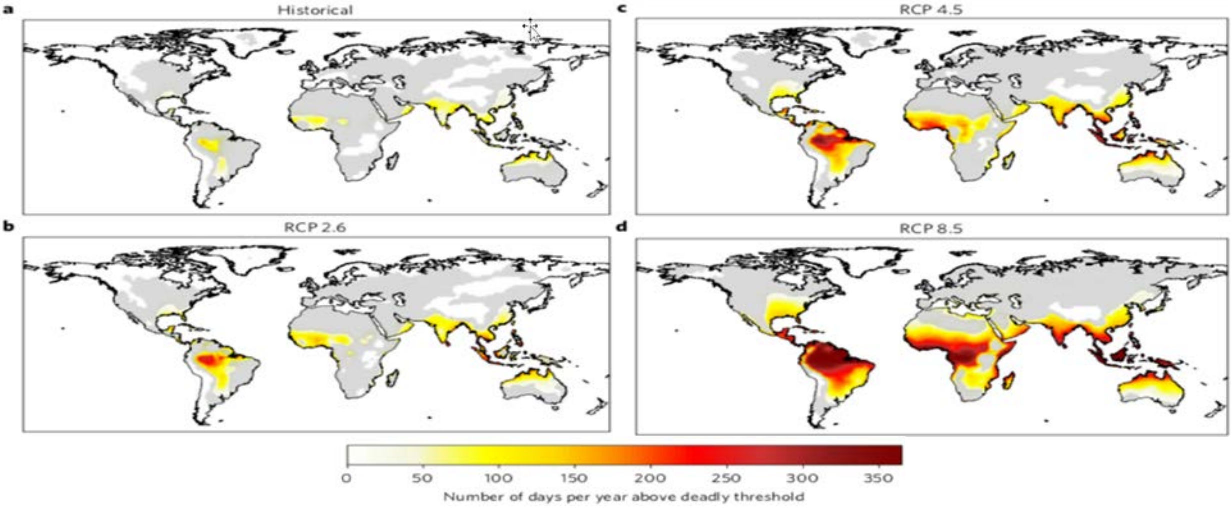
Current trends are on track to lead to systemic disruptions to ecosystems, societies and economies (Steffen et al (2018)). The continued increase in temperatures will lead to multiple impacts (IPCC (2018)) such as rising sea levels, greater intensity and incidence of storms, more droughts and floods, and rapid changes in landscapes. For instance, mean sea levels rose 15 centimetres in the 20th century, and the rate of rising is increasing. The impacts on ecosystems will be significant, potentially leading to species loss or even a massive extinction of wildlife (Ripple et al (2017)). Soil erosion could also accelerate, thereby decreasing food security and biodiversity (IPCC (2019)). Marine biodiversity, marine ecosystems and their ecological functions are also threatened (Masson-Delmotte and Moufouma-Okia (2019)).

The effects of climate change may be catastrophic and irreversible for human populations, potentially leading to "untold suffering", according to more than 11,000 scientists (Ripple et al (2019)). Sea levels could rise by several metres with critical impacts for small islands, low-lying coastal areas, river deltas and many ecological systems on which human activity depends. For instance, increased saltwater intrusion could lead to major agricultural losses, and flooding could damage existing infrastructure (Masson-Delmotte and Moufouma-Okia (2019)). A two-metre sea level rise triggered by the potential melting of ice sheets could displace nearly 200 million people by 2100 (Bamber et al (2019)). Even more worrisome, past periods in the Earth's history indicate that even warming of between 1.5°C and 2°C could be sufficient to trigger long-term melting of ice in Greenland and Antarctica and a sea level rise of more than 6 metres (Fischer et al (2018)).

Humans may have to abandon many areas in which they currently manage to sustain a living, and entire regions in South America, Central America, Africa, India, southern Asia and Australia could become uninhabitable due to a mix of high temperatures and humidity levels (Im et al (2017), Mora et al (2018); see Graph 2). About 500 million people live in areas already affected by desertification, especially in southern and East Asia, the Middle East and sub-Saharan Africa, which will only be under greater socioeconomic pressure due to climate change (IPCC (2019)).

Average temperature changes

Graph 2



Number of days per year above a deadly threshold by the end of the century in a business as usual scenario.

Source: Mora et al (2017).

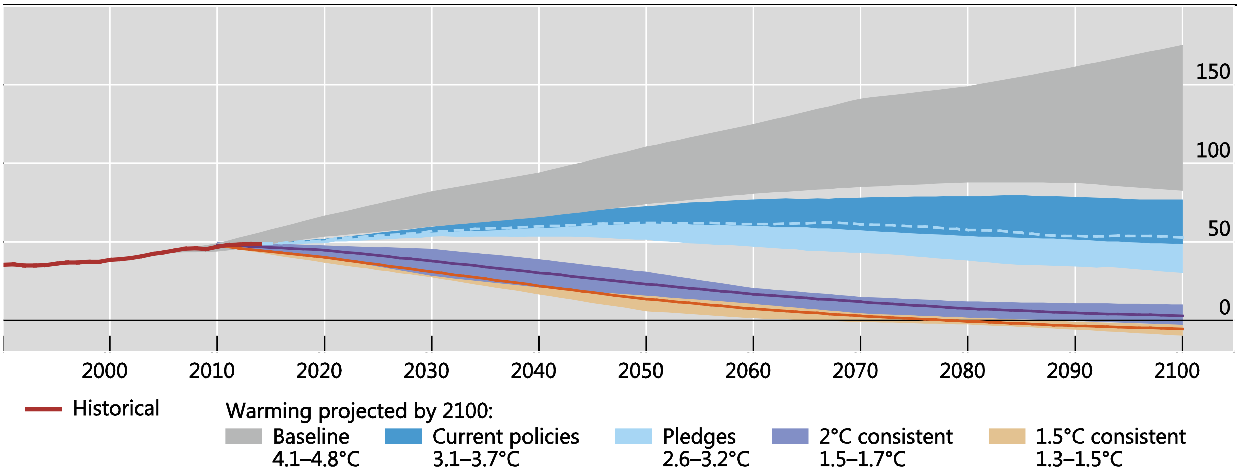
Climate change is not just a future risk: it has actually already started to transform human and non-human life on Earth,[13] although the worst impacts are yet to come. Crop yields and food supply are already affected by climate change in many places across the globe (Ray et al (2019)). Parts of India are undergoing chronic severe water crises (Subramanian (2019)). Heatwaves are becoming more frequent in most land regions, and marine heatwaves are increasing in both frequency and duration (Masson-Delmotte and Moufouma-Okia (2019)). Extreme weather events have increased significantly over the past 40 years (Stott (2016)). Large-scale losses of coral reefs have started to occur (Hughes et al (2018)). Even keeping global warming below 1.5°C could result in the destruction of 70–90% of reef-building corals (IPCC (2018)), on which 25% of all marine life depends (Gergis (2019)).

In turn, avoiding the worst impacts of climate change amounts to a massive, unprecedented, challenge for humanity. The planet is producing close to 40 gigatonnes (Gt) of CO_2 per year, and it is on track to double by 2050. We should reduce emissions to almost zero by then (Graph 3) in order to comply with the UN Paris Agreement of 2015 (UNFCCC (2015)), which set the goal of keeping global warming well below 2°C and as close as possible to 1.5°C above pre-industrial levels (defined as the climate conditions experienced during 1850–1900).

Nevertheless, the special report of the IPCC on the 1.5°C goal (IPCC (2018)) shows that the gap between current trends and emission reduction targets set by countries through their nationally determined contributions (NDCs) – which were already insufficient to limit global warming to 2°C – is widening and leading to somewhere between 3°C and 4°C of warming, which is consistent with a "Hothouse Earth" pathway (Steffen et al (2018)).

2100 warming projections: emissions and expected warming based on pledges and current policies

Global greenhouse gas emissions ($GtCO_2e$/year) Graph 3



Source: Climate Action Tracker.

The impacts on economic output could be significant if no action is taken to reduce carbon emissions. Some climate-economic models indicate that up to a quarter of global GDP could be lost (Burke et al (2015a)), with a particularly strong impact in Asia, although these predictions should be taken cautiously given the deep uncertainty involved (as discussed in Chapter 3). In any case, both the demand side and the supply side are affected (examples in Table 1).

---

[13] A list of observed impacts, with links to relevant studies, can be found at: impact.gocarbonneutral.org/.

Climate change-related shocks and their effects on… Table 1

	Type of shock	From gradual global warming	From extreme weather events
Demand	Investment	Uncertainty about future demand and climate risks	Uncertainty about climate risk
	Consumption	Changes in consumption patterns, eg more savings for hard times	Increased risk of flooding to residential property
	Trade	Changes in trade patterns due to changes in transport systems and economic activity	Disruption to import/export flows due to extreme weather events
Supply	Labour supply	Loss of hours due to extreme heat. Labour supply shock from migration	Loss of hours worked due to natural disasters, or mortality in extreme cases. Labour supply shock from migration
	Energy, food and other inputs	Decrease in agricultural productivity	Food and other input shortages
	Capital stock	Diversion of resources from productive investment to adaptation capital	Damage due to extreme weather
	Technology	Diversion of resources from innovation to adaptation capital	Diversion of resources from innovation to reconstruction and replacement

Sources: NGFS (2019b), adapted from Batten (2018).

Demand-side shocks are those that affect aggregate demand, such as private (household) or public (government) consumption demand and investment, business investment and international trade. Climate damages could dampen consumption, and business investments could be reduced due to uncertainty about future demand and growth prospects (Hallegatte (2009)). Climate change is also likely to disrupt trade flows (Gassebner et al (2010)) and reduce household wealth. Even less exposed economies can have extensive interactions with global markets and be affected by extreme climate shocks.

Supply-side shocks could affect the economy's productive capacity, acting through the components of potential supply: labour, physical capital and technology. For instance, higher temperatures tend to reduce the productivity of workers and agricultural crops (IPCC (2019)). Moreover, climate change can trigger massive population movements (Opitz Stapleton et al (2017)), with long-lasting effects on labour market dynamics and wage growth. Supply-side shocks can also lead to a diversion of resources form investment in productive capital and innovation to climate change adaptation (Batten (2018)). Damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)). Even if the relevant capital stocks might survive, efficiency might be reduced and some areas might have to be abandoned (Batten (2018)).

These economic shocks can have major impacts on the price and financial instability, as respectively explored next.

2.2 The redistributive effects of climate change

Climate change has important distributional effects both between and within countries. The geographical distribution of potential physical risks triggered by rising temperatures (Graph 2) clearly shows that they primarily affect poor and middle-income countries. Moreover, transition risks might also disproportionately impact the natural endowments, traditional carbon-intensive industries and consumption habits of poor countries and low-income households. The cost of mitigation and adaptation might also be prohibitive for both groups.

The degree of awareness about the risks posed by climate change is also unevenly shared within societies, following – and sometimes reinforced by – inequalities of wealth and income. In some cases, denial has been a convenient demagogic response to these issues, compounded by accusations of intrusion into national sovereignty. Another popular political stance has been to dismiss the challenges posed by climate change as merely a concern of the wealthy and well protected. The debate with climate change sceptics is a legitimate and necessary step towards improving the analytics on these issues while creating the sociopolitical conditions to start implementing policies to mitigate risks. There is a relatively old and large literature calling for fairness and social justice when designing adaptation and mitigation policies (eg Adger et al (2006), Cohen et al (2013)). All this will require a better understanding of the redistributive effects of climate change, of the policies to adapt our economies and of the associated costs of mitigation. Without a clear map for how the costs and benefits of climate change mitigation strategies will be distributed, it is almost certain – as we have been observing in many recent cases – that political backlashes will increase against a lower-carbon society. Thus, the sociopolitical viability of combating climate change depends on addressing its distributional consequences.

Indeed, the enormous challenges described above mean that the policies to combat climate change will be quite invasive and are likely to have significant collateral effects on our societies and our production and consumption processes, with associated distributional effects. Zachmann et al (2018) conduct a study of the distributional consequences of mitigation policies and point out that the intensity of these effects depends on the choice of the policy instrument used, the targeted sector, the design of the intervention and the country's degree of development and socioeconomic conditions. They study the impact of climate policies on households of different income levels (low to high) and assess policies addressing climate change as regressive, proportionate or progressive. They take into account households' budget and wealth constraints (eg their inability to quickly shift to lower carbon consumption baskets as well as investment in lower-carbon houses and durable goods). They conclude that the regressive distributional effects of many climate policies requires compensating lower-income households for their negative income effects as well as being gradual and progressive in the introduction of such policies.

Dennig et al (2015) also study regional and distributional effects of climate change policies. They use a variant of the Regional Integrated model of Climate and the Economy (RICE) – a regionally disaggregated version of the Dynamic Integrated model of Climate and the Economy (DICE) – and introduce economic inequalities in the model's regions. Their study confirm that climate change impacts are not evenly distributed within regions and that poorer people are more vulnerable, suggesting that this must be taken into account when setting the social cost of carbon. However, improving the poverty and inequality modelling in climate research requires more efforts as the current approaches are limited as argued by Rao et al (2017) because current models do not capture well household heterogeneity and proper representation of poor and vulnerable societal segments.

Finally, there is an extensive literature and numerous studies pointing to the distributional impact of climate change on poor countries and the need to scale up international mechanisms to finance their transition and reduce their vulnerability to climate change-related events with well known implications for massive migration. This has been a significant part of the discussions of the UN Conference of the Parties (COP) since its inception. For example, the Adaptation Fund was established at the COP 7 in 2001 but only set up under the Kyoto Protocol of the United Nations Framework Convention on Climate Change

(UNFCCC) and officially launched in 2007. The mechanism has revolved around the need for rich countries to contribute to the adaptation cost by developing countries. At COP 2015 in 2009, this resulted in the pledge by advanced economies to mobilise $100 billion in aid by 2020. So far, the practical implementation has remained limited.

2.3 Climate change as source of monetary instability

Although this book focuses on financial stability, it should be noted that climate-related shocks are likely to affect monetary policy through supply-side and demand-side shocks, and thereby affect central banks' price stability mandate. Regarding supply-side shocks (McKibbin et al (2017)), pressures on the supply of agricultural products and energy are particularly prone to sharp price adjustments and increased volatility. The frequency and severity of such events might increase, and impact supply through more or less complex channels. There are still relatively few studies analysing the impact of climate-related shocks on inflation, but some studies indicate that food prices tend to increase in the short term following natural disasters and weather extremes (Parker (2018), Heinen et al (2018), Debelle (2019)).

In addition to these short-term pressures on prices, supply shocks can also reduce economies' productive capacity. For instance, climate change could have long-standing impacts on agricultural yields, lead to frequent resource shortages or to a loss in hours worked due to heat waves. These effects, in turn, can reduce the stock of physical and human capital, potentially resulting in reduced output (Batten (2018), McKibbin et al (2017)). But climate change can also translate into demand shocks, for instance by reducing household wealth and consumption (Batten (2018)). Climate mitigation policies could also affect investment in some sectors, with various indirect impacts further discussed in the next chapter.

In sum, the impacts of climate change on inflation are unclear partly because climate supply and demand shocks may pull inflation and output in opposite directions, and generate a trade-off for central banks between stabilising inflation and stabilising output fluctuations (Debelle (2019)). Moreover, if climate-related risks end up affecting productivity and growth, this may have implications for the long-run level of the real interest rate, a key consideration in monetary policy (Brainard (2019)).

Traditionally, monetary policy responses are determined by looking at their impact on prices and expectations. If there is a presumption that the impact is temporary, the response can be to wait and see or "look through" the shock as it does not affect prices and expectations on a permanent basis. However, if the shock has more lasting effects, there could be motives to consider a policy reaction to adjust aggregate demand conditions. In the case of climate-related risks, the irreversibility of certain climate patterns and impacts poses at least three new challenges for monetary policy (Olovsson (2018)):

(i) While the use of cyclical instruments aims to stimulate or subdue activity in the economy over relatively short periods, climate change is expected to maintain its trajectory for long periods of time (Cœuré (2018)). This situation can lead to stagflationary supply shocks that monetary policy may be unable to fully reverse (Villeroy de Galhau (2019a)).

(ii) Climate change is a global problem that demands a global solution, whereas monetary policy seems, currently, to be difficult to coordinate between countries (Pereira da Silva (2019a)). As such, the case for a single country or even a monetary zone to react to inflationary climate-related shocks could be irrelevant.

(iii) Even if central banks were able to re-establish price stability after a climate-related inflationary shock, the question remains whether they would be able to take pre-emptive measures to hedge ex ante against fat-tail climate risks, ie green swan events (Cœuré (2018)).

It should nevertheless be admitted that studies on the impact of climate change on monetary stability are still at an early stage, and that much more research is needed. Far more evidence has been collected on the potential financial impacts of climate change, as discussed in the rest of this book.

2.4 Climate change as a source of financial instability

Even though a growing number of stakeholders has recognised the socioeconomic risks posed by climate change over the past decades, much of the financial sector seemed to remain unconcerned until a few years ago. The situation has changed radically over the past few years, as the potentially disruptive impacts of climate change on the financial system started to become more apparent (Carney (2015)). As further detailed in Chapter 4, some central banks, regulators and supervisors are already taking steps towards integrating climate-related risks into supervisory practices, and more could follow in the near future. The NGFS, created in December 2017, quickly recognised that "climate-related risks are a source of financial risk. It is therefore within the mandates of central banks and supervisors to ensure the financial system is resilient to these risks" (NGFS (2018), p 3).

There are two main channels[14] through which climate change can affect financial stability:

Physical risks are "those risks that arise from the interaction of climate-related hazards […] with the vulnerability of exposure to human and natural systems" (Batten et al (2016)). They represent the economic costs and financial losses due to increasing frequency and severity of climate-related weather events (eg storms, floods or heat waves) and the effects of long-term changes in climate patterns (eg ocean acidification, rising sea levels or changes in precipitation). The losses incurred by firms across different financial portfolios (eg loans, equities, bonds) can make them more fragile.

The destruction of capital and the decline in profitability of exposed firms could induce a reallocation of household financial wealth. For instance, rising sea levels could lead to abrupt repricing of real estate (Bunten and Kahn (2014)) in some exposed regions, causing large negative wealth effects that may weigh on demand and prices through second-round effects. Climate-related physical risks can also affect the expectation of future losses, which in turn may affect current risk preferences. For instance, homes exposed to sea level rise already sell at a discount relative to observationally equivalent unexposed properties equidistant from the beach (Bernstein et al (2019)).

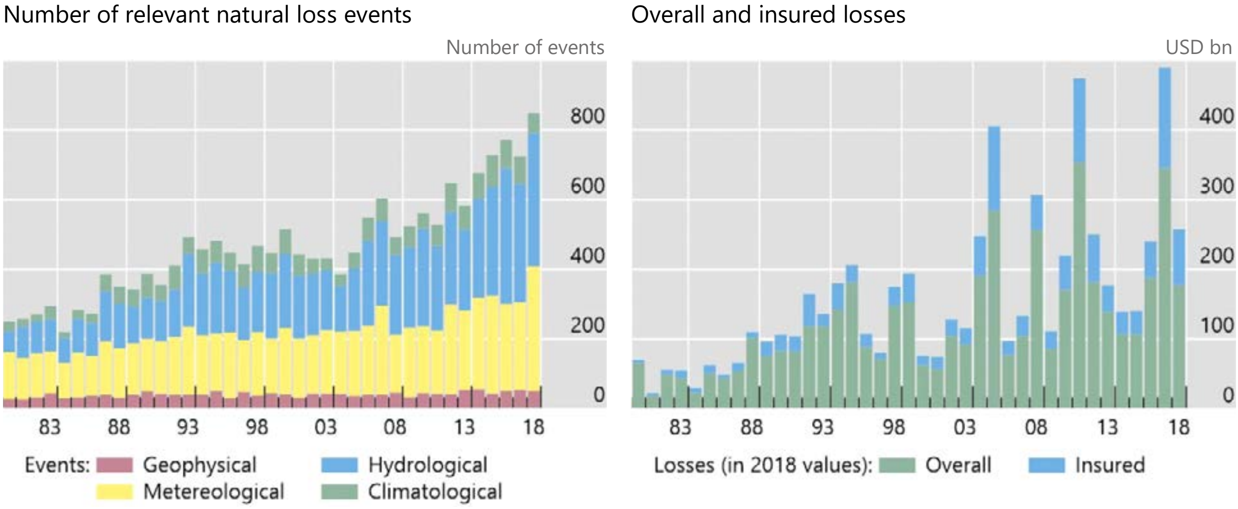
As natural catastrophes increase worldwide (Graph 4), non-insured losses (which represent 70% of weather-related losses (IAIS (2018)) can threaten the solvency of households, businesses and governments, and therefore financial institutions. Insured losses, on their end, may place insurers and reinsurers in a situation of fragility as claims for damages keep increasing (Finansinspektionen (2016)). More broadly, damages to assets affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol (2005)).

---

[14] A third type of risk, liability risk, is sometimes mentioned. This refers to "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible" (Carney (2015), p 6). However, such costs and losses are often considered to be part of either physical or transition risk.

Increase in the number of extreme weather events and their insurance,[15] 1980–2018

Graph 4


Number of relevant natural loss events

Overall and insured losses

Includes copyrighted material of Munich Re and its licensors.

Source: MunichRe (2018).

Moreover, the fat-tailed probability distributions of many climate parameters are such that the possibility of extreme values cannot be ruled out (Weitzman (2009, 2011)). This could place financial institutions in situations in which they might not have sufficient capital to absorb climate-related losses. In turn, the exposure of financial institutions to physical risks can trigger contagion and asset devaluations propagating throughout the financial system.

Transition risks are associated with the uncertain financial impacts that could result from a rapid low-carbon transition, including policy changes, reputational impacts, technological breakthroughs or limitations, and shifts in market preferences and social norms. In particular, a rapid and ambitious transition to lower emissions pathways means that a large fraction of proven reserves of fossil fuel cannot be extracted (McGlade and Elkins (2015)), becoming "stranded assets", with potentially systemic consequences for the financial system (see Box 1). For instance, an archetypal fire sale might result if these stranded assets suddenly lose value, "potentially triggering a financial crisis" (Pereira da Silva (2019a)). As Mark Carney puts it: "too rapid a movement towards a low-carbon economy could materially damage financial stability. A wholesale reassessment of prospects, as climate-related risks are re-evaluated, could destabilise markets, spark a pro-cyclical crystallisation of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment" (Carney (2016), p 2).

Moreover, the value added of many other economic sectors dependent on fossil fuel companies will probably be impacted indirectly by transition risks (Cahen-Fourot et al (2019a,b)). For instance, the automobile industry may be strongly impacted as technologies, prices and individual preferences evolve. Assessing how the entire value chain of many sectors could be affected by shocks in the supply of fossil fuels is particularly challenging, as will be further discussed in the next chapter.

Physical and transition risks are usually assessed separately, given the complexity involved in each case (as discussed in the next chapter). However, they should be understood as part of the same framework and as being interconnected (Graph 5). A strong and immediate action to mitigate climate change would increase transition risks and limit physical risks, but those would remain existent (we are already

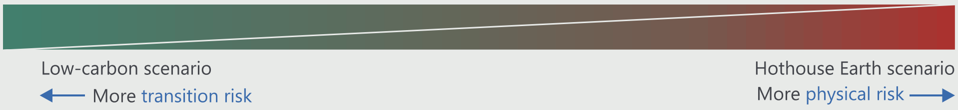
---

[15] This figure does not allow them to be extrapolated into the future, and they should be interpreted carefully. For instance, some natural catastrophes, such as typhoons, could become less frequent but more intense.

experiencing some of the first physical risks of climate change). In contrast, delayed and weak action to mitigate climate change would lead to higher and potentially catastrophic physical risks, without necessarily entirely eliminating transition risks (eg some climate policies are already in place and more could come). Delayed actions followed by strong actions in an attempt to catch up would probably lead to high both physical and transition risks (not represented in Graph 5).

Framework for physical and transition risks

Graph 5



Scenario	**Rapid Transition**	**Two-degree**	**Business-as-intended**	**Business-as-usual**
Corrective transition response	Very strong	Strong	Substantial	Limited
Change in temperature, 2100 vs pre-industrial era	1.5°C	2°C	3°C	4°C

Source: adapted from Oliver Wyman (2019); authors' elaboration.

Box 1: Introduction to stranded assets

Limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). These are referred to as stranded assets. For instance, a study (McGlade and Elkins (2015)) found that in order to have at least a 50% chance of keeping global warming below 2°C, over 80% of current coal reserves, half of gas reserves and a third of oil reserves should remain unused from 2010 to 2050. As the risk related to stranded assets is not reflected in the value of the companies that extract, distribute and rely on these fossil fuels, these assets may suffer from unanticipated and sudden writedowns, devaluations or conversion to liabilities.

Estimates of the current value and scope of stranded assets vary greatly from one study to another. For instance, Mercure et al (2018) estimate that the discounted loss in global wealth resulting from stranded fossil fuel assets may range from $1 trillion to $4 trillion. Carbon Tracker (2018)[16] approximates the amount at $1.6 trillion, far below the International Renewable Energy Agency's (IRENA) (2017) estimate of $18 trillion, but the scope and definitions used by each of them differ. Therefore, as discussed more extensively in Chapter 3, it is critical to understand the models used by each of these studies to fully appreciate their respective outcomes and potential limitations.

Physical and transition risks can materialise in terms of financial risk in five main ways (DG Treasury et al (2017)), with many second-round effects and spillover effects among them (Graph 6):

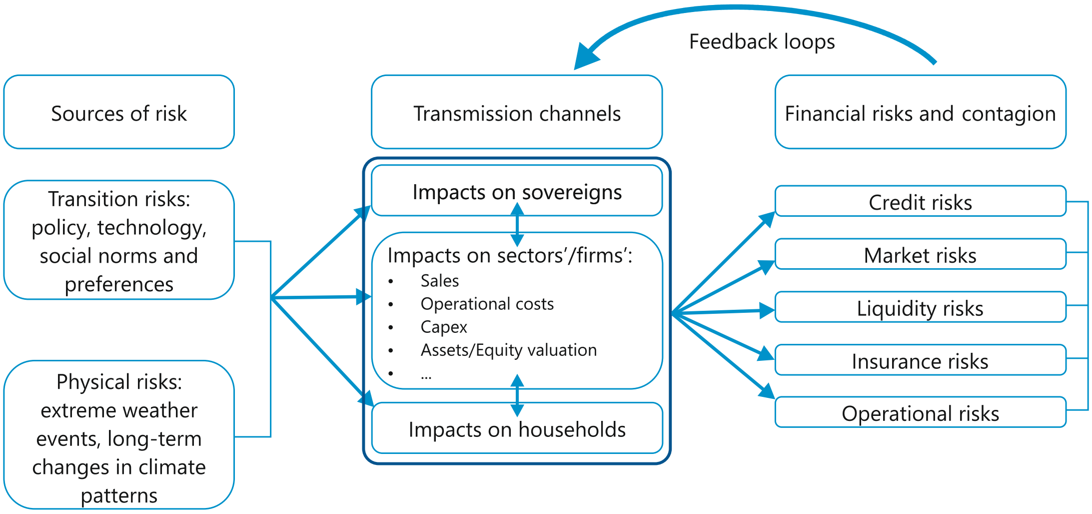
- ***Credit risk***: climate-related risks can induce, through direct or indirect exposure, a deterioration in borrowers' ability to repay their debts, thereby leading to higher probabilities of default (PD) and a higher loss-given-default (LGD). Moreover, the potential depreciation of assets used for collateral can also contribute to increasing credit risks.

---

[16] In a scenario with an increase in temperatures of 1.75°C.

- ***Market risk***: Under an abrupt transition scenario (eg with significant stranded assets), financial assets could be subject to a change in investors' perception of profitability. This loss in market value can potentially lead to fire sales, which could trigger a financial crisis. The concept of climate value-at-risk (VaR) captures this risk and will be further discussed in the next chapter.
- ***Liquidity risk***: although it is covered less in the literature, liquidity risk could also affect banks and non-bank financial institutions. For instance, banks whose balance sheet would be hit by credit and market risks could be unable to refinance themselves in the short term, potentially leading to tensions on the interbank lending market.
- ***Operational risk***: this risk seems less significant, but financial institutions can also be affected through their direct exposure to climate-related risks. For instance, a bank whose offices or data centres are impacted by physical risks could see its operational procedures affected, and affect other institutions across its value chain.
- ***Insurance risk***: for the insurance and reinsurance sectors, higher than expected insurance claim payouts could result from physical risks, and potential underpricing of new insurance products covering green technologies could result from transition risks (Cleary et al (2019)).

Channels and spillovers for materialisation of physical and transition risks Graph 6



Sources: adapted from DG Treasury et al (2017); authors' elaboration.

2.5 The forward-looking nature of climate-related risks – towards a new epistemology of risk

The potentially systemic risks posed by climate change explain why it is in the interest of central banks, regulators and financial supervisors to ensure that climate-related risks are appropriately understood by all players (NGFS (2019a)). It is therefore not surprising that the first recommendation made by the NGFS in its first comprehensive report called for "integrating climate-related risks into financial stability monitoring and micro-supervision" (NGFS (2019a), p 4). This integration helps ensure that financial institutions and the financial system as a whole are resilient to climate-related risks (NGFS (2019a)).

Moreover, a systematic integration of climate-related risks by financial institutions could act as a form of shadow pricing on carbon, and therefore help shift financial flows towards green assets. That is, if investors integrate climate-related risks into their risk assessment, then polluting assets will become more costly. This would trigger more investment in green assets, helping propel the transition to a low carbon economy (Pereira da Silva (2019a)) and break the tragedy of the horizon by better integrating long-term risks (Aufauvre and Bourgey (2019)). A better understanding of climate-related risks is therefore a key component of Article 2.1.c of the Paris Agreement, which aims to "mak[e] finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development" (UNFCCC (2015)).

However, integrating climate-related risks into financial stability monitoring and prudential supervision presents a significant challenge: traditional approaches to risk management are based on historical data and assumptions that shocks are normally distributed (Dépoues et al (2019)). The fundamental financial concept of value-at-risk (VaR) captures losses that can be expected with a 95–99% level of confidence and over a relatively short-term horizon. Capital requirements are also typically calculated (through estimated PD, exposure at default and estimated LGD) on a one-year horizon and based on credit ratings that largely rely on historical track records of counterparties.

The problem is that extrapolating historical trends can only lead to mispricing of climate-related risks, as these risks have barely started to materialise: physical risks will become worse as global warming goes on, and transition risks are currently low given the lack of ambitious policies on a global scale. Moreover, climate-related risks typically fit fat-tailed distributions and concentrate precisely in the 1% not considered by VaR. Finally, climate change is characterised by deep uncertainty: assessing the physical risks of climate change is subject to uncertainties related to climate patterns themselves, their potentially far-reaching impacts on all agents in the economy, and complex transmission channels (NGFS (2019a,b)), especially in the context of globalised value chains; transition risks are also subject to deep or radical uncertainty with regard to issues such as the policies that will be implemented (eg carbon pricing versus command-and-control regulations), their timing, the unpredictable emergence of new low-carbon technologies or changes in preferences and lifestyles that could take place. All these issues are further discussed in Chapter 3.

As a result, the standard approach to modelling financial risk consisting in extrapolating historical values (eg PD, market prices) is no longer valid in a world that is fundamentally reshaped by climate change (Weitzman (2011), Kunreuther et al (2013)). In other words, green swan events cannot be captured by traditional risk management.

The current situation can be characterised as an "epistemological obstacle" (Bachelard (1938)). The latter refers to how scientific methods and "intellectual habits that were useful and healthy" under certain circumstances, can progressively become problematic and hamper scientific research. Epistemological obstacles do not refer to the difficulty or complexity inherent to the object studied (eg measuring climate-related risks) but to the difficulty related to the need of redefining the problem. For instance, as a result of the incompatibility between probabilistic and backward-looking risk management approaches and the uncertain and forward-looking nature of climate-related risks, "investors, at this stage, face a difficult task to assess these risks – there is for instance no equivalent of credit ratings for climate-related financial risks" (Pereira da Silva (2019a)).

As scientific knowledge does not progress continuously and linearly but rather through a series of discontinuous jumps with changes in the meaning of concepts, nothing less than an epistemological break (Bachelard, 1938) or a "paradigm shift" (Kuhn (1962)) is needed today to overcome this obstacle and more adequately approach climate-relate risks (Pereira da Silva (2019a)).

In fact, precisely an epistemological break may be taking place in the financial sector: recently emerged methodologies aim to assess climate-related risks while relying on the fundamental hypothesis that, given the lack of historical financial data related to climate change and the deep uncertainty involved, new approaches based on the analysis of prospective scenarios are needed.[17] Unlike probabilistic approaches to financial risk management, they seek to set up plausible hypotheses for the future. This can help financial institutions integrate climate-related risks into their strategic and operational procedures (eg for the purpose of asset allocation, credit rating or insurance underwriting) and financial supervisors assess the vulnerability of specific institutions or the financial system as a whole.

A consensus is emerging among central banks, supervisors and practitioners involved in climate-related risks about the need to use such forward-looking, scenario-based methodologies (Batten et al (2016), DG Treasury et al (2017), TCFD (2017), NGFS (2019a), Regelink et al (2017)). As shown by the Task Force on Climate-related Financial Disclosures[18] (TCFD; Graph 7), managing climate-related risks through a forward-looking approach can lead financial institutions to test the resilience of corporations in their portfolios to potential materialisations of physical and transition risks, their impact on key performance indicators and the adaptive capacities of these firms.

Testing the resilience of corporations to potential materialisations of physical and transition risks

Graph 7

What scenarios (and narratives) are appropriate, given the exposures? Consider input parameters, assumptions, and analytical choices. What reference scenario(s) should be used?

Evaluate the potential effects on the organisation's strategic and financial position under each of the defined scenarios. Identify key sensitivities.

Use the results to identify applicable, realistic decisions to manage the identified risks and opportunities. What adjustments to strategic/financial plans would be needed?

Source: Adapted from TCFD (2017).

These methodologies may already be facilitating a more systematic integration of climate-related risks in the financial sector: some insurance companies are reassessing their cost of insuring physical risk; some rating agencies are increasingly re-evaluating credit risks in the light of growing climate-related risks; and some asset managers are becoming more selective and inclined to start picking green assets and/or ditching brown assets in their portfolio allocation (Bernardini et al (2019), Pereira da Silva (2019a)).

Hence, it is critical for central banks, regulators and supervisors to assess the extent to which these forward-looking, scenario-based methodologies can ensure that the financial system is resilient to climate-related risks and green swan events. The next chapter undertakes a critical assessment of these methodologies.

---

[17] It is noteworthy that these methodologies have been produced by a variety of players including consulting firms, non-profit organisations, academics, international organisations and financial institutions themselves.

[18] See www.fsb-tcfd.org/. The TCFD was set up in 2015 by the Financial Stability Board (FSB), to develop voluntary, consistent climate-related financial risk disclosures for use by companies, banks and investors in providing information to stakeholders.

3. MEASURING CLIMATE-RELATED RISKS WITH SCENARIO-BASED APPROACHES: METHODOLOGICAL INSIGHTS AND CHALLENGES

Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way future strategies, designs or plans are developed.

Maier et al (2016)

This chapter reviews some of the methodological challenges that financial institutions and supervisors face when conducting forward-looking, scenario-based analysis aimed at identifying and managing climate-related risks. It focuses on the main conceptual issues; a detailed discussion of the technical features of each existing methodology is beyond the scope of this book (for more exhaustive reviews see, for instance, Hubert et al (2018), UNEP-FI (2018a,b, 2019)). Also, our discussion is focused mostly on methodologies aimed at measuring transition risks,[19] although some challenges related to physical risks are mentioned.

Our key conclusion is that, despite their promising potential, forward-looking analyses cannot fully overcome the limitations of the probabilistic approaches discussed in the previous chapter and provide sufficient hedging against "green swan" events. That is, although the generalised use of forward-looking, scenario-based methodologies can help financial and economic agents to better grapple with the long-term risks posed by climate change, they will not suffice to "break the tragedy of the horizon" and induce a significant shift in capital allocation towards low-carbon activities. Two main limitations exist.

First, the materialisation of physical and transition risks depends on multiple nonlinear dynamics (natural, technological, societal, regulatory and cultural, among others) that interact with each other in complex ways and are subject to deep uncertainty. Climate-economic models are inherently incapable of representing all these interactions, and they therefore overlook many social and political forces that will strongly influence the way the world evolves. With this in mind, the outcomes of a scenario-based analysis should be assessed very cautiously and cannot suffice to guide decision-making. The broad range of results concerning the monetary value of stranded assets – one of the most prominent transition risks – are symptomatic of the complexity and uncertainty at stake (see Box 2 below).

In particular, the complex and multiple interactions between climate and socioeconomic systems are such that the task of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of scenarios describing how technologies, policies, behaviours, macroeconomic and even geopolitical dynamics and climate patterns may interact in the future (Chapter 3.2), especially given the intrinsic limitations of most equilibrium climate-economic models (Chapter 3.1);

(ii) The translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in largely unpredictable ways (Chapter 3.3).

---

[19] This choice is notably informed by the fact that physical risks arising from a global warming beyond 2°C can be so systemic that aiming to measure them quickly becomes impossible. Transition risks can therefore be seen as those that must arise if we decide to remain within safer climate boundaries. In practice, physical and transition risks are interconnected, as discussed in Chapter 2.3. However, current climate-related risk methodologies generally fail to analyse physical and transition risks jointly, in spite of recent efforts in this direction.

Second, and more fundamentally, climate-related risks will remain largely uninsurable or unhedgeable as long as system-wide action is not taken (Chapter 3.4). In contrast to specific areas where scenario analysis can help financial institutions avoid undesirable outcomes (eg avoiding a dam collapse for a hydropower project), climate-related scenario analysis cannot by itself enable a financial institution or the financial system as a whole to avoid and withstand "green swan" events. For instance, a financial institution willing to hedge itself against an extreme transition risk (eg a sudden and sharp increase in carbon pricing) in the current context of weak climate policies may simply be unable to find adequate climate-risk-free assets if these are not viable in the current environment ("green" assets and technologies are still nascent and also present significant risks).

The first limitation can be partially resolved through better data (Caldecott (2019), NGFS (2019a)) and through the development of new models, in particular non-equilibrium models that can better account for nonlinearity, uncertainty, political economy considerations and the role of money and finance (Mercure et al (2019), Monasterolo et al (2019)). However, the second limitation is a reminder that only a structural transformation of our global socioeconomic system can really shield the financial system against "green swan" events. This calls for alternative epistemological positions that can fully embrace uncertainty and the need for structural transformations, including through more qualitative and politically grounded approaches (Aglietta and Espagne (2016), Chenet et al (2019a, 2019b), Ryan-Collins (2019)).

This does not mean that the development of forward-looking methodologies is not useful. On the contrary, non-financial and financial firms alike will increasingly need to rely on them to explore their potential vulnerabilities. But for central banks, regulators and supervisors concerned about the resilience of the system as a whole, the development of forward-looking, scenario-based methodologies should be assessed with a more critical stance. Much like a carbon price and other policies, they are a critical step that can become fully operational only if a system-wide transition takes place, as further discussed in Chapter 4.

Box 2: Methodological uncertainty surrounding the monetary value of stranded assets

As discussed in Chapter 2, limiting global warming to less than 1.5°C or 2°C requires keeping a large proportion of existing fossil fuel reserves in the ground (Matikainen (2018)). The case has often been made that risks related to stranded assets are not reflected in the value of the companies that extract, distribute and rely on these fossil fuels. This could lead to a significant and sudden drop in their value if ambitious climate policies are adopted.

However, estimating precisely the current value of fossil fuel assets that may be stranded in the future is an exercise replete with uncertainty. As such, the diverging estimates obtained (eg between $1 trillion and $4 trillion according to Mercure et al (2018); around $1.6 trillion as estimated by Carbon Tracker (2018);[20] and up to $18 trillion according to IRENA (2017)) should be carefully assessed as they are based on different geographical scopes, assumptions and valuation methods, among others. For instance, some estimates (eg IRENA (2017)) cover the stranded value of fossil fuel assets (eg the discounted cash flows of future revenues that will be lost) whereas others (eg IEA (2014)) focus on the stranded capital, ie the losses related to the capital invested in a project subject to stranding.

One source of uncertainty has to do with today's valuation of fossil fuel reserves. Some methodologies assume that these reserves significantly contribute to the current valuation of fossil fuel companies. In contrast, IHS Markit (2015) argues that oil and gas companies' market valuations are mostly driven by commercially proved reserves that will be monetised over the next 10 to 15 years, and not so much by the resources that would be likely to be stranded over a longer-term horizon. If this is true, the market mispricing of fossil fuel assets may not be as large as often expected. Some studies also suggest that investors are already reacting to climate-related risks: based on the

---

[20] In a scenario with an increase in temperatures of 1.75°C.

performance of high-emissions industries in the S&P 500 index before and after the Paris Agreement, Ilhan et al (2018) suggest that investors are actually already incorporating information about climate-related risks when assessing risk profiles. Other studies also find that the risk premium of fossil fuel firms has increased following the Paris Agreement (de Greiff et al (2018)) and that this rise in risk premium is due to increased awareness of transition risks (Delis et al (2018)). In short, the extent to which stranded assets are already valued remains unclear.

Estimating the impacts of stranding fossil assets with geographical granularity is essential to appreciate which companies can be hit, yet it also requires making uncertain choices with regard to which resources will actually be stranded (McGlade and Ekins (2015)). In this respect, Mercure et al (2018) conduct a precise geographical analysis of stranded assets based on the costs of extraction of fossil fuels around the world, assuming that resources in locations with higher extraction costs will be stranded first. They find that Saudi Arabia could keep selling oil in a low-carbon scenario given its competitive prices, whereas Canadian and US unconventional oils could be stranded much faster, with potential significant impacts on their GDPs. In practice, the most vulnerable countries (Canada and the United States in this case) would probably be tempted to subsidise their fossil fuel production to avoid such negative impacts.

Financial institutions can also be impacted indirectly through complex cascades of stranded assets (Cahen-Fourot et al (2019a,b)). For instance, in addition to the direct risk borne by investors exposed to stranded assets, financial assets can also suffer from the economic impacts of the transition triggered by a fall in corporate profits in different sectors that rely on stranded assets and (Caldecott (2017), Dietz et al (2016)). For jurisdictions where fossil fuel companies are state-owned (and therefore not valued by markets), the main financial impacts may only be indirect, eg through loss of revenues that could affect sovereign risk and/or GDP growth.

When mixing geographical with indirect impacts, it appears that stranding assets could have significant geopolitical repercussions and potentially deeply transform existing global value chains, but such considerations remain largely out of the scope of current assessments. For instance, the scenario developed by Mercure et al (2018) asks the question of how OPEC members would recycle their oil-related surpluses. Similarly, if all coal resources were to be stranded, the immediate impacts would fall significantly on China, which consumed 50% of the world's coal in 2018 (BP (2019)); yet this could also have system-wide impacts on global value chains, including potential sharp price increases in advanced economies.

Finally, estimating the value of stranded assets while relying on climate-economic models can lead to paradoxical assumptions. In particular, and as discussed in Chapter 3.2, some climate-economic models rely so much on negative emissions technologies and on carbon capture and storage (CCS) to meet the 1.5°C or 2°C targets that fossil fuels may no longer need to be stranded that rapidly. Under certain scenarios, these technologies can increase the remaining carbon budget to reach a 2°C world by up to 290% (Carbon Brief (2018)). This poses the question of the technological assumptions supporting each assessment of stranded assets and for transition risks in general, as discussed in this chapter.

3.1 Climate-economic models versus deep uncertainty – an overview

The very first step in conducting a scenario analysis is to determine a narrative of how climate and socioeconomic factors will interact, so that they can be translated into a sectoral and firm-level scenario. For instance, to embed a climate-related shock into existing stress test methodologies (see Borio et al (2014)), the first step is to assess how such a shock would impact the economy (eg through variables such as GDP or interest rates), which in turn translates into impacts to the financial system. In the case of transition risks, some critical elements of the narrative of a scenario refer to:

- What climate target is sought: as of today, most transition scenarios rely on limiting global warming to 2°C above pre-industrial temperatures by 2100, but more scenarios based on a 1.5°C limit may emerge as this latter target is increasingly understood as the more "acceptable" upper limit (eg IPCC (2018));

– When mitigation measures start (eg immediately and relatively smoothly, or with delay and more abruptly) and over which time horizon they take place;

– What kind of "shock" is applied: for instance a policy shock (such as a carbon tax, but other regulations can also be used) or a technological shock (eg a technological breakthrough leading to declining cost of renewable energy, or on the contrary a situation where substitution between carbon-intensive and low-carbon technologies is limited).

These initial inputs can then be translated into macroeconomic and/or sectoral outputs. In order to do this, most methodologies rely on climate-economic models such as Integrated Assessment Models (IAMs). For instance, Oliver Wyman's (2019) and Carbon Delta's (2019)[21] respective transition scenarios apply data from IAMs such as REMIND[22], GCAM[23] and IMAGE[24], and Battiston (2019) relies on IAMs to conduct system-wide climate stress tests.

IAMs cover a great range of methodological approaches and sectoral and regional disaggregation, but at their core they generally combine a climate science module linking greenhouse gas (GHG) emissions to temperature increases, and an economic module linking increases in temperatures to economic and policy outcomes. Some key variables serve to link the climate and economic modules, such as: the accumulation of GHGs in the atmosphere; the evolution of mean temperatures; a measure of well-being (GDP); a damage function linking increases in global temperatures to losses in GDP; and a cost function generated by the policies aimed at reducing GHG emissions (eg a carbon tax).

Although IAMs are used by the UN Intergovernmental Panel on Climate Change (IPCC)[25] to explore some of the relationships between society and the natural world, their limitations with regard to economic modelling are increasingly recognised. In particular, critical assumptions about the damage functions (impacts of climate change on the economy) and discount rates (how to adjust for climate-related risk) have been subject to numerous debates (Ackerman et al (2009), Pindyck (2013), Stern (2016)), as further discussed below. Other oft-mentioned limitations include: the absence of an endogenous evolution of the structures of production[26] (Acemoğlu et al (2012, 2015), Pottier et al (2014)); the choice of general equilibrium models with unrealistic assumptions on well-functioning capital markets and rational expectations (Keen (2019)); the emphasis on relatively smooth transitions to a low-carbon economy and the quick return to steady state following a climate shock (Campiglio et al (2018)); and the suppression of the critical role of financial markets (Espagne (2018); Mercure et al (2019)).

---

[21] See www.carbon-delta.com/climate-value-at-risk/.

[22] REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows for the analysis of technology options and policy proposals for climate mitigation. The REMIND model was developed by the Potsdam Institute for Climate Impact Research (PIK). www.pik-potsdam.de/research/transformation-pathways/models/remind/remind.

[23] The Global Change Assessment Model (GCAM) is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations and accelerated deployment of energy technology. The Joint Global Change Research Institute (JGCRI) is the home and primary development institution for GCAM. jgcri.github.io/gcam-doc/v4.2/.

[24] IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The IMAGE modelling framework has been developed by the IMAGE team under the authority of PBL Netherlands Environmental Assessment Agency. models.pbl.nl/image/index.php/Welcome_to_IMAGE_3.0_Documentation.

[25] The IPCC is composed of three working groups. Working Group I assesses scientific aspects of the climate system and climate change; Working Group II assesses the vulnerabilities of socioeconomic and natural systems to climate change, as well as their consequences and adaptation options; Working Group III assesses the options for limiting greenhouse gas emissions and mitigating climate change.

[26] It should be noted that some IAMs feature endogenous technological change (IPCC (2014, p 423)).

For all these reasons, it is increasingly recognised that "today's macroeconomic models may not be able to accurately predict the economic and financial impact of climate change" (NGFS (2019a, p 4), Weyant (2017)). This does not mean that IAMs and climate-economic models in general are not useful for specific purposes and under specific conditions (Espagne (2018)). In particular, a new wave of models embracing uncertainty and complexity seems better able to account for heterogeneity and nonlinearities, as well as for cascade effects, policy path dependency and interactions between macroeconomic and financial dynamics (see Dafermos et al (2017), Espagne (2017), Mercure et al (2019), Monasterolo et al (2019)). The central bank community could gain from exploring these new modelling approaches, as discussed in Chapter 3.5.

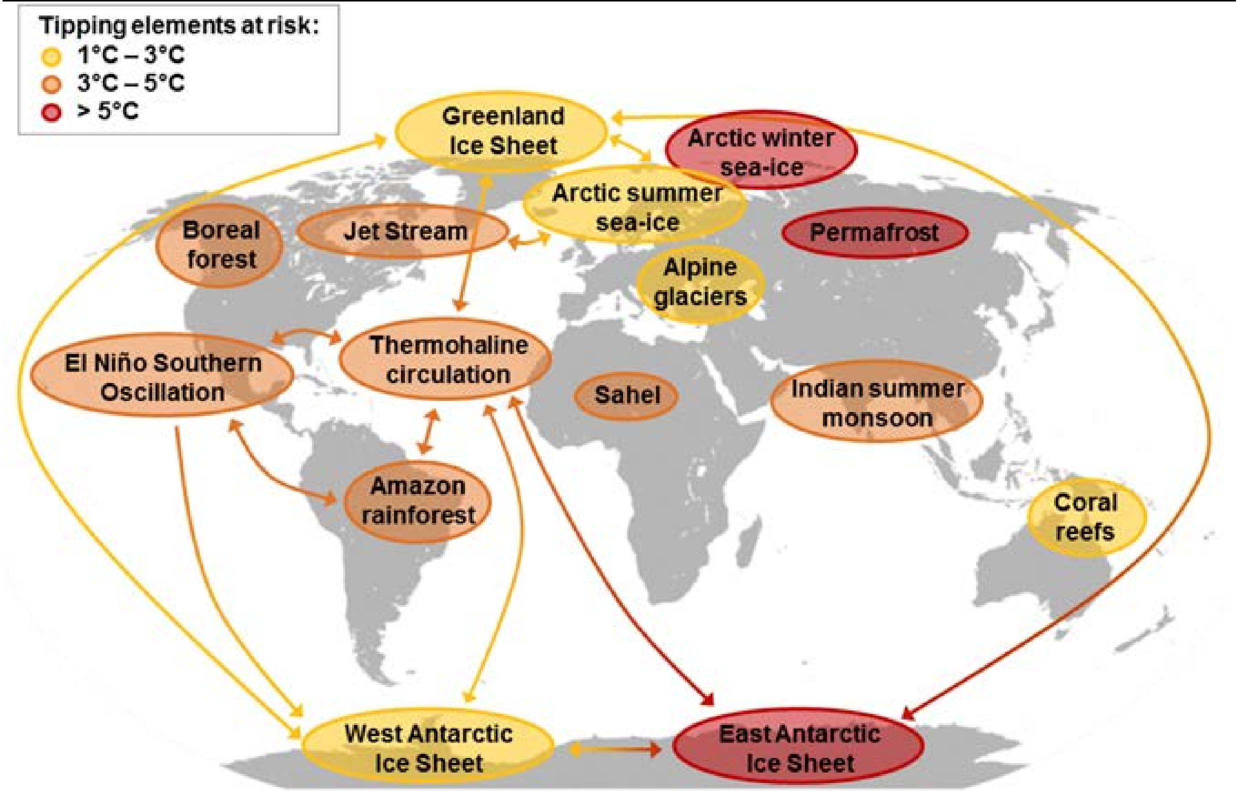
Nevertheless, the deep uncertainty related to physical and transition risks means that both the neoclassical approach of most IAMs and alternative approaches such as demand-led and non-equilibrium models will remain unable to capture many forces triggered by climate change. A corollary is that the outcomes of such models should be interpreted cautiously by both financial practitioners and financial regulators and supervisors. Some of the key sources of uncertainty with respect to climate-related physical and transition risks are outlined below and further detailed in Annexes 1 and 2.

With regard to physical risks (see Annex 1), some of the main sources of modelling uncertainty relate to the following features:

- Deep uncertainty exists with regard to the biogeochemical processes potentially triggered by climate change. Climate scientists have shown not only that tipping points exist but remain difficult to estimate with precision, but also that they could generate tipping cascades on other biogeochemical processes, as shown in Graph 8 below. Evidence is now mounting that tipping points in the Earth system such as the loss of the Amazon forest or the West Antarctic ice sheet could occur more rapidly than was thought (Lenton et al (2019));
- The impacts of such biogeochemical processes on socioeconomic systems can be highly nonlinear, meaning that small changes in one part of the system can lead to large changes elsewhere in the system (Smith (2014)) and to chaotic dynamics that become impossible to model with high levels of confidence. For instance, it seems that climate change will mostly impact developing economies, which could increase global inequality (Diffenbaugh and Burke (2019)) and generate mass migrations and conflicts (Abel et al (2019), Bamber et al (2019), Kelley et al (2015)). These could have major implications for development across the world (Human Rights Council (2019)) but their probability of occurrence and degrees of impact remain largely impossible to appropriately integrate into existing models. However, advanced economies are not exempt from significant impacts either. For instance, Dantec and Roux (2019) assess how climate change may affect different French territories and demand multiple adaptation strategies in areas such as urban planning, water management or agricultural practices;
- In the light of these considerations, it has been argued that the damage functions used by IAMs are unable to account for the tail risks related to climate change (Calel et al (2015)), and in some cases lead studies to suggest "optimal" warming scenarios that would actually correspond to catastrophic conditions for the future of human and non-human life on Earth: for instance, while DICE (Dynamic Integrated Climate-Economy) modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)). Similarly, the social cost of carbon (which adds up in monetary terms all the costs and benefits of adding one additional tonne of CO_2), and the choice of a rate of discount of future damages can provide "almost any result one desires" (Pindyck (2013, p 5)) and lead to outcomes and policy recommendations that are "grossly misleading" (Stern (2016)). Climate modellers typically embrace uncertainty by showing the great range of outcomes that can result from a specific event or pattern (eg a specific CO_2 atmospheric concentration can translate into different increases in global temperature and different sea level rises, with respective confidence intervals),

but this dimension tends be lost in climate-economic models based on benefit-cost analysis (Giampietro et al (2013), Martin and Pindyck (2015)).

Global map of potential tipping cascades Graph 8



The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements that could generate cascades, based on expert elicitation.

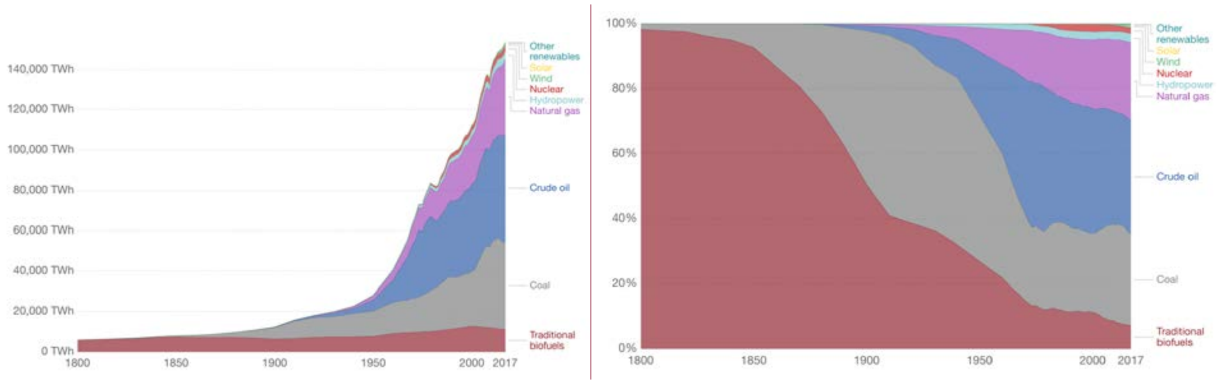
Source: Adapted from Steffen et al (2018).

With regard to transition risks (see Annex 2), one of the main sources of modelling uncertainty relates to the general use of economy-wide carbon prices as a proxy for climate policy in IAMs. This assumption tends to overlook many social and political forces that can influence the way the world evolves, as recognised by the IPCC itself (IPCC (2014, p 422)). As the history of energy and social systems shows (Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)), the evolution of primary energy uses is deeply influenced by structural factors and requires deep transformations of existing socioeconomic systems (Graph 9, left-hand panel). Past transformations have responded to a variety of stimuli including relative prices but also many other considerations such as geopolitical (eg choice of nuclear energy by certain countries to guarantee energy independence) and institutional ones (eg proactive policies supporting urban sprawl and its related automobile dependency). Attempts to reverse these inertias through pricing mechanisms alone could be insufficient.

Moreover, all major energy transitions in the past (Graph 9, right-hand panel) have taken the form of energy additions in absolute terms (Graph 9, left-hand panel). That is, they were energy additions more than energy transitions. For instance, biomass (in green) has decreased in relative terms but not in absolute terms. This highlights the sobering reality that achieving a low-carbon transition in a smooth manner represents an unprecedented challenge with system-wide implications. With this in mind, estimating the social cost of carbon with confidence is all the more difficult "due to considerable uncertainties […] and [results that] depend on a large number of normative and empirical assumptions that are not known with any certainty" (IPCC (2007, p 173)).

Evolution of energy systems, in absolute and relative terms

Graph 9



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

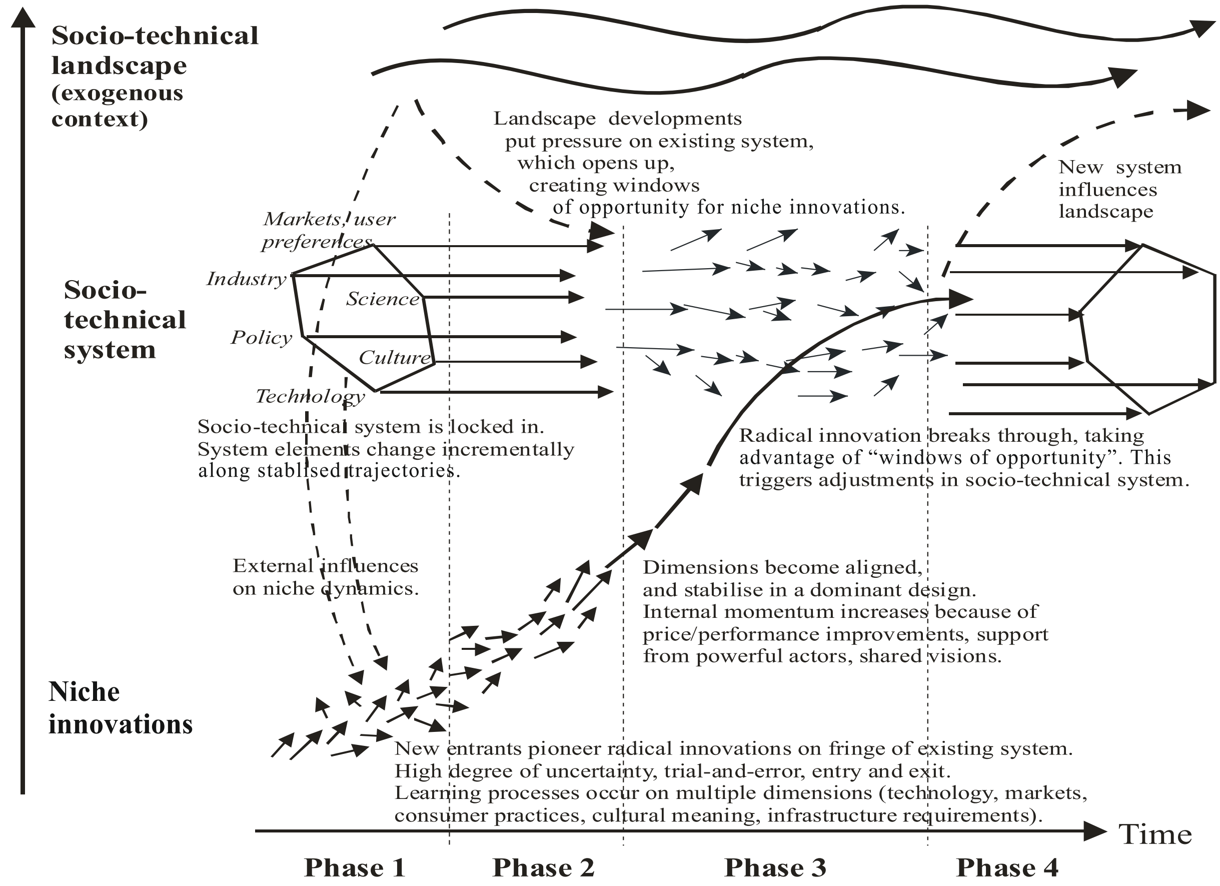
To account for this complexity, transdisciplinary approaches around concepts such as socio-technical systems and transitions (Geels et al (2017)) seem more appropriate to embrace the multiple dimensions involved in any climate change mitigation transition (Box 3). These approaches are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011, pp 356–7)). In particular, socio-technical transition scholars provide a framework for more sophisticated qualitative and quantitative approaches to three parameters that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

In short, the physical and transition risks of climate change are subject to multiple forces (natural, technological, societal, regulatory and cultural, among others) that interact with each other and are subject to uncertainty, irreversibility, nonlinearity and fat-tailed distributions. Moreover, physical and transition risks will increasingly interact with each other, potentially generating new cascade effects that are not yet accounted for (Annex 3).

In the rest of this chapter, we discuss how to go beyond the limitations of climate-economic models as discussed above to better assess climate-related risks, especially with regard to: (i) the choice of scenarios regarding how technologies, policies, behaviours, and macroeconomic – and even geopolitical – dynamics will interact in the future (Chapter 3.2); (ii) the translation of such scenarios into granular sectoral and corporate metrics in an evolving environment where all firms and value chains will be impacted in unpredictable ways (Chapter 3.3); and (iii) the matching of climate-related risk assessments with appropriate financial decision-making (Chapter 3.4). One key finding is that alternative approaches are needed to fully embrace the uncertainty and the need for structural transformation at stake (Chapter 3.5).

Phases of transformations of existing socio-technical systems

Graph 10



Source: Adapted from Geels et al (2017).

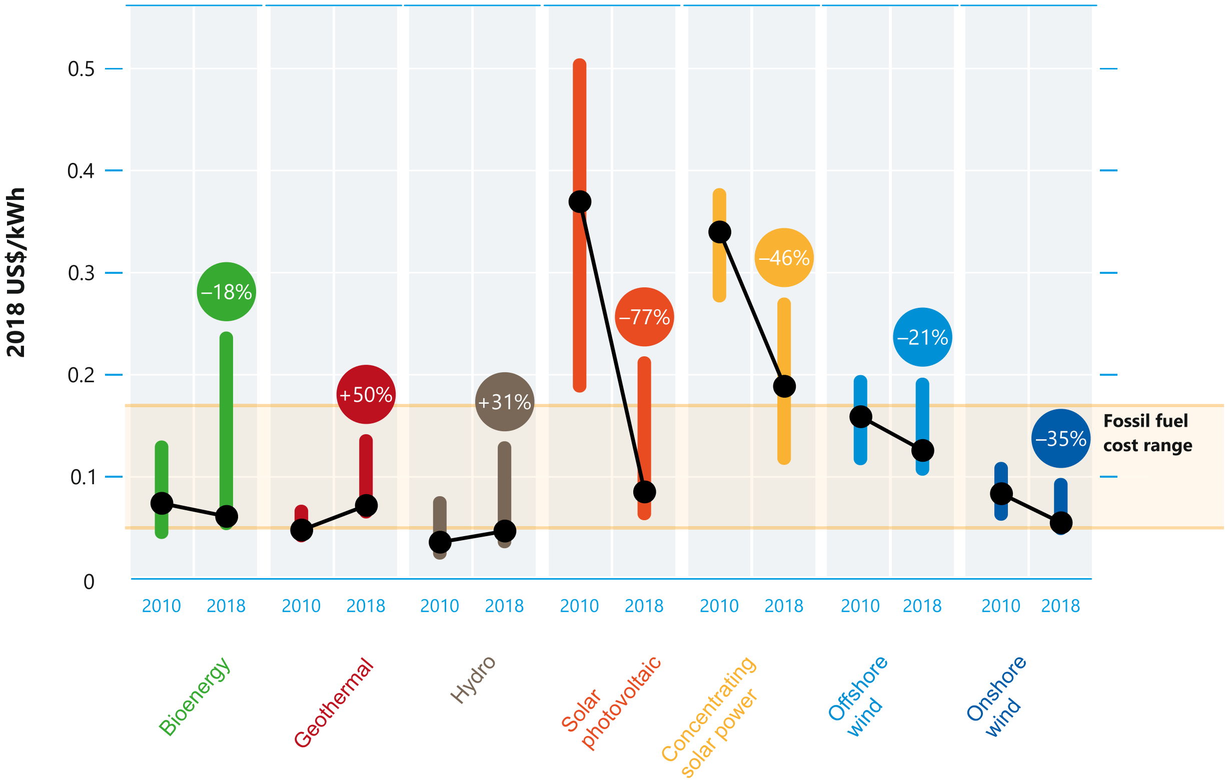
Box 3: A multi-layered perspective on socio-technical transition

Multi-layered perspectives on socio-technical transition can provide a framework for more sophisticated qualitative and quantitative approaches to the interactions between three layers that are essential to a low-carbon transition: technological niches, socio-technical regime, and socio-technical landscape (Graph 10).

First, technological niches and innovations will, unsurprisingly, be a key parameter of a successful transition. Yet their representation in existing models fails to reflect the unpredictable and disruptive nature of technological innovations. As an example, the sharp increase of usage and cost variation in many renewable energy technologies over the past few years (Graph 3.A) has outpaced most predictions, and this seems to have responded more to massive investments in R&D and targeted subsidies to solar energy than to any ambitious carbon pricing mechanism (Zenghelis (2019)). In contrast, the intermittency of renewable energy remains a considerable problem that tends to be overlooked (Moriarty and Honnery (2016), Smil (2017a)). Moreover, other sectors may be impossible to decarbonise in the medium term regardless of carbon pricing, as we can observe (so far) not only with aviation or cement, but also with parts of the energy sector. In short, the type of technological solution that will prevail in a low-carbon world is largely unpredictable. A case in point is the transportation sector: the most promising technological alternatives have varied greatly over short time horizons (Graph 3.B) and with new technologies such as hydrogen fuel (Morris et al (2019), Li (2019), Xin (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

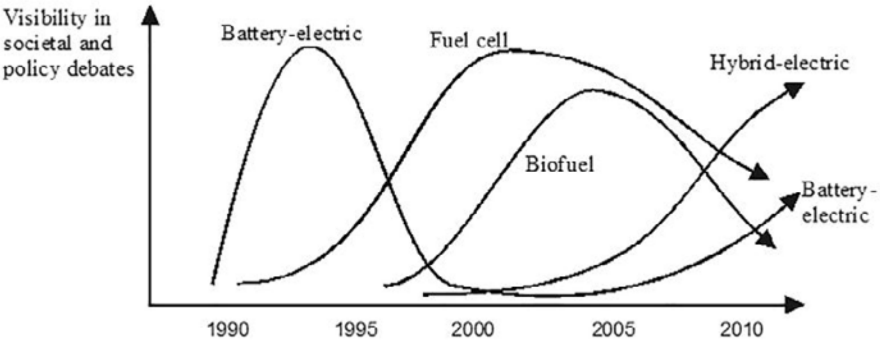
Graph 3.A



Source: UNEP (2019).

Changes in visibility of transportation technologies through time

Graph 3.B



Source: Geels et al (2017).

Second, the successful implementation of technologies does not depend only on their relative prices but also on the so-called socio-technical regimes in which they operate, ie the rules and norms guiding the use of particular technologies. For instance, once car-based transportation systems are set up in a city or country, they largely become self-sustaining "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017, p 465)). Although pricing mechanisms can surely contribute to overcoming this institutional inertia, other regulations may be needed such as rules on the weight of new cars (to avoid rebound effects[27]) and proactive support to the development of public transportation to limit the number of personal vehicles. More broadly, some solutions may depend not on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)), along with positive impacts for the national rail operator (Henley (2019)), are responses to a "Greta Thunberg effect" rather than a technological breakthrough.

Third, technological, behavioural and regulatory changes do not take place in a vacuum but in specific socio-technical landscapes, ie in contexts comprising "both slow-changing trends (eg demographics, ideology, spatial structures, geopolitics) and exogenous shocks (eg wars, economic crises, major accidents, political upheavals)" (Geels et al (2017, p 465)). In other words, assessing specific transition paths requires integrating many real-world considerations into the scope of the analysis, which is particularly difficult for modellers whose objective is precisely to simplify the representation of the world for reasons of tractability. Some features of the current "socio-technical landscape" that will prove essential to consider for the transition (further developed in Annex 2) include:

- A rather weakened multilateral order that is an important barrier to address the multiple trade-offs that a global low-carbon transition will generate. For instance, stranding fossil fuels may require the United States and Canada to immediately stop extracting unconventional oil, with potentially significant impacts on the output of their national economies (Mercure et al (2018)). Similarly, as China consumed half of the world's coal in 2018 (BP (2019)) and Asia has accounted for 90% of new coal plants over the past two decades (IEA (2019)), stranding such assets could have major impacts on global value chains, for example with sharp increases in the price of imports for advanced economies, sharp decreases in corporate profits in Asia, and potential relocations of certain economic activities. These could have significant implications for global imbalances. With this in mind, aiming to strand these assets rapidly and in a fair manner would probably require unprecedented international cooperation, including significant compensation mechanisms for countries that do not exploit fossil fuel reserves. However, past experiences such as the Yasuni-ITT initiative in Ecuador show the difficulty of reaching agreements on compensation for not polluting (Martin and Scholz (2014), Warnars (2010)). Finally, a low-carbon transition could trigger new geopolitical tensions and potential conflicts, including conflicts related to the quest for resources needed for renewable energy (IRENA (2019), Pitron (2018)). Hence, existing models still have a long way to go to account for the international political economy of climate change and for the principle of "common but differentiated responsibilities" enshrined in international climate negotiations (UNFCCC (2015)).
- Significant transformations of market economies have taken place over the past decades, including a decrease in growth rates in advanced economies but also at the global level (despite rapid growth in emerging and developing economies). Discussions are under way about the causes of this slowdown (eg a new "secular stagnation", whether structural and possibly related to a long-term decline in productivity (Gordon (2012)), or a more conjunctural slowdown in aggregate demand that can be addressed by new macroeconomic policies). Other transformations include a shift in corporate governance towards maximisation of shareholder value and short-termism (Mazzucato (2015)) and increased inequalities within nations (Piketty (2014)) despite a relative decrease in inequalities among nations (Milanovic (2016)). These features pose significant questions such as the social acceptability of a low-carbon transition. For

---

[27] In energy economics, rebound effects occur when initial energy efficiency gains are cancelled out by behavioural or systemic responses, for instance if a consumer uses the financial gains from increased housing energy efficiency to set higher temperatures or to increase energy use elsewhere. As a concrete example, increases in cars' energy efficiency over the past few years have been offset by the fact that households are buying larger cars and that the number of passengers per car is decreasing (IEA (2019)).

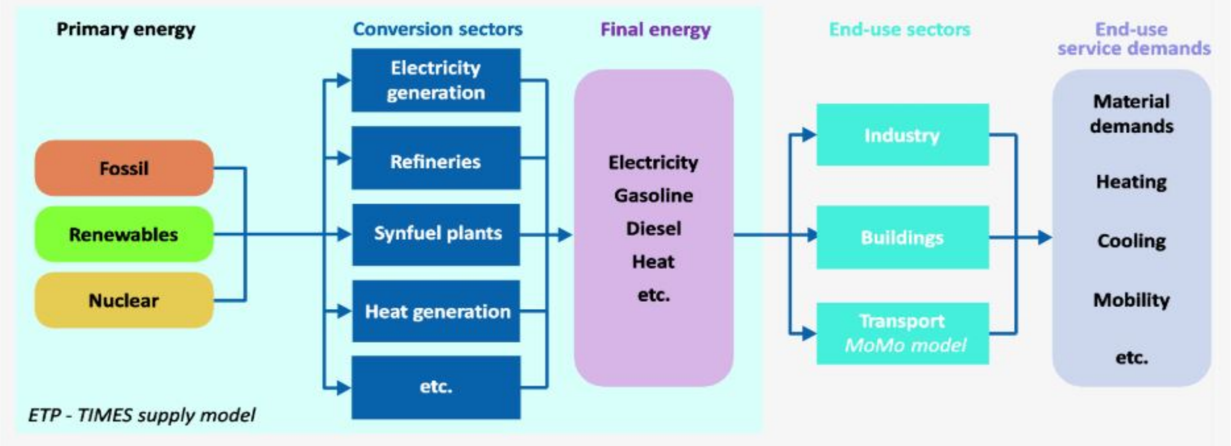
instance, given that such a transition requires "intensive public discussion" (Stern (2008, p 33)), it is unclear whether mechanisms such as revenue-neutral carbon taxes will be sufficient. Some argue that if inequalities were lower in the first place, it could become easier to reach consensus on difficult topics such as the burden-sharing efforts to mitigate and adapt to climate change (Chancel (2017), Otto et al (2019)). That is, without suggesting an optimal specific path, climate change needs to be considered as being embedded in a myriad of real-world socioeconomic challenges, not as an ad hoc challenge that should simply not interfere with other challenges.

3.2 Climate-related uncertainties and the choice of scenarios

Forward-looking approaches that are built around an IAM inevitably inherit all the limitations of the climate-economic models mentioned in the previous chapter. Here we focus mostly on technological uncertainties, given the difficulty of accounting for the other sources of uncertainty discussed above (eg international political economy uncertainties associated with the transition). It should also be noted that some methodology providers do not rely on IAMs but rather on "technologically-based" models. For instance, the ET Risk Project,[28] developed by a consortium of stakeholders, uses scenarios provided by the International Energy Agency (IEA) and adapts these based on bottom-up market analyses. The IEA produces scenarios on the development of energy technologies and the investments needed to upscale them under different climate pathways and policy tracks (regulations, carbon pricing, etc).[29] For instance, the IEA's 2017 *Energy Technology Perspectives* (ETP) report (Graph 11) seeks to offer a "technology-rich, bottom-up analysis of the global energy system" (IEA (2017)).

Structure of the ETP model

Graph 11



Source: IEA (2017). All rights reserved.

---

[28] http://et-risk.eu/.

[29] These include a "Current Policies Scenario" akin to a "business as usual" setup, a "New Policies Scenario" focused on the Nationally Determined Contributions (NDCs) set by each country following the Paris Agreement (UNFCCC (2015)), and a more ambitious "Sustainable Development Scenario".

Whether they rely on IAMs or "technology-based" models, it is critical to assess which choices inform the selected technological pathway (eg development of carbon capture and storage (CCS) technologies, nuclear energy, price of renewable energy, gains obtained from energy efficiency, etc) as these strongly determine which sectors and companies could benefit from it. However, the representation of clean technology diffusion rates in energy-systems models is inherently subject to much uncertainty (Barreto and Kemp (2008)). Some scenarios rely on the rapid development of existing technologies to respond to increasing demand for energy (eg IEA (2017)), while others focus on the potential reduction in energy demand to be achieved through energy efficiency and modification of existing behaviours (eg Negawatt (2018)). Other technology-based scenarios include BP's Rapid transition scenario, IRENA's REmap scenario, Greenpeace's Advanced Energy Revolution scenario (for a comprehensive review of scenarios, see Colin et al (2019), The Shift Project and IFPEN (2019)) or, with a different approach, the Science-Based Targets Initiative.[30]

An important source of technological uncertainty has to do with the role allocated to negative emissions and to CCS technologies.[31] Their relative importance varies widely across models: in a subset of 2°C scenarios, between 400 and 1,600 gigatonnes of carbon dioxide ($GtCO_2$) can be compensated through negative emissions and CCS, corresponding to 10–40 years of current emissions (Carbon Brief (2018)). This increases the size of the remaining carbon budget by between 72 and 290%, compared to scenarios where negative emissions and CCS do not occur. In practice, however, significant uncertainty exists with regard to CCS technologies due to technological constraints, potentially high costs and environmental and health risks (IPCC (2014)).

As a result, a scenario with a large role for negative emissions and CCS will naturally reduce the amount of assets that are stranded (eg the GCAM model in the graph below, for a 2°C scenario), whereas a scenario with less room for negative emissions will require a more massive development of renewables (as in the MESSAGE, REMIND and WITCH models) or considerable improvements in energy efficiency (as in IMAGE). This means that the financial impacts of a specific financial portfolio will be entirely different depending on which scenario is chosen.

---

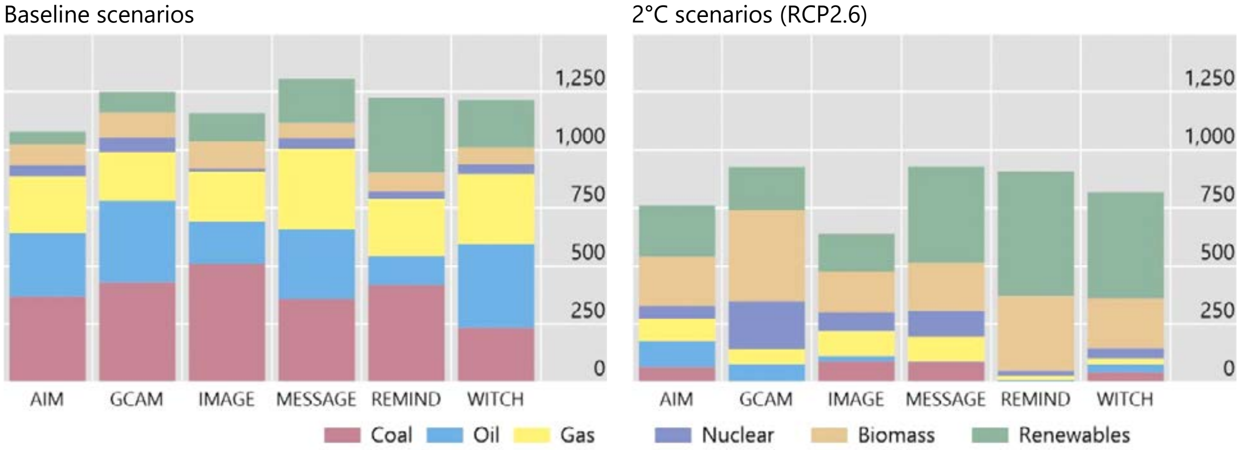
[30] The Science-Based Targets Initiative (sciencebasedtargets.org/) differs from the other listed scenarios. Instead of a comprehensive approach, it aims to provide companies with pathways to align their emissions to climate targets on a sectoral basis, based on current scientific knowledge.

[31] CCS is technically not a "negative emissions" technology since it does not remove CO_2 from the atmosphere, but stores new emissions instead. That is, it avoids new emissions but does not capture past emissions. CCS is usually included in the category of BECCS (bioenergy with carbon capture and storage).

The 2100 primary energy mix

Exajoules of primary energy

Graph 12



Baseline scenarios

2°C scenarios (RCP2.6)

The 2100 primary energy mix according to six IAMs, for SSP2 ("middle of the road") RCP2.6 scenarios. The energy mix in a "baseline" scenario is shown on the left, and scenarios that limit global warning to 2°C are shown on the right. Fossil fuel categories include CCS and non-CCS use.

Sources: Carbon Brief (2018); IIASA SSP Database.

Partially as a result of these sources of technological uncertainty, the volume of investments needed (a critical element to assess the risk and opportunities related to a low-carbon transition) can vary significantly. The survey of six models estimating the additional annual average energy-related investments needed to limit global warming to 1.5°C (over the period 2016 to 2050, compared to the baseline) finds significant variations, with values ranging from $150 billion ($2010) to $1,700 billion ($2010). Total investments (ie not just additional ones) in low-carbon energy also vary greatly, from $0.8 trillion ($2010) to $2.9 trillion ($2010; IPCC (2018, p 153)). Estimated needed investments vary even over shorter time horizons. For instance, global investments needed in sustainable infrastructure for the period 2015–30 range from less than $20 trillion to close to $100 trillion (Bhattacharya et al (2016, p 27)).

These estimates depend significantly on initial assumptions and methodological choices. For instance, in MESSAGE (the energy core of IIASA's[32] IAM framework), emissions-reduction investments occur in the models' regions and at the time they are cheapest to implement (assuming full temporal and spatial flexibility), based on the cost assumptions of 10 representative generation technologies (Zhou et al (2019)). In contrast, the New Climate Economy project estimates the investments needed in infrastructure by using existing technologies and investment patterns, assuming an exogenous growth rate of 3% and no productivity gains (Bhattacharya et al (2016)). Other assumptions are also critical, eg supply side investments could be lowered by up to 50% according to some studies if strong policies to limit energy demand growth are implemented (Grubler et al (2018), in IPCC (2018)).

Therefore, scenarios "should be considered illustrative and exploratory, rather than definitive [...]. It is important to remember that scenarios represent plausible future pathways under uncertainty. Scenarios are not associated with probabilities, nor do they represent a collectively exhaustive set of potential outcomes or actual forecasts" (Trucost ESG Analysis (2019, p 39)). Their "results are subject to a

---

[32] The International Institute for Applied Systems Analysis (IIASA)'s model is composed of five different models: the two most important that represent the energy system (MESSAGE) and land-use competition (GLOBIOM), and three that represent the macroeconomic system (MACRO), the climate system (MAGICC) and air pollution and GHG emissions (GAINS). The MESSAGE framework divides the world into 11 regions. For an overview, see: https://message.iiasa.ac.at/projects/global/en/latest/overview/index.html.

high degree of uncertainty" (Zhou et al (2019, p 3)) and cannot be allocated probabilities of occurrence, ie they should be assessed with extreme caution by finance supervisors engaged in financial stability monitoring.

3.3 Translating a climate-economic scenario into sector- and firm-level risk assessments

To incorporate climate-related risks into financial institutions' risk management procedures and financial stability monitoring, the main challenge to determining a reasonable scenario consists in translating it into granular metrics at the sector (see Box 4 below) and firm level. A firm-level assessment is critical as it can distinguish how firms with a similar exposure to climate scenarios have different adaptive capacities, making them more or less vulnerable. Indeed, the climate vulnerability of a firm does not depend only on its exposure to climate-related risks (which can be relatively similar for different firms in the same sector) but also on its sensitivity and its adaptive capacity to a specific scenario (eg its ability to develop new low-carbon technologies in response to climate-related risks, or to pass through additional costs to its suppliers or customers). For instance, two oil and gas companies may fall under the same industry classification but be exposed to transition risks in very different ways, depending on factors such as the likelihood of owning stranded assets (as discussed above) or their degree of diversification into renewable energy.

Box 4: The Netherlands Bank's climate stress test

The Netherlands Bank's methodology (Vermeulen et al (2018, 2019)) first defines climate scenarios and shocks (mostly via carbon taxes and technological development paths) based on literature and validated by experts (block I in figure below). The policy shock consists in the abrupt implementation of a \$100 carbon tax, and the technology shock in the rapid development of renewable energy, which leaves fossil fuel dependent technologies obsolete, resulting in capital stock write-offs. These shocks can be assessed separately or jointly (double shock); they can also lead to a negative confidence shock affecting the behaviour of consumers, producers and investors. These scenarios are translated into macroeconomic impacts on GDP, consumer prices, stock prices and interest rates through NiGEM (block II.a in Graph 4.A), a multi-country macroeconomic model. The central bank then estimates the vulnerability of each sector to transition risks, based on the embodied CO_2 emissions of 56 NACE industries[33] (ie including the emissions related to their value chain) weighted by their contribution to GDP (block II.b in the graph). The impact of the transition on each NACE industry is then connected to the national financial sector portfolios of corporate loans, bonds and equities (block III in the figure below). In the last step (block IV in Graph 4.A), the central bank calculates losses for financial institutions with the aid of traditional top-down approaches to stress testing. The results of the climate stress test indicate losses of up to 11% of assets for insurers and up to 3% for banks, potentially leading to a reduction of about 4 percentage points in Dutch banks' CET1 ratio[34].

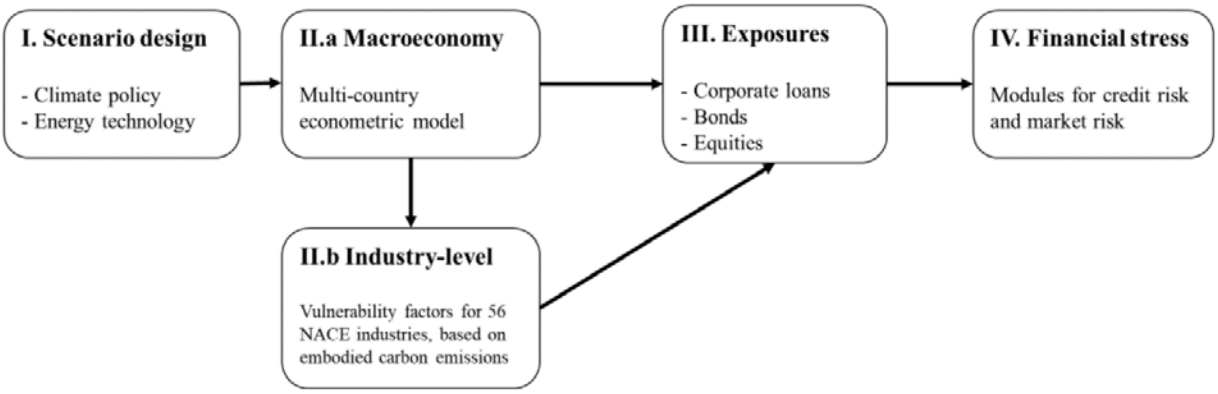
---

[33] NACE is the industry standard classification system used in the European Union.

[34] Common Equity Tier 1 (CET1) is a component of Tier 1 capital that consists mostly of common stock held by a bank or other financial institution. It is the highest quality of regulatory capital, as it absorbs losses immediately when they occur. See: https://www.bis.org/fsi/fsisummaries/defcap_b3.pdf.

Overview of the stress test framework

Graph 4.A

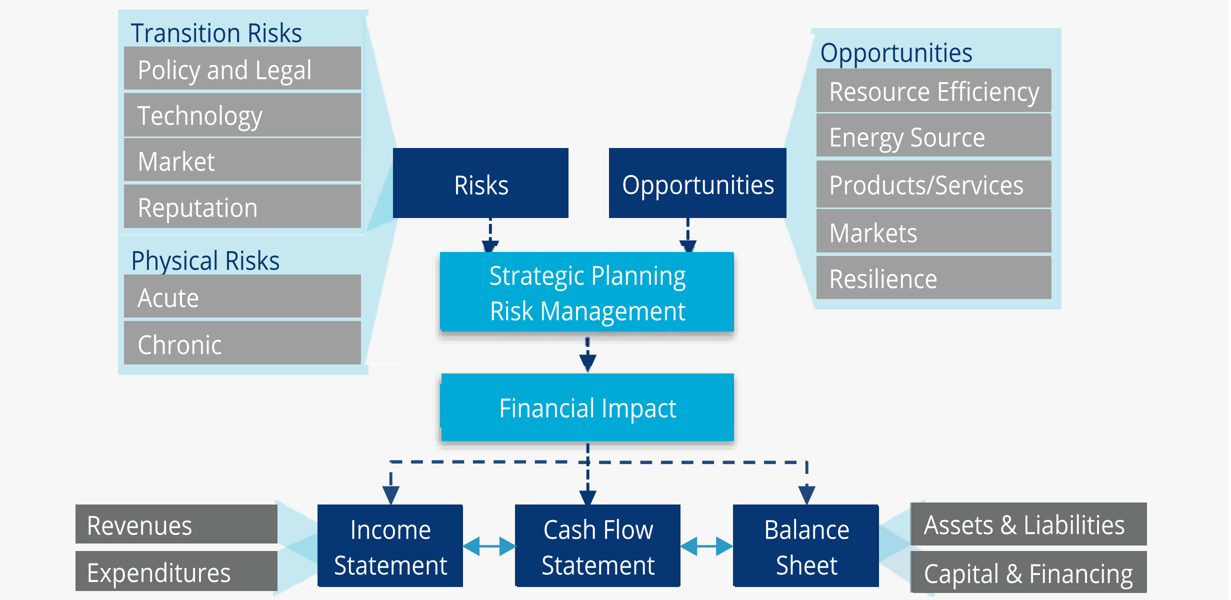


Source: Vermeulen et al (2019).

Climate change mitigation and adaptation also brings opportunities related to the development of low-carbon technologies and climate-friendly policies (see Graph 13), which are captured by several climate-related risk assessment methodologies (eg Mercer, Oliver Wyman and Carbon Delta). UNEP-FI (2019) estimates that profits generated by a 30,000-company universe in the transition to a 2°C world could amount to $2.1 trillion, although this number should be taken cautiously given the many sources of uncertainty discussed above. It is therefore important to assess how climate-related risks and opportunities will impact specific key performance indicators (KPIs) of a firm, such as its sales, operational and maintenance costs, capital expenditures, R&D expenditures, and potential impairment of fixed assets.

Climate-related risks, opportunities and financial impact

Graph 13



Source: TCFD (2017).

One of the main difficulties at this stage is determining how a firm is exposed to climate-related risks throughout its value chain. A firm can be exposed to these risks through: (i) direct, so-called "scope 1" emissions (particularly important in sectors such as mining, aviation or the chemical industry); (ii) indirect, so-called "scope 2" emissions resulting from purchased energy (eg real estate or energy-intensive industries); and (iii) other indirect emissions related to its entire upstream and downstream value chain, so-called "scope 3" emissions.[35] A case in point for scope 3 is the automotive industry, where the main exposure lies not so much with the sector's own emissions (scope 1) or its energy sources (scope 2), but with carbon combustion by end users (scope 3). For buildings, scope 3 emissions are twice as high as direct emissions (Hertwich and Wood (2018)). This is not to say that the emissions related to scopes 1, 2 and 3 are sufficient to assess the exposure of a firm. For instance, a firm with high emissions today could become decarbonised and seize many opportunities under specific transition paths. Still, focusing on scopes 1, 2 and 3 means that a comprehensive risk assessment should look at potential vulnerabilities throughout the entire value chain.

The assessment of a firm's exposure to its scope 1, 2 and 3 emissions and its translation into risk metrics can be conducted in quantitative or qualitative manners. The PACTA stress test model,[36] based on International Energy Agency (IEA) technological pathways up to 2050 compatible with a specific climate scenario (eg a 2°C or 1.75°C rise in temperatures) and on proprietary databases including existing investment plans at the firm level, determines how each firm within specific sectors may become aligned or misaligned with the scenario. This insight then informs a delayed stress test tool that calculates shocks based on alternative cash flows, discounted in a valuation or credit risk model. The assessment of the risk materiality by sector is a key dimension of this methodology, which involves technological, market and policy considerations.

Another methodology, developed by Carbon Delta (2019), proceeds by breaking down each country's emission reduction pledge (as indicated by its Nationally Determined Contribution, or NDC) into sector-level targets, and then assigning emission reduction quantities to a firm's production facilities based on its emission profile within each sector, using a proprietary asset location database. The costs relative to the transition are then obtained by multiplying the required GHG reduction amount by the price per tonne of carbon dioxide (tCO_2) obtained via IAMs for the scenario under analysis (eg for a 3°C, 2°C and 1.5°C rise in temperatures). In order to estimate the revenues that each firm could obtain from a low-carbon transition, Carbon Delta (2019) uses a database covering millions of low-carbon patents granted by authorities worldwide, and a qualitative assessment of each low-carbon patent portfolio as a proxy for firms' adaptive capacity.

Other approaches rely more extensively on qualitative judgments regarding the adaptive capacity of firms in each sector. For instance, Oliver Wyman (2019) resorts to experts' judgments to forecast how specific companies in the portfolio may adapt to climate-related risks, although it also includes quantitative tools to estimate impacts of scenarios on prices, volumes, cost, impairment and capital expenditure of counterparties. Carbone 4's (2016) bottom-up assessment considers firms' adaptive capacities to a low-carbon transition, relying on a mix of qualitative and quantitative indicators such as the investments made in R&D and the CO_2 reduction objectives of the firm related to its scope 1, 2 and 3 emissions. Allianz Global Investor integrates technological, regulatory and physical considerations qualitatively into its asset allocation procedures (IIGCC (2018)).

---

[35] The GHG Protocol Corporate Standard classifies a company's GHG emissions into three "scopes". "Scope 1 emissions are direct emissions from owned or controlled sources. Scope 2 emissions are indirect emissions from the generation of purchased energy. Scope 3 emissions are all indirect emissions (not included in scope 2) that occur in the value chain of the reporting company, including both upstream and downstream emissions." Source: ghgprotocol.org/sites/default/files/standards_supporting/FAQ.pdf.

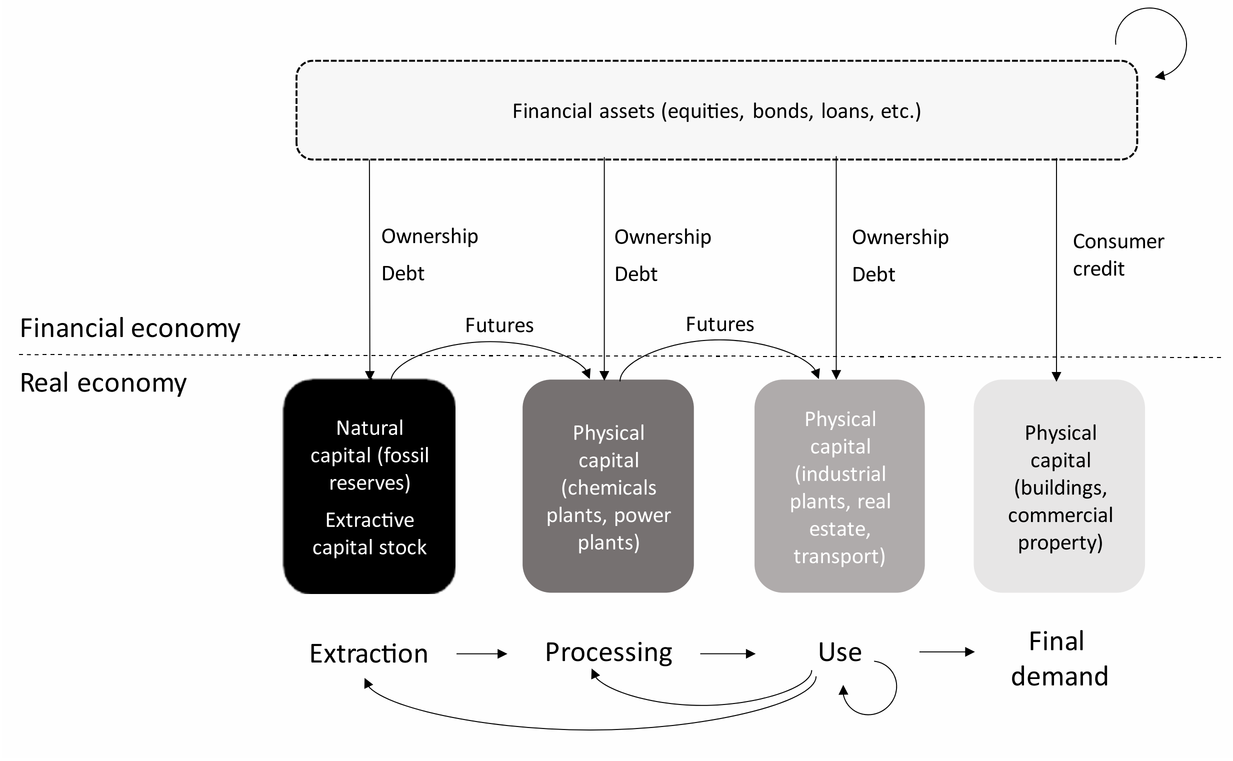
[36] www.transitionmonitor.com/.

Other approaches have also emerged to better account for the indirect exposures to climate-related risks, without necessarily relying on scopes 1, 2 and 3. For instance, Battiston et al (2017) classify economic activities into six sectors (fossil-fuel, utility, energy intensive, transportation, housing, and finance) and twenty subsectors based on their relative vulnerability to climate transition risks (as a function of their emissions). They further map out the exposure of financial institutions (through equity and debt) to these different sectors, which enables them to capture potential knock-on effects within financial networks. When applying a sectoral shock (eg a carbon tax), the firms in sectors that have not adapted their business model to the energy transition face increased costs and reduced revenues, whereas the firms that have invested in alternative technologies are able to increase their profits. This methodology can be applied to the financial system as a whole or to specific financial institutions (Battiston et al (2017)), and to different asset classes such as equity, corporate and sovereign bonds (Battiston and Monasterolo (2019)), while capturing second-round effects related to the holding of financial assets.

Another way of estimating indirect exposures is to look at production networks, as suggested by Cahen-Fourot et al (2019a,b). Using input-output tables for 10 European economies and based on the monetary value of productive capital stocks (Cahen-Fourot et al (2019b)), the authors seek to provide a systemic perspective on how the reduction in production in one sector can cascade to physical stocks supporting the rest of the economic activity through chains of intermediate exchange. That is, as physical inputs stop flowing from one sector to another, more sectors along value chains are also impacted. For instance, the mining and quarrying sector (including the extraction of fossil fuels), although it accounts for a relatively low share of value added, tends to provide crucial inputs for many other downstream economic activities such as construction, electricity and gas, coke and refined petroleum products or land transport; in turn, these sectors are critical for the correct functioning of public administration, machinery and equipment and real estate activities; and so on. In short, stranding an asset in one specific sector can trigger a "cascade of stranded assets" affecting many other sectors of the economy.

While these two approaches bring critical insights into the interconnectedness among sectors and potential transmission channels of transition shocks and could greatly benefit from being combined (see Graph 14), applying them to future scenarios is not without its challenges. Indeed, relying on existing sectoral classifications and interconnections cannot be assumed to serve as a good proxy for future interconnectedness, given the need to change the very productive structures of the economy. In this sense, they are probably more tailored to the conduct of a climate stress test with a relatively short-term horizon (assuming a static portfolio) than as a tool to be used by financial institutions in a dynamic environment.

Natural, physical and financial assets at risk of stranding Graph 14



Source: Campiglio et al (2017).

Regardless of the approach chosen, some critical sources of uncertainty to keep in mind when conducting forward-looking risk assessments concern the ability to predict:

- *The development and diffusion of new technologies*: As new technologies that do not yet exist or are not yet widespread appear and scale up, they may reshape existing market structures in unpredictable ways. For instance, wholesale online distribution would have been unpredictable a few decades ago. With this in mind, it is difficult to predict how a specific firm will perform in a new environment that will be determined not only by its own strategy but also by multiple elements in its value chain;
- *Each firm's market power:* In response to climate regulations, some firms may be able to offset an increase in operating costs through their customers (by increasing final prices) or suppliers (by decreasing purchasing prices), while others may not have this market power. For instance, after the introduction of the EU Emissions Trading Scheme (ETS) in 2005, some electricity generators were able to pass through more than 100% of the cost increase to consumers (UNEP-FI (2019)). Determining each firm's market position and power and its related pass-through capacity in a dynamic environment remains a considerable task. Some methodologies (eg Oliver Wyman) aim to assess firms' ability to withstand a decrease in demand due to possible product substitutions and cost pass-through (based among other things on the estimated price elasticity of demand); others examine the adaptive capacity of firms based on the potential development of low-carbon and emissions abatement technologies (eg Carbone 4; ET Risk).

– *The exposure to liability risks that have not yet arisen:* Existing methodologies focus on physical and transition risks, but liability risks[37] may become increasingly important in the future. A case in point is PG&E (Baker and Roston (2019), Gold (2019)), the owner of California's largest electric utility, which filed for bankruptcy in early 2019 after wildfire victims sued the company for failing to adjust its grid to the risks posed by increasingly drier climate conditions. Several legal actions against energy and oil and gas companies (eg Drugmand (2019)) are also under way, often brought by cities or civil society organisations seeking compensation for climate-related disasters or the non-compliance of their business plans with the Paris Agreement (Mark (2018)). These examples show how in the future, firms may be exposed not only to the physical and transition risks of climate change, but also to legal risks. However, assessing liability risks is a major challenge not only because of their inherent uncertainty (eg predicting which lawsuits will be triggered by future uncertain events) but also because of variations in the legal framework of each jurisdiction. For instance, in some jurisdictions the government acts as reinsurer "of last resort" in the case of natural disasters; in this case the risks end up being borne by the government rather than the firm or insurer.

Overall, the outcomes provided by each methodology are therefore highly sensitive to the ways in which they account for specific scenarios and how they translate them into static or dynamic corporate metrics that take into account the scope 1, 2 and 3 emissions. Although the lack of data is commonly and rightly invoked as a barrier to the development of climate-related risk assessment, it is also important to emphasise that bridging the data gap will not fully "resolve" the sources of uncertainty discussed above.

3.4 From climate-related risk identification to a comprehensive assessment of financial risk

Once a scenario has been translated into specific metrics at the firm or sector level, there remains the challenging task of integrating such an analysis into a financial institution's internal risk management procedures/a supervisor's practices. In this respect, some methodologies provide a scorecard or climate risk rating and estimates of the carbon impact of a portfolio (eg Carbone 4). Other methodologies aim to calculate the specific impact on asset pricing or credit risks, for instance through the concept of climate value-at-risk (climate VaR), which compares a climate disaster scenario to a baseline scenario. For instance, Carbon Delta estimates future cash flows generated by each firm and discounts them to measure current values that can inform credit risk models (eg a Merton model).

Regardless of the method chosen, at least three main methodological challenges should be kept in mind when conducting such an exercise.

First, it is possible for investors to see the long-term risks posed by climate change, while remaining exposed to fossil fuels in the short term (Christophers (2019)), especially if they believe that hard regulations will not be put in place anytime soon. The identification of the risk is one thing; mitigation is entirely another. For instance, Lenton et al (2019) find that the emergency to act is not only a factor of the risk at stake but also the urgency (defined as reaction time to an alert divided by the intervention time left to avoid a bad outcome). In other words, even identifying all the risks (if even possible) would not necessarily suffice to "break the tragedy of the horizon". Accordingly, new approaches to risk such as MinMax rules (Battiston (2019)), where the economic agent takes a decision based on the goal of minimising losses (or future regrets) in a worst case scenario, may be needed. Other approaches to risk management such as real option analyses, adaptation pathways or robust decision analysis are also already used for specific projects such as infrastructure and large industrial projects (Dépoues et al (2019)).

---

[37] As described by Carney (2015): "the impacts that could arise tomorrow if parties who have suffered loss or damage from the effects of climate change seek compensation from those they hold responsible". It should be noted that in some approaches (eg TCFD (2017)), "legal" risks (which share similar features with liability risks) are captured under physical and/or transition risks.

However, there are no indications that financial institutions would naturally choose this approach (except in specific cases such as project finance), and it is unclear how regulators could promote its use by financial institutions. In other words, the question of how to adjust risk modelling approaches to allow for longer time horizons remains a challenging one (Cleary (2019, p 28)).

Second, it is possible for financial institutions to hedge individually against climate change, without reducing the exposure of the system as a whole as long as system-wide action is not taken. For instance, Kling et al (2018) find that climate-vulnerable countries exhibit a higher cost of debt on average. This means that as markets hedge against climate-related risks by increasing risk premiums, the risk is transferred to other players such as climate-vulnerable sovereigns, which also happen to be poorer countries on average. Carney (2015) had also noted that insurers' rational responses to physical risks can paradoxically trigger new risks: for instance, storm patterns in the Caribbean have left many households unable to get private cover, prompting "mortgage lending to dry up, values to collapse and neighbourhoods to become abandoned" (Carney (2015, p 6)). Another risk may have to do with the development of financial products in response to climate-related risks, such as weather derivatives: these may help individual institutions hedge against specific climate-related risks, but they can also amplify systemic risk (NGFS (2019b, p 14)). In short, reckoning climate-related risks can lead financial institutions to take rational actions that, while hedging them individually from a specific shock, do not hedge against the systemic risks posed by climate change. For central banks, regulators and supervisors, this poses difficult questions, such as the adequate prudential regulation that should be deployed in response.

Third, in order to fully appreciate the potential systemic dimension of "green swan" events or "climate Minsky moments", more work is still needed on how a climate-related asset price shock (eg stranded assets) could trigger other losses within a dynamic financial network, including contagion effects towards non-climate-related sectors. The 2007–08 Great Financial Crisis has shown how a shock in one sector, subprime mortgages, can result in multiple shocks in different regions and sectors with little direct exposure to subprimes (for instance, affecting German Landesbanken and southern Europe's banking systems and sovereign credit risks). In this respect, abrupt shifts in market sentiment related to climate change could affect all players, including those who were hedged against specific climate-related risks (Reynolds (2015)).

These challenges go a long way towards explaining the "cognitive dissonance" (Lepetit (2019)) between the increased acceptance of the materiality of climate-related risks by financial institutions, and the relative weakness of their actions in response. In short, accounting for the multiple transmission channels of climate-related risks across firms, sectors and financial contracts while reflecting a structural change of economic structures remains a task filled with uncertainty. As a result, the question of how much asset values are affected and how much credit ratings should be impacted today in the face of future uncertain events remains unclear for deeper reasons than purely methodological ones. Despite these limitations, scenario-based analysis will remain critical for financial and non-financial firms aiming to increase their chances of adapting to future risks. That is, these methodological obstacles should not be a pretext for inaction, since climate-related risks remain real.

3.5 From climate-related risk to fully embracing climate uncertainty – towards a second "epistemological break"

The previous analyses have highlighted that regardless of the approach taken, the essential step of measuring climate-related risks presents significant methodological challenges related to: (i) the inability of macroeconomic and climate scenarios to holistically capture a large range of climate, social and economic factors; (ii) their translation into corporate metrics within a dynamic economic environment; and (iii) the difficulty of matching the identification of a climate-related risk with the adequate mitigation action. Climate-economic models and forward-looking risk analysis are important and can still be improved, but they will not suffice to provide all the information required to hedge against "green swan" events.

As a result of these limitations, two main avenues of action have been proposed. We argue that they should be pursued in parallel rather than in an exclusive manner. First, central banks and supervisors could explore different approaches that can better account for the uncertain and nonlinear features of climate-related risks. Three particular research avenues (see Box 5 below) consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels. Nevertheless, the descriptive and normative power of these alternative approaches remain limited by the sources of deep and radical uncertainty related to climate change discussed above. That is, the catalytic power of scenario-based analysis, even when grounded in approaches such as non-equilibrium models, will not be sufficient to guide decision-making towards a low-carbon transition.

As a result of this, the second avenue from the perspective of maintaining system stability consists in "going beyond models" and in developing more holistic approaches that can better embrace the deep or radical uncertainty of climate change as well as the need for system-wide action (Aglietta and Espagne (2016), Barmes (2019), Chenet et al (2019a), Ryan-Collins (2019), Svartzman et al (2019)). The concept of "risk" refers to something that has a calculable probability, whereas uncertainty refers to the possibility of outcomes that do not lend themselves to probability measurement (Knight (2009) [1921], Keynes (1936)), such as "green swan" events. The question of decision-making under deep or radical uncertainty is making a comeback following the 2007–08 Great Financial Crisis (Webb et al (2017)). According to former governor of the Bank of England Mervyn King, embracing radical uncertainty requires people to overcome the belief that "uncertainty can be confined to the mathematical manipulation of known probabilities" (King (2017, p 87)) with alternative and often qualitative strategies aimed at strengthening the resilience and robustness of the system (see also Kay and King (2020)).

As such, a second "epistemological break" is needed to approach the role of central banks, regulators and supervisors in the face of deep or radical uncertainty. This demands a move from an epistemological position of risk management to one that seeks to build the resilience of complex adaptive systems that will be impacted in one way or another by climate change. What should then be the role of central banks, regulators and supervisors in this approach? In the next chapter, we argue that the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within an institutional environment involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a more systematic integration of sustainability considerations into financial and economic decision-making.

Box 5: New approaches for forward-looking risk management: non-equilibrium models, sensitivity analysis and case studies

In order to better account for the specific features of climate-related risks (deep uncertainty, nonlinearity, multiple and complex transmission channels within and among transition and physical risks, etc), three complementary research avenues seem particularly promising. They consist in: (i) working with non-equilibrium models; (ii) conducting sensitivity analyses; and (iii) conducting case studies focusing on specific risks and/or transmission channels.

Non-equilibrium models:

Mercure et al (2019) find that "equilibrium" and "non-equilibrium" models tend to yield opposite conclusions regarding the economic impacts of climate policies. Equilibrium models (such as DSGE) remain the most widely used for climate policy, yet their central assumption that prices coordinate the actions of all agents (under constrained optimisation) so as to equilibrate markets for production factors fails to represent transition patterns (including some discussed above) in a consistent manner.

In this context, non-equilibrium models may be better positioned to address three critical features of the transition:

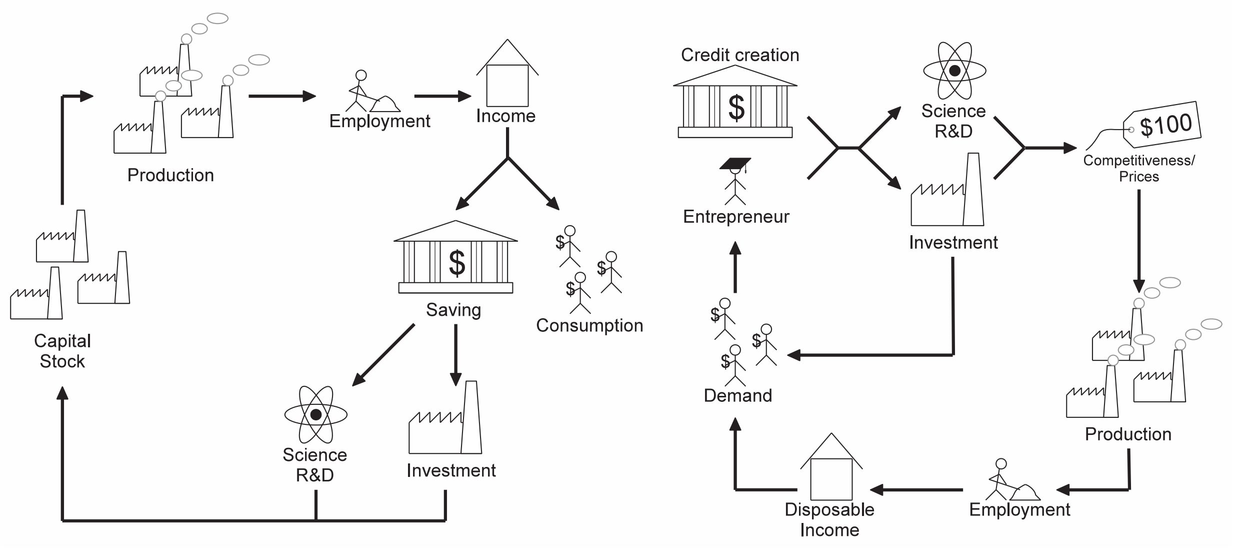
1. Path dependency: in non-equilibrium models, the state of the economy depends on its state in previous time steps. This approach seems particularly aligned with the purpose of scenario analysis, consisting as it does in describing the economy under different possible and diverging circumstances that are dependent on past and present decisions. For instance, it is easier to represent how socio-technical inertia shapes current behaviours, beyond and despite pricing mechanisms.

2. Role of money and finance: the need to better account for the dynamics of the financial sector has been widely discussed after the 2007–08 Great Financial Crisis, yet the discussion has only slightly permeated the field of climate economics so far (Mercure et al (2019)). A more central role is often attributed to finance in non-equilibrium models, particularly in the post-Keynesian school of thought through stock-flow consistent models: money is created by banks in response to demand for loans, and therefore investments are not constrained by existing savings (Graph 5.A). This may better represent the behavioural dynamics of financial institutions than DSGE (Dafermos et al (2017)), especially when merged with agent-based models (Monasterolo et al (2019)). For instance, financial institutions can expand lending and investments in times of economic optimism and restrict them when the perceived risk of default is too high, including because of climate-related issues.

3. Role of energy: standard economic theory, based on the cost share of energy in GDP, implies that a decrease in energy use reduces GDP but only to a limited extent. For instance, as energy costs typically represent less than 10% of GDP, a 10% reduction in energy use would lead to a loss in GDP of less than 1% (Batten (2018, p 28)). However, a growing literature suggests that the role of energy in production should not be treated as a third input independently from labour and capital (as in three-factor Cobb-Douglas production functions) but through a different "epistemological perspective" (Keen et al (2019)): energy is an input to labour and capital, without which production becomes impossible (Ayres (2016)). In this view, an improvement in energy efficiency may paradoxically lead (all other things being equal) to a sharp decrease in GDP. Given the critical role of energy for the transition, non-equilibrium models that can account for the peculiar role of energy in economics (Ayres (2016), Keen et al (2019), The Shift Project and IFPEN (2019)) may be critical for future scenario-based analysis.

Alternative models

Graph 5.A



Supply-led / Equilibrium

Demand-led / Non-equilibrium

Source: Mercure et al (2019).

Sensitivity analysis:

Conducting relatively simple scenario-based risk assessments, also called sensitivity analyses, may be another approach to capture some features of climate-related risks, especially transition risks. Sensitivity analyses "represent a fast and easy method for assessing the sensitivity of a portfolio to a given risk" (DG Treasury et al (2017, p 67)) and they do not need to rely on complex scenarios. The methodological difficulties related to scenario-based models "argue in favor of sensitivity analyses that measure the impact of a shock without necessarily incorporating it into a comprehensive scenario" (DG Treasury et al (2017, p 6)).

An example of such sensitivity analysis is ICBC (2016): the bank subjected firms in two sectors of its portfolio, thermal power and cement, to a selection of heavy, medium and light environmental stresses (tighter atmospheric pollution emissions limits for thermal power; tighter atmospheric pollutant emissions and discharges for cement). The test was carried out assuming that all other things remain equal, ie without factoring in the macroeconomic effects of such measures (eg carbon leakage to neighbouring countries). It estimated:

– The impacts of these regulatory shocks on the firms' costs, prices and quantity sold under each scenario;

– How credit ratings would be impacted;

– The possible changes in the firm credit rating and probability of default, and derived the change in the non-performing loan (NPL) ratio.

The recent climate stress test conducted by the UK's Prudential Regulation Authority (PRA (2019a)) takes a similar approach. The PRA translated three broad categories of climate scenarios (sudden and disorderly transition; progressive and orderly transition; no transition) into impacts on the asset side of insurance companies' balance sheets by applying a negative shock to the value of some companies they have in their investment portfolios. For instance, as part of the sudden and disorderly scenario (see Scenario A in Table 5.A), general insurance companies are required to simulate the impact of a valuation shock on their power generation firms (–65% for the coal sector, –35% for oil, –20% for gas, and +10% for renewable energy). Different shocks are applied to several sectors, such as fuel extraction (see below) but also transport, utilities, agriculture and real estate.

The PRA recognises that "the development of hypothetical values affecting investments are based on the interpretation of available literature by the PRA and discussions with specialists in the field" (PRA (2019a, p 50)), including several of the methodologies mentioned above. That is, the valuation shocks correspond to a coherent narrative aimed at signalling potential risks to financial institutions, rather than an attempt at precise modelling of the valuation shock.

Sensitivity analysis

Table 5.A

Sector	**% of investment portfolio in following sectors**	**Assumptions**	**Transition risk**			**Physical risk**		
			Scenario			**Scenario**		
			A	**B**	**C**	**A**	**B**	**C**
Fuel extraction	Gas/coal/oil (incl crude)	Change in equity value for sections of the investment portfolio comprising material exposure to the energy sector as below						
		Coal	–45%	–40%				
		Oil	–42%	–38%				
		Gas	–25%	–15%				
							–5%	–20%
Power generation		Coal	–65%	–55%				
		Oil	–35%	–30%				
		Gas	–20%	–15%				
		Renewables (incl nuclear)	+10%	+20%				
							–5%	–20%

Source: PRA (2019a).

Case studies:

A third avenue for forward-looking analyses in the presence of climate uncertainty consists in assessing the potential impacts of a climate-related transition or physical shock on one specific sector or region. This can provide a level of analysis that stands in between scenario analysis (which lacks granularity and suffers from many sources of uncertainty) and sensitivity analysis (which lacks a systemic view).

Along these lines, Huxham et al (2019) assess the transition risks for the South African economy in a scenario consistent with temperature rises well below 2°C above pre-industrial levels, by examining potential impacts of a reduction in demand and price of energy sources such as coal (which provides 91% of South African electricity and significantly contributes to the country's export revenues). For instance, infrastructure that supports carbon-intensive activities such as power plants and port infrastructure may have to be replaced or retired early, companies (assessed on an individual basis) and investors could be hurt and could lay off workers, leading to reduced demand for certain products. Governments could face lower tax revenues while also having to deal with increasing expenditures related to industries and workers in transition.

One advantage of such studies is that they can explore the vulnerability of firms and sovereigns to potential economic policies within a limited perimeter, which enables greater transparency regarding the assumptions made and greater detail in the narratives chosen. For instance, the South African case study considers the impact of government policies shifting fiscal incentives from climate-vulnerable sectors to low-carbon activities, and the support from international development finance institutions in this process.

4. POLICY RESPONSES – CENTRAL BANKS AS COORDINATING AGENTS IN THE AGE OF CLIMATE UNCERTAINTY

Rien n'est plus puissant qu'une idée dont l'heure est venue ("There is nothing more powerful than an idea whose time has come").

Attributed to Victor Hugo

Acknowledging the limitations of risk-based approaches and embracing the deep uncertainty at stake suggests that central banks may inevitably be led into uncharted waters in the age of climate change. On the one hand, they cannot resort to simply measuring risks (hoping that this will catalyse sufficient action from all players) and wait for other government agencies to jump into action: this could expose central banks to the real risk that they will not be able to deliver on their mandates of financial and price stability. In the worst case scenario, central banks may have to intervene as climate rescuers of last resort or as some sort of collective insurer for climate damages. For example, a new financial crisis caused by such "green swan" events severely affecting the financial health of the banking and insurance sectors could put central banks under pressure to buy their large set of assets devalued by physical or transition impacts.

But there is a key difference from an ordinary financial crisis, because the accumulation of atmospheric CO_2 beyond certain thresholds can lead to irreversible impacts, meaning that the biophysical causes of the crisis will be difficult if not impossible to undo at a later stage. While banks in financial distress in an ordinary crisis can be resolved, this will be far more difficult in the case of economies that are no longer viable because of climate change. A potential intervention as climate rescuer of last resort would then expose in a painful manner the limited substitutability between financial and natural capital, and therefore affect the credibility of central banks.

On the other hand, central banks cannot succumb to the growing social demand arguing that, given the severity of climate-related risks and the role played by central banks following the 2007–08 Great Financial Crisis, central banks could now substitute for many (if not all) government interventions. For instance, pressures have grown to have central banks engage in different versions of "green quantitative easing" in order to "solve" the complex socioeconomic problems related to a low-carbon transition. However, the proactive use of central bank balance sheets is highly politically controversial and would at the very least require rethinking the role of central banks with a historical perspective. Goodhart (2010) argues that central banks have had changing functional roles throughout history, alternating between price stability, financial stability and support of the State's financing in times of crisis. Central bankers in advanced economies have grounded their actions around the first role (price stability) over the past decades, and increasingly around the second role (financial stability) since the 2007–08 Great Financial Crisis. Proposals concerning "green quantitative easing" could be seen as an attempt to define a third role through a more explicit and active support of green fiscal policy.

Without denying the reality of evolutionary perspectives on central banking (eg Aglietta et al (2016), Goodhart (2010), Johnson (2016), Monnet (2014)) and the fact that climate change could perhaps be the catalyst of new evolutions, the focus on central banks as the main agents of the transition is risky for many reasons, including potential market distortions and the risk of overburdening central banks' existing mandates (Villeroy de Galhau (2019a), Weidmann (2019)). More fundamentally, mandates can evolve but these changes in mandates and institutional arrangements are also very complex issues because they require new sociopolitical equilibria, reputation and credibility. Central bankers are not elected officials and they should not replace or bypass the necessary debates in civil society (Volz (2017)). From a much more pragmatic perspective, mitigating climate change requires a combination of fiscal, industrial and land planning policies (to name just a few) on which central banks have no experience.

To overcome this deadlock, we advocate a third position: without aiming to replace policymakers and other institutions, central banks must also be more proactive in calling for broader and coordinated change, in order to continue fulfilling their own mandates of financial and price stability over longer time horizons than those traditionally considered. The risks posed by climate change offer central banks a special perspective that private players and policymakers cannot necessarily adopt given their respective interests and time horizons. In that context, central banks have an advantage in terms of proposing new policies associated with new actions, in order to contribute to the societal debates that are needed. We believe that they can best contribute to this task in a role that we call the five Cs: **c**ontribute to **c**oordination to **c**ombat **c**limate **c**hange. This coordinating role would require thinking concomitantly within three paradigmatic approaches to climate change and financial stability: the "risk", "time horizon" and "system resilience" approaches (see Table 3).

Embracing deep or radical uncertainty therefore calls for a second "epistemological break" to shift from a management of risks approach to one that seeks to assure the resilience of complex adaptive systems in the face of such uncertainty (Fath et al (2015), Schoon and van der Leeuw (2015)).[38] In this view, the current efforts aimed at measuring, managing and supervising climate-related risks will only make sense if they take place within a much broader evolution involving coordination with monetary and fiscal authorities, as well as broader societal changes such as a better integration of sustainability into financial and economic decision-making.

Importantly, central banks can engage in this debate not by stepping out of their role but precisely with the objective of preserving it. In other words, even though some of the actions required do not fall within the remit of central banks and supervisors, they are of direct interest to them insofar as they can enable them to fulfil their mandates in an era of climate-related uncertainty.

This chapter explores some potential actions that are needed precisely to preserve the mandate and credibility of central banks, regulators and supervisors in the long term. The purpose here is not to provide an optimal policy mix, but rather to contribute to the emerging field of climate and financial stability from the perspective of deep or radical uncertainty. We suggest two broad ranges of measures. First, as detailed in Chapter 4.1, we recall that central banks, supervisors and regulators have a role to play through prudential regulation related to their financial stability mandate. However, while assessing and supervising climate-related risks is essential, it should be part of a much broader political response aimed at eliminating the economy's dependence on carbon-intensive activities, where central banks cannot and should not become the only players to step forward.

We then suggest and critically discuss four non-exhaustive propositions[39] that could contribute to guaranteeing system resilience and therefore financial stability in the face of climate uncertainty: (i) Beyond climate-related risk management, central banks can themselves and through their relationship with their financial sectors proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance in order to "break the tragedy of the horizon" (Chapter 4.2); (ii) Better coordination of fiscal, monetary and prudential and carbon regulations is essential to successfully support an environmental transition, especially at the zero lower bound (Chapter 4.3); (iii) Increased international cooperation on environmental issues among monetary and financial authorities will be essential (Chapter 4.4); (iv) More systematic integration of climate and sustainability dimensions within corporate

---

[38] This system resilience view holds that: (i) new analytical frameworks are needed to represent the interactions between humans and their natural environment; (ii) these interactions need transdisciplinary approaches (rather than multidisciplinary ones where each discipline continues to adhere to its own views when approaching another discipline requiring a different paradigm); and (iii) open systems are generally not in equilibrium, ie their behaviour is adaptive and dependent upon multiple evolving interactions.

[39] In particular, "command and control" policies are not discussed (given that their implementation tends to depend on specific national and subnational factors), although they also probably have a critical role to play in the transition.

and national accounting frameworks can also help private and public players manage environmental risks (Chapter 4.5). Some potential obstacles related to each proposition are also discussed.

We do not touch on carbon pricing not because we think it is not important. On the contrary, we take it as given that higher and more extensive carbon pricing is an essential part of the policy mix going forward, and that it will become both more politically accepted and more economically efficient if the other measures outlined here are implemented.

The five Cs – contribute to coordination to combat climate change:
The "risk", "time horizon" and "system resilience" approaches

Table 3

<table>
<tr><th>Responsibilities
Paradigmatic approach to climate change</th><th>Measures to be considered[1] by central banks, regulators and supervisors</th><th>Measures to be implemented by other players[2] (government, private sector, civil society)</th></tr>
<tr><td>Identification and management of climate-related risks
>> Focus on risks</td><td>Integration of climate-related risks (given the availability of adequate forward-looking methodologies) into:
– Prudential regulation
– Financial stability monitoring</td><td>– Voluntary disclosure of climate-related risks by the private sector (TCFD)
– Mandatory disclosure of climate-related risks and other relevant information (eg French Article 173, taxonomy of "green" and "brown" activities)</td></tr>
<tr><td colspan="3">Limitations:
– Epistemological and methodological obstacles to the development of consistent scenarios at the macroeconomic, sectoral and infra-sectoral levels
– Climate-related risks will remain unhedgeable as long as system-wide transformations are not undertaken</td></tr>
<tr><td>Internalisation of externalities
>> Focus on time horizon</td><td>Promotion of long-termism as a tool to break the tragedy of the horizon, including by:
– Integrating ESG into central banks' own portfolios
– Exploring the potential impacts of sustainable approaches in the conduct of financial stability policies, when deemed compatible with existing mandates</td><td>– Carbon pricing
– Systematisation of ESG practices in the private sector</td></tr>
<tr><td colspan="3">Limitations:
– Central banks' isolated actions would be insufficient to reallocate capital at the speed and scale required, and could have unintended consequences
– Limits of carbon pricing and of internalisation of externalities in general: not sufficient to reverse existing inertia/generate the necessary structural transformation of the global socioeconomic system</td></tr>
</table>

Structural transformation towards an inclusive and low-carbon global economic system **>> Focus on resilience of complex adaptive systems in the face of uncertainty**	Acknowledgment of deep uncertainty and need for structural change to preserve long-term climate and financial stability, including by exploring: – “Green” monetary-fiscal-prudential coordination at the effective lower bound – The role of non-equilibrium models and qualitative approaches to better capture the complex and uncertain interactions between climate and socioeconomic systems – Potential reforms of the international monetary and financial system, grounded in the concept of climate and financial stability as interconnected public goods	– Green fiscal policy (enabled or facilitated by low interest rates) – Societal debates on the potential need to revisit policy mixes (fiscal-monetary-prudential) given the climate and broader ecological imperatives ahead – Integration of natural capital into national and corporate accounting systems – Integration of climate stability as a public good to be supported by the international monetary and financial system

[1] Considering these measures does not imply full support to their immediate implementation. Nuances and potential limitations are discussed in the book. [2] Measures deemed essential to achieve climate and financial stability, yet which lie beyond the scope of what central banks, regulators and supervisors can do.

Source: Authors’ elaboration.

4.1 Integrating climate-related risks into prudential supervision – insights and challenges

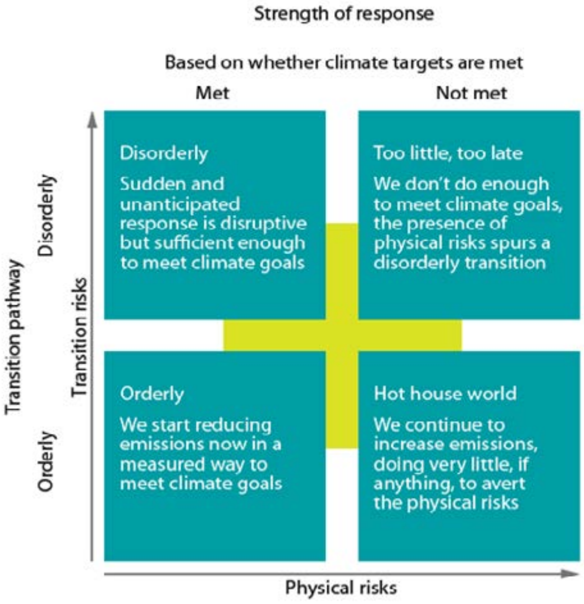
While acknowledging the methodological challenges associated with measuring climate-related risks and the need for alternative approaches (Chapter 3.5), central banks and supervisors should keep pushing for climate-related risks to be integrated into both financial stability monitoring and micro-supervision (NGFS (2019a, p 4)).

The first task, assessing the size of climate-related risks in the financial system, requires developing new analytical tools, for example by integrating climate scenarios into regular stress tests. In the same way that stress tests are conducted by regulatory authorities to assess the resilience of banking institutions in an adverse macro-financial scenario (Borio et al (2014)), proposals have been made over the past years to develop so-called “climate stress-tests” (eg ESRB (2016), Regelink et al (2017), Schoenmaker and Tilburg (2016), UNEP-FI (2019)). Some central banks, regulators and supervisors have already started to consider or develop climate risk scenario analyses for stress tests (Vermeulen et al (2018, 2019), EBA (2019), EIOPA (2019), PRA (2019a), Allen et al (2020)).

In practice, a stress test focusing on the physical risks of climate change (bottom-right scenario in Graph 15), which typically involves projections over several decades, seems particularly difficult to reconcile with the relatively short-term period considered under traditional stress tests (DG Treasury et al (2017, p 19)). In contrast, a climate stress test seems more adapted to manage abrupt transition risks (top-left scenario in Graph 15) that may occur over a relatively short-term horizon compatible with traditional stress tests.

In theory, if climate stress tests find that climate-related risks are material, systemic capital buffers could be applied to mitigate the exposure to climate-related risks (ESRB (2016)). In practice, the main use of these scenarios at this stage is to help financial institutions familiarise themselves with such exercises (Cleary (2019)) and to potentially create catalytic change as well as gaining experience through "learning by doing". A key task for supervisors is to establish a set of reference scenarios that could be used for climate stress tests, while identifying and disclosing the key sources of uncertainty attached to each scenario, as well as leaving flexibility for users to modify the assumptions and parameters of the scenario as deemed appropriate to their national and regional context.

Four representative high-level scenarios for climate stress tests Graph 15



Source: NGFS (2019a).

The second task for central banks and supervisors consists in ensuring that climate-related risks are well incorporated into individual financial institutions' strategies and risk management procedures. In addition to initiatives based on the voluntary disclosure of climate-related risks such as the Task Force on Climate-related Financial Disclosures (TCFD), it is increasingly accepted that mandatory disclosure should be implemented to strengthen and systematise the integration of climate-related risks. Financial institutions should better understand climate-related risks and consider them in their risk management procedures and investment decisions, as well as in their longer-term strategies (NGFS (2019a)).

Discussions have emerged with regard to how the three pillars of the Basel Framework could integrate climate-related risks:[40]

---

[40] In the absence of a carbon price, it has also been suggested that the structure of capital of non-financial firms could be adjusted to reflect their exposure to climate-related risks (ESRB (2016), Bolton and Samama (2012)). If both financial institutions and non-financial firms need to align their capital requirements to their exposure to climate-related risks, the cost of capital could increase for non-financial firms and lead financial firms to assess risks differently. However, such an idea would necessitate much more careful analysis and would not necessarily fall under the remit of central banks and supervisors.

- *Pillar 1 on minimum capital requirements:* If being exposed to climate-related risks is seen as part of financial risks, then it might be appropriate to consider capital requirements to reflect such risks. In this respect, proposals have emerged in favour of either a "green supporting factor" (which would reduce capital requirements for banks with lower exposure to climate-related risks) or a "brown penalising factor", which would increase capital requirements for banks with higher exposure to exposed sectors (Thöma and Hilke (2018)). Although additional research is needed, it seems that discussions are evolving towards favouring a "brown penalising factor" as more appropriate. Exposure to "brown" assets can increase financial risks, but it is not obvious why being exposed to "green" sectors would necessarily reduce non-climate-related financial risks, and thereby justify lower capital requirements. In any case, regulations based on distinguishing "green" from "brown" assets require working on an agreed upon "taxonomy", defining which assets can be considered "green" (or "brown" if the goal is to penalise exposure to fossil fuels). China has already established a definition for green loans and the European Commission has tabled a legislative proposal to develop such a taxonomy (NGFS (2019a)). It is noteworthy that such a classification is not exempt from conflicting views over what is "green" (Husson-Traoré (2019)), and that classifications could differ significantly from one country or region to another.[41] Even more fundamentally, it should be recalled that the "greenness" or "brownness" of assets do not necessarily correspond to their vulnerability to climate-related risks. For instance, "green" assets are subject to both transition risks (eg because of the technological and regulatory[42] uncertainty related to the transition) and physical risks (eg a renewable power plant could be impacted by extreme weather events);
- *Pillar 2 on the supervision of institutions' risk management:* Regulators could prescribe additional capital on a case by case basis, *for instance* if a financial institution does not adequately monitor and manage climate-related risks. This would first require new expectations to be set in this regard. For instance, banks and insurers in the United Kingdom are now required to allocate responsibility for identifying and managing climate-related risks to senior management functions (PRA (2019b)). And Brazil's central bank requires commercial banks to incorporate environmental risks into their governance framework (FEBRABAN (2014));
- *Pillar 3 on disclosure requirements:* Supervisory authorities can contribute to improving the pricing of climate-related risks and to a more efficient allocation of capital by requiring more systematised disclosure of climate-related risks. As indicated in the NGFS first comprehensive report, "authorities can set out their expectations when it comes to financial firms' transparency on climate-related issues" (NGFS (2019a, p 27)). For this to happen, guidance is needed to ensure a more systematic, consistent and transparent disclosure of climate-related risks. Some regulators and supervisors have already paved the way for such systematic disclosure. Article 173 of the French Law on Energy Transition for Green Growth (*loi relative à la transition énergétique pour la croissance verte,* 2015) requires financial and non-financial firms to disclose the climate-related risks they are exposed to and how they seek to manage them.[43] In doing so, Article 173 encourages financial sector firms to become increasingly aware of how climate change can affect

---

[41] For instance, "green coal" or nuclear energy are subject to diverging interpretations from one jurisdiction to another. Moreover, the fact that an activity is deemed "green" does not necessarily mean that it is less risky: as discussed in the previous chapter, the uncertainty regarding future technologies is such that some "green" sectors and technologies may not succeed in the transition. It is therefore important to keep in mind that taxonomies cannot replace or be conflated with a climate-related risk analysis, although the two topics are often discussed together.

[42] For instance, renewable energy capacity can be affected by a change in feed-in tariffs. "Feed-in tariff" refers to a policy instrument offering long-term contracts to renewable energy producers (households or businesses).

[43] Paragraph V of Article 173 requires banks to identify and disclose their climate-related risks and tasks the French government with providing guidance on the implementation of a scenario to conduct climate stress tests on a regular basis; paragraph VI requires institutional investors and asset managers to report on the integration of ESG (environmental, social and governance) criteria and climate-related risks into their investment decision processes (DG Treasury et al (2017)).

their risk management processes and supervising authorities to follow these developments closely (ACPR (2019)). And the European Commission has set up a Technical Expert Group (TEG) on sustainable finance that seeks, among other things, to provide guidance on how to improve corporate disclosure of climate-related risks (UNEP-FI (2019)).

Some developing and emerging economies have already started developing climate-related regulations (see D'Orazio and Popoyan (2019)), although no measures on capital requirements have yet been implemented. Different categories of intervention can be found across developing and emerging economies (Dikau and Ryan-Collins (2017)), such as credit guidance (Bezemer et al (2018)), which reflects the often broader mandate of central banks in these countries. For instance, commercial banks and non-bank financial institutions in Bangladesh are required to allocate 5% of their total loan portfolio to green sectors (Dikau and Ryan-Collins (2017)). Other countries such as China and Lebanon have established (or are in the process establishing) differentiated reserve requirements in proportion to local banks' lending to green sectors (D'Orazio and Popoyan (2019)).

The potential impacts of climate-related prudential regulation remain unclear. Most of the proposals discussed above remain subject to accurately assessing climate-related risks, as discussed in Chapter 3. More fundamentally, the role of prudential policy is to mitigate excessive financial risks on the level of individual financial institutions and the financial system as a whole, not to reconfigure the productive structures of the economy (ESRB (2016)); nevertheless, the latter is precisely what is needed to mitigate climate-related risks. The SME Supporting Factor introduced in the European Union in 2014 (reducing capital requirements for loans to small and medium-sized enterprises) does not seem to have generated major changes in bank lending to SMEs (EBA (2016), Mayordomo and Rodríguez-Moreno (2017)), although it demanded far less structural transformation than decarbonising our global economic system. Hence, adopting climate-related prudential regulations such as additional capital buffers may only very partially contribute to hedging financial institutions from "green swan" events.

Perhaps even more problematically, trade-offs could appear between short-term and long-term financial stability in the case of ambitious transition pathways. As stated by Bank of England Governor Mark Carney (Carney (2016)), the "paradox is that success is failure": extremely rapid and ambitious measures may be the most desirable from the point of view of climate change mitigation, but not from the perspective of financial stability over a short-term horizon. Minimising the occurrence of "green swan" events therefore requires a more holistic approach to climate-related risks, as discussed in the rest of this chapter.

4.2 Promoting sustainability as a tool to break the tragedy of the horizon – the role of values

Beyond approaches based strictly on risks, central banks and supervisors can help disseminate the adoption of so-called environmental, social and governance (ESG) standards in the financial sector, especially among pension funds and other asset managers.[44] The definition of ESG criteria and their integration into investment decisions can vary greatly from one institution to another, but it generally involves structuring a portfolio (of loans, bonds, equities, etc) in a way that aims to deliver a blend of financial, social and environmental benefits (Emerson and Freundlich (2012)). ESG-based asset allocation has grown steadily over the past years, and now funds that consider ESG in one form or another total $30.7 trillion of assets under management.[45]

[44] As stated by the NGFS, central banks and supervisors "may lead by example by integrating sustainable investment criteria into their portfolio management (pension funds, own accounts and foreign reserves), without prejudice to their mandates" (NGFS (2019a, p 28)).

[45] Estimated by the Global Sustainable Investment Alliance (2019).

Some central banks have also started to lead by example by integrating sustainability factors into their own portfolio management. For instance, the Banque de France and Netherlands Central Bank have adopted a Responsible Investment Charter for the management of own funds as well as pension portfolios, and are in the process of integrating ESG criteria into their asset management. Moreover, central banks are increasingly looking at "green" financial instruments as an additional tool for their foreign exchange (FX) reserve management. In a context of a prolonged period of low returns on the traditional safe assets (eg negative yields on a significant portion of government fixed income instruments), the requirements of liquidity, return and sustainability/safety need to be gauged against the properties of these new instruments. The eligibility of green bonds as a reserve asset will depend on several evolving factors such as their outstanding amount (still relatively small) and their risk-return profile. Fender et al (2019) suggest that the results of an illustrative portfolio construction exercise show that including both green and conventional bonds can help generate diversification benefits and hence improve the risk-adjusted returns of traditional government bond portfolios.

This being said, one should not confuse ESG- or green-tilted portfolios with hedging climate-related risks. As a general matter, ESG and green filters consider the impact of a firm on its environment rather than the potential impacts of climate change on the risk profile of the firm (UNEP-FI (2019)). Moreover, the integration of ESG metrics with pure risk-return considerations is far from straightforward. Some studies find that ESG and socially responsible investment (SRI) can enhance financial performance and/or reduce volatility (eg Friede et al (2015)), while others find that divesting from controversial stocks reduces financial performance (eg Trinks and Scholtens (2017)). Revelli and Viviani's (2015) meta-analysis of 85 papers finds that the consideration of sustainability criteria in stock market portfolios "is neither a weakness nor a strength compared with conventional investments", and that results vary considerably depending on the thematic approach or the investment horizon among other factors.

The main benefit of promoting a sustainable finance approach, including through ESG, may actually not lie in the greater impetus for asset managers to reduce their exposure to climate-related risks, but rather in broadening the set of values driving the financial sector. The financial industry has in recent decades mostly focused on financial risks and returns, and has often been criticised for its increased short-termism. By accepting potentially lower financial returns in the short run to ameliorate longer-term social and environmental results, time can be valued in a manner that better corresponds to environmental systems' "own patterns of time sequences for interactions among parts, abilities to absorb inputs, or produce more resources" (Fullwiler (2015, p 14)). This can promote long-termism in the financial sector and thereby contribute to overcoming the "tragedy of the horizon" (and therefore indirectly reduce climate-related risks). As such, the recent rise in the sustainable finance movement may offer "an opportunity to build a more general theory of finance" (Fullwiler (2015)) that would seek to balance risk-return considerations with longer-term social and environmental outcomes.

An additional ambitious and controversial proposal is to apply climate-related considerations to central banks' collateral framework. The goal of this proposal is not that central banks should step out of their traditional role when implementing monetary policies, but rather to recognise that the current implementation of market neutrality, because of its implicit bias in favour of carbon-intensive industries (Matikainen et al (2017), Jourdan and Kalinowski (2019)) could end up affecting central banks' very own mandates in the medium to long term. Honohan (2019) argues that central banks' independence will be more threatened by staying away from greening their interventions than by carefully paying attention to their secondary mandates such as climate change. Thus, and subject to safeguarding the ability to implement monetary policy, a sustainable tilt in the collateral framework could actually contribute to reducing financial risk, ie it would favour market neutrality over a longer time horizon (van Lerven and Ryan-Collins (2017)).

In this spirit, several proposals and initiatives have started to emerge. For instance, Monnin (2018) relies on a specific climate-related risks methodology to measure how the European Central Bank's corporate sector purchase programme (CSPP, which stood at €176 billion as of November 2018) could have differed from the current model if assessment of climate-related risks had been conducted. The study finds that about 5% of the issuers within the ECB's CSPP portfolio would fall out of the investment grade category if climate-related risks were factored in. The author suggests that the ECB could integrate such procedures not only into its unconventional monetary policies but also into its collateral framework. Following a simpler approach for the management of its FX reserves, the Swedish central bank recently decided to reject issuers with a "large climate footprint" (Flodén (2019)), for instance by selling bonds issued by a Canadian province and two Australian states.

Although legal opinions have yet to be issued on this matter, it appears that in many cases central banks already do have a legal mandate for considering the type of assets to use as collateral when implementing monetary policy. For instance, in the case of the Eurosystem the primary responsibility of central banks is to maintain price stability, with a secondary responsibility to support economic growth. In turn, the definition of economic growth by the European Union includes the sustainable development of Europe (Schoenmaker (2019)). The mandates of several central banks other than the ECB also include broader socioeconomic goals than price stability (Dikau and Volz (2019)).

However, the potential impact of such actions is still under debate and needs a cautious approach. It is true that a reweighting of eligible collateral towards low-carbon assets is likely to reduce the credit spread of newly eligible companies (Mésonnier et al (2017)) and to provide a powerful signalling effect to other financial market participants (Braun (2018), Schoenmaker (2019)). Nevertheless, the main challenge in the short run with regard to climate change is not the cost of credit of green projects but their insufficient number in the first place. It is therefore not entirely obvious how large an effect the greening of central banks' collateral framework could have. In fact, the ECB has already bought almost one quarter of the eligible public sector green bonds and one fifth of the eligible corporate green bonds (Cœuré (2018)). This may have already encouraged more issuers to sell green debt (Stubbington and Arnold (2019)), yet central bank monetary operations are clearly insufficient and do not even seek to trigger structural changes in the "real economy". Even if central bank actions could lead to downgrading of the price of carbon-intensive assets that are not compatible with a low-carbon trajectory, only climate policy can ensure that they simply disappear.

Governments could play a much more critical role in supporting sustainable investments. In this respect, it is noteworthy that the European Commission's (2018) action plan on sustainable finance also seeks to mainstream sustainability into investment decisions, and promote "long termism" among financial institutions. Many measures could be taken in this regard. For instance, the French Economic, Social and Environmental Council (ESEC (2019)) recommends that household savings should be channelled towards long-term sustainable investments through fiscal incentives (see also Aussilloux and Espagne (2017)). And Lepetit et al (2019) further recommend offering a public guarantee on all household savings channelled to long-term SRI vehicles (and certified as such). Therefore, even if investments in a low-carbon economy were to provide lower returns and/or returns over a longer time horizon than current market expectations (Grandjean and Martini (2016)), those could then be partially offset by a lower risk for households.

4.3 Coordinating prudential regulation and monetary policy with fiscal policy – Green New Deal and beyond

In addition to promoting sustainable investments, direct government expenditures will also be an opportunity to develop new technologies in a timely fashion and to regulate their use in ways that guarantee lower-carbon production and consumption patterns (eg by avoiding rebound effects in the transportation sector, as discussed above). This is not a reason for central banks not to address climate change; rather, it is a simple observation of the fact that fiscal policies are key to climate change mitigation and that prudential and monetary tools can only complement these policies (Krogstrup and Oman (2019)). Indeed, the public sector is usually in a better position to fund investments in R&D for early-stage technologies with uncertain and long-term returns. In a series of case studies across different sectors (eg nanotech and biotech), Mazzucato (2015) has shown how government investment in high-risk projects has proved essential to create the conditions for private investments to follow.

Sustainable public infrastructure investments are also fundamental as they lock in carbon emissions for a long time (Arezki et al (2016), Krogstrup and Oman (2019)). They can provide alternative means of production and consumption, which would then enable economic agents to change their behaviour more effectively in response to a carbon price (Fay et al (2015), Krogstrup and Oman (2019)). Indeed, carbon prices alone may not suffice to shift individual behaviour and firms' replacement of physical capital towards low-carbon alternatives until infrastructures suited for alternative energies are in place. For instance, building an efficient public transit system may be a precondition to effective taxation of individual car use in urban areas.

It is noteworthy that under this approach, government action would not seek to manage climate-related risks optimally but rather to steer markets "in broadly the right direction" (Ryan-Collins (2019)). In turn, such a proactive shift in policymaking could lead market players to reassess the risks related to climate change. Public investments in the low-carbon transition could "become the next big technological and market opportunity, stimulating and leading private and public investment" (Mazzucato and Perez (2015)), and potentially create millions of jobs that could compensate for those that might be lost due to the changes in labour markets caused by technological progress (Pereira da Silva (2019a)).

In spite of a rapidly growing literature pointing towards better coordination between fiscal, monetary and prudential regulation, arguments regarding the optimal climate policy mix remain scarce. However, and as a general matter, fiscal tools are critical to accelerate the transition, whereas prudential and monetary tools can mostly support and complement them (Krogstrup and Oman (2019)). Public banks may also have an important role to play in providing a significant part of the long-term funding needed for the transition (Aglietta and Espagne (2016), Campiglio (2016), Marois and Güngen (2019)). In this regard, the European Investment Bank (EIB (2019)) announcement that it will cease financing fossil fuel energy projects by the end of 2021 could be a major landmark.

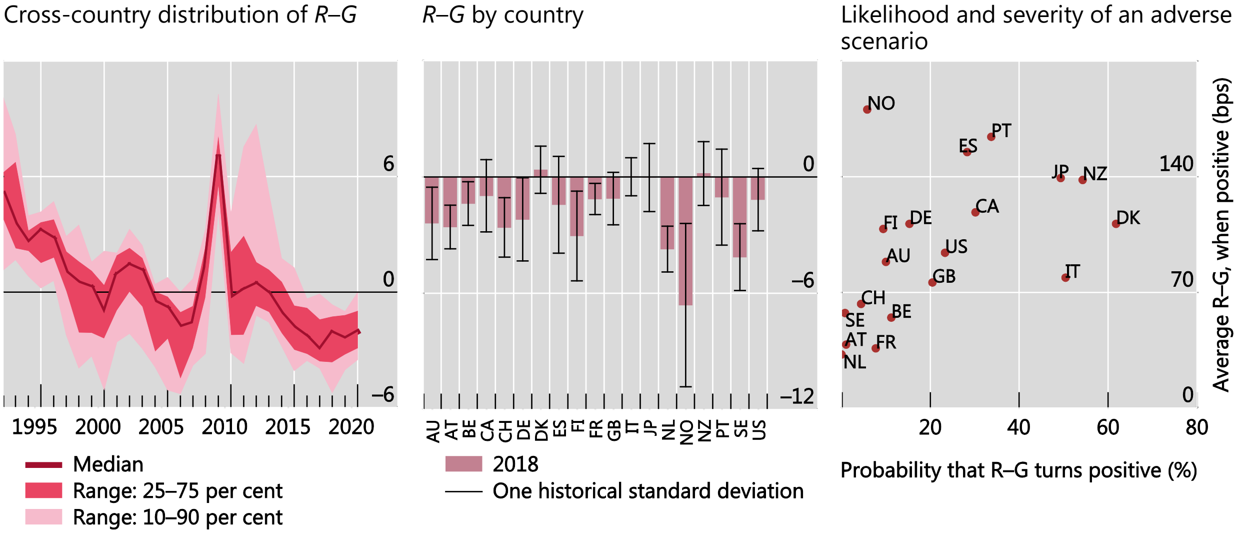
The key question that has arisen with regard to fiscal policy is that of how governments could fund such investments, and what kind of policy mix this could entail. Revisiting the nature of the interactions between fiscal and monetary policy (and prudential regulation) is precisely what has been suggested by some proponents of a Green New Deal in the United States (eg Kelton (2019), Macquarie (2019)), which partly relies on Modern Monetary Theory (MMT), also known as Neo-Chartalism. One key argument of MMT is that currency is a public monopoly for any government, as long as it issues debts in its own currency and maintains floating exchange rates. Following that reasoning, the sovereign could use money creation to achieve full employment (or a climate-related objective) by a straightforward financing of economic activity. The obvious risk of inflation can be addressed subsequently by raising taxes and issuing bonds as the policy goes to remove excess liquidity from the system. A government that by definition issues its own money cannot be forced to default on debt denominated in its own currency. The major underlying assumption is therefore that of "seigniorage without limits": governments can incur deficit spending "without" limits other than those imposed by biophysical scarcity, without automatically generating inflation (Wray (2012)). MMT scholars are generally considered to be outliers in the broader post-Keynesian school, and some of their claims related to the unlimited spending power of governments have been criticised by other post-Keynesian or closely related authors (Lavoie (2013), Palley (2019)). Some of them have suggested more traditional green countercyclical fiscal and monetary policy instead (Harris (2013), Jackson (2017)). Other commentators have pointed out (Summers (2019a), Krugman (since 2011, but more recently 2019)), that MMT poses significant problems. It would undermine the complex set of institutional and contractual arrangements that have maintained price and financial stability in our societies. Moreover, numerous experiments in the history of hyperinflation in advanced economies and mostly in developing countries show that, while outright default in a country's own central bank currency might be avoided, the value of domestic assets including money could be reduced to almost zero.

From a very different perspective, and without sharing the conceptual premises of MMT, several economists have recently argued that financing the low-carbon transition with public debt is both politically more feasible than through carbon taxation and economically more sustainable in the current low interest rate environment, which provides several countries with a larger than previously anticipated fiscal room for manoeuvre (Bernanke (2017), Borio and Song Shin (2019), DeLong and Summers (2012), Blanchard (2019), Summers (2019b)). McCulley and Pozsar (2013) suggest that what matters in times of crisis is not monetary stimulus per se but whether monetary policy helps the fiscal authority maintain stimulus. In this respect, the fact that central banks in advanced economies are globally setting interest rates near or even below zero at a time where massive investments are needed is probably the greatest contribution from central banks to governments' capability to play their role in combating climate change.

As zero or negative interest rates may remain in place for a long period (Turner (2019)), financing the transition to a low-carbon economy via government debt presents fewer risks and would not threaten the mandate of central banks, as long as private and public debt growth continues to be closely monitored and regulated (Adrian and Natalucci (2019)) and there is fiscal space. When it is measured by the cost of servicing debt (*R*) minus the output growth (*G*) rate or (*R* – *G*) to assess the sustainability of debt-to-GDP, there is room in many advanced economies. Over the last 25 years there has been a secular downward trend in government funding costs relative to nominal growth. Graph 16 shows that the difference between government effective funding costs and nominal growth became negative for the median advanced economy around 2013 (left-hand panel) and has since then gone deeper and deeper into negative territory. And, according to the most recent data available (2018), almost all advanced economies now pay an effective interest cost of debt that is below their nominal GDP growth rate. In particular, lower funding costs for the government mean that previously accumulated debts will be cheaper to refinance than previously expected. That is, lower government funding costs mean that the primary balance required to stabilise public debt as a ratio of GDP also falls, down to the point where governments could even run primary deficits while keeping public debt (as a share of GDP) constant.

Government interest burden and snapback risk

In percentage points Graph 16


Cross-country distribution of *R*–*G*

R–*G* by country

Likelihood and severity of an adverse scenario

Using current government yields. AU = Australia; AT = Austria; BE = Belgium; CA = Canada; CH = Switzerland; DE = Germany; DK = Denmark; ES = Spain; FI = Finland; FR = France; GB = United Kingdom; IT = Italy; JP = Japan; NL = Netherlands; NO = Norway; NZ = New Zealand; PT = Portugal; SE = Sweden; US = United States.

Sources: OECD, *Economic Outlook*; BIS calculations.

Combating climate change and financing the set of policies with public debt could perhaps be the way out of the existing conundrum for policymakers in advanced economies (Pereira da Silva (2019b)): low unemployment coexisting with low inflation for a prolonged period of time despite low interest rates. Reigniting growth through investment in low-carbon technologies is most probably more sustainable from a macroeconomic and environmental perspective than any of the previous consumption-led and household debt-based recoveries (Pereira da Silva (2016)). Some of the investments that could foster productivity in the long run include long overdue infrastructure spending, including in projects that are necessary to develop a low-carbon economy. For example, this type of fiscal stimulus may help create the necessary new science/technology/engineering/maths (STEM) jobs in new green industries, services and infrastructure. These jobs might be able to compensate for the jobs that are very likely to be significantly curtailed by technological progress in the new digital economy. Finally, where fiscal space is available, financing the transition to a lower-carbon economy with public debt could build greater social consensus for eventually accepting carbon taxation.

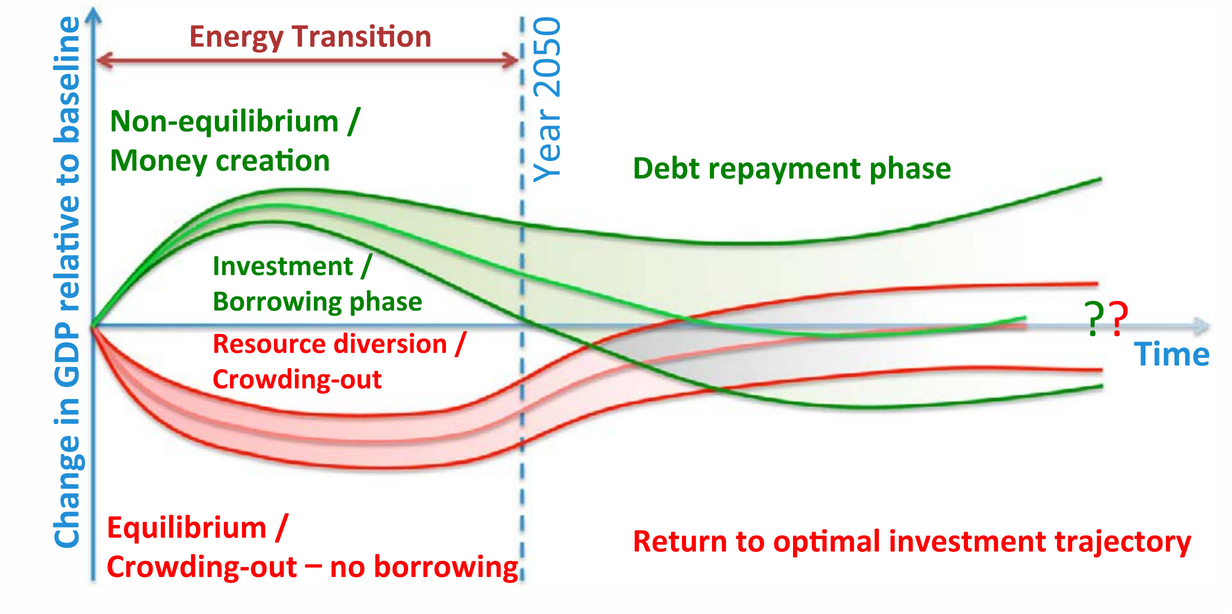
All this should not lead us to consider that there is a "silver bullet" and that the transition to a low-carbon economy can – under current financial circumstances – be easily funded through fiscal policy, as if we had a "free lunch". There could be a risk of a yield snapback. But there are other issues too. In particular, most of the literature calling for fiscal policy action assumes in a more or less explicit manner that it will have a positive impact on economic growth, employment and environmental outcomes, without paying attention to potential technical and institutional limitations and trade-offs between those goals. For instance, the strong reliance of a low-carbon economy on labour-intensive activities may strengthen the "Baumol's cost disease" effect and contribute to slowing down productivity and economic growth (Jackson (2017)). Moreover, the slowdown in productivity gains could be structural (Gordon (2012), Cette et al (2016)) and it is far from clear how the low-carbon transition will reverse it: most of the low-carbon investments needed in advanced economies aim to replace business-as-usual (more carbon-intensive) expected investments, without necessarily creating the conditions for a new boost in productivity. Some have gone further by casting doubt on whether it is even technically possible to decouple economic growth from environmental harm, including but not limited to CO_2 emissions (Jackson (2017), Hickel (2019), Macquarie (2019), OECD (2019b), Parrique et al (2019)).

These potential limitations, in turn, pose major questions for macroeconomic theory, such as estimating the size of the investment multiplier in a low-carbon transition. For instance, an improvement in energy efficiency could lead to a sharp decline in the supply side investments needed for the transition (Grubler et al (2018), in IPCC (2018)), and the latter could paradoxically lead (all other things being equal) to a decrease in GDP, especially if we rely on models where energy plays a critical and non-substitutable role in production (See Box 5 in Chapter 3.5). With this in mind, arguing that public investments will naturally crowd in private investments seems to rely on optimistic (or at least uncertain) assumptions regarding the nature of the transition. Moreover, a "crowding in" effect could paradoxically lead to undesirable (and still poorly accounted for) rebound effects (eg Gillingham et al (2016), Ruzzenenti et al (2019)): savings related to energy efficiency improvements can lead to an increase in the consumption of other fossil-intensive goods and services. In fact, assumptions about crowding out (in supply-led equilibrium models) or crowding in (in demand-led non-equilibrium models) may both (Graph 17) fail to discuss the specific technological, institutional and behavioural assumptions that specific transition paths entail.

These considerations suggest that the low-carbon transition consists in much more than just an investment plan, and that the socio-technical transition needed involves broader considerations than an optimal policy mix, including other ways of measuring system resilience and performance in the context of a low-carbon transition (Fath et al (2015), Ripple et al (2019), Svartzman et al (2019), UNEP (2019)). Without aiming for exhaustiveness, we discuss two of these broader considerations next: potential reforms of the international monetary and financial system in the light of climate considerations and the integration of sustainability into corporate and national accounting.

Impacts of the energy transition on GDP in non-equilibrium (demand-led) vs equilibrium (supply-led) models

Graph 17



Source: Mercure et al (2019).

4.4 Calling for international monetary and financial cooperation

Climate stability is a global public good, which raises difficult questions regarding international policy coordination and burden-sharing between countries at different stages of economic development. Unfair or poorly coordinated international action may simply incentivise some countries to free-ride (Krogstrup and Obstfeld (2018)). Achieving a smooth transition where all countries do their fair share means that a significant compensation mechanism must be agreed upon between developed and developing and emerging economies. As mentioned earlier, these economies need to see that their support for action combating climate change takes into account their stage of industrialisation.

Thus, climate change mitigation actions need to be built on international cooperation between advanced and developing countries (Villeroy de Galhau (2019b)) and recognition of the need for technology transfers and increases in official development assistance to developing countries. So far, developed countries have committed to jointly mobilise $100 billion per year by 2020 for climate action in developing countries (UNFCCC (2015)). But will this commitment be honoured, as current pledges are still far from this amount (OECD (2019c))? And will they suffice to trigger the massive investments needed in developing economies? If not, what are the implications and likely repercussions?

A sober assessment of international cooperation is that there has been uneven progress so far in mitigating climate change. On the one hand, collective action and stated commitments have flourished in multilateral conferences and internationally agreed commitments such as the Paris Agreement (UNFCCC (2015)). For instance, the recently created Coalition of Finance Ministers for Climate Action and the signing of the "Helsinki Principles"[46] could become a critical platform to articulate the need for fiscal policy and the use of public with prudential and monetary action and international coordination. The creation of the Network for Greening the Financial System (NGFS) is another success of such cooperation, possibly in the

---

[46] See www.cape4financeministry.org/coalition_of_finance_ministers.

very spirit of Bretton Woods (Villeroy de Galhau (2019c)). On the other hand, recent global debates have been dominated by a reaction against multilateralism (BIS (2017)). This mindset obviously does not help in combating climate change and delays collective action on the real problems. For instance, although coal, oil and gas are the central drivers of climate change, they are rarely the subject of ad hoc international climate policy and negotiations (SEI et al (2019)).

Inspiration for overcoming these limitations can be found in the literature on the commons and more precisely in Elinor Ostrom's (1990, 2010) principles for the governance of Common Pool Resources (CPRs). CPRs are "systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others" (Ostrom (2002)). In this sense, the remaining stock of carbon that can be used while still having a fair chance of remaining below 1.5°C or 2°C can be considered as a CPR: burning fossil fuels in one place decreases the carbon budget available to others. One of Ostrom's key insights was to show that the over-exploitation of CPRs is due not so much to the lack of property rights, as often believed (Hardin (1968)), as to the lack of an adequate governance regime regulating the use of CPRs.

Building on Ostrom's insights, which are increasingly being adopted in both the climate and economic communities,[47] central banks along with other stakeholders could implement a governance regime based on CPRs by: (i) further identifying the risks to these resources (eg over-exploitation of the carbon budget); (ii) finding actions that reduce climate-related risks at the global and local levels; and (iii) monitoring these arrangements through the design and enforcement of rules for system stability. This implies coordination, local participation, some sense of fairness in burden-sharing, incentives and penalties, among others.

Given the difficulty of managing global commons (Ostrom et al (1999)), one concrete way of moving towards such a global joint governance of climate and financial stability would be to set up a new international agency (Bolton et al (2018)) that would play a role on two levels with: (i) a financial support mechanism between countries in case of severe climate events; and (ii) supervision of the climate policies being put in place. The theoretical justification of such an agency lies in the fact that, similarly to the creation of an international institutional framework after World War II to face the major global challenges of the time (such as postwar reconstruction), there is now a need for ad hoc institutions to tackle the new global challenges posed by climate change. In a similar spirit, Rogoff (2019) calls for the creation of a World Carbon Bank, which would constitute a vehicle for advanced economies to coordinate aid and technical transfers to developing countries.

Rather than creating new ad hoc institutions, other proposals have focused on embedding climate concerns within existing international institutions such as the International Monetary Fund (IMF), as part of their responsibilities to manage the international monetary and financial system. In particular, proposals have been made to issue "green" Special Drawing Rights (SDRs) through the IMF to finance green funds (Aglietta and Coudert (2019), Bredenkamp and Pattillo (2010), Ferron and Morel (2014), Ocampo (2019)). For instance, Aglietta and Coudert (2019, p 9) suggest creating "Trust Funds in which unused SDRs could be invested to finance the guaranteed low-carbon investment program. A more ambitious method consists of SDR loans to national and international public development banks being pledged to finance the national intentions of carbon emission reductions under the Paris Agreement".[48] Scaling up these "commons-based" mechanisms may require a major overhaul of the global governance system; yet they could become essential to build a "green" and multilateral financial system capable of channelling savings from all parts of the world to finance the low-carbon transition (Aglietta and Coudert (2019), Aglietta and Espagne (2018)).

---

[47] The third part of the IPCC (2014) report was dedicated to Elinor Ostrom, who was also awarded the Nobel Memorial Prize in Economic Sciences in 2009.

[48] A prerequisite to such a system would be for the IMF to take on the role of a "green" international lender of last resort, by issuing SDRs in exchange for excess reserves held by central banks and governments.

4.5 Integrating sustainability into corporate and national accounting frameworks

Beyond mechanisms aimed at financing the low-carbon transition, the severity of climate and other environmental crises has led a flourishing stream of research to reconsider how to account for economic value in an age of increasing ecological degradation. In particular, accounting standards at the corporate and national levels have increasingly been criticised for their incapacity to value the role of natural capital in supporting economic activity (see Costanza et al (1997)).

The concept of natural capital refers to "the stock of natural ecosystems on Earth including air, land, soil, biodiversity and geological resources … (which) underpins our economy and society by producing value for people, both directly and indirectly" (Natural Capital Coalition[49]). In turn, this stock of natural ecosystems provides a flow of services, called ecosystem services. These consist of provisioning, regulating, cultural and supporting services (Graph 18). For instance, a forest is a component of natural capital; the associated timber (provisioning service), climate regulation (regulating service) and touristic activities (cultural service) are examples of the ecosystem services it provides; and the forest nutrient cycle is a supporting service that enables all of the above.

Ecosystem services – an overview

Graph 18

Source: Millennium Ecosystem Assessment (2005).

Copyright holder: World Resources Institute.

Natural capital and ecosystem services are essential to economic activity in many forms and their degradation (eg soil erosion due to climate change) can have a major impact on human and produced capital (UN Environment (2018)). Important efforts and new frameworks have emerged in the past few years to integrate natural capital into accounting standards at the corporate level and into national accounts, as respectively outlined below.

With regard to corporate accounting, some suggest that a key step in getting companies to achieve a better trade-off between their financial objectives and their environmental and social impact is to transform corporate accounting, ie how companies report their performance to investors (de Cambourg (2019), Rambaud and Richard (2015)). A first encouraging development is the more systematic reporting of carbon emissions by companies under the standardised greenhouse gas protocol.[50] Another

---

[49] See www.naturalcapitalcoalition.org.

[50] See ghgprotocol.org/.

encouraging development is the creation of the Task Force on Climate-related Financial Disclosures (TCFD), which (as discussed above) seeks to coordinate and standardise reporting of company exposures to climate-related risks so as to allow investors to better manage their exposures to these risks. A third encouraging development is the rise of the integrated reporting movement (see Eccles et al (2015), UN Environment (2018)), which seeks to expand standardised accounting statements to include both financial and non-financial performance in a single integrated annual report. A particularly important initiative in this respect is the creation of the Sustainability Accounting Standards Board (SASB),[51] which already proposes standards for the reporting of non-financial ESG metrics.

In order to systematise integrated reporting approaches, regulatory action will be needed to induce or compel companies to systematically report their environmental and social performance according to industry-specific reporting standards. Few examples exist but some exceptions can be found, eg in the case of Article 173 of the French Law on Energy Transition for Green Growth (discussed above) and the recent support from French public authorities for the development of environmental and social reporting (de Cambourg (2019)). More debate will also be needed to streamline the reporting requirements. For instance, a specific question concerns whether natural capital should remain confined to extra-financial considerations or lead to changes in existing accounting norms, such as in the CARE/TDL model (see Rambaud (2015)).

Nevertheless, there is still a long way to go, as the fiduciary duties of CEOs and asset managers must be redefined and firms' non-financial performance metrics put on par with accounting measures of financial performance. An internationally coordinated effort to encourage the adoption of these standards would significantly accelerate the transition towards integrated reporting and/or new ways of accounting for natural capital. Such efforts would benefit central banks and supervisors as standardised accounting measures can allow investors to make relative comparisons across companies' respective exposure to environmental and social risks.

With regard to the integration of natural capital into national accounts, one of the main arguments put forward has to do with the fact that GDP accounts for only a portion of a country's economic performance. It provides no indication of the wealth and resources that support this income. For example, when a country exploits its forests, wood resources are identified in national accounts but other forest-related services, such as the loss in carbon sequestration and air filtration, are completely ignored. Several steps have been made towards better integration of natural capital into national accounts. The Inclusive Wealth Report (UN Environment (2018)) evaluates the capacities and performance of the national economies around the world, based on the acknowledgment that existing statistical systems are geared to measure flows of income and largely miss the fact that these depend upon the health and resilience of capital assets like natural capital. The World Bank Group has also spearheaded a partnership to advance the accounting of natural wealth and ecosystem services.[52]

Better accounting systems for natural capital are necessary to internalise climate externalities, but it should be recognised that the concepts of natural capital and ecosystem services are difficult to define precisely. For instance, pricing and payment mechanisms for ecosystem services can hardly account for the inherent complexity of any given ecosystem (eg all the services provided by a forest) and often lead to trade-offs by valuing a subset of services only, sometimes to the detriment of others (Muradian and Rival (2012)). They can also fail to provide the desired incentives if they are not designed in ways that recognise the complexity of socio-ecological systems (Muradian et al (2013)) and the need to strengthen cooperation in governing the local and global commons (Ostrom (1990, 2010), Ostrom et al (1999)). Hence, rather than envisaging it as an easy solution, accounting for natural capital and its related ecosystem services should constitute but one among a diverse set of potential solutions (Muradian et al (2013)).

---

[51] See www.sasb.org/.

[52] See www.wavespartnership.org/.

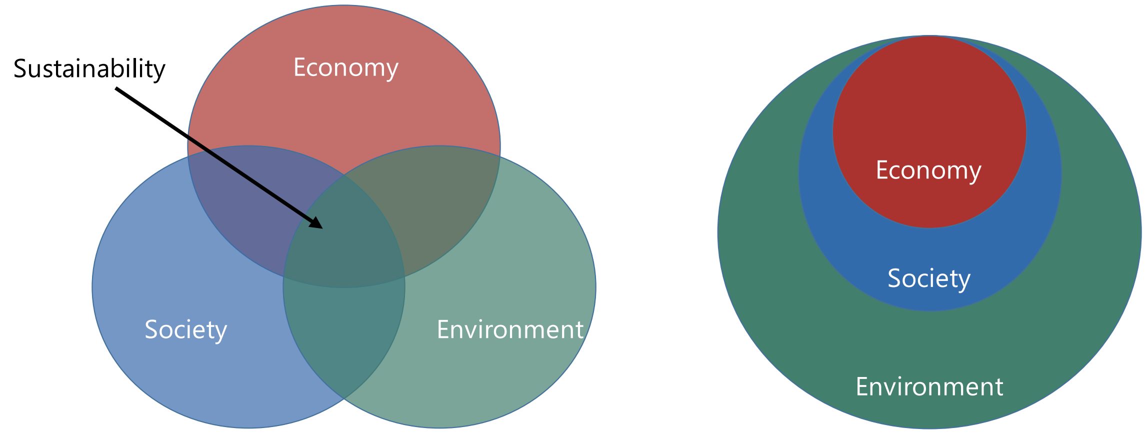
Another significant limitation of the concept of natural capital has to do with the common assumption that it is substitutable for other forms of capital (Barker and Mayer (2017)). According to this assumption, what matters is that capital as a whole increase, not which components make up the increase. If, for example, an increase in manufactured capital (eg machines and roads) exceeds the depletion of natural capital, then the conclusion would be that society is better off. This view has been coined the "weak sustainability" approach. In contrast, proponents of an alternative "strong sustainability" argue that the existing stocks of natural capital and the flow of ecosystem services they provide must be maintained because their loss cannot be compensated by an increase in manufactured or human capital (Daly and Farley (2011)). For instance, the depletion of natural capital in a warming world cannot be compensated by higher income. In this view, the economy is embedded in social and biophysical systems (Graph 19, right-hand panel); it is not a separate entity as the traditional approach to sustainable development is framed (Graph 19, left-hand panel).

Two approaches to sustainability

Graph 19

"Weak sustainability" approach

"Strong sustainability" approach – economic system is embedded in social and ecological systems



Source: Authors' elaboration.

Instead of seeking to "internalise" external costs in order to correct market failures, proponents of the "strong sustainability" approach, including ecological economists, suggest "a more fundamental explanation" (OECD (2019b, p 13)) of the dependence of economic systems upon the maintenance of life support ecosystem services (such as climate regulation). Bringing the economic system back within Earth's "sustainability limits" therefore involves much more than marginal changes in the pricing and accounting systems, and could entail re-evaluating the notion of endless economic growth itself (Georgescu-Roegen (1971), Martinez-Alier (1987), Daly and Farley (2011), Jackson (2017), Spash (2017)). Rethinking macroeconomic and financial systems in the light of these considerations is still an underdeveloped area of research in most of the economic discipline, although great progress has been achieved in recent times towards mainstreaming this question (eg OECD (2019b)).

New approaches will be needed in the process of mainstreaming these questions (see Annex 4). In particular, the development of systems analysis has been identified as a promising area of research that should inform economic policies in the search for fair and resilient socio-ecological systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). In contrast to risk management, a system resilience approach "accepts that transitions to new phases are part of its nature and the system will not return to some previous equilibrium. New normals are normal" (OECD (2019a, p 3)). Greater focus on institutional and evolutionary approaches and on political economy considerations may also be needed

(Gowdy and Erickson (2005), Vatn (2007)), as overcoming the roadblocks to sustainability can be seen as requiring an evolutionary redesign of worldviews, institutions and technologies (Beddoe et al (2009)).

Notwithstanding these important limitations, the ways in which accounting norms incorporate (or not) environmental dimensions remains critical: accounting norms reflect broader worldviews of what is valued in a society (Jourdain (2019)), at both the microeconomic and macroeconomic level. From a financial stability perspective, it therefore remains critical to integrate biophysical indicators into existing accounting frameworks to ensure that policymakers and firm managers systematically include them in their risk management practices over different time horizons.

5. CONCLUSION – CENTRAL BANKING AND SYSTEM RESILIENCE

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems.

Ripple et al (2019)

Climate change poses an unprecedented challenge to the governance of socioeconomic systems. The potential economic implications of physical and transition risks related to climate change have been debated for decades (not without methodological challenges), yet the financial implications of climate change have been largely ignored.

Over the past few years, central banks, regulators and supervisors have increasingly recognised that climate change is a source of major systemic financial risks. In the absence of well coordinated and ambitious climate policies, there has been a growing awareness of the materiality of physical and transition risks that would affect the stability of the financial sector. Pursuing the current trends could leave central banks in the position of "climate rescuers of last resort", which would become untenable given that there is little that monetary and financial flows can do against the irreversible impacts of climate change. In other words, a new global financial crisis triggered by climate change would render central banks and financial supervisors powerless.

Integrating climate-related risks into prudential regulation and identifying and measuring these risks is not an easy task. Traditional risk management relying on the extrapolation of historical data, despite its relevance for other questions related to financial stability, cannot be used to identify and manage climate-related risks given the deep uncertainty involved. Indeed, climate-related risks present many distinctive features. Physical risks are subject to nonlinearity and uncertainty not only because of climate patterns, but also because of socioeconomic patterns that are triggered by climate ones. Transition risks require including intertwined complex collective action problems and addressing well known political economy considerations at the global and local levels. Transdisciplinary approaches are needed to capture the multiple dimensions (eg geopolitical, cultural, technological and regulatory ones) that should be mobilised to guarantee the transition to a low-carbon socio-technical system.

These features call for an epistemological break (Bachelard (1938)) with regard to financial regulation, ie a redefinition of the problem at stake when it comes to identifying and addressing climate-related risks. Some of this break is already taking place, as financial institutions and supervisors increasingly rely on scenario-based analysis and forward-looking approaches rather than probabilistic ones to assess climate-related risks. This is perhaps compounding a new awareness that is beginning to produce a repricing of climate-related risks. That, in turn, can contribute to tilting preferences towards lower-carbon projects and might therefore act, to some extent, as a "shadow price" for carbon emissions.

While welcoming this development and strongly supporting the need to fill methodological, taxonomy and data gaps, the essential step of identifying and measuring climate-related risks presents significant methodological challenges related to:

(i) The choice of a scenario regarding how technologies, policies, behaviours, geopolitical dynamics, macroeconomic variables and climate patterns will interact in the future, especially given the limitations of climate-economic models.

(ii) The translation of such scenarios into granular corporate metrics in an evolving environment where all firms and value chains will be affected in unpredictable ways.

(iii) The task of matching the identification of a climate-related risk with the adequate mitigation action.

In short, the development and improvement of forward-looking risk assessment and climate-related regulation will be essential, but they will not suffice to preserve financial stability in the age of climate change: the deep uncertainty involved and the need for structural transformation of the global socioeconomic system mean that no single model or scenario can provide sufficient information to private and public decision-makers. A corollary is that the integration of climate-related risks into prudential regulation and (to the extent possible) into monetary policy would not suffice to trigger a shift capable of hedging the whole system again against green swan events.

Because of these limitations, climate change risk management policy could drag central banks into uncharted waters: on the one hand, they cannot simply sit still until other branches of government jump into action; on the other, the precedent of unconventional monetary policies of the past decade (following the 2007–08 Great Financial Crisis), may put strong sociopolitical pressure on central banks to take on new roles like addressing climate change. Such calls are excessive and unfair to the extent that the instruments that central banks and supervisors have at their disposal cannot substitute for the many areas of interventions that are necessary to achieve a global low-carbon transition. But these calls might be voiced regardless, precisely because of the procrastination that has been the dominant modus operandi of many governments for quite a while. The prime responsibility for ensuring a successful low-carbon transition rests with other branches of government, and insufficient action on their part puts central banks at risk of no longer being able to deliver on their mandates of financial (and price) stability.

To address this latter problem, a second epistemological break is needed. There is also a role for central banks to be more proactive in calling for broader change. In this spirit, and grounded in the transdisciplinary approach that is required to address climate change, this book calls for actions beyond central banks that are essential to guarantee financial (and price) stability.

Central banks can also play a role as advocates of broader socioeconomic changes without which their current policies and the maintenance of financial stability will have limited chances of success. Towards this objective, we have identified four (non-exhaustive) propositions beyond carbon pricing:

(i) Central banks can help proactively promote long-termism by supporting the *values* or *ideals* of sustainable finance.

(ii) Central banks can call for an increased role for fiscal policy in support of the ecological transition, especially at the zero lower bound.

(iii) Central banks can increase cooperation on ecological issues among international monetary and financial authorities.

(iv) Central banks can support initiatives promoting greater integration of climate and sustainability dimensions within corporate and national accounting frameworks.

Financial and climate stability are two increasingly interdependent public goods. But, as we enter the Anthropocene (Annex 4), long-term sustainability extends to other human-caused environmental degradations such as biodiversity loss, which could pose new types of financial risks (Schellekens and van Toor (2019)). Alas, it may be even more difficult to address these ecological challenges. For instance, preserving biodiversity (often ranked second in terms of environmental challenges) is a much more complex problem from a financial stability perspective, among other things because it relies on multiple local indicators despite being a global problem (Chenet (2019b)).

The potential ramifications of these environmental risks for financial stability are far beyond the scope of this book. Yet, addressing them could become critical for central banks, regulators and supervisors insofar as the stability of the Earth system is a prerequisite for financial and price stability. In particular, the development of systems analysis has been identified as a promising area of research that should inform economic and financial policies in the search for fair and resilient complex adaptive systems in the 21st century (Schoon and van der Leeuw (2015), OECD (2019a)). Future research based on institutional, evolutionary and political economy approaches may also prove fundamental to address financial stability in the age of climate- and environment-related risks.

Faced with these daunting challenges, a key contribution of central banks and supervisors may simply be to adequately frame the debate. In particular, they can play this role by: (i) providing a scientifically uncompromising picture of the risks ahead, assuming a limited substitutability between natural capital and other forms of capital; (ii) calling for bolder actions from public and private sectors aimed at preserving the resilience of Earth's complex socio-ecological systems; and (iii) contributing, to the extent possible and within the remit of the evolving mandates provided by society, to managing these risks.

6. ANNEXES

ANNEX 1 – Uncertainties related to physical risks: Earth's climate as a complex, nonlinear system

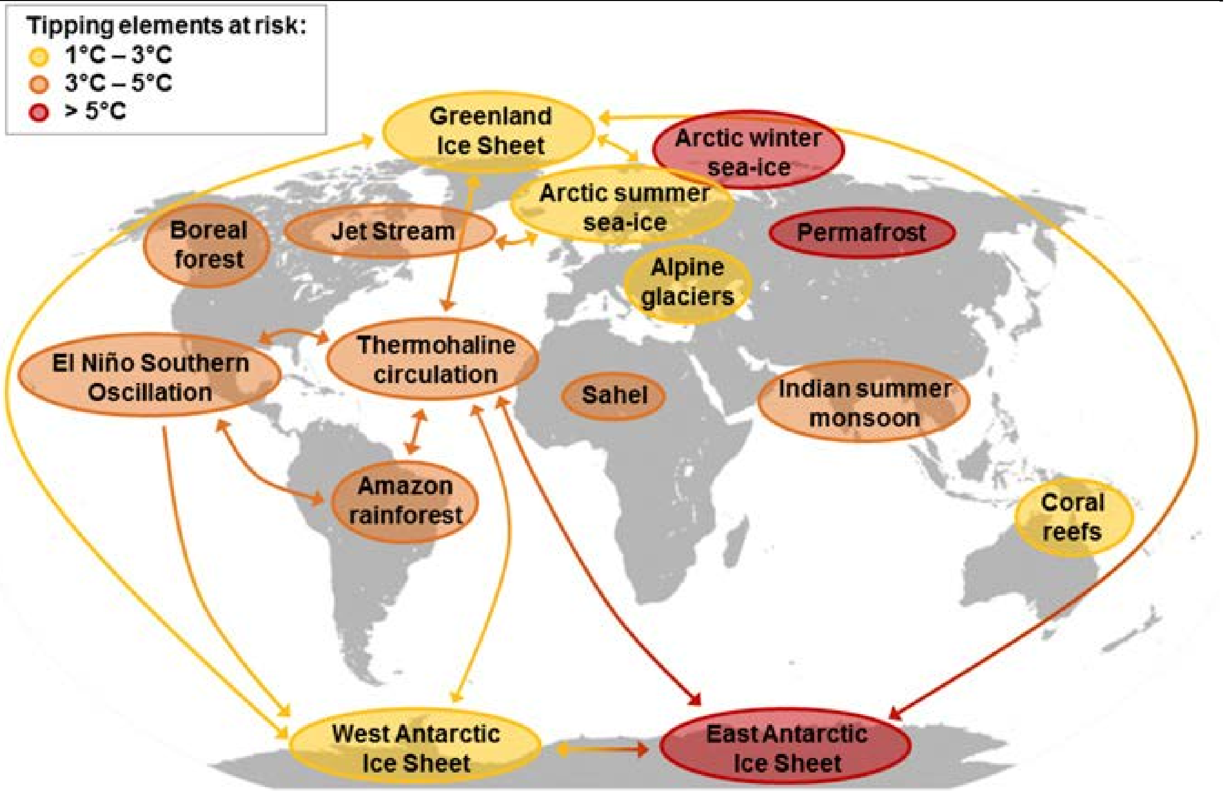
The Earth's climate system is a complex system, with multiple interacting subsystems that can give rise to so-called emerging properties, which refer to new endogenous collective responses. A fundamental (for the purpose of this book) source of emerging properties tied to climate change is irreversibility, ie changes that persist even when the original forcing (eg amount of atmospheric CO_2) is restored (Schneider (2003)). Moreover, the effects of climate change on the planet are "highly nonlinear, meaning that small changes in one part can lead to much larger changes elsewhere" (Smith (2014)).

Highly nonlinear systems can lead to chaotic dynamics, which are extremely difficult to model with any accuracy and confidence. As global warming continues, we face a situation of deep uncertainty related to the biogeochemical processes that can be triggered by climate change. The *IPCC Special Report on Global Warming of 1.5°C* (IPCC (2018)) indicates that beyond 2°C of global warming, the chances of reaching tipping points (such as a melting of the permafrost) become much more likely, which could in turn trigger multiple chain reactions between different ecosystems.

As shown in the graph below, some potential tipping cascades are more likely to occur if there is global warming of between 1°C and 3°C, whereas others are more likely to occur if global warming exceeds 3°C or 5°C. It is noteworthy that many tipping points may occur even if we manage to keep global warming below 2°C (Steffen et al (2018)). Indeed, climate change models predict significant and robust differences between a 1.5°C and a 2°C world. These include increases in intensity of extreme temperature events in most inhabited areas, with a higher frequency and intensity of heavy precipitation and drought events from one region to another (Masson-Delmotte and Moufouma-Okia (2019)).

Global map of potential tipping cascades

Graph A.1



The individual tipping elements are colour-coded according to estimated thresholds in global average surface temperature. Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades.

Sources: Adapted from Steffen et al (2018).

Estimates of when certain tipping point cascades could be triggered are regularly reassessed by the scientific community. For instance, a recent study (Bamber et al (2019)) found that due to accelerated melting in Greenland and Antarctica, global sea levels could rise far more than predicted by most studies so far, potentially leading to other tipping cascades that have not been anticipated. Other studies find that rainforests, which act as a critical climate stabiliser by absorbing and storing CO_2, may be losing their ability to do so faster than expected (eg Fleischer et al (2019)), which could trigger important increases in global warming and other cascades.

In the light of these challenges, the case has often been made that the damage functions used by IAMs are unable to capture the full uncertainty and complexity of the effects of climate change. In particular, they do not incorporate the high probabilities of extreme risks (or fat-tailed distribution of risks) relative to normal distributions (Calel et al (2015), Thomä and Chenet (2017)), especially those resulting from crossing tipping points that trigger knock-on effects on other biophysical subsystems (Curran et al (2019)). For instance, the DICE model (one of the most famous IAMs) assumes that damages are a quadratic function of temperature change, ie that there are no discontinuities and tipping points (Keen (2019)). This can lead to predictions at odds with all scientific evidence: while DICE modellers find that a 6°C warming in the 22nd century would mean a decline of less than 0.1% per year in GDP for the next 130 years, in practice such a rise in global temperatures could mean extinction for a large part of humanity (Keen (2019)).

The physical impacts of climate change will also lead to complex social dynamics that are not only difficult to predict but also problematic to address from an ethical perspective, especially when it comes to translating them in economic terms. Climate change poses critical intergenerational equity issues as damages will tend to increase throughout time, thereby affecting people who are not yet born. Of particular importance for macroeconomic modelling of climate change is the choice of the discount rate applied to future damages, which are supposed to reflect our current economic valuation of the welfare of these future generations (Heal and Millner (2014)). But finding the "accurate" discount rate of future damages is subject to many interpretations. For instance, Nordhaus (2007) finds an optimal increase in temperatures of 3.4°C by using market-based discount rates. More recently, finance-based studies that take into account the pricing of risk and separate risk aversion from intertemporal substitution (eg Daniel et al (2019)) find lower risk-adjusted discount rates, meaning that immediate and drastic action is needed to avoid physical damages stemming from climate change.

Regardless of the rate of discount chosen, climate-economic models can hardly provide accurate responses to many intergenerational ethical issues posed by climate change. Climate change could lead to an increase in human migrations (see image below), conflicts (Abel et al (2019), Bamber et al (2019), Burke et al (2015b), Kelley et al (2015)) and deaths. For instance, the World Bank (2018) estimates that there could be at least 143 million migrants due to climate change by 2050 (taking into account only South America, Africa and India). These trends could also widen global inequality (Burke et al (2015a), Diffenbaugh and Burke (2019)). Although the top 10% wealthiest individuals generate 45% of greenhouse gas emissions while the 50% least affluent individuals generate 13% of them (Chancel (2017)), climate-related shocks will very likely have adverse consequences concentrated in countries with relatively hot climates, which include most low-income countries (IMF (2017)). A recent report commissioned by the United Nations (Human Rights Council (2019)) estimates that climate change could lead to the reversal of all the progress made in the last 50 years in terms of poverty reduction.

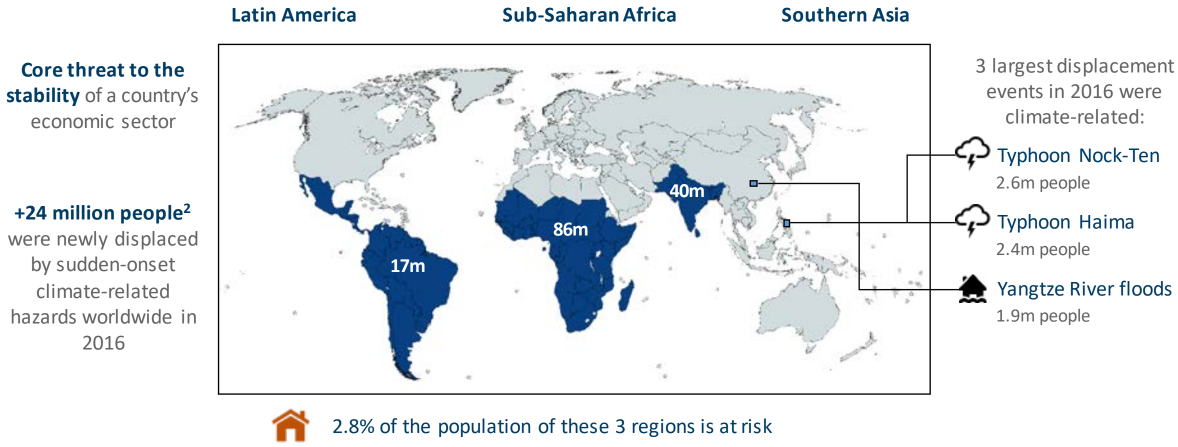
Migration risks of climate change

Environmental changes cause an increasing number of human displacements

Graph A.2

"By 2050, climate change could force more than **143 million people in just 3 regions to move within their countries**"

– World Bank Group



Core threat to the stability of a country's economic sector

+24 million people[2] were newly displaced by sudden-onset climate-related hazards worldwide in 2016

3 largest displacement events in 2016 were climate-related:

2.8% of the population of these 3 regions is at risk

Sources: Adapted from World Bank Group (2018).

While these developments speak for themselves from an ethical perspective, their translation into economic variables is not obvious and can be dangerously misleading. From a mainstream economic perspective, the losses incurred due to climate-related physical impacts in low-income economies could be compensated, eg if economic agents in high-income economies show a strong willingness to pay for adaptation. However, this is at odds with scientific evidence: climate change can lead to irreversible patterns and impacts, which may be only very partially compensated by cash transfers, regardless of their amount.

As a result of these sources of uncertainty, the social cost of carbon (which attempts to quantify in monetary terms the costs and benefits of emitting one additional tonne of CO_2) varies considerably from one model to another (Pindyck (2013)). The selection of parameter values that inform the damage functions as well as the rate of discount rely on arbitrary choices, and IAMs "can be used to obtain almost any result one desires" (Pindyck (2013), p 5). Going further, Lord Nicholas Stern now argues that IAMs are "grossly misleading" (Stern (2016)). Rather than simply rejecting them, we need at least a more nuanced and contextualised support to IAMs (Espagne (2018)).

In any case, addressing climate change adequately requires that we consider it a moral issue (much like avoiding a war or any other major threat to human and non-human lives), not a purely economic one. Assessing these trends merely through discounted individual preferences and/or damage functions, all the more while using cost-benefit analysis, can hardly provide any meaningful insight into what matters most: finding socially fair solutions to guarantee that greenhouse gas atmospheric concentration remains as far as possible from any tipping point. Fighting climate change is therefore a paramount ethical issue that cannot be reduced to a calibration exercise of an IAM.

ANNEX 2 – Uncertainties related to transition risks: towards comprehensive approaches to socio-technical transitions

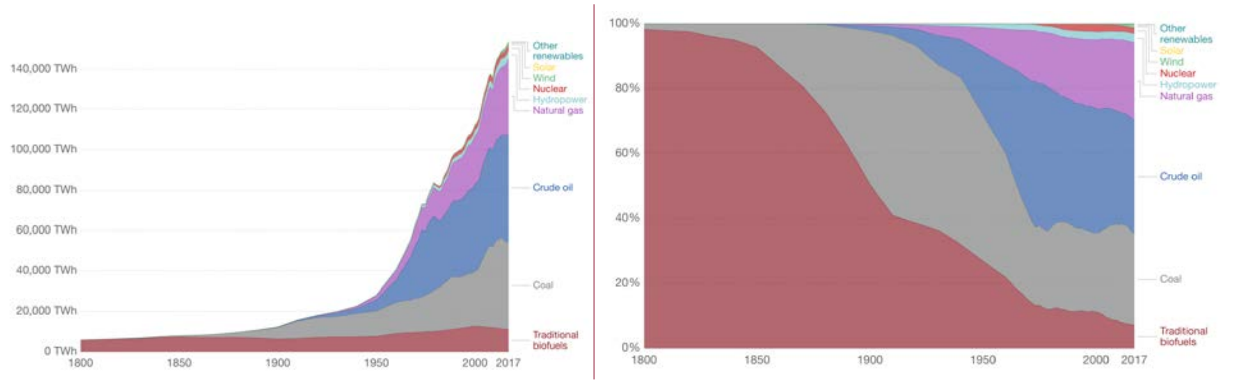
The textbook solution to mitigating climate change is a globally coordinated Pigovian carbon tax that reflects the shadow social cost of carbon emissions. However, as discussed in the Introduction, the prospects for an adequate carbon price as an effective, immediate policy intervention to combat climate change look dim, for the following reasons. First, it is far-fetched to assume that a significant global carbon tax will be implemented in the current political and economic environment, which is sufficient reason in itself to look for other interventions. Second, given the importance of the climate externality ("the greatest market failure ever seen", according to Stern (2007)), estimating the adequate level of a carbon tax and its potential impacts (eg its ability to elicit the desired behaviours and technological breakthroughs without unintended consequences) is a delicate exercise. And third, the decarbonisation paths we need to take may involve such a dramatic shift in the productive structures of the global economic system that climate change may be best understood as more than an externality.

Focusing on the last two points, it is increasingly understood that climate change is a source of structural change in the global economy (NGFS (2019a)). Mitigating climate change in order to avoid its worst physical impacts amounts to nothing less than an unprecedented socioeconomic challenge, requiring the replacement of existing technologies, infrastructure and life habits over a very short time frame. The scale and timing of this required transition has even led some to analyse it in terms of a war mobilisation or rapid urbanisation, rather than the typical transformation of modern economies (Stiglitz (2019)).

In support of the view that a low-carbon transition involves much more than just pricing mechanisms, the history of energy (eg Bonneuil and Fressoz (2016), Global Energy Assessment (2012), Pearson and Foxon (2012), Smil (2010, 2017a)) indicates that the evolution of primary energy uses is intricately related to deep transformations of human societies and economic systems (Graph A.3, left-hand panel. Today's challenge brings an additional layer of complexity, as it requires not only a reduction in the proportion of fossil fuels in the share of global primary energy (right-hand panel) but also a reduction in absolute terms, something that has never been done up to now: as the left-hand panel shows, the energy history of the past centuries has always involved adding new energy sources to old ones (energy additions), not in transitioning from one to another in absolute terms (energy transition). For instance, the share of biomass decreased from almost 100% to less than 10% of total primary energy use between 1850 and the 21st century, but its use in absolute terms has remained more or less constant.

Evolution of energy systems, in absolute and relative terms

Graph A.3



Global primary energy consumption, measured in terawatt-hours (TWh) per year (left-hand panel) and in percentage by primary energy source (right-hand panel).

Note: "other renewables" are renewable technologies not including solar, wind, hydropower and traditional biofuels.

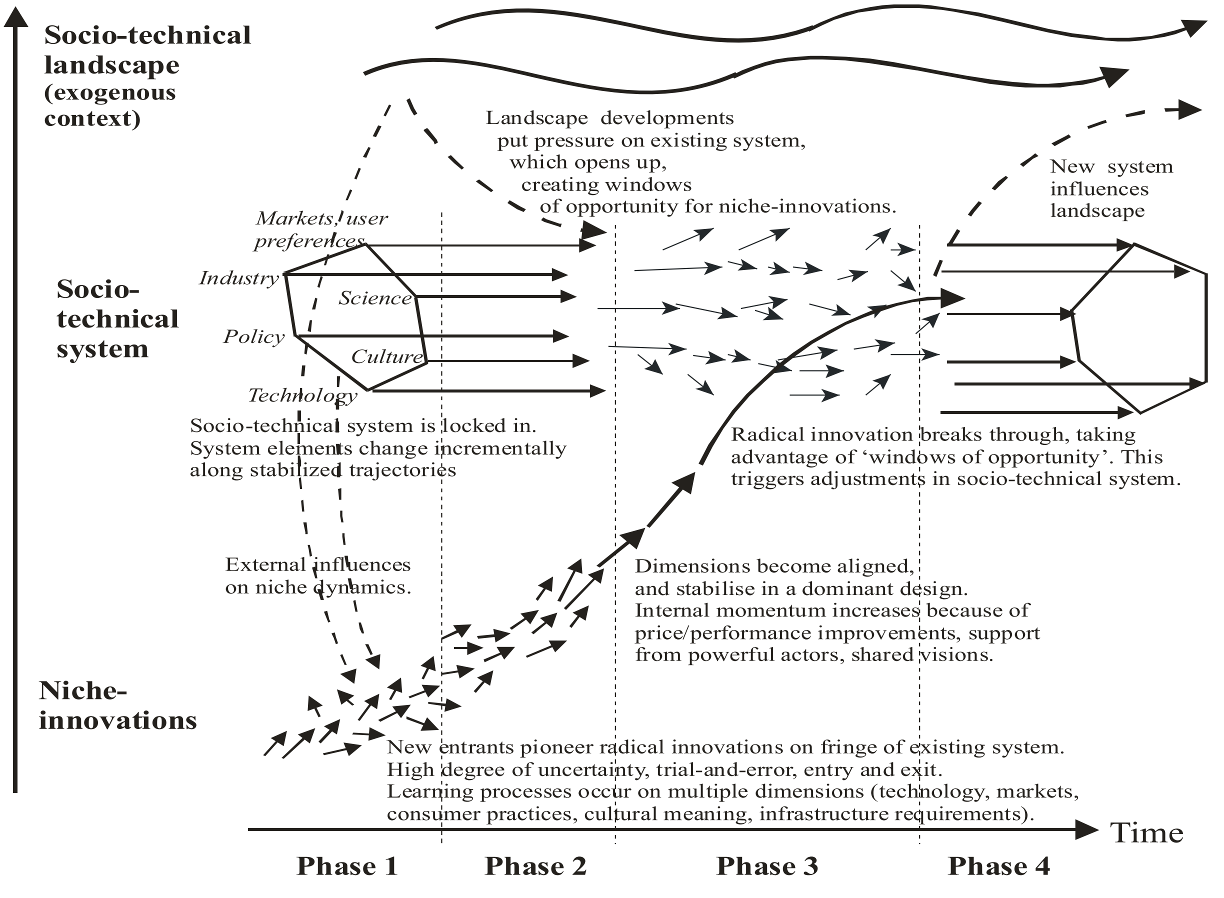
Source: Smil (2017b) and BP (2019). Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/energy.

Hence, the use of a global, economy-wide carbon price as a proxy for climate policy in IAMs (Carbon Brief (2018)) tends to "not structurally represent many social and political forces that can influence the way the world evolves" (IPCC (2014), p 422). In particular, a low-carbon transition will probably involve a broad range of actions guided not only by cost-benefit calculations and revolving around carbon prices, as put forward by a transdisciplinary group of scholars using the concept of socio-technical transition (Geels et al (2017)). Socio-technical transition scholars are concerned with "understanding the mechanisms through which socio-economic, biological and technological systems adapt to changes in their internal or external environments" (Lawhon and Murphy (2011), p 356–7). Prices surely play a role in these processes, but a far more limited one than in most IAMs.

In the quest for more comprehensive accounts of how transitions may come about, socio-technical systems scholars show that a low-carbon transition could result from complex interactions within and between three levels (Graph A.4): technological niches, socio-technical regime and socio-technical landscape, as respectively discussed below.

Phases of transformations of existing socio-technical systems

Graph A.4

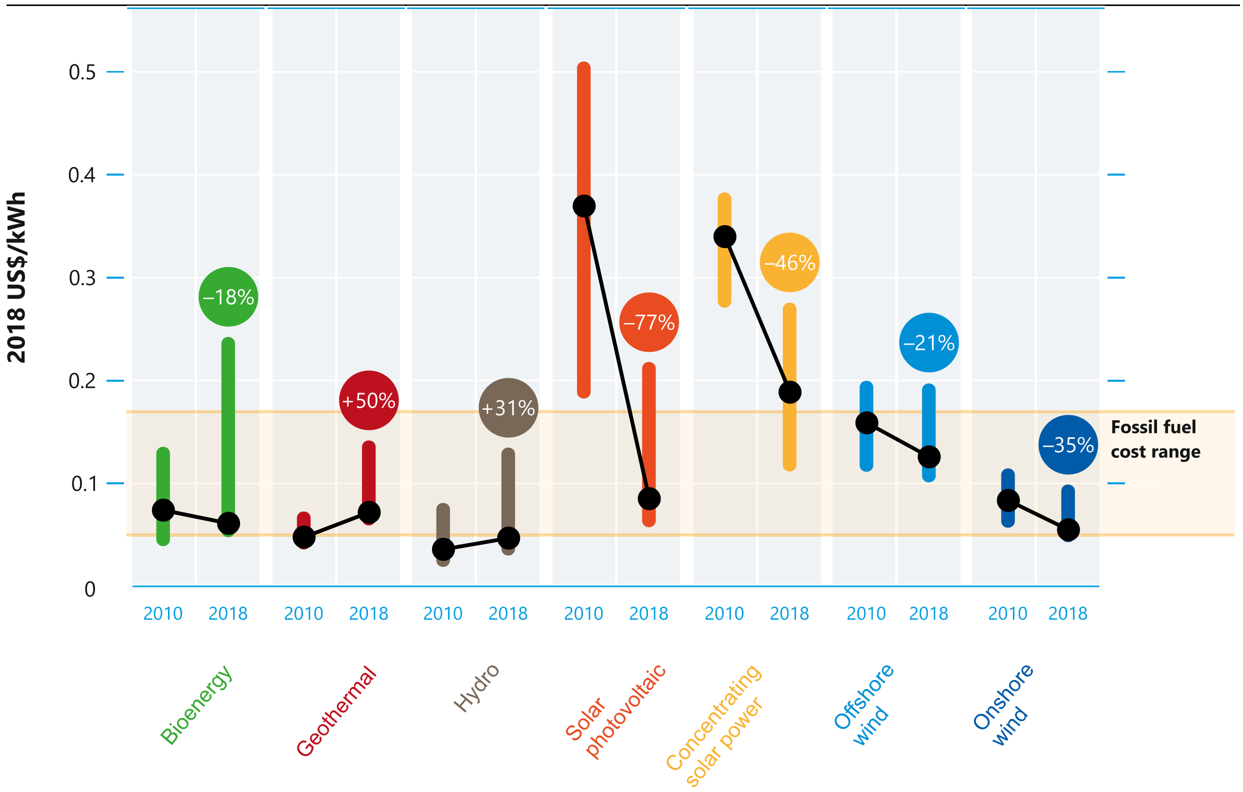


Source: adapted from Geels et al (2017).

First, at the lowest level, niche-innovations are innovations that "differ radically from the prevailing socio-technical system and regime, but are able to gain a foothold in particular applications, geographical areas, or markets" (Geels et al (2017), p 465). In this respect, the path of development of low-carbon technologies is unsurprisingly a key parameter for the transition. Yet it is also a significant source of uncertainty, with both potential barriers and breakthroughs to a rapid and smooth transition. The rapidly declining levelised costs of many renewable energy technologies (Graph A.5) is an example of unpredictable technological development. Moreover, technologies that are still unknown today may emerge and develop much more quickly than usually assumed in IAMs (Curran et al (2019)).

Changes in global levelised cost of energy for key renewable energy technologies, 2010–18

Graph A.5

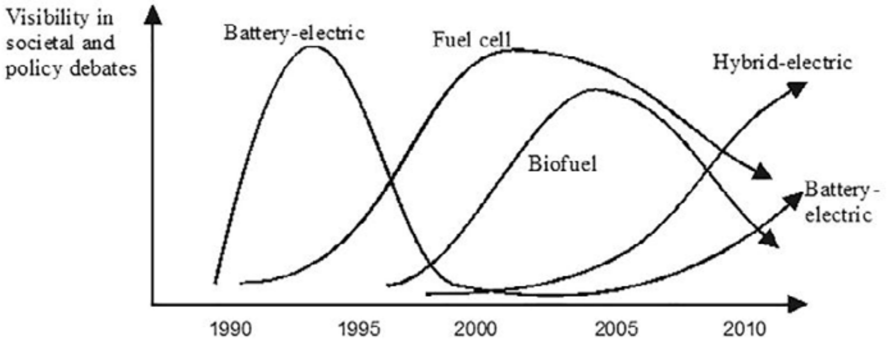


Source: UNEP (2019).

On the other hand, renewable energy is still subject to potential barriers to its development, such as intermittent and unpredictable power output (Moriarty and Honnery (2016)), which requires major improvements in current energy storage technologies (and/or maintaining backup conventional energy capacity). Developing renewable energy capacity may also demand transforming existing land uses, as energy sources such as solar and wind require larger land masses than oil, gas and coal (Smil (2017a)). In addition, the cost of hydropower (the main source of renewable energy so far) could increase because of the physical impacts of climate change (eg increased frequency in droughts could lead to water shortages). In short, many barriers could stand in the way of smooth development of renewable energy capacity.

Modelling technological development paths is a delicate exercise, which can greatly vary over time. For instance, with regard to transportation technologies (Graph A.6), biofuel-powered vehicles were seen as a technological alternative to fossil-powered vehicles more than a decade ago, while today it seems that electric vehicles are a more promising alternative, despite potentially significant limitations with regard to resources and pollution (Pitron (2018)). But these assessments could also be challenged by emerging solutions such as hydrogen (Morris et al (2019)), not represented in the graph below although countries such as China may already be moving towards hydrogen fuel (Li (2019), Xin (2019)). Biofuels could also be discussed again, with the development of third- and fourth-generation biofuels (Aro (2016)) that would not compete with food security in terms of use of land and resources. In short, predicting which technologies will prevail is far from obvious, regardless of the price on carbon. This calls for a very prudent use of IAMs and the technological assumptions informing them, as explained in Chapter 3.2.

Changes in visibility of transportation technologies throughout time Graph A.6



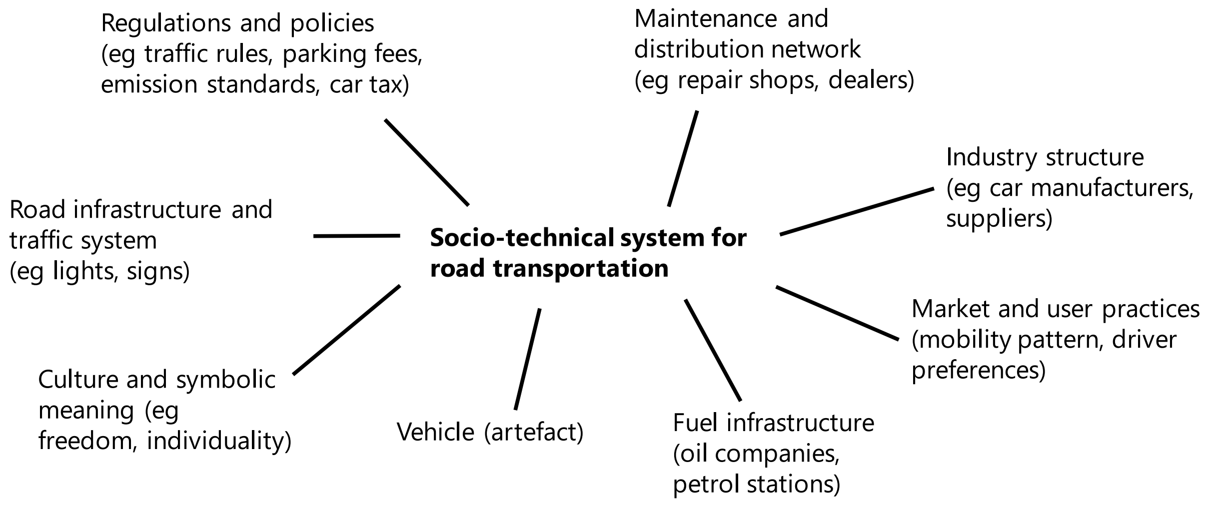
Source: Geels et al (2017).

Second, the middle level of Graph A.4 corresponds to socio-technical regimes, which are "constituted by the conventions, rules, and norms that guide the uses of particular technologies and the everyday practices of the producers, workers, consumers, state agencies, scientists, societal groups, and business people who participate in the regime" (Lawhon and Murphy (2011), p 357). This includes the process leading to the implementation of a carbon price or any other climate-related regulation, eg a feed-in tariff to accelerate the speed of renewable energy capacity installation.

Modelling a realistic transition may require better accounting for many dimensions of the current socio-technical system and the institutional inertia it generates. For instance, reducing the number of individual cars (which may be an important part of the solution along with developing cleaner fuels) is much more difficult once cities and suburbs have been planned on the basis of individual vehicle ownership. Indeed, once car-based transportation systems are institutionalised, they become self-sustaining (Graph A.7) "by formal and informal institutions, such as the preferences and habits of car drivers; the cultural associations of car-based mobility with freedom, modernity, and individual identity; the skills and assumptions of transport planners; and the technical capabilities of car manufacturers, suppliers, and repair shops" (Geels et al (2017), p 465).

Although pricing mechanisms can contribute to addressing these issues, other regulations may be needed, such as rules on the weight of new cars and improved public transportation to limit the amount of personal vehicles (The Shift Project and IFPEN (2019)) and potential rebound effects. Other solutions may not even depend on new technologies but rather on shifting social norms towards the use of already existing technologies (Bihouix (2015)). For instance, the recent "flight shame" movement in Sweden and its negative impact on airline companies (Fabre (2019)) along with positive effects for the national rail operator (Henley (2019)) are responses to the so-called "Greta Thunberg effect" rather than a technological breakthrough.

Socio-technical system of auto-mobility Graph A.7



Source: Adapted from Geels et al (2017).

An additional element of the socio-technical regime has to do with the social acceptability of carbon taxes, which is closely tied to its perceived fairness, and more generally to the fairness of the current wealth distribution. Some argue that designing a carbon tax that varies with household income and between urban and rural areas will be critical to ensure that the worst off households are not disproportionately affected (Bureau et al (2019)). Others argue that the link between carbon pricing and inequalities is even deeper: reducing economic inequalities may be a pre-condition for an effective carbon tax, as it may be easier for a group to collectively reach a consensus on difficult topics (such as burden-sharing efforts for climate mitigation) when inequalities are considered to be within acceptable boundaries in the first place (Chancel (2017)). Alternatively, carbon mitigation efforts may need to focus first on the lifestyles of the wealthiest individuals, since they are the biggest emitters by far (Otto et al (2019)). These considerations suggest that the transformation of an existing socio-technical system requires an even deeper dive into the third level of socio-technical transitions.

Third, the upper level of socio-technical transitions refers to the socio-technical landscape, which considers “the broader contextual developments that influence the socio-technical regime and over which regime actors have little or no influence. Landscape developments comprise both slow-changing trends (e.g., demographics, ideology, spatial structures, geopolitics) and exogenous shocks (e.g., wars, economic crises, major accidents, political upheavals)” (Geels et al (2017), p 465). In particular, complex issues of coordination and well known collective action problems arise when there is a common pool of resources (such as the remaining stock or budget of carbon that can be used) to be administered. In a nutshell, there is a political economy of climate change. That is about who will pay for what, and, inter alia, when and how to share the burden of abatement and transition costs, and how climate-related considerations can be incorporated into practical decision-making processes in a way that is sustainable from a sociopolitical viewpoint.

Historically, advanced economies’ emissions were responsible for a larger share of the depletion/consumption of the stock of carbon. They are now enjoying a higher standard of living, while climate change demands us to limit future GHG emissions. Thus, limiting emissions raises obvious issues of fairness in burden-sharing across nations (Millar et al (2017)). How should we respond to developing countries’ claims for rights to emissions since they are now beginning to industrialise and thus are increasingly responsible for the new flows? Many textbook solutions (eg taxes and subsidies for carbon pricing and trading, even when adjusted for the respective levels of economic development) might create political economy difficulties and, if so, delay decisions and create inertia. The implementation of the principle of "common but differentiated responsibilities" (UNFCCC (2015)) enshrined in international climate negotiations is still an unresolved conundrum.

If no common but differentiated responsibilities or burden-sharing principles prevail on climate negotiations, ambitious climate action from one country could lead to free-riding behaviours from others and/or to outsourcing production to less stringent jurisdictions, potentially offsetting the gains in one country with an increase in GHG emissions elsewhere. One way of mitigating this would be to link trade agreements to climate change mitigation (Bureau et al (2019), German Council of Economic Experts (2019)). In particular, climate clubs (agreements between groups of countries to introduce harmonised emission reduction efforts and sanction non-participants through low and uniform tariffs on exports to countries in the club) could help limit free-riding behaviour by countries (Krogstrup and Oman (2019)). Yet this could lead to potential tensions between climate progress and gains from trade (Pisani-Ferry (2019)). For instance, as China consumed about 50% of the world's coal in 2018 (BP (2019)) and Asia contains 90% of coal plants built over the past two decades (IEA (2019)), it remains unclear how a rapid phase-out of coal would impact global value chains, and how it could take place without impinging on poorer countries' development path.

In this context, the geopolitical dimension of the socio-technical landscape is critical yet particularly difficult to grasp through climate-economic models. For instance, models aiming to estimate the amount of stranded assets need to make assumptions about which sources of fossil fuels will remain stranded, as discussed in the next chapter. While assuming that fossil fuels that are more expensive to extract will be stranded first makes sense from an economic standpoint (eg Canadian and US unconventional oil in Mercure et al (2018)), it is doubtful that countries sitting on these reserves will resort to exploiting them, at least not if major coordination and compensation schemes are designed at the international level. In this regard, the Yasuni-ITT initiative is a striking example of how difficult it can be to design compensation mechanisms: the Ecuadorian government proposed an innovative scheme in 2007, seeking $3.6 billion in contributions from foreign governments to maintain a moratorium on oil drilling in an Amazon rainforest preserve that is also home to indigenous people. The plan was abandoned in 2013 after actual donations and pledges barely exceeded $100 million (Martin and Scholz (2014), Warnars (2010)).

Still at the geopolitical level, it has been argued that a transition away from fossil fuels could significantly reshape geopolitical patterns. The International Renewable Energy Agency released a recent report (IRENA (2019)) arguing that the rise of renewable energy can affect the balance of power between states, reconfigure trade flows and transform the nature of conflicts, eg with fewer oil-related conflicts but possibly more conflicts related to access to minerals. Handling such transition risks smoothly (ie avoiding a conflict-prone transition) requires an unprecedented level of international cooperation, possibly requiring important international fiscal transfers. One step in this direction is the commitment by developed countries to jointly mobilise $100 billion per year by 2020 for climate change mitigation in developing countries (UNFCCC (2015)). However, this amount will surely fall short of being sufficient and, more importantly, current pledges are still far from this target (OECD (2019c)).

Going further into the assessment of the socio-technical landscape in which the low-carbon transition should take place, another major issue is the increasingly limited capabilities of governments to cope with the climate change challenge and the energy transition. Several disturbing developments in the current economic environment are worth mentioning briefly in this respect:

(i) Governments have not changed the way they operate much since the 1970s (Collier (2018)): they are still chasing a redistribution of growth that is now reduced and they must face widening inequalities, high levels of long-term unemployment and higher levels of debt. The transition to low carbon emissions adds an additional layer of complexity to this, as it is unclear whether climate change mitigation will represent a way out of current low growth rates[53] and therefore boost governments' power or, on the contrary, an additional drag toward the possibility of a secular stagnation (Gordon (2012)), as discussed in Chapter 4. In advanced economies in particular, most investments needed for the transition are expected to replace business-as-usual investments, not come as additional investments. Regardless of the price on carbon, the articulation between monetary, fiscal and prudential policy may be critical (as discussed in Chapter 4) to address these issues while fighting climate change.

(ii) Other major transformations of capitalism may also be worth considering when addressing the question of which strategy is realistically the most adequate to tackle climate change. For instance, the shift since the 1970s in the objectives of corporates with a narrow focus on shareholder value maximisation and the still-prevailing dominance of the efficient market hypothesis (Mazzucato (2015)) may lead to a situation where corporates are structurally unable to fully embrace the old and new responsibilities associated with their growing power. The "continued erosion of workers' bargaining power" (BIS (2019) p 9) is another, related major structural force that should not be forgotten when devising strategies for a socially fair low-carbon transition. Others argue that the evolution to societies driven more by passions than by reason (Dupuy (2013)) and by the pursuit of self-interest at the expense of the common good (Collier (2018)) is particularly disturbing as climate change demands social responsibility of all the players.

As a result, the fight against climate change must take place at a time when the global institutional framework established after World War II and some of the values it officially promotes (such as democracy and multilateralism) are increasingly under pressure. These patterns are significant institutional roadblocks to the low-carbon transition, which requires unprecedented participation and coordination. As Lord Nicholas Stern puts it, "it is intensive public discussion that will […] be the ultimate enforcement mechanism" (Stern (2008), p 33). Or as David Pitt-Watson, the former Chair of the United Nations Environmental Program Finance Initiative (UNEP-FI) elegantly observed: "When it comes to climate change we are all players, we are not spectators" (cited in Andersson et al (2016), p 29). Climate-economic models still have a long way to go to grasp these fundamental international political economy dimensions. In order to embrace these features and the international and national political economy dimensions of a low-carbon transition discussed above, inspiration can be found in Elinor Ostrom's principles for governance of common pool resources (CPRs), as discussed in Chapter 4.

It is noteworthy that the Shared Socioeconomic Pathways (SSPs), a group of five narratives built by an international team of climate scientists, economists and energy systems modellers (Carbon Brief (2018)), aim precisely to capture some of these patterns. SSPs notably provide qualitative narratives describing alternative socioeconomic developments. They suggest, for instance, that a strong pushback against multilateralism would make ambitious climate targets almost impossible to achieve. SSPs still need to be fully coupled with Representative Concentration Pathways (RCPs), which describe different levels of greenhouse gases and other radiative forcings that might occur in the future. In spite of representing a significant step forward, it is unclear how simply considering the narratives put forth by the SSPs could lead climate-economic models to embrace the socio-technical patterns discussed above. It seems that SSPs could be better tailored to alternative analytical approaches and models such as those discussed in Chapter 3.5 (non-equilibrium models, case studies and sensitivity analyses) and in Chapter 4.

---

[53] Environmental policy can boost innovation, with positive spillover effects leading to increased competitiveness at the national scale (Porter (1991)). For instance, climate change mitigation and adaptation could lead to the creation of millions of jobs in green industries, services and infrastructure, which could even compensate for the jobs threatened by technological progress (Pereira da Silva (2019a)).

ANNEX 3 – Multiple interactions between physical and transition risks

Although physical and transition risks are usually treated separately, these are likely to interact with each other in practice. There could be multiple interactions and feedback loops within and among three subsystems: socio-ecological systems, socioeconomic systems and regulatory systems.[54] These interactions can generate new, complex cascade effects that cannot be captured by physical or transition risks separately. We present some examples below, which do not intend to be exhaustive but rather to exemplify the largely unpredictable patterns that can arise when the uncertain, complex and nonlinear patterns of Earth's systems and human ones are combined.

First, with regard to socio-ecological systems: climate change can have multiple impacts, as detailed in Annex 1. For instance, it can generate water scarcity, which in turn can trigger agricultural losses and cause food insecurity (IPCC (2019)). These knock-on effects, in turn, can feed back into climate patterns, as shown by the recent IPCC report on climate change and land use (IPCC (2019)). For instance, current land exploitation accounts for almost a quarter of GHGs emitted through human activity, but it is also responsible for soil erosion (due to intensive agricultural practices) that end up reducing the soil's ability to absorb carbon; the latter then contributes to accelerating climate change, which will further contribute to land degradation (eg increased rainfall can result in more surface run-off and subsequent losses in organic matter and nutrients (Lugato et al (2018)).

Second, with regard to socioeconomic systems, climate change can have multiple impacts such as increases in deaths due weather extremes (Mora et al (2018)), migrations (World Bank (2018)), inequalities within and between countries (Burke et al (2015a)) and violence and conflicts (Burke et al (2015b)). All these forces can generate emerging properties and chaotic forces such as asset destruction or reduction of economic growth. Conversely, they can trigger societal responses leading to new consumer behaviours and/or more investments in R&D in renewable energy, with potential nonlinear technological breakthroughs (eg utility-scale solar is now cheaper on a lifetime basis than the marginal cost of running nuclear or coal plants).

Third, with regard to regulatory and legal systems: climate change has already led to multiple but limited regulatory responses and laws. These can generate positive cascade effects, but they can also put some countries at risk if their economy is mainly based on fossil fuel reserves (McGlade and Ekins (2015)). For diesel cars, for example, the restrictive Corporate Average Fuel Economy (CAFE) regulation requires that EU fleet-wide average emissions be 95 g CO_2/km by 2020. This, in turn, will trigger many chain reactions within the industry; for instance, several large automobile groups are facing heavy potential fines as they are currently unable to meet these stringent new standards.

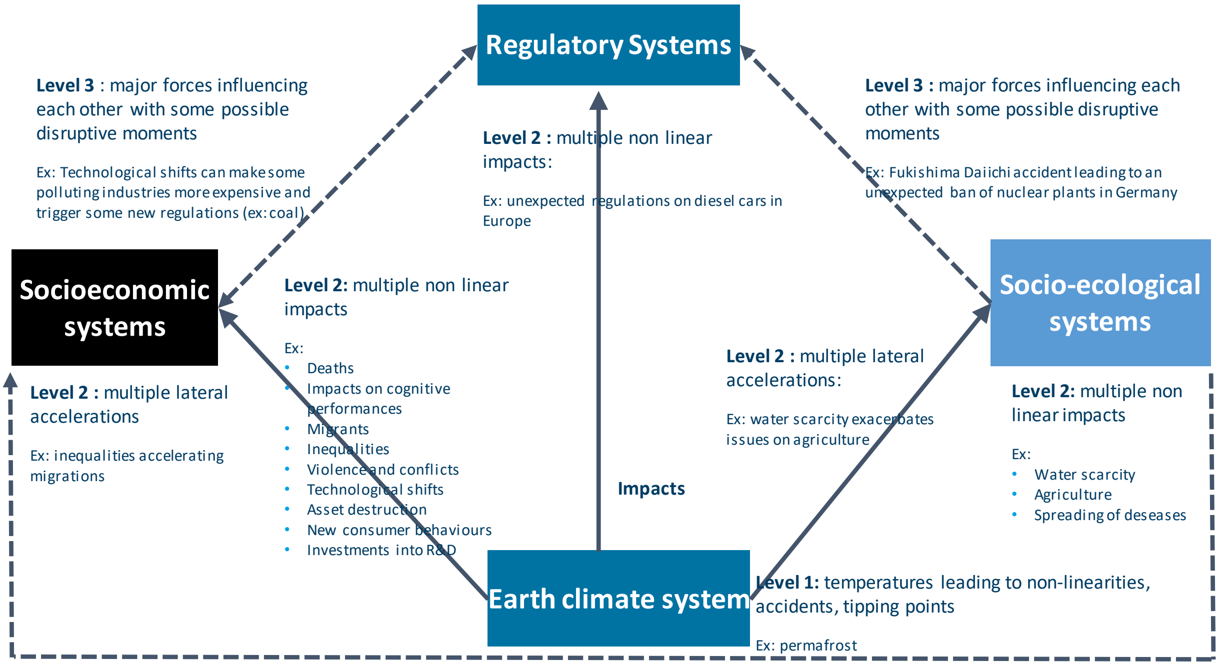
Lastly, these three subsystems (socio-ecological, socioeconomic and regulatory) interact with each other and generate new chain reactions (Graph A.8). For example, water scarcity could affect some corporates if water is allocated giving priority to basic human needs, or affect humans if it is allocated to corporates based on their ability to pay for it without any equity considerations. Similarly, extreme weather events could have major impacts on socioeconomic systems and lead to unexpected new regulations (such as the Fukushima Daiichi accident leading to an unexpected ban of nuclear plants in Germany). In turn, millennials' mobilisation against climate change (see the numerous climate marches across the world or the eruption of new social movements such as Extinction Rebellion) could increase the pressure on policymakers and lead to new rounds of unpredictable regulatory measures.

---

[54] We acknowledge that regulatory systems can be considered as part of socioeconomic systems. Nevertheless, we consider them as separate subsystems for the purposes of this annex.

Chain reactions at all levels

Graph A.8



Source: Authors' elaboration.

Box A1. Example of disruptive moment driven by regulation: the automotive industry

Today most changes are driven by consumers and technologies. The automotive industry is experiencing a crucial evolution driven by regulatory constraints and pressure from public opinion: the energy transition.

The Kyoto Protocol adopted by COP 3 in 1997 was the starting point of legally binding reduction targets in GHG emissions. However, the EU target was divided between its member states according to the burden-sharing agreement, while at the sectoral level the automobile sector was considered to not be doing enough to reduce emissions despite sectoral commitments set in 1998 by the ACEA (European Automobile Manufacturer's Association). However, forcing the automotive industry to reduce emissions drove the European Commission to pursue an integrated approach across the EU and pushed auto makers to achieve technological improvements in motor vehicle technology.

An example is the Volkswagen emissions scandal of September 2015, known as Dieselgate. It highlighted the weaknesses of an industry that had not sufficiently addressed the consequences of the technological revolution in relation to the energy transition pushed by regulators. On the financial side, while stock value collapsed, and credit spreads widened, residual value risk increased on captive finance units. This has changed the entire landscape for car makers. Europe has experienced less diesel use while seeing efforts to reduce CO_2 emissions hit by a boom of SUV commercialisation and a shift towards petrol engines. The additional pressure from public opinion and more stringent local regulators with the implementation of a diesel ban and ban on combustion engines in a mid-term horizon also contributed: car manufacturers had to adapt abruptly in order to propose new products and relevant technologies to address the EU's 2021 target of 95 g of CO_2/km.

Nevertheless, demand for electrified cars is still very low while capex and R&D investments remain very high, leading to pressure on company cash flow generation. Thus, uncertainty about the future profitability of electrified vehicles implies margin pressure for car manufacturers in a period of unfavourable timing due to the end of the cycle: more than 300 electric vehicle models are expected to be available on the European market by 2025.

The industry is at a time of change, driven by stronger regulation which will foster industry consolidation, alliance and M&A operations, for example PSA and FCA transactions. A key factor will be the cost of sector transition as operations driven by cost-sharing are increasing (eg the alliance between Ford and Volkswagen on vans and commercial vehicles).

At auto suppliers, the shift towards electric vehicles has led to lower valuations of their historical powertrain businesses and spin-off transactions. New entrants in the industry, like battery producers and mobility providers, will challenge traditional car manufacturers and suppliers by competing on multiple fronts, increasing the complexity of an already competitive landscape.

ANNEX 4 – From climate-related risk management to a systems view of resilience for the Anthropocene

Fighting climate change is paramount to preserve financial stability, but it should not be forgotten that climate change is only the "tip of the iceberg" (Steffen et al (2011)). Other biogeochemical cycles than the carbon cycle that are critical to life on Earth are also being altered, and may present even higher risks than climate change. For instance, the accelerating decline of the Earth's natural life support systems also poses significant risks to human societies (in addition to the ethical problems related to the erosion of non-human forms of life). The UN Global Assessment Report on Biodiversity and Ecosystem Services (IPBES (2019)) found that human activity caused a catastrophic decline in Earth's biodiversity, unprecedented in human history (for instance, the biomass of wild mammals fell by 82% since the pre-industrialisation era, and about a third of reef-building corals is threatened with extinction). Other risks include pressures on freshwater availability and soil erosion, which is becoming a vital stake for humanity according to the United Nations Convention to Combat Desertification (UNCCD).

Rockström et al (2009) have identified and quantified nine planetary boundaries, which define the "safe operating space for humanity" associated with the planet's biophysical subsystems or processes. These subsystems are "particularly sensitive around threshold levels of certain key variables. If these thresholds are crossed, then important subsystems, such as a monsoon system, could shift into a new state, often with deleterious or potentially even disastrous consequences for humans" (Rockström et al (2009), p 472).

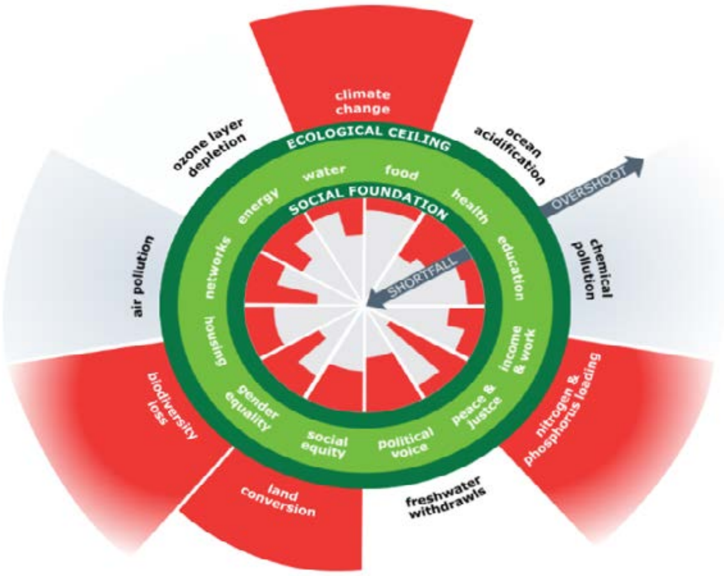
The dramatic and unprecedented changes in the Earth system caused by human activity have led many to consider that we have entered the Anthropocene,[55] an age in which "human impacts on essential planetary processes have become so profound that they have driven the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed" (Steffen et al (2018)). In 2017, a group of 15,000 scientists (Ripple et al (2017)) issued a "warning to humanity", reminding that runaway consumption by a growing population in a world of limited resources and waste absorption capacity is now posing an existential threat.

In this context, avoiding the unmanageable risks that may arise if we cross different planetary boundaries requires nothing less than creating a stabilised Earth pathway, which "can only be achieved and maintained by a coordinated, deliberate effort by human societies to manage our relationship with the rest of the Earth System, recognizing that humanity is an integral, interacting component of the system" (Steffen et al (2017)). This requires finding an "environmentally safe and socially just space in which humanity can thrive", between social foundations and ecological ceilings (Raworth (2017); Graph A.9). Ecological ceilings map into nine planetary boundaries set out by Rockström et al (2015), while "the social foundations are derived from internationally agreed minimum social standards, as identified by the world's governments in the Sustainable Development Goals in 2015. Between social and planetary boundaries lies an environmentally safe and socially just space in which humanity can thrive" (Raworth (2017)).

---

[55] The term Anthropocene is used acknowledging that different societies around the world have contributed differently to pressures on the Earth system, as reminded by different authors critical of the narrative behind this term (eg Malm and Hornborg (2014)).

A comprehensive approach to social foundations and ecological ceilings Graph A.9



Source: Raworth (2017).

To be sure, such an approach raises difficult questions as to which "planetary stewardship strategies are required to maintain the Earth System in a manageable" state (Steffen et al (2018)), and which set of worldviews, institutions and technologies will be up to the task (Beddoe et al (2009), Vatn (2006)). Moreover, a systems approach would require shifting the focus from handling specific environmental crises (eg climate change) on a case by case basis to a much more holistic view that can better account for the cascading effects of system failure (OECD (2019a)).

It is noteworthy that the IPCC's Shared Socio-Economic Pathways (SSP) implicitly support revisiting GDP growth rates, as part of a broader socio-technical transition touching upon several points discussed in this book: the SSP1 "Sustainability" narrative, corresponding to the road towards a low-carbon world, strongly emphasises international cooperation and education to manage the global commons and the demographic transition, and shifts emphasis from economic growth towards other indicators such as human well-being and reduced inequalities (Carbon Brief (2018)).

This is a tab page.
Please title tab
“Deloitte”

Deloitte.

The turning point

A Global Summary

May 2022

MAKING AN IMPACT THAT MATTERS since 1845

Foreword

The passage of time frames history—but it is the choices we make that define progress, and our humanity. Turning points can be purposeful—or imposed on us through either inertia or external forces beyond our control. Time and again, our actions, as one humanity, have demonstrated that we can solve the most daunting challenges and change for the better.

As the scientific evidence confirms our planet is at a crossroads, the power of economics, as seen in Deloitte's Turning Point series, is to point the way to collective and individual prosperity. But this path to prosperity can only be realized when we confront the hard economic truths in meeting the challenges of climate change and decarbonization. Through the analysis in these reports, we call for a change in mindset—building for opportunity not catastrophe. We recognize the needed investments in technology and people that build human and planetary prosperity, while acknowledging the inevitable questions about inequality and uncertainty that surround these choices.

The Deloitte reports highlight that inaction or insufficient action on climate change will see global economic growth, productivity, trade, and competition deteriorate. This is the new baseline for our collective economic futures. But collective action to realize a low-emissions economy will generate growth and prosperity over the coming decades.

Transitions are necessary, though never easy. This truth is written into the DNA of the business community. It is this recognition by business, which is now driving the transformative shifts required to address climate change.

What this analysis also demonstrates is that, despite global differences and divisions, collective action on climate change can benefit every region of the world with meaningful gains in growth and income, and jobs for their citizens. Herein lies the power of these reports—to demonstrate the shared prosperity our choices can bring, and so to bring hope to the fight against climate change. And done well, this future holds the prospect of a more equitable and sustainable world.

Even as the world confronts war and economic uncertainty, the window to confront the climate crisis is rapidly closing. We must not lose sight of a key truth: a collective investment in addressing climate change can pay handsome dividends for the global economy.

Economics is on the side of a low-emissions future. As governments, industries, and financial markets continue to reallocate capital toward decarbonization, the world can accelerate to net-zero emissions and unlock the economic opportunity that comes with it.

This is our *Turning Point.*

Punit Renjen
Deloitte Global Chief Executive Officer

The Intergovernmental Panel on Climate Change's (IPCC) latest report delivers the message we already know in our gut is true.[1] Time is no longer running out. It's up.

Over the past 18 months alone, there have been storms, wildfires, droughts, downpours, and floods around the globe. Regardless of where these events occurred, the result was tragically similar. People hurt and lost. Homes reduced to rubble. Infrastructure destroyed.

People are seeing and experiencing the changing environment, and global opinion polls and business surveys alike have started to reflect this growing awareness. People are aligning their spending with their values. Investors are questioning the environmental, social, and governance impact of their choices. Business leaders now recognize climate change as a planetary emergency.[3]

The need for action has never been clearer. The question before us now is: How do we pivot from awareness to action?

49%

Deloitte's 2022 Sustainable Actions Index Survey covering 23 countries finds that nearly half of respondents (49%) reported experiencing a climate-related event—drought, wildfire, extreme heat, severe storms—in the previous six months.[2]

89%

Eighty-nine percent of C-level executives surveyed by Deloitte agree there is a "global climate emergency." Seventy-nine percent today see the world at a tipping point for responding to climate change.[4]

Answering that question lies partly in a better understanding of the economics of climate change. The Deloitte Economics Institute modeled region-level data from 15 geographies[5] across Asia Pacific, Europe, and the Americas to estimate how much it could cost the global economy if we aren't able to prevent global average temperatures from rising 3°C by the end of the century.

Using scenario analysis from Deloitte's Regional Climate Integrated Assessment Computable General Equilibrium Model (D.Climate), which demonstrates how climate impacts could affect economic output (GDP), employment, and industry, the researchers established a new economic baseline, one that incorporates the climate impacts the IPCC report describes. The team then compared this three-degrees-hotter world to a more hopeful scenario: a future in which the world makes a different choice—and changes.

The status quo is the costlier choice.

According to the modeling, unchecked climate change could cost the global economy US$178 trillion in net present value terms from 2021–2070. The human costs would be far greater: a lack of food and water, a loss of jobs, worsening health and well-being, and reduced standard of living.

If, on the other hand, the world acts now to rapidly achieve net-zero emissions by midcentury, the transformation of the economy could set the world up for stronger economic growth by 2070, according to Deloitte's analysis. Such a transformation could increase the size of the world economy by US$43 trillion in net present value terms from 2021–2070.[6]

3°C

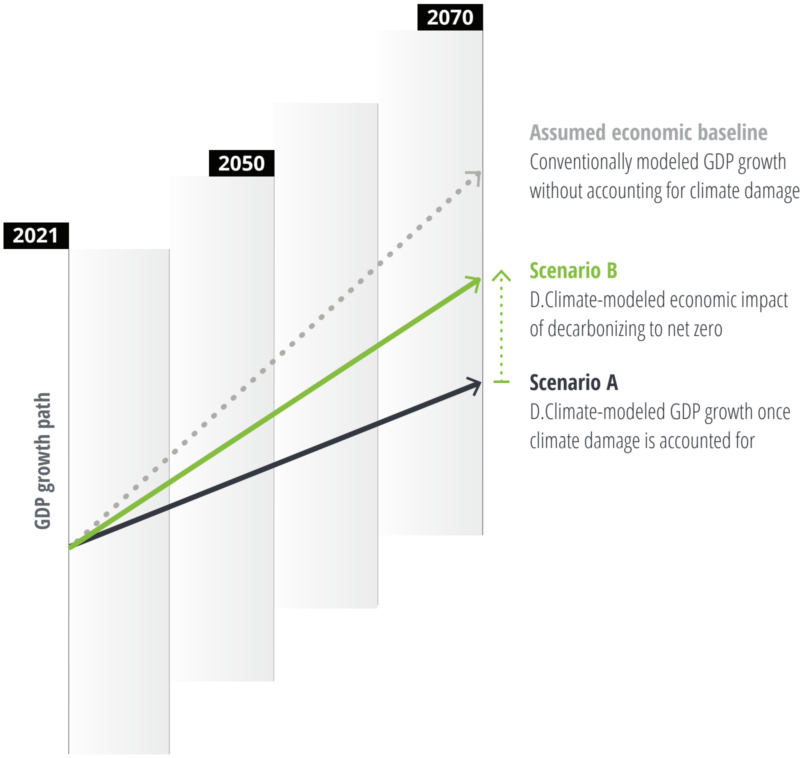
Deloitte's modeling shows that unchecked climate change, where global average temperatures rise by 3°C, hinders growth in every region. Unless the world takes rapid and coordinated action, an increasingly climate-damaged economy could become the new normal.

The transition to net-zero emissions would create fundamental changes to the structure of economic growth as the economy switches the energy mix from reliance on fossil fuels to renewable electricity augmented by fuel sources such as hydrogen. During the initial stage, the combined cost of the upfront investments in decarbonization coupled with the already locked-in damages of climate change would temporarily lower economic activity compared to the current emissions-intensive path.

As the economy completes the transition, however, the economic benefits of avoided climate damage and the emergence of new sources of growth and job creation would start to outweigh the costs. At this moment, called the "turning point" in this analysis, the economy would be able to grow more significantly, than if we continue on the current path (figure 1).

A net-zero future offers opportunity compared to a path of inaction

FIGURE 1. This illustration depicts the opportunity of new economic growth under a net-zero scenario



Note: Illustrative depiction of alternative levels of trends in economic growth.
Source: Deloitte Economics Institute.

Regardless of when it begins, there will be costs associated with the transition. But because climate impacts worsen with each degree of temperature rise, the greatest opportunities—both environmental and economic—are expected to occur if we achieve net-zero emissions by midcentury.

The speed and contours of the transformation will vary by region, but nearly every country and sector would gain through rapid decarbonization, the Deloitte Economics Institute's research shows. And those most exposed to the economic damages of unchecked climate change would also have the most to gain from embracing a low-emissions future.

Despite the uncertainties that come with modeling a 50-year scenario, the Turning Point results offer a compelling vision of a future within our power to create—one in which climate change has been limited, where new industries are employing former fossil-fuel workers, and where countries are exporting low-emissions goods and services for the global decarbonized economy.

Central to this analysis is the contention that climate change is not just a scenario, but the trend, and it should be accounted for in our decision-making. Despite the climate science, this hasn't been the case in most economic modeling. This means that when leaders see economic projections, they're usually looking at forecasts that don't account for the damage that unmitigated climate change will inflict. This view of the world has come up against overwhelming scientific consensus—and, increasingly, our own lived experiences. If the economic impacts of a changing climate are left out of economic baselines, the result is likely to be poor decision-making, ineffective risk management, and dangerously inadequate efforts to address the climate crisis.

Because the climate has changed, our economics, too, need to change.

Because the climate has changed, our economics, too, need to change.

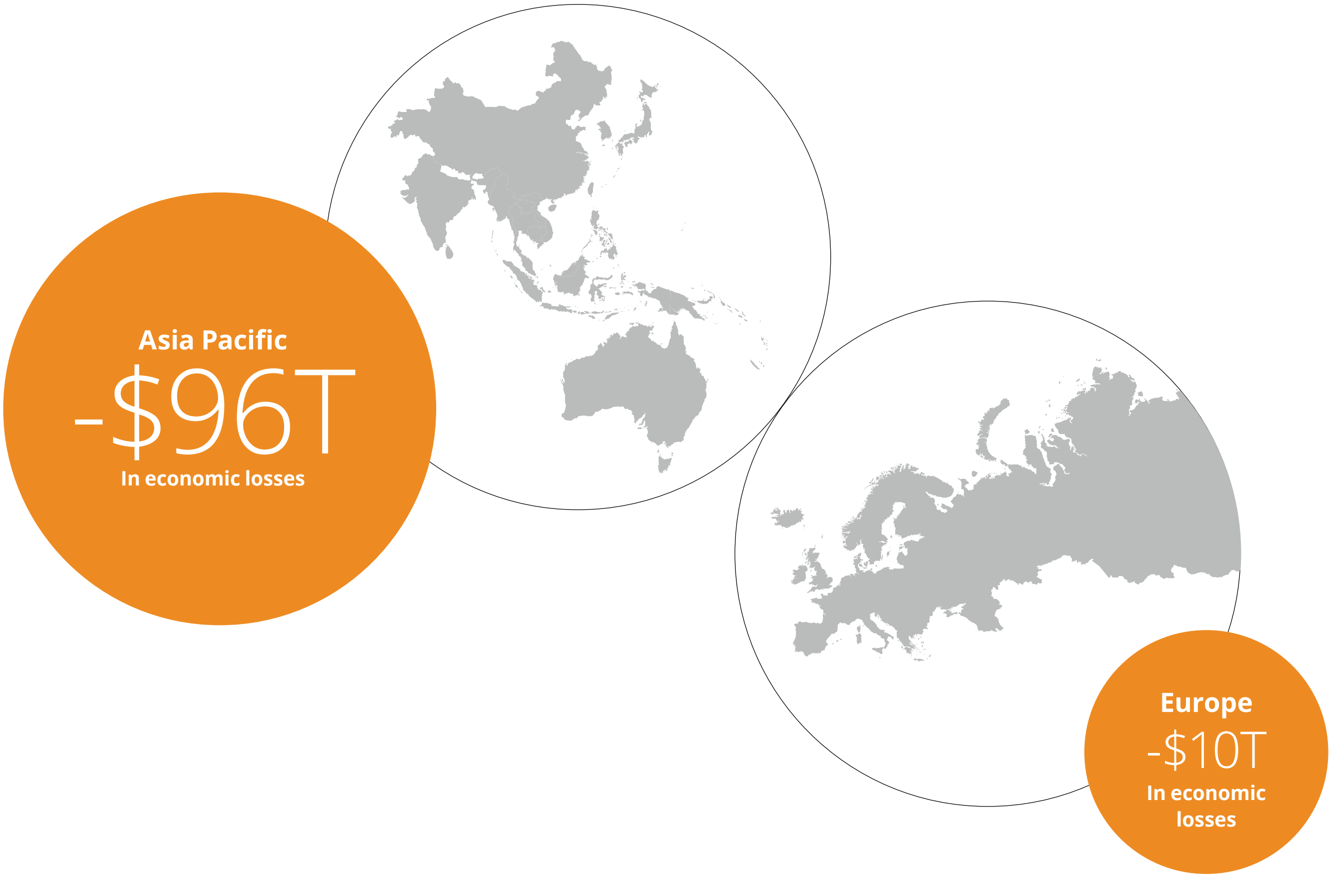
Deloitte's modeling shows that unchecked climate change, where global average temperatures rise by 3°C, hinders growth in every region. Unless the world takes rapid and coordinated action, an increasingly climate-damaged economy could become the new normal. The economic costs would likely be deep and widespread, destroying productivity and jobs.

Unchecked climate change could create US$178 trillion[7] in global economic losses (in present value terms) between now and 2070 compared to a baseline that does not account for climate change (figure 2), the analysis shows. In 2070 alone, global GDP could be 7.6% lower compared to a baseline that does not account for climate change.

Globally, these numbers portray a future in which climate change results in significant declines in productivity, job creation, standards of living, and well-being. Translated into human terms, job opportunities would dry up. Crops would fail. Health care spending would rise. People would stop traveling.

Instead of investing in new, value-adding innovations and infrastructure, our productive capital would be concentrated on repairing climate damage (figure 3).

Climate change imposes heavy costs across geographies



The Deloitte Economics Institute has not separately modeled Africa, Middle East, and the Rest of the World (figure 2). Instead, an estimate is provided that takes a long-term economic projection of each region and imposes the damage impacts of similarly modeled regions onto these projections to provide an approximation of their possible scenario outcomes.

FIGURE 2. Global economic losses associated with unchecked climate change.[1]

Region	Net present value, 2021–2070 ($ trillion)	GDP impact in 2070 ($ trillion)	GDP impact in 2070 (%)
Asia Pacific	-96	-16	-9.4
Europe	-10	-1	-1.5
Americas	-36	-4	-5.7
Total (modeled regions)	-138	-20	-6.8
Africa, Middle East, and Rest of World (estimate)[2]	-40	-5	-14.7
Global[3]	**-178**	**-25**	**-7.6**

Notes:
1. All dollar figures reported in US Dollars.
2. The rest of the world includes: Central America and a number of countries in Europe and Asia Pacific that were not separately modeled as part of those reports (roughly 1% and 2% of the GDP of those regions, respectively). The Deloitte Economics Institute has not separately modeled Africa, Middle East, and the rest of the world. Instead, an estimate is provided that takes a long-term economic projection of each region and imposes the damage impacts of similar modeled regions onto these projections to provide an approximation of their possible scenario outcomes.
3. Numbers may not sum due to rounding.
Source: Deloitte Economics Institute.

Disruptions to the physical environment would impede productivity, business continuity, and trade

The D.Climate model analyzes six pathways through which climate change affects the economy: the labor force, productive land, productivity, health and well-being, the flow of global currency (tourism/travel), and agriculture.

FIGURE 3. Economic impact associated with climate change

Heat stress
Lost labor productivity from extreme heat

Sea-level rise
Lost productive land, both agricultural and urban

Damaged capital
Stalling productivity and investment

Human health
Increased incidence of disease and mortality

Lost tourism
Disrupted flow of global currency

Agriculture loss
Reduced agricultural yields from changing climate patterns

The climate risk to health and well-being

Climate change endangers the life of every person on Earth, universally exacerbating a host of health conditions and damaging the essential drivers of our overall health and wellness.

The medical research community now fully recognizes the human health impacts of climate change, as more than 200 medical journals released an unprecedented joint statement last September citing it as the "greatest threat" to global public health.[8]

The most apparent and associated effects of climate change originate from its impacts on the physical environment, namely extreme temperatures, poor air quality, and precipitation extremes (from droughts to severe storms). These impacts extend well past personal health to threaten food security, stable housing, secure employment, and entire community relationships.

Climate change not only contributes to a host of health issues but also exacerbates the health inequities that the health care industry has recently begun working in earnest to rectify. That's because the communities that are the most vulnerable to the effects of a changing climate tend to be those that are the least equipped to manage and recover from the physical, economic, mental, and social devastation that accompanies it.

In this sense, climate change is both an urgent environmental and social priority.

Source: Deloitte[9].

Each regional economy would be smaller if global average temperatures increase by 3°C, but the damage would not be distributed equally across geographies, the research shows.

The stakes are highest in Asia Pacific. If climate change continues unmitigated, the Asia Pacific economy is exposed to a cumulative US$96 trillion loss by 2070.[10] In 2050, 2°C of global warming could shave US$3.4 trillion from Asia Pacific's regional GDP, a figure that could grow to US$16 trillion in 2070. To put it in perspective, the 2070 loss would exceed the current value of the entire Chinese economy (US$14 trillion). In percentage terms, Asia Pacific's GDP could be 9.4% smaller in 2070 compared to a world with no climate change.

Europe faces a loss of US$10 trillion and 110 million jobs by 2070 compared to a lower-emissions world without climate damages.[11] In 2070 alone, Europe could lose US$1 trillion, and continental growth could be just 1% in the decade leading up to it. As a comparison, such a growth rate is equivalent to that in the 2010–2020 decade, which saw the ripple effects of the global financial crisis, the European debt crisis, and the COVID-19 pandemic.

In the Americas (North and South), losses are projected to reach a cumulative US$36 trillion by 2070. A US$4 trillion loss in 2070 alone could continue to grow beyond the modeled years. For the United States, the damages to 2070 are projected to reach US$14.5 trillion, a lifetime loss of nearly US$70,000 for each working American. The GDP in 2070 would be 4% lower compared to a nondamaged world—a US$1.5 trillion loss in that year alone.

We already have many of the technologies, business models, and policy approaches today to deliver rapid decarbonization and limit global warming to as close to 1.5°C as possible by the century's end. The turning point analysis not only demonstrates how we could do it but shows that it could be good for long-term growth too.

Such a transformation could reduce the economic harm of continued warming and bring new jobs, industries, innovations, and opportunities in a decarbonized global economy.

The world economy could be larger by US$43 trillion in net present value between 2021 and 2070, compared to a climate-damaged baseline.

With global coordination and rapid action, the world can still achieve net-zero emissions by 2050 and have a chance of meeting the Paris Agreement goal to limit warming to as close to 1.5°C as possible. Such an achievement would require an industrial transformation of unprecedented speed and scale, a once-in-a-generation opportunity to reorient the global economy for more sustainable, resilient, and equitable long-term growth (figure 4).

$43T

The world economy could be larger by US$43 trillion in net present value between 2021 and 2070, compared to a climate-damaged baseline.

Decarbonization could create widespread opportunity and growth

Because each country is starting from a different point, the speed, contours, and upfront costs will vary, but by 2070, every region in the world could benefit from the investment in decarbonization, according to the analysis (figure 4).

FIGURE 4. Net economic benefits associated with limiting warming to close to 1.5°C[1]

Region	Net present value, 2021–2070 ($ trillion)	GDP impact in 2070 ($ trillion)	GDP impact in 2070 (%)
Asia Pacific	47	9	5.7
Europe[2]	-1	1	1.8
Americas[2]	-3	1	1.6
Total (modeled regions)[3]	**43**	**11**	**3.8**

Notes:
1. All dollar figures reported in US dollars.
2. For Europe and Americas, the net present value of limiting warming to close to 1.5°C is marginally negative over the period analysed. However, having both reached their turning points, continuing the modeling for a few additional years would show that this would also turn positive.
3. Numbers may not sum due to rounding.
Source: Deloitte Economics Institute.

Americas

$1Trillion

Turning Point: 2060s

Relative to the 3°C warming pathway, decarbonization across the Americas could boost regional GDP by 1.8% in the year 2070 alone. The United States could reap $885 billion of this benefit, a single dividend that exceeds the current combined annual revenues of Amazon, Alphabet, and Microsoft.

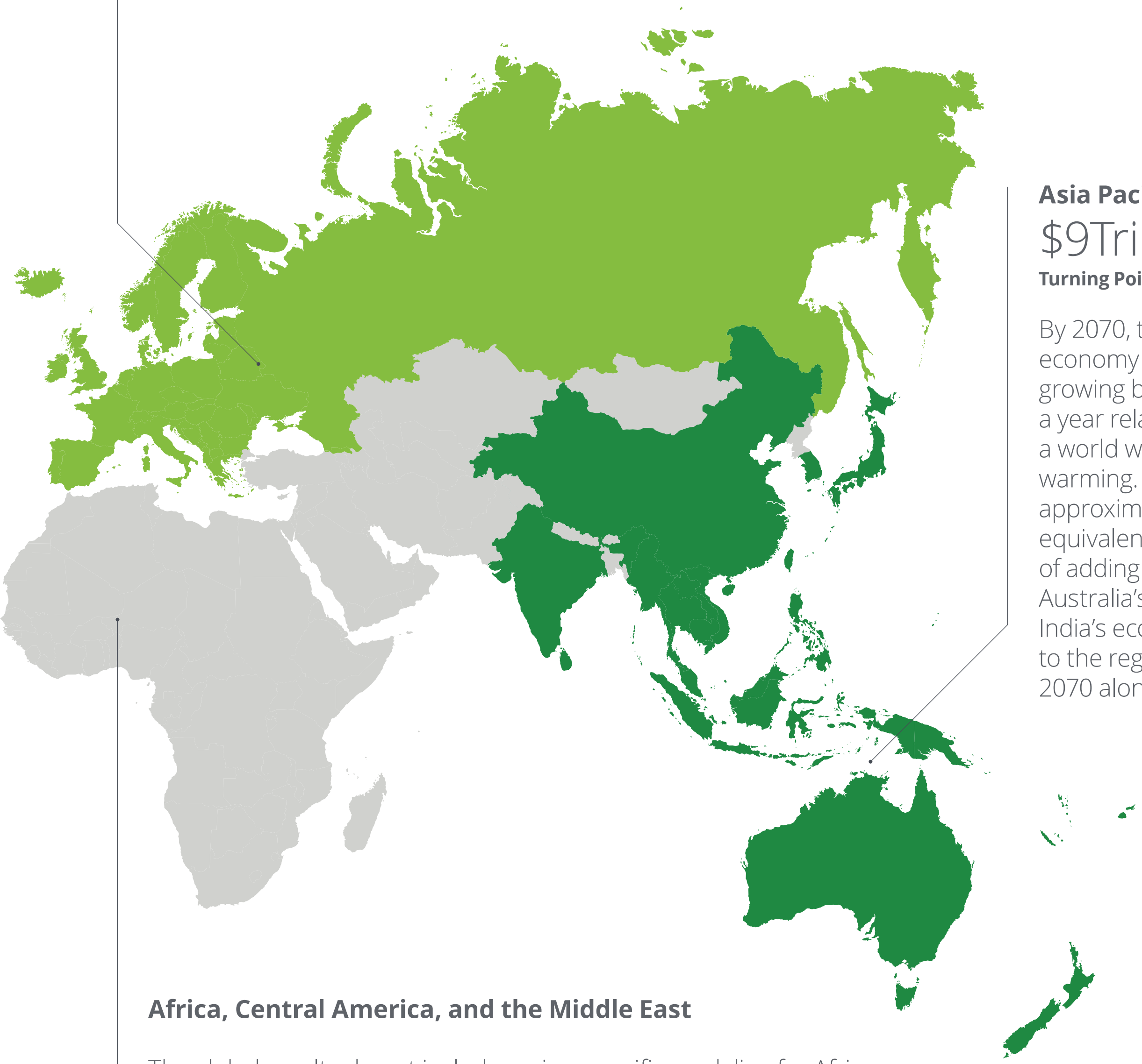
Note: Numbers may not sum due to rounding.
Source: Deloitte Economics Institute.

Europe

$1Trillion

Turning Point: 2050s

Europe can capitalize on a relatively low-cost transition to reap the benefits of becoming the world's first carbon-neutral region. Decarbonization would increase regional GDP by 1.8% in 2070 compared to the 3°C baseline, a benefit that would continue expanding in subsequent years, as the results of the industrial revolution appear.



Asia Pacific

$9Trillion

Turning Point: 2020s

By 2070, the region's economy could be growing by $9 trillion a year relative to a world with 3°C warming. This is approximately the equivalent value of adding Japan's, Australia's, and India's economies to the region in 2070 alone.

Africa, Central America, and the Middle East

The global results do not include region-specific modeling for Africa, Middle East, and the Rest of the World. These regions are not captured in the overall results due to data limitations. However, the macroeconomics of making an industrial revolution to reach net zero are the same. Economies can avoid the worst impacts and gain the greatest benefits if we act now.

Note: Numbers may not sum due to rounding.
Source: Deloitte Economics Institute.

To achieve this comparatively better future will require an industrial revolution over the next 50 years. And the time to act is right now. With global emissions continuing to rise over the past two decades, we have squandered the chance to decarbonize at our leisure. Given the costs associated with each tenth of a degree of temperature increase,[12] every month of delay brings greater risk and forestalls the eventual economic gains. The global economy needs to execute a rapid, coordinated, and sequenced energy and industrial transition that will play out in distinct phases.[13]

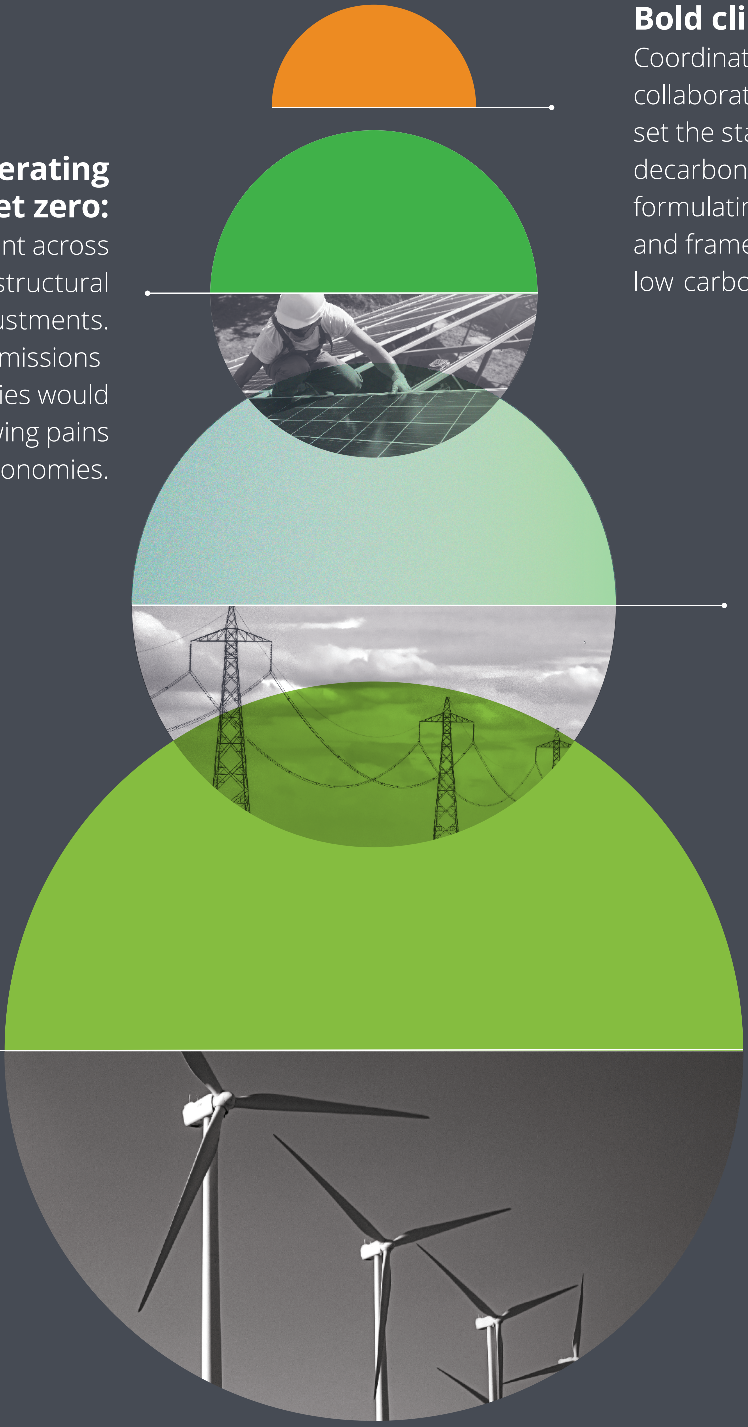
A rapid transformation of the global energy mix could lay the foundation for decarbonization across sectors and throughout the global economy. But this is just the first step. Important changes would be required in other sectors. Existing industries would be reconstituted as a series of complex, interconnected, emissions-free systems: energy, mobility, industry and manufacturing, food and land use, and negative emissions.

A coordinated transition would require governments, along with the financial services and technology sectors, to catalyze, facilitate, and accelerate progress; foster information flows across systems; and align individual incentives with collective goals. The financial industry could provide the additional capital investment to develop low-carbon solutions and nurture the infant industries that will grow with global decarbonization. Governments, meanwhile, could build the architecture for a net-zero emissions ecosystem through policy levers and regulation, and the technology sector could facilitate the transformation by applying its digital infrastructure and solutions to decarbonize systems. A diverse set of societal and economic forces also would drive the transition.

The modeling provides the contours of how that transition could play out, building on the sizable body of work that has identified the actions and sequencing needed to avoid the worst climate impacts and capitalize on the opportunity presented by decarbonization.[14] Four distinct phases of decarbonization emerge from the integrated climate and economic scenario that lay out what needs to happen and when (figures 5 and 6).

Shifting the dialogue around decarbonization opens the door for new policies and investments

FIGURE 5. Illustrative growth path during the four phases of transition



Bold climate plays:
Coordination and collaboration set the stage for decarbonization by formulating policies and frameworks for a low carbon future.

Accelerating to net zero:
Deep investment across systems instigates structural economic adjustments. The decline of emissions intensive industries would create growing pains for some economies.

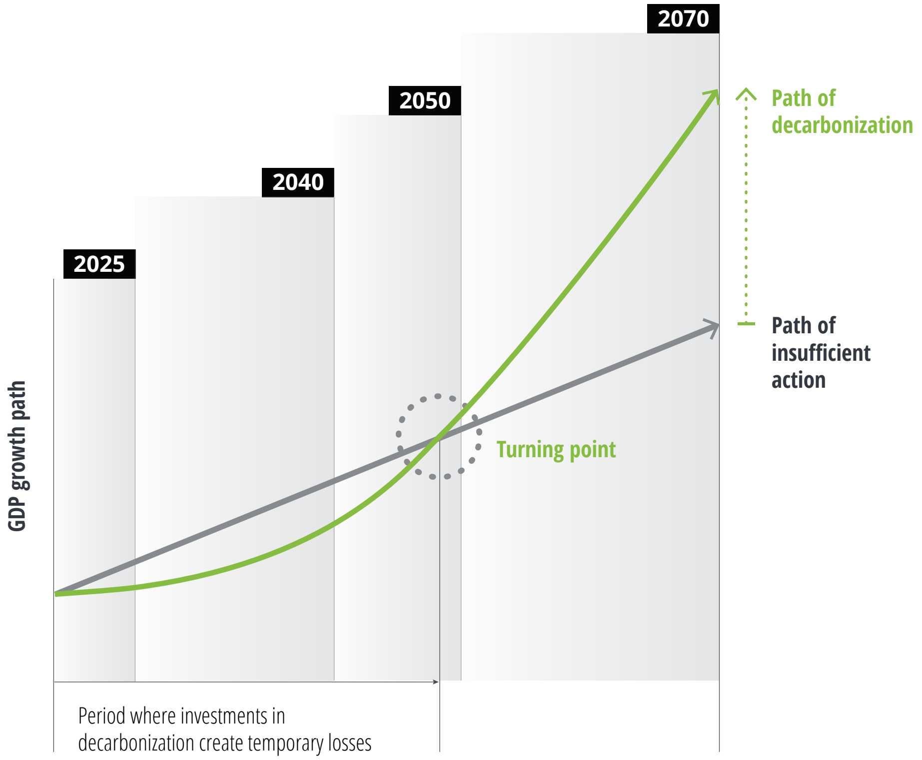
Turning point:
Investment in structural economic adjustment is almost complete. Economies would realize the dividend of the transformation and experience net positive growth.

Low-emissions future:
Interconnected, low carbon systems underpin a clean economy that would grow at an increasingly faster rate than its carbon intensive alternative.

The phases of decarbonization provide a clear structure for thinking about the opportunity. While benefits wouldn't be felt immediately and economic disruption is inevitable, delay only locks in further damages and postpones regions' arrival at the turning point.

Achieving net zero by midcentury could spur economic gains by 2070

FIGURE 6. Illustrative growth path during the four phases of transition



Note: Illustrative depiction of the level change (deviation) to economic growth due to alternative paths.
Source: Deloitte Economics Institute.

Achieving this transformation—an industrial revolution in just a few decades—won't be easy. Even if decarbonization occurs rapidly and collectively, the timing of the costs and benefits that come with each phase would be different for each region.

Every region needs to achieve net-zero emissions by 2050, but each will take a unique path to reaching this outcome based on its existing economic structure and carbon intensities, its exposure to climate damage, its institutional arrangements, and its economic strengths and capabilities. In Asia Pacific, for example, the region's acute exposure to climate events is why it could gain more and more rapidly from global decarbonization (5.7% GDP deviation in 2070) than Europe (1.8% GDP deviation in 2070).

Accordingly, the turning point is different for each region too. In Asia Pacific, this comes early, in the 2020s. In Europe, it wouldn't arrive until the 2050s, while in the Americas, it wouldn't arrive until the 2060s (projected as 2048 in the United States). While the transition would play out at varying speeds, all regions would reach their turning point before 2070, and these benefits could continue to grow beyond the modeled years (figure 7).

Because each country is starting from a different point, the speed, contours, and upfront costs will vary, but by 2070, every region in the world will benefit from the investment in decarbonization, according to our analysis.

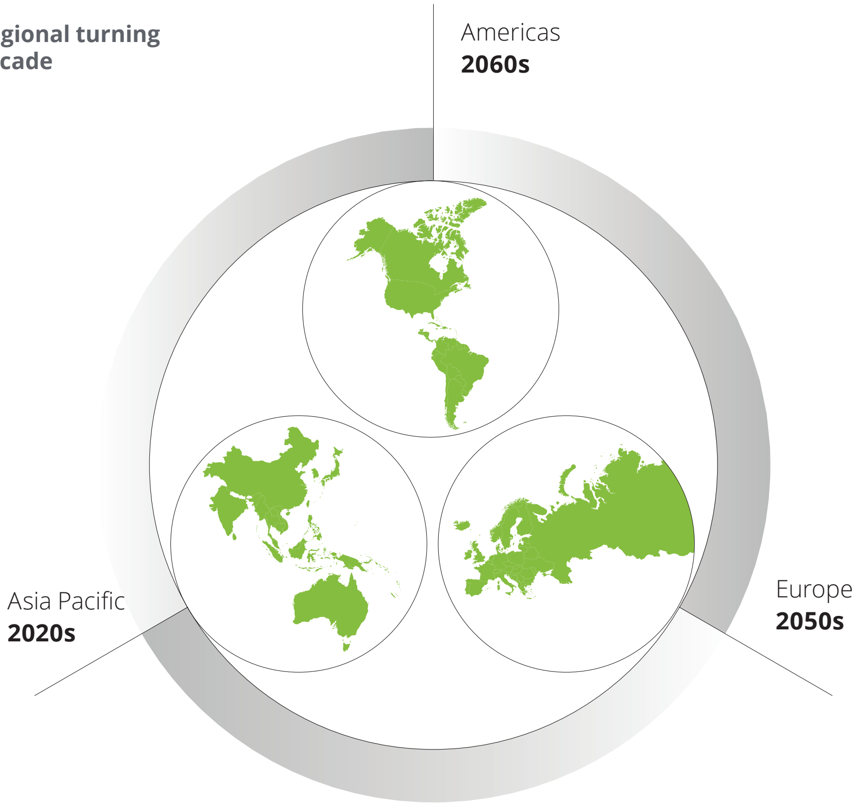
1.5°C*

Disparate climate impacts are likely to challenge policymakers and business leaders to commit to a transition that more equitably distributes the costs (figure 1).

Changing together creates global benefits

While the transition would play out at varying speeds, all regions would reach their turning point before 2070, and these benefits could continue to grow beyond the modeled years.

FIGURE 7. Regional turning points by decade



The effects are expected to be uneven within these regions, too. In the United States, for example, the southeastern energy belt could be particularly affected by extreme temperatures as well as the labor impacts of the economic transition. In Europe, the Mediterranean countries could experience twice the GDP impacts as their northern counterparts.

These kinds of disparate impacts are likely to challenge policymakers and business leaders to commit to a transition that more equitably distributes the costs.

Source: Deloitte Economics Institute.

The facts of climate change are clear. The economics are clear. We cannot afford to waste another year, another month, on debating the merits of taking decisive action today versus continuing to take insufficient action.

We must instead turn our considerable resources and ingenuity to action that rapidly slashes greenhouse gas emissions, transitions our economy to a low-emissions footing, builds resiliency, and addresses the damage that is already affecting the most vulnerable in our society.

It is daunting but also a thrilling opportunity: To remake our economic system in ways that regenerate our planet and enable human flourishing and prosperity. As leaders, and as citizens, every choice, every day can speed the realization of this vision.

Will we—will you—rise to the challenge?

Appendix: Modeling climate change impacts

To quantify its conclusions, the Deloitte Economics Institute modeled the economic impacts of a changing climate on long-term economic growth using the following process:

1. The model projects economic output (as measured by GDP) with emissions reflecting a combined Shared Socioeconomic Pathway (SSP)-Representative Concentration Pathway (RCP) scenario, SSP2-6.0, to the year 2100.[15] The socioeconomic pathway, SSP2, is the "middle of the road" among five broad narratives of future socioeconomic development that are conventional in climate change-modeling. The climate scenario, RCP6.0, is an emissions pathway without significant additional mitigation efforts (a baseline scenario).[16] This results in a projected emissions-intensive global economy.[17]
2. Increased atmospheric GHGs cause average global surface temperatures to continue rising above preindustrial levels. In the SSP2-6.0 baseline scenario, global average temperatures increase more than 3°C above preindustrial levels by the end of the century according to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).[18] (Note that present-day temperatures have already risen more than 1°C above preindustrial levels.)
3. Warming causes the climate to change and results in physical damage to the factors of production. The Deloitte's model includes six types of economic damage, regionalized to the climate, industry, and workforce structure of each defined geography across Asia Pacific, Europe, and the Americas. These damages capture the trend or chronic impacts of global mean surface temperature increases. The approach does not explicitly model individual acute economic shocks driven by extreme climatic events, such as natural disasters, although these are implicitly captured in an increasing trend of climate change damage.
4. The damage to the factors of production is distributed across the economy, impacting GDP. Any change in emissions (and, correspondingly, temperatures) over time results in a change to these impacts and their interactions. The economy impacts the climate, and the climate impacts the economy.
5. The key variables of time, global average temperatures, and the nature of economic output across industry structures combine to offer alternative baseline views of economic growth. Specific-scenario analysis is then conducted, referencing a baseline that includes climate change damage. Scenarios could also include policy actions that either reduce or increase emissions and global average temperatures relative to the current SSP2-6.0 baseline view.

This modeling framework involves significant research on climate and economic impacts across Asia Pacific, Europe, and the Americas, which are used as inputs for Deloitte's D.Climate model (refer to the technical appendices at deloitte.com/global-turningpoint).

Endnotes

1. Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2022: Mitigation of Climate Change*, Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, April 4, 2022.
2. Deloitte, *The world is ready for climate action,* accessed May 2, 2022.
3. Deloitte, *Deloitte 2022 CxO sustainability report*, accessed May 2, 2022.
4. Ibid.
5. Asia Pacific includes China, Japan, South Korea, India, Southeast Asia and Taiwan, Pacific Nations, Australia, and New Zealand. Europe includes the United Kingdom, France, Germany, Italy, all other European Union countries, Belarus, Moldova, Russia, Ukraine, Iceland, Norway, Albania, Andorra, Bosnia and Herzegovina, Montenegro, North Macedonia, San Marino, Serbia, Liechtenstein, Monaco, and Switzerland. The Americas series includes the United States and South America.
6. This does not include Africa, the Middle East, and the Rest of the World, whose pathways to close to 1.5°C have not been modeled.
7. Asia Pacific includes China, Japan, South Korea, India, Southeast Asia and Taiwan, Pacific Nations, Australia, and New Zealand. Europe includes the United Kingdom, France, Germany, Italy, all other European Union countries, Belarus, Moldova, Russia, Ukraine, Iceland, Norway, Albania, Andorra, Bosnia and Herzegovina, Montenegro, North Macedonia, San Marino, Serbia, Liechtenstein, Monaco, and Switzerland. The Americas series includes the United States and South America.
8. Winston Choi-Schagrin, Medical journals call climate change the 'greatest threat to global public health,' ***New York Times***, September 7, 2021.
9. Neal Batra et al., *Why climate resilience is key to building the health care organization of the future*, Deloitte Insights, April 4, 2022.
10. At a 2% discount rate.
11. Jobs measured in FTE.
12. H. O. Pörtner et al. (eds), *Climate Change 2022: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, 2022).
13. See for example, IEA, *Net zero by 2050*, accessed May 18, 2022; Mekala Krishnan et al., *The net-zero transition: What it would cost, what it could bring*, McKinsey Global Institute, January 2022; Seb Henbest et al., *New Energy Outlook 2021*, *BloombergNEF*, 2021.

14. Ibid.
15. IPCC-adopted emission scenarios vary widely, depending on socioeconomic development and climate mitigation policy settings. SSP2-6.0 is chosen as one of the most frequently used "baseline" scenarios in the literature. It describes an intermediate baseline scenario as it carries historical social, economic, and technological trends forward and includes no specific or significant climate mitigation policy effort, making it an appropriate baseline for reference. For a more detailed description of SSP2-6.0 and the rationale for its adoption, see the technical appendix.
16. IPCC, *Climate Change 2013: The Physical Science Basis*, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, 2013).
17. Preindustrial is defined in IPCC assessments as the multicentury period before the onset of large-scale industrial activity around 1750.
18. The associated climate data (such as annual temperature increases and atmospheric concentrations) is estimated using MAGICC as described in Meinshausen et al. (2011) and Meinshausen et al. (2020) and configured by Nicholls et al. (2021). See the technical appendix for further detail.

This is a tab page.
Please title tab
“McKinsey”

McKinsey
Global Institute

Climate risk and response

Physical hazards and socioeconomic impacts

January 2020

Contents

In brief

Climate risk and response: Physical hazards and socioeconomic impacts

After more than 10,000 years of relative stability—the full span of human civilization—the Earth's climate is changing. As average temperatures rise, acute hazards such as heat waves and floods grow in frequency and severity, and chronic hazards, such as drought and rising sea levels, intensify. Here we focus on understanding the nature and extent of physical risk from a changing climate over the next three decades, exploring physical risk as it is the basis of both transition and liability risks. We estimate inherent physical risk, absent adaptation and mitigation, to assess the magnitude of the challenge and highlight the case for action. Climate science makes extensive use of scenarios ranging from lower (Representative Concentration Pathway 2.6) to higher (RCP 8.5) CO_2 concentrations. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. We link climate models with economic projections to examine nine cases that illustrate exposure to climate change extremes and proximity to physical thresholds. A separate geospatial assessment examines six indicators to assess potential socioeconomic impact in 105 countries. The research also provides decision makers with a new framework and methodology to estimate risks in their own specific context. Key findings:

Climate change is already having substantial physical impacts at a local level in regions across the world; the affected regions will continue to grow in number and size. Since the 1880s, the average global temperature has risen by about 1.1 degrees Celsius with significant regional variations. This brings higher probabilities of extreme temperatures and an intensification of hazards. A changing climate in the next decade, and probably beyond, means the number and size of regions affected by substantial physical impacts will continue to grow. This will have direct effects on five socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

The socioeconomic impacts of climate change will likely be nonlinear as system thresholds are breached and have knock-on effects. Most of the past increase in direct impact from hazards has come from greater exposure to hazards versus increases in their mean and tail intensity. In the future, hazard intensification will likely assume a greater role. Societies and systems most at risk are close to physical and biological thresholds. For example, as heat and humidity increase in India, by 2030 under an RCP 8.5 scenario, between 160 million and 200 million people could live in regions with an average 5 percent annual probability of experiencing a heat wave that exceeds the survivability threshold for a healthy human being, absent an adaptation response. Ocean warming could reduce fish catches, affecting the livelihoods of 650 million to 800 million people who rely on fishing revenue. In Ho Chi Minh City, direct infrastructure damage from a 100-year flood could rise from about $200 million to $300 million today to $500 million to $1 billion by 2050, while knock-on costs could rise from $100 million to $400 million to between $1.5 billion and $8.5 billion.

The global socioeconomic impacts of climate change could be substantial as a changing climate affects human beings, as well as physical and natural capital. By 2030, all 105 countries examined could experience an increase in at least one of the six indicators of socioeconomic impact we identify. By 2050, under an RCP 8.5 scenario, the number of people living in areas with a non-zero chance of lethal heat waves would rise from zero today to between 700 million and 1.2 billion (not factoring in air conditioner penetration). The average share of annual outdoor working hours lost due to extreme heat and humidity in exposed regions globally would increase from 10 percent today to 15 to 20 percent by 2050. The land area experiencing a shift in climate classification compared with 1901–25 would increase from about 25 percent today to roughly 45 percent.

Financial markets could bring forward risk recognition in affected regions, with consequences for capital allocation and insurance. Greater understanding of climate risk could make long-duration borrowing unavailable, impact insurance cost and availability, and reduce terminal values. This could trigger capital reallocation and asset repricing. In Florida, for example, estimates based on past trends suggest that losses from flooding could devalue exposed homes by $30 billion to $80 billion, or about 15 to 35 percent, by 2050, all else being equal.

Countries and regions with lower per capita GDP levels are generally more at risk. Poorer regions often have climates that are closer to physical thresholds. They rely more on outdoor work and natural capital and have less financial means to adapt quickly. Climate change could also benefit some countries; for example, crop yields could improve in Canada.

Addressing physical climate risk will require more systematic risk management, accelerating adaptation, and decarbonization. Decision makers will need to translate climate science insights into potential physical and financial damages, through systematic risk management and robust modeling recognizing the limitations of past data. Adaptation can help manage risks, even though this could prove costly for affected regions and entail hard choices. Preparations for adaptation—whether seawalls, cooling shelters, or drought-resistant crops—will need collective attention, particularly about where to invest versus retreat. While adaptation is now urgent and there are many adaptation opportunities, climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.

How a changing climate could impact socioeconomic systems

Five systems directly affected by physical climate change

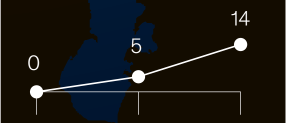
- Livability and workability
- Food systems
- Physical assets
- Infrastructure services
- Natural capital

Examples of direct impact of physical climate risk across geographies and sectors, **today, 2030, and 2050**

This assessment of the hazards and impacts of physical climate risk is based on an "inherent risk" scenario absent any adaptation and mitigation response. Analysis based on modeling of an RCP 8.5 scenario of greenhouse gas concentrations.

India

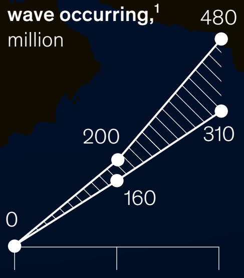
Annual likelihood of experiencing a lethal heat wave[1] in climate-exposed regions, %



~10%

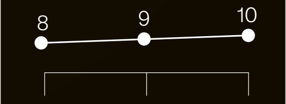
of Indian households owned an air conditioning unit in 2018

People living in areas having some probability of a lethal heat wave occurring,[1] million



Global breadbaskets

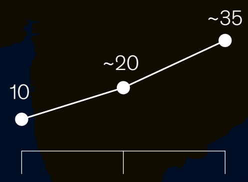
Land-weighted global average share of decade spent in drought, %



~60%

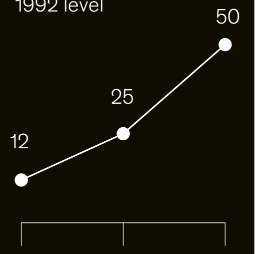
of global food production occurs in only 5 regions

Global annual harvest >15% below average at least once per decade, % likelihood



Florida

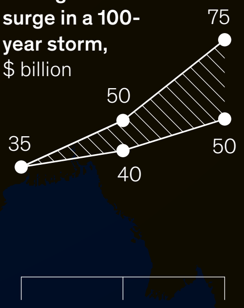
Sea level rise, cm over 1992 level



$200B

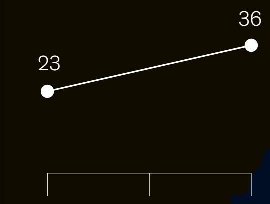
of residential real estate is < 1.8 meters above high tide

Residential real estate damage from storm surge in a 100-year storm, $ billion



Ho Chi Minh City

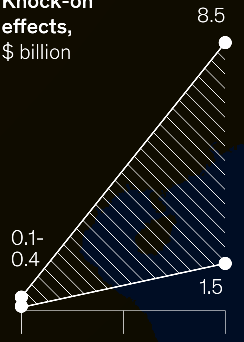
Flooded area of city in a 100-year flood, %



~10M–13M

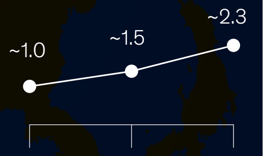
people living in Ho Chi Minh city by 2050

Knock-on effects, $ billion



Glaciers

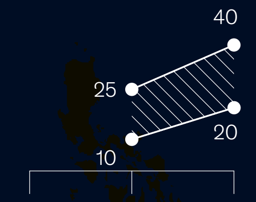
Median temperature anomaly, °C relative to 1850–1900



>16%

of people rely on glacial water for drinking and irrigation

Glacial mass melt in some Hindu Kush Himalayan subregions, %



A global geospatial assessment of climate risk **by 2050**

0.7B–1.2B

people living in areas with a 14 percent average annual likelihood of lethal heat waves.

Increase

in volatility of yields globally, some countries could benefit while others could see increased risk.

2×–4×

the amount of capital stock that could be damaged from riverine flooding by 2030 and 2050.

~45%

of the earth's land area projected to experience biome shifts, impacting ecosystem services, local livelihoods, and species' habitat.

What can be done to adapt to increased physical climate risk?

- **Protect people and assets**
- **Build resilience**
- **Reduce exposure**
- **Insure**
- **Finance**

---

[1] Lethal heat waves are defined as three-day events during which average daily maximum wet-bulb temperature could exceed the survivability threshold for a healthy human being resting in the shade. The numbers here do not factor in air conditioner penetration. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.

For the dates, the climate state today is defined as the average conditions between 1998 and 2017, 2030 refers to the average of the years 2021–40, while 2050 refers to the average of the years 2041–60.

McKinsey
Global Institute

Executive summary

McKinsey has a long history of research on topics related to the economics of climate change. Over the past decade, we have published a variety of research including a cost curve illustrating feasible approaches to abatement and reports on understanding the economics of adaptation and identifying the potential to improve resource productivity.[1] This research builds on that work and focuses on understanding the nature and implications of physical climate risk in the next three decades.

We draw on climate model forecasts to showcase how the climate has changed and could continue to change, how a changing climate creates new risks and uncertainties, and what steps can be taken to best manage them. Climate impact research makes extensive use of scenarios. Four “Representative Concentration Pathways“ (RCPs) act as standardized inputs to climate models. They outline different atmospheric greenhouse gas concentration trajectories between 2005 and 2100. During their inception, RCPs were designed to collectively sample the range of then-probable future emission pathways, ranging from lower (RCP2.6) to higher (RCP 8.5) CO_2 concentrations. Each RCP was created by an independent modeling team and there is no consistent design of the socio-economic parameter assumptions used in the derivation of the RCPs. By 2100, the four RCPs lead to very different levels of warming, but the divergence is moderate out to 2050 and small to 2030. Since the research in this report is most concerned with understanding inherent physical risks, we have chosen to focus on the higher-emission scenario, i.e. RCP 8.5, because of the higher-emissions, lower-mitigation scenario it portrays, in order to assess physical risk in absence of further decarbonization (Exhibit E1).

We focus on physical risk—that is, the risks arising from the physical effects of climate change, including the potential effects on people, communities, natural and physical capital, and economic activity, and the implications for companies, governments, financial institutions, and individuals. Physical risk is the fundamental driver of other climate risk types—transition risk and liability risk.[2] We do not focus on transition risks, that is, impacts from decarbonization, or liability risks associated with climate change. While an understanding of decarbonization and the risk and opportunities it creates is a critical topic, this report contributes by exploring the nature and costs of ongoing climate change in the next one to three decades in the absence of decarbonization.

---

[1] See, for example, *Shaping climate-resilient development: A framework for decision-making*, Economics of Climate Adaptation, 2009; “Mapping the benefits of the circular economy,” *McKinsey Quarterly*, June 2017; *Resource revolution: Meeting the world’s energy, materials, food, and water needs*, McKinsey Global Institute, November 2011; and *Beyond the supercycle: How technology is reshaping resources*, McKinsey Global Institute, February 2017. For details of the abatement cost curves, see *Greenhouse gas abatement cost curves*, McKinsey.com.

[2] Transition risk can be defined as risks arising from transition to a low-carbon economy; liability risk as risks arising from those affected by climate change seeking compensation for losses. See *Climate change: What are the risks to financial stability?* Bank of England, KnowledgeBank.

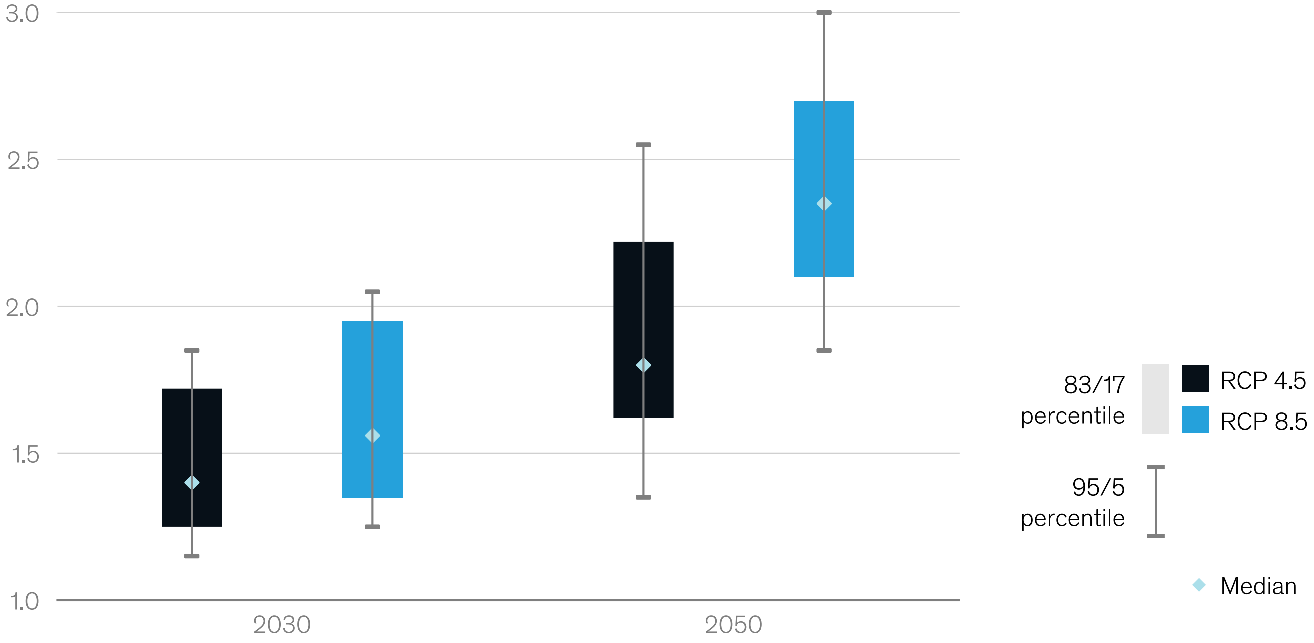
Our work offers both a call to action and a set of tools and methodologies to help assess the socioeconomic risks posed by climate change. We assess the socioeconomic risk from “acute” hazards, which are one-off events like floods or hurricanes, as well as from “chronic” hazards, which are long-term shifts in climate parameters like temperature.[3] We look at two periods: between now and 2030 and from 2030 to 2050. In doing so, we have relied on climate hazard data from climate scientists and focused on establishing socioeconomic impact, given potential changes in climate hazards (see Box E1, “Our research methodology”). We develop a methodology to measure the risk from the changing climate and the uncertainties associated with these estimates (see Box E2, “How our methodology addresses uncertainties”). At the end of this executive summary, we highlight questions for stakeholders seeking to respond to the challenge of heightened physical climate risk (see Box E3, “Questions for individual stakeholders to consider”).

Exhibit E1

We make use of RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization.

Global average land and sea surface temperature anomaly relative to 1850–1900 average

°C



Note: For clarity of graph, outliers beyond 95th to 5th percentile are not shown. This chart shows two RCPs that are most commonly used in climate models, to provide a sense of the spread in scenarios.

Source: Intergovernmental Panel on Climate Change, The Physical Science Basis, 2013

---

[3] By hazards, we mean climate-induced physical phenomena that have the potential to impact natural and socioeconomic systems.

Box E1

Our research methodology

In this report, we measure the impact of climate change by the extent to which it could affect human beings, human-made physical assets, and the natural world. While many scientists, including climate scientists, are employed at McKinsey & Company, we are not a climate modeling institution. Our focus in this report has been on translating the climate science data into an assessment of physical risk and its implications for stakeholders. Most of the climatological analysis performed for this report was done by Woods Hole Research Center (WHRC), and in other instances, we relied on publicly available climate science data, for example from institutions like the World Resources Institute. WHRC's work draws on the most widely used and thoroughly peer-reviewed ensemble of climate models to estimate the probabilities of relevant climate events occurring. Here, we highlight key methodological choices:

Case studies

In order to link physical climate risk to socioeconomic impact, we investigate nine specific cases that illustrate exposure to climate change extremes and proximity to physical thresholds. These cover a range of sectors and geographies and provide the basis of a "micro-to-macro" approach that is a characteristic of MGI research. To inform our selection of cases, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We find these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital.

We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds. As such, these cases represent leading-edge examples of climate change risk. They show that the direct risk from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" of capital (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). Through our case studies, we also assess the knock-on effects that could occur, for example to downstream sectors or consumers. We primarily rely on past examples and empirical estimates for this assessment of knock-on effects, which is likely not exhaustive given the complexities associated with socioeconomic systems. Through this "micro" approach, we offer decision makers a methodology by which to assess direct physical climate risk, its characteristics, and its potential knock-on impacts.

Global geospatial analysis

In a separate analysis, we use geospatial data to provide a perspective on climate change across 105 countries over the next 30 years. This geospatial analysis relies on the same five-systems framework of direct impacts that we used for the case studies. For each of these systems, we identify a measure, or measures, of the impact of climate change, using indicators where possible as identified in our cases.

Similar to the approach discussed above for our cases, our analyses are conducted at a grid-cell level, overlaying data on a hazard (for example, floods of different depths, with their associated likelihoods), with exposure to that hazard (for example, capital stock exposed to flooding), and a damage function that assesses resilience (for example, what share of capital stock is damaged when exposed to floods of different depth). We then combine these grid-cell values to country and global numbers. While the goal of this analysis is to measure direct impact, due to data availability issues, we have used five measures of socioeconomic impact and one measure of climate hazards themselves—drought. Our set of 105 countries represents 90 percent of the world's population and 90 percent of global GDP. While we seek to include a wide range of risks and as many countries as possible, there are some we could not cover due to data limitations (for example, the impact of forest fires and storm surges).

What this report does not do

Since the purpose of this report is to understand the physical risks and disruptive impacts of climate change, there are many areas which we do not address.

— We do not assess the efficacy of climate models but instead draw on best practice approaches from climate science literature and highlight key uncertainties.

— We do not examine in detail areas and sectors that are likely to benefit from climate change such as the potential for improved agricultural yields in parts of Canada, although we quantify some of these benefits through our geospatial analysis.

— As the consequences of physical risk are realized, there will likely be acts of adaptation, with a feedback effect on the physical risk. For each of our cases, we identify adaptation responses. We have not conducted a detailed bottom-up cost-benefit analysis of adaptation but have built on existing literature and expert interviews to understand the most important measures and their indicative cost, effectiveness, and implementation challenges, and to estimate the expected global adaptation spending required.

— We note the critical importance of decarbonization in a climate risk management approach but a detailed discussion of decarbonization is beyond the scope of this report.

— While we attempt to draw out qualitatively (and, to the extent possible, quantitatively) the knock-on effects from direct physical impacts of climate change, we recognize the limitations of this exercise given the complexity of socioeconomic systems. There are likely knock-on effects that could occur which our analysis has not taken into account. For this reason, we do not attempt to size the global GDP at risk from climate change (see Box 4 in Chapter 4 for a detailed discussion).

— We do not provide projections or deterministic forecasts, but rather assess risk. The climate is the statistical summary of weather patterns over time and is therefore probabilistic in nature. Following standard practice, our findings are therefore framed as "statistically expected values"—the statistically expected average impact across a range of probabilities of higher or lower climate outcomes.[1]

---

[1] We also report the value of "tail risks"—that is, low-probability, high-impact events like a 1-in-100-year storm—on both an annual and cumulative basis. Consider, for example, a flooding event that has a 1 percent annual likelihood of occurrence every year (often described as a "100-year flood"). In the course of the lifetime of home ownership—for example, over a 30-year period—the cumulative likelihood that the home will experience at least one 100-year flood is 26 percent.

Box E2

How our methodology addresses uncertainties

One of the main challenges in understanding the physical risk arising from climate change is the range of uncertainties involved. Risks arise as a result of an involved causal chain. Emissions influence both global climate and regional climate variations, which in turn influence the risk of specific climate hazards (such as droughts and sea-level rise), which then influence the risk of physical damage (such as crop shortages and infrastructure damages), which finally influence the risk of financial harm. Our analysis, like any such effort, relies on assumptions made along the causal chain: about emission paths and adaptation schemes; global and regional climate models; physical damage functions; and knock-on effects. The further one goes along the chain, the greater the intrinsic model uncertainty.

Taking a risk-management lens, we have developed a methodology to provide decision makers with an outlook over the next three decades on the inherent risk of climate change—that is, risk absent any adaptation and mitigation response. Separately, we outline how this risk could be reduced via an adaptation response in our case studies. Where feasible, we have attempted to size the costs of the potential adaptation responses. We believe this approach is appropriate to help stakeholders understand the potential magnitude of the impacts from climate change and the commensurate response required.

The key uncertainties include the emissions pathway and pace of warming, climate model accuracy and natural variability, the magnitude of direct and indirect socioeconomic impacts, and the socioeconomic response. Assessing these uncertainties, we find that our approach likely results in conservative estimates of inherent risk because of the skew in uncertainties of many hazard projections toward “worse” outcomes as well as challenges with modeling the many potential knock-on effects associated with direct physical risk.[1]

Emissions pathway and pace of warming

As noted above, we have chosen to focus on the RCP 8.5 scenario because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization. Under this scenario, science tells us that global average temperatures will reach just over 2 degrees Celsius above preindustrial levels by 2050. However, action to reduce emissions could mean that the projected outcomes—both hazards and impacts—based on this trajectory are delayed post 2050. For example, RCP 8.5 predicts global average warming of 2.3 degrees Celsius by 2050, compared with 1.8 degrees Celsius for RCP 4.5. Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080.

Climate model accuracy and natural variability

We have drawn on climate science that provides sufficiently robust results, especially over a 30-year period. To minimize the uncertainty associated with any particular climate model, the mean or median projection (depending on the specific variable being modeled) from an ensemble of climate models has been used, as is standard practice in the climate literature. We also note that climate model uncertainty on global temperature increases tends to skew toward worse outcomes; that is, differences across climate models tend to predict outcomes that are skewed toward warmer rather than cooler global temperatures. In addition, the climate models used here omit potentially important biotic feedbacks including greenhouse gas emissions from thawing permafrost, which will tend to increase warming.

---

[1] See Naomi Oreskes and Nicholas Stern, “Climate change will cost us even more than we think,” *New York Times*, October 23, 2019.

To apply global climate models to regional analysis, we used techniques established in climate literature.[2] The remaining uncertainty related to physical change is variability resulting from mechanisms of natural rather than human origin. This natural climate variability, which arises primarily from multiyear patterns in ocean and/or atmosphere circulation (for example, the El Niño/La Niña oscillation), can temporarily affect global or regional temperature, precipitation, and other climatic variables. Natural variability introduces uncertainty surrounding how hazards could evolve because it can temporarily accelerate or delay the manifestation of statistical climate shifts.[3] This uncertainty will be particularly important over the next decade, during which overall climatic shifts relative to today may be smaller in magnitude than an acceleration or delay in warming due to natural variability.

Direct and indirect socioeconomic impacts

Our findings related to socioeconomic impact of a given physical climate effect involve uncertainty, and we have provided conservative estimates. For direct impacts, we have relied on publicly available vulnerability assessments, but they may not accurately represent the vulnerability of a specific asset or location. For indirect impacts, given the complexity of socioeconomic systems, we know that our results do not capture the full impact of climate change knock-on effects. In many cases, we have either discussed knock-on effects in a qualitative manner alone or relied on empirical estimations. This may underestimate the direct impacts of climate change's inherent risk in our cases, for example the knock-on effects of flooding in Ho Chi Minh City or the potential for financial devaluation in Florida real estate. This is not an issue in our 105-country geospatial analysis, as the impacts we are looking at there are direct and as such we have relied on publicly available vulnerability assessments as available at a regional or country level.

Socioeconomic response

The amount of risk that manifests also depends on the response to the risk. Adaptation measures such as hardening physical infrastructure, relocating people and assets, and ensuring backup capacity, among others, can help manage the impact of climate hazards and reduce risk. We follow an approach that first assesses the inherent risk and then considers a potential adaptation response. The inherent or ex ante level of risk is the risk without taking any steps to reduce its likelihood or severity. We have not conducted a detailed bottom-up cost-benefit analysis of adaptation measures but have built on existing literature and expert interviews to understand the most important measures and their indicative cost, effectiveness, and implementation challenges in each of our cases, and to estimate the expected global adaptation spending required. While we note the critical importance of decarbonization in an appropriate climate risk management approach, a detailed discussion of decarbonization is beyond the scope of this report.

How decision makers incorporate these uncertainties into their management choices will depend on their risk appetite and overall risk-management approach. Some may want to work with the outcome considered most likely (which is what we generally considered), while others may want to consider a worse- or even worst-case scenario. Given the complexities we have outlined above, we recognize that more research is needed in this critical field. However, we believe that despite the many uncertainties associated with estimates of impact from a changing climate, it is possible for the science and socioeconomic analysis to provide actionable insights for decision makers. For an in-depth discussion of the main uncertainties and how we have sought to resolve them, see Chapter 1.

---

[2] See technical appendix for details.

[3] Kyle L. Swanson, George Sugihara, and Anastasios A. Tsonis, "Long-term natural variability and 20th century climate change," *Proceedings of the National Academy of Sciences*, September 2009, Volume 106, Number 38.

We find that risk from climate change is already present and growing. The insights from our cases help highlight the nature of this risk, and therefore how stakeholders should think about assessing and managing it. Seven characteristics stand out. Physical climate risk is:

— **Increasing.** In each of our nine cases, the level of physical climate risk increases by 2030 and further by 2050. Across our cases, we find increases in socioeconomic impact of between roughly two and 20 times by 2050 versus today's levels. We also find physical climate risks are generally increasing across our global country analysis even as some countries find some benefits (such as increased agricultural yields in Canada, Russia, and parts of northern Europe).

— **Spatial.** Climate hazards manifest locally. The direct impacts of physical climate risk thus need to be understood in the context of a geographically defined area. There are variations between countries and also within countries.

— **Non-stationary.** As the Earth continues to warm, physical climate risk is ever-changing or non-stationary. Climate models and basic physics predict that further warming is "locked in" over the next decade due to inertia in the geophysical system, and that the temperature will likely continue to increase for decades to come due to socio-technological inertia in reducing emissions.[4] Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions. Furthermore, given the thermal inertia of the earth system, some amount of warming will also likely occur after net-zero emissions are reached.[5] Managing that risk will thus require not moving to a "new normal" but preparing for a world of constant change. Financial markets, companies, governments, or individuals have mostly not had to address being in an environment of constant change before, and decision making based on experience may no longer be reliable. For example, engineering parameters for infrastructure design in certain locations will need to be re-thought, and home owners may need to adjust assumptions about taking on long-term mortgages in certain geographies.

— **Nonlinear.** Socioeconomic impacts are likely to propagate in a nonlinear way as hazards reach thresholds beyond which the affected physiological, human-made, or ecological systems work less well or break down and stop working altogether. This is because such systems have evolved or been optimized over time for historical climates. Consider, for example, buildings designed to withstand floods of a certain depth, or crops grown in regions with a specific climate. While adaptation in theory can be carried out at a fairly rapid rate for some systems (for example, improving the floodproofing of a factory), the current rate of warming—which is at least an order of magnitude faster than any found in the past 65 million years of paleoclimate records—means that natural systems such as crops are unable to evolve fast enough to keep pace.[6] Impacts could be significant if system thresholds are breached even by small amounts. The occurrence of multiple risk factors (for example, exposure to multiple hazards, other vulnerabilities like the ability to finance adaptation investments, or high reliance on a sector that is exposed to climate hazard) in a single geography, something we see in several of our cases, is a further source of potential nonlinearity.

— **Systemic.** While the direct impact from climate change is local, it can have knock-on effects across regions and sectors, through interconnected socioeconomic and financial systems. For example, flooding in Florida could not only damage housing but also raise insurance costs, affect property values of exposed homes, and in turn reduce property tax revenues

---

[4] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters,* January 2018, Volume 13, Number 1.

[5] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters,* January 2018, Volume 13, Number 1; H. Damon Matthews & Ken Caldeira, "Stabilizing climate requires near zero emissions". *Geophysical Research Letters* February 2008, Volume 35; Myles Allen et al, *"Warming caused by cumulative carbon emissions towards the trillionth ton."* Nature, April 2009, Volume 485.

[6] Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science,* August 2013, Volume 341, Number 6145; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," Proceedings of the National Academy of Sciences, March 2014, Volume 111, Number 9.

for communities. Like physical systems, many economic and financial systems have been designed in a manner that could make them vulnerable to a changing climate. For example, global production systems like supply chains or food production systems have optimized efficiency over resiliency, which makes them vulnerable to failure if critical production hubs are impacted by intensifying hazards. Insurance systems are designed so that property insurance is re-priced annually; however, home owners often have longer-term time horizons of 30 years or more on their real estate investments. As a result of this duration mismatch, home owners could be exposed to the risk of higher costs, in the form of rising premiums (which could be appropriate to reflect rising risks), or impacts on the availability of insurance. Similarly, debt levels in many places are also at thresholds, so knock-on effects on relatively illiquid financial instruments like municipal bonds should also be considered.

- **Regressive.** The poorest communities and populations within each of our cases typically are the most vulnerable. Across all 105 countries in our analysis, we find an increase in at least one of six indicators of socioeconomic impact by 2030. Emerging economies face the biggest increase in potential impact on workability and livability. Poorer countries also rely more on outdoor work and natural capital and have less financial means to adapt quickly. Climate change can bring benefits as well as costs to specific areas, for example shifting tourism from southern to northern Europe.

- **Under-prepared.** While companies and communities have been adapting to reduce climate risk, the pace and scale of adaptation are likely to need to significantly increase to manage rising levels of physical climate risk. Adaptation is likely to entail rising costs and tough choices that may include whether to invest in hardening or relocate people and assets. It thus requires coordinated action across multiple stakeholders.

Climate change is already having substantial physical impacts at a local level; these impacts are likely to grow, intensify, and multiply

Earth's climate is changing, and further change is unavoidable in the next decade and in all likelihood beyond. The planet's temperature has risen by about 1.1 degrees Celsius on average since the 1880s.[7] This has been confirmed by both satellite measurements and by the analysis of hundreds of thousands of independent weather station observations from across the globe. The rapid decline in the planet's surface ice cover provides further evidence. This rate of warming is at least an order of magnitude faster than any found in the past 65 million years of paleoclimate records.[8]

The average conceals more dramatic changes at the extremes. In statistical terms, distributions of temperature are shifting to the right (towards warmer) and broadening. That means the average day in many locations is now hotter ("shifting means"), and extremely hot days are becoming more likely ("fattening tails"). For example, the evolution of the distribution of observed average summer temperatures for each 100-by-100-kilometer square in the Northern Hemisphere shows that the mean summer temperature has increased over time (Exhibit E2). The percentage of the Northern Hemisphere (in square kilometers) that experiences a substantially hotter summer—a two-standard-deviation warmer average temperature in a given year—has increased more than 15 times, from less than 1 percent to 15 percent. The share of the Northern Hemisphere (in square kilometers) that experiences an extremely hot summer—three-standard-deviation hotter average temperature in a given summer—has increased from zero to half a percent.

Averages also conceal wide spatial disparities. Over the same period that the Earth globally has warmed by 1.1 degrees, in southern parts of Africa and in the Arctic, average temperatures

---

[7] NASA GISTEMP (2019) and Nathan J. L. Lenssen et al., "Improvements in the GISTEMP uncertainty model," *Journal of Geophysical Resources: Atmospheres*, June 2019, Volume 124, Number 12.

[8] Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science*, August 2013, Volume 341, Number 6145; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," *Proceedings of the National Academy of Sciences*, March 2014, Volume 111, Number 9.

have risen by 0.2 and 0.5 degrees Celsius and by 4 to 4.3 degrees Celsius, respectively.[9] In general, the land surface has warmed faster than the 1.1-degree global average, and the oceans, which have a higher heat capacity, have warmed less.

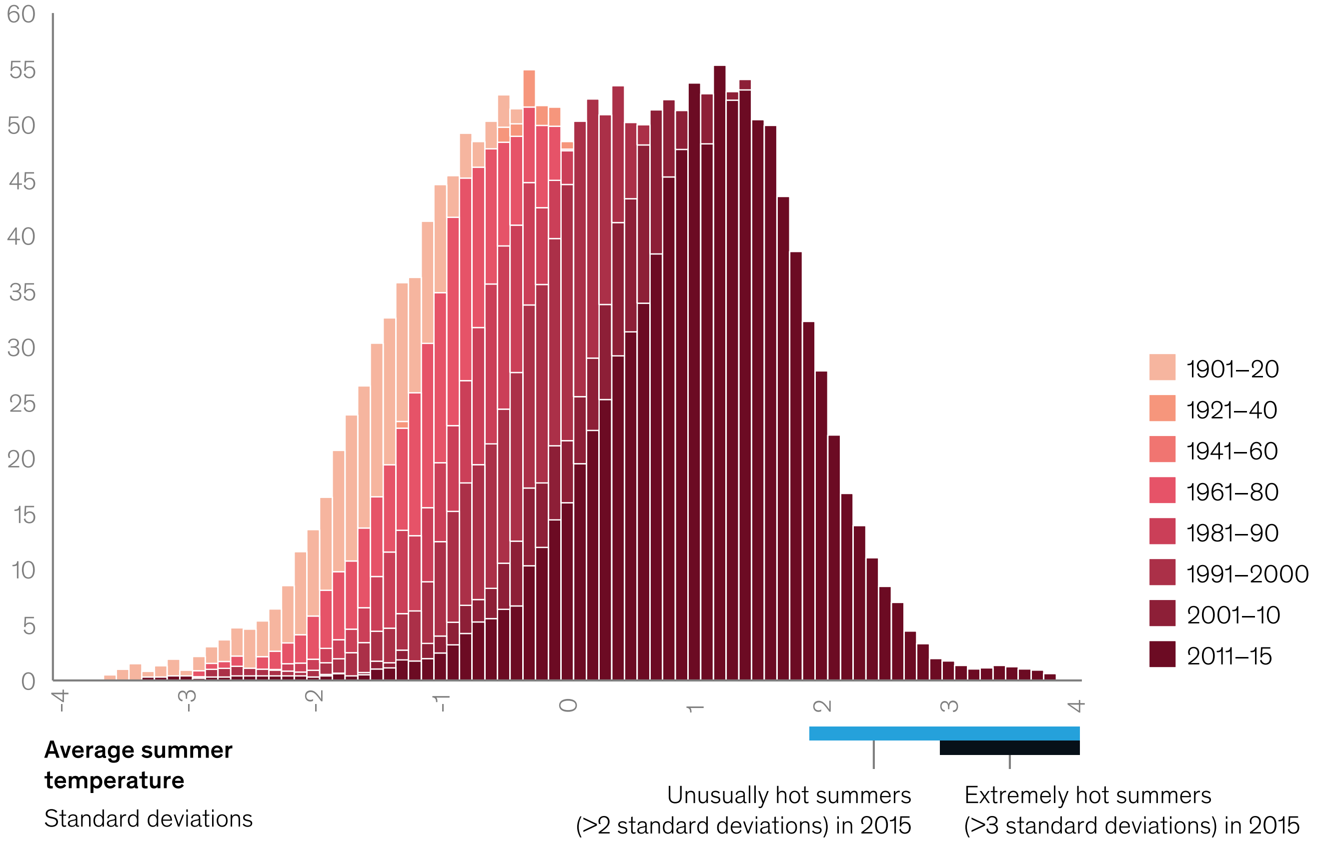
Looking forward, further change is unavoidable over the next decade at least, and in all likelihood beyond. The primary driver of the observed rate of temperature increase over the past two centuries is the human-caused rise in atmospheric levels of carbon dioxide (CO_2) and other greenhouse gases, including methane and nitrous oxide.[10] Since the beginning of the Industrial Revolution in the mid-18th century, humans have released nearly 2.5 trillion tonnes of CO_2 into the atmosphere, raising atmospheric CO_2 concentrations from about 280 parts per million by volume (ppmv) to 415 ppmv, increasing at more than 2 ppmv per year .

Exhibit E2

A small shift in the average can hide dramatic changes at the extremes.

Frequency of local temperature anomalies in the Northern Hemisphere

Number of observations, thousands



Unusually hot summers (>2 standard deviations) in 2015 occur at 15% of land surface, compared with 0.2% prior to 1980

Extremely hot summers (>3 standard deviations) in 2015 occur at 0.5% of land surface, compared with 0% prior to 1980

Note: Because the signal from anthropogenic greenhouse gas emissions did not emerge strongly prior to 1980, some of the early time period distributions in the above figure overlap and are difficult to see. Northern Hemisphere land surface divided into 100km x 100km grid cells. Standard deviations based on measuring across the full sample of data across all grid-cells and years.
Source: Sippel et al., 2015; McKinsey Global Institute analysis with advice from University of Oxford Environmental Change Institute

---

[9] Goddard Institute for Space Studies (GISS), GISTEMP Reanalysis dataset (2019).

[10] Between 98 and 100 percent of observed warming since 1850 is attributable to the rise in atmospheric greenhouse gas concentrations, and approximately 75 percent is attributable to CO_2 directly. The remaining warming is caused by short-lived greenhouse gases like methane and black carbon, which, because they decay in the atmosphere, warm the planet as a function of rate (or flow) of emissions, not cumulative stock of emissions. Karsten Haustein et al., “A real-time Global Warming Index,” *Nature Scientific Reports*, November 13, 2017; Richard J. Millar and Pierre Friedlingstein, “The utility of the historical record for assessing the transient climate response to cumulative emissions,” *Philosophical Transactions of the Royal Society*, May 2018, Volume 376, Number 2119.

Carbon dioxide persists in the atmosphere for hundreds of years.[11] As a result, in the absence of large-scale human action to remove CO_2 from the atmosphere, nearly all of the warming that occurs will be permanent on societally relevant timescales.[12] Additionally, because of the strong thermal inertia of the ocean, more warming is likely already locked in over the next decade, regardless of emissions pathway. Beyond 2030, climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.[13]

With increases in global average temperatures, climate models indicate a rise in climate hazards globally. According to climate science, further warming will continue to increase the frequency and/or severity of acute climate hazards across the world, such as lethal heat waves, extreme precipitation, and hurricanes, and will further intensify chronic hazards such as drought, heat stress, and rising sea levels.[14] Here, we describe the prediction of climate models analyzed by WHRC, and also publicly available data for a selection of hazards for an RCP 8.5 scenario (Exhibits E3 and E4):

— **Increase in average temperatures.**[15] Global average temperatures are expected to increase over the next three decades, resulting in a 2.3-degree Celsius (+0.5/-0.3) average increase relative to the preindustrial period by 2050, under an RCP 8.5 scenario. Depending on the exact location, this can translate to an average local temperature increase of between 1.5 and 5.0 degrees Celsius relative to today. The Arctic in particular is expected to warm more rapidly than elsewhere.

— **Extreme precipitation.**[16] In parts of the world, extreme precipitation events, defined here as one that was a once in a 50-year event (that is, with a 2 percent annual likelihood) in the 1950–81 period, are expected to become more common. The likelihood of extreme precipitation events is expected to grow more than fourfold in some regions, including parts of China, Central Africa, and the east coast of North America compared with the period 1950–81.

— **Hurricanes.**[17] While climate change is seen as unlikely to alter the frequency of tropical hurricanes, climate models and basic physical theory predict an increase in the average severity of those storms (and thus an increase in the frequency of severe hurricanes). The likelihood of severe hurricane precipitation—that is, an event with a 1 percent likelihood annually in the 1981–2000 period—is expected to double in some parts of the southeastern United States and triple in some parts of Southeast Asia by 2040. Both are densely populated areas with large and globally connected economic activity.

— **Drought.**[18] As the Earth warms, the spatial extent and share of time spent in drought is projected to increase. The share of a decade spent in drought conditions is projected to be up to 80 percent in some parts of the world by 2050, notably in parts of the Mediterranean, southern Africa, and Central and South America.

---

[11] David Archer. *"Fate of Fossil Fuel CO_2 in geological time."* Journal of Geophysical Research, March 2005, Volume 110.

[12] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters,* January 2018, Volume 13, Number 1. David Archer. *"Fate of Fossil Fuel CO_2 in geological time."* Journal of Geophysical Research, March 2005, Volume 110; H. Damon Matthews & Susan Solomon. *"Irreversible does not mean unavoidable."* Science. April 2013, Volume 340, Issue 6131.

[13] H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters,* January 2018, Volume 13, Number 1; H. Damon Matthews & Ken Caldeira, "Stabilizing climate requires near zero emissions". *Geophysical Research Letters* February 2008, Volume 35; Myles Allen et al, *"Warming caused by cumulative carbon emissions towards the trillionth ton."* Nature, April 2009, Volume 485.

[14] This list of climate hazards is a subset, and the full list can be found in the full report. The list is illustrative rather than exhaustive. Due to data and modeling constraints, we did not include the following hazards: increased frequency and severity of forest fires, increased biological and ecological impacts from pests and diseases, increased severity of hurricane wind speed and storm surge, and more frequent and severe coastal flooding due to sea-level rise.

[15] Taken from KNMI Climate Explorer (2019), using the mean of the full CMIP5 ensemble of models.

[16] Modeled by WHRC using the median projection from 20 CMIP5 Global Climate Models (GCMs). To accurately estimate the probability of extreme precipitation events, a process known as statistical bootstrapping was used. Because these projections are not estimating absolute values, but rather changes over time, bias correction was not used.

[17] Modeled by WHRC using the Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019. Time periods available for the hurricane modeling were 1981–2000 baseline, and 2031–50 future period. These are the results for two main hurricane regions of the world; other including the Indian sub-continent were not modeled.

[18] Modeled by WHRC using the median projection of 20 CMIP5 GCMs, using the self-correcting Palmer Drought Severity Index (PDSI). Projections were corrected to account for increasing atmospheric CO_2 concentrations.

Exhibit E3

Climate hazards are projected to intensify in many parts of the world.

Based on RCP 8.5

Today **2030** **2050**

Increase in average annual temperature

Shift compared to preindustrial climate

°C

■ 0–0.5 ■ 0.6–1.0 ■ 1.1–1.5 ■ 1.6–2.0 ■ 2.1–2.5 ■ 2.6–3.0 ■ 3.1–3.5 ■ 3.6–4.0 ■ 4.1–4.5 ■ 4.6–5.0 ■ 5.1–5.5 ■ 5.6–6.0 ■ 6.1–6.5 ■ 6.6–7.0 ■ >7.0

Extreme precipitation

Change of likelihood compared to 1950–81 of an 1950–81 50-year precipitation event

■ ≤1x ■ 1–2x ■ 2–3x ■ 3–4x ■ >4x

Hurricane (precipitation)

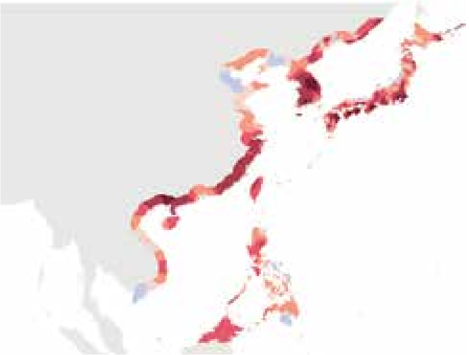
Change of likelihood in 2040 compared with 1981–2000 of a 1981–2000 100-year hurricane

Southeast United States

- ■ ≤1.0x
- ■ 1.1–1.5x
- ■ 1.6–2.0x
- ■ >2.0x

Southeast Asia

- ■ ≤1.00x
- ■ 1.01–1.25x
- ■ 1.26–1.75x
- ■ 1.76–2.25x
- ■ 2.26–3.00x
- ■ >3.00x



Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

Exhibit E4

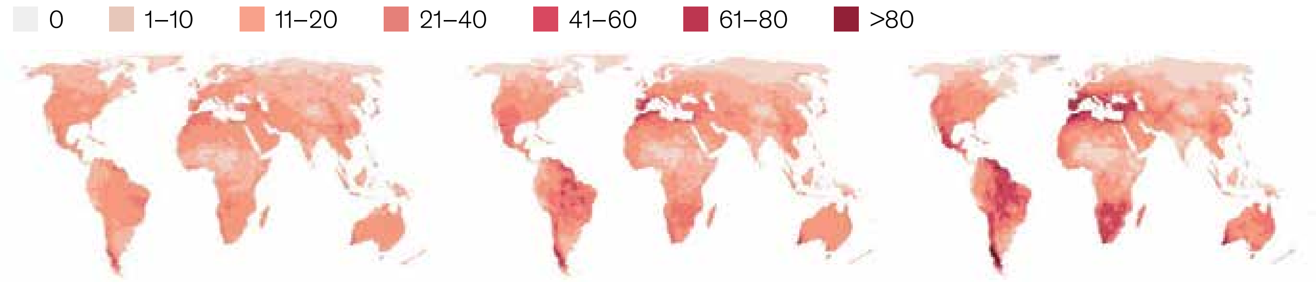
Climate hazards are projected to intensify in many parts of the world (continued).

Based on RCP 8.5

Today **2030** **2050**

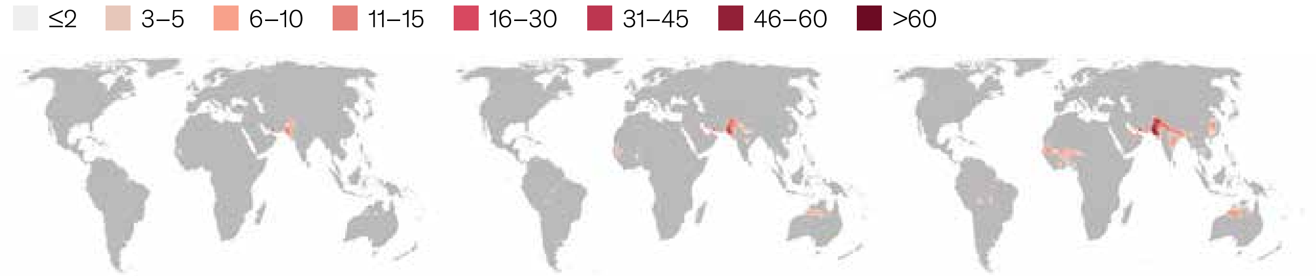
Drought frequency[1]

% of decade in drought



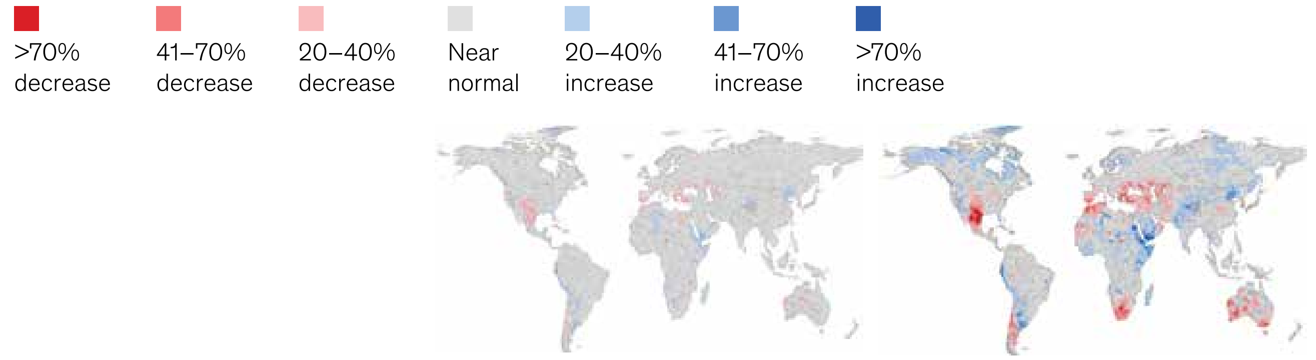
Lethal heat wave probability[2]

% p.a.



Water supply

Change in surface water compared with 2018 (%)
Boundaries on the map represent water basins



1. Measured using a three-month rolling average. Drought is defined as a rolling three month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature and precipitation-based drought index calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to -4 (extremely dry).
2. A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in the shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

- **Lethal heat waves.**[19] Lethal heat waves are defined as three-day events during which average daily maximum wet-bulb temperature could exceed the survivability threshold for a healthy human being resting in the shade.[20] Under an RCP 8.5 scenario, urban areas in parts of India and Pakistan could be the first places in the world to experience heat waves that exceed the survivability threshold for a healthy human being, with small regions projected to experience a more than 60 percent annual chance of such a heat wave by 2050.

- **Water supply.**[21] As rainfall patterns, evaporation, snowmelt timing, and other factors change, renewable freshwater supply will be affected. Some parts of the world like South Africa and Australia are expected to see a decrease in water supply, while other areas, including Ethiopia and parts of South America, are projected to experience an increase. Certain regions, for example, parts of the Mediterranean region and parts of the United States and Mexico, are projected to see a decrease in mean annual surface water supply of more than 70 percent by 2050. Such a large decline in water supply could cause or exacerbate chronic water stress and increase competition for resources across sectors.

The socioeconomic impacts of climate change will likely be nonlinear as system thresholds are breached and have knock-on effects

Climate change affects human life as well as the factors of production on which our economic activity is based and, by extension, the preservation and growth of wealth. We measure the impact of climate change by the extent to which it could disrupt or destroy stocks of capital—human, physical, and natural—and the resultant socioeconomic impact of that disruption or destruction. The effect on economic activity as measured by GDP is a consequence of the direct impacts on these stocks of capital.

Climate change is already having a measurable socioeconomic impact. Across the world, we find examples of these impacts and their linkage to climate change. We group these impacts in a five-systems framework (Exhibit E5). As noted in Box E1, this impact framework is our best effort to capture the range of socioeconomic impacts from physical climate hazards.

---

[19] Modeled by WHRC using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 GCMs. Models were independently bias corrected using the ERA-Interim dataset.

[20] We define a lethal heat wave as a three-day period with maximum daily wet-bulb temperatures exceeding 34 degrees Celsius wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35 degrees Celsius wet-bulb, and large cities with significant urban heat island effects could push 34C wet-bulb heat waves over the 35C threshold. At this temperature, a healthy human being, resting in the shade, can survive outdoors for four to five hours. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See the India case and our technical appendix for more details. Analysis based on an RCP 8.5 scenario.

[21] Taken from the World Resources Institute Water Risk Atlas (2018), which relies on 6 underlying CMIP5 models. Time periods of this raw dataset are the 20-year periods centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base dataset.

Exhibit E5

Socioeconomic impact of climate change is already manifesting and affects all geographies.

Impacted economic system	Area of direct risk		Socioeconomic impact	How climate change exacerbated hazard
Livability and workability	1	2003 European heat wave	$15 billion in losses	2x more likely
	2	2010 Russian heat wave	~55,000 deaths attributable	3x more likely
	3	2013–14 Australian heat wave	~$6 billion in productivity loss	Up to 3x more likely
	4	2017 East African drought	~800,000 people displaced in Somalia	2x more likely
	5	2019 European heat wave	~1,500 deaths in France	~10x more likely in France
Food systems	6	2015 Southern Africa drought	Agriculture outputs declined by 15%	3x more likely
	7	Ocean warming	Up to 35% decline in North Atlantic fish yields	Ocean surface temperatures have risen by 0.7°C globally
Physical assets	8	2012 Hurricane Sandy	$62 billion in damage	3x more likely
	9	2016 Fort McMurray Fire, Canada	$10 billion in damage, 1.5 million acres of forest burned	1.5 to 6x more likely
	10	2017 Hurricane Harvey	$125 billion in damage	8–20% more intense
Infrastructure services	11	2017 flooding in China	$3.55 billion of direct economic loss, including severe infrastructure damage	2x more likely
Natural capital	12	30-year record low Arctic sea ice in 2012	Reduced albedo effect, amplifying warming	70% to 95% attributable to human-induced climate change
	13	Decline of Himalayan glaciers	Potential reduction in water supply for more than 240 million people	~70% of global glacier mass lost in past 20 years is due to human-induced climate change

Source: R. Garcia-Herrera et al., 2010; K. Zander et al., 2015; Yin Sun et al., 2019; Parkinson, Claire L. et al., 2013; Kirchmeier-Young, Megan C. et al., 2017; Philip, Sjoukje et al., 2018; Funk, Chris et al., 2019; ametsoc.net; Bellprat et al., 2015; cbc.ca; coast.noaa.gov; dosomething.org; eea.europa.eu; Free et al., 2019; Genner et al., 2017; iopscience.iop.org; jstage.jst.go.jp; Lin et al., 2016; livescience.com; Marzeion et al., 2014; Perkins et al., 2014; preventionweb.net; reliefweb.int; reuters.com; Peterson et al., 2004; theatlantic.com; theguardian.com; van Oldenburgh, 2017; water.ox.ac.uk; Wester et al., 2019; Western and Dutch Central Bureau of Statistics; worldweatherattribution.org; McKinsey Global Institute analysis

Individual climate hazards could impact multiple systems. For example, extreme heat may affect communities through lethal heat waves and daylight hours rendered unworkable, even as it shifts food systems, disrupts infrastructure services, and endangers natural capital such as glaciers. Extreme precipitation and flooding can destroy physical assets and infrastructure while endangering coastal and river communities. Hurricanes can impact global supply chains, and biome shifts can affect ecosystem services. The five systems in our impact framework are:

- **Livability and workability.** Hazards like heat stress could affect the ability of human beings to work outdoors or, in extreme cases, could put human lives at risk. Heat reduces labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent overexertion. Increased temperatures could also shift disease vectors and thus affect human health.

- **Food systems.** Food production could be disrupted as drought conditions, extreme temperatures, or floods affect land and crops. A changing climate could both improve and degrade food system performance while introducing more or less volatility. In some cases, crop yields may increase; in other cases, thresholds could be exceeded beyond which some crops fail entirely.

- **Physical assets.** Physical assets like buildings could be damaged or destroyed by extreme precipitation, tidal flooding, forest fires, and other hazards. Hazards could even materially affect an entire network of assets such as a city's central business district.

- **Infrastructure services.** Infrastructure assets are a particular type of physical asset that could be destroyed or disrupted in their functioning, leading to a decline in the services they provide or a rise in the cost of these services. For example, power systems could become less productive under very hot conditions. A range of hazards including heat, wind, and flooding can disrupt infrastructure services. This in turn can have knock-on effects on other sectors that rely on these infrastructure assets.

- **Natural capital.** Climate change is shifting ecosystems and destroying forms of natural capital such as glaciers, forests, and ocean ecosystems, which provide important services to human communities. This in turn imperils the human habitat and economic activity. These impacts are hard to model but could be nonlinear and in some cases irreversible, such as glacier melting, as the temperature rises. In some cases, human mismanagement may play a role—for example, with forest fires and water scarcity—but its extent and impact are multiplied by climate change.

The nine distinct cases of physical climate risk in various geographies and sectors that we examine, including direct impact and knock-on effects, as well as adaptation costs and strategies, help illustrate the specific socioeconomic impact of the different physical climate hazards on the examined human, physical, or natural system. Our cases cover each of the five systems across geographies and include multiple climate hazards, sometimes occurring at the same location. Overall, our cases highlight a wide range of vulnerabilities to the changing climate.

Specifically, we looked at the impact of climate change on livability and workability in India and the Mediterranean; disruption of food systems through looking at global breadbaskets and African agriculture; physical asset destruction in residential real estate in Florida and in supply chains for semiconductors and heavy rare earth metals; disruption of five types of infrastructure services and, in particular, the threat of flooding to urban areas; and destruction of natural capital through impacts on glaciers, oceans, and forests.

Our case studies highlight that physical climate risk is growing, often in nonlinear ways. Physical climate impacts are spreading across regions, even as the hazards grow more intense within regions.

To assess the magnitude of direct physical climate risk in each case, we examine the severity of the hazard and its likelihood; the exposure of people, assets, or economic activity to the hazard; and the extent to which systems are vulnerable to the hazard. Researchers have examined insurance data on losses from natural disasters and found that most of the increase in direct impact to date has come more from greater exposure than from increases in the climate hazards themselves.[22] Changes in climate itself in the future are likely to play a bigger role. As the Earth warms, hazards will become more intense and or more frequent. Since physiological, human-made, and ecological systems have evolved or been optimized over time for historical climates, even small changes in hazard intensity can have large consequences if physical thresholds for resilience are breached.

Indeed, thresholds exist for all systems we have examined. For example: the human body functions at a stable core temperature of about 37 degrees Celsius, above which physical and mental functioning could be fatally impaired; corn yields can decline significantly above 20 degrees Celsius; cell phone towers have typically been built to withstand certain wind speeds above which they may fail (Exhibit E6).

The impacts, once such thresholds are crossed, could be significant. For example, by 2030 in an RCP 8.5 scenario, absent an effective adaptation response, we estimate that 160 million to 200 million people in India could live in regions with a 5 percent average annual probability of experiencing a heat wave that exceeds the survivability threshold for a healthy human being (without factoring in air conditioner penetration).[23]

Outdoor labor productivity is also expected to fall, thus reducing the effective number of hours that can be worked outdoors (Exhibit E7). As of 2017, in India, heat-exposed work produces about 50 percent of GDP, drives about 30 percent of GDP growth, and employs about 75 percent of the labor force, some 380 million people.[24] By 2030, the average number of lost daylight working hours in India could increase to the point where between 2.5 and 4.5 percent of GDP could be at risk annually, according to our estimates.

---

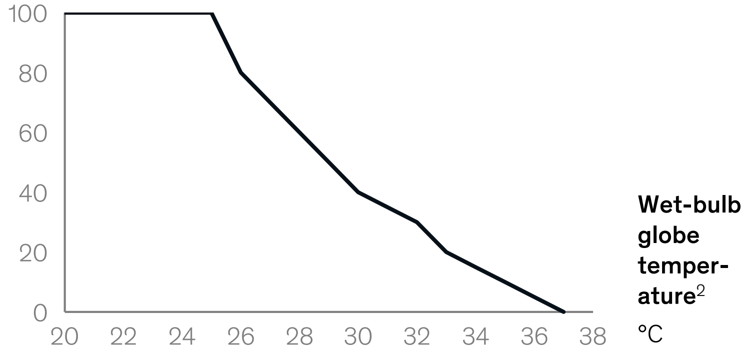
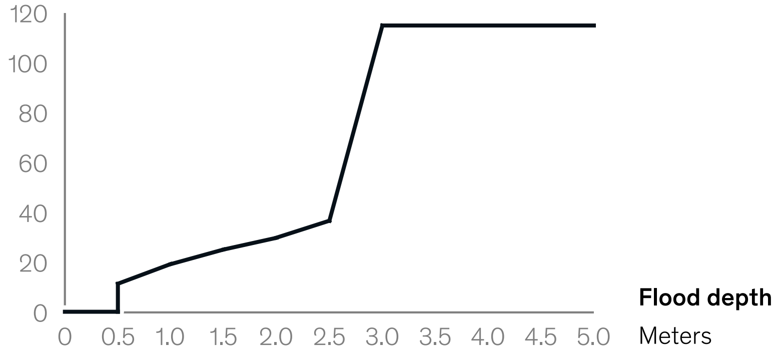
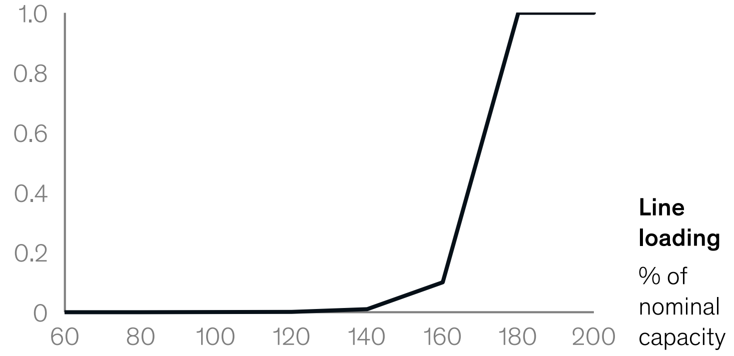
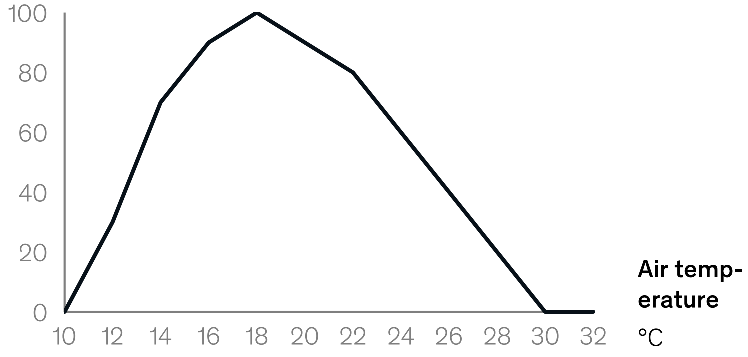
[22] Various researchers have attempted to identify the role played by each of these factors in driving economic losses to date. Insurance records of losses from acute natural disasters like floods, hurricanes, and forest fires show a clear upward trend in losses in real terms over time, and analyses show that the majority of this is driven by an increase in exposure. This is based on normalizing the real losses for increases in GDP, wealth, and exposure to strip out the effects of a rise in exposure. See for example, Roger Pielke, "Tracking progress on the economic costs of disasters under the indicators of the sustainable development goals," *Environmental Hazards*, 2019, Volume 18, Number 1. The work by Pielke finds no upward trend in economic impact after normalizing the damage data, and indeed a decrease in weather /climate losses as a proportion of GDP since 1990. Other researchers find a small upward trend after accounting for effects of GDP, wealth, and population, suggesting some potential role of climate change in losses to date. See for example, Fabian Barthel and Eric Neumayer, "A trend analysis of normalized insured damage from natural disasters," *Climatic Change*, 2012, Volume 113, Number 2; Robert Muir-Wood et al., "The search for trends in a global catalogue of normalized weather-related catastrophe losses," Climate Change and Disaster Losses Workshop, May 2006; and Robert Ward and Nicola Ranger, *Trends in economic and insured losses from weather-related events: A new analysis*, Centre for Climate Change Economics and Policy and Munich Re, November 2010. For example, Muir-Wood et al. conduct analysis of insurance industry data between 1970 to 2005 and find that weather-related catastrophe losses have increased by 2 percent each year since the 1970s, after accounting for changes in wealth, population growth and movement, and inflation (notably, though, in some regions including Australia, India, and the Philippines, such losses have declined). Analysis by Munich Re finds a statistically significant increase in insured losses from weather-related events in the United States and in Germany over the past approximately 30 to 40 years.

[23] A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34 degrees Celsius wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35 degrees Celsius wet-bulb, and large cities with significant urban heat island effects could push 34C wet-bulb heat waves over the 35C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance.

[24] Exposed sectors include exclusively outdoor sectors such as agriculture, mining, and quarrying, as well as indoor sectors with poor air-conditioning penetration, including manufacturing, hospitality, and transport. Reserve Bank of India, Database on Indian Economy, dbie.rbi.org.in/DBIE/dbie.rbi?site=home.

Exhibit E6

Direct impacts of climate change can become nonlinear when thresholds are crossed.

System	Example	Nonlinear behavior	
Human	**Impact of heat and humidity on outdoor labor**	**Share of labor capacity in a given hour**[1] %	
Physical	**Floodwater impacts on an exemplary UK train station**	**Asset impact**[3] $ million	
	Effects of line over-loading (eg, sagging due to heat) in an electrical grid[4]	**Probability of line tripping**	
Natural	**Temperature impact on crop yield**	**Corn reproductive growth rate** %	

[1] Immediate effect; longer exposure will cause rapidly worsening health impacts. Humans can survive exposure to 35C wet-bulb temperatures for between four to five hours. During this period, it is possible for a small amount of work to be performed, which is why the working hours curve does not approach zero at 35C WBGT (which, in the shade, is approximately equivalent to 35C wet-bulb).

[2] Based on in-shade wet-bulb globe temperature (WBGT). WBGT is defined as a type of apparent temperature which usually takes into account the effect of temperature, humidity, wind speed, and visible and infrared radiation on humans.

[3] Average cost of a new build train station globally used for asset impact/cost on UK train station; salvageable value is assumed zero once asset passes destruction threshold.

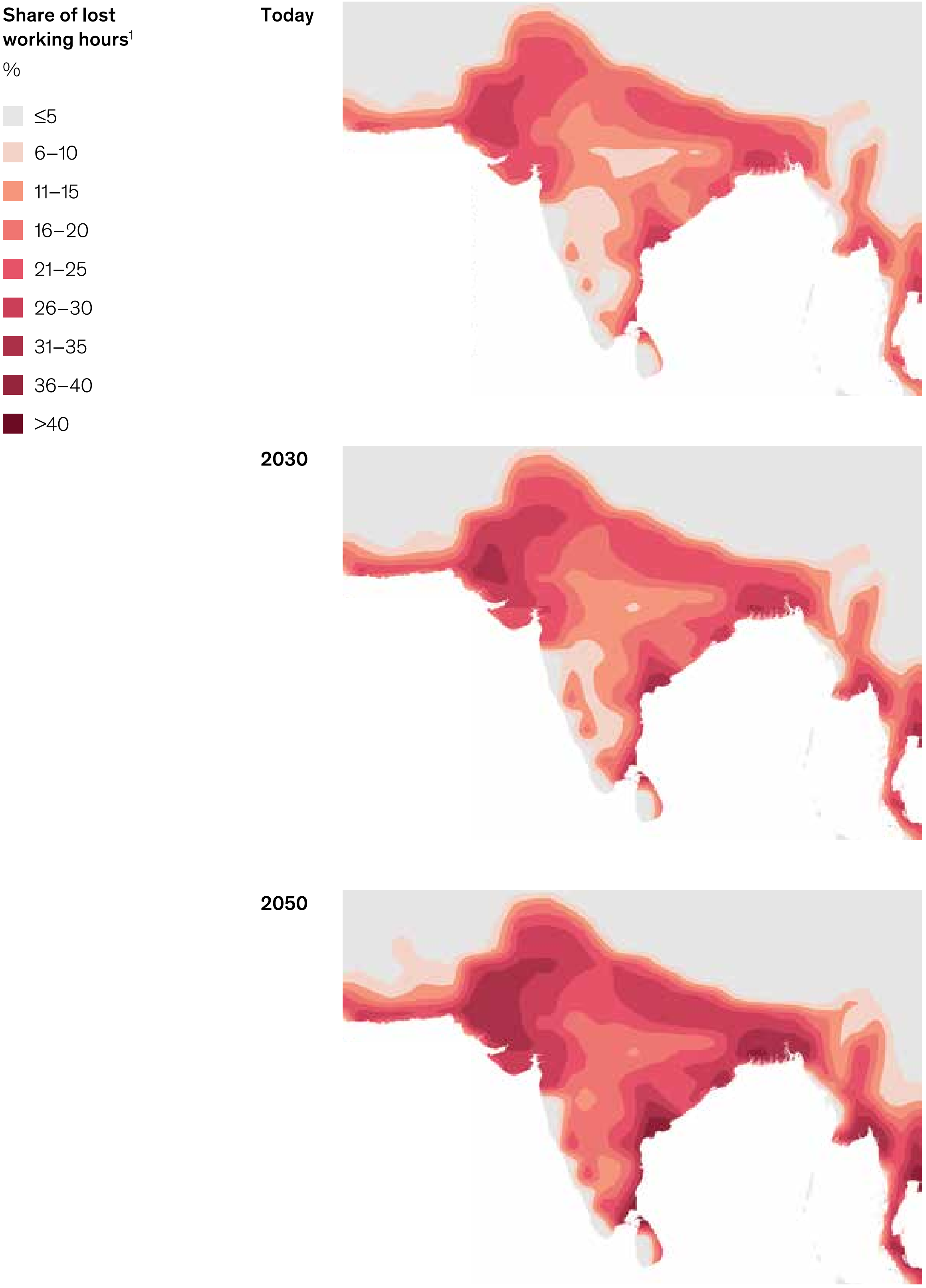
[4] Both acute events (eg, flooding, fires, storms) and chronic changes in climatic conditions (eg, heat) can affect the grid and may lead to outages.

Source: Dunne et al., 2013, adjusted according to Foster et al., 2018; Henneaux, 2015; Korres et al., 2016; CATDAT global database on historic flooding events; McKinsey infrastructure benchmark costs; EU Commission Joint Research Centre damage functions database; historical insurance data and expert engineer interviews on failure thresholds; McKinsey Global Institute analysis

Exhibit E7

The affected area and intensity of extreme heat and humidity is projected to increase, leading to a higher expected share of lost working hours.

Based on RCP 8.5



1. Lost working hours include loss in worker productivity as well as breaks, based on an average year that is an ensemble average of climate models.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center

Economic and financial systems have similarly been designed and optimized for a certain level of risk and increasing hazards may mean that such systems are vulnerable. We have already noted that supply chains are often designed for efficiency over resiliency, by concentrating production in certain locations and maintaining low inventory levels. Food production is also heavily concentrated; just five regional "breadbasket" areas account for about 60 percent of global grain production. Rising climate hazards might therefore cause such systems to fail, for example if key production hubs are affected. Finance and insurance have vulnerabilities, too; while they were designed to manage for some level of risk, intensifying climate hazards could stretch their limits. For example, consider the residential real estate market in Florida (Exhibit E8). Home owners rely on insurance to build financial resilience against risks like floods, but premiums could rise in the face of increasing risk and insurance does not cover devaluations of home prices. Lenders may bear some risk if home owners default. Among other possible repercussions, federal governments have been acting as backstops but may need to be prepared to finance more.

Other cases we examined highlight large knock-on impacts when thresholds are breached. These come about in particular when the people and assets affected are central to local economies and those local economies are tied into other economic and financial systems.

Ho Chi Minh City, a city prone to monsoonal and storm surge flooding, is one example. We estimate that direct infrastructure asset damage from a 100-year flood today would be on the order of $200 million to $300 million. This could rise to $500 million to $1 billion in 2050, assuming no additional adaptation investment and not including real estate–related impacts. Beyond this direct damage, we estimate that the knock-on costs could be substantial. They would rise from $100 million to $400 million today to between $1.5 billion and as much as $8.5 billion in 2050. We estimate that at least $20 billion of new infrastructure assets are currently planned for construction by 2050, more than doubling the number of major assets in Ho Chi Minh City (Exhibit E9). Many of these new infrastructure assets, particularly the local metro system, have been designed to tolerate an increase in flooding. However, in a worst-case scenario such as a sea-level rise of 180 centimeters, these thresholds could be breached in many locations.[25]

A further example from our case studies, that of coastal real estate in Florida, shows how climate hazards could have unpredictable financial impacts. The geography of Florida, with its expansive coastline, low elevation, and porous limestone foundation, makes it vulnerable to flooding. Absent any adaptation response, direct physical damages to real estate could grow with the changing climate. Average annual losses for residential real estate due to storm surge from hurricanes amount to $2 billion today. This is projected to increase to about $3 billion to $4.5 billion by 2050, depending on whether exposure is constant or increasing.[26] For a tail 100-year hurricane event, storm surge damages could rise from $35 billion today to between $50 billion and $75 billion by 2050.

---

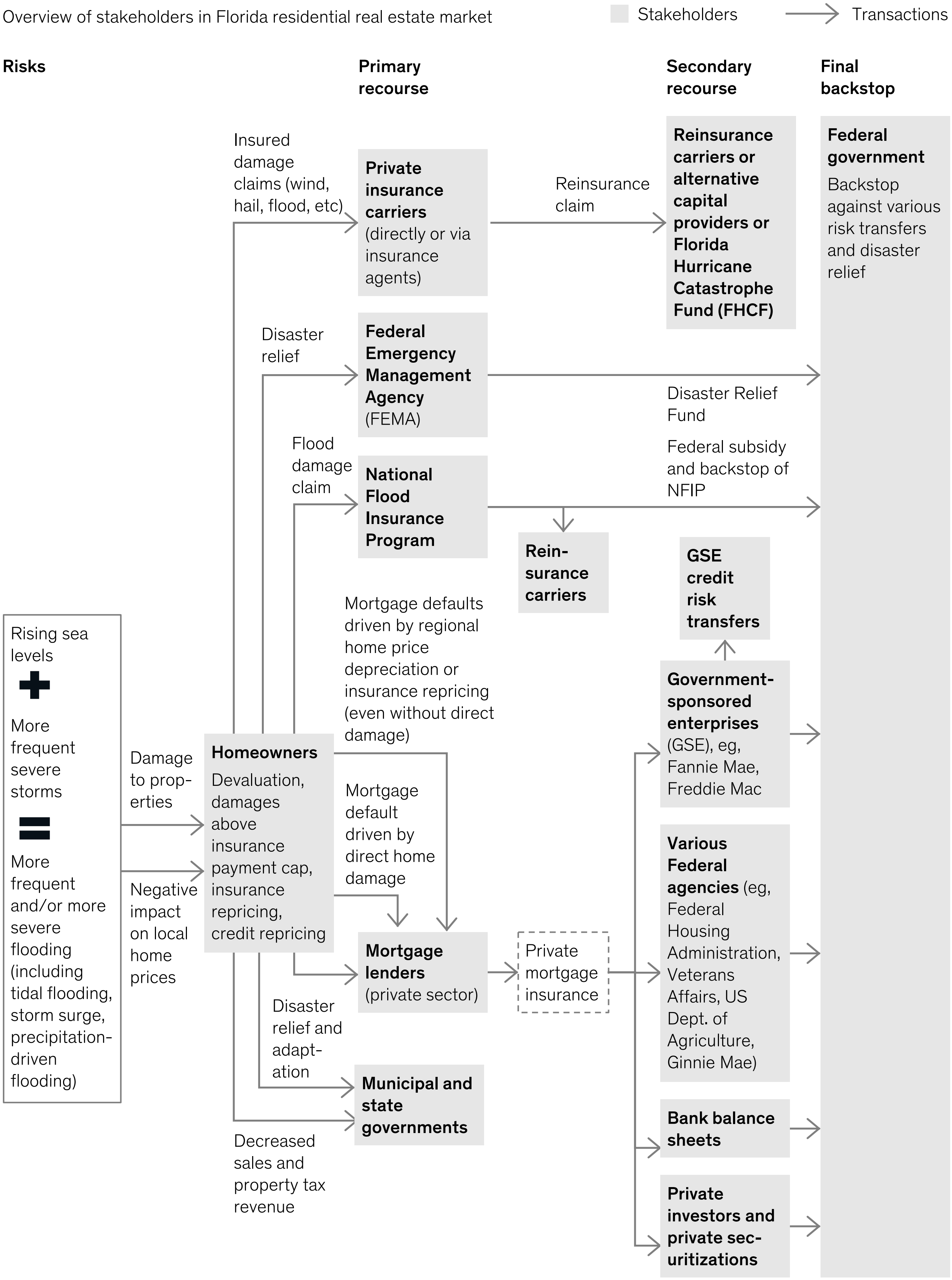
[25] This scenario is extreme, and the probability of it occurring by 2050 is negligible. Nonetheless, it illustrates that infrastructure planned for completion in or shortly before 2050 could experience another step change in risk at some point in 2060 or beyond if significant mitigation does not take place.

[26] Analysis conducted by KatRisk; direct average annual losses to all residential real estate (insured and uninsured properties). This is the long-term average loss expected in any one year, calculated by modeling the probability of a climate hazard occurring multiplied by the damage should that hazard occur, and summing over events of all probabilities. Analyses based on sea level rise in line with the US Army Corps of Engineers high curve, one of the recommended curves from the Southeast Florida Regional Climate Change Compact. Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, *Unified sea level rise projection: Southeast Florida,* October 2015. More broadly, considering the hurricane hazard, while total hurricane frequency is expected to remain unchanged or to decrease slightly as the climate changes, cumulative hurricane rainfall rates, average intensity, and proportion of storms that reach Category 4–5 intensity are projected to increase, even for a 2°C or less increase in global average temperatures. Thomas Knutson et al., *Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming*, American Meteorological Society, 2019. Range based on assessing how exposure varies; from constant exposure to exposure based on historical rates of growth of real estate.

Exhibit E8

Who holds the risk?

Overview of stakeholders in Florida residential real estate market

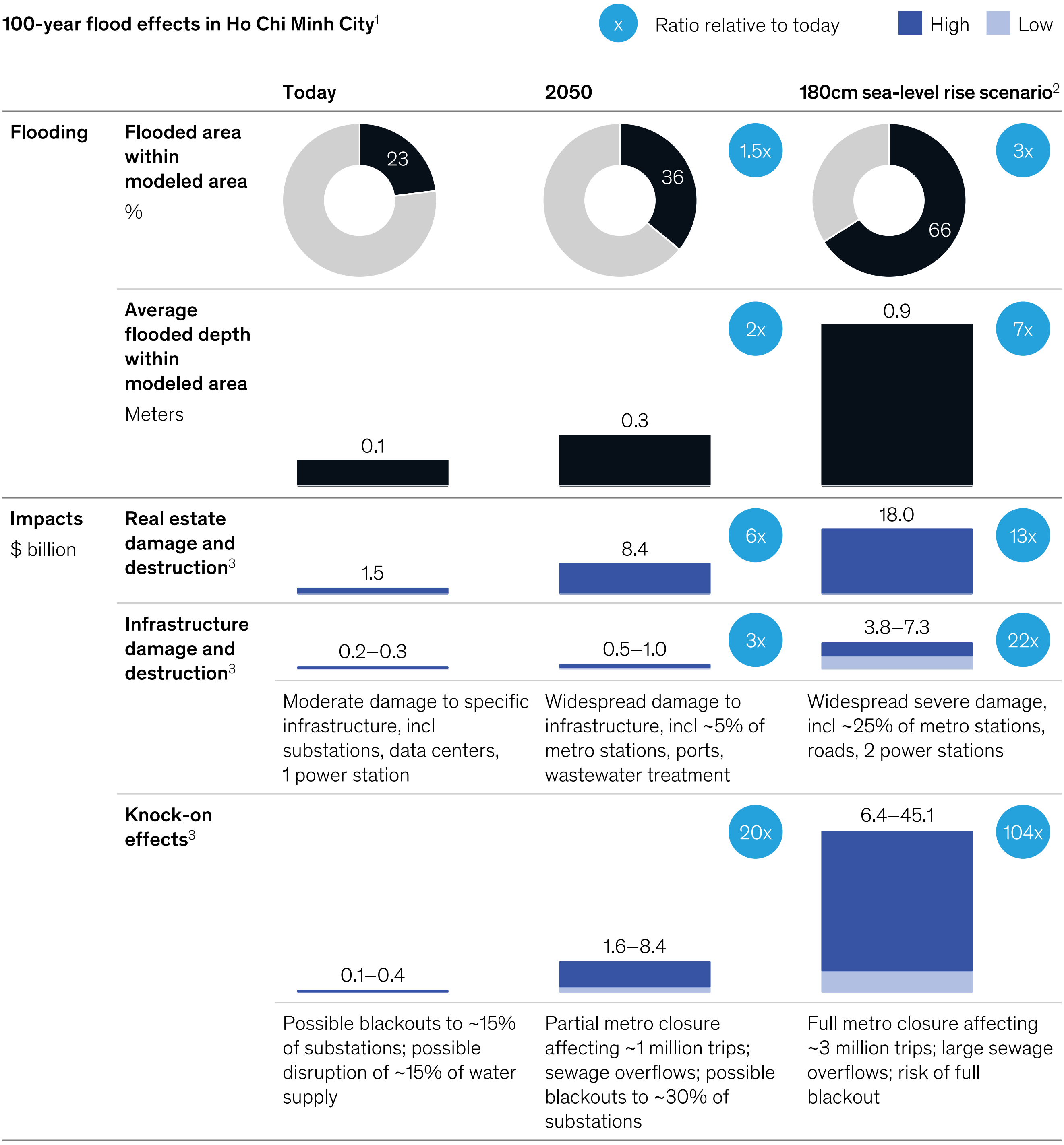


Source: McKinsey Global Institute analysis

Exhibit E9

Ho Chi Minh City could experience 5 to 10 times the economic impact from an extreme flood in 2050 vs today.

Based on RCP 8.5



Moderate damage to specific infrastructure, incl substations, data centers, 1 power station

Widespread damage to infrastructure, incl ~5% of metro stations, ports, wastewater treatment

Widespread severe damage, incl ~25% of metro stations, roads, 2 power stations

Possible blackouts to ~15% of substations; possible disruption of ~15% of water supply

Partial metro closure affecting ~1 million trips; sewage overflows; possible blackouts to ~30% of substations

Full metro closure affecting ~3 million trips; large sewage overflows; risk of full blackout

1. Repair and replacement costs. Qualitative descriptions of damage and knock-on effects are additional to previous scenarios.
2. Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
3. Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure, includes loss of freight movement, lost data revenues, and lost working hours due to a lack of access to electricity, clean water, and metro services. Adjusted for economic and population growth to 2050 for both 2050 and 180cm sea-level rise scenarios.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Following standard practice, we define future states (current, 2030, 2050) as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998–2017, in 2030 as the average between 2021–40, and in 2050 between 2041–60. Assumes no further adaptation action is taken. Figures may not sum to 100% because of rounding.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; ECLAC; EU Commission; HAZUS; Oxford Economics; People's Committee of Ho Chi Minh City; Scussolini et al., 2017; UN; Viet Nam National University, Ho Chi Minh City; World Bank; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

These numbers do not include the potential devaluation of flooding affected real estate. Exposed homes could see a devaluation of $30 billion to $80 billion, or about 15 to 35 percent, by 2050, all else being equal.[27] Lower real estate prices could in turn have knock-on effects, including forgone property tax revenue (a major source of state income), reduced wealth and spending by home owners, reduced, halted, or reversed resident inflow, and forced changes in government spending. For example, rough estimates suggest that the price effects discussed above could impact property tax revenue in some of the most affected counties by about 15 to 30 percent (though impacts across the state could be less, at about 2 to 5 percent). Business activity could be negatively affected, as could the availability and/or price of insurance and mortgage financing in high-risk counties. Financial markets could bring these risks forward, and the recognition of large future changes could lead to price adjustments. Awareness of climate risk could make long-duration borrowing more expensive or unavailable and reduce valuations, for example. This recognition could happen quickly, with the possibility of cascading consequences.

Climate change could create inequality—simultaneously benefiting some regions while hurting others. For example, rising temperatures may boost tourism in areas of northern Europe while reducing the economic vitality of southern European resorts. The volume of water in basins in northern Africa, Greece, and Spain could decline by more than 15 percent by 2050 even as volume in basins in Germany and the Netherlands increases by between 1 and 5 percent.[28] The mild Mediterranean climate is expected to grow hotter—by 2050, the climate in the French port city of Marseille could more closely resemble that of Algiers today—which could disrupt key sectors such as tourism and agriculture.[29]

Within regions, the poorest communities and populations within each of our cases typically are the most vulnerable to climate events. They often lack financial means. For example, acute climate events could trigger harvest failure in multiple breadbasket locations—that is, significantly lower-than-average yields in two or more key production regions for rice, wheat, corn, and soy. We estimate that the chance of a greater than 15 percent yield shock at least once in the decade centered on 2030 could rise from 10 percent today to 18 percent, while the chance of a greater than 10 percent yield shock occurring at least once could rise from 46 to 69 percent.[30] Given current high grain stocks, totaling about 30 percent of consumption, the world would not run out of grain. However, historical precedent suggests that prices could spike by 100 percent or more in the short term, in the event of a greater than 15 percent decline in global supply that reduces stocks. This would particularly hurt the poorest communities, including the 750 million people living below the international poverty line.

The global socioeconomic impacts of climate change could be substantial as a changing climate directly affects human, physical, and natural capital

While our case studies illustrate the localized impacts of a changing climate, rising temperatures are a global trend. To understand how physical climate hazards could evolve around the world, we developed a global geospatial assessment of climate impacts over the next 30 years covering 105 countries.[31] We again rely on our framework of the direct impacts of climate change on five human, physical, and natural systems. For each system we have identified one or more measures

---

[27] Analysis supported by First Street Foundation, 2019. Ranges based on whether homes that frequently flood (>50x per year), see more significant devaluations or not. Note that other factors could also affect the prices of homes and that has not been factored in. Much of the literature finds that, at least historically, prices of exposed properties have risen slower than prices of unexposed properties, rather than declined in absolute terms. For further details, see the Florida case study.

[28] World Resources Institute Water Risk Atlas, 2018.

[29] Jean-Francois Bastin et al., Understanding climate change from a global analysis of city analogues. PLoS ONE 14(7): e0217592, 2019.

[30] To estimate the likelihood, we employ crop models from the AgMIP model library that translate outputs from climate models into crop yields for each modeled grid cell. Using all available climate models over a period of 20 years, we construct a probability distribution of yields for each crop in each grid cell. Note that we are taking into account potentially positive effects on plant growth from higher CO_2 levels ("CO_2 fertilization"). Analysis is based on an assumption of no improvements in agricultural productivity (consistent with our "inherent risk" framing). See breadbasket case for further details.

[31] To conduct this analysis, we have relied on geospatial climate hazard data, including from Woods Hole Research Center analysis of CMIP5 Global Climate Model output, the World Resources Institute, the European Center for Medium-Range Weather Forecasts and data from Rubel et al. (obtained from the National Oceanic and Atmospheric Administration). We used geospatial data on population, capital stock, and GDP from the European Commission Global Human Settlement (GHS) and the UN *Global Assessment Report on Disaster Risk Reduction*, as well as data from other sources as described in Chapter 4. Notably, we have focused our analysis on a subset of possible climate hazards: lethal heat waves, heat and humidity and its impact on workability, water stress, riverine flooding, drought, and the impact of increased temperature and changes in precipitation on biome shifts. Analysis based on an RCP 8.5 scenario.

to define the impact of climate change, often building on the risk measures used in our case studies, and choosing the best possible measures based on broad country coverage and data availability.[32] For example, for livability and workability, we use the measures of the share of population living in areas projected to experience a non-zero annual probability of lethal heat waves as well as the annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions. This is similar to the approach followed in our India case study.

We find that all 105 countries are expected to experience an increase in at least one major type of impact on their stock of human, physical, and natural capital by 2030. Intensifying climate hazards could put millions of lives at risk, as well as trillions of dollars of economic activity and physical capital, and the world's stock of natural capital. The intensification of climate hazards across regions will bring areas hitherto unexposed to impacts into new risk territory.

— **Livability and workability.** By 2030, under an RCP 8.5 scenario, our research suggests that between 250 million and 360 million people could live in regions where there is a non-zero probability of a heat wave exceeding the threshold for survivability for a healthy human being in the shade (a measure of livability, without factoring in air conditioner penetration).[33] The average probability of a person living in an at-risk region experiencing such a lethal heat wave at least once over the decade centered on 2030 is estimated to be approximately 60 percent.[34] Some exposed regions will have a lower probability, and some regions higher. By 2050, the number of people living in regions exposed to such heat waves could rise further, to between 700 million and 1.2 billion, again without factoring in an adaptation response via air conditioner penetration. This reflects the fact that some of the most heavily populated areas of the world are usually also the hottest and most humid, and, as described below, these areas are becoming even hotter and more humid. Today, air conditioner penetration is roughly 10 percent across India, and roughly 60 percent across China.[35] The global average number of working hours that could be lost due to increasing heat and humidity in exposed regions (a measure of workability impacts) could almost double by 2050, from 10 percent to 15 to 20 percent. This is because more regions of the world are exposed, and the ones that are exposed would see higher intensity of heat and humidity effects. We used these projections to estimate the resulting GDP at risk from lost working hours. This could amount to $4 trillion to $6 trillion globally at risk by 2050 in an average year (Exhibit E10). This the equivalent of 2 to 3.5 percent of 2050 GDP, up from about 1.5 percent today.[36]

---

[32] The indicators used in our geospatial analysis include: share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves, annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions, water stress as measured by the annual demand of water as a share of annual supply of water (these three are measures of livability and workability, and are considered in our India case and Mediterranean cases), annual share of capital stock at risk of flood damage in climate-exposed regions (asset destruction and infrastructure services; similar measures of capital stock damage are used in our Florida and Inundation cases), share of time spent in drought over a decade (measure of food systems; we also consider the impact of drought in our Mediterranean case), share of land surface changing climate classification annually (measure of natural capital; this was used for our geospatial analysis to allow us to develop a global measure of natural capital risk). Notably, drought is the one measure of hazard rather than risk used in this framework. This was done because of data limitations with obtaining data on impacts on agricultural yield by country, since the AgMIP climate models used to project agricultural yields tend only to be used for relatively large breadbasket regions, rather than at a country level. We are able to use the AgMIP results to provide global trends on breadbaskets and results pertaining to large breadbasket regions; however, such results were not included in the country-by-country analysis. We also excluded risk due to hazards like hurricanes, storm surge, and forest fires due to challenges obtaining sufficiently granular and robust data across countries. See Chapter 4 for details.

[33] Here, as before, lethal heat wave refers to a three-day period with average daily maximum wet-bulb temperatures exceeding 34 degrees Celsius. This temperature was chosen because urban areas with a high urban heat island effect could amplify 34°C ambient temperatures over the 35°C wet-bulb survivability threshold. These numbers are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cool island effects. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance. Additionally, these numbers assume no air-conditioning protection, and as such should be considered an upper bound. See Chapter 2 for details. Analysis based on an RCP 8.5 scenario.

[34] This calculation is a rough approximation. It assumes that the annual probability of roughly 9 percent applies to every year in the decade centered around 2030. We first calculate the cumulative probability of a heat wave not occurring in that decade, which is 91 percent raised to the power of 10. The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number.

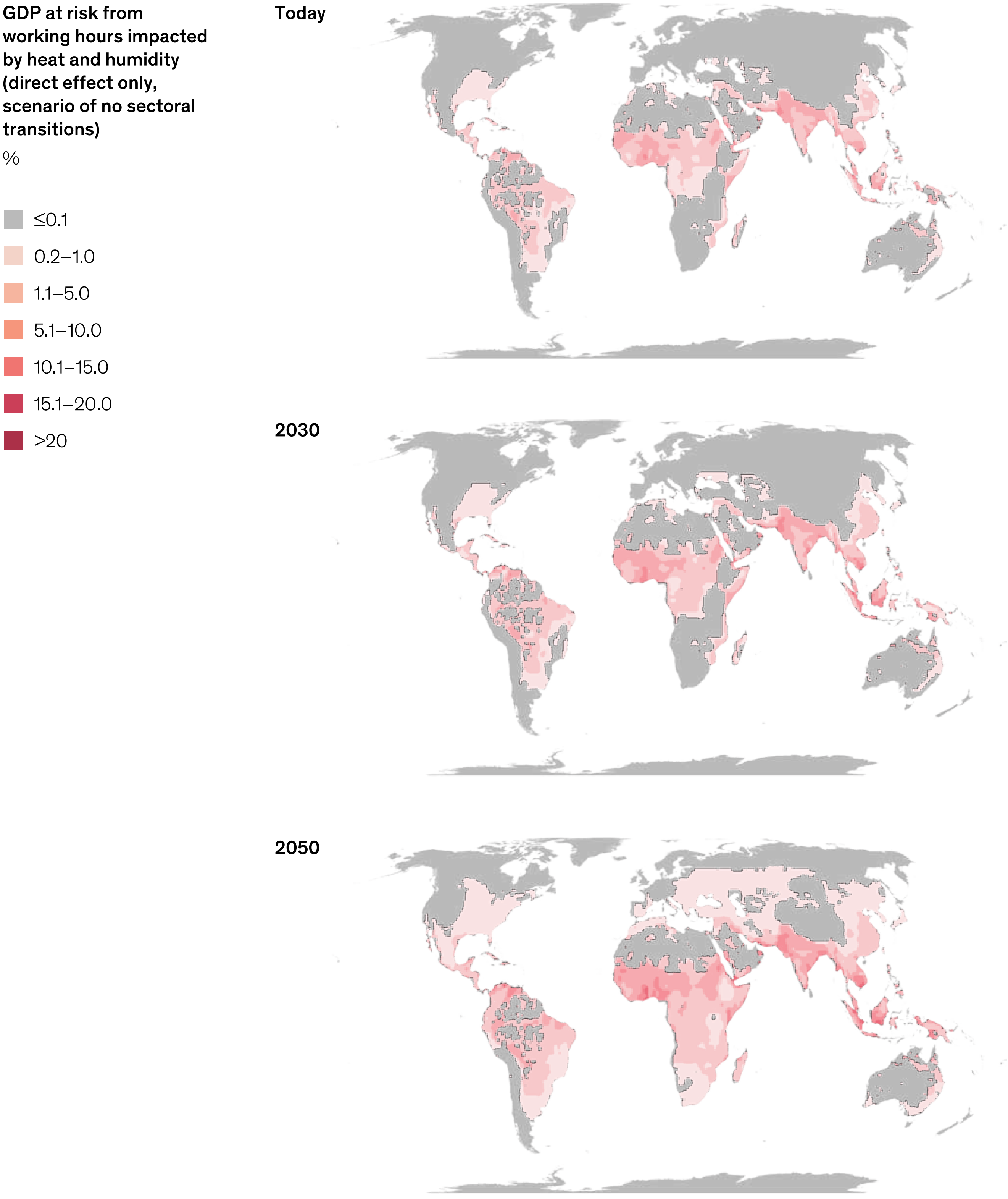
[35] India Cooling Action Plan Draft, Ministry of Environment, Forest & Climate Change, Government of India, September 2018; The Future of Cooling in China, IEA, Paris, 2019.

[36] The range here is based on the pace of sectoral transition across countries. GDP at risk will be higher if a greater portion of the economy is occupied in outdoor work. The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions.

Exhibit E10

GDP at risk from the effect of extreme heat and humidity on effective working hours is expected to increase over time.

Based on RCP 8.5



Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. These maps do not consider sectoral shifts when projecting impact on labor productivity into the future—the percentage and spatial distribution of outdoor labor are held constant. For this analysis, outdoor labor is considered to include agriculture, construction, and mining and quarrying only, and knock-on impacts on other sectors are not considered. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: IHS Markit Economics and Country Risk; Woods Hole Research Center; McKinsey Global Institute analysis

- **Food systems.** Our research suggests an increase in global agricultural yield volatility that skews toward worse outcomes. For example, by 2050, the annual probability of a greater than 10 percent reduction in yields for wheat, corn, soy, and rice in a given year is projected to increase from 6 to 18 percent.[37] The annual probability of a greater than 10 percent increase in yield in a given year is expected to rise from 1 percent to 6 percent. These trends are not uniform across countries and, importantly, some could see improved agricultural yields, while others could suffer negative impacts. For example, the average breadbasket region of Europe and Russia is expected to experience a 4 percent increase in average yields by 2050. While the annual probability of a greater than 10 percent yield failure there will increase, from 8 percent to 11 percent annually by 2050, the annual probability of a bumper year with a greater than 10 percent higher-than-average yield in the same period will increase by more, from 8 percent to 18 percent.

- **Physical assets and infrastructure services.** Assets can be destroyed or services from infrastructure assets disrupted from a variety of hazards, including flooding, forest fires, hurricanes, and heat. Statistically expected damage to capital stock from riverine flooding could double by 2030 from today's levels and quadruple by 2050. Data availability has made it challenging to develop similar estimates for the much larger range of impacts from tidal flooding, fires, and storms.[38]

- **Natural capital.** With temperature increases and precipitation changes, the biome in parts of the world is expected to shift. The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. For this report, we have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.[39] For example, tropical rainforests exist in a particular climatic envelope that is defined by temperature and precipitation characteristics. In many parts of the world, this envelope could begin to be displaced by a much drier "tropical Savannah" climate regime that threatens tropical rainforests. Today, about 25 percent of the Earth's land area has already experienced a shift in climate classification compared with the 1901–25 period. By 2050, that number is projected to increase to about 45 percent. Almost every country will see some risk of biome shift by 2050, affecting ecosystem services, local livelihoods, and species' habitat.

Countries with the lowest per capita GDP levels are generally more exposed

While all countries are affected by climate change, our research suggests that the poorest countries are generally more exposed, as they often have climates closer to dangerous physical thresholds. The patterns of this risk increase look different across countries. Broadly speaking, countries can be divided into six groups based on their patterns of increasing risk (Exhibits E11, E12, and E13).[40]

---

[37] Global yields based on an analysis of six global breadbaskets that make up 70 percent of global production of four crops; wheat, soy, maize, and rice. Cumulative likelihood calculated for the decade centered on 2030 and 2050 by using annual probabilities for the climate state in the 2030 period, and the 2050 period respectively. Annual probabilities are independent and can therefore be aggregated to arrive at a cumulative decadal probability. Yield anomalies here are measured relative to the 1998-2017 average yield.

[38] See Chapter 4 for details.

[39] The Köppen climate system divides climates into five main climate groups with each group further subdivided based on seasonal precipitation and temperature patterns. This is not a perfect system for assessing the location and composition of biomes; however, these two characteristics do correlate very closely with climate classification, and therefore this was assessed as a reasonable proxy for risk of disruptive biome changes.

[40] These patterns were primarily based on looking at indicators relating to livability and workability, food systems, and natural capital. The annual share of capital stock at risk of riverine flood damage in climate-exposed regions indicator was considered but was not found to be the defining feature of any country grouping aside from a lower-risk group of countries.

Exhibit E11

We identify six types of countries based on their patterns of expected change in climate impacts.

Based on RCP 8.5

░ Risk decrease ▒ No or slight risk increase ▓ Moderate risk increase █ High risk increase

Country	Change in… (2018–50, pp) Livability and workability: Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Food systems: Share of time spent in drought over a decade	Physical assets/ infrastructure services: Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Natural capital: Share of land surface changing climate classification
Significantly hotter and more humid countries						
Bangladesh	█	█	░	░	▒	▓
India	█	█	░	░	▓	█
Nigeria	█	█	░	▒	▒	▒
Pakistan	█	▓	░	▒	▒	▓
Other countries in group: Benin, Burkina Faso, Cambodia, Cote d'Ivoire, Eritrea, Ghana, Myanmar, Niger, Senegal, Thailand, Vietnam, Yemen						
Average (all countries in group)	█	█	░	░	▓	▓
Hotter and more humid countries						
Ethiopia	▒	▓	░	░	▓	█
Indonesia	▒	█	░	▒	█	▒
Japan	▒	▓	░	▒	█	█
Philippines	▒	█	░	░	▒	▓
Other countries in group: Angola, Cameroon, Chad, Ecuador, Guinea, Guyana, Jordan, Laos, Liberia, Madagascar, Papua New Guinea, Saudi Arabia, Somalia, Suriname, Tanzania, Uganda, Uruguay, Zambia						
Average (all countries in group)	▒	█	░	▓	▓	▓
Hotter countries						
Colombia	▒	▓	▒	▒	█	▓
Dem. Rep. Congo	▒	█	▒	▓	▓	▓

---

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit E12

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5

□ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase █ High risk increase

	Change in… (2018–50, pp)	**Livability and workability**			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
Country		Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Hotter countries (continued)							
Malaysia		░	█	░	□	▒	░
South Korea		░	▒	▒	░	▒	█
Other countries in group: Botswana, Central African Rep., Cuba, Gabon, Guatemala, Honduras, Hungary, Libya, Malawi, Mali, Mauritania, Mozambique, Namibia, Nicaragua, Oman, Paraguay, Rep. Congo, Romania, Serbia, Venezuela, Zimbabwe							
Average (all countries in group)		░	█	░	█	▒	█
Increased water stress countries							
Egypt		░	█	█	█	░	░
Iran		░	▒	█	▒	█	█
Mexico		░	▒	█	░	█	█
Turkey		░	▒	█	█	▒	█
Other countries in group: Algeria, Australia, Azerbaijan, Bulgaria, Greece, Italy, Kazakhstan, Kyrgyzstan, Morocco, Portugal, South Africa, Spain, Syria, Tajikistan, Tunisia, Turkmenistan, Ukraine, Uzbekistan							
Average (all countries in group)		░	▒	█	█	▒	█
Lower-risk countries							
France		░	▒	░	░	█	█
Germany		░	▒	░	░	▒	█

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

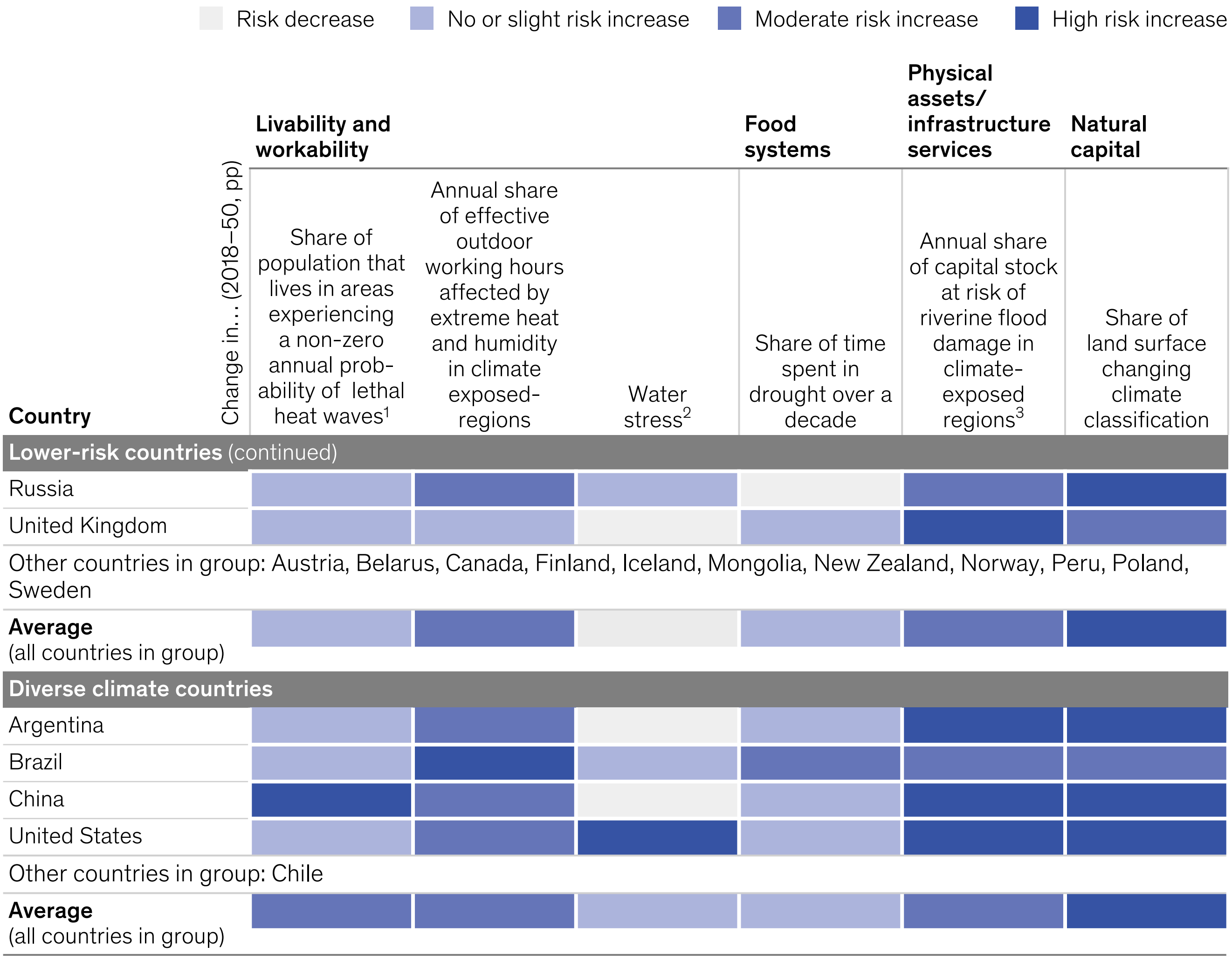
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit E13

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



□ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase ▓ High risk increase

Country	Livability and workability: Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Livability and workability: Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Livability and workability: Water stress[2]	Food systems: Share of time spent in drought over a decade	Physical assets/ infrastructure services: Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Natural capital: Share of land surface changing climate classification
Lower-risk countries (continued)						
Russia	░	▒	░	□	▒	▓
United Kingdom	░	░	□	░	▓	▒
Other countries in group: Austria, Belarus, Canada, Finland, Iceland, Mongolia, New Zealand, Norway, Peru, Poland, Sweden						
Average (all countries in group)	░	▒	□	░	▒	▓
Diverse climate countries						
Argentina	░	▒	□	░	▓	▓
Brazil	░	▓	░	▒	▒	▒
China	▓	▒	□	░	▓	▓
United States	░	▒	▓	░	▓	▓
Other countries in group: Chile						
Average (all countries in group)	▒	▒	░	░	▒	▓

Change in… (2018–50, pp)

Change in potential impact, 2018–50[4] (percentage points)

Risk decrease	n/a	n/a	<0	<0	<0	n/a
Slight risk increase	0.0–0.5	0.0–0.5	0–3	0–3	0–0.05	0–5
Moderate risk increase	0.5–5.0	0.5–5.0	3–7	3–7	0.05–0.10	5–10
High risk increase	>5.0	>5.0	>7	>7	>0.10	>10

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.
4. Calculated assuming constant exposure. Constant exposure means that we do not factor in any increases in population or assets, or shifts in the spatial mix of population and assets. This was done to allow us to isolate the impact of climate change alone. Color coding for each column based on the spread observed across countries within the indicator.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

— **Significantly hotter and more humid countries.** Hot and humid countries such as India and Pakistan are expected to become significantly hotter and more humid by 2050. Countries in this group are near the equator in Africa, Asia, and the Persian Gulf. They are characterized by extreme increases in heat and humidity impacts on workability, as well as a decrease in water stress. The potential livability impact that countries in this group face is projected to increase, because of the combination of heat and humidity.

— **Hotter and more humid countries.** This group includes the Philippines, Ethiopia, and Indonesia. These countries are typically between the equator and the 30-degree north and 30-degree south lines of latitude. They face a large potential increase in heat and humidity impacts on workability but may not become so hot or humid that they exceed livability thresholds. Water stress is also expected to decrease for these countries.

— **Hotter countries.** This group includes Colombia, the Democratic Republic of Congo, and Malaysia. Many countries in this group are near the equator. They are characterized by a large increase in heat and humidity impact on workability but are not expected to become so hot or humid that they pass livability thresholds. This group of countries is not expected to become wetter, and some of these countries could even become substantially drier and see increased water stress.

— **Increased water stress countries.** This group includes Egypt, Iran, and Mexico, which intersect the 30-degree north or south line of latitude. They are characterized by a large increase in water stress and drought frequency, and among the largest increases in biome change. In these locations, Hadley cells (the phenomenon responsible for the atmospheric transport of moisture from the tropics, and therefore location of the world's deserts) are expanding, and these countries face a projected reduction in rainfall.

— **Lower-risk increase countries.** This group includes Germany, Russia, and the United Kingdom. Many countries in this group lie outside the 30-degree north and south lines of latitude and are generally cold countries. Some are expected to see a decrease in overall impact on many indicators. These countries are characterized by very low levels of heat and humidity impacts and many countries are expected to see decreases in water stress and time spent in drought. As these countries grow warmer, they will likely see the largest increase in biome change as the polar and boreal climates retreat poleward and disappear. The share of capital stock at risk of riverine flood damage in climate-exposed regions could also potentially increase in some of these countries.

— **Diverse climate countries.** The final group consists of countries that span a large range of latitudes and therefore are climatically heterogeneous. Examples include Argentina, Brazil, Chile, China, and the United States.[41] While average numbers may indicate small risk increases, these numbers mask wide regional variations. The United States, for example, has a hot and humid tropical climate in the Southeast, which will see dramatic increases in heat risk to outdoor work but is not projected to struggle with water scarcity. The West Coast region, however, will not see a big increase in heat risk to outdoor work, but will struggle with water scarcity and drought. In Alaska, the primary risk will be the shifting boreal biome and the attendant ecosystem disruptions.

The risk associated with the impact on workability from rising heat and humidity is one example of how poorer countries could be more vulnerable to climate hazards (Exhibit E14).

---

[41] To some extent, many countries could experience diversity of risk within their boundaries. Here we have focused on highlighting countries with large climatic variations, and longitudinal expanse, which drives different outcomes in different parts of the country.

Exhibit E14

Countries with the lowest per capita GDP levels face the biggest increase in risk for some indicators.

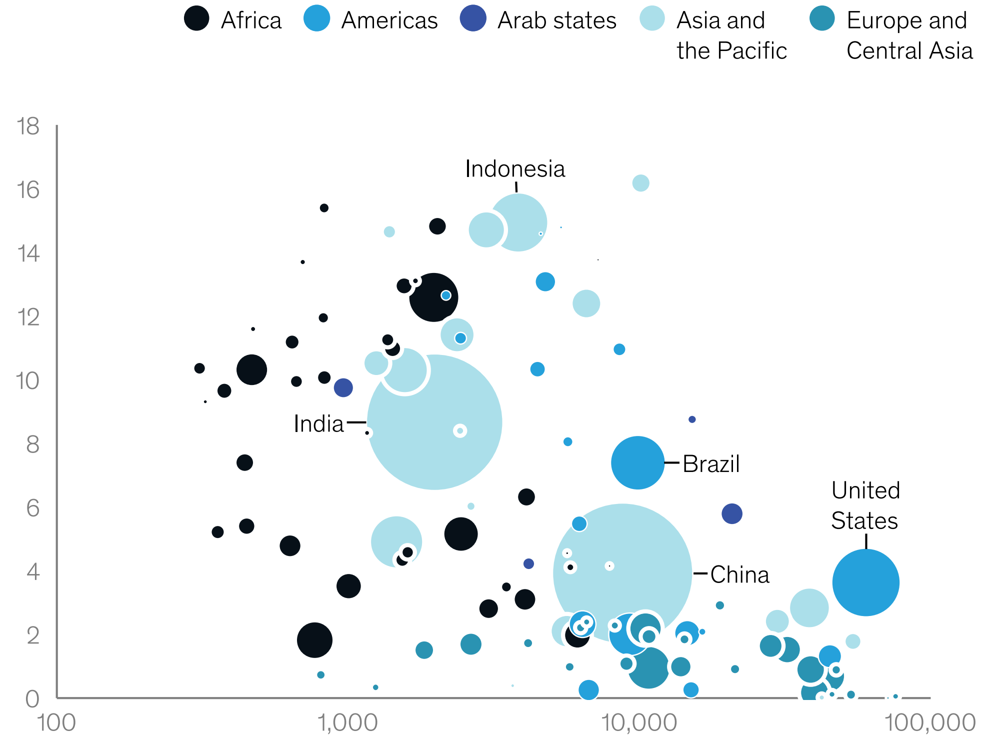
Based on RCP 8.5

Change, 2018–50

Percentage points

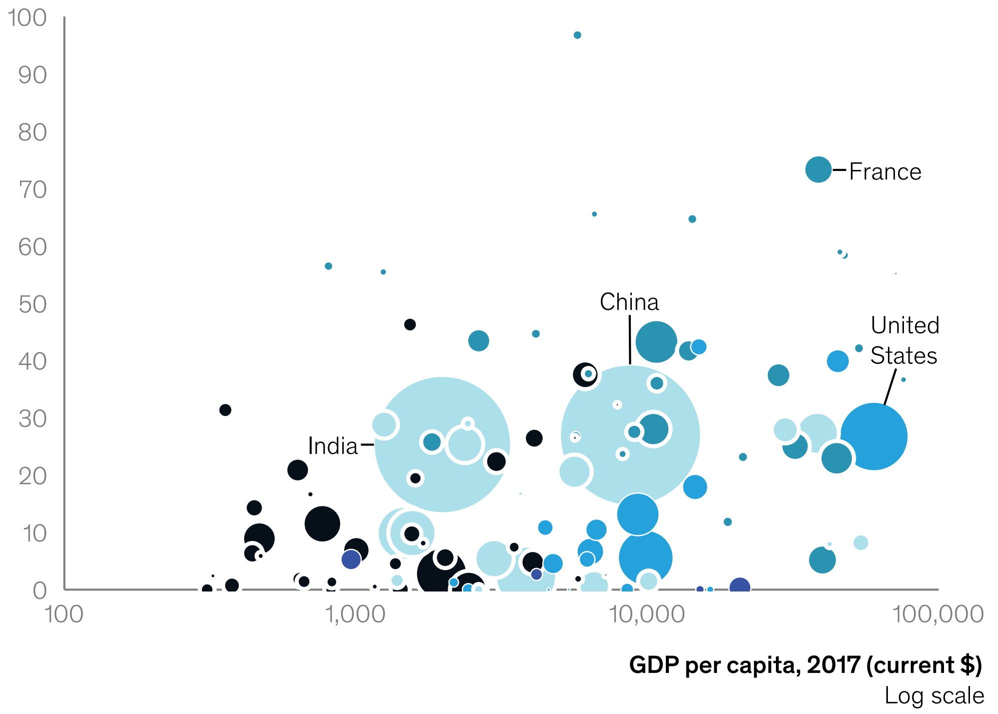
Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions

Correlation coefficient:
r = -0.49



Share of land surface changing climate classification

Correlation coefficient:
r = 0.35



Note: Not to scale. See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; Rubel and Kottek, 2010; IMF; World Bank; UN; McKinsey Global Institute analysis

When looking at the workability indicator (that is, the share of outdoor working hours lost to extreme heat and humidity), the top quartile of countries (based on GDP per capita) have an average increase in risk by 2050 of approximately one to three percentage points, whereas the bottom quartile faces an average increase in risk of about five to ten percentage points. Lethal heat waves show less of a correlation with per capita GDP, but it is important to note that several of the most affected countries—Bangladesh, India, and Pakistan, to name a few—have relatively low per capita GDP levels.

Conversely, biome shift is expected to affect northern and southern latitude countries. Since many of these countries have higher per capita GDP levels, this indicator shows a positive correlation with development levels.

Leaders will need to better understand the impacts of physical climate risk, while accelerating adaptation and mitigation

In the face of these challenges, policy makers and business leaders will need to put in place the right tools, analytics, processes, and governance to properly assess climate risk, adapt to risk that is locked in, and decarbonize to reduce the further buildup of risk. In Box E3 that concludes this summary, we present a range of questions that stakeholders could consider as they look to manage risk.

Integrating climate risk into decision making

Much as thinking about information systems and cyber-risks has become integrated into corporate and public-sector decision making, climate change will also need to feature as a major factor in decisions. For companies, this will mean taking climate considerations into account when looking at capital allocation, development of products or services, and supply chain management, among others. For cities, a climate focus will become essential for urban planning decisions. Financial institutions could consider the risk in their portfolios.[42] Moreover, while this report has focused on physical risk, a comprehensive risk management strategy will also need to include an assessment of transition and liability risk, and the interplay between these forms of risk.

Developing a robust quantitative understanding is complex, for the many reasons outlined in this report. It requires the use of new tools, metrics, and analytics. Companies and communities are beginning to assess their exposure to climate risk, but much more needs to be done. Lack of understanding significantly increases risks and potential impacts across financial markets and socioeconomic systems, for example, by driving capital flows to risky assets in risky geographies or increasing the likelihood of stakeholders being caught unprepared.

At the same time, opportunities from a changing climate will emerge and require consideration. These could arise from a change in the physical environment, such as new places for agricultural production, or for sectors like tourism, as well as through the use of new technologies and approaches to manage risk in a changing climate.

One of the biggest challenges could stem from using the wrong models to quantify risk. These range from financial models used to make capital allocation decisions to engineering models used to design structures. As we have discussed, there is uncertainty associated with global and regional climate models, underlying assumptions on emissions paths, and, most importantly, in translating climate hazards to potential physical and financial damages. While these uncertainties are non-negligible, continued reliance on current models based on stable historical climate and economic data presents an even higher “model risk.”

---

[42] See, for example, *Getting physical: Scenario analysis for assessing climate-related risks*, Blackrock Investment Institute, April 2019.

Three examples of how models could be inappropriate for the changing climate are as follows:

- **Geography.** Current models may not sufficiently take into account geospatial dimensions. As this report highlights, direct impacts of climate change are local in nature, requiring understanding exposure to risk via geospatial analysis. For example, companies will need to understand how their global asset footprint is exposed to different forms of climate hazard in each of their main locations and indeed in each of the main locations of their critical suppliers.

- **Non-stationarity.** Given the constantly changing or non-stationary climate, assumptions based on historical precedent and experience will need to be rethought. That could include, for example, how resilient to make new factories, what tolerance levels to employ in new infrastructure, and how to design urban areas. Decisions will need to take into consideration that the climate will continue to change over the next several decades.

- **Sample bias.** Decision makers often rely on their own experiences as a frame for decisions; in a changing climate, that can result in nonlinear effects and thus lead to incorrect assessments of future risk.

Accelerating the pace and scale of adaptation

Societies have been adapting to the changing climate, but the pace and scale of adaptation will likely need to increase significantly. Key adaptation measures include protecting people and assets, building resilience, reducing exposure, and ensuring that appropriate financing and insurance are in place.

- **Protecting people and assets.** Measures to protect people and assets to the extent possible can help limit risk. Steps can range from prioritizing emergency response and preparedness to erecting cooling shelters and adjusting working hours for outdoor workers exposed to heat. Hardening existing infrastructure and assets is a key response. According to the UN Environment Programme, the cost of adaptation for developing countries may range from \$140 billion to \$300 billion a year by 2030. This could rise to \$280 billion to \$500 billion by 2050.[43] Hardening of infrastructure could include both "gray" infrastructure—for example, raising elevation levels of buildings in flood-prone areas—and natural capital or "green" infrastructure. One example of this is the Dutch Room for the River program, which gives rivers more room to manage higher water levels.[44] Another example is mangrove plantations, which can provide storm protection.

  Factoring decisions about protection into new buildings will likely be more cost-effective than retrofitting.[45] For example, infrastructure systems or factories may be designed to withstand what used to be a 1-in-200-year event. With a changing climate, what constitutes such an event may look different, and design parameters will need to be reassessed. Estimates suggest that \$30 trillion to \$50 trillion will be spent on infrastructure in the next ten years, much of it in developing countries.[46] Designing such infrastructure with climate risk in mind may help reduce downstream repair and rebuilding costs. Moreover, infrastructure that specifically helps protect assets and people will be needed, for example cooling technologies including green air-conditioning (high energy efficiency HVAC powered by low carbon power, for example), emergency shelters, and passive urban design.

---

[43] Anne Olhoff et al., *The adaptation finance gap report*, UNEP DTU Partnership, 2016.

[44] See Room for the River, ruimtevoorderivier.nl/english/.

[45] Michael Della Rocca, Tim McManus, and Chris Toomey, *Climate resilience: Asset owners need to get involved now*, McKinsey.com, January 2009.

[46] *Bridging global infrastructure gaps*, McKinsey Global Institute, June 2016; *Bridging infrastructure gaps: Has the world made progress?* McKinsey Global Institute, October 2017.

— **Building resilience.** Asset hardening will need to go hand-in-hand with measures that make systems more resilient and robust in a world of rising climate hazard. Building global inventory to mitigate risks of food and raw material shortages is an example of resilience planning, leveraging times of surplus and low prices. To make the food system more resilient, private and public research could be expanded, for example on technology that aims to make crops more resistant to abiotic and biotic stresses. As noted, climate change challenges key assumptions that have been used to optimize supply chain operations in the past. Those assumptions may thus need to be rethought, for example by building backup inventory levels in supply chains to protect against interrupted production, as well as establishing the means to source from alternate locations and/or suppliers.

— **Reducing exposure.** In some instances, it may also be necessary to reduce exposure by relocating assets and communities in regions that may be too difficult to protect, that is, to retreat from certain areas or assets. Given the long lifetimes of many physical assets, the full life cycle will need to be considered and reflected in any adaptation strategy. For example, it may make sense to invest in asset hardening for the next decade but also to shorten asset life cycles. In subsequent decades, as climate hazards intensify and the cost-benefit equation of physical resilience measures is no longer attractive, it may become necessary to relocate and redesign asset footprints altogether.

— **Insurance and finance.** While insurance cannot eliminate the risk from a changing climate, it is a crucial shock absorber to help manage risk.[47] Insurance can help provide system resilience to recover more quickly from disasters and reduce knock-on effects. It can also encourage behavioral changes among stakeholders by sending appropriate risk signals—for example, to homeowners buying real estate, lenders providing loans, and real estate investors financing real estate build-out.

Instruments such as parametrized insurance and catastrophe bonds can provide protection against climate events, minimizing financial damage and allowing speedy recovery after disasters. These products may help protect vulnerable populations that could otherwise find it challenging to afford to rebuild after disasters. Insurance can also be a tool to reduce exposure by transferring risk (for example, crop insurance allows transferring the risk of yield failure due to drought) and drive resilience (such as by enabling investments in irrigation and crop-management systems for rural populations who would otherwise be unable to afford this).

However, as the climate changes, insurance might need to be further adapted to continue providing resilience and, in some cases, avoid potentially adding vulnerability to the system. For example, current levels of insurance premiums and levels of capitalization among insurers may well prove insufficient over time for the rising levels of risk; and the entire risk transfer process (from insured to insurer to reinsurer to governments as insurers of last resort) and each constituents' ability to fulfil their role may need examination. Without changes in risk reduction, risk transfer, and premium financing or subsidies, some risk classes in certain areas may become harder to insure, widening the insurance gap that already exists in some parts of the world without government intervention.

Innovative approaches will also likely be required to help bridge the underinsurance gap. Premiums are already sometimes subsidized—one example is flood insurance, which is often nationally provided and subsidized. Such support programs however might need to be carefully rethought to balance support to vulnerable stakeholders with allowing appropriate risk signals in the context of growing exposure and multiple knock-on effects. One answer might be providing voucher programs to help ensure affordability for vulnerable populations, while maintaining premiums at a level that reflects the appropriate

---

[47] Goetz von Peter, Sebastian von Dahlen, and Sweta Saxena, *Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes*, BIS Working Papers, Number 394, December 2012.

risk. Trade-offs between private and public insurance, and for individuals, between when to self-insure or buy insurance, will need to be carefully evaluated. In addition, underwriting may need to shift to drive greater risk reduction in particularly vulnerable areas (for example, new building codes or rules around hours of working outside). This is analogous to fire codes that emerged in cities in order to make buildings insurable. Insurance may also need overcome a duration mismatch; for example, homeowners may expect long-term stability for their insurance premiums, whereas insurers may look to reprice annually in the event of growing hazards and damages. This could also apply to physical supply chains that are currently in place or are planned for the future, as the ability to insure them affordably may become a criterion of growing significance.

Mobilizing finance to fund adaptation measures, particularly in developing countries, is also crucial. This may require public-private partnerships or participation by multilateral institutions, to prevent capital flight from risky areas once climate risk is appropriately recognized. Innovative products and ventures have been developed recently to broaden the reach and effectiveness of these measures. They include "wrapping" a municipal bond into a catastrophe bond, to allow investors to hold municipal debt without worrying about hard-to-assess climate risk. Governments of developing nations are increasingly looking to insurance/reinsurance carriers and other capital markets to improve their resiliency to natural disasters as well as give assurances to institutions that are considering investments in a particular region.

— **Addressing tough adaptation choices.** Implementing adaptation measures could be challenging for many reasons. The economics of adaptation could worsen in some geographies over time, for example, those exposed to rising sea levels. Adaptation may face technical or other limits. In other instances, there could be hard trade-offs that need to be assessed, including who and what to protect and who and what to relocate. For example, the impact on individual home owners and communities needs to be weighed against the rising burden of repair costs and post-disaster aid, which affects all taxpayers.

Individual action will likely not be sufficient in many interventions; rather, coordinated action bringing together multiple stakeholders could be needed to promote and enable adaptation. This may include establishing building codes and zoning regulations, mandating insurance or disclosures, mobilizing capital through risk-sharing mechanisms, sharing best practices within and across industry groups, and driving innovation. Integrating diverse perspectives including those of different generations into decision making will help build consensus.

Decarbonizing at scale

An assessment and roadmap for decarbonization is beyond the scope of this report. However, climate science and research by others tell us that the next decade will be decisive not only to adapt to higher temperatures already locked in but also to prevent further buildup of risk through decarbonization at scale.[48] Stabilizing warming (and thus further buildup of risk) will require reaching net-zero emissions, meaning taking carbon out of future economic activity to the extent possible, as well as removing existing CO_2 from the atmosphere to offset any residual hard-to-abate emissions (that is, achieving negative emissions).[49] An important consideration in this context is that climate science also tells us a number of feedback loops are present in the climate system, such as the melting of Arctic permafrost, which would release significant amounts of greenhouse gases. If activated, such feedback loops could cause significant further warming, possibly pushing the Earth into a "hot house" state.[50] Scientists estimate that restricting warming to below 2 degrees Celsius would reduce the risk of initiating many of the serious feedback loops, while further restricting warming to 1.5 degrees Celsius would reduce the risk of initiating most of them.[51] Because warming is a function of cumulative emissions, there is a specific amount of CO_2 that can be emitted before we are expected to reach the 1.5- or 2-degree Celsius thresholds (a "carbon budget").[52] Scientists estimate that the remaining 2-degree carbon budget of about 1,000 $GtCO_2$ will be exceeded in approximately 25 years given current annual emissions of about 40 $GtCO_2$.[53] Similarly, the remaining 1.5-degree carbon budget is about 480 $GtCO_2$, equivalent to about 12 years of current annual emissions. Hence, prudent risk management would suggest aggressively limiting future cumulative emissions to minimize the risk of activating these feedback loops. While decarbonization is not the focus of this research, decarbonization investments will need to be considered in parallel with adaptation investments, particularly in the transition to renewable energy. Stakeholders should consider assessing their decarbonization potential and opportunities from decarbonization.

---

[48] Christina Figueres, H. Joachim Shellnhuber, Gail Whiteman, Johan Rockstrom, Anthony Hobley, & Stefan Rahmstorf. "Three years to safeguard our climate". Nature. June 2017.

[49] Jan C. Minx et al. (2018) "Negative emissions – Part 1: Research landscape and synthesis." *Environmental Research Letters.* May 2018, Volume 13, Number 6.

[50] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences,* August 2018, Volume 115, Number 33; M. Previdi et al. "Climate sensitivity in the Anthropocene." *Royal Meteorological Society,* 2013. Volume 139; Makiko Sato et al. "Climate sensitivity, sea level, and atmospheric carbon dioxide." *Philosophical Transactions of the Royal Society,* 2013. Volume 371.

[51] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences*, August 2018, Volume 115, Number 33; Hans Joachim Schellnhuber, "Why the right goal was agreed in Paris," *Nature Climate Change*, 2016, Volume 6; Timothy M. Lenton et al., "Tipping elements in the Earth's climate system," *Proceedings of the National Academy of Sciences*, March 2008, Volume 105, Number 6; Timothy M. Lenton, "Arctic climate tipping points," *Ambio*, February 2012, Volume 41, Number 1; Sarah Chadburn et al., "An observation-based constraint on permafrost loss as a function of global warming," *Nature Climate Change*, April 2017, Volume 7, Number 5; and Robert M. DeConto and David Pollard, "Contribution of Antarctica to past and future sea-level rise," *Nature*, March 2016, Volume 531, Number 7596.

[52] This budget can increase or decrease based on emission rates of short-lived climate pollutants like methane. However, because of the relative size of carbon dioxide emissions, reducing short-lived climate pollutants increases the size of the carbon budget by only a small amount, and only if emission rates do not subsequently increase; H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1.

[53] Richard J. Millar et al., "Emission budgets and pathways consistent with limiting warming to 1.5°C," *Nature Geoscience*, 2017, Volume 10; Joeri Rogelj et al., "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature*, July 2019, Volume 571, Number 7765.

Box E3

Questions for individual stakeholders to consider

All stakeholders can respond to the challenge of heightened physical climate risk by integrating it into decision making. Below we outline a broad range of questions that stakeholders may consider as they prepare themselves and their communities for physical climate risk, based on their risk exposure and risk appetite. Stakeholders may fall into one or more categories (for example, a nonfinancial corporation may also conduct investment activities).This list is not exhaustive and the implications of the changing climate will prompt others.

Insurers

- Should we continue to invest in forward-looking climate-related modeling capabilities in order to better price climate risk in insurance products and quantify value at risk from climate change in today's portfolio and future investments?
- Could we further drive innovations in insurance products, for example by developing new parametric insurance products that can help reduce transaction costs in writing and administering insurance policies, and by considering coverage caps and public-private partnerships?
- Could we offer risk advisory services to complement standard insurance products including educating target communities on the present and future risks from climate change and developing tool kits for building adaptation and resilience?
- What are possible new measures and incentives to encourage risk-reducing behavior, for example by rewarding implementation of adaptation measures such as hardening physical assets?
- Where insurance can help reduce risk without inducing buildup of further exposure, how can we work with reinsurers, national insurance programs, governments, and other stakeholders to make coverage affordable (for example, crop insurance for smallholder farmers)?

Investors and lenders

- How could we use recommendations of the Task Force on Climate-related Financial Disclosures to develop better risk management practices?[1] Should investees and borrowers be encouraged to make appropriate financial disclosures of climate risk in order to increase transparency?
- How could we integrate climate risk assessments into portfolio allocation and management decisions, including via stress tests and quantifying climate value at risk (VAR) in portfolios using probabilistic forward-looking models that reflect physical climate risk, based on the best available science?
- Is it possible to incorporate climate risk into new lending and investment activity by understanding its potential impact on different geographies and on loans and investments of differing durations, and then adjusting credit policies to reflect VAR for future investments?
- What opportunities exist for capital deployment in sectors and product classes with increasing capital need driven by higher levels of climate change, such as resilient infrastructure bonds?
- In what innovative ways could capital be deployed to fill the growing need for adaptation, especially in areas where business models currently do not provide an operating return (for example, marrying tourism revenues to coral reef protection, providing long-term finance for wastewater treatment systems tied to flood cost reduction, or developing country adaptation funds, possibly with risk-sharing agreements with public financial institutions)?
- How could we best educate debtors on current and future climate risks, including developing tool kits and data maps to help build investee information and capabilities?

Regulators, rating agencies, and central banks

- What could be appropriate measures to increase risk awareness (for example, providing guidance on stress testing, supporting capability building on forward-looking models, or supporting risk disclosures)?
- How could we encourage sharing of best practices across private-sector entities, for example through convening industry associations or publishing risk management tool kits?
- How could we help manage the risk of discontinuous movement of capital, or "capital flight," based on climate change, including considering whether and how to adjust the sovereign risk ratings of low-income, highly climate-exposed countries?

---

[1] *Final report: Recommendations of the Task Force on Climate-related Financial Disclosures,* Task Force on Climate-related Financial Disclosures, June 2017.

Companies outside the financial sector

- What opportunities exist to convene the industry around physical risk, including by building knowledge that is sector- and region-specific?
- How could we incorporate a structured risk-management process that enables good decision making and integrates an assessment of physical and transition climate risk into core business decisions (for example, sourcing, capital planning, and allocation decisions)?
- How might climate change affect core production (risk of disruption or interruption of production, increased cost of production factors); sourcing and distribution (risk of disruption of the upstream supply chain or the downstream distribution, delaying or preventing inflow of inputs and distribution of goods, increasing costs or reducing product prices); financing and risk management (risk of reduced availability or increased cost of financing, insurance, and hedging); and franchise value (risk of declining value of investments and goodwill, disruption of right to operate or legal liabilities)? What business model shifts will be needed?
- How big and urgent are the most relevant climate change risks and what countermeasures should be taken to adapt to and manage them, based on risk appetite (for instance, if risks to sourcing of inputs have been recognized, identifying alternate suppliers or raising inventory levels to create backup stock; or if climate exposure is expected to drive market shifts or impact terminal value of assets, reallocating growth investment portfolio)?

Governments

- How could we integrate an understanding of physical climate risk into policy and strategic agendas especially around infrastructure and economic development planning, including by investing in probabilistic future-based modeling of physical climate impact?
- How could we best address areas of market failure and information asymmetry in the community (for example, making hazard maps readily available, providing adaptation finance directly to affected communities) and agency failures (for instance, in flood insurance)?
- Based on assessments of risk and cost-benefit analysis, how could we plan and execute appropriate adaptation measures, especially physical hardening of critical assets such as public infrastructure? How to think about measures that involve difficult choices—for example, when to relocate versus when to spend on hardening?
- How could we integrate diverse voices into decision making (for example, using public forums or convening local communities) to support more effective adaptation planning, and help identify and reduce distributional effects (for example, unexpected costs of adaptation measures on neighboring communities)?
- How could we best ensure financial resilience to enable adaptation spending and support disaster relief efforts, including drawing on global commitments and multilateral institutions, and collaborating with investors and lenders?
- Do we need to play a role in the provision of insurance, including potential opportunities for risk pooling across regions, and if so, where?

Individuals

- Am I increasing my personal and peer education and awareness of climate change through dialogue and study?
- Do I incorporate climate risk in my actions as a consumer (for example, where to buy real estate), as an employee (for instance, to inform corporate action), and as a citizen?

1. Understanding physical climate risk

A changing climate is introducing new risks that are significant today and will grow. These risks can be grouped into three types: physical risk (risks arising from the physical effects of climate change); transition risk (risks arising from transition to a low-carbon economy); and liability risk (risks arising from those affected by climate change seeking compensation for losses).[54] While some regions and sector could benefit, this report assesses the physical risk from a changing climate, including the potential effects on people, communities, natural and physical capital, and economic activity, and the implications for companies, governments, financial institutions, and individuals. We do not focus on transition risks or liability risks associated with climate change. While decarbonization and the risks and opportunities it creates is a critical topic, this report contributes by exploring the nature and costs of ongoing climate change in the absence of decarbonization.

Physical climate risks are probabilistic because of the probabilistic nature of the underlying climate hazards that create risk; for example, there is a certain likelihood associated with having floods of a given severity, or days above a certain temperature, in a year. By hazards, we mean climate-induced physical phenomena (acute or chronic) that have the potential to impact natural and socioeconomic systems. A changing climate means these likelihoods are shifting. We consider the "inherent" level of risk that results from these shifts —that is, the risk before consideration of adaptation and mitigation measures that could reduce the likelihood or magnitude of socioeconomic impacts—as well as the potential adaptation and mitigation response. We believe this approach is appropriate to help stakeholders understand the potential magnitude of the impacts from climate change and the commensurate response required. We look at two periods: between today and 2030, and from 2030 to 2050.

To develop meaningful local estimates of physical climate risk, we draw on climate models to understand how geospatially specific climate hazards could evolve under an RCP 8.5 scenario. We then create a taxonomy for physical risk by examining the impact of those hazards on five critical socioeconomic systems. They are: livability and workability, food systems, physical assets, infrastructure services, and natural capital. Together, these represent impacts on human beings, human-made physical assets, and the natural world. For each type of system, we assess impact by examining nine cases across sectors and geographies that were chosen based on their exposure to the extremes of climate change and their proximity today to key physical and biological thresholds. As such, they represent leading-edge examples of climate change. In a separate analysis, we use geospatial data to provide a perspective on physical climate risk across 105 countries over the next 30 years, using the same five-systems framework of direct impacts. Details of our modeling are described in the executive summary, Chapter 4, and the technical appendix.

---

[54] *Climate change: What are the risks to financial stability?* Bank of England, KnowledgeBank.

Our intent is not to provide point forecasts. Climate is the statistical summary of weather patterns over time and is therefore probabilistic in nature. Following standard practice, our findings are therefore framed as “statistically expected values”—the statistically expected average impact across a range of probabilities of different hazard manifestations. We also report the value of “tail risks”—that is, low-probability, high-impact events like a 1-in-100-year storm—on an annual basis. In some cases, we show the cumulative probability of a tail risk over a period. Consider for example a flooding event that has a 1 percent likelihood of occurrence every year (often described as a “100-year flood”). In the lifetime of home ownership, the cumulative likelihood that the home will experience at least one 100-year flood is 26 percent.[55] Understanding such cumulative probabilities is important for stakeholders looking to design appropriate risk-management strategies.

A five-systems framework for measuring potential direct and indirect impacts of the changing climate

We measure the impact of climate change by the extent to which it could disrupt or destroy stocks of capital—human, physical, and natural—and the resultant socioeconomic impact of that disruption or destruction. As climate hazards manifest, they can affect these systems and thus create risk. For example, flooding in a particular location could damage a physical structure like a factory. To provide a framework for our analysis, we conducted an extensive review of direct impacts and classified them into five groups of system directly affected by physical climate hazards. The five are livability and workability, food systems, physical assets, infrastructure services, and natural capital. This five-systems impact framework is our best effort to capture the entire range of potential impacts from physical climate hazards. In the course of our work, we have not identified any other material impacts of climate change outside these five groups. We define each of the five as follows:

— **Livability and workability.** Livability refers to the ability of an area to sustain human life and activity; workability is the capacity to engage in outdoor work. Hazards like heat stress and flooding could affect the ability of human beings to work outdoors or put human lives at risk. Heat reduces labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts in order to prevent over-exertion. Increased temperatures could also shift disease vectors and thus affect human health.

— **Food systems.** Food systems include the production and distribution of agricultural products and the associated revenues and livelihoods. Food production could be disrupted as drought conditions, extreme temperatures, or floods affect land and crops. Conversely, some climatic shifts could also make some regions more suitable for agriculture. A changing climate change can both improve and degrade food system performance, while introducing more or less volatility. In some cases, crop yields may increase; in other cases, thresholds could be exceeded beyond which some crops fail entirely.

— **Physical assets.** Physical assets like buildings could be damaged or destroyed by extreme precipitation, tidal flooding, forest fires, and other hazards. Hazards could even materially impact an entire network of assets such as a city’s central business district.

— **Infrastructure services.** Infrastructure assets are a particular type of physical asset that could be destroyed in their functioning, leading to a decline in the services they provide or a rise in the cost of these services. For example, power systems could become less productive under very hot conditions. A range of hazards including heat, wind, and precipitation can disrupt infrastructure services. This in turn can have knock-on effects on other sectors.

---

[55] Assuming that probabilities stay constant throughout the 30-year period.

— **Natural capital.** Climate change is shifting ecosystems and destroying forms of natural capital such as glaciers, forests, and ocean ecosystems, which provide important services to humans. Natural capital is at risk from both acute hazards like wildfires and chronic hazards like rising temperatures. These impacts are hard to model but could be nonlinear and in some cases—such as glacier melting—irreversible. In some cases, human mismanagement may play a role, for example with forest fires and water scarcity, but the effect of this mismanagement is multiplied by climate change.

To assess the magnitude of direct physical climate risk in each case and for our geospatial analysis, we examine the severity of the hazard and its likelihood; the exposure of people, assets, or economic activity to the hazard; and the extent to which systems are vulnerable to the hazard, for example, how vulnerable buildings are to damage from different depths of flood. Direct impacts could have knock-on effects. For example, flood damage to a factory could interrupt production and affect downstream players in a supply chain.

How our methodology addresses possible sources of uncertainty

One of the main challenges in understanding the physical risk arising from climate change is the range of uncertainties involved. Yet a key insight of this research has been that, despite the many uncertainties associated with estimations of impact from a changing climate, it is possible for the science and socioeconomic analyses and methodologies presented here to provide actionable insights. In this chapter, we outline some of these uncertainties and our approach to addressing them. It is important for decision makers to understand these uncertainties and incorporate that understanding into a risk-management approach that aligns with their risk appetite.

Here, we highlight the possible sources of uncertainty and our methodological approach to addressing these in this report. The discussion below relates both to the results from our case studies and from our geospatial analysis. Risks arise as a result of an involved causal chain: Emissions influence both global climate as well as regional climate variations, which in turn influence the frequency and severity of specific climate hazards (such as droughts and sea-level rise), which then influence the frequency and severity of physical damage (such as crop shortage and infrastructure damages), which finally influence broader economic, social and financial harm. Our analysis, like any such effort, relies on assumptions made along the causal chain: about emission paths and adaptation schemes; global and regional climate models; physical damage functions; and knock-on effects. The further one goes along the chain, the greater the intrinsic model uncertainty.

The key uncertainties include: emissions pathways and the pace of warming; climate model accuracy and natural variability; the magnitude of direct and indirect socioeconomic impacts, given a certain hazard; and the socioeconomic response.

Emissions pathways and pace of warming

Climate impact research has inherent uncertainties and as a result makes extensive use of scenarios. One particular input around which scenarios are frequently constructed is atmospheric greenhouse gas levels. Projections of future climate must be based upon an assumed trajectory for future atmospheric greenhouse gas concentrations. Because future human emissions of greenhouse gases are inherently unpredictable, the climate community has developed a set of four standardized scenarios for future atmospheric greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs).[56] They outline different atmospheric greenhouse gas concentration trajectories between 2005 and 2100 that roughly range from lower (RCP2.6) to higher (RCP 8.5) CO_2 concentrations. During their inception, RCPs were designed to collectively sample the range of then-probable future emission pathways. Each RCP was created by an independent modeling team and there is

---

[56] Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An overview," *Climatic Change*, November 2011, Volume 109, Issue 1–2.

no consistent design of the socioeconomic parameter assumptions used in the derivation of the RCPs.

Uncertainty in future greenhouse gas emissions is a key contributor to long-term (for example, end-of-century) uncertainty in future temperatures but is less important on the shorter time horizons (out to 2050) considered in this report. As we discuss in detail in Chapter 2, warming during the next decade is determined largely by past emissions and by physical inertia in the climate system. Beyond the next decade, warming is primarily a function of *cumulative* emissions of carbon dioxide. Because decarbonization takes time, even a scenario of targeted decarbonization action will result in significant cumulative emissions over the next three decades. Climate simulations driven by the four RCP scenarios show a small divergence in warming over the next two decades, and a moderate divergence by 2050 (see also Exhibit 1, which shows projected warming for RCP 8.5 and RCP 4.5; the two RCPs that are most commonly used in climate models, to provide a sense of the spread in scenarios).[57]

We rely on RCP 8.5 for the analyses in this report. RCP 8.5 was created to model a case of no further climate action and relatively higher rates of baseline greenhouse gas emissions. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization.

While RCP 8.5 has been criticized for assuming unrealistically high use of coal and thus projecting too-high emissions in the second half of the century, we only consider a timeframe out to 2050, and we adopted RCP 8.5 as a best available description for an 'inherent risk' scenario over the next two to three decades.[58]

This assessment was also made for the following reasons.

— Since the starting point of the RCPs in 2005, RCP 8.5 has most closely tracked actual greenhouse gas emissions (and going forward, RCP 8.5 is broadly consistent with a continuation of the emissions trend of the last decade).[59] As a result, it best matches current CO_2 concentrations, whereas the other RCPs assume lower CO_2 concentrations than observed.

— Changes in the relative cost of renewable and fossil energy sources are forecast to lead to a moderate downward divergence from the historic trendline of energy-related CO_2 emissions over the coming decades, even in absence of further decarbonization policies.[60] In contrast, emissions from biotic feedbacks, such as permafrost thaw or increasing wildfires, are expected to increase. These feedbacks are not considered in the current generation of CMIP5 models and need to be accounted for exogenously. According to a recent review of the literature on biotic feedbacks, in the near term these feedbacks are estimated to reduce the 1.5 degree Celsius carbon budget by 100 $GtCO_2$, and 2 degree Celsius carbon budget by 150 $GtCO_2$.[61]

---

[57] Ibid.

[58] Justin Ritchie and Hadi Dowlatabadi, "The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible?" *Energy Economics*, June 2017, Volume 65; Justin Ritchie and Hadi Dowlatabadi, "Why do climate change scenarios return to coal?" *Energy*, December 2017, Volume 140, Part 1; Keywan Riahi et al., "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Global Environmental Change*, January 2017, Volume 42; Keywan Riahi, Arnulf Grübler, and Nebojsa Nakicenovic, "Scenarios of long-term socio-economic and environmental development under climate stabilization," *Technological Forecasting and Social Change*, September 2007, Volume 74, Issue 7; Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An overview," *Climatic Change*, November 2011, Volume 109, Issue 1–2.

[59] Hayhoe, K., J. Edmonds, R.E. Kopp, A.N. LeGrande, B.M. Sanderson, M.F. Wehner, and D.J. Wuebbles, 2017: Climate models, scenarios, and projections. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 133-160, doi: 10.7930/J0WH2N54.

[60] IEA World Energy Outlook 2019.

[61] Jason A Lowe and Daniel Bernie, "The impact of Earth system feedbacks on carbon budgets and climate response," *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

— Early results from the next generation of climate models, CMIP6, suggest that the climate system may be more sensitive to CO_2 than the current generation of models (CMIP5) used here, suggesting that the CMIP5 models may tend to underestimate future warming.[62]

Based upon these considerations we chose to employ RCP 8.5 as a base case for considering 2030 to 2050. Were this study investigating the risk outlook for 2100, we would consider multiple emissions pathways, but for the next three decades, we consider RCP 8.5 to be the best guide for understanding inherent risk.

Restricting warming to below two degrees, the goal of the 2015 Paris agreement, would mean reaching net-zero emissions in the next 40 to 50 years. If this were achieved, the impact estimates presented in this report would likely not manifest to their full extent. Alternately, a decarbonization approach somewhere between business-as-usual and a two-degree-compliant pathway would mean that temperatures in 2050 would be below the roughly 2 degrees Celsius increase reflected in the RCP 8.5 scenario, but that such temperature increases would be reached at some point post-2050. This means that the impact assessments presented in this report would manifest but only after 2050; it would push the 2050 impacts further back into the second half of the century but would not prevent them.

Another way to frame this would be that if we were to limit warming to 2 degrees Celsius, our 2050 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2050), and if we were to limit warming to 1.5 degrees Celsius, correspondingly our 2030 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2030). For example, RCP 8.5 predicts global average warming of 2.3 degrees Celsius by 2050, compared with 1.8 for RCP 4.5. Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080.[63]

Climate model accuracy

This refers to modeling uncertainty associated with climate models that translate greenhouse gas emissions into temperature increases and effects on other hazards, both globally and in specific regions. While uncertainty is inherent in any model, scientists have tested the ensemble of climate models used in this report against both observations and paleoclimate records, and as a result have confidence in their probabilistic predictions of how climate hazards will evolve over the next decades, given a particular emissions pathway.[64] To reduce model error, this report uses the mean or median projection of an ensemble of models, depending on the requirements of the specific analysis.[65] This approach has been found to generate a more robust projection than any individual model.[66] It is important to note that, when looking across a full range of climate science models, the uncertainty in global temperatures tends to skew primarily toward worse rather than better outcomes (Exhibit 1).

---

[62] Stephen Belcher, Olivier Boucher, and Rowan Sutton, *Why results from the next generation of climate models matter*, Carbon Brief, March 2019.

[63] Intergovernmental Panel on Climate Change (IPCC), 2014: Annex II: Climate System Scenario Tables, 2013.

[64] Gregory Flato et al., “Evaluation of climate models,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014; Sandy P. Harrison, Patrick J. Bartlein, and I. Colin Prentice, “What have we learnt from paleoclimate simulations ?” *Journal of Quaternary Science*, May 2016, Volume 31, Number 4; Zeke Hausfather, “Analysis: How well have climate models projected global warming ?” Carbon Brief, 2017.

[65] For most of the analysis used in the report, we rely on analysis from the Woods Hole Research Center (WHRC) on an ensemble of climate models, as described here. In some instances (for example, modeling changes in water supply), we have relied on publicly available data sets showcasing shifts in climate hazards. This has been noted where relevant.

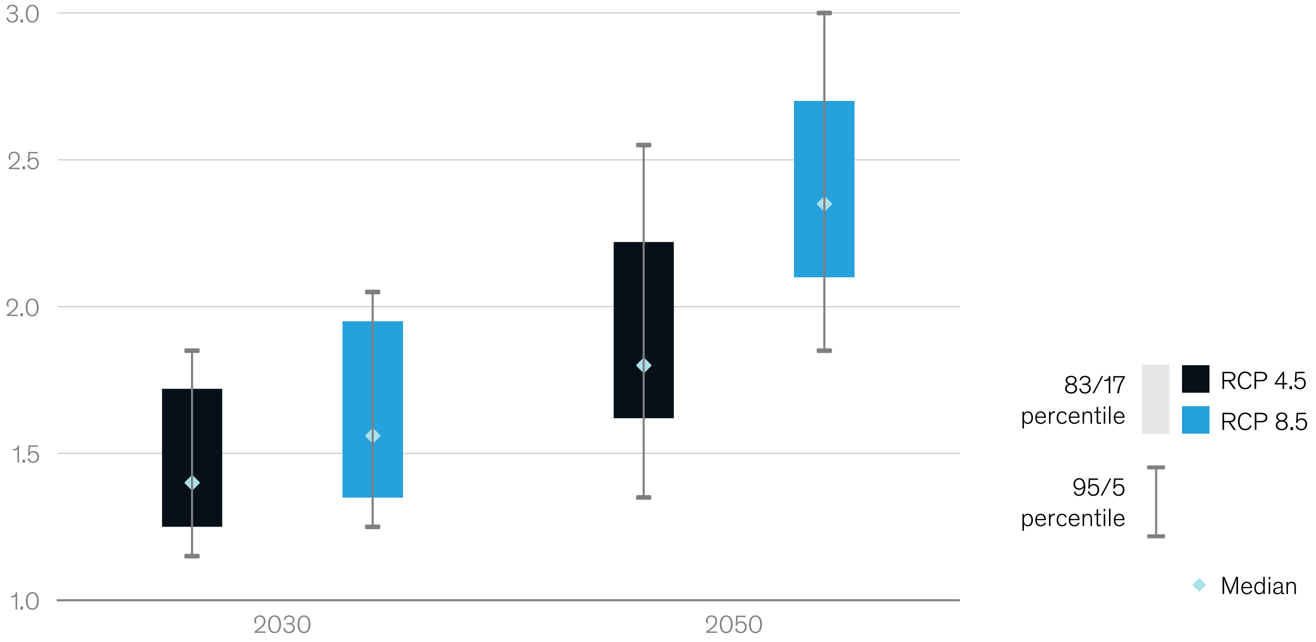
[66] See the technical appendix for further details.

Exhibit 1

We make use of RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization.

Global average land and sea surface temperature anomaly relative to 1850–1900 average

°C



Note: For clarity of graph, outliers beyond 95th to 5th percentile are not shown. This chart shows two RCPs that are most commonly used in climate models, to provide a sense of the spread in scenarios.

Source: Intergovernmental Panel on Climate Change, The Physical Science Basis, 2013

Under RCP 8.5, for example, Earth is projected to warm by an estimated 2.3 degrees Celsius, +0.5 / –0.3 degree, by 2050.[67] This spread is primarily due to uncertainty surrounding the strength of modeled fast-acting, non-carbon feedback mechanisms (for example, the way clouds respond to a warming planet), which amplify warming from greenhouse gases. Different models make different assumptions about the strength of these feedback mechanisms, contributing to the spread across models.[68] It should be noted that while the current generation of models does represent some feedbacks, both carbon and non-carbon, it does not model others. Many of the missing mechanisms are primarily slow-acting, and so warming outside of the 5–95th percentile projections of the model ensemble are considered unlikely in the next three decades.[69]

---

[67] Ben Kirtman et al., “Near-term Climate Change: Projections and Predictability,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[68] Jessica Vial, Jean-Louis Dufresne, and Sandrine Bony, “On the interpretation of inter-model spread in CMIP5 climate sensitivity estimates,” *Climate Dynamics,* December 2013, Volume 41, Number 11–12.

[69] Jason A. Lowe and Daniel Bernie, “The impact of Earth system feedbacks on carbon budgets and climate response,” *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

Modeling climate changes at a regional level introduces additional sources of uncertainty. Because global climate models are generally spatially coarse, on the order of 100 by 100 kilometers, they are unable to resolve, or simulate, small geographical, atmospheric, or biological features that exert significant influence over local climates. The global climate system can also distribute additional heat in multiple different ways, and so the same emissions scenario can result in different regional warming outcomes.[70] Some of this uncertainty can be reduced through technical methods (for example, the use of historical regional data to calibrate global climate models), and some cannot.[71] To make “skillful” regional predictions requires careful choices of the specific modeling tool, climatic variable of interest, region, and time period.[72] The analyses in this study have been designed in such a way as to minimize uncertainty from regional natural variability (through region, time period, and variable choice), as well as to minimize uncertainty from model error (through technical methods).[73] For more details, see the technical appendix.

Natural variability

Natural variability is another consideration influencing how hazards could evolve. It refers to climatic changes that occur independently of changes in the amount of energy trapped in the Earth system. Natural variability arises primarily from multiyear patterns in ocean circulation that can temporarily warm or cool the surface of the planet. These changes are included in climate models, but because of their stochastic, or random, nature, their timing cannot be accurately projected.[74] One example is the El Niño / La Niña oscillation. Another is the so-called global warming hiatus between 1998 and 2012, during which the global average temperature did not seem to increase as much as climate models projected, as warming of the planet’s surface was masked by changes in ocean heat uptake.[75] The presence of natural variability introduces uncertainty into our projections because it can temporarily accelerate or delay the manifestation of longer-term statistical climate shifts.[76] This uncertainty will be particularly important over the next decade, during which overall climatic shifts relative to today may be smaller in magnitude than a potential acceleration or delay in warming due to natural variability.[77]

Direct and indirect socioeconomic impacts

To measure direct impact as hazards manifest, we have relied on publicly available vulnerability assessments or “damage functions” for this but note that they may not accurately represent the vulnerability of a specific asset or location. Another factor that could create uncertainty is the magnitude of exposure to climate hazards. If more people or assets are located in regions that are exposed to climate hazards, impacts could be higher. For this report, we assume that exposure is constant for instances where we do not expect significant shifts in exposure—for example, when we consider breadbasket failures, we do not assume significant shifts in where crops are grown today. In other instances, we do consider changes in exposure, such as sectoral shifts out of agriculture and manufacturing in the case of the

---

[70] Clara Deser et al., “Communication of the role of natural variability in future North American climate,” *Nature Climate Change*, October 26, 2012.

[71] Ed Hawkins and Rowan Sutton, “The potential to narrow uncertainty in regional climate predictions,” *Bulletin of the American Meteorological Society*, August 2009, Volume 90, Number 8.

[72] A “skillful” prediction in the climate-science context refers to the ability of a climate model to produce accurate or robust projections of change in a given variable (for example, daily maximum temperature) over a given area and time scale.

[73] Ed Hawkins and Rowan Sutton, “The potential to narrow uncertainty in regional climate predictions,” *Bulletin of the American Meteorological Society*, August 2009, Volume 90, Number 8; Nurul Nadrah Aqilah Tukimat, “Assessing the implementation of bias correction in the climate prediction,” *IOP Conference Series: Materials Science and Engineering*, April 2018; Gerhard Krinner and Mark G. Flanner, “Striking stationarity of large-scale climate model bias patterns under strong climate change,” Proceedings of the National Academy of Sciences, September 2018, Volume 115, Number 38.

[74] Kyle L. Swanson, George Sugihara, and Anastasios A. Tsonis, “Long-term natural variability and 20th century climate change,” *Proceedings of the National Academy of Sciences*, September 2009, Volume 106, Number 38.

[75] While the planet continued to warm during this period, the warming was masked by changes in ocean heat uptake, which can produce temporary average global surface temperature trends of +/– 0.25 degree on time scales of up to a decade. Given that global surface temperature warming is currently occurring at approximately 0.2 degree per decade, the warming trend was obfuscated during the 1998–2012 period. Iselin Medhaug et al., “Reconciling controversies about the ‘global warming hiatus,’” *Nature,* May 2017, Volume 545; Zeke Hausfather et al., “Assessing recent warming using instrumentally homogeneous sea surface temperature records,” *Science Advances,* January 2017, Volume 3, Number 1.

[76] Ed Hawkins and Rowan Sutton, “The potential to narrow uncertainty in regional climate predictions,” *Bulletin of the American Meteorological Society*, August 2009, Volume 90, Number 8.

[77] Ibid.

impact of heat on India. We also consider increased infrastructure buildup when we look at the impact of flooding on cities in developing countries.

Finally, there is uncertainty related to the indirect, or knock-on, impacts of a changing climate. Given the complexity of socioeconomic systems, we know that our case results do not capture the full impact of climate change. Socioeconomic systems are dynamic, with many interacting and interdependent elements. As is typical for such systems, changes in one element can have nonlinear repercussions on other elements and lead to unexpected phenomena. Assessing possible social or political knock-on effects from phenomena like lethal heat waves, for example, is difficult, and we have almost certainly not identified the full range of knock-on effects (see Box 1, "Three channels through which climate risk could trigger disruption in extreme cases"). Even in instances where we have identified knock-on effects, sizing the magnitude of potential impact in a given case—for example, the degree to which real estate valuations in Florida could change and when—is difficult. In many cases, we have relied either on past trends and empirical estimates of knock-on effects or discussed them in a qualitative manner alone.

Socioeconomic response

How much risk manifests also depends on the robustness of the response to the risk that is forecast. Adaptation measures such as hardening physical infrastructure, relocating people and assets, and ensuring backup capacity, among others, can help manage the impact of climate hazards and reduce risk. We therefore follow an approach that first assesses the inherent risk and then considers a potential adaptation response. We have not conducted a detailed bottom-up cost-benefit analysis of adaptation measures but have built on existing literature and expert interviews to understand the most important measures and their indicative cost, effectiveness, and implementation challenges in each of our cases, and to estimate the expected global adaptation spending required. While we note the critical importance of decarbonization in an appropriate climate risk management approach, a detailed road map for decarbonization is beyond the scope of this report.

We conclude that despite many uncertainties that need to be reflected in decision making, climate science and the socioeconomic analyses and methodologies presented here can provide actionable insights for decision makers. Uncertainties tend to be skewed toward larger rather than smaller impact. How decision makers incorporate these uncertainties into their management choices will depend on their risk appetite and overall risk management approach. Some may want to work with the outcome considered most likely (which is what we generally considered with our analysis of "statistically expected outcomes"), while others may want to consider a worse- or even worst-case scenario. Given the complexities we have outlined above, we recognize that more research is needed in this critical field.

Box 1

Three channels through which physical climate risk could trigger disruption in extreme cases

As physical climate risk spreads beyond local economies, it could trigger broader economic, financial, social, and political disruption. While the likelihood and potential magnitude of such disruption is impossible to predict, it could occur through several channels, including the following three.

First, physical risks—and the anticipation thereof—which may prompt an abrupt policy response. Sudden regulatory responses to rising climate hazards, for example following a series of natural disasters or a marked change in political priorities, could destabilize markets and companies. Such an abrupt transition would leave companies across the world with assets that could become too expensive or even impossible to operate. This could in turn lead to a range of knock-on effects for the owners of the asset, their ability to finance other assets, and creditworthiness.

Second, sudden asset repricing and capital reallocation. Financial markets could experience a devaluation due to an abrupt repricing of assets or a loss of access to long-term capital. Such a climate "Minsky moment" might occur if a significant number of market participants were to come to believe they have not adequately factored in physical climate risks which could lead to a sudden depreciation of, for example, real estate prices.[1] Knock-on financial effects could then result from such a depreciation of collateral depending on the degree of leverage, complexity (securitization and pooling), and transparency around the financing of those assets. As an example, significant storm surge losses from hurricanes hitting coastal real estate could lead to a substantial rise in insurance premiums, followed by an abrupt devaluation of that real estate market, which in turn might lead investors to reappraise their investments in other coastal real estate markets. A recognition by capital markets of projected hazards and possible impacts over the coming decades could also lead to changes in the cost or availability of long-term capital for certain sectors or regions and to changes in credit ratings, disclosure, and regulations which could have the potential of creating a period of heightened uncertainty and illiquidity until ratings, information, and regulation meet the new market expectations. Unlike other financial sector booms and busts, the downside risk in climate change-driven depreciation would likely not be cyclical—it would reflect higher long-lasting, structural risks in particular geographies or sectors—hence requiring structural responses. A swing from not considering climate risk to extreme caution in climate-sensitive assets is a real concern.

Third, disruptive relocation of population and assets. Severe climate change effects could trigger migration, social and political unrest, and potentially even conflict in affected regions, which in turn may have global repercussions. Between 2008 and 2018, natural disasters displaced as many as 265 million people, according to the Internal Displacement Monitoring Centre.[2] The World Bank projects that by 2050, in Latin America, South Asia, and sub-Saharan Africa, climate change may cause about 140 million people to migrate within their countries, away from areas with lower water availability and crop productivity or rising sea level and storm surges.[3] While climate change is often not the sole factor in migration decisions, it may amplify existing motivations such as poverty, war, and strife. As early as 2014, the US Department of Defense identified climate change as a "threat multiplier" and "accelerant of instability."[4]

---

[1] A "Minsky moment"—named for the American economist Hyman Minsky—is the onset of a market collapse brought on by the reckless speculative activity that defines an unsustainable bullish period. For a discussion of how climate risks could create a Minsky moment that disrupts financial markets, see Mark Carney, *A Transition in Thinking and Action*, speech at the International Climate Risk Conference for Supervisors, De Nederlandsche Bank, Amsterdam, April 6, 2018.

[2] Sylvain Ponserre and Justin Ginnetti, *Disaster displacement: A global review, 2008–2018*, Internal Displacement Monitoring Centre, May 2019.

[3] Kanta Kumari Rigaud et al., *Groundswell: Preparing for internal climate migration,* World Bank, March 2018.

[4] *2014 quadrennial defense review*, US Department of Defense, 2014.

2. A changing climate and resulting physical risk

A changing climate requires us to assess the impact of physical climate risk over time horizons relevant for decision makers today. Energy trapped by increasing atmospheric greenhouse gases leads to rising temperatures, which in turn intensifies chronic climate hazards and increases the frequency and or severity of acute events. These developments have an impact on socioeconomic systems around the world. Looking ahead, climate science tells us that additional warming is locked in for the next decade, regardless of mitigation measures that may be adopted. Beyond the next decade, further warming will occur as a function of cumulative emissions of long-lived greenhouse gases, like carbon dioxide. Climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions. As the Earth continues to warm, climate science finds that physical climate hazards will intensify.

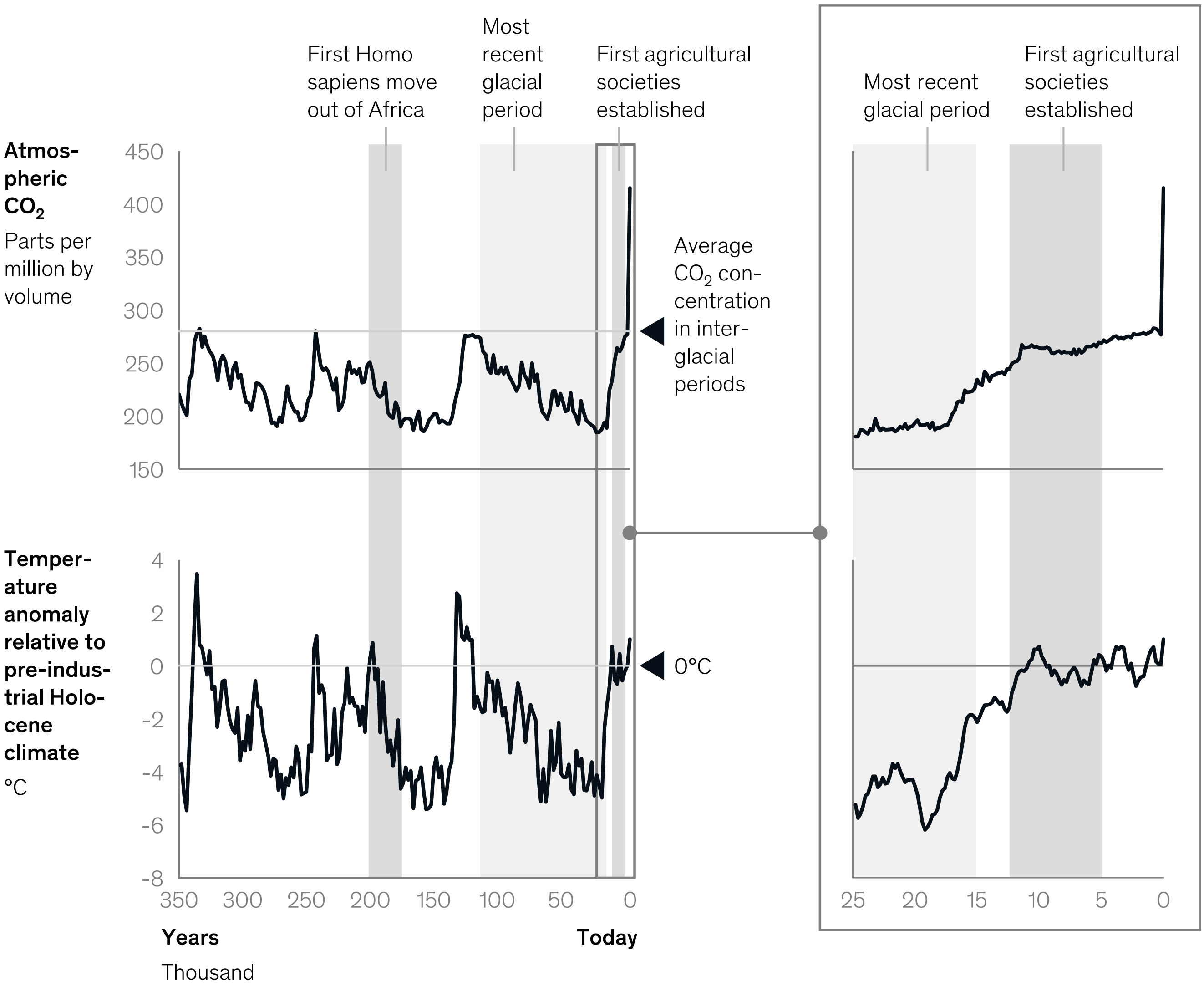
Earth's climate is warming and climate hazards are intensifying

During the past 2.6 million years or so of Earth's 4.5-billion-year history, the planet oscillated between long cooling, or glacial, periods during which large ice sheets covered as much as one-third of the planet's surface, and short warming, or interglacial, periods when the climate was more temperate for, typically, 10,000 to 30,000 years. For approximately the past 12,000 years, Earth has been in an interglacial period, characterized by a relatively stable, temperate climate. During this time, human civilization developed. Roughly 10,000 years ago, relatively soon after the climate stabilized, humans made the shift from hunter-gatherers to farmers (Exhibit 2).

Modern society was built during this time of stable climate, which shaped the world in three fundamental ways. First, it produced a habitable planet, allowing humans to spread across the world. Second, it shaped the design of physiological, human-made and ecological systems that are optimized for historical local climate parameters. For example, the choice of which crops to grow where and the engineering design standards used for infrastructure are both based on temperature and precipitation levels from this stable past. Third, the stable climate created a predictable physical environment, which contributed to the emergence of the modern economy. Much of the economic and financial activity, particularly for the long-term—including buying, selling, investing, borrowing, and lending—requires a degree of confidence that tomorrow will be similar to today.

Exhibit 2

Human civilization developed during a period of relatively stable climate.



Source: Bereiter et al., 2015; Feynman and Ruzmaikin, 2018; Uemura et al., 2012; McKinsey Global Institute analysis

This is now changing. The average combined global land-and-sea-surface temperature has increased by 1.1 +/– 0.05 degrees Celsius since 1880 (Exhibit 3).[78] This has been confirmed by both satellite measurements and the analysis of hundreds of thousands of independent weather station observations from across the globe. The rapid decline in the planet's surface ice cover provides further evidence. Earth is warming at a rate of about 0.2 degree Celsius per decade and losing Arctic sea ice at roughly 3,000 cubic kilometers per decade.[79] This rate of warming is at least an order of magnitude faster than any currently identified in the past 65 million years of paleoclimate records and could be unprecedented as far back as 250 million years.[80]

---

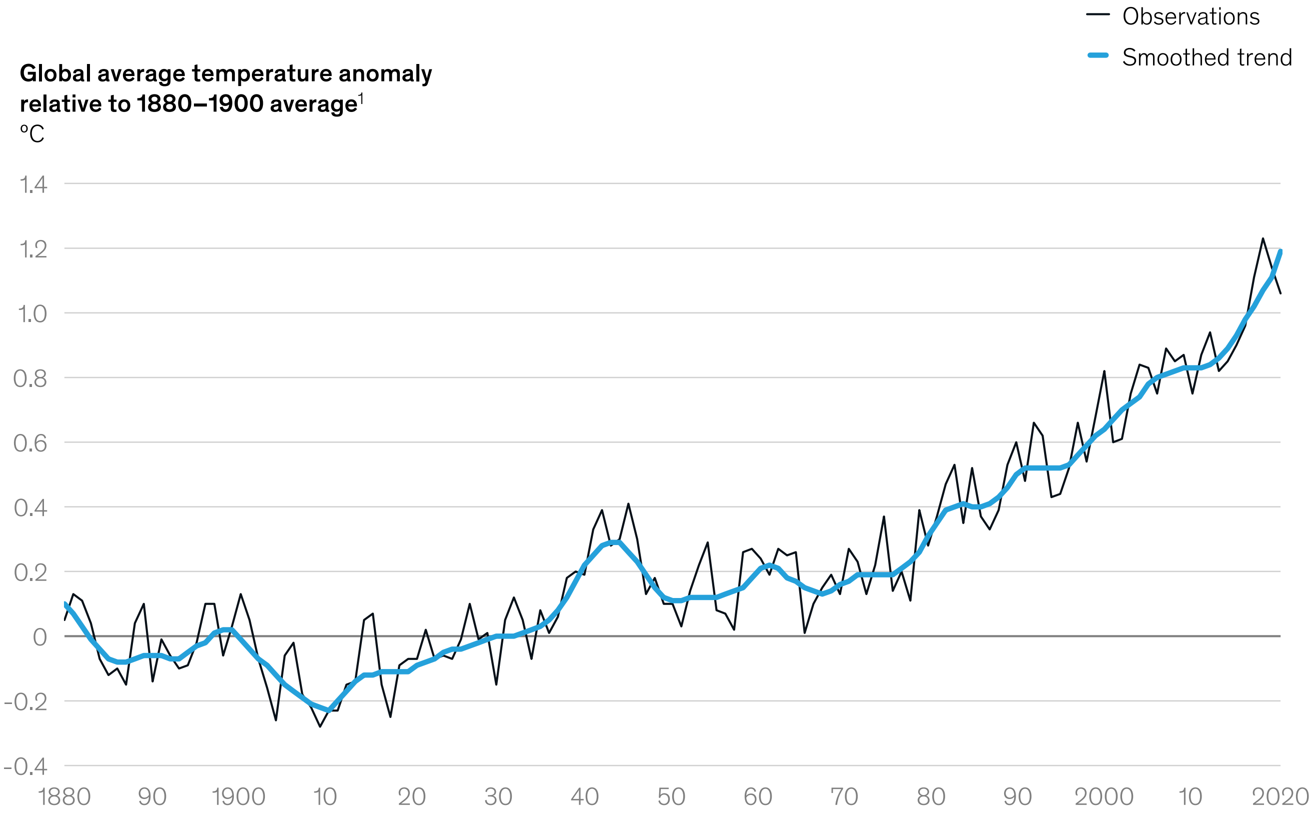
[78] NASA GISTEMP (2019) and, Nathan J. L. Lenssen et al., "Improvements in the GISTEMP uncertainty model," *Journal of Geophysical Resources: Atmospheres,* June 2019, Volume 124, Number 12.

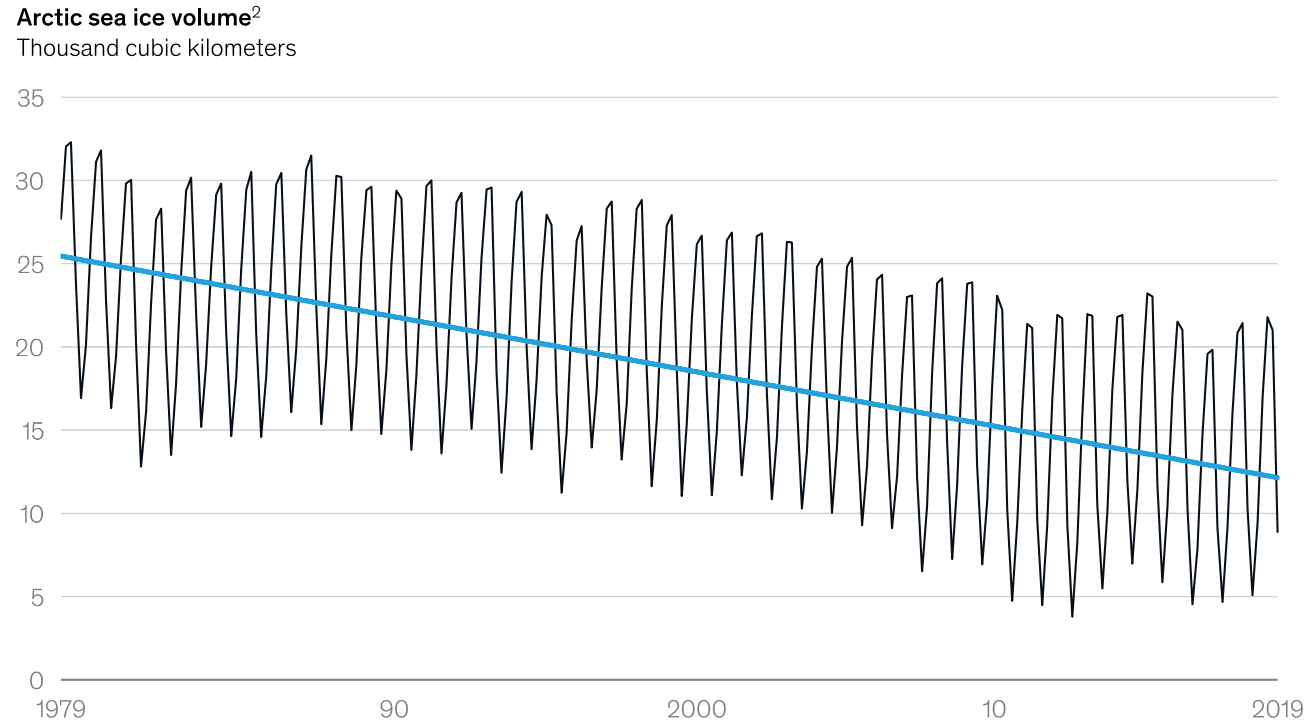
[79] National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), 2019; University of Washington Polar Science Center PIOMAS, 2019.

[80] Noah S. Diffenbaugh and Christopher B. Field, "Changes in ecologically critical terrestrial climate conditions," *Science*, August 2013, Volume 341, Number 6145; Seth D. Burgess, Samuel Bowring, and Shu-zhong Shen, "High-precision timeline for Earth's most severe extinction," *Proceedings of the National Academy of Sciences,* March 2014, Volume 111, Number 9.

Exhibit 3

Earth has warmed by roughly 1.1 degrees Celsius since the late 1800s.





1. Temperature anomaly is defined as increase in average global temperature (ie, average of all daily mean temperatures across all locations [both land and sea] for all days in a given year).
2. Periodicity in the data is because sea ice volume follows a periodic cycle with the Earth's seasonal cycle: sea ice traditionally reaches annual low volumes in September and maximum volumes in late Northern Hemisphere spring.

Source: NASA Goddard Institute for Space Studies, GISTEMP 2019; University of Washington Pan -Arctic Ice Ocean Modeling and Assimilation System, PIOMAS 2019

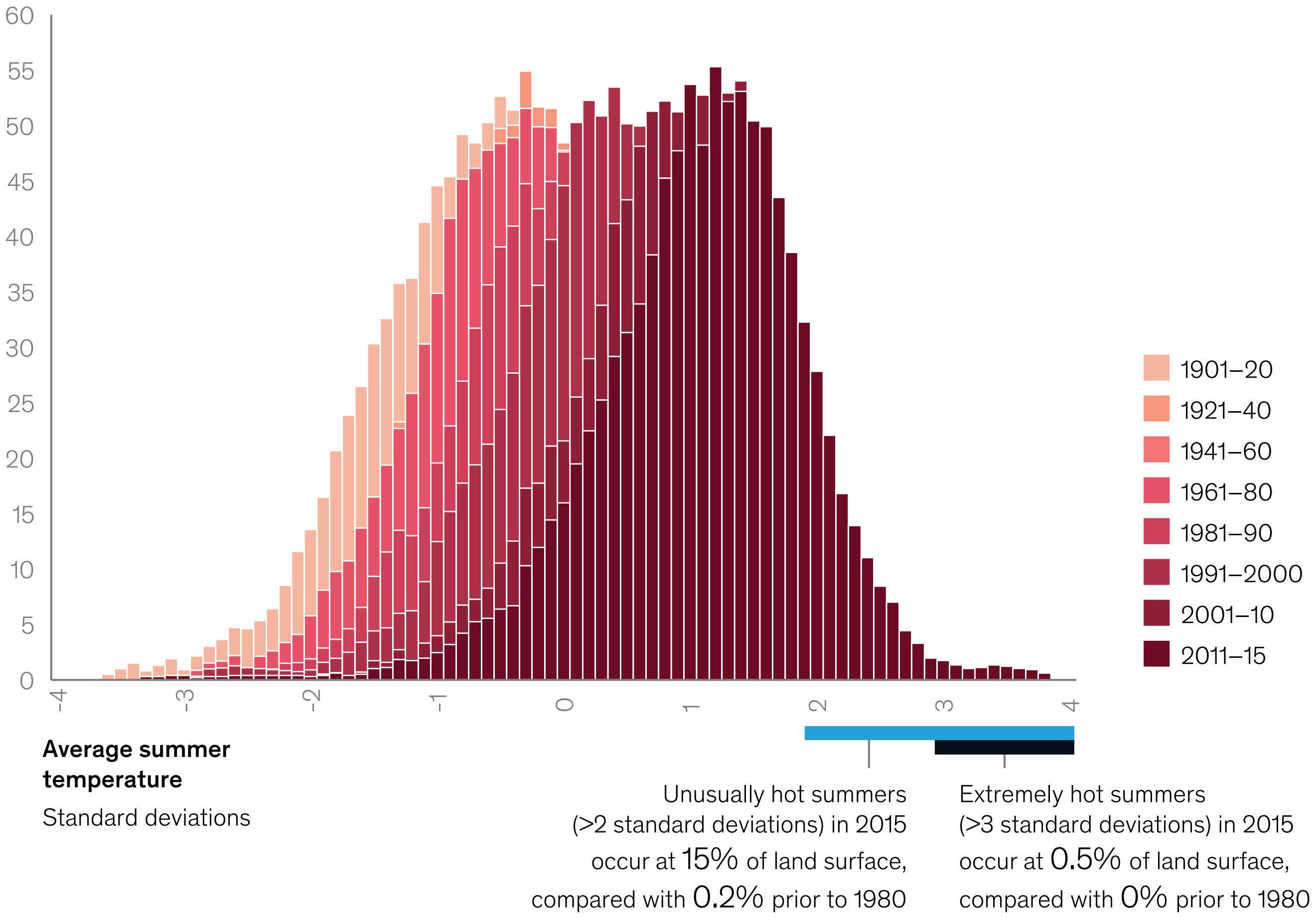
With this warming, historically rare events are becoming increasingly common. Global averages mask how the extreme end of the temperature distribution in a given region is changing. In statistical terms, distributions of temperature are shifting to the right and broadening. That means the average day in many locations is now hotter ("means shifting"), and extremely hot days are becoming more likely ("tails fattening"). For example, the evolution of the distribution of observed average summer temperatures for each 100-by-100-kilometer square in the Northern Hemisphere shows that the mean summer temperature has increased over time (Exhibit 4). The percentage of the Northern Hemisphere (in square kilometers) that experiences a substantially warmer summer—a two-standard-deviation warmer average temperature in a given year—has increased by more than 15 times, from less than 1 percent to approximately 15 percent. The share of the Northern Hemisphere (in square kilometers) that experiences an extremely warm summer—three-standard-deviation warmer average temperature in a given summer—went from zero percent to half a percent between 1980 and 2015. In other words, observations show unusually warm summers becoming more common across a greater percentage of the Northern Hemisphere, while summers so hot they have not occurred before in human temperature records have now become possible.

Exhibit 4

A small shift in the average can hide dramatic changes at the extremes.

Frequency of local temperature anomalies in the Northern Hemisphere

Number of observations, thousands



Note: Because the signal from anthropogenic greenhouse gas emissions did not emerge strongly prior to 1980, some of the early time period distributions in the above figure overlap and are difficult to see. Northern Hemisphere land surface divided into 100km x 100km grid cells. Standard deviations based on measuring across the full sample of data across all grid-cells and years.
Source: Sippel et al., 2015; McKinsey Global Institute analysis with advice from University of Oxford Environmental Change Institute

Averages also conceal wide spatial disparities. Over the same period that the Earth warmed by 1.1 degrees Celsius, in southern parts of Africa and the Arctic, average temperatures have risen by 0.2 to 0.5 degree and by 4 to 4.3 degrees, respectively.[81] In general, the land surface has warmed faster than the 1.1-degree global average, and the oceans, which have a higher heat capacity, have warmed less. As average temperatures rise, acute hazards such as heat waves, extreme precipitation, and forest fires grow in frequency and or severity, and chronic hazards such as drought and rising sea levels intensify.[82] Hotter summers and warmer winters change frequency and volume of precipitation, increasing risks of severe drought and extreme flooding. Rising temperatures also cause sea-level rise via the thermal expansion of water and melting of land ice, as well as increasing tropical storm severity and the risk of forest fires.[83] Some of these hazard-specific trends are already identifiable. For example: since 1950, increases in the frequency and severity of heat waves have already been positively identified in Asia, Australia, and Europe. Increases in frequency and severity of extreme precipitation events have been identified in North America. Increases in drought frequency and severity have been identified in the Mediterranean and West Africa, while decreases have been identified in central North America.[84]

A changing climate affects socioeconomic systems

Climate change is already having an impact on human, physical, and natural systems. Across the world, we find examples of these impacts across each system in our five-systems framework (Exhibit 5). Researchers have found that in each case climate change intensified the natural hazard or increased its likelihood. For example:

— Hurricane Harvey, which made landfall in Texas on August 25, 2017, caused about $125 billion in damage and shut down economic activity for weeks, including about 20 percent of US crude oil refining capacity and a similar share of production in the Gulf of Mexico. Research suggests that the hurricane precipitation was about 8 to 19 percent more intense because of climate change.[85]

— Recent floods in Asia provide another example of economic damage. The 2017 Hunan province floods affected 7.8 million people and resulted in $3.55 billion of direct economic loss, including severe infrastructure damage. Researchers estimate that climate change made the floods twice as likely.[86]

— The July 2019 heat wave in Europe exceeded 37.5 degrees Celsius across the United Kingdom, the Netherlands, France, Germany, Italy, Spain, and Belgium, taking a toll on the region's physical infrastructure, such as rail, roads, and power. This led to noticeable delays in transportation and to power outages. Economic activity slowed as small businesses and restaurants without air-conditioning closed.[87] Climate change made this heat wave approximately 10 times more likely in France, according to academic research.[88]

---

[81] Goddard Institute for Space Studies (GISS), GISTEMP Reanalysis dataset (2019).

[82] By hazards, we mean climate-induced physical events that have the potential to impact natural and socioeconomic systems.

[83] Predictions of how Earth is likely to respond to further greenhouse gas emissions are drawn primarily from climate models: computer simulations based on our understanding of physical laws and observations, laboratory experiments, and investigations into the past. These models simulate the atmosphere, ocean, land surface, and in some cases biosphere at resolutions down to tens of kilometers. They have proved successful at replicating past climates and at predicting more recent global and regional changes. Using those tools, it is possible to identify how climate hazards are likely to change by 2030 and 2050 around the world and to translate that to potential socioeconomic impact. See the technical appendix for more details.

[84] D. L. Hartmann et al., "Observations: Atmosphere and Surface," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[85] Geert Jan van Oldenborgh et al., "Attribution of extreme rainfall from Hurricane Harvey, August 2017," *Environmental Research Letters*, December 2017, Volume 12, Number 12.

[86] Yin Sun et al., "Anthropogenic influence on the heaviest June precipitation in southeastern China since 1961," *Bulletin of the American Meteorological Society*, January 2019, Volume 100, Number 1.

[87] Stephen Beard, "Europe's economy wilts in one of the continent's hottest heat waves," *Marketplace*, July 11, 2019.

[88] Geert Jan van Oldenborgh et al., *Human contribution to record-breaking June 2019 heat wave in France,* World Weather Attribution, July 2019.

Exhibit 5

Socioeconomic impact of climate change is already manifesting and affects all geographies.

Impacted economic system	Area of direct risk		Socioeconomic impact	How climate change exacerbated hazard
Livability and workability	1	2003 European heat wave	$15 billion in losses	2x more likely
	2	2010 Russian heat wave	~55,000 deaths attributable	3x more likely
	3	2013–14 Australian heat wave	~$6 billion in productivity loss	Up to 3x more likely
	4	2017 East African drought	~800,000 people displaced in Somalia	2x more likely
	5	2019 European heat wave	~1,500 deaths in France	~10x more likely in France
Food systems	6	2015 Southern Africa drought	Agriculture outputs declined by 15%	3x more likely
	7	Ocean warming	Up to 35% decline in North Atlantic fish yields	Ocean surface temperatures have risen by 0.7°C globally
Physical assets	8	2012 Hurricane Sandy	$62 billion in damage	3x more likely
	9	2016 Fort McMurray Fire, Canada	$10 billion in damage, 1.5 million acres of forest burned	1.5 to 6x more likely
	10	2017 Hurricane Harvey	$125 billion in damage	8–20% more intense
Infrastructure services	11	2017 flooding in China	$3.55 billion of direct economic loss, including severe infrastructure damage	2x more likely
Natural capital	12	30-year record low Arctic sea ice in 2012	Reduced albedo effect, amplifying warming	70% to 95% attributable to human-induced climate change
	13	Decline of Himalayan glaciers	Potential reduction in water supply for more than 240 million people	~70% of global glacier mass lost in past 20 years is due to human-induced climate change

Source: Garcia-Herrera et al., 2010; Zander et al., 2015; Yin Sun et al., 2019; Parkinson et al., 2013; Kirchmeier-Young, Megan C. et al., 2017; Philip, Sjoukje et al., 2018; Funk et al., 2019; ametsoc.net; Bellprat et al., 2015; cbc.ca; coast.noaa.gov; dosomething.org; eea.europa.eu; Free et al., 2019; Genner et al., 2017; Lin et al., 2016; livescience.com; Marzeion et al., 2014; Perkins et al., 2014; preventionweb.net; reliefweb.int; reuters.com; Peterson et al., 2004; theatlantic.com; theguardian.com; van Oldenburgh, 2017; water.ox.ac.uk; Wester et al., 2019; Western and Dutch Central Bureau of Statistics; worldweatherattribution.org; McKinsey Global Institute analysis

Warming of the Earth is “locked in” over the next decade, and further warming will continue until net-zero emissions are reached

The primary driver of the observed rate of temperature increase over the past two centuries is the human-caused rise in atmospheric levels of carbon dioxide (CO_2) and other greenhouse gases, including methane and nitrous oxide.[89] Since the beginning of the Industrial Revolution in the mid-18th century, humans have released nearly 2.5 trillion tonnes of CO_2 into the atmosphere, raising atmospheric CO_2 concentrations from about 280 parts per million by volume (ppmv) to 415 ppmv. Other greenhouse gas concentrations have similarly increased due to human activity.[90] Scientists know that changes in atmospheric concentrations of CO_2 and other greenhouse gases are responsible for the observed increase in temperature because they have measured the magnitude of the three other drivers that have changed the state of Earth’s climate in the past. These are incoming energy from the sun; Earth’s albedo or “reflectivity”; and changes in other atmospheric constituents. They have found that only the influence of greenhouse gases is significant enough to explain observed temperature changes and patterns over the past 200 years.[91] In February 2019, scientists confirmed this finding to a five-sigma level of statistical significance; in other words, they estimate the chance that natural variability of the climate system could have caused the observed pattern and magnitude of global temperature increase at 1 in 3.5 million.[92]

Carbon dioxide persists in the atmosphere for hundreds of years. As a result, nearly all of the warming that occurs will be permanent on societally relevant timescales in the absence of large-scale human action to remove CO_2 from the atmosphere.[93] Because of the strong thermal inertia of the ocean, more warming is likely already locked in over the next decade, regardless of emissions pathway.[94]

The future of Earth’s climate after the next decade is dependent on the cumulative amount of long-lived greenhouse gases that humans emit. That means the planet will continue to warm until net-zero emissions are reached.[95] Furthermore, given the thermal inertia of the earth system, some amount of warming will also likely occur after net-zero emissions are reached.

---

[89] Between 98 and 100 percent of observed warming since 1850 is attributable to the rise in atmospheric greenhouse gas concentrations, and approximately 75 percent is attributable to CO_2 directly. The remaining warming is caused by short-lived greenhouse gases like methane and black carbon, which, because they decay in the atmosphere, warm the planet as a function of rate (or flow) of emissions, not cumulative stock of emissions. Karsten Haustein et al., “A real-time Global Warming Index,” *Nature Scientific Reports*, November 13, 2017; Richard J. Millar and Pierre Friedlingstein, “The utility of the historical record for assessing the transient climate response to cumulative emissions,” *Philosophical Transactions of the Royal Society,* May 2018, Volume 376, Number 2119.

[90] US National Oceanic and Atmospheric Administration (NOAA), Global Greenhouse Gas Reference Network, 2019; G. Marland, T. A. Boden, and R. J. Andres, *Global, regional, and national fossil-fuel CO_2 emissions,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, 2008; Richard A. Houghton and Joseph L. Hackler, *Carbon flux to the atmosphere from land-use changes: 1850 to 2005,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, 2001.

[91] Thomas R. Knutson, Fanrong Zeng, and Andrew T. Wittenberg, “Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations,” *Journal of Climate,* November 2013, Volume 26, Number 22; Markus Huber and Reto Knutti, “Anthropogenic and natural warming inferred from changes in Earth’s energy balance,” *Nature Geoscience,* January 2012, Volume 5, Number 1; Ron. L. Miller et al., “CMIP5 historical simulations (1850–2012) with GISS ModelE2,” *Journal of Advances in Modeling Earth Systems,* June 2014, Volume 6, Number 2; Benjamin D. Santer et al., “Human and natural influences on the changing thermal structure of the atmosphere,” *Proceedings of the National Academy of Sciences*, October 2013, Volume 110, Number 43.

[92] Benjamin D. Santer et al., “Celebrating the anniversary of three key events in climate change science,” *Nature Climate Change*, March 2019, Volume 9, Number 3.

[93] David Archer, “Fate of fossil fuel CO_2 in geologic time,” *Journal of Geophysical Research: Oceans,* September 2005, Volume 110, Number C9. Note: it is possible to “reverse” a small portion of accrued warming by reducing the emission rates of short-lived climate pollutants like methane. Because methane decays in the atmosphere over a relatively short time, emission rates rather than stocks determine the contribution to experienced warming. Whereas reducing CO_2 emissions rates by 20 percent only slows the rate of warming, reducing CH4 emission rates by 20 percent actually reduces observed warming as “excess” methane is scrubbed from the atmosphere naturally over time.

[94] H. Damon Matthews et al., “Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets,” *Environmental Research Letters,* January 2018, Volume 13, Number 1.

[95] Net-zero emissions refers to a state in which total addition of greenhouse gasses to the atmosphere, on an annual basis, are zero, either because all emitting activities have ceased, all emitting technologies have been replaced with zero-emissions technology, or remaining emissions are balanced by an equal quantity of negative emissions (for example, removing greenhouse gasses from the atmosphere). For an overview of the amount of locked-in warming (called the Zero Emissions Commitment, or ZEC), the mechanics of climate stabilization, net-zero emissions, and carbon budgets, see, H. Damon Matthews et al., “Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets,” *Environmental Research Letters,* January 2018, Volume 13, Number 1. H. Damon Matthews and Ken Caldeira, “Stabilizing climate requires near zero emissions,” *Geophysical Research Letters,* February 2008, Volume 35, Issue 3; Myles R. Allen et al., “Warming caused by cumulative carbon emissions towards the trillionth tonne,” *Nature,* April 2009, Volume 458, Issue 7242.

Climate models show a growing level of physical hazard globally

With increases in greenhouse gases, climate models project a rise in climate hazards globally. According to climate science, further warming will continue to increase the frequency and/or severity of acute climate hazards and intensify chronic hazards.

Here, we describe the prediction of climate models for a selection of hazards under the RCP 8.5 scenario. The results have been drawn from WHRC analysis and publicly available data for a selection of other hazards (Exhibits 6 and 7).[96] This list of climate hazards is illustrative rather than exhaustive. Due to data and modeling constraints, we did not include the following hazards: increased frequency and severity of forest fires, increased ranges for biological and ecological pests and diseases, increased severity of hurricane storm surge, and more frequent and severe flooding due to factors other than precipitation, for example sea-level rise or rapid snowpack or glacier melt.

— **Increase in average temperatures.**[97] As discussed in Chapter 1, global average temperatures are expected to increase over the next three decades, resulting in a 2.3-degree Celsius increase in global average temperature relative to the preindustrial period by 2050, under an RCP 8.5 scenario. Depending on the exact location, this can translate to an average local temperature increase of between 1.5 and 5 degrees Celsius relative to today. Areas like the Arctic in particular are expected to become much warmer.

— **Extreme precipitation.**[98] In parts of the world, extreme precipitation events, defined here as one that was a 50-year event (with a 2 percent annual likelihood) in the 1950–81 period, are expected to become more common. The likelihood of extreme precipitation events is expected to grow more than fourfold in some regions, including parts of China, Central Africa, and the east coast of North America, compared with the period 1950–81. As discussed in our cases, this could affect global supply chains, infrastructure, and real estate around the world.

— **Hurricanes.**[99] While climate change is seen as unlikely to alter the frequency of tropical hurricanes, it is expected to increase the average severity of those storms (and thus increase the frequency of severe hurricanes). The likelihood of severe hurricane precipitation—that is, an event with a 1 percent likelihood annually in the 1981 -2000 period—is expected to double in some parts of the southeastern United States and triple in some parts of Southeast Asia by 2040. Both are densely populated areas with large and globally connected economic activity.

---

[96] Throughout this report, we only attempt to quantify changes in climate and do not try to predict weather. We do this over two periods: the present to 2030 and the present to 2050. Following standard practice, we define future states as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Unless otherwise noted, projections are from WHRC analysis of 20 CMIP5 Global Climate Models (GCMs).

[97] Taken from KNMI Climate Explorer (2019), using the mean of the full CMIP5 ensemble of models.

[98] Modeled by WHRC using the median projection from 20 CMIP5 GCMs. To accurately estimate the probability of extreme precipitation events, a process known as statistical bootstrapping was used. Because these projections are not estimating absolute values, but changes over time, bias correction was not used.

[99] Modeled by WHRC using the Coupled Hurricane Intensity Prediction System (CHIPS) model from Kerry Emanuel, MIT, 2019. Time periods available for the hurricane modeling were 1981-2000 baseline, and 2031-2050 future period. These are the results for two main hurricane regions of the world. Others, for example, those affecting the Indian sub-continent, were not used.

- **Drought.**[100] As the Earth warms, the spatial extent and share of time spent in drought is projected to increase. The share of a decade spent in drought conditions is projected to be up to 80 percent in some parts of the world by 2050, notably the Mediterranean, southern Africa, and Central and South America.

- **Lethal heat waves.**[101] Lethal heat waves are defined as three-day events during which average daily maximum "wet-bulb" temperature could exceed the survivability threshold for a healthy human being resting in the shade. (Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water into the air at a constant pressure.) We took the average wet-bulb temperature of the hottest six-hour period across each rolling three-day period as the relevant threshold. The threshold maximum temperature chosen for this analysis was 34 degrees Celsius wet-bulb because the commonly defined heat threshold for human survivability is 35 degrees wet-bulb. At this temperature, a healthy human being, resting in the shade, can survive outdoors for four to five hours. Large cities with significant urban heat island effects could push 34 degrees Celsius wet-bulb heat waves over the 35-degree threshold.[102] However, the degree of urban heat island effect does pose an uncertainty to these projections. These projections are also subject to uncertainty related to the future behavior of atmospheric aerosols, or air pollution. Atmospheric aerosols reflect a proportion of incoming sunlight and therefore artificially cool regions, reducing air temperatures. The trajectory of future aerosol levels is uncertain. Under an RCP 8.5 scenario, urban areas in parts of India and Pakistan could be the first places in the world to experience heat waves that exceed the survivability threshold for a healthy human being, with small regions experiencing more than a 60 percent annual chance of such a heat wave by 2050. It should be noted that the CMIP5 climate model results show that some of these regions also experience a non-zero likelihood of lethal heat waves today, although to date, no region has actually experienced such a heat wave. This could be because the CMIP5 models have poor representation of the high levels of observed atmospheric aerosols today (see India case for further details).

- **Water supply.**[103] As rainfall patterns across the world change, renewable freshwater supply will be affected. Some parts of the world like Australia and South Africa are expected to see a decrease in water supply, while other areas, including Ethiopia and parts of South America, are projected to see an increase. Certain regions, for example, parts of the Mediterranean region, and parts of the United States and Mexico, are projected to see a decrease in mean annual surface water supply of more than 70 percent by 2050. Such a large decrease in water supply could cause chronic water stress and increase competition for resources across sectors.

The five-systems framework we use provides a starting point to assess physical climate risk and its potential impact on socioeconomic systems around the world. In the following chapter, we apply this framework to real-world case studies. These highlight the extent to which the changing climate could affect the economy and society and the nature of physical climate risk, as well as the types of adaptation measures that could be needed.

---

[100] Modeled by WHRC using the median projection of 20 CMIP5 GCMs, using the self-correcting Palmer Drought Severity Index (PDSI). Projections were corrected to account for increasing atmospheric CO_2 concentrations.

[101] Modeled by WHRC using the mean projection of daily maximum surface temperature and daily mean relative humidity taken from 20 CMIP5 GCMs. Models were independently bias corrected using the ERA-Interim dataset. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See the India case and technical appendix for more details.

[102] A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5 ± 1.2°C, with some outliers up to 7°C warmer. Shushi Peng et al., "Surface urban heat island across 419 global big cities," *Environmental Science & Technology*, January 2012, Volume 46, Issue 2. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. See the India case and our technical appendix for more details.

[103] Taken from the World Resources Institute Water Risk Atlas (2018), which relies on six underlying CMIP5 models. Time periods of this raw dataset are the 20-year periods centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base dataset.

Exhibit 6

Climate hazards are projected to intensify in many parts of the world.

Based on RCP 8.5

Today | **2030** | **2050**

Increase in average annual temperature

Shift compared to preindustrial climate

°C

- 0–0.5
- 0.6–1.0
- 1.1–1.5
- 1.6–2.0
- 2.1–2.5
- 2.6–3.0
- 3.1–3.5
- 3.6–4.0
- 4.1–4.5
- 4.6–5.0
- 5.1–5.5
- 5.6–6.0
- 6.1–6.5
- 6.6–7.0
- >7.0

Extreme precipitation

Change of likelihood compared to 1950–81 of an 1950–81 50-year precipitation event

- ≤1x
- 1–2x
- 2–3x
- 3–4x
- >4x

Hurricane (precipitation)

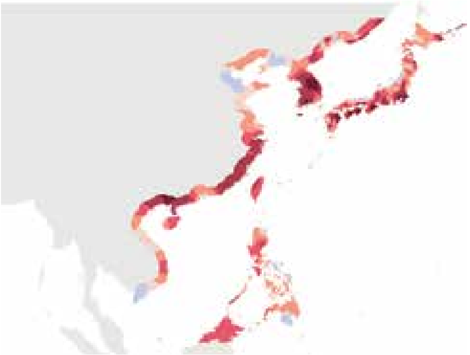
Change of likelihood in 2040 compared with 1981–2000 of a 1981–2000 100-year hurricane

Southeast United States

- ≤1.0x
- 1.1–1.5x
- 1.6–2.0x
- >2.0x

Southeast Asia

- ≤1.00x
- 1.01–1.25x
- 1.26–1.75x
- 1.76–2.25x
- 2.26–3.00x
- >3.00x



Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

Exhibit 7

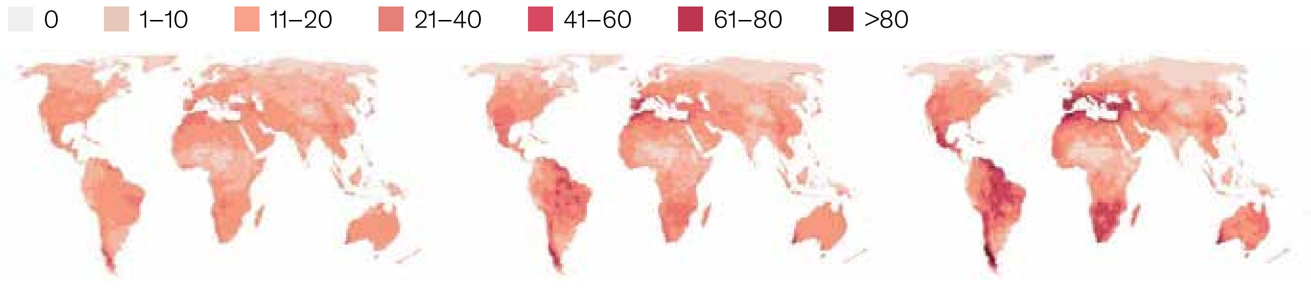
Climate hazards are projected to intensify in many parts of the world (continued).

Based on RCP 8.5

Today **2030** **2050**

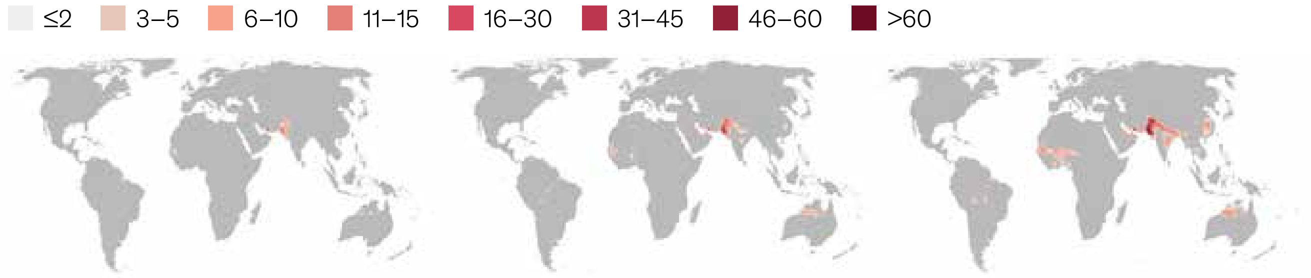
Drought frequency[1]

% of decade in drought



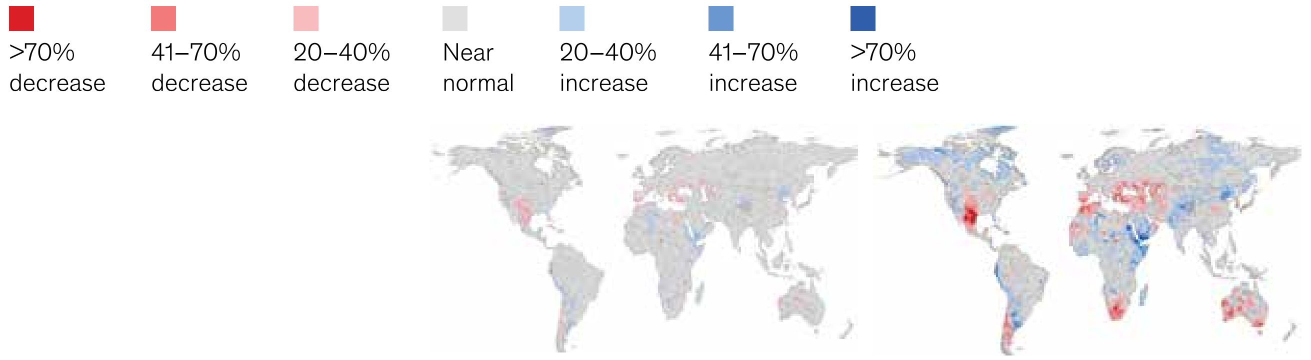
Lethal heat wave probability[2]

% p.a.



Water supply

Change in surface water compared with 2018 (%)
Boundaries on the map represent water basins



1. Measured using a three-month rolling average. Drought is defined as a rolling three month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature and precipitation-based drought index calculated based on deviation from historical mean. Values generally range from +4 (extremely wet) to -4 (extremely dry).
2. A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in the shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we typically define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas (2018); World Resources Institute Aqueduct Global Flood Analyzer; McKinsey Global Institute analysis

3. Physical climate risk—a micro view

In this chapter, we examine how climate hazard becomes risk. We use our five-systems framework as a basis for understanding physical climate risk in the near term. We examine nine case studies from around the world to assess risks to specific sectors, locations, and markets. The cases were chosen based on their exposure to the extremes of climate change and their proximity today to key physical and biological thresholds. Each case is specific to a geography and an exposed system, and as such is not representative of an "average" environment or level of risk across the world. As noted, these cases are based on an RCP 8.5 climate scenario. By understanding the impact of climate change in a leading-edge case, we provide a methodology to assess risk in other instances which may experience rising climate change risk in the future.

Our case studies cover each of the five systems we assess to be directly affected by physical climate risk, across geographies and sectors (Exhibit 8). While climate change will have an economic impact across many sectors, our cases highlight the impact on construction, agriculture, finance, fishing, tourism, manufacturing, real estate, and a range of infrastructure-based sectors. The cases include the following:

- For livability and workability, we look at the risk of exposure to extreme heat and humidity in India and what that could mean for that country's urban population and outdoor-based sectors, as well as at the changing Mediterranean climate and how that could affect sectors such as wine and tourism.

- For food systems, we focus on the likelihood of a multiple-breadbasket failure affecting wheat, corn, rice, and soy, as well as, specifically in Africa, the impact on wheat and coffee production in Ethiopia and cotton and corn production in Mozambique.

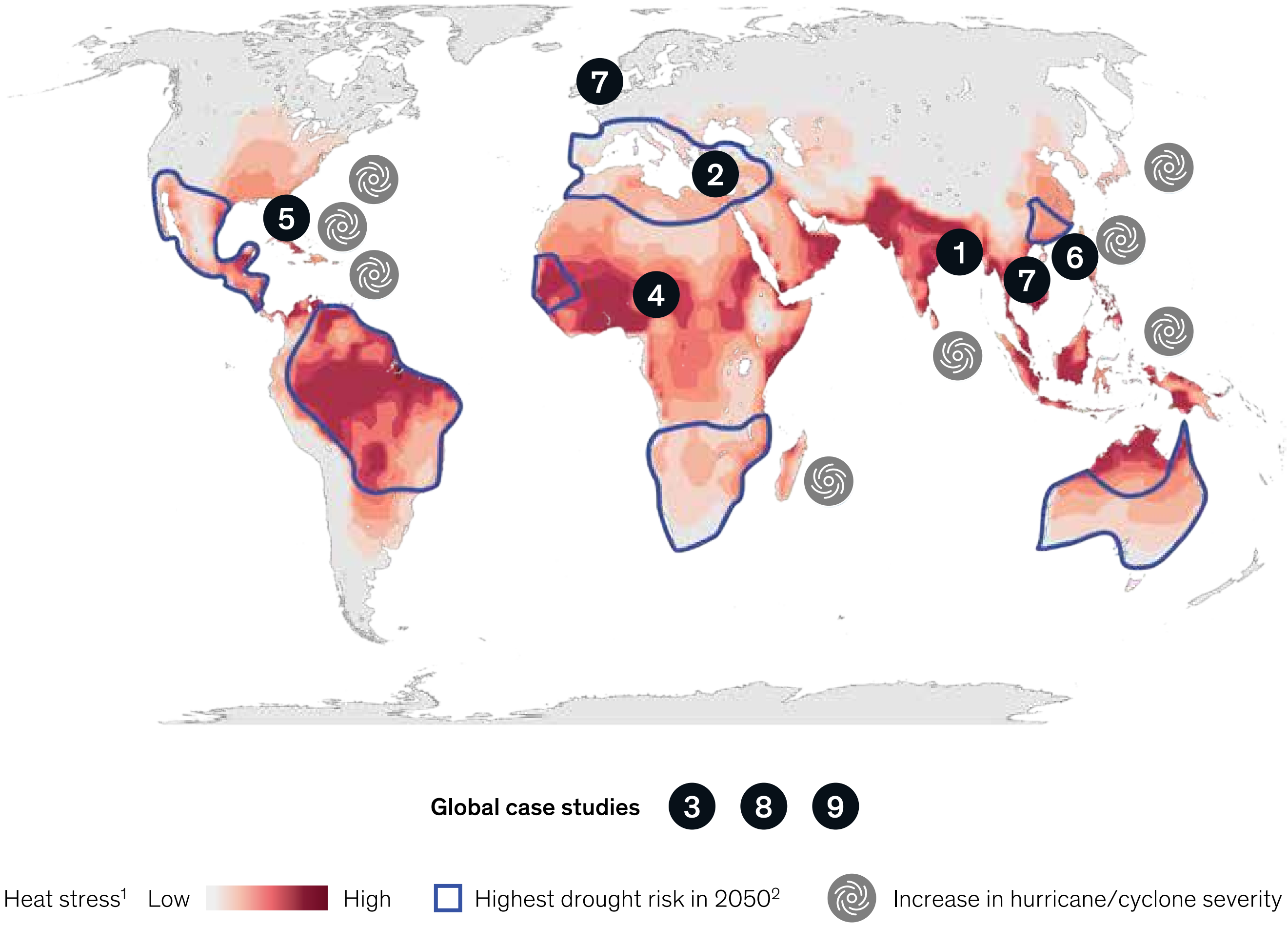
- For physical assets, we look at the potential impact of storm surge and tidal flooding on Florida real estate and the extent to which global supply chains, including for semiconductors and rare earths, could be vulnerable to the changing climate.

- For infrastructure services, we examine 17 types of infrastructure assets, including the potential impact on coastal cities such as Bristol in England and Ho Chi Minh City in Vietnam.

- Finally, for natural capital, we examine the potential impacts of glacial melt and runoff in the Hindu Kush region of the Himalayas; what ocean warming and acidification could mean for global fishing and the people whose livelihoods depend on it; as well as potential disturbance to forests, which cover nearly one-third of the world's land and are key to the way of life for 2.4 billion people.

Exhibit 8

We have selected nine case studies of leading-edge climate change impacts across all major geographies, sectors, and affected systems.



Livability and workability	1	Will India get too hot to work?
	2	A Mediterranean basin without a Mediterranean climate?
Food systems	3	Will the world's breadbaskets become less reliable?
	4	How will African farmers adjust to changing patterns of precipitation?
Physical assets	5	Will mortgages and markets stay afloat in Florida?
	6	Could climate become the weak link in your supply chain?
Infrastructure services	7	Can coastal cities turn the tide on rising flood risk?
	8	Will infrastructure bend or break under climate stress?
Natural capital	9	Reduced dividends on natural capital?

1. Heat stress measured in wet-bulb temperatures.
2. Drought risk defined based on time in drought according to Palmer Drought Severity index (PDSI).

Source: Woods Hole Research Center; McKinsey Global Institute analysis

Across our cases, we find climate risk will increase by 2030 and grow further to 2050, often in nonlinear ways

As we noted in Chapter 1, to assess the magnitude of direct physical climate risk in each of the case studies, we examine the severity of the hazard and its likelihood; the exposure of people, assets, or economic activity to the hazard; and the extent to which systems are vulnerable to the hazard. To date, research suggests that the upward trend in economic losses from natural disasters has primarily been driven by an increase in exposure, rather than climate change effects.[104] Our case studies provide a window into how that is expected to change. We also assess knock-on impacts from direct risk, for example on GDP or prices, and identify the likely adaptation response and key decisions, implementation challenges, and costs involved in each of our cases.

The insights from our cases help highlight the nature and extent of climate risk. Seven characteristics of physical climate risk stand out. Climate risks are:

— **Increasing.** In each of our nine cases, the level of climate risk increases by 2030 and further by 2050. Extreme heat and flooding drove the greatest increases in risk across our leading-edge cases of climate change, with increases in socioeconomic impact of between roughly two and 20 times by 2050 versus today's levels.

— **Spatial.** Climate hazards manifest locally. The direct impacts of physical climate risk thus need to be understood in the context of a geographically defined area. Absent further adaptation, our research suggests that the nature of flood risks and potential response in Bristol and Ho Chi Minh City could differ, reflecting differences in exposure and severity. Likewise, rising temperatures may initially impact India and the Mediterranean in different ways. In India, it may impact outdoor work and diminish labor productivity while in the Mediterranean it may reduce agricultural yields and tourism. Variations within countries are possible or even likely. For example, the coasts and Indo-Gangetic plains in India are exposed to higher risk of extreme heat and humidity compared with the higher elevation and interior Decca plain, because these regions facilitate the mixing of humid oceanic air with hot and dry continental air. Understanding spatial risk requires understanding both spatial climatic conditions and how exposure and resilience to those climatic conditions vary across geographies.

— **Non-stationary.** As the Earth continues to warm, physical climate risk is ever-changing or non-stationary. Managing that risk will require not moving to a "new normal" but preparing for a world of constant change. As we discuss elsewhere in this report, probability distributions of temperature continue to shift rightward. Average risk is rising, but tail risk is also increasing. For example, in Florida we find average annual losses for residential real estate due to storm surge damage are $2 billion today and are projected to increase to about $3 billion to $4.5 billion by 2050, with the range depending on whether exposure

---

[104] Various researchers have attempted to identify the role played by each of these factors in driving economic losses to date. Insurance records of losses from acute natural disasters like floods, hurricanes, and forest fires show a clear upward trend in losses in real terms over time, and analyses show that the majority of this is driven by an increase in exposure. This is based on normalizing the real losses for increases in GDP, wealth, and exposure to strip out the effects of a rise in exposure. See for example, Roger Pielke, "Tracking progress on the economic costs of disasters under the indicators of the sustainable development goals," *Environmental Hazards*, 2019, Volume 18, Number 1. The work by Pielke finds no upward trend in economic impact after normalizing the damage data, and indeed a decrease in weather /climate losses as a proportion of GDP since 1990. Other researchers find a small upward trend after accounting for effects of GDP, wealth, and population, suggesting some potential role of climate change in losses to date. See for example, Fabian Barthel and Eric Neumayer, "A trend analysis of normalized insured damage from natural disasters," *Climatic Change*, 2012, Volume 113, Number 2; and Muir-Wood et al., "The search for trends in a global catalogue of normalized weather-related catastrophe losses," Climate Change and Disaster Losses Workshop, 2006; Robert Ward and Nicola Ranger, *Trends in economic and insured losses from weather-related events: A new analysis*, Centre for Climate Change Economics and Policy and Munich Re, November 2010. For example, Muir-Wood et al. conduct analysis of insurance industry data between 1970 to 2005 and find that weather-related catastrophe losses have increased by 2 percent each year since the 1970s, after accounting for changes in wealth, population growth and movement, and inflation (notably, though, in some regions, including Australia, India, and the Philippines, such losses have declined). Analysis by Munich Re finds a statistically significant increase in insured losses from weather-related events in the United States and in Germany over the past approximately 30 to 40 years.

is constant or increasing.[105] Real estate losses during a 100-year hurricane event in the state are $35 billion today; by 2050, that could rise to $50 billion to $75 billion. In India, the number of people with a non-zero probability of experiencing a lethal heat wave is effectively zero today and projected to be 160 million to 200 million by 2030 (of which 80 million to 120 million are estimated not to have air-conditioned homes) and 310 million to 480 million by 2050 (of which effectively all are likely to have air-conditioned homes by that time).

— **Nonlinear.** Climate risk can have nonlinear increases in impacts. As climate hazards intensify and become more frequent, our analysis suggests a substantial increase in risk. Physical systems, including physiological, human-made and ecological, have either evolved or been designed to operate within certain climate parameters (Exhibit 9). Even small changes in climate hazard can therefore have significant impact if physical thresholds for resilience are breached. Inherent risk is high when regions are already close to systemic thresholds for climate hazards. For example, some parts of India are close to crossing temperature thresholds that would make outdoor work extremely challenging. As of 2017, heat-exposed work produced about 50 percent of GDP, drove about 30 percent of GDP growth, and employed about 75 percent of the labor force, some 380 million people.[106]

The human body provides one example of physical thresholds and the nonlinear effect if those thresholds are breached. It must maintain a relatively stable core temperature of approximately 37 degrees Celsius to function properly. The core temperature needs to rise only 0.2 degree to compromise multitasking ability, 0.9 degree to compromise neuromuscular coordination, 1.3 degrees to affect simple mental performance, 3 degrees to induce dangerous heatstroke, and 5 degrees to cause death.[107] In environments where air temperatures are higher than core body temperature, the body loses its ability to dissipate heat through radiation and convection. Core temperature is determined primarily by a combination of activity level and wet-bulb temperature—a measure of air temperature and relative humidity—that determines how much heat the body can exhaust through the evaporation of sweat. At a wet-bulb temperature of 35 degrees Celsius, healthy, well-hydrated human beings resting in the shade would see core temperatures rise to lethal levels after roughly four to five hours of exposure.[108] Labor capacity would be impaired at wet-bulb temperatures well below that.

Other examples include corn, which has a plant physiological threshold at about 20 degrees Celsius, beyond which yields decline dramatically. Human-made assets like power infrastructure and cell phone towers have been designed with certain tolerances for heat, wind, and flooding. Intensifying hazards could thus lead such infrastructure assets to fail with increasing frequency. During Hurricane Maria in 2018, for example, winds of up to 280 km/h felled more than 90 percent of the cell phone towers in Puerto Rico.[109]

---

[105] Analysis conducted by KatRisk; direct average annual losses to all residential real estate (insured and uninsured properties). This is the long-term average loss expected in any one year, calculated by modeling the probability of a climate hazard occurring multiplied by the damage should that hazard occur, and summing over events of all probabilities. Analyses based on sea level rise in line with the US Army Corps of Engineers high curve, one of the recommended curves from the Southeast Florida Regional Climate Change Compact. Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group, *Unified sea level rise projection: Southeast Florida,* October 2015.

[106] Reserve Bank of India, Database on Indian Economy, dbie.rbi.org.in/DBIE/dbie.rbi?site=home. Exposed sectors include exclusively outdoor sectors such as agriculture, mining, and quarrying, as well as indoor sectors with poor air-conditioning penetration, including manufacturing, hospitality, and transport.

[107] P. A. Hancock and Ioannis Vasmatzidis, "Human occupational and performance limits under stress: The thermal environment as a prototypical example," *Ergonomics*, 1998, Volume 41, Number 8.

[108] Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences*, May 25, 2010, Volume 107, Number 21; threshold confirmed, assuming light clothing cover, using the physiological Predicted Heat Strain (PHS) model; Jacques Malchaire et al., "Development and validation of the predicted heat strain model," *Annals of Occupational Hygiene*, March 2001, Volume 45, Number 2.

[109] *The 2017 Atlantic Hurricane Season: Mobile industry impact and response in the Caribbean,* GSMA.

Exhibit 9

Direct impacts of climate change can become nonlinear when thresholds are crossed.

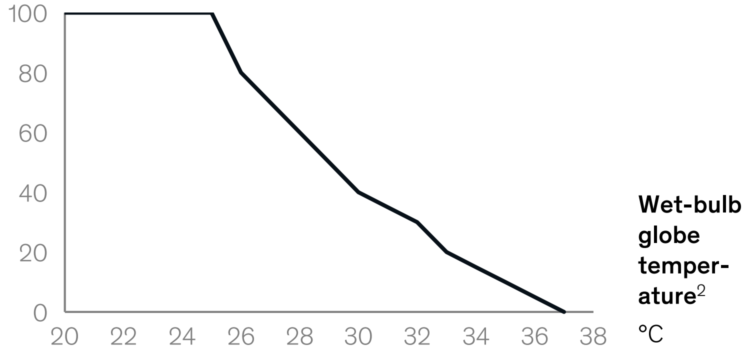
System | **Example** | **Nonlinear behavior**

Human

Impact of heat and humidity on outdoor labor

Share of labor capacity in a given hour[1]

%

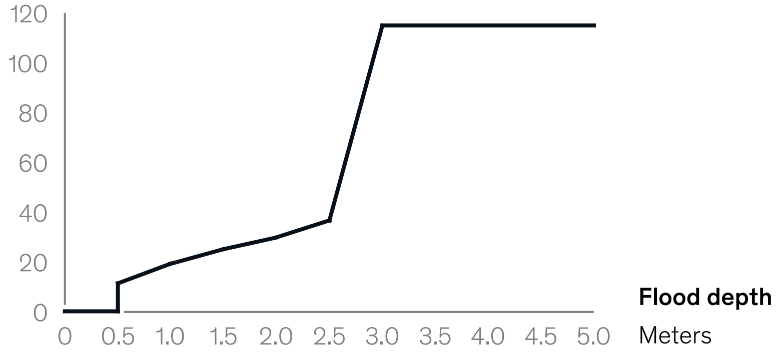


Physical

Floodwater impacts on an exemplary UK train station

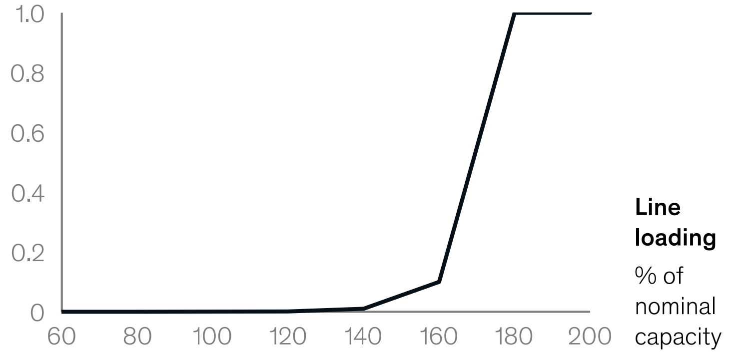
Asset impact[3]

$ million



Effects of line overloading (eg, sagging due to heat) in an electrical grid[4]

Probability of line tripping

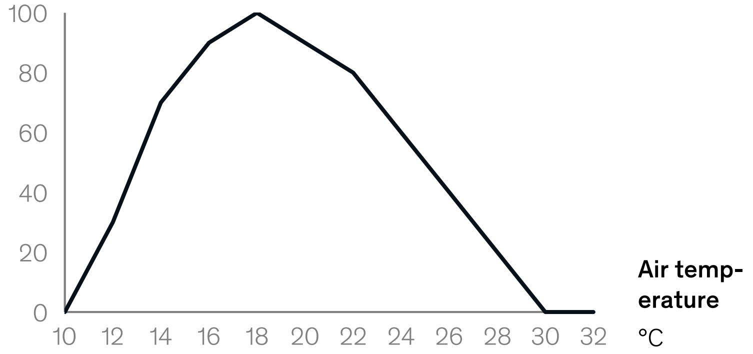


Natural

Temperature impact on crop yield

Corn reproductive growth rate

%



1. Immediate effect; longer exposure will cause rapidly worsening health impacts. Humans can survive exposure to 35C wet-bulb temperatures for between 4 to 5 hours. During this period, it is possible for a small amount of work to be performed, which is why the working hours curve does not approach zero at 35C WBGT (which, in the shade, is approximately equivalent to 35C wet-bulb).
2. Based on in-shade wet-bulb globe temperature (WBGT). WBGT is defined as a type of apparent temperature which usually takes into account the effect of temperature, humidity, wind speed, and visible and infrared radiation on humans.
3. Average cost of a new build train station globally used for asset impact/cost on UK train station; salvageable value is assumed zero once asset passes destruction threshold.
4. Both acute events (eg, flooding, fires, storms) and chronic changes in climatic conditions (eg, heat) can affect the grid and may lead to outages.

Source: Dunne et al., 2013, adjusted according to Foster et al., 2018; Henneaux, 2015; Korres et al., 2016; CATDAT global database on historic flooding events; McKinsey infrastructure benchmark costs; EU Commission Joint Research Centre damage functions database; historical insurance data and expert engineer interviews on failure thresholds; McKinsey Global Institute analysis

Extreme heat is already disrupting global air travel. In July 2017, for example, about 50 flights out of Phoenix, Arizona, were grounded for physical and regulatory reasons when temperatures rose to 48 degrees Celsius.[110] We find the disruption could increase; by 2050, as many as 185,000 passengers per year could be affected by flights that are grounded because of extreme heat, according to our estimates.

The thresholds we describe above pertain to physical systems. The economic, financial, and social systems that rely on these physical systems also have thresholds, which are harder to quantify. Nonetheless, intensifying direct impacts of climate change could trigger nonlinear responses in those systems, too. For example, there could be psychological thresholds for home buyers, for when the flooding frequency of homes changes from being merely "inconvenient" to "intolerable." Financial markets, too, may hit a point at which they limit long-term lending to risky geographies. Some intensifying hazards could even trigger widespread internal or external displacement of people. As CO_2 concentrations rise and the climate changes, natural systems may not be able to evolve fast enough to keep pace, requiring a targeted focus on adaptation action to build resilience and prevent such nonlinear responses.

— **Systemic.** While the direct impact from physical climate risk is local, it can have knock-on effects across regions and sectors, through interconnected socioeconomic systems. We find that knock-on impacts could be especially large when people and assets that are affected are central to local economies and those local economies are tied into other economic and financial systems. Florida's economy, for example, relies on real estate, with 22 percent of GDP, 30 percent of local tax revenue, and home owner wealth linked to the sector (primary residences represent 42 percent of median home owner wealth in the United States).[111] Flooding in the state could thus not only damage housing but also affect property values of exposed homes, in turn reducing property tax revenues and potentially affecting future price or availability of insurance. We estimate that devaluation of flood-exposed homes in Florida could total $10 billion to $30 billion by 2030, all else being equal.

— **Regressive.** Climate risk is regressive. The poorest communities and populations within each of our cases are often the most exposed to climate risk, for example, those dependent on outdoor work in areas of increasing heat duress. They are often the most vulnerable, lacking financial means. For example, in the case of a multiple breadbasket failure, a yield failure in two or more key production regions for rice, wheat, corn, and soy, we estimate that prices could spike by 100 percent or more in the short term. This would particularly hurt the poorest communities, including the 750 million people living below the international poverty line. Climate risk creates spatial inequality, as it may simultaneously benefit some regions while hurting others. Rising temperatures may boost tourism in areas of northern Europe while reducing the economic vitality of southern ones, for example. The volume of water in basins in northern Africa, Greece, and Spain could decline by more than 15 percent by 2050 even as the volume in basins in Germany and the Netherlands increases by 1 to 5 percent, in turn affecting agriculture such as wine and tomatoes.

---

[110] Regulators only certify planes to fly below certain temperatures. As air temperature rises, the density of the air decreases and negatively affects lift. As a result, planes require a combination of more thrust, lighter takeoff weights, and longer runways to take off. See Rhett Allain, "Why Phoenix's airplanes can't take off in extreme heat," *Wired*, June 20, 2017.

[111] National Association of Realtors, *The economic impact of a typical home sale in Florida*, 2018; other income sources are value-added taxes, fees, and business revenues. For more details, see *Household wealth & real estate,* UPFINA, September 2018; Federal Reserve Bank of St. Louis, FRED database, *Homeownership rate for Florida,* fred.stlouisfed.org/series/FLHOWN; Michael Neal, "Housing remains a key component of household wealth," *Eye on Housing*, National Association of Home Builders, September 4, 2013.

— **Under-prepared.** While companies and communities have been adapting to reduce climate risk, the pace and scale of adaptation may need to increase significantly to manage rising levels of physical climate risk. Adaptation can be challenging, as it can entail rising costs and tough choices. These could include whether to invest in hardening or to relocate people and assets. Adaptation will likely also require coordinated action across multiple stakeholders, although this varies across cases. For semiconductor plants, effective adaptation might be feasible in a comparatively cost-effective manner through either asset hardening or insurance. Due to hazard intensity increasing, the economics of adaptation will likely worsen over time, and there may eventually be technical or other limits to effective adaptation. In some parts of Florida, the cost of building new sea walls and other protection from flooding hazards might increase over time and prove technically challenging. If that is the case, hard choices will need to be made between spending on hardening or relocation. In other cases, such as warming oceans that reduce the fish stocks that fishing communities rely on, collective action may be needed, making the path to adaptation more challenging. In some cases, local economic conditions may make financing difficult.

Livability and workability: Parts of India could become intolerably hot and humid, while in the Mediterranean, agriculture and tourism may be affected

In India, the impact of extreme heat and humidity may be underappreciated today as communities grapple with issues of air quality and water stress. Conditions in the country are already relatively hot and humid, but rising heat and humidity resulting from the changing climate could push conditions over physiological thresholds for livability and workability, in particular for already-vulnerable parts of the population. This will threaten the lives of millions of people and make outdoor work, which accounts for about half of GDP today, far more challenging.

Climate models we draw on predict that under an RCP 8.5 scenario, India may become one of the first places in the world to experience heat waves that cross the survivability threshold for a healthy human being resting in the shade.[112] By 2030, some 160 million to 200 million people (of whom 80 million to 120 million people are estimated not to have air-conditioned homes) are expected to live in urban areas with a non-zero probability of such heat waves occurring. This could rise to between 310 million and 480 million by 2050, without factoring in air conditioner penetration, which at current rates of growth could rise to cover the full population by that time.[113] Most of this population is projected to live in regions with a roughly 5 percent average annual probability of experiencing a lethal heat wave by 2030, and as much as 14 percent by 2050 (Exhibit 10). This means that the average person living in an at-risk region has a probability of roughly 40 percent of experiencing a lethal heat wave at least once in the decade centered on 2030. In the decade centered on 2050, that probability could rise to roughly 80 percent.[114]

---

[112] Researchers have established the survivability threshold as wet-bulb temperatures that exceed 35°C for more than five hours. Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences*, May 25, 2010, Volume 107, Number 21.

[113] Range is based on the range of population projections from the UN World Population Prospects and the UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rates.

[114] Note that if atmospheric aerosol concentration does not decrease over the next decade, the probability of lethal heat waves could be reduced, as atmospheric aerosols (particularly black carbon) are not currently appropriately represented in the CMIP5 ensemble Global Climate Models. See India case for more details.

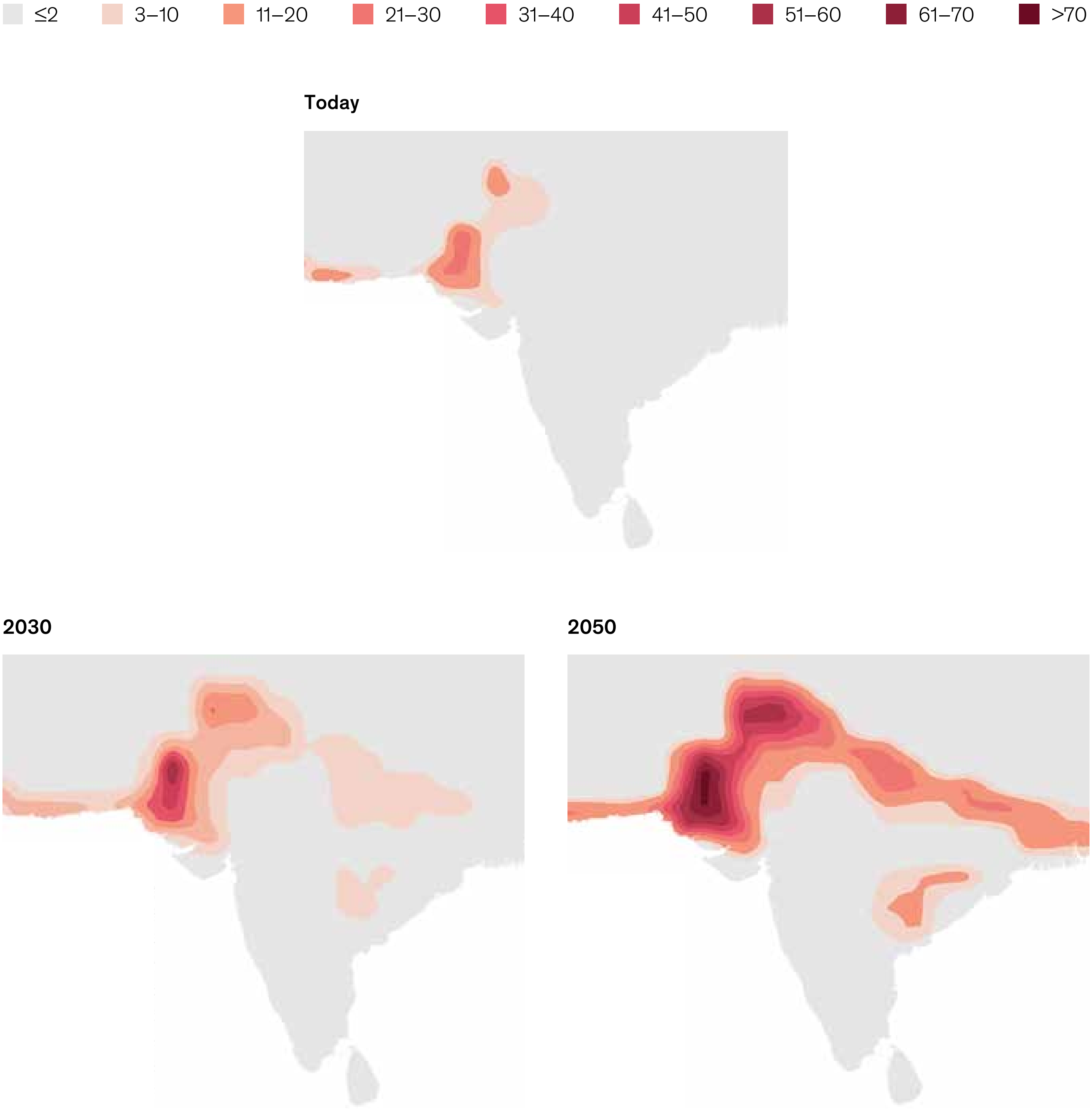
Exhibit 10

The annual probability of lethal heat waves in India is expected to increase between 2018 and 2050.

Based on RCP 8.5

Annual probability of a lethal heat wave[1]

%



---

1. A lethal heat wave is defined as a three-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb, where wet-bulb temperature is defined as the lowest temperature to which a parcel of air can be cooled by evaporation at constant pressure. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. Under these conditions, a healthy, well-hydrated human being resting in the shade would see core body temperatures rise to lethal levels after roughly 4–5 hours of exposure. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects, and do not factor in air conditioner penetration.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center

As heat and humidity increase, this also could affect labor productivity in outdoor work, as workers will need to take breaks to avoid heatstroke. Moreover, their bodies will protectively fatigue, in a so-called self-limiting process, to avoid overheating. We estimate that the effective number of outdoor daylight hours lost in an average year because of diminished labor productivity would increase by about 15 percent by 2030 compared with today, equivalent to an additional four weeks of work from 11 a.m. to 4 p.m. lost, assuming a 12-hour workday.[115] This would likely cause a reduction in GDP of between 2.5 and 4.5 percent by 2030, where the range is based on the 25th and 75th percentile climate model ensemble projections (Exhibit 11).[116] By 2050, it is expected that some parts of India will be under such intense heat and humidity duress that working outside would effectively not be feasible for almost 30 percent of annual daylight hours. The urban poor without access to cooling systems and those engaged in outdoor activities like agriculture and construction will be among the vulnerable who are disproportionately affected.

India, however, has potential for adaptation in the short term. Steps include early-warning systems and cooling shelters to protect those without air-conditioning. Working hours for outdoor workers could be shifted, and cities could implement albedo heat-management efforts. At the extreme, coordinated movement of people and capital from high-risk areas could be organized. Beyond the costs involved, adaptation could be challenging if it changes how people conduct their daily lives or requires them to move to less at-risk areas.

Rising temperatures would also affect the Mediterranean, albeit with less severe impacts than in India. The mild Mediterranean climate will grow hotter, which could disrupt key industries such as tourism and agriculture. By 2050, drought conditions are expected to prevail for at least six months of every year (Exhibit 12).[117] Even under a conservative scenario of reduced emissions, Madrid's climate in 2050 is projected to resemble today's climate in Marrakech, while the climate in Marseille in 2050 may be like that of Algiers today.[118] Climate scientists expect an increase in the number of days considered uncomfortably hot in many Mediterranean beach tourism locations, while northern European coasts could become more agreeable as summer holiday destinations. This could change visitor flows and exacerbate spatial inequality.[119] Farmers have already seen their crop yields diminish and become less predictable, a trend that is likely to continue.[120] Areas known for the quality of their wine grapes risk losing their prominence on the viticulture map, while nontraditional growing regions may gain advantage.

Adaption will need to be place-based, given the strong ties to location of agriculture and tourism. For example, wineries could harvest earlier, reduce sunlight on grapes, or irrigate vineyards. Additionally, approaches such as modified fertilizer use and planting resilient varieties of crops might mitigate decreases in yield.[121] Tourism destinations at risk from rising summer temperatures might explore ways to shift visitor flows to shoulder seasons and diversify local economies.

---

[115] An average year is defined as the ensemble mean projection across the 2012–40 period.

[116] Lost working hours calculated according to the methodology of John P. Dunne et al., "Reductions in labour capacity from heat stress under climate warming," *Nature Climate Change,* February 2013, Volume 3, but corrected using empirical data from Josh Foster et al., "A New Paradigm To Quantify The Reduction Of Physical Work Capacity In The Heat," *Medicine and Science in Sports and Exercise,* June 2019, Volume 51, Issue 6.

[117] A month in drought is defined as a month with Palmer Drought Severity index < -2. The index is a temperature and precipitation-based metric calculated based on deviation from historical mean. Values range from +4 (extremely wet) to -4 (extremely dry).

[118] This is considering an RCP 4.5 emissions pathway scenario. Jean-Francois Bastin et al., "Understanding climate change from a global analysis of city analogues," *PLOS ONE*, July 2019, Volume 14, Number 7.

[119] We use 37 degrees Celsius as the temperature at which days start to feel "too hot." The actual threshold varies by individual.

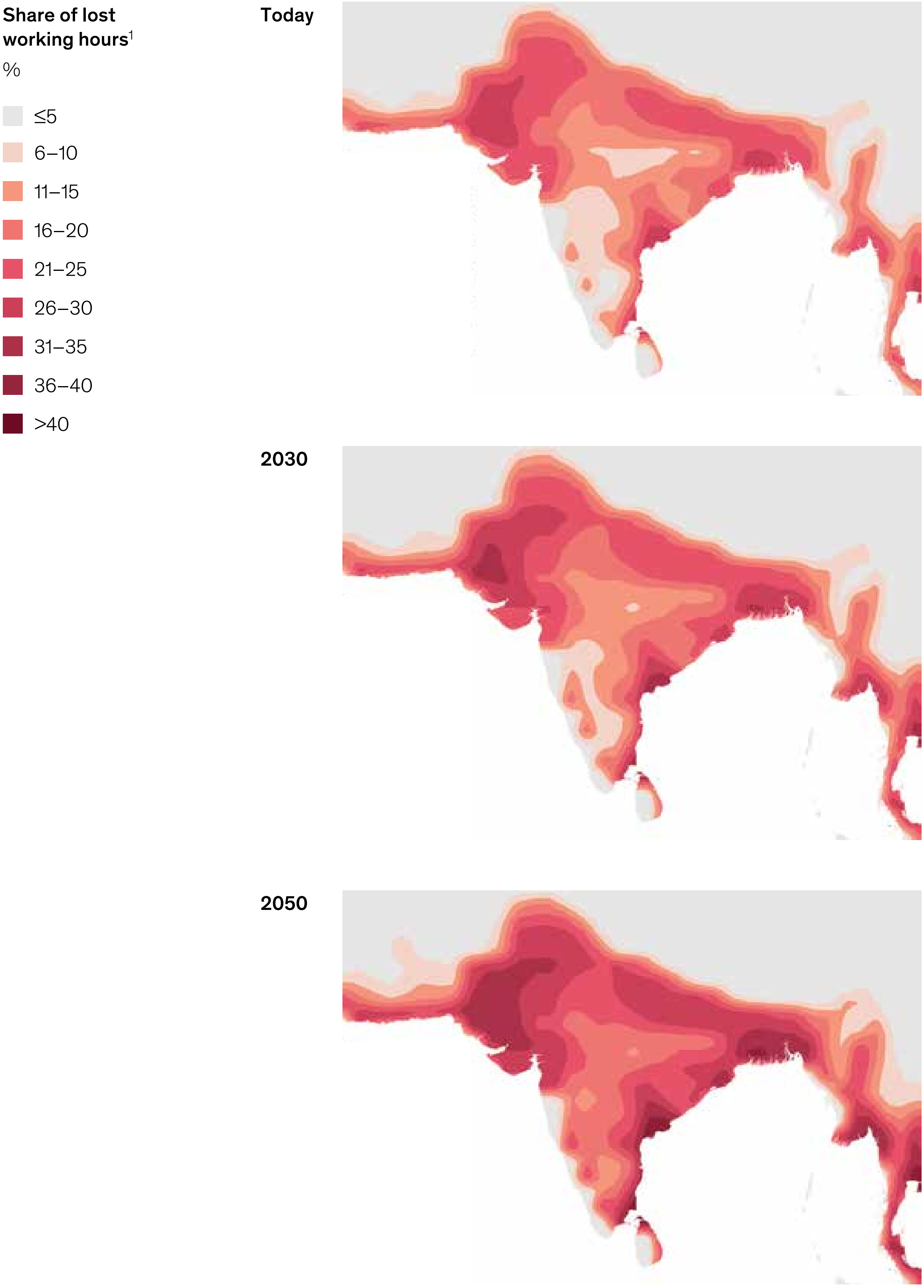
[120] Deepak K. Ray et al., "Climate change has likely already affected global food production," *PLoS ONE*, May 2019, Volume 14, Issue 5.

[121] Our analysis does not account for the potential migration of planting areas for a crop within a country. For farmers who can change what they grow, this can create opportunities. For example, a high-latitude country like Canada could have significantly increased agricultural opportunities due to climate change. But in many countries, as the crop-growing regions shift, farmers may not be able to adapt.

Exhibit 11

The affected area and intensity of extreme heat and humidity is projected to increase, leading to a higher expected share of lost working hours in India.

Based on RCP 8.5



---

1. Lost working hours include loss in worker productivity as well as breaks, based on an average year that is an ensemble average of climate models.

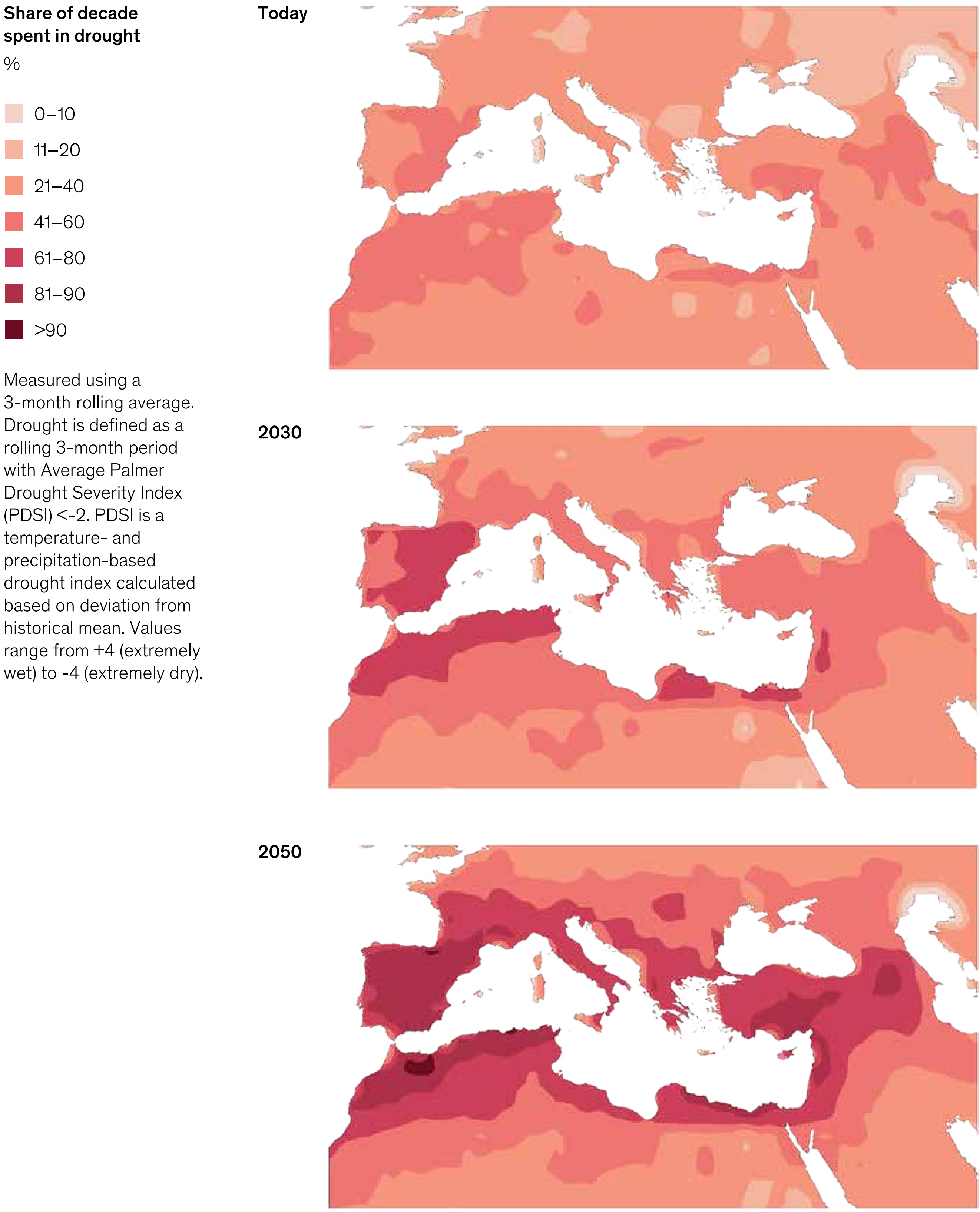
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center

Exhibit 12

Drought is expected to become prevalent in the Mediterranean region by 2030 and further increase by 2050.

Based on RCP 8.5



Measured using a 3-month rolling average. Drought is defined as a rolling 3-month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature- and precipitation-based drought index calculated based on deviation from historical mean. Values range from +4 (extremely wet) to -4 (extremely dry).

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 60.

Source: Woods Hole Research Center

Food systems: A global yield shock is projected to become more likely, while African countries may experience shifts in their agricultural endowment

We find an increasing risk of a concurrent harvest failure in multiple breadbasket locations, an example of a tail event. We define a multiple breadbasket failure as a global harvest decline of 15 percent relative to average.[122] About 60 percent of global grain production today occurs in just five regional breadbaskets, and four grains make up almost half of the calories in the average global diet (Exhibit 13). Rising temperatures, changing patterns of precipitation, and increasing episodes of climate-related stress such as drought, heat waves, and floods are expected to raise the likelihood of a multiple-breadbasket failure in the decades ahead. However, it is also important to note that some countries are projected to benefit and experience rising yields due to climate change; we discuss this further in Chapter 4.[123]

We estimate that the chance of a greater than 15 percent yield shock at least once in the decade centered on 2030 rises from 10 percent today to 18 percent, while the chance of a greater than 10 percent yield shock occurring at least once rises from 46 to 69 percent (Exhibit 14).[124] Since there is a built-up stock of grain (current stock-to-use ratios are high, at 30 percent of consumption), such a yield shock would most likely not directly lead to food shortages. It is highly unlikely that the world will run out of grain within any one year. However, even limited reductions in stock-to-use ratios have triggered episodes of food price spikes. A 15 percent drop in global supply, for example, would likely cause stock-to-use ratios to drop to about 20 percent. In that case, historical precedent suggests that prices could spike by 100 percent or more in the short term, although we acknowledge that food commodity prices are difficult to predict. If such a food price spike were to occur, this would particularly hurt poor people worldwide, including the 750 million people living below the international poverty line.

To make the food system more resilient, private and public research could be expanded. For instance, research on technologies could aim to make crops more resistant to abiotic and biotic stresses. This may include conventional breeding, gene editing, and other biological or physical approaches. To offset the risk of a harvest failure of greater than 15 percent, the current global stock-to-use ratio could be increased to 35 to 40 percent, leveraging times of surplus and low prices. We estimate total costs for the required additional storage at between $5 billion and $11 billion per year. Investment in water management systems is another potential adaptation measure. Incentives for farmers, however, are not aligned with stock buildup. Storing grain can be expensive (given direct costs as well as working capital requirements), and the reduced risk of food shortages is to some extent a positive externality that farmers do not necessarily factor into their cost-benefit analysis. Multilateral organizations such as the Food and Agriculture Organization of the United Nations could potentially play a role, managing storage closely to prevent “leakages” and encouraging the private sector to store more grains. In any case, affected stakeholders may need to work together to solve storage issues, possibly through global interventions.

---

[122] We define a breadbasket as a key production region for food grains (rice, wheat, corn, and soy) and harvest failure as a major yield reduction in the annual crop cycle of a breadbasket region where there is a potential impact on the global food system. Note that we are taking into account potentially positive effects on plant growth from higher CO_2 levels (“CO_2 fertilization”). However, those benefits could be reduced as increased CO_2 levels could lead to a reduction in the protein and micronutrient content of crops, which in turn would require humans to eat more volume to achieve the same level of nutrition. For more detail, see Chunwu Zhu et al., “Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries,” *Science Advances,* May 23, 2018, Volume 4, Number 5.

[123] For this case, we modeled only the impact of changes in temperature and precipitation on yields. We did not model extreme events (such as flooding, hail, or extreme wind) nor the impact of pests and diseases.

[124] See the breadbasket case study for details.

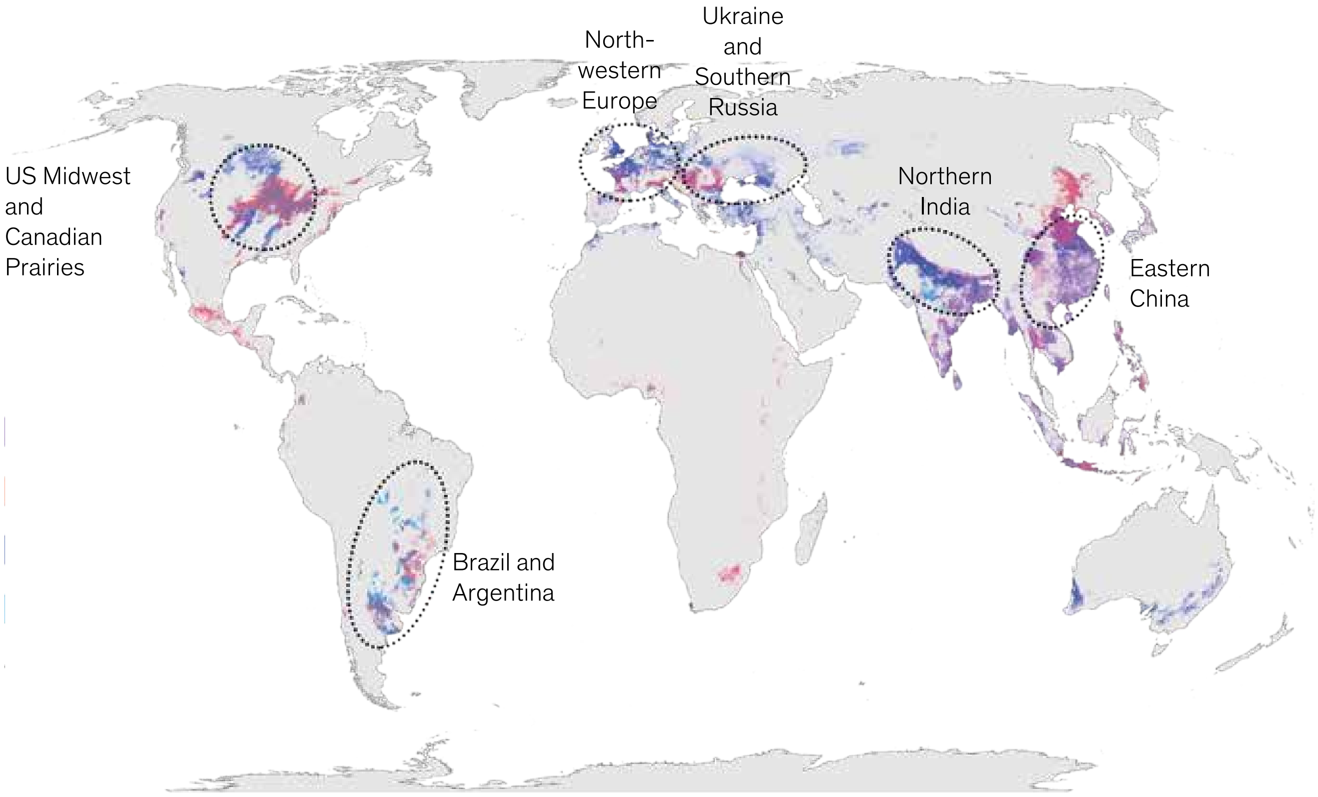
Exhibit 13

Production of the world's major grains is highly concentrated in a few growing regions.

🟪 Rice 🟧 Corn 🟦 Wheat 🟦 Soy[1] ◌ Major grain production areas

---

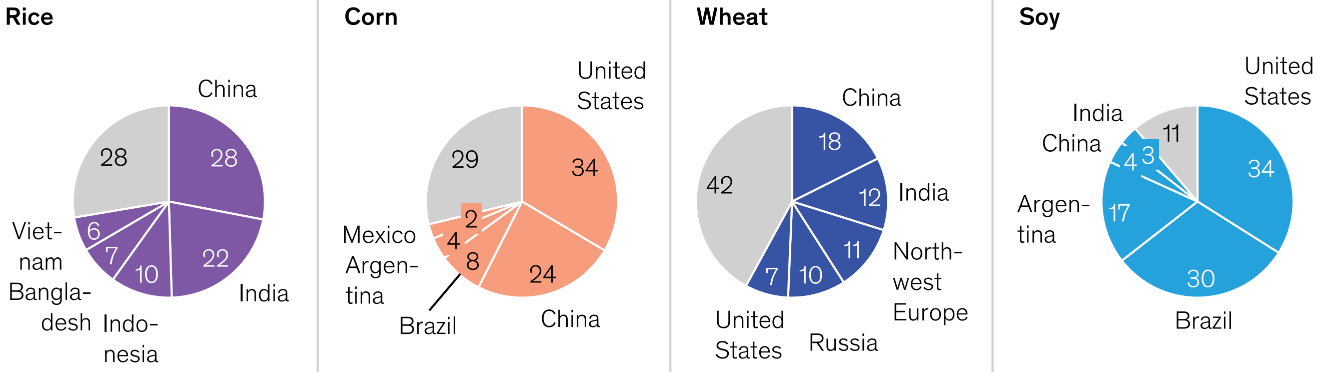
Global agricultural production[2]



Share of grain production by country, 2015–17

% of average annual production

⬜ Rest of world



---

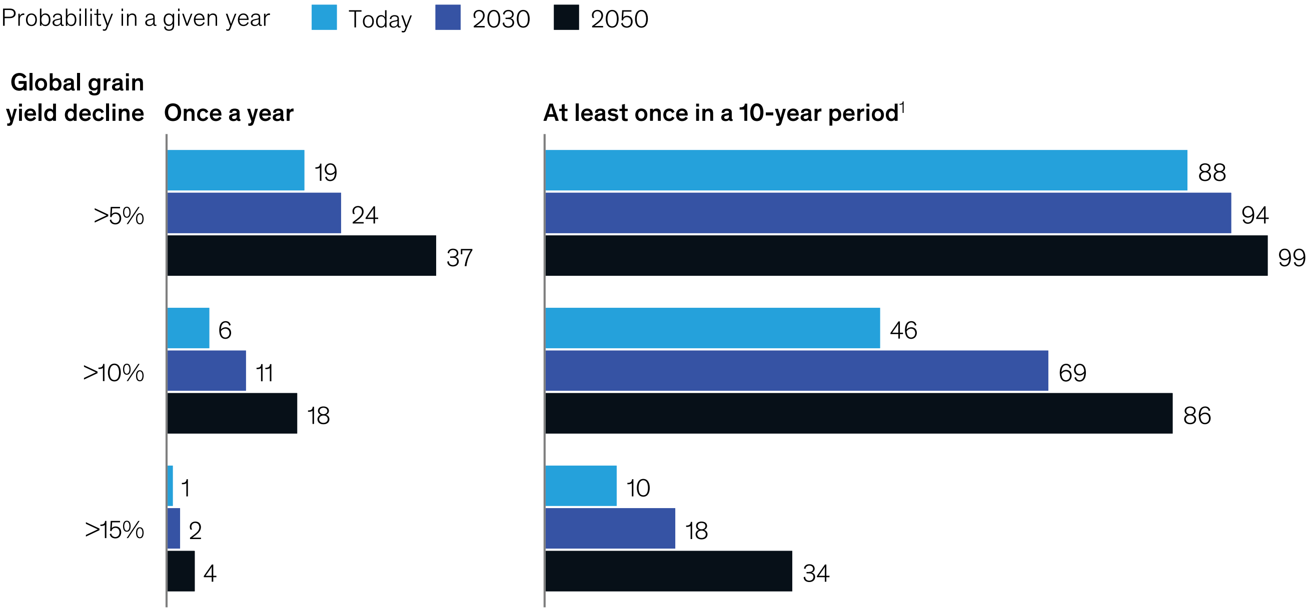
1. Soybeans and oil.
2. Colors indicate where particular grain is produced. Darker shading within each color indicates higher density of production, lighter (more transparent) shading indicates lower density of production.

Source: FAOSTAT; Earth Stat, 2000; McKinsey Global Institute analysis

Exhibit 14

In our inherent risk assessment, the annual risk of a >15 percent global yield failure is projected to double by 2030 and quadruple by 2050.

Based on RCP 8.5



1. Calculated as a cumulative probability assuming independence between years.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; McKinsey Global Institute analysis

In Africa, agriculture is critical to the continent's economic growth and development, generating more than one-fifth of sub-Saharan Africa's economic output. Yet we find that rising temperatures and the increased likelihood of drought are expected to create significant volatility in agricultural yields in some parts of Africa and for certain crops, which would make investment decisions and economic development more challenging (Exhibits 15 and 16). Besides increasing storage levels, crop insurance may be an option to manage these climate-related risks. While insurance policies in theory are easy to establish, financing may be an issue because farmers might not have sufficient means to pay their premiums.

We analyze how precipitation volatility affects crop yields in two African countries, Ethiopia and Mozambique. In Ethiopia, we project that by 2030, wheat farmers are 11 percent more likely to experience a 10 percent or greater decrease in yield in any given year compared with today. The same decrease becomes 23 percent more likely by 2050. For coffee growers, the likelihood of a 25 percent or greater drop in yield in any given year currently stands at about 3 percent but is expected to climb to about 4 percent, a roughly 30 percent increase, by 2030. Should yield shocks of this magnitude take place for both crops in the same year, Ethiopia's GDP would drop about 3 percent in that year.[125]

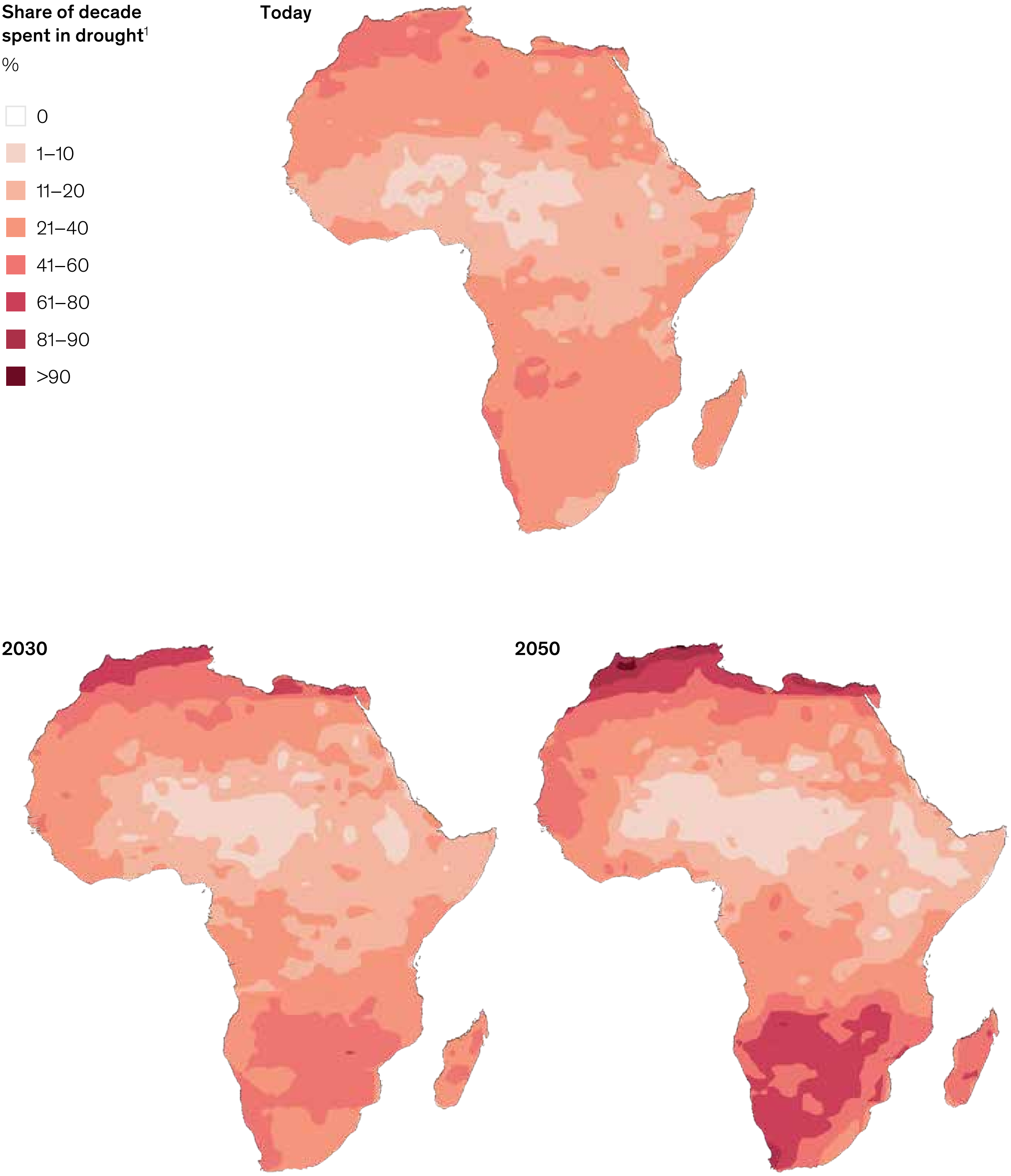
---

[125] To gauge the potential economic effects of changes in Ethiopia's wheat and coffee production, we relied on the economic modeling capabilities of the International Food Policy Research Institute. Researchers there incorporated our near-term yield predictions in their country economic models. These models estimate how reduced crop production affects downstream sectors (such as food processing and trade) and the broader economy (for example, GDP, foreign trade, and rural and urban household incomes), along with input-output flows between sectors and consumers, accounting for macroeconomic and resource constraints (foreign exchange constraints on food imports, for example). See Africa case study for details.

Exhibit 15

Expected evolution of drought differs by region in Africa, with the most affected areas in the north and south.

Based on RCP 8.5



1. Measured using a 3-month rolling average. Drought is defined as a rolling 3-month period with Average Palmer Drought Severity Index (PDSI) <-2. PDSI is a temperature- and precipitation-based drought index calculated based on deviation from historical mean. Values range from +4 (extremely wet) to -4 (extremely dry).

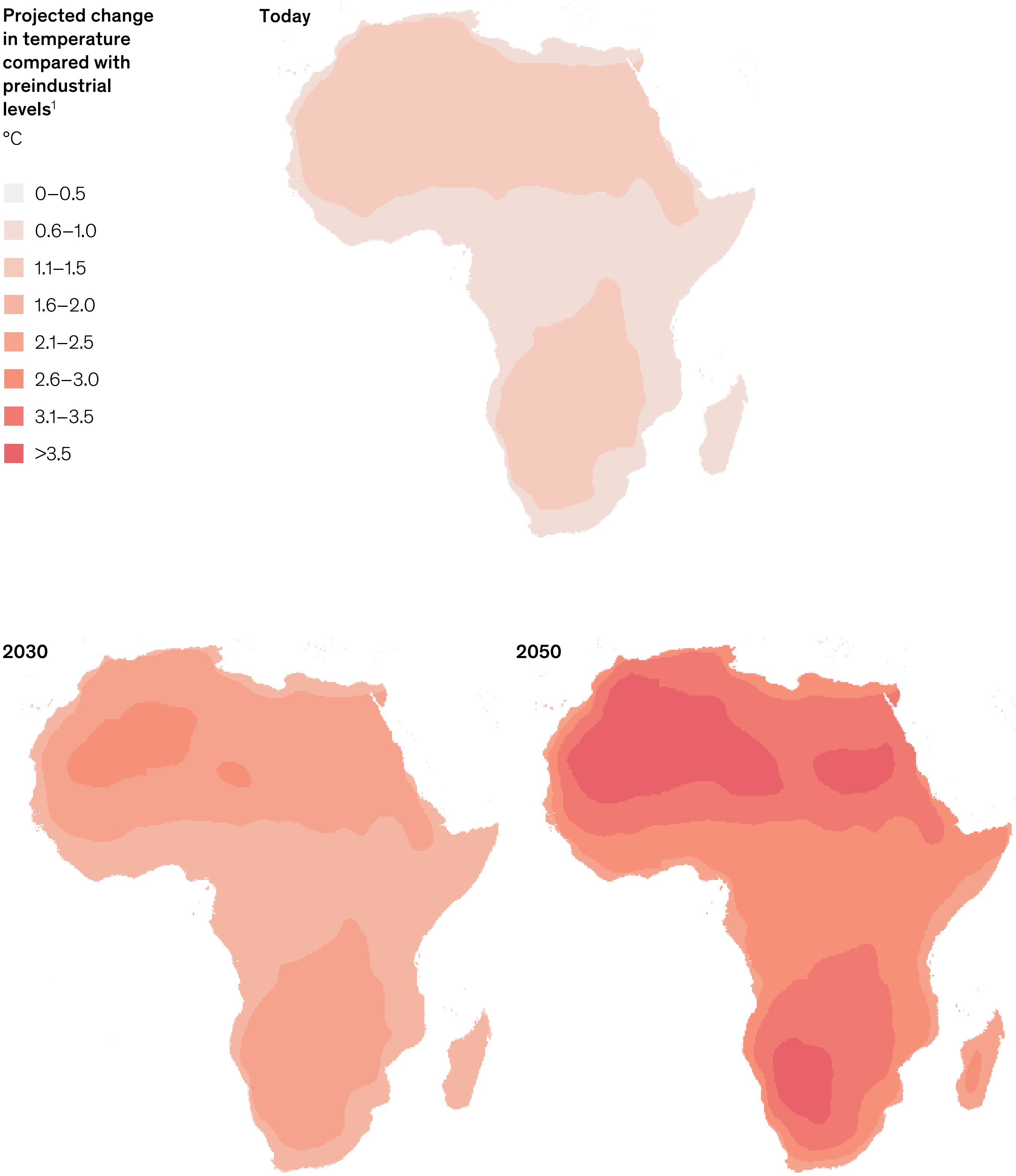
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; McKinsey Global Institute analysis

Exhibit 16

Average temperatures in Africa are expected to increase in most regions, with increases of more than 3.5°C from preindustrial levels in some areas in the north and south.

Based on RCP 8.5



---

1. Preindustrial levels defined as period between 1880-1910.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: climate-lab-book.ac.uk; KNMI Climate Explorer, 2019; Woods Hole Research Center

In Mozambique, two of the most important crops are corn (maize), which is grown primarily as a food crop, and cotton, which is raised primarily as a cash crop for export. Our analysis suggests that the changing climate will make corn yields more volatile and have the opposite effect on cotton, which typically prefers hotter temperatures. In the case of corn, the likelihood of a large seasonal crop loss (exceeding 30 percent) is currently near zero. By 2030, we project that such a loss will have a 2 percent likelihood of occurring in a given year. However, our projections also indicate that the likelihood of unusually high yields (20 to 30 percent greater than normal) will also increase.[126] Cotton growers in Mozambique, by contrast, are projected to experience more stability in yields and thus to benefit from the effects of climate change. We project that a 20 percent or greater drop in yields, compared with average yields, will be 95 percent less likely in 2030 than it was between 1990 and now. Barring other influences, like changes in pests, this reduction in volatility should help the many rural households that rely on cotton crops for much of their income (overall, cotton contributes about one-fifth of Mozambique's agricultural export earnings).

Physical assets: Increased flooding in Florida could have financial costs beyond physical damages. For supply-chains, rising risk of disruption may require hardening production sites and raising inventories

In Florida, expected direct physical damages to real estate are expected to grow with the changing climate, but financial knock-on effects could be even greater. Storm surge from hurricanes is projected to become more severe and tidal flooding more frequent.[127] The geography of the state—an expansive coastline, low elevation, and a porous limestone foundation—makes it vulnerable to flooding and makes adaptation challenging. Rising sea levels could push saltwater into the freshwater supply and damage water management systems. Climate hazards will likely have a direct impact on home owners as well as significant knock-on effects on the state's economy more broadly.

With increasing hurricane intensity and rising sea levels, tail events are likely to cause more impact and become more likely than they are today. Florida's real estate losses during storm surge from a 100-year hurricane event would be $35 billion today, which are forecast to grow to $50 billion by 2050, assuming no change in building stock (Exhibit 17).[128]. Real estate is both a physical and a financial store of value for most economies. Damages and the expectation of future damages to homes and infrastructure could drive down prices of exposed homes. The state's assets and people and its economic activity tend to be concentrated in coastal areas exposed to these hazards. Based on historical trends on the impacts of frequent tidal flooding, devaluation of exposed homes could be $10 billion to $30 billion in 2030 and $30 billion to $80 billion in 2050, all else being equal.[129] This corresponds to about a 15 to 35 percent impact. The devaluation could be significantly larger if climate hazards affect public infrastructure assets like water, sewage, and transportation systems, or if home owners more deliberately factor climate risk into their buying decisions. For example, rough estimates suggest that the price effects discussed above could impact property tax revenue in some of the most affected counties by about 15 to 30 percent (though impacts across the state could be less, at about 2 to 5 percent).

---

[126] Although the country's overall corn production is projected to become more volatile, the impacts we modeled for corn crops obscure the possibility that impacts could differ from one area to another. Subnational predictions for agro-ecological zones will better inform country planning.

[127] Thomas Knutson et al., *Tropical cyclones and climate change assessment: Part II. Projected response to anthropogenic warming,* American Meteorological Society, 2019. Kristina A. Dahl, Melanie F. Fitzpatrick, Erika Spanger-Siegfried, "Sea level rise drives increased tidal flooding frequency at tide gauges along the U.S. East and Gulf Coasts: Projections for 2030 and 2045," PLoS ONE 12(2): e0170949, 2017.

[128] Analysis conducted by KatRisk; direct average annual losses to all residential real estate (insured and uninsured properties).

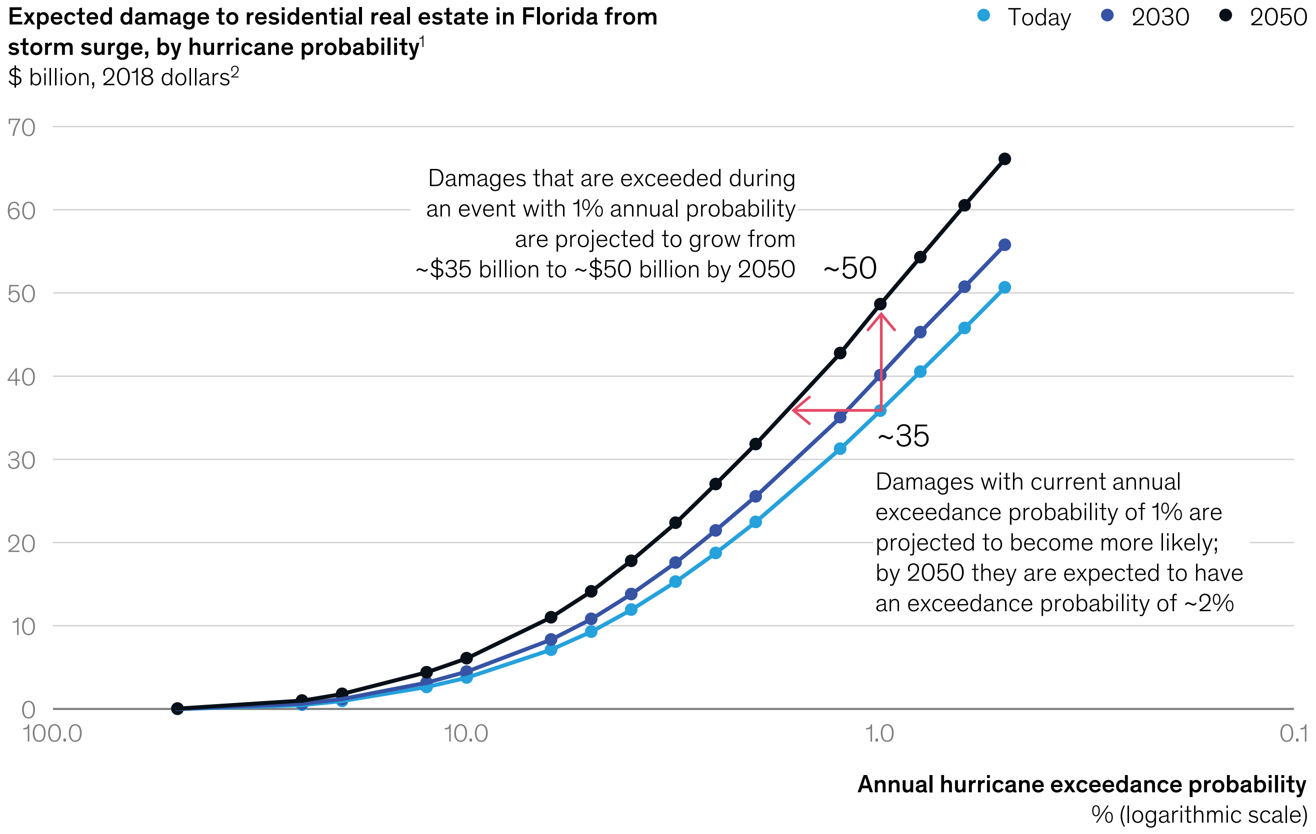
[129] Analysis supported by First Street Foundation, 2019. See Florida case for further details on analysis.

Exhibit 17

"Tail" events are projected to cause more damage; losses from an event with 1 percent annual probability in Florida are projected to grow from approximately $35 billion to approximately $50 billion by 2050.

Based on USACE high scenario

Expected damage to residential real estate in Florida from storm surge, by hurricane probability[1]
$ billion, 2018 dollars[2]



Damages that are exceeded during an event with 1% annual probability are projected to grow from ~$35 billion to ~$50 billion by 2050

Damages with current annual exceedance probability of 1% are projected to become more likely; by 2050 they are expected to have an exceedance probability of ~2%

1. Sea level rise based on USACE high curve. High curve results in 1.5 meter eustatic sea level rise by 2100 (within range of RCP 8.5 scenario; see, for example, Jevrejevaet et al., 2014). Based on current exposure. Buildup of additional residential real estate in areas prone to storm surge could further increase expected damage.
2. Based on damages if event occurs; damages not adjusted for likelihood of event. Damages based on constant exposure, ie, increase in projected damages to 2030 or 2050 is due to change in expected hazards.

Note: See the Technical Appendix for why this climate scenario was chosen. We define "today" based on sea level rise in 2018.
Source: Analysis conducted by KatRisk

As already noted earlier in this chapter, lower real estate prices could have knock-on effects including forgone property taxes, which could affect municipal bond ratings and the spending power of local governments on adaptation as well as broader infrastructure investment. Business activity could be negatively affected, as could the price or availability of insurance and mortgage financing in high-risk areas. Home owners cannot protect against the risk of devaluation with insurance. Furthermore, while mortgages can be 30 years long, insurance is repriced every year. This duration mismatch means that current risk signals from insurance premiums might not build in the expected risk over an asset's lifetime. This may lead to insufficiently informed decisions. If insurance premiums rise to account for future climate change, this could create a risk to lending activity for new homes and to the wealth of existing home owners.

Even home owners who are not financially distressed may choose to strategically default if their homes fall steeply in value with little prospect of recovery. One comparison point is Texas: during the first months after Hurricane Harvey hit Houston in 2017, the mortgage delinquency rate almost doubled, from about 7 to 14 percent.[130] As mortgage lenders start to recognize these risks, they could change lending rates for risky properties or, in some cases, stop providing 30-year mortgages. This would affect both individuals and the state's economy.

Adaptation poses hard choices in Florida and will require thoughtful planning and preparation. For example, should the state increase hurricane and flooding protection or curtail development in risk-prone areas and perhaps even abandon some of them? The Center for Climate Integrity estimates that 9,200 miles of seawalls would be necessary to protect Florida by 2040, at a cost of $76 billion.[131] Seawalls are only one part of the solution and may also not be technically or economically viable in the entire state. Other strategies include hardening and improving the resiliency of existing infrastructure and installing new green infrastructure.

Our examination of the potential impact of climate change on supply chains suggests that the knock-on effects could be more significant than the physical asset damage. Global supply chains are typically optimized for efficiency over resiliency and hence often designed with low buffers, for example regarding inventory. We identify a spectrum of supply chains to help assess the nature of climate risk that companies may face. These include specialty, commodity, and intermediate supply chains (Exhibit 18). We focus on two global supply chains: semiconductors, a specialty supply chain, and heavy rare earths, a commodity.

For semiconductors, the probability of an event with the magnitude of what is today a 1-in-100-year hurricane, with the potential to disrupt semiconductor manufacturing, occurring in any given year in the western Pacific, is projected to double or even quadruple by 2040. In this scenario, such hurricanes could potentially lead to months of lost production for the directly affected companies. For unprepared downstream players, for example, those without buffer inventories, insurance, or the ability to find alternate suppliers, the revenue loss in a disaster year could be as high as 35 percent, according to our estimates. For heavy rare earths, which are mined in southeastern China, the likelihood of extreme rainfall in the region sufficient to trigger mine and road closures is projected to rise from about 2.5 percent per year today to about 4 percent per year in 2030 and 6 percent in 2050.[132] Given the commoditized nature of this supply chain, impacts on production could result in increased prices for all downstream players.

Building hazard-protected plants and boosting inventory levels could prepare companies for the immediate consequences of climate risk. Securing plants in southeast Asia against hazards comes at a comparatively low cost, of approximately 2 percent of building costs. In both cases of rare earths and semiconductors, downstream players could mitigate impacts by holding higher inventory levels and by sourcing from different suppliers across multiple geographies. For buyers of semiconductors, raising inventory to provide a meaningful buffer could be quite cost-effective, with estimated costs for warehousing and working capital increasing input costs by less than 1 percent.

Implementation is relatively straightforward because it lies within the responsibility of specific actors. Nonetheless, it comes at the cost of decreased efficiency in production processes, for example by creating limitations on lean or just-in-time inventory.

---

[130] Daniel Hartley et al., *Flooding and finances: Hurricane Harvey's impact on consumer credit*, Chicago Fed Letter, 2019, Number 415.

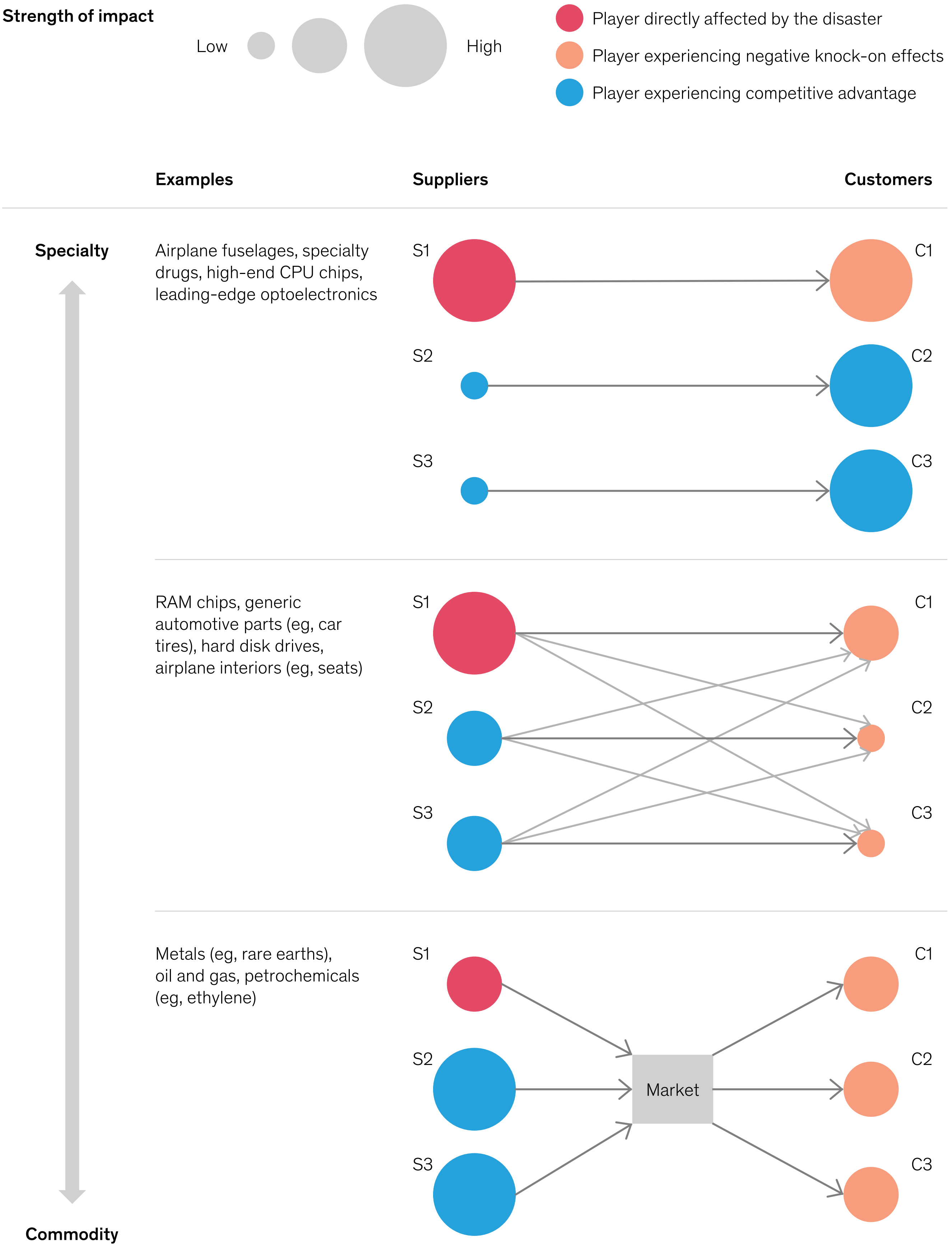
[131] The estimated cost, spread over 20 years ($3.8 billion per year), represents about 0.4 percent of Florida's GDP. *Climate costs in 2040: Florida,* Center for Climate Integrity.

[132] Woods Hole Research Center analysis. It is important to note that near-term regional projections of precipitation extremes have been assessed as highly sensitive to the influence of natural variability, particularly in lower latitudes. The 30-year projection is thus more robust than the decadal projection. Furthermore, there is recent evidence from observational records indicating that in many regions climate models may underestimate changes in precipitation volume. For more details on the relevant uncertainties, see Ben Kirtman et al., "Near-term Climate Change: Projections and Predictability," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

Exhibit 18

Supply chains face different knock-on effects from production disruption depending on the degree of commoditization.

Illustrative



Source: McKinsey Global Institute analysis

Infrastructure services: Flood management and other infrastructure will require adaptation investment to address growing hazard and potential knock-on effects

We find growing risk from climate change across all 17 types of infrastructure assets we examined in the domains of energy, water, transportation, and telecommunications (Exhibit 19). Both the asset itself and the economic activity it sustains are at risk. This can create significant knock-on effects.

Each infrastructure asset type has unique vulnerabilities to climate hazards. In transportation, for example, only a few millimeters of flooding on an airport runway can cause disruption. With 25 percent of the world's 100 busiest airports less than 10 meters above sea level, coastal flooding and risk from storms could be a serious vulnerability.[133] Extreme heat may cause shutdowns and efficiency losses in some airports and with some aircraft models, but it is not expected to be a significant risk for most airports over the coming decades. Rail and roads are more affected by flooding than by heat, because of the vulnerability of signaling systems to water exposure and the traffic-slowing effects of even small amounts of water; traffic can slow by 30 percent with even a few centimeters of water on a road's surface.[134]

Telecommunications infrastructure assets may be affected only to a minimal or moderate degree by climate hazards, although cell phone towers and cables are vulnerable to high winds. In Puerto Rico, 90 percent of towers were downed by 280 kilometer-per-hour winds from Hurricane Maria in 2017, and in New York during Hurricane Sandy in 2012, 80-mile-per-hour winds downed 25 percent of towers.[135] Freshwater infrastructure such as reservoirs, wells, and aquifers are vulnerable to sustained drought conditions. Coastal, riverine, and pluvial flooding can also overwhelm and damage wastewater treatment infrastructure and water treatment systems. Hurricane Sandy, for example, led to the release of 11 billion gallons of sewage as coastal wastewater systems were inundated.[136]

The power grid is also vulnerable. Extreme heat can lead to the combined effects of efficiency losses and increase in peak load from greater use of air-conditioning. One example is the electricity grid infrastructure in Los Angeles County, which could be at risk of overloading and load shedding.[137]

The knock-on effects may also be significant but hard to estimate. Strain on government services and public health services would increase immediately. In the longer term, if outages become a regular occurrence, businesses—particularly small and medium-size enterprises that are less able to tolerate interruptions than larger operations—may lose productivity or choose to relocate.

Adaptation costs for infrastructure are typically estimated to be fairly low relative to total spending, about 1 to 2 percent of total annual infrastructure spending.[138] The Los Angeles Department of Water and Power, which manages infrastructure within the city of Los Angeles, plans to replace 800 transformers each year between 2017 and 2020.

---

[133] Xi Hu et al., "The spatial exposure of the Chinese infrastructure system to flooding and drought hazards," *Natural Hazards,* January 2016, Volume 80, Number 2.

[134] Katya Pyatkova et al., "Flood Impacts on Road Transportation Using Microscopic Traffic Modelling Techniques," in Simulating Urban Traffic Scenarios: 3rd SUMO Conference 2015 Berlin, Germany, Michael Behrisch and Melanie Weber, eds., Cham, Switzerland: Springer, 2019; Maria Pregnolato et al., "The impact of flooding on road transport: A depth-disruption function," Transportation Research Part D: Transport and Environment, August 2017, Volume 55; Pablo Suarez et al., "Impacts of flooding and climate change on urban transportation: A systemwide performance assessment of the Boston metro area," Transportation Research Part D: Transport and Environment, May 2005, Volume 10, Number 3.

[135] *2016 broadband progress report,* US Federal Communications Commission, 2016.

[136] Alyson Kenward, Daniel Yawitz, and Urooj Raja, *Sewage overflows from Hurricane Sandy,* Climate Central, April 2013.

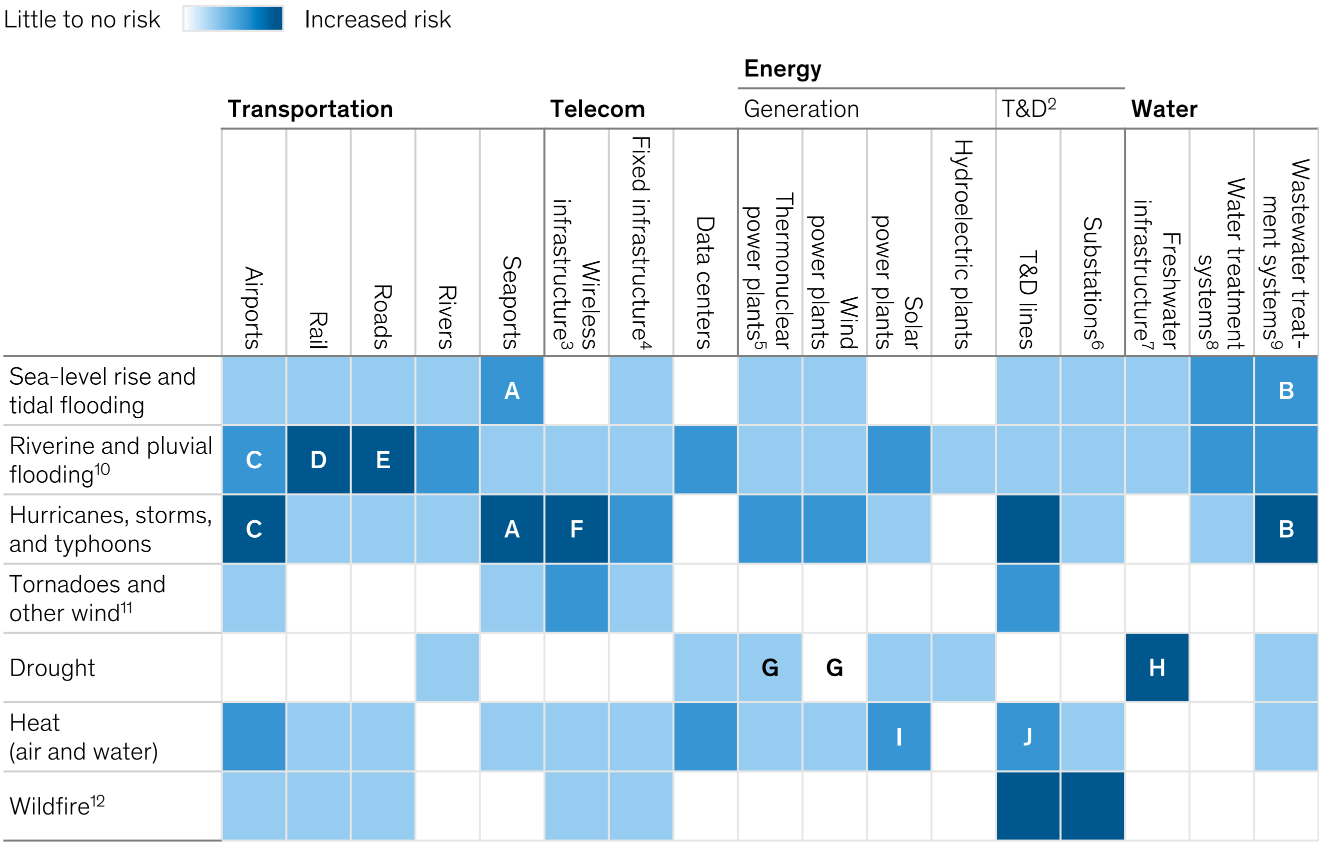
[137] California's Fourth Climate Change Assessment, for example, estimates that by 2060, 5 percent annual probability heat waves in Los Angeles County may reduce overall grid capacity by between 2 and 20 percent. At a substation level, overloading would increase significantly, pushing some substations to automatic shut-off mode, disconnecting entire neighborhoods and leaving others with significant load shedding. California's Fourth Climate Change Assessment, August 2018, from Ca.gov.

[138] Gordon Hughes et al., *The costs of adapting to climate change for infrastructure,* World Bank, August 2010.

Exhibit 19

Global infrastructure assets have highly specific vulnerability to hazards: at least one element in each type of infrastructure system sees high risk.

Risk Defined as potential future losses as a result of exposure to climate hazards by 2030[1]



A. Seaports, by definition, are exposed to risk of all types of coastal flooding. Typically, seaports are resistant and can more easily adjust to small sea-level rise. However, powerful hurricanes are still a substantial risk. In 2005, Hurricane Katrina destroyed ~30% of the Port of New Orleans.

B. Wastewater treatment plants often adjoin bodies of water and are highly exposed to sea-level rise and hurricane storm surge. Hurricane Sandy in 2012 led to the release of 11 billion gallons of sewage, contaminating freshwater systems.

C. Many airports are near water, increasing their risk of precipitation flooding and hurricane storm surge. Of the world's 100 busiest airports, 25% are less than 10m above sea level, and 12—including hubs serving Shanghai, Rome, San Francisco, and New York—are less than 5m. Only a few mm of flooding is necessary to cause disruption.

D. Rail is at risk of service interruption from flooding. Disruption to signal assets in particular can significantly affect rail reliability. Inundation of 7% of the UK's signaling assets would disrupt 40% of passenger journeys. Damage can occur from erosion, shifting sensitive track alignments.

E. Roads require significant flood depths and/or flows to suffer major physical damage, but incur ~30% speed limitations from 0.05m inundation and can become impassable at 0.3m. Compounding effects of road closures can increase average travel time in flooded cities 10–55%.

F. Cell phone towers are at risk from high wind speeds. During Hurricane Maria in 2018, winds of up to 175mph felled 90+% of towers in Puerto Rico. Risks are more moderate at lower wind speeds, with ~25% of towers downed by ~80mph winds during Hurricane Sandy.

G. Wind power plants are highly resistant to drought; thermoelectric power plants, which regularly use water for cooling (seen in >99% of US plants), are at risk during significant shortages.

H. Freshwater infrastructure and associated supplies are highly vulnerable to impact of drought, as seen when Cape Town narrowly averted running out of drinking water in 2018.

I. Solar panels can lose efficiency through heat, estimated at 0.1–0.5% lost per 1°C increase.

J. Transmission and distribution suffers 2 compounding risks from heat. Rising temperatures drive air conditioning use, increasing load. Concurrently, heat reduces grid efficiency.

1. Losses are defined as asset interruption, damage, or destruction. 2. Transmission and distribution. 3. Base substations and radio towers. 4. Including above- and below-ground cable. 5. Including nuclear, gas, and oil. 6. Including large power transformers. 7. Reservoirs, wells, and aquifers. 8. Plants, desalination, and distribution. 9. Plants and distribution. 10. Pluvial flooding is flooding caused by extreme precipitation, independent of the actions of rivers and seas. 11. Including both rain and wind impacts. 12. Wildfire is a derivative risk primarily driven by drought.
Source: Dawson et al., 2016; Federal Communications Commission, 2016; Mobile Association, 2018; *New York Times,* 2006; Pablo, 2005; Prelenato, 2019; Pyatkova, 2019; Xi, 2016; McKinsey Global Institute analysis

In urban areas, floods from extreme events could leave populations without critical services such as power, transportation, and communications. We find the potential direct and knock-on effects of flooding to be significant. In the case of Bristol, a port city in the west of England that has not experienced major flooding for decades, we find that absent adaptation investment, extreme flood risk could grow from a problem costing millions of dollars today to costing billions by 2065. During very high tides, the river Avon becomes "tide locked" and limits land drainage in the lower reaches of river catchment area. As a result, Bristol is vulnerable to combined tidal and pluvial floods, which are sensitive to both sea-level rise and precipitation increase. Both are expected to climb with climate change. While Bristol is generally hilly and most of the urban area is far from the river, the most economically valuable areas of the city center and port regions are on comparatively low-lying land. More than 200 hectares of automotive storage near the port could be vulnerable to even low levels of floodwater, and the main train station could become inaccessible. Bristol has flood defenses that would prevent the vast majority of damage from an extreme flood event today. By 2065, as extreme flood risk rises, however, those defenses could be overwhelmed, in which case water would reach infrastructure that was previously safe.[139]

Specifically, we estimate that a 200-year flood today (that is, a flood of 0.5 percent likelihood per year) in Bristol would cause infrastructure asset damages totaling between $10 million and $25 million. This is projected to rise to $180 million to $390 million by 2065, for what will then constitute a 200-year event. The costs of knock-on effects could also rise, from $20 million to $150 million today to as much as $2.8 billion by 2065, if businesses became unable to function, industrial stores were destroyed, and transportation halted.[140] That impact translates to between 2 and 9 percent of the city's gross value added in 2065. As an outside-in estimate, based on scaling costs to build the Thames Barrier in 1982, plus additional localized measures that might be needed, protecting the city to 2065 may cost $250 million to $500 million (roughly 0.5 to 1.5 percent of Bristol's GVA today). However, the actual costs will largely depend on the specific adaptation approach.

For Ho Chi Minh City, a city prone to monsoonal and storm surge flooding, we estimate that direct infrastructure asset damage from a 100-year flood today (that is, a flood of 1 percent likelihood per year) could be on the order of $200 million to $300 million, rising to $500 million to $1 billion in 2050, assuming no additional adaptation investment and not including real estate–related impacts. Here, too, the knock-on costs in economic activity disrupted are expected to be more substantial, rising from between $100 million and $400 million today to $1.5 billion to $8.5 billion in 2050.[141]

Many new infrastructure assets, particularly the local metro system, have been designed to tolerate an increase in flooding. Yet the hazards to which these assets may be subjected could be greater even than the higher thresholds. In a worst-case scenario of 180 centimeters of sea-level rise, these thresholds could be breached in many locations, and some assets possibly damaged beyond repair (Exhibit 20).

---

[139] Data for this case and expert review were kindly provided by Bristol City Council.

[140] Our model assumptions suggest that a flood could cause damage to a major power plant, inundate a major substation that feeds an area covering approximately 20 to 30 percent of Bristol, cut off the main train station from all access, and flood the port, including one of the largest car storage areas in the United Kingdom, with a capacity of 90,000 new automobiles. It may also cause $160 million to $240 million of property damage, particularly to high-value riverfront homes and large swaths of the central business district, as well as $10 million to $130 million of lost infrastructure operating revenues, largely dependent on whether the power station is disrupted.

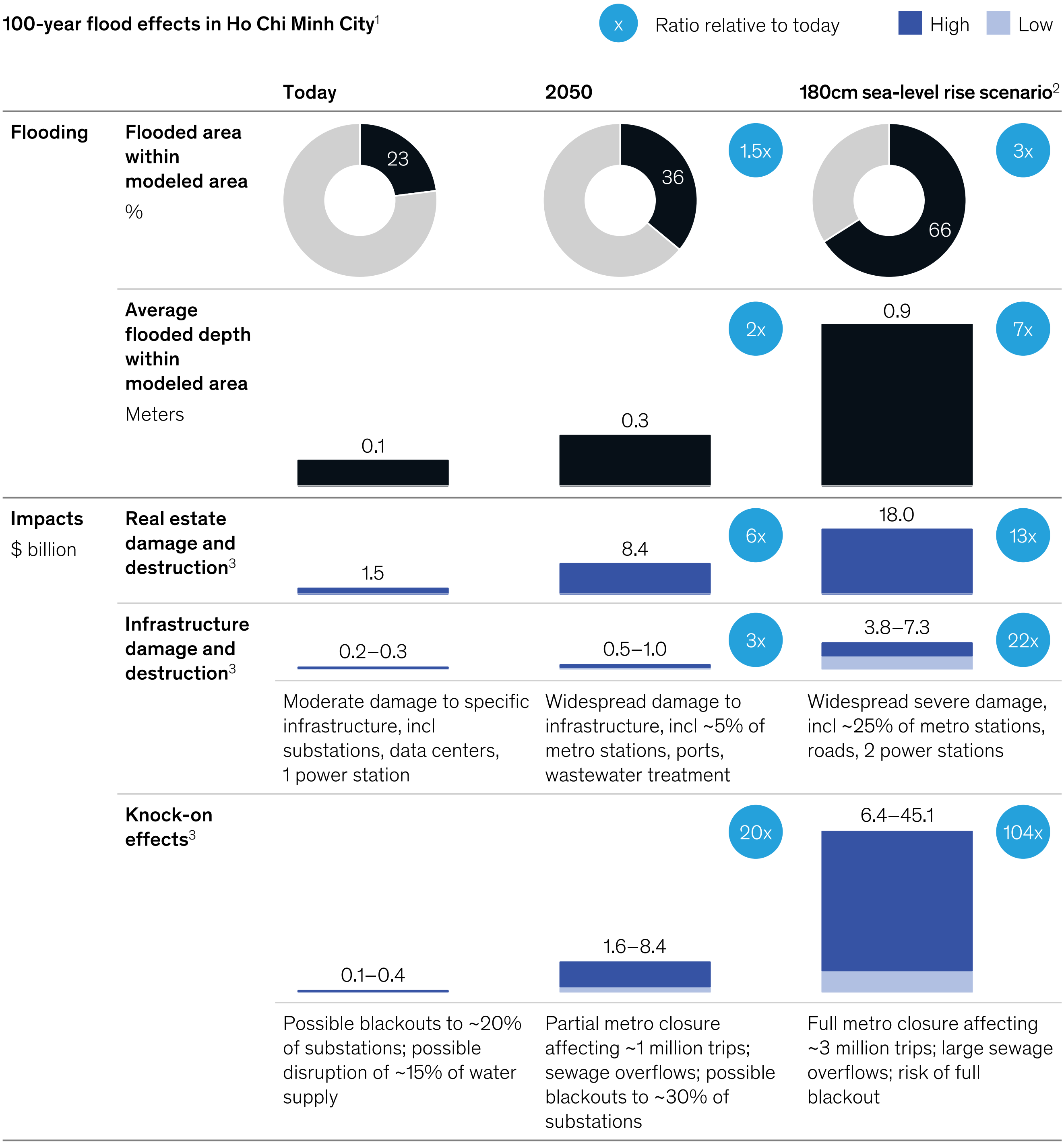
[141] For our modeling, we assume that 36 percent of the city becomes flooded. Small increases in flood exposure and flood depth would be enough to trip the thresholds of some infrastructure, with the average flooded asset at 0.5 meter. In addition, many of the 200 new infrastructure assets are planned to be built in flooded areas. New, sensitive, and expensive assets such as the city's underground metro stations in the highest-risk areas would be damaged. Damaged assets could include 5 percent of new metro stations, 50 percent of data centers, 10 percent of wastewater facilities, two power stations, 30 percent of substations, and a port. Roads would begin to reach damage thresholds, with 10 percent requiring repair. About $8.4 billion of damage could also be incurred on real estate as larger areas flood to greater depths. See case study for details.

Exhibit 20

Ho Chi Minh City could experience 5 to 10 times the economic impact from an extreme flood in 2050 vs today.

Based on RCP 8.5

100-year flood effects in Ho Chi Minh City[1]



Infrastructure damage and destruction:

- Today: Moderate damage to specific infrastructure, incl substations, data centers, 1 power station
- 2050: Widespread damage to infrastructure, incl ~5% of metro stations, ports, wastewater treatment
- 180cm sea-level rise scenario: Widespread severe damage, incl ~25% of metro stations, roads, 2 power stations

Knock-on effects:

- Today: Possible blackouts to ~20% of substations; possible disruption of ~15% of water supply
- 2050: Partial metro closure affecting ~1 million trips; sewage overflows; possible blackouts to ~30% of substations
- 180cm sea-level rise scenario: Full metro closure affecting ~3 million trips; large sewage overflows; risk of full blackout

---

1. Repair and replacement costs. Qualitative descriptions of damage and knock-on effects are additional to previous scenarios.
2. Assets in planning today with long expected design lives (such as the metro) could exist long enough to experience a 1% probability flood in a 180-centimeter sea-level-rise worst-case scenario by the end of the century if significant action is not taken to mitigate climate change.
3. Value of wider societal consequences of flooding, with a focus on those attributable to infrastructure failure, includes loss of freight movement, lost data revenues, and lost working hours due to a lack of access to electricity, clean water, and metro services. Adjusted for economic and population growth to 2050 for both 2050 and 180cm sea-level rise scenarios.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Following standard practice, we define future states (current, 2030, 2050) as the average climatic behavior over multidecade periods. The climate state today is defined as the average conditions between 1998–2017, in 2030 as the average between 2021–40, and in 2050 between 2041–60. Assumes no further adaptation action is taken. Figures may not sum to 100% because of rounding.

Source: Asian Development Bank; BTE; CAPRA; CATDAT disaster database; Daniell et al., 2017; Dutch Ministry of Infrastructure and Environment; ECLAC; EU Commission; HAZUS; Oxford Economics; People's Committee of Ho Chi Minh City; Scussolini et al., 2017; UN; Viet Nam National University, Ho Chi Minh City; World Bank; historical insurance data; review of critical points of failure in infrastructure assets by chartered engineering consultants; McKinsey Global Institute analysis

Compared with Bristol, Ho Chi Minh City has many more adaptation options, as less than half of the city's major infrastructure needed for 2050 exists today. Potential adaptation options could be effective. However, it is unlikely that any single measure will be easy or without disadvantages, A tidal barrier is one example of a potential hardening measure. A cost estimate for the Soài Rap tidal barrier is not available. However, one potential comparison is Jakarta's major coastal defense plans, which have a potential cost of roughly $40 billion. That is comparable to Ho Chi Minh City's current GDP.[142]

Natural capital: Climate change may accelerate the destruction of natural capital such as glaciers, ocean ecosystems, and forests, and the services they provide to human communities

Natural capital is found globally and is defined as the world's stock of natural resources (Exhibit 21). Climate change is having a substantial impact on natural capital. We look at three manifestations of climate change impact on natural capital globally: glacier melt, ocean warming and acidification, and forest disturbance.

Natural capital is one of the most challenging domains in which to understand and respond to the effects of climate change. Protecting and adapting natural capital is a complex task because the systems and their interconnections can be difficult to understand and the effectiveness of solutions may be fully assessed only over the long term. Experts could create metrics, data, and tools to measure nature's benefits to people and monitor natural capital; provide tangible ways to identify trade-offs; and better understand complex ecosystem dynamics, including feedbacks and the impact of climate change.

Glaciers in most parts of the world are shrinking. They are losing an average of 335 billion tons of snow and ice each year, enough to raise sea levels by almost one millimeter per year.[143] In the longer term, this loss will diminish the flow of glacier-fed rivers that provide one-sixth of the world's people with freshwater for drinking and irrigation.[144] In the Hindu Kush Himalayan region, where glaciers provide water for more than 240 million people, glacial mass is expected to drop by about 10 to 25 percent by 2030, and by 20 to 40 percent by 2050 in some subregions.[145] In response, integrated water planning and management across sectors (such as energy, land, forest, ecosystems, and agriculture) could make water use more efficient and reduce environmental impacts. More water storage could help when discharges are low. Physical protections (such as flood-prevention structures, better irrigation systems, upgraded canals, precision land leveling, and proper implementation and enforcement of building codes) and management tools (such as land-use planning laws and early-warning systems) are also needed to manage risk.

---

[142] Philip Sherwell, "$40bn to save Jakarta: The story of the Great Garuda," *Guardian*, November 22, 2016, theguardian.com/cities/2016/nov/22/jakarta-great-garuda-seawall-sinking.

[143] Michael Zemp et al., "Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016," *Nature,* April 2019, Volume 568, Number 7752.

[144] Matthias Huss and Regine Hock, "Global-scale hydrological response to future glacier mass loss," *Nature Climate Change,* February 2018, Volume 8, Number 2, pp. 135–40; *State of the planet*, "The glaciers are going," blog entry by Renee Cho, May 5, 2017.

[145] Philippus Wester et al., eds., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People,* Cham, Switzerland: Springer, 2019.

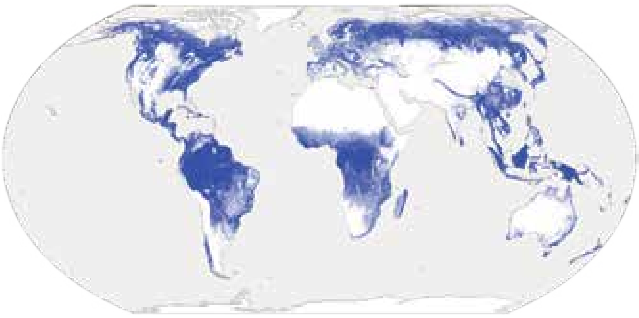
Exhibit 21

Natural capital can be found all over the globe.

Forest

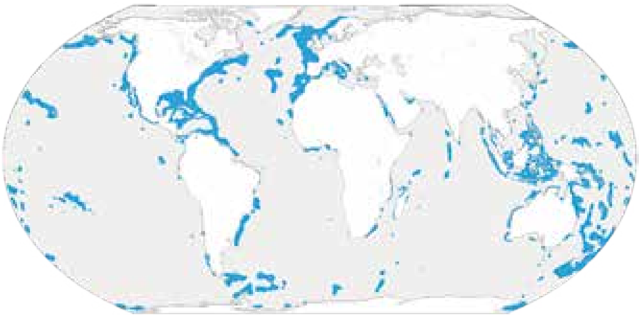
Tree density (%)

0 ▨ 100



Coral reefs

🟦



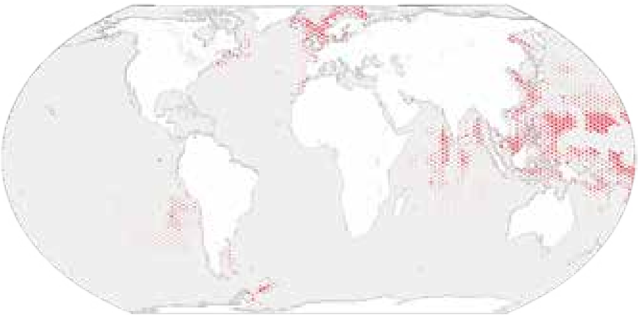
Freshwater

Regions with high freshwater availability

▨

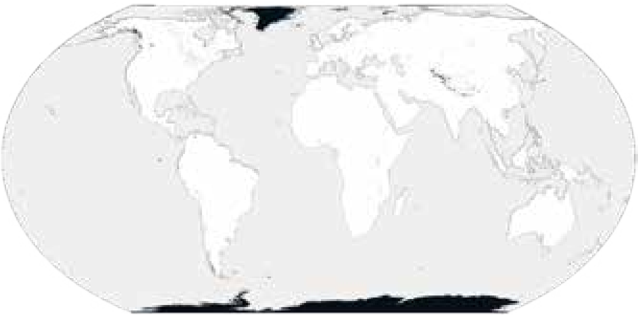
Fish stocks[1]

0 ⬢⬢⬢⬢ 100



Land ice

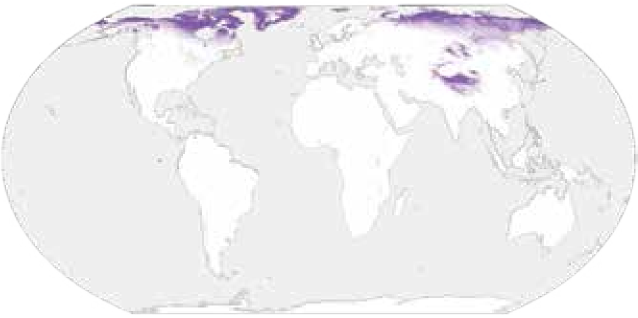
■



Permafrost

Permafrost coverage (%)

0 ▨ 100



[1] Index of global fishing activity used as proxy for fish stocks.

Source: Data Basin, 2016; FAO, 2010; Halpern et al., 2015; Hughes et al., 2019; James, National Geographic, 2018; Lam et al., 2016; NASA Earth Observatory; UNEP, 2014; Wester et al., 2018; Witt et al., 2014; Zemp et al., 2019; McKinsey Global Institute analysis

At the same time, the world's oceans are becoming warmer, less oxygenated, and more acidic. By 2050, ocean warming is expected to reduce fish catches by about 8 percent and associated revenue by about 10 percent, affecting the livelihoods of 650 million to 800 million people globally who directly or indirectly rely on these revenues.[146] Catch potential in many tropical regions is projected to decline by up to 50 percent, hurting fishing communities in those regions even more.[147] Experts have suggested that mitigating pressures (such as pollution, commercial fishing, invasive species, and coastal habitat modification) could reduce and delay the effects of climate change on the world's oceans. Potential adaptation measures include creation of alternative livelihoods and retraining of fishing crews. In the short term, better governance mechanisms could protect regional marine ecosystems and the services they provide. To help fishing communities, microcredit mechanisms have been set up in four of Senegal's marine protected areas to help fishing communities develop alternative sources of income.

Forests cover nearly one-third of the world's land. About 1.6 billion people depend on them to make their living and some 2.4 billion people use wood as fuel to cook, boil and sterilize water, and heat their dwellings.[148] Like oceans, forests act as important carbon sinks; the biosphere currently absorbs approximately 30 percent of fossil fuel CO_2 emissions, with the majority stored in forests and mangroves. Because forests take a long time to grow but then live for decades or longer, they are likely to face risks from both changes in mean climate variables and extreme weather events like prolonged drought, wildfires, storms, and floods.[149] This is especially relevant when considering that fires, drought, and insect activity are likely to increase in warmer and drier conditions.[150] Although forests can be restored, their full range of ecosystem services might not recover.

Potential adaptation measures for natural capital in general include sustaining important ecological functions by means of interventions, for example by altering hydrology to help ecosystems during droughts and by maintaining and restoring coastal vegetation. Moreover, ecosystems can be made more adaptable, for instance by enhancing genetic diversity within and among species, as well as by investing in green infrastructure by integrating natural processes with spatial planning and territorial development. Where natural capital is already lost, economic diversification may help communities adapt.

From our case study analysis, we gain insight into both the nature of climate risk and the way climate risk is evolving. Across the cases, we note some key characteristics that include the non-stationary and nonlinear nature of impacts, as well as the systemic, knock-on effects that these can produce. Our estimates of climate risk based on these cases suggest both an increase in physical climate risk by 2030 and even more by 2050, and the importance of looking at that risk through a spatial approach, given that some geographies and sectors tend to experience more significant impact than others. In the next chapter, we use a detailed geospatial analysis of 105 countries to highlight how climate risk could evolve globally.

---

[146] Vicky W. Y. Lam et al., "Projected change in global fisheries revenues under climate change," *Scientific Reports*, September 2016, Volume 6.

[147] Robert Blasiak et al., "Climate change and marine fisheries: Least developed countries top global index of vulnerability," *PLOS ONE,* June 2017, Volume 12, Number 6.

[148] *The state of the world's forests: Forest pathways to sustainable development*, UN Food and Agriculture Organization, 2018; World Bank; Sooyeon Laura Jin et al., *Sustainable woodfuel for food security: A smart choice: Green, renewable and affordable*, UN Food and Agriculture Organization, 2017; Philippe Ciais et al., "Carbon and Other Biogeochemical Cycles," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[149] Marcus Lindner et al., "Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems," *Forest Ecology and Management,* February 2010, Volume 259, Number 4.

[150] Rupert Seidl et al., "Forest disturbances under climate change," *Nature Climate Change*, June 2017, Volume 7, Number 6.

4. Physical climate risk—a macro view

While our case studies illustrate localized impacts of a changing climate and help us understand the nature of physical climate risk, rising temperatures and the resulting hazards are a global trend. To understand how physical climate risk could evolve around the world, we developed a global geospatial assessment of direct impact from climate change over the next 30 years covering 105 countries. This geospatial analysis relies on the same five-systems framework of direct impacts that we used for the case studies and is based on an RCP 8.5 climate scenario. We used the framework to derive a set of six indicators that assess potential impacts across countries.[151] Using these indicators, we arrived at a global view of how many lives could be affected, as well as the impact on physical and natural capital. We also discuss the implications for economic activity.[152] (See Box 2, "Methodology for global geospatial analysis").

We find that all 105 countries we studied would see an increase in potential direct impacts from climate change for at least one indicator by 2030, and further increases to 2050. Of these, 16 countries—roughly 15 percent—would see an increase in three indicators by 2050 compared to today, while 44 countries see an increase in five of six indicators.

Climate change is not occurring uniformly, and risk varies across countries. We look at individual countries to identify the nature and magnitude of physical climate risk in each case and draw out patterns.

---

[151] Significant data constraints limited both the choice of our six indicators and the number of countries we included in the analysis. For countries, the minimum skillful predictive scale of GCMs prevented the creation of robust projections for a set of small countries.

[152] To conduct this analysis, we have relied on geospatial climate hazard data, including from Woods Hole Research Center analysis of CMIP5 Global Climate Model output, the World Resources Institute, the European Center for Medium-Range Weather Forecasts and data from Rubel et al. (obtained from the National Oceanic and Atmospheric Administration). We used geospatial data on population, capital stock, and GDP from the European Commission Global Human Settlement (GHS) and the UN *Global Assessment Report on Disaster Risk Reduction,* as well as data from other sources as described in Box 2. Notably, we have focused our analysis on a subset of possible climate hazards: lethal heat waves, heat and humidity and its impact on workability, water stress, riverine flooding, drought, and biome shifts. In some places, we also include a discussion about hurricanes.

Box 2

Methodology for global geospatial analysis

We used geospatial data to provide a perspective on direct impacts from climate change across 105 countries over the next 30 years.[1] Our set of 105 countries represents 90 percent of the world's population and 90 percent of global GDP. For each of the systems in our five-systems framework, we have identified one or more measures to define the direct impact of climate change, primarily building on the risk measures used in our case studies. We attempted to include impacts from a wide range of hazards. However, due to difficulties in obtaining sufficiently granular and robust data across countries, we were unable to include the potential impact from some hazards including tidal flooding, hurricanes, storm surge, and forest fires.

To conduct this analysis, we have relied on geospatial climate hazard data, including from Woods Hole Research Center analysis of CMIP5 Global Climate Model output, the World Resources Institute, the European Center for Medium-Range Weather Forecasts and data from Rubel et al. (obtained from the National Oceanic and Atmospheric Administration).[2] We used geospatial data on population, capital stock, and GDP from the European Commission Global Human Settlement (GHS) and the UN *Global Assessment Report on Disaster Risk Reduction*. For our analyses, we have assumed that geospatial distribution of these variables stays constant over time because of data limitations with geospatial time series data. However, we have accounted for increases in the magnitude of these variables at a national and global level (for example, population at a country level increasing between today, 2030, and 2050). Other data used include population data from the UN *World Population Prospects 2019* and the *UN World Urbanization Prospects,* employment data from Oxford Economics , data on GDP from IHS Markit Economics and Country Risk, and regional damage functions for flooding from the European Commission Joint Research Centre.

The indicators used in our geospatial analysis include:

— Share of population that live in areas experiencing a non-zero annual probability of lethal heat waves. This is a similar measure of livability and workability impact to that considered in our India case.

— Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions. This is a similar measure of livability and workability to that considered in our India case.

— Water stress measured as the annual demand of water as a share of annual supply of water. This is a similar measure of livability and workability to that considered in our Mediterranean case.

— Annual share of capital stock at risk of riverine flood damage in climate-exposed regions. Similar measures of capital stock damage to physical assets and infrastructure are used in our Florida and city inundation cases, although these cases also considered different forms of flooding.

— Share of time spent in drought over a decade, as a measure of food systems. We also consider the impact of drought in our Mediterranean case.

— Share of land surface changing climate classification. While we did not use this indicator in our case studies, it allows us to develop a global measure of potential natural capital impacts through an examination of shifts in the biome.[3]

For this analysis, we combine the categories of physical assets and infrastructure services. Both derive from physical capital impacts. Data limitations affected our ability to assess infrastructure effects globally. We often report results as relative measures compared with a baseline of population, physical capital stock, or GDP in the sub-regions affected by the hazard in question, rather than in all regions (referred to as "climate-exposed" regions). By sub-regions affected, we mean areas in which a non-zero likelihood of the specific climate hazard in question is projected. For example, for global capital stock damage, the numerator reflects the global statistically expected value of capital stock damage, and the denominator is the capital stock only in those parts of the world where damages are expected to occur rather than global capital stock. The reason for this choice is to reflect the local nature of climate risk and its impact on specific regions.

---

[1] These results are based on geospatial analysis of 1km X 1km resolution for some cases to 80km by 80km for others, bias correcting where possible. We have also attempted our best effort robustness tests and removed countries, and in some cases also grid-cells within countries, where the statistical significance of results was low. Global and individual country results may vary if hazard or other data at a different geospatial resolution was used, or if different considerations for robustness were applied.

[2] Data taken from Franz Rubel and Markus Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift*, April 2010, Volume 19, Number 2.

[3] The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. For this report, we have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.

The goal of this analysis was to measure direct impact (that is, how climate hazards interact and affect socioeconomic systems). However, one of the six measures of socioeconomic impact—drought—is in itself a climate hazard and is used to measure the effect on food systems. The five others are measures of socioeconomic impact. The reason for this choice of a hazard-based indicator was because country-level agricultural yield results (the measure used to assess impact on food systems in our cases) were challenging to obtain; AgMIP-coupled climate and crop models used to project agricultural yields can make high-confidence projections for relatively large breadbasket regions, rather than at a country level.[4] We are able to use the AgMIP results to provide global trends and results pertaining to large regional breadbaskets and have included those results in the discussion in this chapter. While we have attempted to include a wide range of countries in our analysis, there were some we could not cover because of data limitations (countries where the spatial resolution of the climate models we drew on was poor).[5]

In our cases, the potential direct impact from climate hazards is determined by the severity of the hazard and its likelihood, the exposure of various "stocks" (people, physical capital, and natural capital) to these hazards, and the resilience of these stocks to the hazards (for example, the ability of physical assets to withstand flooding). We followed a similar approach here with our geospatial analyses. We conducted these at a grid-cell level, overlaying data on a hazard (for example, floods of different depths), with exposure to that hazard (for instance, capital stock exposed to flooding), and a damage function (for example, what share of capital stock is damaged when exposed to floods of different depth). We then combined these grid-cell values to country and global numbers. As in our cases, we only attempt to quantify changes in climate and do not try to predict weather. Following standard practice, we define future states as the average climatic behavior over multidecade periods. Unless otherwise noted, the climate state today is defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 between 2041 and 2060. Unless otherwise noted, projections are from WHRC analysis of 20 CMIP5 General Circulation Models.[6]

Finally, while most of the analyses in this chapter are measures of direct impact from climate change, we also have included a discussion of knock-on effects, including impact on GDP. We have calculated the GDP at risk from reduced outdoor working hours due to heat and humidity, similar to the approach followed in our India case. We have not, however, attempted to quantify total GDP at risk. The uncertainties we discussed in Chapter 1 also apply to this geospatial analysis. As in our cases, we have accounted for climate-hazard-related uncertainty through a variety of different methods, including the use of multimodel ensemble mean or median projection of a large ensemble of different climate models, careful selection of regions and variables of interest, and dynamical or statistical downscaling processes, where appropriate.

---

[4] Agricultural Model Intercomparison and Improvement Project (AgMIP), was founded in 2010 by US and international agricultural modelers. See agmip.org

[5] The analytical process began with the full set of 195 member countries of the United Nations. Following the findings of Stanley L. Grotch and Michael Calvin McCracken, "The Use of General Circulation Models to Predict Regional Climatic Change," *Journal of Climate*, March 1991, Volume 4, Issue 3, any countries with a land surface smaller than the resolution of eight grid points was removed, leaving only countries with enough spatial area to be described by Global Climate Models. This process left a set of 105 countries. A hazard-by-hazard robustness check was then performed. Some projections (water supply, biome shift, and flooding) were drawn from external organizations that performed their own robustness checks. For the materially new analyses performed by WHRC, different quality control methods were applied. In some cases, particularly the projections of wet-bulb temperature, bias-correction and spatial disaggregation were performed to improve robustness. The PDSI drought projections were corrected to account for changing atmospheric CO_2 concentrations. With regards to agricultural results drawn from the AgMIP family of models, many of the results for the 105 identified countries were not assessed as robust, due to either small levels of agricultural production or small geographic spread of producing regions. As a result, we present only global and regional aggregated breadbasket results.

[6] The hazard data taken from external organizations includes data on today's river flood plains from the World Resources Institute's Aqueduct Global Flood Analyzer, water stress projections from the World Resources Institute's Water Risk Atlas, and the climate classification shift data from Franz Rubel and Markus Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift*, April 2010, Volume 19, Number 2. See Chapter 2 for a detailed discussion of various hazards.

Growing climate hazards could put millions of lives, physical capital, and natural capital at risk

As climate hazards manifest, they directly create and amplify socioeconomic risk as they impact exposed people, physical and natural capital. In this geospatial analysis, as elsewhere in this report, we assess the nature of inherent risk—that is, risk not adjusted for adaptation response—experienced across countries using our five-systems framework. We do not attempt to calculate global adaptation costs, which others have estimated (see Box 3, "Estimates of adaptation costs").

Box 3

Estimates of adaptation costs

While we have focused on potential adaptation measures in the case studies in this research, we have not attempted to size the cost of adaptation globally. Organizations that have sought to estimate adaptation spending in the next few decades include the UN Environment Programme (UNEP) and the Global Commission on Adaptation (GCA). In 2016, UNEP identified adaptation costs of $140 billion to $300 billion per year for developing countries, rising to $280 billion to $500 billion annually by 2050.[1]

In 2019, the GCA calculated necessary adaptation investments between 2020 and 2030 of $1.8 trillion, equivalent to less than 1 percent of projected total gross fixed capital formation in the period.[2] The calculated investments comprise strengthening early warning systems, making new infrastructure resilient, improving dryland agriculture crop production, protecting mangroves, and making water resources management more resilient. Adaptation investment can not only help reduce risk, but also result in other benefits. The GCA identified three categories of benefits from adaptation: avoided losses of lives and assets, for example as a result of early-warning systems for storms or heat waves; positive economic benefits, for example reduced flood risk in urban areas leading to broader economic investments; and social and environmental benefits, for example as a result of coastal protection measures such as green spaces for flood protection, which in turn improve community cohesion and quality of life.

While these are global estimates, it is important to note that adaptation costs are ultimately incurred at a local level, by individual countries, communities, or companies, and financing of adaptation may be challenging depending on specific economic conditions.

---

[1] Anne Olhoff et al., *The adaptation finance gap report,* UNEP DTU Partnership, 2016.

[2] Manish Bapna et al., *Adapt now: A global call for leadership on climate resilience*, Global Commission on Adaptation, September 2019.

As in our cases, our estimates are primarily statistically expected outcomes in an average year. In any given year, outcomes could be better or worse than this average, an important factor to understand for risk management. We therefore also illustrate “tail” outcomes with select examples.[153]

As stocks of human, physical, and natural capital are directly affected by a changing climate, this would also affect GDP. While we do not attempt to quantify the total impact of climate change on global GDP, we do include a discussion of the short-run impacts on the level of GDP from outdoor working hours lost due to extreme heat and humidity and the impact of yield failure.[154] Beyond direct impacts, destruction of stocks of physical, human, and natural capital could have longer-term effects on GDP which we do not include or estimate (see Box 4, “Why we have not made an estimate of the impact of climate change and adaptation on global GDP”). Note also that our assessment of short-run GDP effects primarily focuses on the implications on directly affected sectors, and in some cases connected sectors, but does not consider systemic knock-on effects that could occur as the impact manifests (for example, the impact on financial markets, migration, etc.).

We highlight findings about potential global impacts from physical climate risk over the 30 years to 2050 below and explore the range of impacts in more detail thereafter:

— In our inherent risk assessment under an RCP 8.5 climate scenario, the number of people living in areas having non-zero annual likelihood of heat waves that exceed the threshold for survivability for a healthy human being in the shade is projected to rise from essentially zero today to 250 million to 360 million by 2030. By 2050, that figure could rise further to between 700 million and 1.2 billion people. Both numbers do not factor in air conditioner penetration. Today, air conditioner penetration is roughly 10 percent across India, and roughly 60 percent across China.[155] The ranges here are based on different population projections for different countries, which influence how many people live in at-risk regions.[156] The increase is significant in part because the hottest and most humid parts of the world tend to be among the most heavily populated, and these areas are becoming even hotter and more humid. For the people living in these regions, the average annual likelihood of experiencing such a heat wave is projected to rise to 14 percent by 2050; however, some regions are expected to have higher probability, and some regions lower. This means that the cumulative average likelihood of a person living in an at-risk area to experience such a heat wave at least once over a ten-year period centered on 2050 is estimated to be 80 percent.[157]

---

[153] It is important to note that such tail impacts cannot be meaningfully added together. Because these are unlikely “tail” events, the probability of more than one of these events occurring in the same year is very small. For example, the likelihood of two (independent) events of 1 percent probability occurring in the same year is 0.01 percent.

[154] This discussion excludes a variety of hazards and their impacts. They include lethal heat waves, water scarcity, sea-level rise, extreme precipitation, hurricanes, chronic heat and disease vector impact on human health, and forest fires. GDP at risk includes both direct effects and immediate knock-on effects, which are calculated using input-output multipliers.

[155] India Cooling Action Plan Draft, Ministry of Environment, Forest & Climate Change, Government of India, September 2018; The Future of Cooling in China,” IEA, Paris, 2019.

[156] Range is based on the range of population projections from the UN World Population Prospects and the UN World Urbanization Prospects, to bound population growth based on high and low variants, and based on urban and total population growth rates. We assume the spatial composition within a country of population remains the same as today, given data availability on geospatial population footprint.

[157] As noted in Chapter 2, lethal heat waves are defined as a three-day period with average daily maximum wet-bulb temperatures exceeding 34 degrees Celsius wet-bulb. The current lethal heat wave risk is restricted to a small area along the Pakistan-India border. Because of the high atmospheric aerosol concentrations there, a cooling effect is created, such that there is no impact today. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance. Cumulative likelihood calculated for the decade centered on 2030 and 2050 by using annual probabilities for the climate state in the 2030 period and the 2050 period, respectively. Annual probabilities are independent and can therefore be aggregated to arrive at a cumulative decadal probability. This calculation is a rough approximation as follows: it assumes that the annual probability of X percent applies to every year in the decade centered on 2030 or 2050. We first calculate the cumulative probability of a heat wave not occurring in that decade, which is 1 minus X raised to the power of 10. The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number. Analysis based on an RCP 8.5 scenario.

- The global average share of annual outdoor working hours potentially lost due to extreme heat and humidity in exposed regions could almost double by mid-century, from 10 percent today to 10 to 15 percent by 2030 and 15 to 20 percent by 2050. This workability impact occurs because more regions of the world are exposed to heat stress and because the regions that are exposed are projected to see higher intensity of heat stress. The ranges here are based on whether the "average" year manifests, or a colder than average or hotter than average period occurs.

- As outdoor working hours are affected, this has an impact on GDP. We consider the share of GDP in climate-exposed regions that could be lost from decreased workability (that is, an impact on outdoor working hours from increased heat and humidity) in agriculture, construction, and mining. We find that could rise to 2 to 3.5 percent by 2050, representing $4 trillion to $6 trillion in GDP at risk in an average year.[158] This is up from 1.5 percent today. About a third of the countries examined could see 5 to 15 percent of GDP at risk in climate-exposed regions within them by 2050.

- Statistically expected damage to capital stock from riverine floods could double by 2030 and rise fourfold from today's levels by 2050; however, our estimates do not reflect the much larger impacts of other forms of flooding or other hazards (for example, tidal flooding, forest fires, and storm surge) given the challenges of modeling such an analysis globally.[159] The statistically expected damage to capital stock from riverine floods as a percentage of capital stock in climate-exposed regions could increase from 0.15 percent today to 0.25 percent in 2050. This is the equivalent of an increase from $35 billion per year to $140 billion per year.

- Share of time spent in drought over a decade across the 105 countries is expected to rise by 25 percent, from 8 percent today to 10 percent by 2050, according to our inherent risk assessment.[160]

- Global agriculture yields could be subject to increased volatility, with a skew toward worse outcomes. The cumulative likelihood over a decade of at least one year with a greater than 10 percent annual increase in global yields occurring once in the decade could rise from zero percent today to 45 percent in the decade centered on 2050. At the same time, the cumulative likelihood of at least one year with a greater than 10 percent decrease occurring would increase from 45 percent today to 90 percent in that time.[161] As we discuss below, these trends are not uniform across countries. While some could see improved agricultural yields, others could suffer negative impacts.

- With temperature increases and precipitation changes, the biome in parts of the world is expected to shift.[162] In our inherent risk assessment, the land area experiencing a shift in climate classification compared with a 1901–25 baseline is projected to increase from about 25 percent today to roughly 45 percent by 2050 (an increase from 30 million square kilometers today to 55 million square kilometers in 2050 in absolute terms).

---

[158] The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions.

[159] This analysis assumes sufficient adaptation against current 50- to 100-year flooding events. Choice of adaptation levels were based on Paolo Scussolini, "FLOPROS: an evolving global database of flood protection standards," *Natural Hazards and Earth Systems Sciences*, May 2016, Volume 16 and Philip J. Ward et al., "Assessing flood risk at the global scale: model setup, results, and sensitivity," *Environmental Research Letters*, October 2013, Volume 8.

[160] Modeled by WHRC using the median projection of 20 CMIP5 GCMs, using the self-correcting Palmer Drought Severity Index (PDSI). Projections were corrected to account for increasing atmospheric CO_2 concentrations.

[161] Global yields based on an analysis of six global breadbaskets that make up 70 percent of global production of four crops: wheat, soy, maize, and rice. Cumulative likelihood calculated for the decade centered on 2030 and 2050 by using annual probabilities for the climate state in the 2030 period and the 2050 period, respectively. Annual probabilities are independent and can therefore be aggregated to arrive at a cumulative decadal probability. Yield anomalies here are measured relative to the 1998–2017 average yield. Yield anomalies here are measured relative to the 1998–2017 average yield.

[162] We have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome. For example, tropical rainforests exist in a particular climatic envelope that is defined by temperature and precipitation characteristics. In many parts of the world, this envelope could begin to be displaced by a much drier "tropical savannah" climate regime that threatens tropical rainforests. Data taken from Franz Rubel and Markus Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift*, April 2010, Volume 19, Number 2.

Box 4

Why we have not made an estimate of the impact of climate change and adaptation on global GDP

Estimating the full consequences of climate change for the global economic system is extremely challenging. As discussed earlier, there are many uncertainties, in particular with quantifying the second-order implications of the direct physical damages from a changing climate. Conceptually, economists treat climate as they do other assets, in terms of economic value. A depreciation of the value of this asset entails substantial consequences for the economic activity and well-being of the current as well as future generations.

Researchers have taken a variety of approaches in their attempts to quantify the GDP impacts of climate change and, in a related field, quantify the economic impact of natural disasters. These have broadly fallen into various forms of "macro" assessments or "micro" assessments.[1]

The most prominent macro approach includes integrated assessment models or IAMs that seek to integrate climate models with economic modeling by using "damage functions" relating temperature to impacts on capital stock. IAMs can produce estimates of a total value-at-risk of between 3-10 percent of GDP by the end of the century, under a business-as-usual scenario.[2] Such models have been critiqued for three reasons. Firstly, and most importantly, the damage functions used to estimate impact are generally arbitrarily chosen functions fit to limited empirical evidence. Secondly, they tend to explicitly assume that damages only impact output and do not interact with endogenous drivers of growth like investment. Thirdly, they largely do not simulate financial systems nor other important sources of second-order impact or risk contagion, including migration, loss of life, and conflict.[3]

A second macro approach has involved using econometric assessments of historical climate hazard data (typically temperature and precipitation), and then applying that assessment to explore future outcomes. Burke, Hsiang, and Miguel (2015) used econometric approaches to demonstrate that overall economic activity is a nonlinear function of temperature for all countries, with productivity peaking and then declining strongly at higher temperatures. This trend was found to be globally generalizable, unchanged since 1960, and apparent for agricultural and non-agricultural activity in both rich and poor countries. Based on these findings, the authors project that 10 to 60 percent of global GDP could be at risk by the end of the century under an RCP 8.5 scenario.[4] An alternate econometric approach by Kahn et al. (2019) finds a value more in line with IAM estimates, at roughly 7 percent of global GDP at risk by end-of-century, and a third approach by Colacito et al. (2018) estimates up to 33 percent of GDP at risk for the United States by end-of-century.[5] The main source of difference across these approaches stems from their assumptions about how economic activity responds to temperature.

A third macro approach ties IAM damage functions at low levels of warming together with the physical science of high-warming outcomes, assuming GDP damages tending toward 100 percent above certain thresholds of warming. For example, at a 10- to 12-degree Celsius increase in global average temperatures, most of the world's surface would have persistent summer temperatures above the habitability threshold for a healthy human being.[6] Using this approach, Weitzman (2012), Dietz and Stern (2014), and Covington and Thamotheram (2015) find economic damages ranging between 10 and 50 percent of global GDP by end-of-century under an RCP 8.5 scenario.[7]

---

[1] W. J. Wouter Botzen, Olivier Deschenes, and Mark Sanders, "The economic impacts of natural disasters: A review of models and empirical studies," *Review of Environmental Economics and Policy*, Summer 2019, Volume 13, Number 2.

[2] Roberto Roson and Dominique van der Mensbrugghe, "Climate change and economic growth: impacts and interactions," *International Journal of Sustainable Economy*, 2012, Volume 4, Issue 3; Frank Ackerman et al., "Fat tails, exponents, extreme uncertainty: Simulating catastrophe in DICE," *Ecological Economics*, 2010, Volume 69, Issue 8; Tom Kompas et al., "The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord," *Earth's Future*, July 2018, Volume 6, Issue 8; Nicholas Stern, *The economics of climate change: the Stern review.* Cambridge, UK: Cambridge University Press, 2007.

[3] Simon Dietz and Nicholas Stern, *Endogenous growth, convexity of damages and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions*, Grantham Research Institute on Climate Change and the Environment, June 2014; J. Doyne Farmer et al., "A third wave in the economics of climate change," *Environmental and Resource Economics,* 2015, Volume 62, Number 2.

[4] Marshall Burke, Solomon M. Hsiang, and Edward Miguel, "Global non-linear effect of temperature on economic production," *Nature*, November 2015, Volume 527, Number 7577.

[5] Matthew E. Kahn et al., *Long-term macroeconomic effects of climate change: A cross-country analysis*, Federal Reserve Bank of Dallas, Globalization Institute Working Paper 365, July 2019; Riccardo Colacito et al., *The impact of higher temperatures on economic growth,* The Federal Reserve Bank of Richmond, North Carolina, Economic Brief EB18-08, August 2018.

[6] Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress." *Proceedings of the National Academy of Sciences*, May 25, 2010, Volume 107, Number 21.

[7] Simon Dietz and Nicholas Stern, *Endogenous growth, convexity of damages and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions*, Grantham Research Institute on Climate Change and the Environment, June 2014; Howard Covington and Raj Thamotheram, "The case for forceful stewardship (Part 1): The financial risk from global warming," *SSRN*, January 19, 2015; Martin L. Weitzman, "GHG targets as insurance against catastrophic climate damages," *Journal of Public Economic Theory*, March 2012, Volume 14, Number 2.

The wide ranges in the magnitude of GDP at risk established by these approaches reflect the high degree of uncertainty involved, primarily related to how economic systems will respond to changing climate hazards. To some degree, they also reflect assumptions related to an adaptation response and the evolution of climate hazards by the turn of the century. Many advances at the micro level have been made to address this uncertainty and better understand how specific aspects of climate change affect components of the economic system. The aim is to improve economic modeling from an understanding of the mechanisms by which climate change affects socioeconomic systems.[8]

Our research seeks to take such a step. Our case studies aim to shed light on the mechanisms by which a changing climate can affect socioeconomic systems. Translating those mechanisms to a global GDP-at-risk number is extremely challenging for all the reasons described above. We have therefore focused here on highlighting the nature of GDP implications as well as the magnitude of short-run GDP at risk for a subset of hazards.

While our case studies describe in more detail how GDP is affected by climate change for each individual hazard, region, and sector studied, some findings across our cases are worth noting. First, we find that the direct impacts of climate change are on the stocks of human, physical, and natural capital. Together, such stocks represent the productive capacity of economies. The impairment of these stocks could in turn have substantial effects on GDP (the economic flows that derive from stocks of capital). The compounding effect of diminished productive capacity over multiple years could potentially be significant. However, more research is needed to estimate how large the long-term effects could be.[9] For example, in the short term, having to rebuild and replace damaged stock could stimulate GDP. In the long term, however, this may act as a drag on GDP growth, if it diverted funds from other investment opportunities (for example, replacing existing damaged structures rather than investing to expand productive capacity or develop new technologies). Alternately, if new investments are made with a focus on adaptation, resilience, and integrating new technologies into new capital stock, this could help boost GDP growth.[10]

Second, we find that impacts to GDP could occur through both supply- and demand-side effects. On the supply side, we find that a changing climate could have direct impacts on labor and capital productivity, and it could also destroy capital stock, diminishing capital services derived from such stock. There could also be knock-on effects on demand. For example, home owners might reduce consumption if their wealth were affected by a fall in real estate prices due to expectations of climate change.[11] Falling property prices could also reduce government tax revenue, with repercussions on government spending.

Third, our cases and global geospatial analysis demonstrate the spatial nature of climate risk. This means that the GDP at risk in specific regions may be significantly higher than in other regions, and significantly higher than a global average. On the flip side, some regions may see much lower-than-average risk, and in some respects like agricultural yields, may even stand to benefit.

As economists have evaluated the economic consequences of climate change, the costs of mitigating and adaptation measures are compared to the benefits arising from the expected reduction in damages result from climate-change. This comes with a number of issues. Firstly of course is assessing the damage functions and costs arising from climate change, as discussed above.[12] Secondly, costs and benefits are defined relative to the preferences of individuals, which might be highly diverse, and which need to be evaluated over time. A key parameter in this debate is the discount rate to be applied to assess the overall implications of a changing climate over time and the level of burden sharing to be achieved between today's consumers and producers and future generations.[13] Identifying an appropriate discount rate is another much debated topic in the climate debate, but out of scope for this report.[14]

---

[8] *The economic risks of climate change in the United States,* Risky Business, 2019; *The price of climate change: Global warming's impact on portfolios*, BlackRock, October 2015.

[9] Jeroen Klomp and Kay Valckx, "Natural disasters and economic growth: A meta-analysis," *Global Environmental Change*, May 2014, Volume 26, Number 1.

[10] Mark Skidmore and Hideki Toya, "Do natural disasters promote long-run growth ?" *Economic Inquiry,* October 2002, Volume 40, Number 4.

[11] Daniel Cooper and Karen Dynan, "Wealth effects and macroeconomic dynamics," *Journal of Economic Surveys*, February 2016, Volume 30, Number 1.

[12] See Gilbert E. Metcalf and James H. Stock, "Integrated Assessment Models and the Social Cost of Carbon: A Review and Assessment of U.S. Experience," *Review of Environmental Economics and Policy*, Volume 11, 2017.

[13] Christian Gollier and James K. Hammitt, "The Long-Run Discount Rate Controversy," *Annual. Review of Resource Economics*, April 2014, Volume 6; Thomas Sterner and Efthymia Kyriakopoulou, "(The Economics of) Discounting: Unbalanced Growth, Uncertainty, and Spatial Considerations," *Annual. Review of Resource Economics*, Volume 4, 2012.

[14] See for example, Mark C. Freeman and Ben Groom, "How certain are we about the certainty-equivalent long term social discount rate?" Journal of Environmental Economics and Management, Volume 79, September 2016; Moritz A. Drupp et al., "Discounting discounted," *American Economic Journal: Economic Policy*, Volume 10 Number 4, November 2018.

Livability and workability

As discussed in the India case, parts of South Asia are projected to become some of the first places over the coming decades to experience heat waves that surpass the survivability threshold for a healthy human being over the coming decades.[163] We find a similar trend in other regions. Under an RCP 8.5 scenario, we find that by 2030, the number of people living in regions with a greater than zero percent annual probability of a lethal heat wave is projected to increase from negligible today to between about 250 million and 360 million, without factoring in air conditioner penetration. Today, air conditioner penetration is roughly 10 percent across India, and roughly 60 percent across China.[164] This dramatic increase in exposed regions, and thus population, is due to the sharp right-hand tail of the distribution of wet-bulb temperatures. It takes a significant rightward (that is, higher) shift of the distribution of wet-bulb temperatures before lethal heat waves are possible, but once they become possible, the annual probability increases rapidly. The most heavily populated areas of the world are usually also among the hottest and most humid, and these areas are becoming even hotter and more humid.

For the 2030 period under an RCP 8.5 scenario, the average annual probability of a lethal heat wave occurring is estimated to be roughly 9 percent across exposed regions (that is, regions with a non-zero annual likelihood of such heat waves). Because this is an average number across regions, some regions have higher probabilities and others have lower.[165] The average probability of a person living in an at-risk region experiencing such a lethal heat wave occurring once in the decade centered on 2030 is estimate to be approximately 60 percent.[166] By 2050, the number of people living in regions experiencing a non-zero likelihood of such heat waves is projected to increase to between 700 million and 1.2 billion people, again without factoring in air conditioner penetration. People living in such regions are projected to have an average 14 percent annual probability of experiencing a lethal heat wave or a roughly 80 percent cumulative likelihood of experiencing such a heat wave at least once over a decade centered 2050.

As discussed in our India case, heat and humidity could also affect labor productivity, with workers needing to take more breaks and the human body naturally limiting its efforts to prevent over-exertion. We measure this effect by considering the effective working hours that could be at risk due to extreme heat and humidity in climate-exposed regions, a measure of impacts on workability.[167] We consider an "average year," predicted based on the mean of 20 climate models, as well as years that are "hotter and more humid than average" and "colder and less humid than average."[168] Considering the impact on workability, we find that today, about 10 percent of working hours are at risk globally due to conditions that reduce labor productivity in heat- and humidity-exposed regions. This is expected to rise to between 10 and 15 percent by 2030 and 15 to 20 percent by 2050, with the range reflecting the variation across years of different heat and humidity.

---

[163] See the discussion of how we define lethal heat waves in Chapter 2. If a non-zero probability of lethal heat waves in certain regions occurred in the models for today, this was set to zero to account for the poor representation of the high levels of observed atmospheric aerosols in those regions in the CMIP5 models. High levels of atmospheric aerosols provide a cooling effect that masks the risk. See India case for further details. This analysis excludes grid-cells where the the likelihood of lethal heat waves is <1 percent, to eliminate areas of low statistical significance.

[164] This estimate does not take into account current or future air-conditioning protection, and therefore should be viewed as an upper bound for exposure. India Cooling Action Plan Draft, Ministry of Environment, Forest & Climate Change, Government of India, September 2018; The Future of Cooling in China", IEA, Paris, 2019.

[165] We calculate the average annual probability in climate-exposed geographies by first calculating the number of people that live in any part of the world with a greater than zero probability of a lethal heat wave occurring. We then calculate, for each geospatial grid-cell with a non-zero probability of lethal heat wave occurrence, the product of the probability of the lethal heat wave occurring and the number of people in that grid-cell. The average annual probability of a lethal heat wave in climate-exposed geographies is then the division of those two numbers.

[166] This calculation is a rough approximation. It assumes that the annual probability of X percent applies to every year in decade centered around 2030. We first calculate the cumulative probability of a heat wave not occurring in the 2030 decade, which is 1 minus X percent raised to the power 10. The cumulative probability of a heat wave occurring at least once in the decade is then 1 minus that number. A similar approach is followed for the 2050 cumulative likelihood.

[167] This is the statistically expected number of hours that are lost in an average year. We consider the probability of different wet-bulb temperatures occurring, and the labor capacity lost at each temperature. See India case and technical appendix for details.

[168] Such years are calculated by looking at the 25th and 75th percentile ensemble projection.

As discussed in our India case, the slowdown in working hours and labor productivity will also affect output in outdoor-based sectors. For this geospatial analysis, we focus on the impact on three outdoor-based sectors: agriculture, construction, and mining.[169] The effective hours available to work outdoors are reduced, which in turn—without adaptation action—would affect output of such sectors. This could then have knock-on effects on connected sectors. We looked at how GDP in our sample of 105 countries could be affected as a result. Given that these effects are spatially defined, we look at the impact of these effects on local economic activity in climate-exposed regions (here, this means heat- and humidity-exposed regions where wet-bulb temperatures are expected to rise).

Across countries, we find that about 2 to 3.5 percent of GDP in climate-exposed regions could be at risk from decreased workability in specific sectors by 2050. This includes both the direct impact on relevant sectors and the knock-on effect on connected sectors.[170] In an average year, between $4 trillion and $6 trillion in GDP could be at risk in 2050, up from about 1.5 percent today.[171] The pace of sectoral shifts in national economies will strongly influence GDP outcomes and drive the range in the GDP at risk. In many of the regions most exposed to impacts on labor productivity from heat, including India and Pakistan, a significant share of GDP currently derives from outdoor sectors like agriculture. If this share is reduced, less of the GDP of these countries will be at risk. We also find that there is a slightly greater skew downward on the range of potential impact: the GDP impact from heat and humidity in a colder-than-average year could be $600 billion to $950 billion lower than in the average year, while the impact of a hotter-than-average year could be $300 billion to $500 billion higher.[172]

Impacts also vary significantly across countries, based on their exposure to heat and humidity as well as the sectoral makeup of their economies. Over time, we find that the share of GDP at risk from workability impacts is expected to increase in affected regions, and that more regions could be affected (Exhibits 22 and 23). For example, about a third of the countries we looked at could see 5 to 15 percent of GDP at risk in climate-exposed regions within them by 2050.

Finally, as discussed in Chapter 2, water supply could also be affected across countries.[173] This has consequences for water stress, the ratio of water demand to water supply. Assuming that demand for water stays at today's levels, we found that, by 2050, 48 countries would see an increase in water stress relative to today's levels, while 57 countries would see a decrease in water stress relative to today's levels.[174]

---

[169] See technical appendix for details on modeling approach.

[170] We consider the impact of reduced labor productivity and lost working hours on three sectors: agriculture, mining, and construction. It is possible that in some countries, those same factors could affect other sectors (for example, labor-intensive manufacturing). We used backward multipliers from input-output tables to arrive at those knock-on effects.

[171] The lower end of the range assumes that today's sectoral composition persists, while the higher end is based on projections from IHS Markit Economics and Country Risk on sectoral transitions and GDP increases. The dollar impact is calculated by multiplying the share of hours lost in outdoor sectors with GDP in these sectors (this assumes that such consensus projections do not factor in losses to GDP from climate change).

[172] We have previously described the skew of uncertainties in climate models to be upward, or toward worse outcomes; it is more likely that CO_2 causes more warming globally than we are estimating, rather than less. However, this relationship does not necessarily hold when evaluating specific climate hazards that are influenced by that warming. For example, it does not hold when evaluating wet-bulb temperatures, whose upper bound is constrained by physics. As humidity rises, atmospheric dynamics entails that, beyond a certain point, the moisture in the air precipitates as rain. As a result, there is more "room to maneuver" on the lower bound than on the upper bound. This means that, assuming the global temperature increase modeled by the RCP 8.5 scenario is correct, uncertainty about wet-bulb temperatures skews toward the lower outcome. However, the global temperature increase has considerable upward uncertainty, and therefore the 75th-percentile outcomes could be more likely given a more aggressive change in global temperatures.

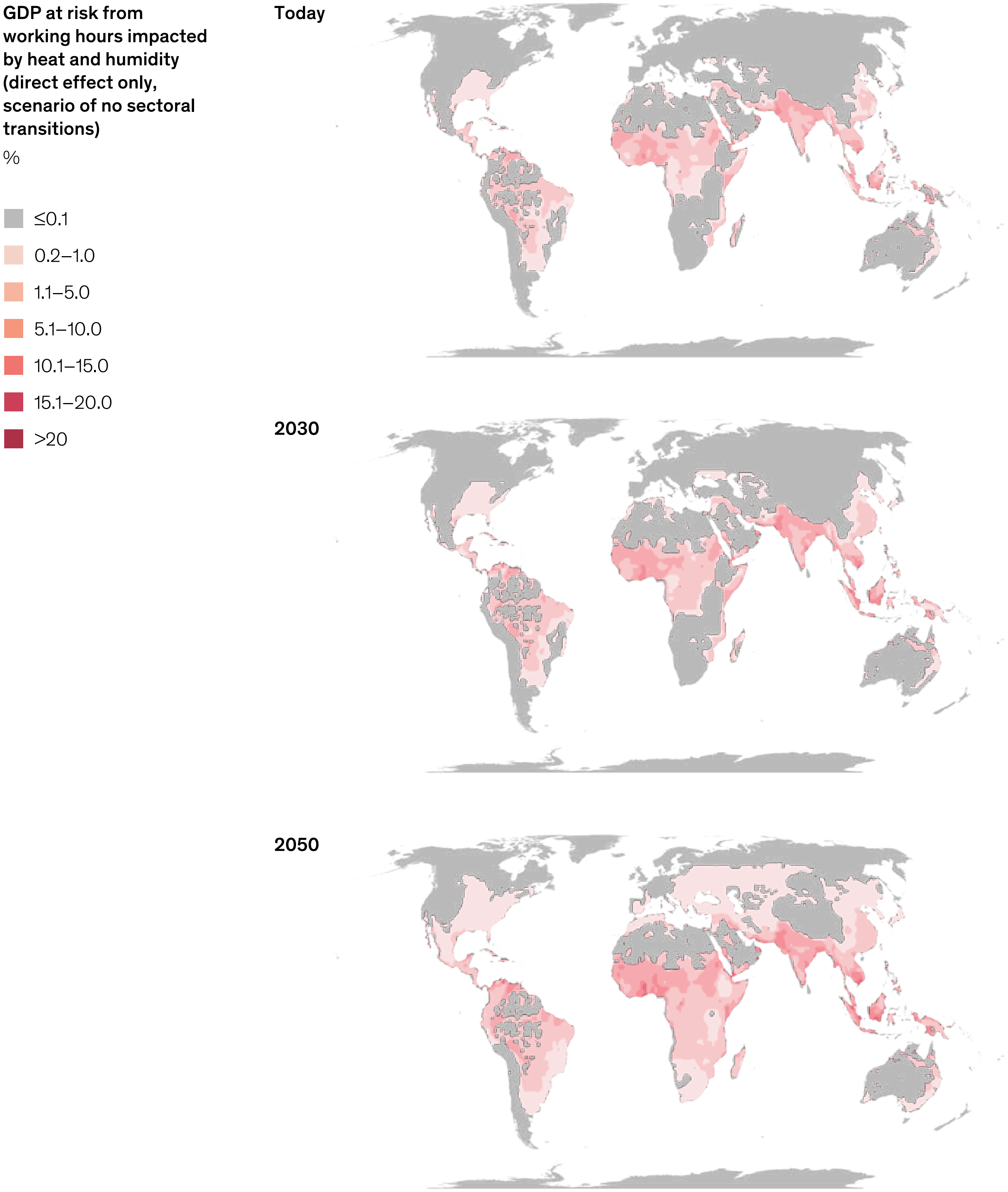
[173] Based on data from the World Resources Institute Water Risk Atlas (2018), which relies on six underlying CMIP5 models..

[174] We have assumed water demand is constant to allow us to isolate the impacts of a change climate only on water stress, and not the impacts of increased population and GDP growth.

Exhibit 22

GDP at risk from the effect of extreme heat and humidity on effective working hours is expected to increase over time.

Based on RCP 8.5



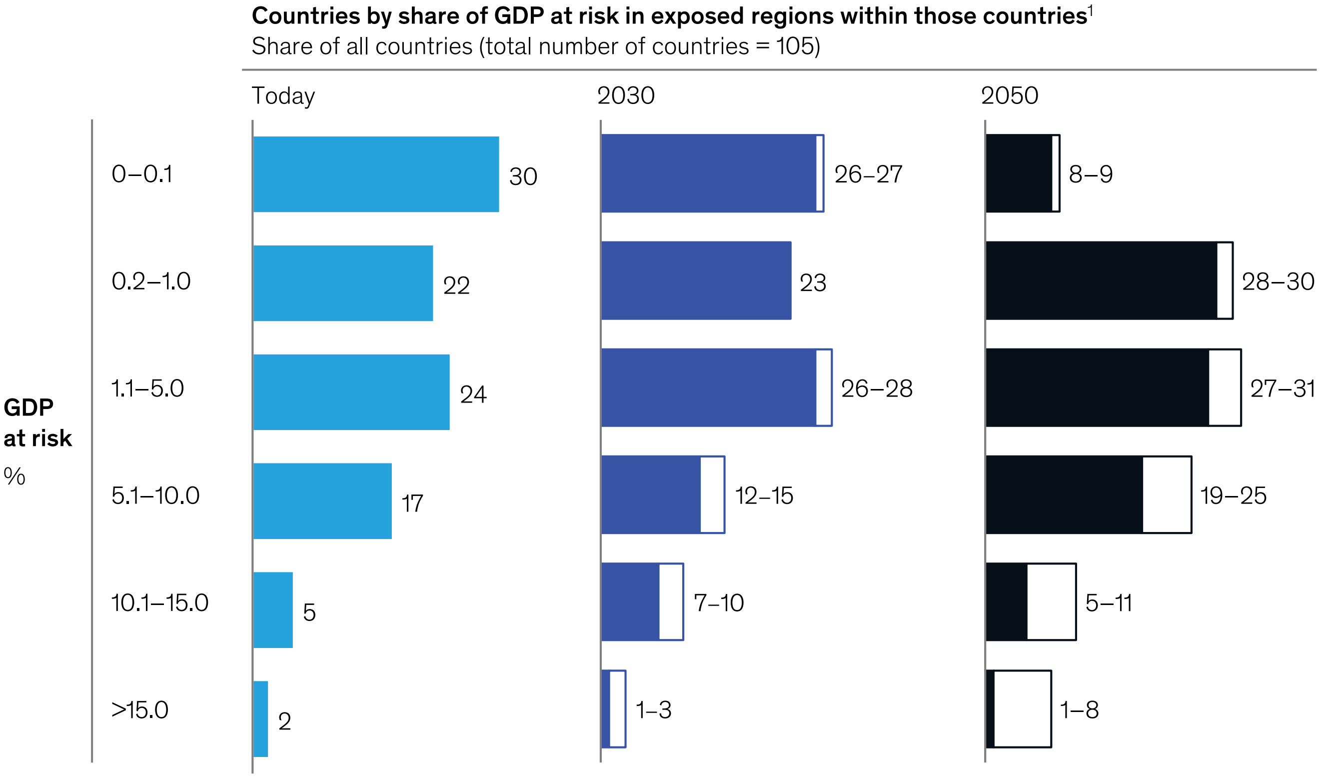
Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. These maps do not consider sectoral shifts when projecting impact on labor productivity into the future—the percentage and spatial distribution of outdoor labor are held constant. For this analysis, outdoor labor is considered to include agriculture, construction, and mining and quarrying only, and knock-on impacts on other sectors are not considered. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: IHS Markit Economics and Country Risk; Woods Hole Research Center; McKinsey Global Institute analysis

Exhibit 23

Countries already at risk will see a further increase in heat and humidity risk to GDP from reduced effective working hours by 2030 and 2050, while other countries will be exposed to risk for the first time.

Based on RCP 8.5



1. Defined as risk from change in share of outdoor working hours affected by extreme heat and humidity in climate-exposed regions annually. Heat and humidity reduce labor capacity because workers must take breaks to avoid heatstroke and because the body naturally limits its efforts to prevent over-exertion.

Note: See the technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi-model ensemble. Heat data bias corrected. This analysis assumes that the spatial distribution of outdoor labor are held constant over time. For this analysis, outdoor labor is considered to include agriculture, construction, and mining and quarrying only, and knock-on impacts on other sectors are not considered. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: IHS Markit Economics and Country Risk; Woods Hole Research Center; McKinsey Global Institute analysis

Food systems

Expanding on the approach of our breadbasket case, we consider the impact of climate change on global and regional yields in the production of four crops: rice, wheat, corn (maize), and soy.[175] The UN's Food and Agriculture Organization estimates that the global annual production of these four crops today is 3.6 billion tonnes. With the changing climate, volatility is expected to increase. This will drive an increase in both risk of years with unusually low global production and the likelihood of unusually abundant bumper crop years. As discussed in the global breadbasket case, the likelihood of yield failures is expected to go up. The annual probability of a global greater than 10 percent reduction in yield in a given year is expected to increase from 6 percent today to 11 percent in 2030.[176] In other words, the cumulative probability of such an event occurring at least once in the decade centered around 2030 is about 70 percent. At the same time, the annual probability of a global greater than 10 percent

---

[175] Here, we follow a somewhat different approach than for other risk measures. Rather than doing this analysis across all 105 countries, we selected the largest producing breadbasket regions in each continent and analyzed changes to those regions. This was done because the AgMIP project, which is the underlying set of climate models used for this assessment, was designed to investigate global or regional changes in agricultural output, and not to do highly geospatially specific country-level analyses.

[176] Yield increases and decreases here are compared to average yield between 1998 and 2017.

increase in yield in a given year is not expected to change meaningfully between now and 2030. By 2050, the annual probability of a greater than 10 percent reduction in yield in a given year is expected to further increase to about 20 percent (or, is expected to occur a 90 percent cumulative probability once in the decade centered around 2050) while the probability of a greater than 10 percent increase in yield in a given year is expected to increase to 6 percent (or, has about a 45 percent chance of occurring once in the decade centered around 2050).

Thus, our analysis suggests variability in both good and bad outcomes, although the volatility is likely to be skewed toward worse outcomes. These shifts in agricultural output will affect agricultural GDP. The tail GDP risk would increase over time as the likelihood of a global reduction in production increases; moreover, the impact of diminished agricultural production could also have knock-on effects through the economy, affecting food prices, consumption, and downstream industries, as discussed in the breadbasket case.

Global findings also hide heterogenous regional trends: some regions are projected to experience increases in statistically expected yields, while others are projected to experience decreases. All regions are projected to experience an increase in volatility, but in some regions that volatility would be skewed toward better outcomes, while in other regions the skew would be toward worse outcomes. While we were not able to exhaustively investigate all regions, we were able to identify some differing regional trends in the large producing parts of the world. For example:

— **North America.** The United States on average is expected to experience net-negative consequences, with statistically expected yields decreasing and volatility skewed toward worse outcomes. By contrast, Canada is expected to see sharp increases in statistically expected yields. The United States is expected to see a greater than 10 percent decrease in statistically expected yields by 2050 compared with the 1998–2017 period, with the annual probability of a greater than 10 percent decrease in yield in a given year increasing from 20 percent today to 50 percent by 2050. The annual probability of a bumper year with a greater than 10 percent increase in yields relative to the 1998–2017 baseline is expected to increase from 0 percent to 6 percent. Canada is expected to see a 50 percent increase in statistically expected yields by 2050 relative to 1998–2017. The annual probability of a greater than 10 percent decrease in yields in a given year is expected to decrease from 16 percent today to 0 percent by 2050, and the annual probability of a greater than 10 percent bumper crop year is expected to increase from 17 percent today to 98 percent by 2050.

— **South America.** South America is a climatologically diverse continent that experiences different agricultural outcomes in different regions. The largest single producer in the region is Brazil. Like the United States, Brazil is expected to suffer net-negative agricultural consequences from climate change, with both decreasing statistically expected yields and volatility skewed toward worse outcomes. Specifically, Brazil is expected to see a 3 percent decrease in statistically expected annual yields by 2050 relative to 1998–2017. The annual probability of a greater than 10 percent yield decline in a given year compared with a 1998–2017 baseline would increase from 3 percent today to 10 percent by 2050, whereas the probability of a 10 percent yield increase is not expected to change meaningfully.

— **Europe.** Europe and western Russia could together experience net agricultural benefits as a result of climate change, with increasing statistically expected yields, and an increase in volatility skewed toward more positive outcomes. However, risk of yield failures does increase through to 2050, and there are many differences within the region. The aggregate region of Europe and Russia is expected to experience a 4 percent increase in statistically expected yields by 2050 relative to 1998–2017. The annual probability of a greater than 10 percent yield failure compared with a 1998–2017 baseline would increase from 8 percent to 11 percent by 2050, while the annual probability of a bumper year with a greater than 10 percent yield increase would rise from 8 percent to 18 percent by 2050.

— **Asia–Pacific.** China is expected to be an agricultural net beneficiary from climate change over the near term, with increasing statistically expected yields and volatility skewed toward positive outcomes. India, on the other hand, is expected to experience a net-negative agricultural impact from climate change. China could see expected yields increase by about 2 percent by 2050 relative to 1998–2017. The annual probability of greater than 10 percent breadbasket failure relative to a 1998–2017 baseline would decrease from 5 percent to 2 percent by 2050, while the annual probability of a bumper year with a greater than 10 percent increase in yield would increase from 1 percent to approximately 12 percent by 2050. India is expected to experience a 7 percent decrease in statistically expected crop yields by 2050, while the annual probability of a greater than 10 percent decrease in yields in a given year would increase from 10 percent to 40 percent by 2050. The annual probability of greater than 10 percent increase in yields in a given year would decrease from 3 percent to 0 percent over the same period.

Physical assets and infrastructure services

As we found in our cases, assets can be destroyed or service from infrastructure assets disrupted by a variety of hazards including flooding, forest fires, hurricanes, and heat. Take flooding, for example. There are various forms of flooding, including riverine floods, flash floods, storm surge, and tidal flooding, all of which could damage capital stock. Due to data limitations, we were unable to examine the impacts of each of these on capital stock globally, but we specifically look at the impact of one hazard—riverine flooding—to illustrate how global capital stock could be affected by rising climate hazards.[177] The approach we take in our cases assesses the evolution of hazard severity and frequency and then overlays that with data on capital stock exposure and capital stock resilience.

Estimating capital stock damage from flooding is highly complex, and the numbers we give here should be taken as directional in their assessment of risk rather than as precise estimates.[178] Moreover, it is important to recognize that such estimates are underestimates of the capital stock at risk of damage from a changing climate, since this represents only one specific hazard. Nonetheless, some important trends emerge. First, the growth in statistically expected damage to capital from riverine flooding is expected to rise steeply, from about $35 billion of capital stock every year globally today to about $60 billion by 2030 and $140 billion by 2050.[179] This represents a 1.7-fold increase between today and 2030, and a fourfold increase between today and 2050. Impacts could be significantly higher than these numbers suggest, depending on the specific form of capital affected, such as infrastructure. This leads to various knock-on effects, as discussed in our infrastructure case.

The numbers above represent statistical averages, and the impacts could be significantly higher in a given year if tail events manifest. This is similar to our finding in the Florida case, where our analysis shows that statistical average impacts on real estate from storm surge could increase from $2 billion to between $3 billion and $4.5 billion between today and 2050, but the impact of 1-in-100-year storm surge events is substantially higher and could increase from $35 billion today to between $50 billion and $75 billion by 2050, an increase of 40 to 110 percent.

---

[177] We chose to analyze riverine flooding due to ease of global data availability.

[178] This analysis is based on using riverine floodplain data from the World Resources Institute to identify today's floodplains and data on increases in precipitation frequency to evaluate how flooding hazards could evolve. This approach therefore should be considered to be only an approximation of the evolution of flooding hazard, and it should be noted that a robust analysis of flooding will require the use of granular flood models. Further limitations of this analysis include the focus on riverine flooding only (versus tidal, flash, or pluvial flooding, or flooding from storm surge), the ability to identify flood protections globally in a robust way and therefore adjust for today's level of adaptation, and the ability to identify damage functions for capital stock that are specific to an individual site, such as a given building or a factory, rather than rely on more general damage functions. See the technical appendix for modeling approach details.

[179] This was calculated by using geospatial data on capital stock from UN Global Assessment Report on Disaster Risk Reduction, assessing exposure of the capital stock to flood depths of different severity, and using regional vulnerability assessments from the European Commission Joint Research Center. We assume that capital stock today is adapted to withstand today's 50- and 100-year floods. We also assume capital stock increases going forward in line with today's ratio of GDP and capital stock and based on consensus GDP projections from IHS Markit Economics and Country Risk. However, we assume that the geospatial breakdown of capital stock remains as today, given data limitations on obtaining time series estimates on how the geospatial breakdown of capital stock varies.

Other researchers have attempted similar estimates for hurricane damage and its potential tail risks. For example, an analysis by the Cambridge Risk Studies Centre found that damage caused by a tail risk hurricane in the eastern United States could potentially be more than $1 trillion, because storms travel long distances and can make multiple landfalls. The Cambridge Risk Studies Centre classifies such a tail hurricane event as a 1-in-200-year event. This could begin as a normal tropical system of low-pressure clouds and thunderstorms, rapidly intensify upon entering the Gulf Stream, grow to a Category 4 hurricane in under six hours, then make landfall in Florida with sustained winds of over 147 miles per hour. It could move across the Gulf of Mexico and finally make second landfall near Santa Rosa Island, near Pensacola, but with lower sustained winds of 127 miles per hour and at Category 3 intensity. The Cambridge Risk Studies researchers expect recovery from the hurricane event would take around a year and personal consumption would dip to 83 percent in the first quarter after the disaster.[180] Climate change contributes to the frequency of such hurricanes, the Cambridge Risk Studies Centre finds.

Natural capital

With temperature increases and precipitation changes, the biome in many parts of the world is expected to shift. The biome refers to the naturally occurring community of flora and fauna inhabiting a particular region. For this report, we have used changes in the Köppen Climate Classification System as an indicative proxy for shifts in biome.[181] For example, tropical rainforests exist in a particular climatic envelope that is defined by temperature and precipitation characteristics. In many parts of the world this envelope could begin to be displaced by a much drier "tropical savannah" climate regime, putting tropical rainforests at risk of collapse. Today, 25 percent of the Earth's land area has already experienced a shift in climate classification compared with the 1901–25 period. By 2050, that number is expected to increase to roughly 45 percent. All countries and their local species would be affected to some degree, and in countries that rely on the natural environment, this could in particular affect ecosystem services and local livelihoods.

By 2030, every country could see an increase in one of our six indicators of potential impacts from a changing climate, with emerging economies facing the biggest increase

Taking together a country view of the six indicators of potential climate impacts we examine—the share of population living in areas experiencing a non-zero annual probability of lethal heat waves, the share of outdoor working hours affected by extreme heat and humidity, the annual demand of water as a share of annual supply of water, the share of time spent in drought over a decade, the annual share of capital stock at risk of riverine flood damage in climate-exposed regions, and the share of land surface changing climate classification—we find that all 105 countries we studied would see an increase in the potential direct impacts from climate change as indicated by at least one measure by 2030. This could then increase further to 2050, under an RCP 8.5 scenario and without adaptation. As noted earlier in the chapter, 16 countries could see an increase in three indicators by 2050 compared to today, while 44 countries see an increase in five of six indicators. Most countries are expected to see rising impacts for the annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions, annual share of capital stock at risk of flood damage in climate-exposed regions, and the share of land surface changing climate classification.

---

[180] *Impacts of severe natural catastrophes on financial markets*, Cambridge Centre for Risk Studies, 2018.

[181] Biome shift was measured using the Köppen climate classification system. The Köppen climate system divides climates into five main groups, with each group further subdivided based on seasonal precipitation and temperature patterns. This is not a perfect system for assessing the location and composition of biomes; however, these two characteristics do correlate very closely with climate classification, and therefore this was assessed as a reasonable proxy for risk of disruptive biome changes.

Broadly speaking, countries can be divided into six groups based on their patterns of change in direct impacts between now and 2050, under an RCP 8.5 scenario (Exhibits 24, 25, and 26).[182]

— **Significantly hotter and more humid countries.** Hot and humid countries such as India and Pakistan are expected to become significantly hotter and more humid by 2050. Countries in this group are near the equator in Africa, Asia, and the Persian Gulf. They are characterized by extreme increases in heat and humidity impacts, that is, the loss of workability (an average roughly ten-percentage-point expected increase in annual share of effective outdoor working hours lost to extreme heat and humidity in heat-exposed regions between today and 2050 across the countries in this group) and a decrease in water stress. The livability risk that countries in this group face is especially large, because of the combination of heat and humidity. The share of the population of the countries in this group exposed to a non-zero chance of lethal heat waves between now and 2050 is expected to rise by roughly ten percentage points, with some differences among countries.

— **Hotter and more humid countries.** This group includes the Philippines, Ethiopia, and Indonesia. These countries are typically between the equator and the 30-degree north and south lines of latitude. As with the previous group, they are characterized by an expected large increase in heat and humidity impacts to workability (with an average eight-percentage-point increase in annual share of effective outdoor working hours lost to extreme heat and humidity in climate-exposed regions between today and 2050 across the countries in this group), but likely do not become so hot or humid that they exceed livability thresholds. Water stress is also expected to decrease for these countries.

— **Hotter countries.** This group includes Colombia, the Democratic Republic of Congo, and Malaysia. Many countries in this group are near the equator. They are characterized by a large increase in heat and humidity impacts to workability (with an average eight-percentage-point increase in annual share of effective outdoor working hours lost to extreme heat and humidity between today and 2050), but do not become so hot or humid as to pass livability thresholds. This group of countries is not expected to grow wetter, and some countries in this group could even become substantially drier and see increased water stress.

— **Increased water stress countries.** This group includes Egypt, Iran, Mexico, and Turkey. In these locations, Hadley cells (the phenomenon responsible for the atmospheric transport of moisture from the tropics, and therefore location of the world's deserts) are expanding, and these countries face a projected reduction in rainfall, in an RCP 8.5 scenario.[183] Some of the countries in this group intersect the 30-degree north or south line of latitude. They are characterized by a potentially large increase in water stress (with an average expected increase of about 47 percentage points in water stress between today and 2050 for the countries in this group), drought frequency (average expected increase of about 11 percentage points of the share of time spent in drought over a decade), and among the largest increase in biome shift (average increase of about 27 percentage points in the share of land surface changing climate classification between today and 2050, as measured against a 1901—25 baseline.

---

[182] These patterns were primarily based on looking at indicators relating to livability and workability, food systems, and natural capital. The annual share of capital stock at risk of riverine flood damage in climate-exposed regions indicator was considered but was not found to be the defining feature of any country, grouping aside from a lower-risk group of countries..

[183] Daniel F. Schmidt and Kevin M. Grise, "The response of local precipitation and sea level pressure to Hadley cell expansion," *Geophysical Research Letters*, October 2017, Volume 44, Number 20.

- **Lower-risk increase countries.** This group includes Germany, Russia, and the United Kingdom. Many countries in this group lie outside the 30-degree north and south lines of latitude. They are generally cold countries and characterized by very low levels of heat and humidity impacts to workability (with an average 0.5-percentage-point increase in the annual share of effective outdoor working hours lost to extreme heat and humidity in climate-exposed regions, and no livability risk). Many are expected to see a decrease in overall impacts from indicators such as water stress or time spent in drought. As these countries grow warmer, one of the biggest changes they are likely to see is a significant shift in biome, for example as the polar and boreal climates retreat poleward and disappear. This group is expected to see the largest increase in biome change (about 40 percentage points average increase in the land surface changing climate classification between today and 2050, measured against a 1901—25 baseline. Another change that many of these countries could experience is an increase in the share of capital stock at risk of riverine flood damage in climate-exposed regions.

- **Diverse climate countries.** The final group consists of countries that span a large range of latitudes and therefore are climatically heterogeneous. Examples include Argentina, Brazil, Chile, China, and the United States.[184] While average numbers may indicate small risk increases, these numbers mask wide regional variations. The United States, for example, has a hot and humid tropical climate in the Southeast, which could see significant increases in heat and humidity risk to outdoor work in our inherent risk scenario but is not projected to see increased water stress. The West Coast region, by contrast, is not expected to see a big increase in heat and humidity risk to outdoor work, but it is projected to have increased impacts from water stress and drought. In Alaska, the primary risk will likely be the shifting boreal biome affecting natural capital and the attendant ecosystem disruptions. To understand the climate risks facing diverse climate countries, one must examine the different regions independently.

---

[184] To some extent, many countries could experience diversity of risk within their boundaries, a key feature of climate risk which is spatial. Here we have focused on highlighting countries with large climatic variations, and longitudinal expanse, which drives different outcomes in different parts of the country.

Exhibit 24

We identify six types of countries based on their patterns of expected change in climate impacts.

Based on RCP 8.5

⬜ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase █ High risk increase

	Livability and workability			Food systems	Physical assets/ infrastructure services	Natural capital
Country — Change in… (2018–50, pp)	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Significantly hotter and more humid countries						
Bangladesh	█	█	⬜	⬜	░	▒
India	█	█	⬜	⬜	▒	█
Nigeria	█	█	⬜	░	░	░
Pakistan	█	▒	⬜	░	░	▒
Other countries in group: Benin, Burkina Faso, Cambodia, Cote d'Ivoire, Eritrea, Ghana, Myanmar, Niger, Senegal, Thailand, Vietnam, Yemen						
Average (all countries in group)	█	█	⬜	⬜	▒	▒
Hotter and more humid countries						
Ethiopia	░	▒	⬜	⬜	▒	█
Indonesia	░	█	⬜	░	█	░
Japan	░	▒	⬜	░	█	█
Philippines	░	█	⬜	⬜	░	▒
Other countries in group: Angola, Cameroon, Chad, Ecuador, Guinea, Guyana, Jordan, Laos, Liberia, Madagascar, Papua New Guinea, Saudi Arabia, Somalia, Suriname, Tanzania, Uganda, Uruguay, Zambia						
Average (all countries in group)	░	█	⬜	▒	▒	▒
Hotter countries						
Colombia	░	▒	░	░	█	▒
Dem. Rep. Congo	░	█	░	▒	▒	▒

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit 25

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5

⬜ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase ▓ High risk increase

Country	Change in… (2018–50, pp) Livability and workability: Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Livability and workability: Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Livability and workability: Water stress[2]	Food systems: Share of time spent in drought over a decade	Physical assets/ infrastructure services: Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Natural capital: Share of land surface changing climate classification
Hotter countries (continued)						
Malaysia	░	▓	░	⬜	▒	░
South Korea	░	▒	▒	░	▒	▓
Other countries in group: Botswana, Central African Rep., Cuba, Gabon, Guatemala, Honduras, Hungary, Libya, Malawi, Mali, Mauritania, Mozambique, Namibia, Nicaragua, Oman, Paraguay, Rep. Congo, Romania, Serbia, Venezuela, Zimbabwe						
Average (all countries in group)	░	▓	░	▓	▒	▓
Increased water stress countries						
Egypt	░	▓	▓	▓	░	░
Iran	░	▒	▓	▒	▓	▓
Mexico	░	▒	▓	░	▓	▓
Turkey	░	▒	▓	▓	▒	▓
Other countries in group: Algeria, Australia, Azerbaijan, Bulgaria, Greece, Italy, Kazakhstan, Kyrgyzstan, Morocco, Portugal, South Africa, Spain, Syria, Tajikistan, Tunisia, Turkmenistan, Ukraine, Uzbekistan						
Average (all countries in group)	░	▒	▓	▓	▒	▓
Lower-risk countries						
France	░	▒	░	░	▓	▓
Germany	░	▒	░	░	▒	▓

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit 26

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5

□ Risk decrease ░ No or slight risk increase ▓ Moderate risk increase █ High risk increase

Change in… (2018–50, pp)	Livability and workability			Food systems	Physical assets/ infrastructure services	Natural capital
Country	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Lower-risk countries (continued)						
Russia	░	▓	░	□	▓	█
United Kingdom	░	░	□	░	█	▓
Other countries in group: Austria, Belarus, Canada, Finland, Iceland, Mongolia, New Zealand, Norway, Peru, Poland, Sweden						
Average (all countries in group)	░	▓	□	░	▓	█
Diverse climate countries						
Argentina	░	▓	□	░	█	█
Brazil	░	█	░	▓	▓	▓
China	█	▓	□	░	█	█
United States	░	▓	█	░	█	█
Other countries in group: Chile						
Average (all countries in group)	▓	▓	░	░	▓	█

Change in potential impact, 2018–50[4] (percentage points)

Risk decrease	n/a	n/a	<0	<0	<0	n/a
Slight risk increase	0.0–0.5	0.0–0.5	0–3	0–3	0–0.05	0–5
Moderate risk increase	0.5–5.0	0.5–5.0	3–7	3–7	0.05–0.10	5–10
High risk increase	>5.0	>5.0	>7	>7	>0.10	>10

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.
4. Calculated assuming constant exposure. Constant exposure means that we do not factor in any increases in population or assets, or shifts in the spatial mix of population and assets. This was done to allow us to isolate the impact of climate change alone. Color coding for each column based on the spread observed across countries within the indicator.

Note: See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Countries and regions with lower per capita GDP levels are generally more at risk. Poorer regions often have climates that are closer to physical thresholds. They rely more on outdoor work and natural capital and have fewer financial means to adapt quickly, meaning that they could be more vulnerable to the effects of climate change.[185] Climate change could also benefit some countries; for example, crop yields in Canada, Russia, and parts of Northern Europe could improve.

The risk associated with the impact on workability from rising heat and humidity is one example of how poorer countries are more exposed to hazards (Exhibit 27). When looking at the workability indicator (that is, the annual share of effective outdoor working hours lost to extreme heat and humidity), the top quartile of countries (based on GDP per capita) have an average increase in risk by 2050 of approximately one to three percentage points, whereas the bottom quartile faces an average increase in risk of approximately five to ten percentage points. Lethal heat waves show less of a correlation with per capita GDP, but it is important to note that several of the most affected countries, under an RCP 8.5 scenario, including Bangladesh, India, and Pakistan, have relatively low per capita GDP levels. Such countries are close to physical thresholds particularly for heat and humidity impacts on workability and livability.

Biome shift is expected to affect northern and southern latitude countries. Since many of these countries have higher per capita GDP levels, this indicator shows a positive correlation with development levels.

---

[185] Note that this could also be true at a sub-national level; specific regions and communities could be more vulnerable than others within a country.

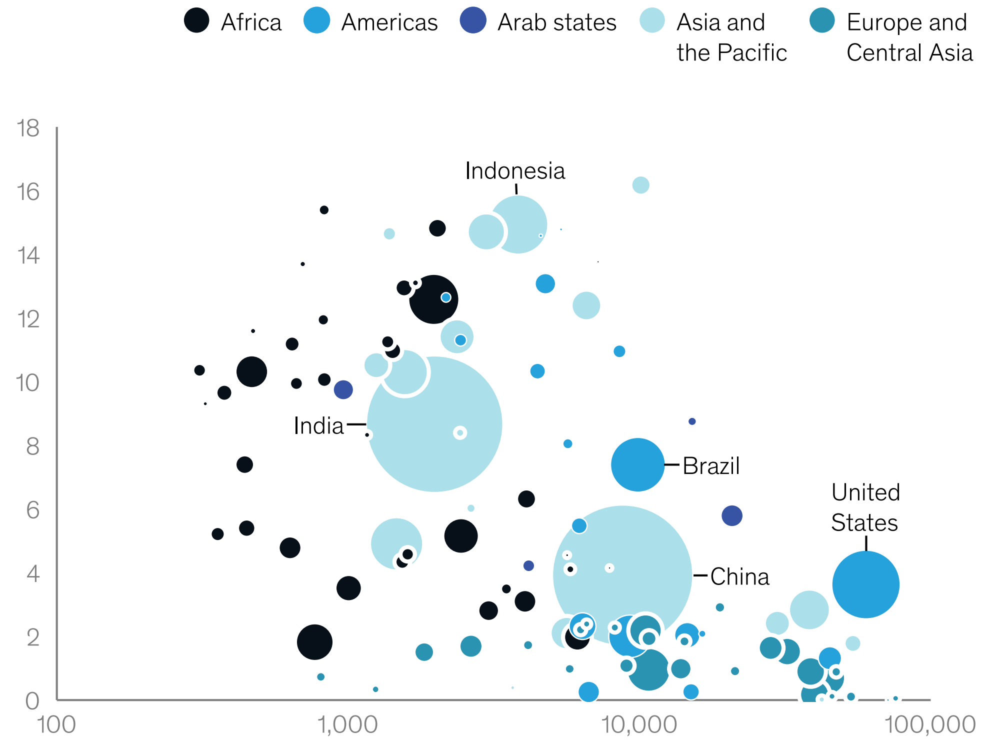
Exhibit 27

Countries with the lowest per capita GDP levels face the biggest increase in risk for some indicators.

Based on RCP 8.5

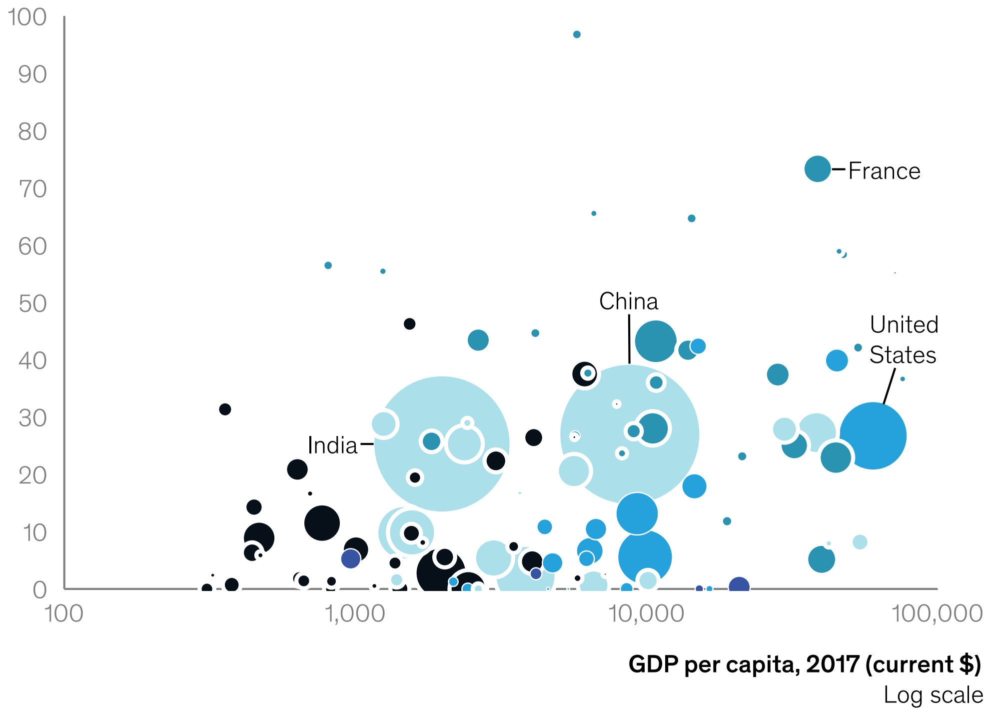
Change, 2018–50

Percentage points



Annual share of effective outdoor working hours affected by extreme heat and humidity in climate-exposed regions

Correlation coefficient: r = -0.49



Share of land surface changing climate classification

Correlation coefficient: r = 0.35

Note: Not to scale. See the Technical Appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; Rubel and Kottek, 2010; IMF; World Bank; UN; McKinsey Global Institute analysis

Our global geospatial analysis illustrates that current and future climate risk is pervasive across the world, with all 105 countries we studied experiencing an increase in at least one risk indicator by 2030. As we have highlighted in this report, sizing that risk is a complex task that requires an analysis of both statisticially expected and tail risks, of direct impacts to the stock of human, physical, and natural capital as well as to flows of GDP activity and other knock-on effects. Given these uncertainties and risks, how should decision makers respond? In the next chapter, we look at steps for stakeholders seeking an effective response to the challenges of a changing climate and the risks that it entails.

5. An effective response

Physical climate risk will affect everyone, directly or indirectly. Responding to it adequately will require careful translation of climate science into specific risk assessments, at a time when old models of assessing and managing risk are losing their relevance. As we have noted in this report, physical and socioeconomic impacts of climate change are characterized by the growing likelihood of long tail events occurring that could result in cascading systemic risks.

In this final chapter, we discuss three steps that stakeholders could consider as they seek an effective response to the socioeconomic impacts of physical climate risk: integrating climate risk into decision making, accelerating the pace and scale of adaptation, and decarbonizing at scale to prevent a further buildup of risk.

Integrating climate risk into decision making

Much as thinking about information systems and cyber-risks has become integrated into corporate and public sector decision making, climate change will also need to feature as a major factor in decisions. As we have noted, physical climate risk is simultaneously spatial and systemic, non-stationary, and can result in nonlinear impacts. We find potential impacts to be rising over time across our cases and regressive; moreover, stakeholders today may be underprepared to manage its impact. Decision making will need to reflect these characteristics. For companies, this will mean taking climate considerations into account when looking at capital allocation, development of products or services, and supply-chain management, among others. For example, large capital projects could be evaluated reflecting the full probability distribution of possible climate hazards at their location. This would include changes in that probability distribution over time and possible changes in cost of capital for exposed assets, as well as how climate risk could affect the broader market context and other implicit assumptions in the investment case. For cities, a climate focus will become essential for urban planning decisions. Moreover, while this report has focused on physical risk, a comprehensive risk management strategy will also need to include an assessment of transition and liability risk, and the interplay between these forms of risk.

Developing a robust quantitative understanding of climate risk is complex, for the many reasons outlined in this report. It requires the use of new tools, metrics, and analytics. Companies and communities are beginning to assess their exposure to climate risk, but much more needs to be done. Lack of understanding significantly increases risks and potential impacts across financial markets, and socioeconomic systems, for example, by driving capital flows to risky geographies, or increasing the likelihood of stakeholders being caught unprepared.

At the same time, opportunities from the changing climate will emerge and require consideration. These could arise from a change in the physical environment, such as new places for agricultural production, or for sectors like tourism, as well as through the use of new technologies and approaches to manage risk in a changing climate.

Changes in mind-set, operating model, and tools and processes will be needed to integrate climate risk into decision making effectively. Decision makers' experiences are based on a world of relative climate stability, and they may not yet be planning for a world of changing climate. For example, statistical risk management is often not part of ordinary processes in industrial companies. With the changing climate, it will be important to understand and embrace the probabilistic nature of climate risk and be mindful of possible biases and outdated mental models; experiences and heuristics of the past are often no longer a reliable guide to the future. The systemic nature of climate risk requires a holistic approach to understand and identify the full range of possible direct and indirect impacts. The spatial nature of hazard means that decision making will need to incorporate a geographic dimension.

One of the biggest challenges from climate risk could be to rethink the current models we use to quantify risk. These range from financial models used to make capital allocation decisions, to engineering models used to design structures. As we have discussed, some uncertainty is associated with a methodology that leverages global and regional climate models, makes underlying assumptions on emissions paths, and seeks to translate climate hazards to potential physical and financial damages. The highest "model risk," however, may not come from exploring new ways to quantify climate risk. Instead, it may derive from continued reliance on current models that are based on stable historical climate and economic data. These models have at least three potential flaws:

— The absence of geographic granularity. Most models do not take into account geospatial dimensions. As this report highlights, direct impacts of climate change are local in nature. This requires an understanding of the exposure to risk via geospatial analysis. For example, companies will need to understand how their global asset footprint is exposed to different forms of current and evolving climate hazard in each one of their main locations—and indeed in each of the main locations of their critical suppliers.

— The "non-stationarity," or constant state of change, of the climate. For example, our entire capital stock is built around physical assumptions that may well be obsolete as relevant climate variables have already changed and continue to change. As a result, assumptions based on historical precedent and experience will need to be rethought. That could include, for example, how resilient to make new factories, what tolerance levels to employ in new infrastructure, and how to design urban areas.

— Potential sample bias could prove to be a flaw. Decision makers often rely on their own experiences as a frame for decision making; in a changing climate, this may result in an incorrect assessment of future risk.

A transformation in operating model could mean optimizing for resiliency rather than simply for efficiency. For example, it may be preferable to rent rather than own fixed assets. Companies may need to think about ways to increase resilience in supply chains, for example, by raising inventory levels or sourcing from multiple locations or suppliers. Resilience will need to be incorporated into capital design, and owners of well-functioning assets will need to maintain them proactively rather than waiting to repair damages.

Adequate tools, metrics, and processes will vary by stakeholder but will likely include transitioning from a reliance on historical data or "worst case" expectations based on experience to relying on climate modeling tools to prepare for the future, including building new analytics capabilities. The process of managing climate change incorporates a full risk diagnostic as the basis for an appropriate response strategy.

Accelerating the pace and scale of adaptation

Societies have been adapting to the changing climate, but the pace and scale of adaptation will likely need to increase significantly. Key adaptation measures include protecting people and assets, building resilience, reducing exposure, and ensuring that appropriate insurance and financing are in place.

Implementing adaptation measures could be challenging for many reasons. With hazard intensity projected to increase, the economics of adaptation could worsen over time and there may eventually be technical or other limits to effective adaptation. In other instances, there could be difficult trade-offs that need to be assessed, including who and what to protect, and who and what to relocate.

In some instances, coordinated action across multiple stakeholders may be required. This may include establishing building codes and zoning regulations, mandating insurance or disclosures, mobilizing capital through risk-sharing mechanisms, sharing best practices across industry groups, and driving innovation. This could be done, for example, by providing tools to integrate climate risk into investment decisions, integrating diverse perspectives including those of different generations into decision making, and addressing the inequalities that climate risk could amplify.

Protecting people and assets

Protecting people is crucial. Steps can range from prioritizing emergency response and preparedness to erecting cooling shelters and adjusting working hours for outdoor workers exposed to heat. For example, the Ahmedabad City Corporation developed the first heat-action plan in India in response to the record-breaking 2010 heat wave that killed 300 people in a single day.[186] As part of the plan, Ahmedabad has implemented programs to build the population's awareness of the dangers of extreme heat. These measures include establishing a seven-day probabilistic heat-wave early-warning system, developing a citywide cool-roofs albedo management program, and setting up teams to distribute cool water and rehydration tablets to vulnerable populations during heat waves.[187]

Measures to harden existing infrastructure and assets to the extent possible can help limit risk. Hardening of infrastructure could include both "gray" infrastructure—for example, raising elevation levels of buildings in flood-prone areas—and natural capital or "green" infrastructure. One example of this is the Dutch Room for the River program, which gives rivers more room to manage higher water levels.[188] Mangroves can also provide storm protection. A systemwide approach to protecting people and assets will be needed. For example, even as homes may need to be floodproofed, so too could the roadways near those homes.

Factoring decisions about protection into new buildings could be more cost-effective than retrofitting.[189] For example, infrastructure systems or factories could be designed to withstand what used to be a one in 200-year event. With a changing climate, what constitute such an event may look different, and design parameters may need to be reassessed. Estimates suggest that $30 trillion to $50 trillion will be spent on infrastructure in the next ten years, much of it in developing countries.[190] Given the lifetime of the assets, new infrastructure will

---

[186] Kim Knowlton et al., "Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India)," *International Journal of Environmental Research and Public Health*, 2014, Volume 11, Issue 4.

[187] Albedo refers to the reflectivity of a surface. Increasing the albedo of a city—through, for example, painting dark surfaces white—reduces temperature by reducing the amount of sunlight absorbed. Thomas R. Knutson, Fanrong Zeng, and Andrew T. Wittenberg, "Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations," *Journal of Climate*, November 2013, Volume 26, Number 22; Markus Huber and Reto Knutti, "Anthropogenic and natural warming inferred from changes in Earth's energy balance," *Nature Geoscience*, January 2012, Volume 5, Number 1; Ron L. Miller et al., "CMIP5 historical simulations (1850–2012) with GISS ModelE2," *Journal of Advances in Modeling Earth Systems,* June 2014, Volume 6, Number 2.

[188] See Room for the River, ruimtevoorderivier.nl/english/.

[189] Michael Della Rocca, Tim McManus, and Chris Toomey, *Climate resilience: Asset owners need to get involved now*, McKinsey.com, January 2009.

[190] *Bridging global infrastructure gaps*, McKinsey Global Institute, June 2016; *Bridging infrastructure gaps: Has the world made progress?* McKinsey Global Institute, October 2017.

need to be built with an eye to the future and factor in future climate hazards. This will also require reassessing engineering and building standards.

Building resilience

Decisions on asset hardening will need to go hand-in-hand with measures to drive operational resilience in systems. An important aspect of this is understanding the impact thresholds for systems and how they could be breached. This will help inform how to make systems more resilient and robust in a world of rising climate hazard. Examples of resilience planning include building global inventory to mitigate risks of food and raw material shortages or building inventory levels in supply chains to protect against interrupted production and establishing the means to source from alternate locations and/or suppliers. Back-up power sources could be established in case there are power failures.

Reducing exposure

Given the long lifetimes of many physical assets, the full life cycle will need to be considered and reflected in any adaptation strategy. For example, it may make sense to invest in asset hardening for the next decade but also to shorten asset life cycles. In subsequent decades, as climate hazards intensify, the cost-benefit equation of physical resilience measures may no longer be attractive. In that case, it may become necessary to relocate and redesign asset footprints altogether. Climate risk will need to be embedded in all capital expenditure decisions to minimize new exposure.

In some instances, it may also be necessary to gradually reduce exposure by relocating assets and communities in regions that may be too difficult to protect. These are often hard choices; for example, the impact on individual home owners and communities needs to be weighed against the rising burden of repair costs and post-disaster aid, which affects all taxpayers. We have already seen some examples, including buyout programs in Canada for residents in flood-prone areas. Since 2005, Quebec has prohibited both the building of new homes and the rebuilding of damaged homes in the 20-year floodplain.[191] In Canada and elsewhere, homes damaged beyond a particular threshold will require mandatory participation in such programs. Decisions will need to be made about when to focus on protecting people and assets versus finding ways to reduce exposure to hazard, what regions and assets to spend on, how much to spend on adaptation, and what to do now versus in the future. This will require being able to conduct appropriate cost-benefit analyses that include a long-term perspective on how risk and adaptation costs will likely evolve, as well as integrating voices of affected communities into decision making.

Equally important will be to support socioeconomic development in ways that recognize the risk of a changing climate. Continuing to shift the basis of economic development from outdoor work to urban indoor environments in extreme heat-prone environments and factoring climate risk into urban planning are examples.

---

[191] Christopher Flavelle, "Canada tries a forceful message for flood victims: Live someplace else," *New York Times*, September 10, 2019.

Insurance and finance

Researchers estimate that only 50 percent of losses today are insured, a condition known as underinsurance. Underinsurance may grow worse as more extreme events unfold, because fewer people carry insurance for them. Insurance models suggest that if extreme events with an exceedance probability of 1 percent manifest, underinsurance could be as high as 60 percent; for 0.4 percent probability events, the figure is 70 percent.[192]

While insurance cannot eliminate risk from a changing climate, it is a crucial shock absorber to help manage risk. Without insurance as a shock absorber, recovery after disaster becomes harder and knock-on effects more likely.[193] Underinsurance or lack of insurance thus reduces resilience. Appropriate insurance can also encourage behavioral changes among stakeholders by sending appropriate risk signals—for example, to homeowners buying real estate, lenders providing loans, and real estate investors financing real estate build-out.

Instruments such as parametrized insurance and catastrophe bonds can provide protection against climate events, minimizing financial damage and allowing speedy recovery after disasters. These products may help protect vulnerable populations that may find it challenging to afford to rebuild after disasters. Insurance can also be a tool to reduce exposure by transferring risk (for example, crop insurance allows transferring the risk of yield failure due to drought) and drive resilience (such as by enabling investments in irrigation and crop-management systems for rural populations who would otherwise be unable to afford this).

However, as the climate changes, insurance might need to be further adapted to continue providing resilience and, in some cases, avoid potentially adding vulnerability to the system. For example, current levels of insurance premiums and levels of capitalization among insurers may well prove insufficient over time for the rising levels of risk; and the entire risk transfer process (from insured to insurer to reinsurer to governments as insurers of last resort) and each constituents' ability to fulfil their role may need examination. Without changes in risk reduction, risk transfer, and premium financing or subsidies, some risk classes in certain areas may become harder to insure, widening the insurance gap that already exists in some parts of the world without government intervention.

Innovative approaches will also likely be required to help bridge the underinsurance gap. Premiums are already sometimes subsidized—one example is flood insurance, which is often nationally provided and subsidized. Such support programs however might need to be carefully rethought to balance support to vulnerable stakeholders with allowing appropriate risk signals in the context of growing exposure and multiple knock-on effects. One answer might be providing voucher programs to help ensure affordability for vulnerable populations, while maintaining premiums at a level that reflects the appropriate risk. Careful consideration will need to be given to the provision of insurance in particularly risky areas to prevent moral hazard (for example, continuing to rebuild in flood-prone areas, with rising damage costs and adaptation need). In the United Kingdom, the government and insurers have established a joint initiative, the UK Flood Re program, to provide affordable flood insurance. Premiums are linked to council tax bands to ensure that support is targeted to those most in need. In the long run, it is expected to transition to a private flood insurance program for which premiums appropriately reflect flood risk. For now, the initiative allows home owners sufficient time to put adaptation measures in place to protect themselves and keep their insurance premiums affordable after Flood Re coverage ends.[194]

Insurance may also need to overcome a duration mismatch; for example, homeowners may expect long-term stability for their insurance premiums, whereas insurers may look to reprice

---

[192] Lucia Bevere et al., *Natural catastrophes and man-made disasters in 2018: 'Secondary' perils on the frontline*, Swiss Re Institute, *Sigma,* 2019, Number 2; *Global modeled catastrophe losses*, AIR, November 2018.

[193] Goetz von Peter, Sebastian von Dahlen, and Sweta Saxena, *Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes*, BIS Working Papers, Number 394, December 2012.

[194] Flood Re, floodre.co.uk.

annually in the event of growing hazards and damages. This could also apply to physical supply chains that are currently in place or are planned for the future, as the ability to insure them affordably may become a factor of growing significance. Trade-offs between private and public insurance, and for individuals, between when to self-insure or buy insurance, will need to be carefully evaluated. In addition, underwriting may need to shift to drive greater risk reduction in particularly vulnerable areas (for example, new building codes or rules around hours of working outside). This is analogous to fire codes that emerged in cities in order to make buildings insurable. In other words, to be insured you had to meet certain underwriting requirements.

Mobilizing finance to fund adaptation measures, particularly in developing countries, is also crucial. This may require public-private partnerships or participation by multilateral institutions, to prevent capital flight from risky areas once climate risk is appropriately recognized. Innovative products and ventures have been developed recently to broaden the reach and effectiveness of these measures. They include "wrapping" a municipal bond into a catastrophe bond, to allow investors to hold municipal debt without worrying about hard-to-assess climate risk. Governments of developing nations are increasingly looking to insurance and reinsurance carriers and other capital markets to improve their resiliency to natural disasters as well as give assurances to institutions that are considering investments in a particular region.

Decarbonization at scale

An assessment and roadmap for decarbonization is beyond the scope of this report. However, climate science and research by others tells us that the future of Earth's climate after the next decade is dependent on the cumulative amount of carbon dioxide that is added to the atmosphere. Considering current emissions and greenhouse-gas-reduction pledges, scientists predict that the global average temperature will increase by 3 to 4 degrees Celsius relative to preindustrial average by the end of the century.[195] Multiple lines of evidence suggest that physical feedback loops could further amplify human-caused warming, causing the planet to warm for hundreds or thousands of years independent of human action (such as the thawing of permafrost leading to the release of significant amounts of greenhouse gases). This could push the Earth into a much warmer "hothouse" state.[196]

Scientists estimate that restricting warming to below 2.0 degrees would reduce the risk of initiating many serious feedback loops, and restricting it to 1.5 degrees would reduce the risk of initiating most of them.[197] Because warming is a function of cumulative emissions, there is a specific amount of CO_2 that can be emitted before reaching the 1.5-degree or 2.0-degree threshold (a "carbon budget").[198] Scientists estimate that the remaining 2.0-degree carbon budget will be exceeded in approximately 25 years and the remaining 1.5 degree carbon budget in 12 years, given the current annual emissions trajectory.[199] To halt further warming would require reaching net zero emissions.

---

[195] Joeri Rogelj et al., "Paris Agreement climate proposals need a boost to keep warming well below 2°C," *Nature*, 2016, Volume 534, Number 7609.

[196] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences*, August 2018, Volume 115, Number 33; Timothy M. Lenton et al., "Tipping elements in the Earth's climate system," *Proceedings of the National Academy of Sciences*, March 2008, Volume 105, Number 6; Timothy M. Lenton, "Arctic climate tipping points," *Ambio*, February 2012, Volume 41, Number 1; Sarah E. Chadburn et al., "An observation-based constraint on permafrost loss as a function of global warming," *Nature Climate Change*, April 2017, Volume 7, Number 5; Robert M. DeConto and David Pollard, "Contribution of Antarctica to past and future sea-level rise," *Nature*, March 2016, Volume 531, Number 7596; Michael Previdi et al., "Climate sensitivity in the Anthropocene," *Quarterly Journal of the Royal Meteorological Society*, July 2013, Volume 139, Issue 674.

[197] Will Steffen et al., "Trajectories of the Earth system in the Anthropocene," *Proceedings of the National Academy of Sciences,* August 2018, Volume 115, Number 33; Hans Joachim Schellnhuber, Stefan Rahmstorf, and Ricarda Winkelmann, "Why the right goal was agreed in Paris," *Nature Climate Change,* July 2016, Volume 6, Number 7.

[198] This budget can increase or decrease based on emission rates of short-lived climate pollutants like methane. However, because of the relative size of carbon dioxide emissions, reducing short-lived climate pollutants increases the size of the carbon budget by just a small amount, and only if emission rates do not subsequently increase; H. Damon Matthews et al., "Focus on cumulative emissions, global carbon budgets, and the implications for climate mitigation targets," *Environmental Research Letters*, January 2018, Volume 13, Number 1.

[199] Richard J. Millar et al., "Emission budgets and pathways consistent with limiting warming to 1.5°C," *Nature Geoscience*, 2017, Number 10; Joeri Rogelj et al., "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature*, July 2019, Volume 571, Number 7765.

Hence, prudent risk management would suggest limiting future cumulative emissions to minimize the risk of activating these feedback loops. While decarbonization is not the focus of this research, decarbonization investments will need to be considered in parallel with adaptation investments, particularly in the transition to renewable energy. Stakeholders should consider assessing their decarbonization potential and opportunities from decarbonization. While adaptation is now urgent and there are many adaptation opportunities, climate science tells us that further warming and risk increase can only be stopped by achieving zero net greenhouse gas emissions.

Recognizing physical climate risk and integrating an understanding of this risk into decision making is an imperative for individuals, businesses, communities, and countries. The next decade will be decisive, as decision makers fundamentally rethink the infrastructure, assets, and systems of the future, and the world collectively sets a path to manage the risk from climate change.

Glossary of terms

Adaptation: Adjustment to a given level of climate change. This could include: reducing exposure to climate risks, for example migration of communities at risk from sea level rise; protecting assets and people, for example building seawalls to protect communities; building resilience, for example creating backup food supply stores or increasing inventory levels in factories; and mobilizing finance and insurance.

Climate: The statistical description of multi-decadal weather conditions, including temperature, precipitation, and wind speed, all of which are determined by the complex ways in which Earth absorbs, distributes, and dissipates energy from the sun.

Climate change: Changes in the Earth's climatic patterns, typically measured against a preindustrial level.

Climate hazard: Adverse climate conditions that can be either chronic or acute. Chronic climate change is a long-term shift in an average parameter value, for example a change in sea levels, or the rise in average temperatures. An acute event is an extreme event like a hurricane or a heat wave.

Climate risk: Risks arising from a changing climate. They can be grouped into three types: physical risk (risks arising from the physical effects of climate change); transition risk (risks arising from transition to a low-carbon economy); and liability risk (risks arising from those affected by climate change seeking compensation for losses). This report assesses the physical risk from a changing climate, including the potential impacts on people, communities, natural and physical capital, and economic activity, and the implications for companies, governments, financial institutions, and individuals.

Impact: The ways in which human, natural, physical, economic, and financial systems are affected by the physical effects of climate change. An example of a direct impact is damage to a home from flooding; a knock-on impact, for example, is the falling price of a home as it becomes less attractive to prospective buyers because of frequent flooding. Knock-on impacts may also be large-scale and systemic, for example the collapse of long-term mortgage lending in a community exposed to a likely significant increase in flooding and sea-level rise. Because future climate hazards are probabilistic, the potential magnitude of impact is also probabilistic. Each potential magnitude of impact (typically referred to as severity) could occur with different probabilities (also referred to as frequency).

Inherent risk: The risk before consideration of adaptation and mitigation measures that could reduce the likelihood or magnitude of socioeconomic impacts.

Mitigation: Often also referred to as decarbonization; the process of reducing the magnitude or rate of warming of the planet through actions to reduce emissions or increase the capacity of carbon sinks.

Resilience threshold: Physical, social, and economic systems are designed to operate within certain climate parameters or thresholds. Above these thresholds, climate hazards will breach the resiliency of the systems and have outsize impacts. Examples include temperatures above which railway tracks start to buckle and power stations lose their efficiency.

Uncertainty: The degree of uncertainty surrounding estimates, for example, those relating to the pace of warming or how climate hazards will evolve in response. Uncertainty arises due to assumption errors—given that influencing factors such as human and societal behavior can only be predicted to a certain extent—and modeling errors.

Weather: The state of the atmosphere at a given time with respect to heat or cold, wetness or dryness, calm or storm, and clearness or cloudiness.

X-year event: An occurrence of a magnitude expected to happen once in an X-year period on average. For example, a 100-year flood is the flood level with a 1 percent probability of occurring or being exceeded in a given year. It is important to note that due to climate change, the magnitude of an X-year event may change over time and past X-year events may happen more frequently. For instance, what used to be a 100-year flood may now occur more frequently.

Technical appendix

This report seeks to provide an understanding of how climate hazards can create risk. In this technical appendix, we outline our key assumptions and approach (Exhibit A1).

Woods Hole Research Center (WHRC) performed most of the climatological analysis for this report, and senior scientists at the University of Oxford's Environmental Change Institute independently reviewed the methodological design. All final design choices and interpretation of climate hazard results were made by WHRC.

From the outset, it is important to understand the distinction between weather and climate. Weather is defined as the behavior of the atmosphere with respect to temperature, wind speed, cloudiness, and precipitation for a given location over a short period such as a day or a week. Climate is defined as the statistical or probabilistic summary of weather patterns over time and space. As a result, climate is possible to predict with reasonably high reliability, whereas weather is not predictable more than two weeks in advance, due to the theoretical constraints of modeling chaotic systems.[1] Throughout this report, we consider only expected changes in climate. We generally do this over two periods: the present to 2030, and the present to 2050 (in some instances, we also consider other periods in our case studies, and highlight where we do so) . Following standard practice, we define future states as the average climatic behavior over multiple-decade periods. The climate state today is typically defined as the average conditions between 1998 and 2017, in 2030 as the average between 2021 and 2040, and in 2050 as the average between 2041 and 2060.[2]

---

[1] Klaus Hasselmann, "Is climate predictable?," in *The Science of Disasters: Climate Disruptions, Heart Attacks, and Market Crashes,* Armin Bunde, Jürgen Kropp, and Hans Joachim Schellnhuber, eds., Berlin, Germany: Springer, 2002; Jaana Sillmann et al., "Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities," *Weather and Climate Extremes,* December 2017, Volume 18.

[2] See Gerald A. Meehl et al., "Decadal prediction: Can it be skillful?," *Bulletin of the American Meteorological Society,* October 2009, Volume 90, Number 10.

How global climate hazard is estimated

The specific projections in this report were derived from climate models. Climate models are complex computational models based on physics that simulate the atmosphere, ocean, land, biosphere, and cryosphere down to resolutions of roughly 100km-by-100km. The climate models used in this report are drawn from an ensemble of 60 climate models known as general circulation models (GCMs) or earth system models; they are developed, owned, and operated independently by 28 leading scientific research institutions across the world.[3] The World Climate Research Programme brought these models together to run standardized experiments to determine the likely outcome of various rates of carbon emissions in an undertaking known as CMIP5: Coupled Model Intercomparison Project 5.[4] The results of the CMIP5 ensemble are the most widely used source of climate projections in climate research today and have been evaluated in more than 1,500 papers.[5]

We also drew on projections from an ensemble of regional climate models, which are dynamic models that take GCM input and refine it to simulate specific regions of the globe at a finer resolution. This allows scientists to more accurately investigate future climates in regions with complex terrain. For the analyses in this report, we use projections from the Coordinated Regional Downscaling Experiment (CORDEX) ensemble.[6] The CORDEX ensemble consists of 80 regional climate models developed at 51 research institutions, using the CMIP5 ensemble or parts thereof as input data.[7]

When modeling the response of agricultural systems to climate change, we drew from an ensemble of coupled climate and agricultural models known as AgMIP, which is coordinated by the Columbia University Earth Institute in partnership with multiple other organizations including NASA, USDA, the Potsdam Institute for Climate Impact Studies, and others.[8] Finally, we also sometimes rely on projections from external sources (for example, the World Resources Insitute on water stress).

When making climate projections, we used the multimodel ensemble mean or median projection (depending on the requirements of the specific analysis)—in other words, the average projection across all selected models—because it has been proven both theoretically and empirically that using the average result across the full ensemble of models gives the most accurate projection.[9]

---

[3] *CMIP Phase 5 (CMIP5),* World Climate Research program, wcrp-climate.org/wgcm-cmip/wgcm-cmip5. The specific models used in this report are: ACCESS1-0, ACCESS1-3, CNRM-CM5, CSIRO-Mk3-6-0, CanESM2, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5B-LR, IPSL-CM5A-MR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MRI-CGCM3, MRI-ESM1, NorESM1-M.

[4] Karl E. Taylor, Ronald J. Stouffer, and Gerald A. Meehl, "An overview of CMIP5 and the experiment design," *Bulletin of the American Meteorological Society,* April 2012, Volume 93, Number 4.

[5] Gregory Flato et al., "Evaluation of climate models," *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Thomas F. Stocker et al., eds., New York, NY: Cambridge University Press, 2014.

[6] Filippo Giorgi, "Thirty years of regional climate modeling: Where are we and where are we going next?," *Grand Challenges in the Earth and Space Sciences,* American Geophysical Union, February 2019.

[7] "About CORDEX," Coordinated Regional Climate Downscaling Experiment, cordex.org/.

[8] C. Rosenzweig et al., *The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies.* Papers in Natural Resources, 2013; C. Rosenzweig et al., *Coordinating AgMIP data and models across global and regional scales for 1.5C and 2C assessments,* The Royal Society, 2018.

[9] Every model in the ensemble performs best at representing some aspect of the climate system, and no model performs best across all aspects, and therefore all models add some measure of skill to the multimodel projection. Furthermore, combining multiple models leads to cancellations of nonsystematic errors.

Emissions pathways and pace of warming

Climate impact research has inherent uncertainties and as a result makes extensive use of scenarios. One particular input around which scenarios are frequently constructed is atmospheric greenhouse gas levels. Projections of future climate must be based upon an assumed trajectory for future atmospheric greenhouse gas concentrations. Because future human emissions of greenhouse gases are inherently unpredictable, the climate community has developed a set of four standardized scenarios for future atmospheric greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs).[10] They outline different atmospheric greenhouse gas concentration trajectories between 2005 and 2100 that roughly range from lower (RCP2.6) to higher (RCP 8.5) CO_2 concentrations. During their inception, RCPs were designed to collectively sample the range of then-probable future emission pathways. Each RCP was created by an independent modeling team and there is no consistent design of the socioeconomic parameter assumptions used in the derivation of the RCPs.

Uncertainty in future greenhouse gas emissions is a key contributor to long-term (for example, end-of-century) uncertainty in future temperatures but is less important on the shorter time horizons (out to 2050) considered in this report. As we discuss in detail in Chapter 2, warming during the next decade is determined largely by past emissions and by physical inertia in the climate system. Beyond the next decade, warming is primarily a function of *cumulative* emissions of carbon dioxide. Because decarbonization takes time, even a scenario of targeted decarbonization action will result in significant cumulative emissions over the next three decades. Climate simulations driven by the four RCP scenarios show a small divergence in warming over the next two decades, and a moderate divergence by 2050 (see also Exhibit 1, which shows projected warming for RCP 8.5 and RCP 4.5; the two RCPs that are most commonly used in climate models, to provide a sense of the spread in scenarios).[11]

We rely on RCP 8.5 for the analyses in this report. RCP 8.5 was created to model a case of no further climate action and relatively higher rates of baseline greenhouse gas emissions. We have chosen to focus on RCP 8.5, because the higher-emission scenario it portrays enables us to assess physical risk in the absence of further decarbonization.

While RCP 8.5 has been criticized for assuming unrealistically high use of coal and thus projecting too-high emissions in the second half of the century, we only consider a timeframe out to 2050, and we adopted RCP 8.5 as a best available description for an 'inherent risk' scenario over the next two to three decades.[12]

---

[10] Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An overview," *Climatic Change*, November 2011, Volume 109, Issue 1–2.

[11] Ibid.

[12] Justin Ritchie and Hadi Dowlatabadi, "The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible?" *Energy Economics*, June 2017, Volume 65; Justin Ritchie and Hadi Dowlatabadi, "Why do climate change scenarios return to coal?" *Energy*, December 2017, Volume 140, Part 1; Keywan Riahi et al., "The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview," *Global Environmental Change*, January 2017, Volume 42; Keywan Riahi, Arnulf Grübler, and Nebojsa Nakicenovic, "Scenarios of long-term socio-economic and environmental development under climate stabilization," *Technological Forecasting and Social Change*, September 2007, Volume 74, Issue 7; Detlef P. van Vuuren et al., "The Representative Concentration Pathways: An overview," *Climatic Change*, November 2011, Volume 109, Issue 1–2.

Three points to note about this choice are:

- Since the starting point of the RCPs in 2005, RCP 8.5 has most closely tracked actual greenhouse gas emissions (and going forward, RCP 8.5 is broadly consistent with a continuation of the emissions trend of the last decade).[13] As a result, it best matches current CO_2 concentrations, whereas the other RCPs assume lower CO_2 concentrations than observed.

- Changes in the relative cost of renewable and fossil energy sources are forecast to lead to a moderate downward divergence from the historic trendline of energy-related CO_2 emissions over the coming decades, even in absence of further decarbonization policies.[14] In contrast, emissions from biotic feedbacks, such as permafrost thaw or increasing wildfires, are expected to increase. These feedbacks are not considered in the current generation of CMIP5 models and need to be accounted for exogenously. According to a recent review of the literature on biotic feedbacks, in the near term these feedbacks are estimated to reduce the 1.5 degree Celsius carbon budget by 100 $GtCO_2$, and 2 degree Celsius carbon budget by 150 $GtCO_2$.[15]

- Early results from the next generation of climate models, CMIP6, suggest that the climate system may be more sensitive to CO_2 than the current generation of models (CMIP5) used here, suggesting that the CMIP5 models may tend to underestimate future warming.[16]

Based upon these considerations we chose to employ RCP 8.5 as a base case for considering 2030 to 2050. Were this study investigating the risk outlook for 2100, we would consider multiple emissions pathways, but for the next three decades, we consider RCP 8.5 to be the best guide for understanding inherent risk.

Restricting warming to below two degrees, the goal of the 2015 Paris agreement, would mean reaching net-zero emissions in the next 40 to 50 years. If this were achieved, the impact estimates presented in this report would likely not manifest to their full extent. Alternately, a decarbonization approach somewhere between business-as-usual and a two-degree-compliant pathway would mean that temperatures in 2050 would be below the roughly 2 degrees Celsius increase reflected in the RCP 8.5 scenario, but that such temperature increases would be reached at some point post-2050. This means that the impact assessments presented in this report would manifest but only after 2050; it would push the 2050 impacts further back into the second half of the century but would not prevent them.

Another way to frame this would be that if we were to limit warming to 2 degrees Celsius, our 2050 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2050), and if we were to limit warming to 1.5 degrees Celsius, correspondingly our 2030 impact estimates would be the most severe impacts we would be expected to see (but at some point after 2030). For example, RCP 8.5 predicts global average warming of 2.3 degrees Celsius by 2050, compared with 1.8 for RCP 4.5. Under RCP 4.5, 2.3 degrees Celsius warming would be reached in the year 2080.[17]

---

[13] Hayhoe, K., J. Edmonds, R.E. Kopp, A.N. LeGrande, B.M. Sanderson, M.F. Wehner, and D.J. Wuebbles, 2017: Climate models, scenarios, and projections. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 133-160, doi: 10.7930/J0WH2N54.

[14] IEA World Energy Outlook 2019.

[15] Jason A Lowe and Daniel Bernie, "The impact of Earth system feedbacks on carbon budgets and climate response," *Philosophical Transactions of the Royal Society A*, May 2018, Volume 376, Number 2119.

[16] Stephen Belcher, Olivier Boucher, and Rowan Sutton, *Why results from the next generation of climate models matter*, Carbon Brief, March 2019.

[17] Intergovernmental Panel on Climate Change (IPCC), 2014: Annex II: Climate System Scenario Tables, 2013.

How climate hazard in a region of interest is estimated

Throughout this report, we seek to answer specific questions about future climate variables for a particular region. Since GCMs tend to apply at continental or global scale, we needed a tool for regional or subregional climate projections.[18] At times, the CORDEX ensemble of regional climate models was used instead of CMIP5 (a process known as dynamical downscaling), and at other times a statistical process known as bias correction and spatial disaggregation was performed. Both methodologies have been proven to increase the skillful resolution of GCM projections to facilitate regional climate study.[19] Some questions required additional methodology. For example, "What is the probability of a heat wave of severity X occurring in a given year in region Y?" To quantify the probability, the scientists with whom we collaborated used a process known as bootstrapping to generate probability distributions drawn from the full ensemble of bias corrected models.[20]

How we determine physical climate risk from climate hazard

Our approach to determine physical climate risk assesses direct impacts from climate change, knock-on effects, and describes adaptation measures to avoid impacts (Exhibit A1). The magnitude of risk from physical climate change depends on the following:

1. **Direct impact:** The magnitude of direct impact of climate change depends on three factors: the magnitude of the climate hazard and the probability of its occurrence; how much assets, population, and economic activity are exposed to the hazard; and to what degree they are vulnerable to the hazard when exposed (direct impact = hazard x exposure x vulnerability). To assess impacts, we typically look at hazards of different severity. For each of our cases, and for our country risk assessment, we identify how hazard and exposure to that hazard could evolve. For case studies, exposure was typically assumed to grow in line with expected trends (for example, for India, including continued sectoral shift of the economy and increasing penetration of air-conditioning). For our geospatial assessment, similarly we assumed increases in population or GDP trends. However, for this analysis, we assumed that geospatial distribution of these variables stays constant over time because of data limitations with geospatial time series data. We also assess the vulnerability of each system to a hazard through identifying appropriate "damage functions"—for example, how damage to capital stock varies based on floods of different depths. Damage functions are obtained from published academic literature or external data sources. We consider three broad types of damage functions: physiological (e.g., impact on human productivity from heat stress), ecological (e.g., impact on agricultural productivity from drought), and physical (e.g., vulnerability of buildings to floods). We identify five types of systems directly impacted by climate hazards: livability and workability, food systems, physical assets, infrastructure services, and natural capital. Collectively, this points to how climate change could affect economic output, capital stock, and lives.

---

[18] Stanley L. Grotch and Michael C. MacCracken, "The use of general circulation models to predict regional climatic change," *Journal of Climate,* March 1991, Volume 4, Number 3, pp. 286–303.

[19] Nurul Nadrah Aqilah Tukimat, "Assessing the implementation of bias correction in the climate prediction," *IOP Conference Series: Materials Science and Engineering,* April 2018, Volume 342; Jie Chen et al., "Bias correcting climate model multi-member ensembles to assess climate change impacts on hydrology," *Climatic Change,* April 2019, Volume 153, Issue 3; Martin Aleksandrov Ivanov, Jürg Luterbacher, and Sven Kotlarski, "Climate model biases and modification of the climate change signal by intensity-dependent bias correction," *Journal of Climate*, August 2018, Volume 31, Number 16; Gerhard Krinner and Mark G. Flanner, "Striking stationarity of large-scale climate model bias patterns under strong climate change," *Proceedings of the National Academy of Sciences,* September 2018, Volume 115, Number 38; Patricio Velasquez, Martina Messmer, and Christoph C. Raible, "A new bias-correction method for precipitation over complex terrain suitable for different climate states," *Geoscientific Model Development* discussion paper, July 2019.

[20] Beran Efron, "Bootstrap methods: Another look at the jackknife," *The Annals of Statistics,* January 1979, Volume 7, Number 1, pp. 1–26; Manfred Mudelsee, "The bootstrap in climate risk analysis," in *In Extremis: Disruptive Events and Trends in Climate and Hydrology,* Jürgen P. Kropp and Hans Joachim Schellnhuber, eds., Heidelberg, Germany: Springer, 2011; Barbara Hennemuth et al., *Statistical methods for the analysis of simulated and observed climate data: Applied in projects and institutions dealing with climate change impact and adaptation,* Climate Service Center, CSC report number 13, 2013; Andrew C. Parnell, "Climate time series analysis: Classical statistical and bootstrap methods," *Journal of Time Series Analysis,* March 2013, Volume 34, Issue 2.

Impacts from climate change can be large, and potentially nonlinear, when climate hazards breach certain system thresholds. For example, the human body functions normally at a stable core temperature of about 37 degrees Celsius. The core temperature needs to rise only by 0.06 degree to compromise task performance, 3 degrees to induce dangerous heatstroke, and 5 degrees to cause death. As part of our analysis, we examine operational thresholds for physical, social, and economic systems in our case studies to determine potential impact.

2. **Knock-on impact:** Local climate risk can spread through interconnected social, financial, and economic systems such as trade in goods and services. Knock-on effects can be large if the direct impacts of climate change affect a sector that is vital to the local, regional, or global economy. Knock-on effects can also be large for sectors that are long term in nature, such as real estate and infrastructure, because risk is amplified beyond the immediate effects of today's damages. Real estate prices, for example, reflect expectations of the future. As buyers and sellers recognize future climate risk and the potential for future damages to homes, this may affect today's prices, thus "pulling forward" future damages. To calculate these knock-on impacts, we first identify potential channels by which risk could spread or be amplified. Where feasible, we then attempt to size such impacts, primarily relying on historical precedents or empirical estimates to help assess the potential magnitude of impact. For example, to assess the knock-on effect of disruption of food systems, we assess how those failures could reduce food storage levels and take into account historical trends on the link between reduced food storage levels and food price increases. Some knock-on effects, such as abrupt repricing of financial assets in response to climate risk, could potentially be destabilizing in nature, but the triggers and magnitude of such effects are challenging to estimate, and we do not attempt to size these impacts. Our assessment of knock-on effects is likely not exhaustive given the complexities associated with socioeconomic systems.

3. **Adaptation costs:** We define adaptation broadly to include protecting people and assets, building resilience, reducing exposure to hazard, and insurance and finance. We first examine inherent risk, assuming there is no significant increase in adaptation efforts, and that exposure continues to increase at historical rates, and vulnerability to risk remains the same as today. Then we explore adaptation measures, and where feasible, costs needed to adapt to climate risk, including exposure reduction where appropriate.

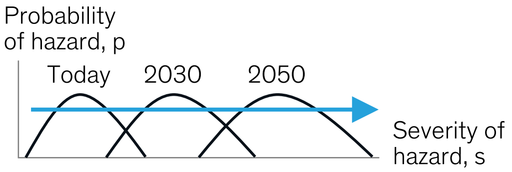
Exhibit A1

Methodology to translate climate hazard to climate risk.

Evaluate climate hazard
h = probability (s)

Description

Changes in the physical environment caused by higher temperatures, measured as probability, p of severity of hazard, s



Types

Acute (storms and hurricanes, wind, flooding, forest fires) and chronic (heat stress, drought, sea-level rise)

Example

Hurricane hits coastal real estate

Evaluate exposure to hazard
E (s)

Description

People, assets, or economic activity exposed to hazard

Types

People, assets, economic activity

Example

Properties close to the coast are exposed to storm surge

People working in outdoor activities are exposed to heat stress

Evaluate vunerability to hazard
v (s)

Description

Impact/damage per exposed "unit" for a given "unit" of climate hazard.

Types

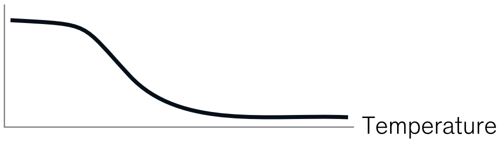
Physiological, eg, % impact on labor productivity at different temperatures

Ecological, eg, % impact on crop yields at different temperatures

Physical, eg, % capital stock damaged at X feet of flooding

Example

Worker productivity



Evaluate direct impacts in absence of adaptation

Description

Immediate impact of climate change on socioeconomic systems

Assumes exposure increases in line with historical trends, vulnerability remains as today

Calculated as
Σ p(s) X E (s) X v(s)

Types of socioeconomic systems impacted

Livability and workability

Food systems

Physical assets

Infrastructure services

Natural capital

Example

Properties are damaged by flooding

GDP is lost due to reduced worker productivity from heat stress

Evaluate knock-on impact

Description

Cascading effects on economic, financial, and social systems from direct impacts of climate change

Types

Impact on connected sectors and regions, eg, downstream parts of supply chains, government revenue, profits

Could also include potentially "destabilizing" impacts (eg, regulatory step change, financial market impacts, migration, social unrest)

Example

Prospective buyers recognize climate risk, and demand for coastal housing falls

This reduces property prices in coastal region

Evaluate cost, effectiveness, and ease of implementation of adaptation measures

Description

Assessment of adaptation needs to reduce vulnerability and exposure to climate risk

Includes discussion of adaptation costs and any residual risk that adaptation cannot address

Types

Identify four types of adaptation responses including protecting assets and people, building resilience, reducing exposure, and insurance and finance

Example

Hardening infrastructure, protecting coastal zones, installing backup power supply, building cooling shelters, etc

Source: McKinsey Global Institute analysis

How we selected our case studies and performed the global geospatial risk analysis
In order to link physical climate risk to socioeconomic impact, we investigate nine specific cases that illustrate exposure to climate change extremes and proximity to physical thresholds. To select our case studies, we considered over 30 potential combinations of climate hazards, sectors, and geographies based on a review of the literature and expert interviews on the potential direct impacts of physical climate hazards. We find these hazards affect five different key socioeconomic systems: livability and workability, food systems, physical assets, infrastructure services, and natural capital. We ultimately chose nine cases to reflect these systems and based on their exposure to the extremes of climate change and their proximity today to key physiological, human-made, and ecological thresholds. As such, these cases represent leading-edge examples of climate change risk. For each case, we used the approach described above to quantify the inherent direct and knock-on risk from climate change, as well as outline a possible adaptation response.

For the global geospatial risk assessment, we began with the full set of 195 member countries of the United Nations, and then removed 90 of those due to their small geographic size, in order to account for the fact that GCMs' predictive skill decreases with spatial resolution. Therefore, we analyzed 105 countries against six indicators that cover the five socio-economic systems impact by climate change (Exhibit A2–A7).[21] We did this using geospatial data on climate hazards (including a probabilistic assessment of the severity of the hazard and the likelihood of occurrence of events of different severity), exposure, and resilience. For example, we evaluated the potential for physical asset destruction by assessing the likelihood of floods of different severity and multiplied that against capital stock exposed to the flooding and the share of capital stock that could be damaged at different flood severities. We then added these up across different flood events to arrive at an annual expected damage number (that is, a probability-weighted assessment of possible impact). Note that this analysis provides an estimate only of the direct impact of physical climate risk and not the knock-on effects. These country-level analyses were then added up, where possible, in order to derive global insights about the evolution and distribution of various forms of climate risk.

A detailed discussion of the indicators used in the assessment is provided in Chapter 4 of the report. Here we primarily discuss the details of the hazard data used in the analysis, and climate models used in the analysis. We examined a subset of possible climate hazards, defining and measuring them as follows:

Lethal heat waves are defined as three-day events during which average daily maximum “wet-bulb” temperature could exceed the survivability threshold for a healthy human being resting in the shade. (Wet-bulb temperature is the lowest temperature to which air can be cooled by the evaporation of water into the air at a constant pressure.) We took the average wet-bulb temperature of the hottest six-hour period across each rolling three-day period as the relevant threshold. This was calculated according to the methodology in Stull (2011).[22] The threshold maximum temperature chosen for this analysis was 34 degrees Celsius wet-bulb because the commonly defined heat threshold for human survivability is 35 degrees wet-bulb. At this temperature, a healthy human being, resting in the shade, can survive outdoors for four to five hours. Large cities with significant urban heat island effects could push 34 degrees Celsius wet-bulb heat waves over the 35-degree threshold. This could lead to widespread mortality in the absence of targeted adaptation.[23] The lethal heatwave projections were derived from the CMIP5 multimodel ensemble, where each model was independently bias-

---

[21] The indicators include: share of annual GDP at risk due to extreme heat and share of people at mortality risk due to lethal heat waves (measures of decrease in workability and livability), expected value of cereal production at risk of agricultural failure (measure of disruption of food systems), capital stock at risk of damage from floods, and share of a given decade spent in drought and land area experiencing biome shift (measures of destruction of natural capital).

[22] R. Stull, 'Wet-bulb Temperature from Relative Humidity and Air Temperature," *Journal of Applied Meteorology and Climatology,* November 2011, Volume 50, pp. 2267–69.

[23] A healthy human being can survive exposure to 35C wet-bulb temperatures for roughly 5 hours, assuming they are well hydrated and resting in the shade. For more details, please see Steven C. Sherwood and Matthew Huber, "An adaptability limit to climate change due to heat stress," *Proceedings of the National Academy of Sciences,* May 2010, Volume 107, Number 21, pp. 9552–55.

corrected using the ERA-Interim dataset.[24] Specifically, the projected incidence of lethal heatwaves between the 2021–40 period were counted across 20 GCMs drawn from the CMIP5 ensemble and independently bias corrected. Because 20 single-year observations across 20 models provides a sample size of only 400 years of data, the sample size was bootstrapped out to 1,000 years. Once a robust statistical sample size was established, the projected annual probability of a lethal heatwave was identified for each specific location by treating each year as independent. To account for a bug in the arid land-atmosphere feedbacks in the MIROC family of models, the analysis was performed both with and without the MIROC models. The results were insensitive to their exclusion.[25] We eventually excluded all grid cells where the annual likelihood of lethal heatwaves was less than 1 percent. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects. High levels of atmospheric aerosols provide a cooling effect that masks the risk. Atmospheric aerosols, or air pollution reflect a proportion of incoming sunlight and therefore artificially cool regions, reducing air temperatures.[26]

Today, the regions that are subject to non-zero risk of lethal heatwaves all have high prevalence of atmospheric aerosols (see India case for further details). However, the CMIP5 models have poor representation of observed atmospheric aerosols in those regions. As a result, if the CMIP5 results showed a non-zero probability of lethal heat waves in certain regions today, this was set to zero.

The other form of uncertainty relates to the urban heat island effect. A global analysis of 419 major cities showed that the average daytime temperature difference between urban areas and their immediate surroundings is +1.5 ± 1.2°C, with some outliers up to 7 degrees Celsuis warmer.[27] Research has demonstrated that many cities in India exhibit a negative urban heat island intensity in summer—that is, during the hot pre-monsoon season, they are cooler than their surroundings. This cooling effect is due to both to atmospheric aerosols and the relatively high vegetation cover in cities compared to their surroundings, which contain largely barren lands that are converted to croplands only post-monsoon. While these findings apply to much of the Indian subcontinent, the authors found that many cities in the north of the country exhibit statistically significant positive urban heat island intensities. Because this area of the country is also projected to be the first to exhibit heat waves close to the 35-degree threshold and because a reduction in atmospheric aerosols could further reduce the artificial cooling effect currently underway, these cities are at risk of having 34-degree heat waves amplified to 35-degree heat waves.[28]

Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions is calculated using the average percentage of a given 12-hour workday lost in regions exposed to these hazards. Labor capacity is lost due to heat and humidity through two mechanisms: the first, because workers must take breaks to avoid heatstroke, and the second because the body will naturally limit physiological output in hot conditions by fatiguing itself in a process known as “self-limiting.” Temperature projections were likewise taken from the CMIP5 multimodel ensemble mean projection, again bias corrected using the ERA-Interim dataset. Conversion to lost working hours was done following the methodology of Dunne et al. (2013), using combined ISO heat-exposure standards corrected with empirical data from Foster et al. (2019).[29] When deriving global GDP

---

[24] Bias corrected using the LOCI method, according to: Jürg Schmidli et al., "Downscaling from GCM precipitation: A benchmark for dynamical and statistical downscaling methods," *International Journal of Climatology,* April 2006, Volume 26, Number 5, p. 679–89.

[25] Geert Jan Van Oldenborgh et al., "Extreme heat in India and anthropogenic climate change," *Natural Hazards and Earth System Sciences,* 2018, Volume 18, Number 1, pp. 365–81.

[26] Geert Jan van Oldenborgh et al., “Extreme heat in India and anthropogenic climate change,” Natural Hazards and Earth System Sciences, 2018, Volume 18, Issue 1.

[27] Shushi Peng et al., “Surface urban heat island across 419 global big cities,” Environmental Science & Technology, January 2012, Volume 46, Issue 2.

[28] Hiteshri Shastri et al., “Flip flop of day-night and summer-winter surface urban heat island intensity in India,” Nature Scientific Reports, January 9, 2017, Volume 7.

[29] John P. Dunne et al., "Reductions in labour capacity from heat stress under climate warming," *Nature Climate Change,* February 2013, Volume 3, pp. 563–66; Josh Foster et al., "A new paradigm to quantify reduction of physical work capacity in the heat," *Medicine and Science in Sports and Exercise,* 2019, Volume 51, Number 6, p. 15.

at risk, we applied lost working hours to GDP generated in sectors that we were confident are exposed to heat and humidity risk globally: agriculture, mining and quarrying, and construction. Lost working hours were applied one-to-one to sector GDP: that is, a projected X percent reduction in working hours is assumed to lead to an X percent reduction in sector GDP. These estimates are, as a result, likely an underestimate, as other sectors (particularly hospitality and tourism) are also exposed to heat. We considered a range based on the pace of sectoral transitions, ranging from keeping sector mix at today's level, to varying it going forward based on projections from IHS Markit Economics and Country Risk. To investigate the potential range of uncertainty around these findings, we explored the range of variability around the mean projection as captured by the ensemble model spread: we performed the same analysis using the 75th and 25th percentile ensemble projections. This was done to capture the potential impacts in an "average" year, compared with a "hotter than average" or "colder than average" year. Countries that include no change in share of effective outdoor working hours affected as a possible outcome within the range of model uncertainty by 2030 were noted as likely not robust. All countries show robust trends by 2050.

For our agricultural investigation, we used projections from the AgMIP ensemble. Changes in yield were quantified relative to the mean yield for the 1998–2017 period. Because projections from the AgMIP ensemble scale in skillfulness as a function of both physical spatial resolution and intensity of crop production, we were not able to perform a country-by-country analysis. (In other words, we were not able to obtain robust projections for small countries and large countries with marginal agricultural output.) Instead, we identified the largest grain breadbaskets in each region and quantified changes to output there. Agricultural projections were done using the mean projection from the full range of available GCMs, as well as the full range of non-potential-yield crop models. Nitrogen limitation and CO_2 fertilization were kept “ON” for all projections. We did not account for reductions in nutritional content of crops. Therefore, these results may be underestimates, as future behavior of CO_2 fertilization is not well constrained.

Water stress and change in water supply is calculated using the increase or decrease in the average annual supply of renewable freshwater available in a given water basin. The amount of available renewable freshwater is a function of annual precipitation over that basin, as well as influx and outflux of water to and from that basin via riverine systems. Water supply data were taken from the World Resources Institute, which combines output from the CMIP5 ensemble with the GLDAS-2 NOAH v. 3.3 hydrological model. Data was taken from the World Resources Institute Water Risk Atlas (2018), which relies on six underlying CMIP5 models. Time periods of this raw dataset are the 20-year periods centered on 2020, 2030, and 2040. The 1998–2017 and 2041–60 data were linearly extrapolated from the 60-year trend provided in the base dataset. For our global geospatial assessment across countries of water stress, we assumed water demand stayed constant at today's levels, to allow us to isolate and investigate the impact of climate change alone.

Our flooding hazard measure starts first by assessing the depth and spatial extent of a riverine flood event (measured in volume) for the full probability exceedance curve (100% to 0% chance) in a given year over the 1960–1999 period in a given 900-by-900-meter grid cell globally. This database was taken from the World Resources Institute, and a full methodology on its development is available on their website. This was then overlaid with data on precipitation changes, to approximate future flood hazards. This approach therefore should be considered to be only an approximation of the evolution of flooding hazard, and it should be noted that a more robust analysis of flooding will require the use of granular flood models. While the probability of extreme precipitation events is increasing over most of the world (due to the ability of warmer air to hold more water vapor than colder air), this increase is not uniform. Change in extreme precipitation probability was taken from a 1,000-year bootstrap of the CMIP5 multimodel ensemble, and then applied to the baseline flood data as a proxy for change in flood probability. When calculating capital stock at risk, the European Research Council’s global flood depth damage functions were applied to UNGAR15’s capital stock database. Existing flood protection for 1-in-50 to 1-in-100 year floods were assumed.

Further limitations of this analysis include the focus on riverine flooding only (versus tidal, flash, or pluvial flooding, or flooding from storm surge), the ability to identify flood protections globally in a robust way and therefore adjust for today's level of adaptation, and the ability to identify damage functions for capital stock that are specific to an individual site, such as a given building or a factory, rather than rely on more general damage functions.

Our drought hazard is calculated using the percentage of a given decade spent in drought conditions, where drought conditions are defined as a running three-month average where the self-calibrating Palmer Drought Severity Index value is less than -2. Drought data were taken from the CMIP5 multimodel ensemble mean projection and corrected for changes in biosphere behavior as a result of increases in atmospheric CO_2.

Our measure of natural capital risk is defined as the percentage of land surface that changes category under the Köppen climate classification system, which evaluates a particular area based on average annual climate statistics, like precipitation and temperature. While not a perfect analogue, ecosystem type correlates very closely with Köppen climate classification, and therefore shifts are a good directional indicator of ecosystem stress or change.[30]

---

[30] Our biome shift data were taken from Franz Rubel and Markus Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift (Contributions to Atmospheric Sciences),* April 2010, Volume 19, Number 2.

Exhibit A2

We identify six types of countries based on their patterns of expected change in climate impacts.

Based on RCP 8.5

○ Risk decrease ◔ No or slight risk increase ◑ Moderate risk increase ● High risk increase

Country	Change in… (2018–50, pp) Livability and workability			Food systems	Physical assets/ infrastructure services	Natural capital
	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Significantly hotter and more humid countries						
Bangladesh	●	●	○	○	◔	◑
Benin	●	●	○	◑	○	◔
Burkina Faso	●	●	○	○	◔	◔
Cambodia	◑	●	○	◔	●	◔
Côte d’Ivoire	◑	●	○	◔	◑	◑
Eritrea	◑	●	○	○	◔	◔
Ghana	◑	●	○	◔	◑	◑
India	●	●	○	○	◑	●
Myanmar	◑	●	○	○	●	●
Niger	●	●	○	○	◔	◔
Nigeria	●	●	○	◔	◔	◔
Pakistan	●	◑	○	◔	◔	◑
Senegal	◑	●	◔	◔	◔	◔
Thailand	◑	●	○	○	●	◔
Vietnam	●	●	○	◔	◑	●
Yemen	●	●	○	○	◔	◑
Hotter and more humid countries						
Angola	◔	●	○	◔	●	●
Cameroon	◔	●	○	◔	◑	◔
Chad	◔	●	○	○	◑	◔

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on “expected values”, ie, probability-weighted value at risk.

Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit A3

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5

□ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase █ High risk increase

	Livability and workability			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
Country — Change in… (2018–50, pp)	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Hotter and more humid countries (continued)						
Ecuador	░	█	□	░	█	▒
Ethiopia	░	▒	□	□	▒	█
Guinea	░	█	□	░	▒	░
Guyana	░	█	□	█	░	░
Indonesia	░	█	□	░	█	░
Japan	░	▒	□	░	█	█
Jordan	░	▒	□	█	█	░
Laos	░	█	□	□	▒	█
Liberia	░	█	□	░	█	█
Madagascar	░	█	□	░	░	█
Papua New Guinea	░	█	□	░	█	░
Philippines	░	█	□	□	░	▒
Saudi Arabia	░	█	□	□	░	░
Somalia	░	█	□	□	▒	░
Suriname	░	█	□	█	░	░
Tanzania	░	▒	□	░	▒	▒
Uganda	░	▒	□	□	█	█
Uruguay	░	▒	□	░	█	░
Zambia	░	▒	□	█	▒	█

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

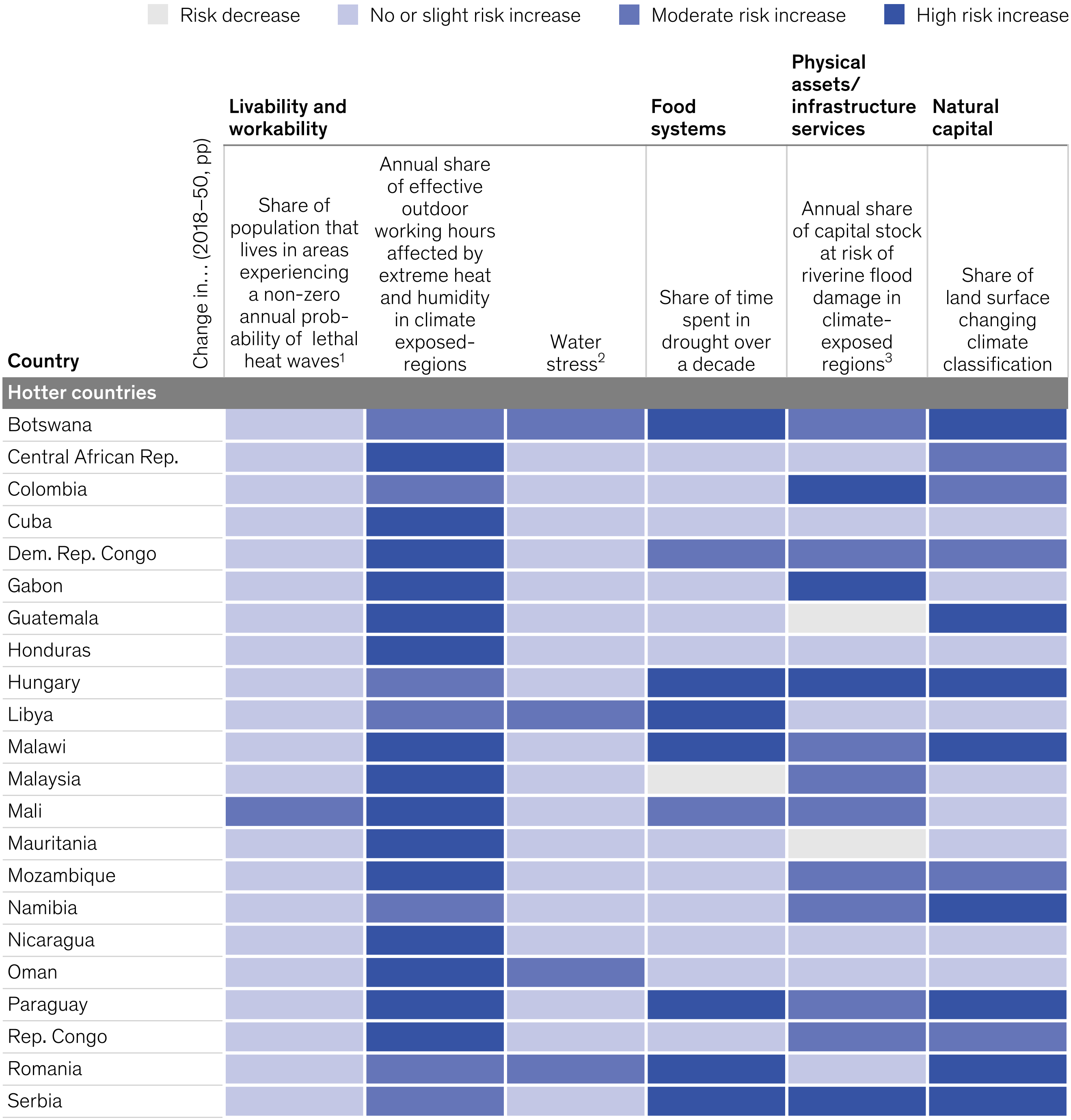
Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit A4

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



□ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase ■ High risk increase

Change in… (2018–50, pp)

Country	**Livability and workability**			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Hotter countries						
Botswana	░	▒	▒	■	▒	■
Central African Rep.	░	■	░	░	░	▒
Colombia	░	▒	░	░	■	▒
Cuba	░	■	░	░	░	░
Dem. Rep. Congo	░	■	░	▒	▒	▒
Gabon	░	■	░	░	■	░
Guatemala	░	■	░	░	□	■
Honduras	░	■	░	░	░	░
Hungary	░	▒	░	■	■	■
Libya	░	▒	▒	■	░	░
Malawi	░	■	░	■	▒	■
Malaysia	░	■	░	□	▒	░
Mali	▒	■	░	▒	▒	░
Mauritania	░	■	░	░	□	░
Mozambique	░	■	░	░	▒	▒
Namibia	░	▒	░	░	▒	■
Nicaragua	░	■	░	░	░	░
Oman	░	■	▒	░	░	░
Paraguay	░	■	░	■	▒	■
Rep. Congo	░	■	░	░	▒	▒
Romania	░	▒	▒	■	░	■
Serbia	░	▒	░	■	■	■

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit A5

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5

⬜ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase ▓ High risk increase

Change in… (2018–50, pp)	**Livability and workability**			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
Country	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Hotter countries (continued)						
South Korea	░	▒	▒	░	▒	▓
Venezuela	░	▓	▒	░	░	░
Zimbabwe	░	▒	░	▓	▓	▓
Increased water stress countries						
Algeria	░	▒	▓	▓	░	░
Australia	░	▒	▓	▒	░	▒
Azerbaijan	░	▒	▓	▓	▒	▓
Bulgaria	░	▒	▓	▓	░	▓
Egypt	░	▓	▓	▓	░	░
Greece	░	▒	▓	▓	░	▓
Iran	░	▒	▓	▒	▓	▓
Italy	░	▒	▓	▓	▒	▓
Kazakhstan	░	▒	▓	░	░	▓
Kyrgyzstan	░	░	▓	▓	▓	▓
Mexico	░	▒	▓	░	▓	▓
Morocco	░	▒	▓	░	░	▓
Portugal	░	▒	▓	░	▒	▓
South Africa	░	▒	▓	░	▓	▓
Spain	░	▒	▓	░	▓	▓
Syria	░	▒	▓	▓	▓	▓
Tajikistan	░	▒	▓	▓	▓	▓
Tunisia	░	▒	▓	▓	░	▒

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

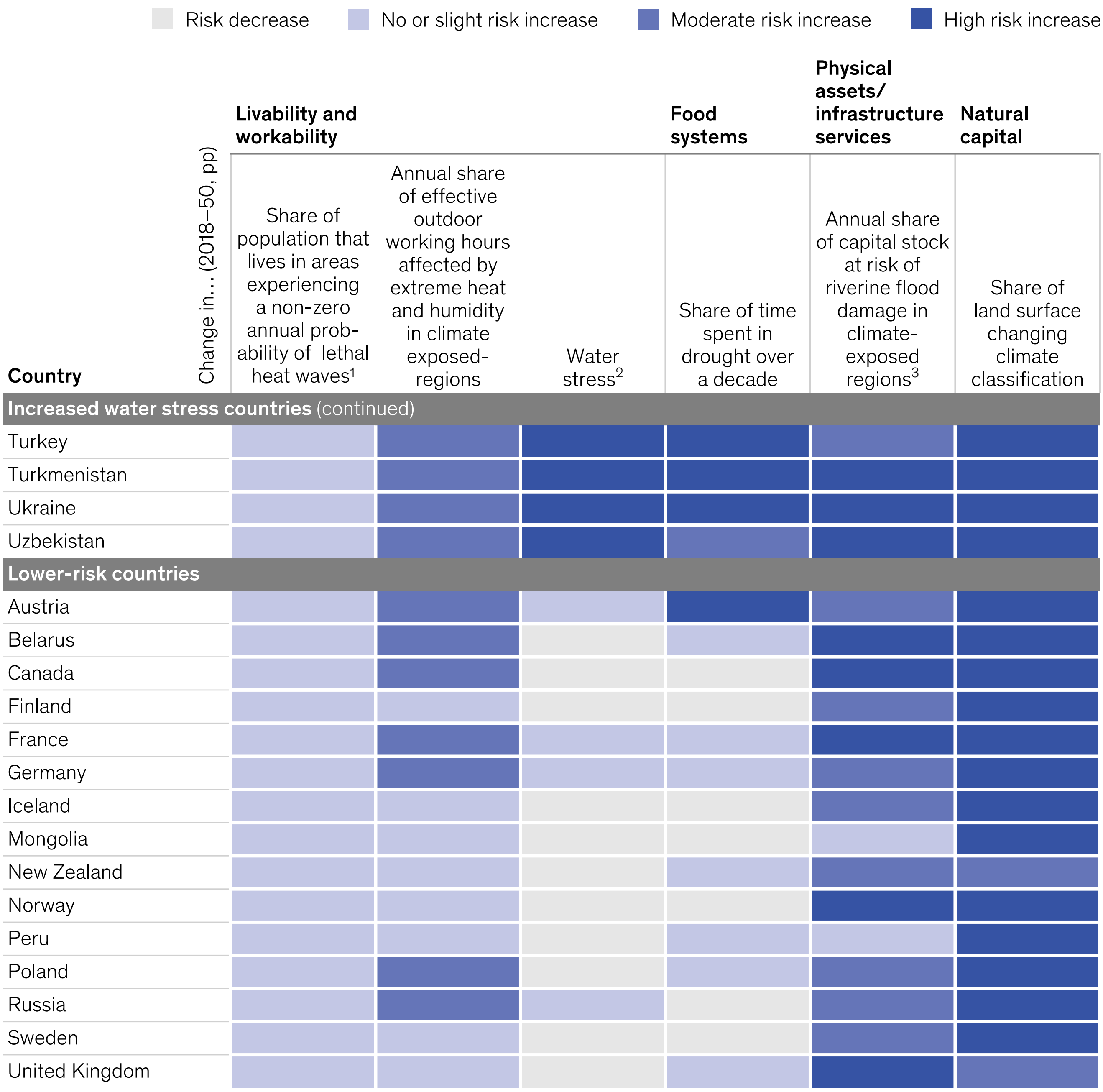
Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit A6

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



⬜ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase ▓ High risk increase

Country	Change in… (2018–50, pp) Livability and workability: Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Livability and workability: Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Livability and workability: Water stress[2]	Food systems: Share of time spent in drought over a decade	Physical assets/infrastructure services: Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Natural capital: Share of land surface changing climate classification
Increased water stress countries (continued)						
Turkey	░	▒	▓	▓	▒	▓
Turkmenistan	░	▒	▓	▓	▓	▓
Ukraine	░	▒	▓	▓	▓	▓
Uzbekistan	░	▒	▓	▒	▓	▓
Lower-risk countries						
Austria	░	▒	░	▓	▒	▓
Belarus	░	▒	⬜	░	▓	▓
Canada	░	▒	⬜	⬜	▓	▓
Finland	░	░	⬜	⬜	▒	▓
France	░	▒	░	░	▓	▓
Germany	░	▒	░	░	▒	▓
Iceland	░	░	⬜	⬜	▒	▓
Mongolia	░	░	⬜	⬜	░	▓
New Zealand	░	░	⬜	░	▒	▒
Norway	░	░	⬜	⬜	▓	▓
Peru	░	░	⬜	░	░	▓
Poland	░	▒	⬜	░	▒	▓
Russia	░	▒	░	⬜	▒	▓
Sweden	░	░	⬜	⬜	▒	▓
United Kingdom	░	░	⬜	░	▓	▒

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.

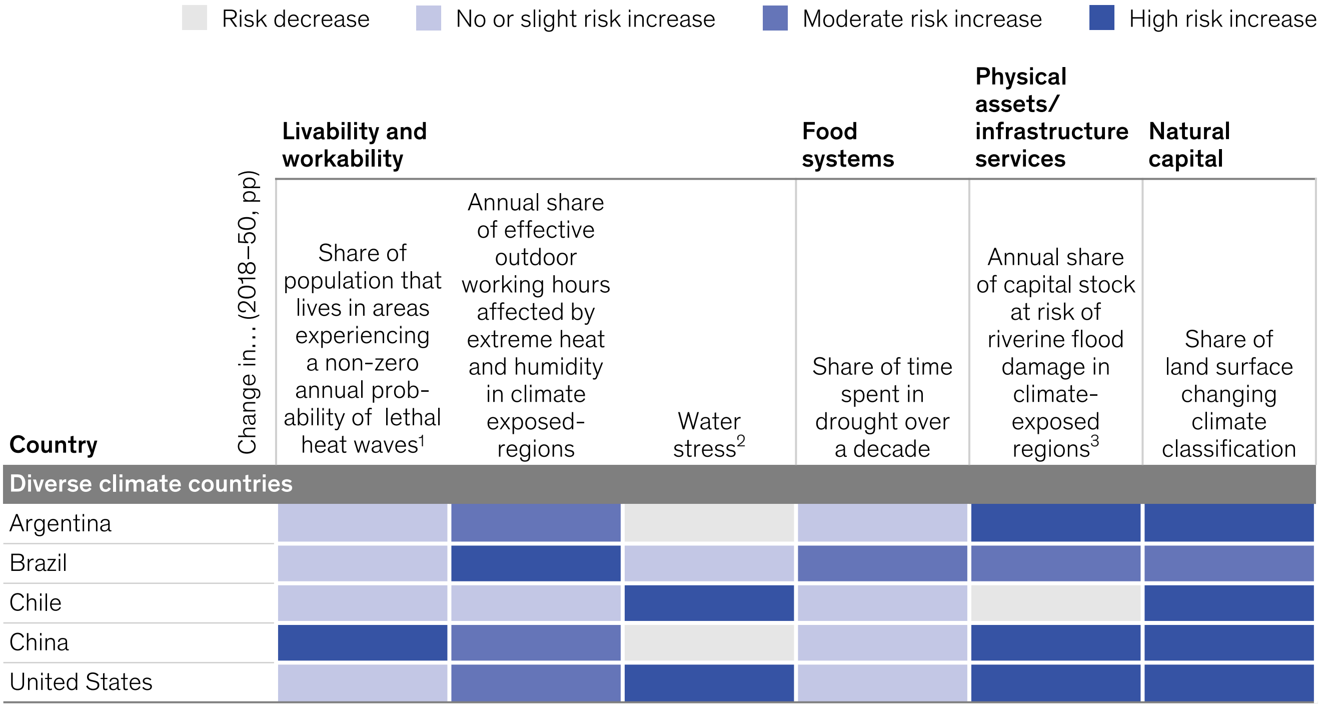
Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

Exhibit A7

We identify six types of countries based on their patterns of expected change in climate impacts (continued).

Based on RCP 8.5



⬜ Risk decrease ░ No or slight risk increase ▒ Moderate risk increase █ High risk increase

Change in… (2018–50, pp)

	Livability and workability			**Food systems**	**Physical assets/ infrastructure services**	**Natural capital**
Country	Share of population that lives in areas experiencing a non-zero annual probability of lethal heat waves[1]	Annual share of effective outdoor working hours affected by extreme heat and humidity in climate exposed-regions	Water stress[2]	Share of time spent in drought over a decade	Annual share of capital stock at risk of riverine flood damage in climate-exposed regions[3]	Share of land surface changing climate classification
Diverse climate countries						
Argentina	░	▒	⬜	░	█	█
Brazil	░	█	░	▒	▒	▒
Chile	░	░	█	░	⬜	█
China	█	▒	⬜	░	█	█
United States	░	▒	█	░	█	█

Change in potential impact, 2018–50[4] (percentage points)

Risk decrease	n/a	n/a	<0	<0	<0	n/a
No or slight risk increase	0–0.5	0–0.5	0–3	0–3	0–0.05	0–5
Moderate risk increase	0.5–5.0	0.5–5.0	3–7	3–7	0.05–0.10	5–10
High risk increase	>5.0	>5.0	>7	>7	>0.10	>10

1. We define a lethal heat wave as a 3-day period with maximum daily wet-bulb temperatures exceeding 34°C wet-bulb. This threshold was chosen because the commonly defined heat threshold for human survivability is 35°C wet-bulb, and large cities with significant urban heat island effects could push 34°C wet-bulb heat waves over the 35°C threshold. These projections are subject to uncertainty related to the future behavior of atmospheric aerosols and urban heat island or cooling island effects.
2. Water stress is measured as annual demand of water as a share of annual supply of water. For this analysis, we assume that the demand for water stays constant over time, to allow us to measure the impact of climate change alone. Water stress projections for arid, low-precipitation regions were excluded due to concerns about projection robustness.
3. Risk values are calculated based on "expected values", ie, probability-weighted value at risk.
4. Calculated assuming constant exposure. Constant exposure means that we do not factor in any increases in population or assets, or shifts in the spatial mix of population and assets. This was done to allow us to isolate the impact of climate change alone. Color coding for each column based on the spread observed across countries within the indicator.

Note: See the Technical appendix for why we chose RCP 8.5. All projections based on RCP 8.5, CMIP 5 multi model ensemble. Heat data bias corrected. Following standard practice, we define current and future (2030, 2050) states as the average climatic behavior over multidecade periods. Climate state today is defined as average conditions between 1998 and 2017, in 2030 as average between 2021 and 2040, and in 2050 as average between 2041 and 2060.

Source: Woods Hole Research Center; World Resources Institute Water Risk Atlas, 2018; World Resources Institute Aqueduct Global Flood Analyzer; Rubel and Kottek, 2010; McKinsey Global Institute analysis

This is a tab page.
Please title tab
“NCA”

29 Reducing Risks Through Emissions Mitigation

Federal Coordinating Lead Author
Jeremy Martinich
U.S. Environmental Protection Agency

Chapter Lead
Jeremy Martinich
U.S. Environmental Protection Agency

Chapter Authors
Benjamin DeAngelo
National Oceanic and Atmospheric Administration

Delavane Diaz
Electric Power Research Institute

Brenda Ekwurzel
Union of Concerned Scientists

Guido Franco
California Energy Commission

Carla Frisch
U.S. Department of Energy

James McFarland
U.S. Environmental Protection Agency

Brian O'Neill
University of Denver (National Center for
Atmospheric Research through June 2018)

Review Editor
Andrew Light
George Mason University

Recommended Citation for Chapter

Martinich, J., B.J. DeAngelo, D. Diaz, B. Ekwurzel, G. Franco, C. Frisch, J. McFarland, and B. O'Neill, 2018: Reducing Risks Through Emissions Mitigation. In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 1346–1386. doi: 10.7930/NCA4.2018.CH29

On the Web: https://nca2018.globalchange.gov/chapter/mitigation

29 Reducing Risks Through Emissions Mitigation

Jasper, New York

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

Executive Summary

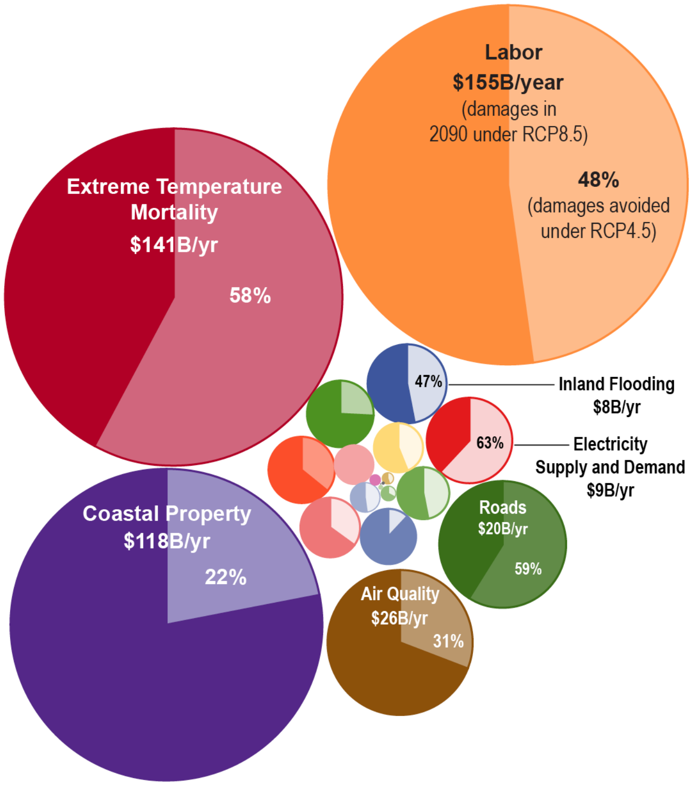
Current and future emissions of greenhouse gases, and thus emission mitigation actions, are crucial for determining future risks and impacts of climate change to society. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those reductions, and the relative mix of mitigation strategies for emissions of long-lived greenhouse gases (namely, carbon dioxide), short-lived greenhouse gases (such as methane), and land-based biologic carbon.[1] Many actions at national, regional, and local scales are underway to reduce greenhouse gas emissions, including efforts in the private sector.

Climate change is projected to significantly damage human health, the economy, and the environment in the United States, particularly under a future with high greenhouse gas emissions. A collection of frontier research initiatives is underway to improve understanding and quantification of climate impacts. These studies have been designed across a variety of sectoral and spatial scales and feature the use of internally consistent climate and socioeconomic scenarios. Recent findings from these multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly at the end of the century—with negative consequences for a large majority of sectors, including infrastructure and human health.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods, the effects are typically dwarfed by changes happening overall within the sector or at broader scales.

Recent studies also show that many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions. While the difference in climate outcomes between scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter. Research supports that early and substantial mitigation offers a greater chance of avoiding increasingly adverse impacts.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population. Physical damages to coastal property and transportation infrastructure are particularly sensitive to adaptation assumptions, with proactive measures estimated to be capable of reducing damages by large fractions. Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies. However, adaptation can require large up-front costs and long-term commitments for maintenance, and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk. Interactions between adaptation and mitigation strategies can result in benefits or adverse consequences. While uncertainties still remain, advancements in the modeling of climate and economic impacts, including current understanding of adaptation pathways, are increasingly providing new capabilities to understand and quantify future effects.

Projected Damages and Potential for Risk Reduction by Sector



	Annual Economic Damages in 2090		
	Sector	**Annual damages under RCP8.5**	**Damages avoided under RCP4.5**
🟧	**Labor**	$155B	48%
🟥	**Extreme Temperature Mortality◊**	$141B	58%
🟪	**Coastal Property◊**	$118B	22%
🟫	**Air Quality**	$26B	31%
🟩	**Roads◊**	$20B	59%
🟥	**Electricity Supply and Demand**	$9B	63%
🟦	**Inland Flooding**	$8B	47%
🟩	**Urban Drainage**	$6B	26%
🟥	**Rail◊**	$6B	36%
🟥	**Water Quality**	$5B	35%
🟦	**Coral Reefs**	$4B	12%
🟩	**West Nile Virus**	$3B	47%
🟨	**Freshwater Fish**	$3B	44%
🟥	**Winter Recreation**	$2B	107%
🟦	**Bridges**	$1B	48%
🟩	**Munic. and Industrial Water Supply**	$316M	33%
🟨	**Harmful Algal Blooms**	$199M	45%
🟪	**Alaska Infrastructure◊**	$174M	53%
⬜	**Shellfish***	$23M	57%
🟩	**Agriculture***	$12M	11%
⬛	**Aeroallergens***	$1M	57%
⬛	**Wildfire**	−$106M	−134%

The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. *From Figure 29.2 (Source: adapted from EPA 2017).*[2]

Introduction

This chapter assesses recent advances in climate science and impacts, adaptation, and vulnerability research that have improved understanding of how potential mitigation pathways can avoid or reduce the long-term risks of climate change within the United States. This chapter does not evaluate technology options, costs, or the adequacy of existing or planned mitigation efforts relative to meeting specific policy targets, as those topics have been the subject of domestic (e.g., Executive Office of the President 2016, CCSP 2007, DeAngelo et al. 2017, NRC 2015[7,8,9,10]) and international analyses (e.g., Fawcett et al. 2015, Clarke et al. 2014[11,12]). Also, this chapter does not assess the potential roles for carbon sinks (or storage) in mitigation, which are discussed in Chapter 5: Land Changes, and in the Second State of the Carbon Cycle Report.[13] Further, it is beyond the scope of this chapter and this assessment to evaluate or recommend policy options.

USGCRP defines risk as threats to life, health and safety, the environment, economic well-being, and other things of value. Risks are often evaluated in terms of how likely they are to occur (probability) and the damages that would result if they did happen (consequences).

Both mitigation and adaptation responses to climate change are likely to occur as part of an iterative risk management strategy in which initial actions are modified over time as learning occurs (Ch. 28: Adaptation). This chapter focuses primarily on the early stages of this iterative process in which risks and vulnerabilities are identified and the potential climate impacts of emissions scenarios are assessed.

Box 29.1: Options for Reducing or Removing Greenhouse Gases

Mitigation refers to measures to reduce the amount and speed of future climate change by reducing emissions of greenhouse gases (GHGs) or by increasing their removal from the atmosphere. Emission reduction measures include replacing conventional, CO_2-emitting fossil fuel energy technologies or systems with low- or zero-emissions ones (such as wind, solar, nuclear, biofuels, fossil energy with carbon capture and storage, and energy efficiency measures), as well as changing technologies and practices in order to lower emissions of other GHGs such as methane, nitrous oxide, and hydrofluorocarbons.[7,14,15] Measures that enhance the removal of CO_2 from the atmosphere (see Box 29.3) include changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] Using captured CO_2 in products such as polymers and cement is a potential alternative to geologic storage.[17]

The adoption of these measures may be promoted through a variety of policy instruments, such as emissions pricing (that is, GHG emission fees or emissions caps with permit trading), regulations and standards (such as emission standards, technology requirements, and building codes), subsidies (for example, tax incentives and rebates), and public funding for research, development, and demonstration programs.

Timing and Magnitude of Action

Current and future emissions, and thus emissions mitigation actions, are crucial for determining future risks and impacts. The scale of risks that can be avoided through mitigation actions is influenced by the magnitude of emissions reductions, the timing of those emissions reductions, and the relative mix of mitigation strategies for emissions of long-lived GHGs (namely, CO_2), short-lived GHGs (such as methane), and land-based biologic carbon.[1] Intentional removal of CO_2 from the atmosphere, often referred to as negative emissions, or other climate interventions have also been proposed[10,18] and may play a role in future mitigation strategies (see Box 29.3).

Net cumulative CO_2 emissions in the industrial era will largely determine long-term global average temperature change[9] and thus the risks and impacts associated with that change in the climate. Large reductions in present-day emissions of the long-lived GHGs are estimated to have modest temperature effects in the near term (over the next couple decades), but these emission reductions are necessary to achieve any long-term objective of preventing warming of any desired magnitude.[9] Decisions that decrease or increase emissions over the next few decades will set into motion the degree of impacts that will likely last throughout the rest of this century, with some impacts (such as sea level rise) lasting for thousands of years or even longer.[19,20,21]

Meeting any climate stabilization goal, such as the oft-cited objective of limiting the long-term globally averaged temperature to 2°C (3.6°F) above preindustrial levels, necessitates that there be a physical upper limit on the cumulative amount of CO_2 that can be added to the atmosphere.[9] Early and substantial mitigation offers a greater chance for achieving a long-term goal, whereas delayed and potentially much steeper emissions reductions jeopardize achieving any long-term goal given uncertainties in the physical response of the climate system to changing atmospheric CO_2, mitigation deployment uncertainties, and the potential for abrupt consequences.[11,22,23] Early efforts also enable an iterative approach to risk management, allowing stakeholders to respond to what is learned over time about climate impacts and the effectiveness of available actions (Ch. 28: Adaptation).[24,25,26] Evidence exists that early mitigation can reduce climate impacts in the nearer term (such as reducing the loss of perennial sea ice and effects on ice-dwelling species) and, in the longer term, prevent critical thresholds from being crossed (such as marine ice sheet instability and the resulting consequences for global sea level change).[27,28,29,30]

State of Emissions Mitigation Efforts

Actions are currently underway at global, national, and subnational scales to reduce GHG emissions. This section provides an overview of agreements, policies, and actions being taken at various levels.

Long-Term Temperature Goals and the Paris Agreement

The idea of limiting globally averaged warming to a specific value has long been examined in the scientific literature and, in turn, gained attention in policy discourse (see DeAngelo et al. 2017 for additional information[9]). Most recently, the Paris Agreement of 2015 took on the long-term aims of “holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”.[31] These targets were developed with the goal of avoiding the most severe climate impacts; however, they should not be viewed as thresholds below which there are zero risks and above which numerous tipping points occur (that is, a point at which a change in the climate triggers a significant environmental event, which may be permanent). In order to reach the Paris Agreement's long-term temperature goal, Parties to the Agreement "aim to reach global peaking of GHG emissions as soon as possible . . . and to undertake rapid reductions thereafter." Many countries announced voluntary, nonbinding GHG emissions reduction targets and related actions in the lead-up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and took a range of forms.[31] The Paris Agreement has been ratified by 180 Parties to the UN Framework Convention on Climate Change, which account for 88% of global GHG emissions.[32,33]

Achieving the Paris Agreement target of limiting global mean temperature to less than 2°C (3.6°F) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net CO_2 emissions to become zero or possibly negative later in the century, relying on as-yet unproven technologies to remove CO_2 from the atmosphere. To remain under this temperature threshold with two-thirds likelihood, future cumulative net CO_2 emissions would need to be limited to approximately 230 gigatons of carbon (GtC), an amount that would be reached in roughly the next two decades assuming global emissions follow the range between the RCP4.5 and RCP8.5 scenarios.[9] Achieving global GHG emissions reduction targets and actions announced by governments in the lead-up to the 2015 Paris climate conference would hold open the possibility of meeting the 2°C (3.6°F) temperature goal, whereas there would be virtually no chance if net global emissions followed a pathway well above those implied by country announcements.[9]

In June 2017, the United States announced its intent to withdraw from the Paris Agreement.[34] The statement is available online: https://www.whitehouse.gov/briefings-statements/statement-president-trump-paris-climate-accord/. The earliest effective date of formal withdrawal is November 4, 2020. Some state governments, local governments, and private-sector entities have announced pledges to reduce emissions in the context of long-term temperature aims consistent with those outlined in the Paris Agreement.[35,36]

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector. Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions.

Many activities within the public and private sectors either aim to or have the effect of reducing these emissions. Fossil fuel combustion accounts for 77% of the total U.S. GHG emissions (using the 100-year global warming potential), with agriculture, industrial processes, and methane from fossil fuel extraction and processing as well as waste accounting for the remainder.[37] A 100-year global warming potential is an index measuring the radiative forcing following an emission of a unit mass of a given substance, accumulated over one hundred years, relative to that of the reference substance, CO_2.[38] At the federal level, a number of measures have been implemented to promote advanced, low-carbon energy technologies and fuels, including energy efficiency. Broadly considered, these measures include

GHG regulations; other rules and regulations with climate co-benefits; codes and standards; research, development, and demonstration projects and programs; federal procurement practices; voluntary programs; and various subsidies (such as production and investment tax credits).[14,39] Federal measures to address sources other than fossil fuel combustion include agriculture and forestry programs to increase soil and forest carbon sequestration and minimize losses through wildfire or other land-use processes, regulations to phase down hydrofluorocarbons, and standards for reducing methane emissions from fossil fuel extraction and processing.[14] The Administration is currently reviewing many of these measures through the lens of Executive Order 13783, which aims to ease regulatory burdens on "the development or use of domestically produced energy resources, with particular attention to oil, natural gas, coal, and nuclear energy resources."[40]

State, local, and tribal government mitigation approaches include comprehensive emissions reduction strategies as well as sector- and technology-specific policies designed for many reasons. As shown in Figure 29.1a, at least 455 cities support emissions reductions in the context of global efforts, including 110 with emissions reduction targets.[36] At the state level, the color shown on each state indicates the total number of activities taken in that state across six policy areas: GHG target/cap/pricing; renewable/carbon dioxide capture and storage (CCS)/nuclear; transportation; energy efficiency; non-CO_2 GHG; and forestry and land use.[36] Figure 29.1b shows the number of activities by policy area for each state. For example, states in the Northeast take part in the Regional Greenhouse Gas Initiative, a mandatory market-based effort to reduce power sector emissions.[41] California has a legal mandate to reduce emissions 40% below 1990 levels by 2030, and in a 2017 law, the state extended its emissions trading program to 2030, as well. Several states have adopted voluntary pledges to reduce emissions. Technology-specific approaches include targets to increase the use of renewable energy such as wind and solar, zero- or low-emissions transportation options, and energy efficient technologies and practices.[42,43] Many tribes are also prioritizing energy-efficiency and renewable-energy projects (Ch. 15: Tribes, KM 1).[44] Mitigation activities related to methane and forestry/land-use activities are growing in number and vary by locale.

In the private sector, many companies seek to provide environmental benefits for a variety of reasons, including supporting environmental stewardship, responding to investor demands for prudent risk management, finding economic opportunities in efforts to reduce GHG emissions, and, in the case of multinationals, meeting mitigation mandates in the European Union or other jurisdictions. Since the last National Climate Assessment, private companies have increasingly taken inventory of their emissions and moved forward to implement science-based emissions reduction targets as well as internal carbon prices.[36] The Carbon Disclosure Project[46] is one example of a voluntary program where companies register their pledges to reduce GHG emissions and/or to manage their climate risks. Corporate purchases of and commitments to purchase renewable energy have increased over the last decade.[47]

Mitigation-Related Activities at State and Local Levels

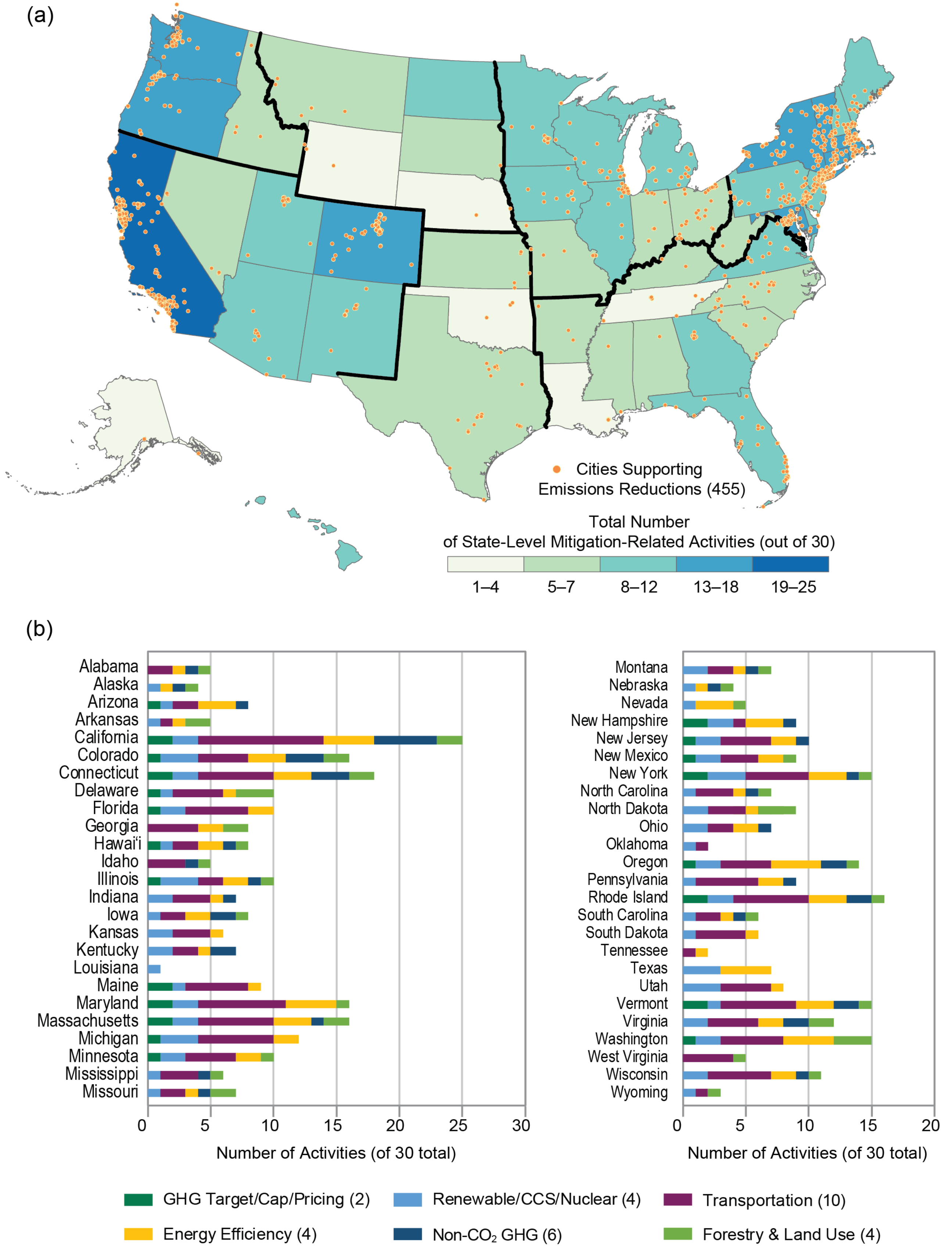


Figure 29.1: The map (a) shows the number of mitigation-related activities at the state level (out of 30 illustrative activities) as well as cities supporting emissions reductions; the chart (b) depicts the type and number of activities by state.[36] Several territories also have a variety of mitigation-related activities including American Sāmoa, the Federated States of Micronesia, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands.[42,45] Sources: (a) EPA and ERT, Inc.; (b) adapted from America's Pledge 2017.[36] *This figure was revised in June 2019. See Errata for details: https://nca2018.globalchange.gov/downloads*

Market forces and technological change, particularly within the electric power sector, have contributed to a decline in U.S. GHG emissions over the past decade. In 2016, U.S. emissions were at their lowest levels since 1994.[37] Power sector emissions were 25% below 2005 levels in 2016, the largest sectoral reduction over this time.[37] This decline was in large part due to increases in natural gas generation as well as renewable energy generation and energy efficiency (Ch. 4: Energy, KM 2).[48] Given these changes in the power sector, the transportation sector currently has the largest annual sectoral emissions (Ch. 12: Transportation).
As of the writing of this report, projections of U.S. fossil fuel CO_2 and other GHG emissions show flat or declining trajectories over the next decade, with a central estimate of about 15%–20% below 2005 levels by 2025.[49,50]
Prior to the adoption of the Paris Agreement, the United States put forward a nonbinding “intended nationally determined contribution” of reducing emissions 26%–28% below 2005 levels in 2025. On June 1, 2017, President Trump announced that the United States would cease implementation of this nationally determined contribution. Some state and local governments, as well as private-sector entities, have announced emission reduction pledges which aim to be consistent with the nonbinding target.[35,36] For more information on trends in, drivers of, and potential efforts to address U.S. GHG emissions, see the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[37]

Reducing Impacts Through Mitigation

To understand how large-scale emissions mitigation can reduce climate impacts, it is useful to look at how the impacts change under various emissions scenarios. In recent years, the science and economics of estimating future climate change impacts have advanced substantially, with increasing emphasis on interdisciplinary approaches to investigate impacts, vulnerabilities, and responses.[51,52,53] These advances have enabled several ongoing frontier research initiatives to improve understanding and quantification of climate impacts at various spatial scales ranging from global to local levels. This section describes findings for the United States from a selection of recent multisector coordinated modeling frameworks listed in Table 29.1, which are frequently cited throughout this chapter because each report provides modeling results across multiple sectors and scenarios similar to those developed for this report. These approaches commonly feature the use of internally consistent climate and socioeconomic scenarios and underlying assumptions across a variety of sectoral analyses. While research projecting physical and economic impacts in the United States has increased considerably since the Third National Climate Assessment (NCA3), it is important to note that this literature is incomplete in its coverage of the breadth of potential impacts.

Collaboration or Project Name	Host/Lead Organization and References	Sectors Covered	Coverage
Benefits of Reduced Anthropogenic Climate changE (BRACE)	National Center for Atmospheric Research (O'Neill et al. 2017)[4]	Heat extremes and health, agriculture and land use, tropical cyclones, sea level rise, drought and conflict	Global
Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth (CIRCLE)	Organisation for Economic Co-operation and Development (OECD 2015)[55]	Tourism, agriculture, coastal, energy, extreme precipitation events, health	Global
Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)	Potsdam Institute for Climate Impact Research (Huber et al. 2014)[56]	Water, agriculture, biomes, infrastructure, health/malaria, fishery, permafrost	Global
American Climate Prospectus (ACP)	Climate Impact Lab (Houser et al. 2015; Hsiang et al. 2017)[3,5]	Agriculture, health, labor productivity, crime and conflict, coastal, energy	United States
Climate Change Impacts and Risk Analysis (CIRA)	U.S. Environmental Protection Agency (EPA 2015, 2017)[2,57]	More than 20 specific impacts categorized into 6 broad sectors: health (including labor productivity), infrastructure, electricity, water resources, agriculture, ecosystems	United States
California Climate Change Assessments	State of California (Cayan et al. 2008, 2013; California Energy Commission 2006)[58,59,60]	Public health, agriculture, energy, coastal, water resources, ecosystems, wildfire, recreation	State-Level
Colorado Climate Change Vulnerability Study	Colorado Energy Office (Gordon and Ojima 2015)[61]	Ecosystems, water, agriculture, energy, transportation, recreation and tourism, public health	State-Level
New York ClimAID Project	New York State Energy Research and Development Authority (Rosenzweig et al. 2011; Horton et al. 2014)[62,63]	Water resources, coastal zones, ecosystems, agriculture, energy, transportation, telecommunications, public health	State-Level

Table 29.1: Selection of Multisector Impacts Modeling Frameworks Since NCA3. Source: adapted from Diaz and Moore 2017.[54]

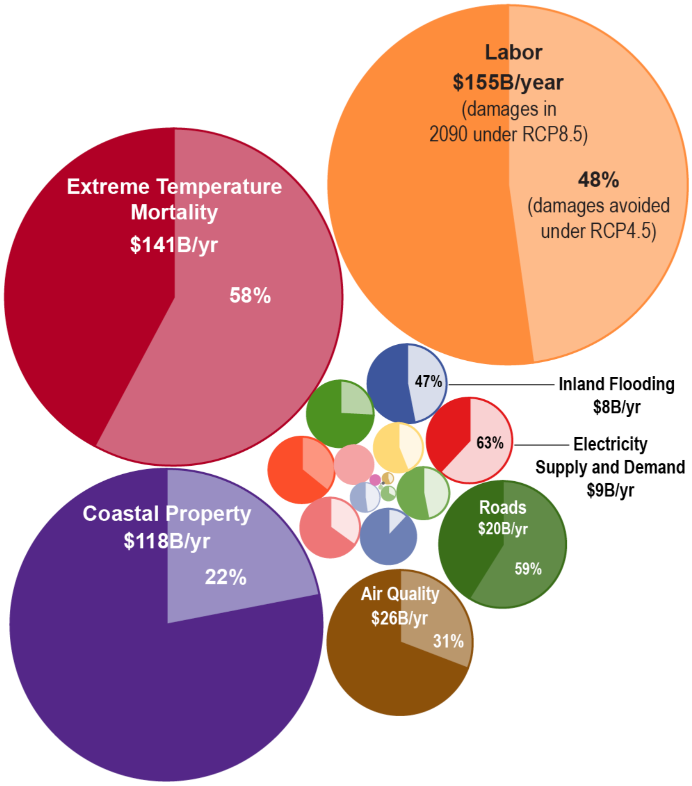
Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century. It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent.

Climate change is projected to significantly affect human health, the economy, and the environment in the United States, particularly in futures with high GHG emissions, such as RCP8.5, and under scenarios with limited or no adaptation (for more on RCPs, see the Scenario Products section of App. 3).[64] Recent findings from multisector modeling frameworks demonstrate substantial and far-reaching changes over the course of the 21st century—and particularly towards the end of the century—with negative consequences for a large majority of sectors. Moreover, the impacts and costs of climate change are already being felt in the United States, and recent extreme weather and climate-related events can now be attributed with increasingly higher confidence to human-caused warming.[65] Impacts associated with human health, such as premature mortality due to extreme temperature and poor air quality, are commonly some of the most economically substantial (Ch. 13: Air Quality; Ch. 14: Human Health).[2,3,4,5] While many sectors face large economic risks from climate change, other impacts can have significant implications for societal or cultural resources.[66,67] Further, some impacts will very likely be irreversible for thousands of years, including those to species, such as corals (Ch. 9: Oceans; Ch. 27: Hawai‘i & Pacific Islands),[1,2,68] or those that involve the exceedance of thresholds, such as the effects of ice sheet disintegration on accelerated sea level rise, leading to widespread effects on coastal development lasting thousands of years.[69,70,71] Figure 29.2 shows that climate change is projected to cause damage across nearly all of the sectors analyzed. The conclusion that climate change is projected to result in adverse impacts across most sectors is consistently found in U.S.-focused multisector impact analyses.[2,3,4,5] For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5]

Projected Damages and Potential for Risk Reduction by Sector



	Annual Economic Damages in 2090		
	Sector	Annual damages under RCP8.5	Damages avoided under RCP4.5
🟧	Labor	$155B	48%
🟥	Extreme Temperature Mortality◊	$141B	58%
🟪	Coastal Property◊	$118B	22%
🟫	Air Quality	$26B	31%
🟩	Roads◊	$20B	59%
🟥	Electricity Supply and Demand	$9B	63%
🟦	Inland Flooding	$8B	47%
🟩	Urban Drainage	$6B	26%
🟥	Rail◊	$6B	36%
🟥	Water Quality	$5B	35%
🟦	Coral Reefs	$4B	12%
🟩	West Nile Virus	$3B	47%
🟨	Freshwater Fish	$3B	44%
🟥	Winter Recreation	$2B	107%
🟦	Bridges	$1B	48%
🟩	Munic. and Industrial Water Supply	$316M	33%
🟨	Harmful Algal Blooms	$199M	45%
🟪	Alaska Infrastructure◊	$174M	53%
⬜	Shellfish*	$23M	57%
🟩	Agriculture*	$12M	11%
⬛	Aeroallergens*	$1M	57%
⬛	Wildfire	−$106M	−134%

Figure 29.2: The total area of each circle represents the projected annual economic damages (in 2015 dollars) under a higher scenario (RCP8.5) in 2090 relative to a no-change scenario. The decrease in damages under a lower scenario (RCP4.5) compared to RCP8.5 is shown in the lighter-shaded area of each circle. Where applicable, sectoral results assume population change over time, which in the case of winter recreation leads to positive effects under RCP4.5, as increased visitors outweigh climate losses. Importantly, many sectoral damages from climate change are not included here, and many of the reported results represent only partial valuations of the total physical damages. See EPA 2017 for ranges surrounding the central estimates presented in the figure; results assume limited or no adaptation.[2] Adaptation was shown to reduce overall damages in sectors identified with the diamond symbol but was not directly modeled in, or relevant to, all sectors. Asterisks denote sectors with annual damages that may not be visible at the given scale. Only one impact (wildfire) shows very small positive effects, owing to projected landscape-scale shifts to vegetation with longer fire return intervals (see Ch. 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity). The online version of this figure includes value ranges for numbers in the table. Due to space constraints, the ranges are not included here. Source: adapted from EPA 2017.[2]

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

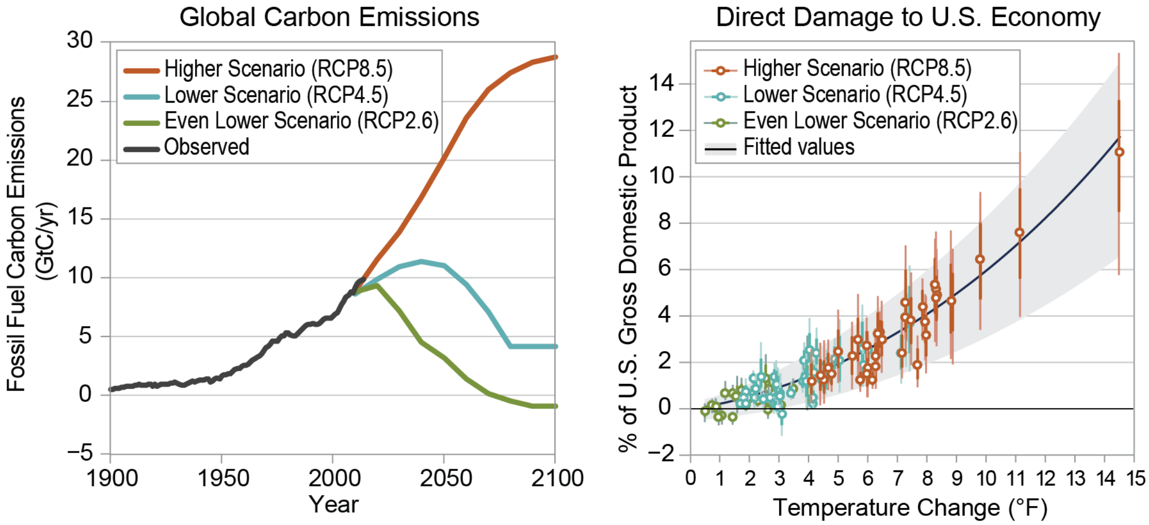
Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region. The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter.

Many climate change impacts in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in GHG emissions (Figure 29.2). While the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[6] the effect of mitigation in avoiding climate change impacts typically becomes clear by 2050 and increases substantially in magnitude thereafter.[2,3,4] For some sectors, this creates large projected benefits of mitigation. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (overall) thousands to tens of thousands of deaths per year from extreme temperatures (Ch. 14: Human Health),[2,3,5] hundreds to thousands of deaths per year from poor air quality (Ch. 13: Air Quality),[2,72] and the annual loss of hundreds of millions of labor hours from extreme temperatures.[2,3] When monetized, each of these avoided health impacts represents domestic economic benefits of mitigation on the order of tens to hundreds of billions of dollars per year.[2,3,73] For example, Figure 29.2 shows that reduced emissions under RCP4.5 can avoid approximately 48% (or $75 billion) of the $155 billion in lost wages per year by 2090 due to the effects of extreme temperature on labor (for example, outdoor industries reducing total labor hours during heat waves). Looking at the economy as a whole, mitigation can substantially reduce damages while also narrowing the uncertainty in potential adverse impacts (Figure 29.3).

Many impacts have significant societal or cultural values, such as impacts to freshwater recreational fishing. However, estimating the full value of these changes remains a challenge. Recent studies highlight that climate change can disproportionately affect socially vulnerable communities, with mitigation providing substantial risk reduction for these populations.[3,74,75,76] Some analyses also suggest that findings are sensitive to assumptions regarding adaptive capacity and socioeconomic change.[5,71,77] In general, studies find that reduced damages due to mitigation also reduce the potential level of adaptation needed.[2,78] As for socioeconomic change, increasing population growth can compound the damages occurring from climate change.[4,79] Some studies have shown that impacts can be more sensitive to demographic and economic conditions than to the differences in future climates between the scenarios.[80] See the Scenario Products section of Appendix 3 for more detail on population and land-use scenarios developed for the Fourth National Climate Assessment (NCA4).

For other sectors, such as impacts to coastal development, the effect of mitigation emerges more toward the end of the century due to lags in the response of ice sheets and oceans to warming (Ch. 8: Coastal).[81] This results in smaller relative reductions in risk. For example, while annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of

Estimates of Direct Economic Damage from Temperature Change


Global Carbon Emissions

Direct Damage to U.S. Economy

Figure 29.3: The left graph shows the observed and projected changes in fossil fuel and industrial emissions of CO_2 from human activities (emissions from land-use change do not appear in the figure; within the RCPs these emissions are less than 1 GtC per year by 2020 and fall thereafter). The right graph shows projections of direct damage to the current U.S. economy for six impact sectors (agriculture, crime, coasts, energy, heat mortality, and labor) as a function of global average temperature change (represented as average for 2080–2099 compared to 1980–2010). Compared to RCP8.5, lower temperatures due to mitigation under either of the lower scenarios (RCP2.6 or RCP4.5) substantially reduce median damages (dots) to the U.S. economy while also narrowing the uncertainty in potential adverse impacts. Dot-whiskers indicate the uncertainty in direct damages in 2090 (average of 2080–2099) derived from multiple combinations of climate models and forcing scenarios (dot, median; thick line, inner 66% credible interval; thin line, inner 90%). The gray shaded area represents the 90% confidence interval in the fit (black line) to the damage estimates. Damage estimates only capture adaptation to the extent that populations employed them in the historical period. Sources: (left) adapted from Wuebbles et al. 2017; [83] (right) adapted from Hsiang et al. 2017[3] and republished with permission of American Association for the Advancement of Science.

the century under RCP8.5, mitigation under RCP4.5 is projected to avoid less than a quarter of these damages.[2,5,82] However, the avoided impacts beyond 2100 are likely to be larger based on projected trajectories of sea level change.[19,20,27]

The marginal benefit, equivalently the avoided damages, of mitigation can be expressed as the social cost of carbon (SCC). The SCC is a monetized estimate of the long-term climate damages to society from an additional amount of CO_2 emitted and includes impacts that accrue in market sectors such as agriculture, energy services, and coastal resources, as well as nonmarket impacts on human health and ecosystems.[84,85] This metric is used to inform climate risk management decisions at national, state, and corporate levels.[86,87,88,89,90] Notably, estimating the SCC depends on normative social values such as time preference, risk aversion, and equity considerations that can lead to a range of values. In recognition of the ongoing examination about existing approaches to estimating the SCC,[91,92,93] a National Academies of Sciences, Engineering, and Medicine report[94] recommended various improvements to SCC models, including that they 1) be consistent with the current state of scientific knowledge, 2) characterize and quantify key uncertainties, and 3) be clearly documented and reproducible.

Although uncertainties still remain, advancements in climate impacts and economics modeling are increasingly providing new capabilities to quantify future societal effects of climate change. A growing body of studies use and assess statistical relationships between observed socioeconomic outcomes and weather or climate variables to estimate the impacts of climate change (e.g., Müller et al. 2017, Hsiang et al. 2017 [3,95]). In the United States, in particular, the rise of big data (large volumes of data brought about via the digital age) and advanced computational power offer potential improvements to study climate impacts in many sectors like agriculture, energy, and health, including previously omitted sectors such as crime, conflict, political turnover, and labor productivity. Parallel advancements in high-resolution integrated assessment models (those that jointly simulate changes in physical and socioeconomic systems), as well as process-based sectoral models (those with detailed representations of changes in a single sector), enable impact projections with increased regional specificity, which across the modeling frameworks shown in Table 29.1 reveal complex spatial patterns of impacts for many sectors. For example, this spatial variability is consistently observed in the agriculture sector,[2,5,96,97] where the large number of domestic crops and growing regions respond to changes in climate and atmospheric CO_2 concentrations in differing ways. As such, the benefits of mitigation for agriculture can vary substantially across regions of the United States and summing regional results into national estimates can obscure important effects at the local level.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences. Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors. This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable.

The reduction of climate change risk due to mitigation also depends on assumptions about how adaptation changes the exposure and vulnerability of the population (Ch. 28: Adaptation). For example, recent studies have found that adaptation can substantially reduce climate damages in a number of sectors in both the higher (RCP8.5) and lower (RCP4.5) scenarios.[2,5] Damages to infrastructure, such as road and rail networks, are particularly sensitive to adaptation assumptions, with proactive measures (such as planned maintenance and repairs that account for future climate risks) estimated to be able to reduce damages by large fractions. More than half of damages to coastal property are estimated to be avoidable through well-timed adaptation measures, such as shoreline protection and beach replenishment.[2,5,196] In the health sector, accounting for possible physiological adaptation (acclimatization) to higher temperatures and for increased air conditioning use reduced estimated mortality by half,[2,5] a finding supported by other analyses of mortality from extreme heat.[99,100] However, adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Broadly, quantifying the potential effect of adaptation on impacts remains a research challenge (see the “Direction for Future Research” section) (see also Ch. 17: Complex Systems).[102] Because society is already committed to a certain amount of future climate change due to past and present emissions and because mitigation activities cannot avoid all climate-related risks, mitigation and adaptation activities can be considered complementary strategies.[196,103,104,105]

Adaptation and mitigation strategies can also interact, with the potential for benefits and/or adverse consequences.[106] An iterative risk-management approach for assessing and modifying these strategies as experience is gained can be advantageous (Ch. 28: Adaptation). Benefits occur when mitigation strategies make adaptation easier (or vice versa). For example, by reducing climate change and its subsequent effects on the water cycle, mitigation has been projected to reduce water shortages in most river basins of the United States, making adaptation to hydrologic impacts more manageable.[107] Also, carbon sequestration through reforestation and/or other protective measures can promote forest ecosystem services (including reduced flood risk), provide habitat for otherwise vulnerable species, or abate urban heat islands. Carbon sequestration measures in agriculture can reduce erosion and runoff, reducing vulnerability to extreme precipitation. Agricultural adaptation strategies that increase yields (such as altering crop varieties, irrigation practices, and fertilizer application), particularly in already high-yielding regions including North America, can have mitigation benefits (Ch. 10: Ag & Rural).[108] First, higher productivity lessens the need for clearing new land for production, thereby reducing associated emissions.[109] Second, these strategies counteract yield losses due to climate change,[2,110,111] which could enhance the ability to produce bioenergy crops or make additional land available for carbon sequestration.

In buildings and industrial facilities, adaptation measures such as investments in energy efficiency (for example, through efficient building materials) would reduce building energy demand (and therefore emissions), as well as lessen the impacts of extreme heat events.[112,113]

Adaptation and mitigation can also interact negatively. For example, if mitigation strategies include large-scale use of bioenergy crops to produce low-carbon energy, higher irrigation demand can lead to an increase in water stress that more than offsets the benefits of lessened climate change.[114] Similarly, mitigation approaches such as afforestation (the establishment of a forest where no previous tree cover existed) and concentrated solar power would increase demand for water and land.[115] Likewise, some adaptation measures such as irrigation, desalination, and air conditioning are energy intensive and would lead to increased emissions or create greater demands for clean energy. Higher air conditioning demands are projected to increase annual average and peak demands for electricity, putting added stress on an electrical grid that is already vulnerable to the effects of climate change (Ch. 4: Energy, KM 1).[2,116,117] Meeting these higher demands becomes more challenging as higher temperatures reduce the peak capacity of thermal generation technologies and lower peak transmission capacity.[118] In addition, complications are expected to arise when climate change impacts occur simultaneously and undermine adaptation measures, such as when a severe storm disrupts power over an extended time of intense heat, which can nullify the benefits of air conditioning adaptation.

Box 29.2: Co-Effects of Mitigation Actions

Recent scientific studies suggest that considering the indirect effects of mitigation can significantly reduce or eliminate the potential costs associated with cutting GHG emissions. This is due to the presence of co-benefits, often immediate, associated with emissions reductions, such as improving air quality and public health. There is now a large body of scientific literature evaluating 1) the health co-benefits of mitigation actions, [5,119,120,121,122,123,124,125] 2) improvement to crop yields,[126,127] and 3) a reduction in the probability of occurrence of extreme weather and climate-related events over the next decades that would otherwise occur with unabated emissions.[29] In transportation, for example, switching away from petroleum to potentially lower GHG fuels, such as electricity and hydrogen, is projected to reduce local air pollution. In California, drastic GHG emissions reductions have been estimated to substantially improve air quality and reduce local particulate matter emissions associated with freight transport that disproportionately impact disadvantaged communities.[128,129] Decarbonization of the energy system is also expected to increase energy security by increasing reliance on sources of energy that are produced domestically.[130,131]

At the same time, mitigation actions can have potential adverse effects, such as impacts to the cost of food and biodiversity loss due to the increased use of energy from biomass.[132,133] For this reason, it is more appropriate to use the term co-effects to refer to both benefits and costs associated with efforts to reduce GHG emissions.[123] The co-effects of investments in GHG emissions reductions generally occur in the near term, whereas the benefits of reducing GHG emissions will likely be mostly realized over longer timescales.

Box 29.3: Reducing Risk Through Climate Intervention

Climate intervention techniques (or geoengineering) are aimed at limiting global or regional temperature increase by affecting net radiative forcing through means other than emissions reductions (for a more detailed discussion see DeAngelo et al. 2017 [9]).There are two broad categories of climate intervention techniques. One is carbon dioxide removal (CDR), which would reduce atmospheric CO_2 concentrations by changing land-use and management practices to store carbon in plants, trees, and soils; increasing ocean carbon storage through biological or chemical means; capturing atmospheric CO_2 through engineered chemical reactions and storing it in geologic reservoirs; or converting terrestrial biomass into energy while capturing and storing the CO_2.[16] The second is solar radiation management (SRM), which would increase Earth’s regional and/or global reflectivity by, for example, injecting sulfur gases or other substances into the stratosphere or brightening marine clouds. CDR is estimated to have long implementation times, and while costs (and their uncertainties) range widely across different measures,[134] it is estimated to be expensive at scale.[10] Nonetheless, large-scale CDR can be competitive with more traditional GHG mitigation options when substantial mitigation is required, and therefore it is an element of many scenarios that feature deep emissions reductions or negative emissions. Its climate benefits are likely to be similar to those from emissions reductions since both strategies act through reduced atmospheric concentrations of GHGs. Studies point to the risks of reaching the limits of available land, water, or biogeochemical requirements of biomass-based approaches at scale sufficient to offset large emissions.[13,16,99,135,136] In contrast to CDR, SRM strategies are estimated to be relatively inexpensive and realize climate benefits within a few years. They could be targeted at regional as well as global temperature modification[137] and could be combined with mitigation to limit the rate or the peak magnitude of warming. However, SRM effects on other outcomes, including precipitation patterns, light availability, and atmospheric circulation, are less well understood. In addition, SRM would not reduce risks from increasing atmospheric CO_2 concentra-

Box 29.3: Reducing Risk Through Climate Intervention, *continued*

tions such as ocean acidification.[138,139] Moreover, a sudden cessation of large-scale SRM activities could lead to very rapid climate changes, although a gradual phaseout of SRM as emissions reductions and CDR are phased in could avoid these abrupt changes. As concluded in Chapter 14 of the *Climate Science Special Report*, "Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as-yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence."[9]

Direction for Future Research

Coordinated Impacts Modeling Analyses

Multisector impacts modeling frameworks can systematically address specific mitigation and adaptation research needs of the users of the National Climate Assessment. Improved coordination amongst multidisciplinary impact modeling teams could be very effective in informing future climate assessments.

The recent multisector impacts modeling frameworks described above have demonstrated several key advantages for producing policy-relevant information regarding the potential for mitigation to reduce climate change impacts. First, the use of internally consistent scenarios and assumptions in quantifying a broad range of impacts produces comparable estimates across sectors, regions, and time. Second, these frameworks can simulate specific mitigation and adaptation scenarios to investigate the multisector effectiveness of these actions in reducing risk over time. Third, these frameworks can be designed to systematically account for key dimensions of uncertainty along the causal chain—a difficult task when assessing uncoordinated studies from the literature, each with its own choices of scenarios and assumptions.

Advancements to Address Research Needs from the Third National Climate Assessment

While not an exact analog to this chapter, the Third National Climate Assessment (NCA3)[140] included a Research Needs chapter as part of the Response Strategies section that recommended five research goals: 1) improve understanding of the climate system and its drivers, 2) improve understanding of climate impacts and vulnerability, 3) increase understanding of adaptation pathways, 4) identify the mitigation options that reduce the risk of longer-term climate change, and 5) improve decision support and integrated assessment.[141] Several of these topics have seen substantial advancements since publication of NCA3, informing our understanding of avoided climate risks. For example, research findings related to climate system drivers and the characterization of uncertainty have helped to differentiate the physical and economic outcomes along alternative mitigation pathways.[3,20,30] Enormous growth in impacts, adaptation, and vulnerability (IAV) research has enabled more robust quantification of the relative impacts (avoided damages) corresponding to different climate outcomes. However, challenges remain in accounting for the reduced risks and impacts associated with nonlinearities in the climate system, including tipping points such as destabilization of the West Antarctic ice sheet or rapid methane release from thawing permafrost.[22,98,142,143] Mitigation options continue to be studied to better understand their potential role in meeting different climate targets, and while many low-emitting or renewable technologies have seen rapid penetration, other strategies involving negative-emissions technologies have prompted caution due to the challenges of achieving widespread deployment at low cost. Adaptation pathways are better understood but continue to be a source of uncertainty related to understanding climate risk and local adaptation decision-making processes. Decision support for climate risk management, especially under uncertainty, is an area of active research,[144,145] and despite the limitations of integrated assessment models,[146,147] they offer useful insights for decision-makers.[148]

Remaining Knowledge Gaps

Despite ongoing progress, this assessment finds that significant knowledge gaps remain in many of the research goals and foundational crosscutting capabilities identified in NCA3. Going forward, it will be critically important to reduce uncertainties under different mitigation scenarios in 1) avoided sectoral impacts, such as agriculture and health, and 2) the capacity for adaptation to reduce impacts. Gaps in information on social vulnerability and exposure continue to hamper progress on disaster risk reduction associated with climate impacts.[51] Directions for future research in the climate science and impacts field include improved understanding of the avoided/increased risk of thresholds, tipping points, or irreversible outcomes (see Kopp et al. 2017[22]). Specific examples deserving further study include marine ice sheet instability and transformation of specific terrestrial carbon sinks into sources of greenhouse gas emissions.[149,150]

Gaps remain in quantifying combined impacts and natural feedbacks. For example, coral reef health includes combined stress/relief from changes in local activities (for example, agricultural and other nutrient runoff and fishery management), ocean acidification, ocean temperature, and the ability of coral species to adapt to changing conditions or repeated extreme events.[151,152] Additional knowledge gaps include an understanding of how mitigation and adaptation actions affect climate outcomes due to interactions in the coupled human–earth system.[142,153]

Interdisciplinary collaboration can play a critical role in addressing these knowledge gaps (such as coordinating a research plan across physical, natural, and social sciences).[52,154] Combining advances in scientific understanding of the climate system with scenarios to explore socioeconomic responses is expected to lead to an improved understanding of the coupled human–earth system that can better support effective adaptation and mitigation responses. Barriers to implementation arise from data limits (for example, the need for long-term observational records), as well as computational limits that increase model uncertainties.[53]

Acknowledgments

USGCRP Coordinators

David Reidmiller
Director

Christopher W. Avery
Senior Manager

Opening Image Credit

Jasper, NY: © John Gretchel/Flickr (CC BY-NC 2.0). Adaptation: cropped top and bottom to conform to the size needed for publication.

Traceable Accounts

Process Description

The scope for this chapter was determined by the federal Fourth National Climate Assessment (NCA4) Steering Committee, which is made up of representatives from the U.S. Global Change Research Program (USGCRP) member agencies (see App. 1: Process for more information regarding the Steering Committee). The scope was also informed by research needs identified in the Third National Climate Assessment (NCA3) and in subsequent gap analyses.[155] Prospective authors were nominated by their respective agency, university, organization, or peers. All prospective authors were interviewed with respect to their qualifications and expertise. Authors were selected to represent the diverse perspectives relevant to mitigation, with the final team providing perspectives from federal and state agencies, nonfederal climate research organizations, and the private sector. The author team sought public input on the chapter scope and outline through a webinar and during presentations at conferences and workshops.

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors during extensive teleconferences, workshops, and email exchanges. These discussions were informed by the results of a comprehensive literature review, including the research focused on estimating the avoided or reduced risks of climate change. The authors considered inputs submitted by the public, stakeholders, and federal agencies and improved the chapter based on rounds of review by the public, National Academies of Sciences, Engineering, and Medicine, and federal agencies. The author team also engaged in targeted consultations during multiple exchanges with contributing authors from other chapters of this assessment, as well as authors of the *Climate Science Special Report* (CSSR). For additional information on the overall report process, see Appendix 1: Process.

Key Message 1

Mitigation-Related Activities Within the United States

Mitigation-related activities are taking place across the United States at the federal, state, and local levels as well as in the private sector (*very high confidence*). Since the Third National Climate Assessment, a growing number of states, cities, and businesses have pursued or deepened initiatives aimed at reducing emissions (*very high confidence*).

Description of evidence base

Since NCA3, state, local, and tribal entities have announced new or enhanced efforts to reduce greenhouse gas (GHG) emissions. While some policies with emissions co-benefits have been eliminated, on net there has been an increase in initiatives aimed at reducing emissions. Figure 29.1 includes several types of state-level efforts and is sourced from Figure ES-3 of the America's Pledge Phase 1 report, the most comprehensive listing of efforts across sectors currently available. The underlying state information is sourced from the U.S. Department of Energy, Appliance Standards Awareness Project, Open Energy Information, Rethink Food Waste Through Economics and Data, World Resources Institute, State of New York, California Air Resources Board, University of Minnesota, Land Trust Alliance, and the U.S. Forest Service.

U.S. state and local carbon pricing programs have increased in number since NCA3.[156] The Regional Greenhouse Gas Initiative has expanded the depth of emissions reductions activities and is considering adding transportation to their scope. California's cap and trade program started in 2012 and expanded by linking to Quebec and Ontario in 2017. Emissions trading systems are scheduled in Massachusetts and under consideration in Virginia.[156]

U.S. states have both mandatory and voluntary programs that vary in stringency and impact. For example, 29 states, Washington, DC, and 3 territories have Renewable Portfolio Standards (RPS; https://energy.gov/eere/slsc/renewable-portfolio-standards-resources), which require some portion of electricity to be sourced from renewable energy; while 8 states and 1 territory have voluntary renewable portfolio goals.[42,45] Likewise, 20 states have mandatory statewide Energy Efficiency Resource Standards (EERS; https://energy.gov/eere/slsc/energy-efficiency-resource-standards-resources), and 8 states have energy efficiency goals.[42] While the number of states with RPS and EERS policies remains similar to that during NCA3, emissions reductions associated with the impact of these policies have and are projected to increase.[157] In 2013, 8 states initiated an effort to coordinate implementation of their state zero-emission vehicle programs and have since taken a wide range of actions.[158]

Federal budget levels for activities that have reduced GHG have remained steady over recent years. There is uncertainty around the implementation of federal initiatives, in part owing to the implementation of Executive Order 13783.[40,159] Federal energy-related research and development have several co-benefits, including reduced emissions.[15]

U.S. companies that report through the Carbon Disclosure Project increasingly (although not comprehensively) reported board-level oversight on climate issues, which rose from 50% in 2011 to 71% in 2017. Likewise, 59 U.S. companies recently committed to set science-based emissions reduction targets.[46] U.S. businesses are increasingly pricing carbon.[46,160] Corporate procurement of utility-scale solar has grown by an order of magnitude since 2014.[47]

As indicated in the Education Institutions Reporting Database, a growing number of universities have made emissions reduction commitments or deepened existing commitments[161] as well as publicized the progress on their efforts.[162]

Major uncertainties

Figure 29.1 shows a count of each type of 30 measures across 6 categories, but it does not explore the relative stringency or emissions impact of the measures. The size, scope, time frame, and enforceability of the measures vary across states. Some state efforts and the majority of city efforts are voluntary, and therefore standards for reporting are heterogeneous. Efforts are underway to provide a rigorous accounting of the cumulative scale of these initiatives. Data collection through the America's Pledge effort is an ongoing, iterative process and, by necessity, involves aggregating different measures into categories. Historically, state, local, and corporate policies change on different cycles.

Description of confidence and likelihood

There is *very high confidence* that state, local, and private entities are increasingly taking, or are committed to taking, GHG mitigation action. Public statements and collated indices show an upward trend in the number of commitments, as well as the breadth and depth of commitments over the past five years.

Key Message 2

The Risks of Inaction

In the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment (*very high confidence*). Under scenarios with high emissions and limited or no adaptation, annual losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century (*high confidence*). It is very likely that some physical and ecological impacts will be irreversible for thousands of years, while others will be permanent (*very high confidence*).

Description of evidence base

Recent scientific and economic advances are improving the ability to understand and quantify the physical and economic impacts of climate change in the United States, including how those risks can be avoided or reduced through large-scale GHG mitigation. While the projected impacts of climate change across sectors and regions are well documented throughout this assessment, several multisector modeling projects are enabling the comparison of effects through the use of consistent scenarios and assumptions.[2,3,4,5] A well-recognized conclusion from the literature produced by these projects is that climate change is projected to adversely affect the U.S. economy, human health, and the environment, each of which is further detailed below. These estimated damages increase over time, especially under a higher scenario (RCP8.5). For sectors where positive effects are observed in some regions or for specific time periods (for example, reduced mortality from extreme cold temperatures or beneficial effects on crop yields), the effects are typically dwarfed by changes happening overall within the sector or at broader scales (for example, comparatively larger increases in mortality from extreme heat or many more crops experiencing adverse effects).[2,3,4,5] In Figure 29.2, wildfire is the only sector showing positive effects, a result driven in this particular study by projected shifts to vegetation with longer fire return intervals.[2] However, it is important to note that the analysis underlying this result did not quantify the broader economic effects associated with these vegetative shifts, including ecosystem disruption and changes to ecosystem services. See Chapter 6: Forests for a discussion on the weight of evidence regarding projections of future wildfire activity, which generally show increases in annual area burned over time. See Chapter 25: Southwest for a discussion on aridification toward the end of this century under high emissions.

There is robust and consistent evidence that climate change is projected to adversely affect many components of the U.S. economy. Increasing temperatures, sea level rise, and changes in extreme events are projected to affect the built environment, including roads, bridges, railways, and coastal development. For example, coastal high tide flooding is projected to significantly increase the hours of delay for vehicles.[163] Annual damages to coastal property from sea level rise and storm surge, assuming no adaptation, are projected to range in the tens to hundreds of billions of dollars by the end of the century under RCP8.5 (Ch. 8: Coastal).[2,5] Projected annual repair costs in order for roads, bridges, and railways to maintain levels of service in light of climate change range in the billions to tens of billions of dollars under RCP8.5.[2,164] Numerous studies suggest that regional economies can also be at risk, especially when they are tied to environmental resources or ecosystem services that are particularly vulnerable to climate change. For example, projected declines in coral reef-based recreation[152,165,166] would lead to decreases in tourism revenue; shorter seasons for winter recreation would likely lead to the closure of ski areas and resorts;[167,168,169,170] and increased risks of harmful algal blooms can limit reservoir recreation (Ch. 3: Water).[171,172]

An increasing body of literature indicates that impacts to human health are likely to have some of the largest effects on the economy. Studies consistently indicate that climate-driven changes to morbidity and mortality can be substantial.[72,100,173,174,175,176] In some sectors, the value of health damages is estimated to reach hundreds of billions of dollars per year under RCP8.5 by the end of the century. A large fraction of total health damages is due to mortality, quantified using the Value of a Statistical Life (VSL) approach based on standard VSL values used in federal government regulatory analysis.[177] For example, annual damages associated with extreme temperature-related deaths are estimated at $140 billion by the end of the century under RCP8.5, while lost wages from extreme temperatures, especially for outdoor industries, are projected at $160 billion per year by 2090.[2] Adaptive actions, including physiological adaptation and increased availability of air conditioning, are projected to reduce extreme temperature mortality by approximately half; however, the implementation costs of those adaptations were not estimated. Although less studied compared to the research on the direct effects of temperature on health, climate-driven impacts to air quality[72,178] and aeroallergens[173,179] are also projected to have large economic effects, due to increases in medical expenditures (such as emergency room visits) and premature mortality (Ch. 13: Air Quality).

Multiple lines of research have also shown that some climate change impacts will very likely be irreversible for thousands of years. For some species, the rate and magnitude of climate change projected for the 21st century is projected to increase the risk of extinction or extirpation (local-scale extinction) from the United States.[180,181,182,183] Coral reefs, coldwater fish, and high-elevation species are particularly vulnerable (Ch. 9: Oceans; Ch. 7: Ecosystems). The rapid and widespread climate changes occurring in the Arctic and Antarctic are leading to the loss of mountain glaciers and shrinking continental ice sheets.[69,184] The contribution of this land ice volume to the rate of global sea level rise is projected to affect U.S. coastlines for centuries (Ch. 8: Coastal).[19,30,185]

Major uncertainties

This Key Message reflects consideration of the findings of several recent multisector modeling projects (e.g., Hsiang et al. 2017, O'Neill et al. 2017, EPA 2017, Houser et al. 2015 [2,3,4,5]) released since NCA3. Despite these improvements to quantify the physical and economic impacts of climate change across sectors, uncertainty exists regarding the ultimate timing and magnitude of changes, particularly at local to regional scales. The sources of uncertainty vary by sector and the modeling approaches applied. Each approach also varies in its capacity to measure the ability of adaptation to reduce vulnerability, exposure, and risk. While the coverage of impacts has improved with recent advancements in the science, many important climate change effects remain unstudied, as do the interactions between sectors (Ch. 17: Complex Systems).[85] Finally, as climate conditions pass further outside the natural variability experienced over past several millennia, the odds of crossing thresholds or tipping points (such as the loss of Arctic summer sea ice) increase, though these thresholds are not well represented in current models.[22,142]

Description of confidence and likelihood

There is *very high confidence* that climate change is projected to substantially affect American livelihoods and well-being in the future compared to a future without climate change. The evidence supporting this conclusion is based on agreement across a large number of studies analyzing impacts across a multitude of sectors, scenarios, and regions. The literature clearly indicates that the adverse impacts of climate change are projected to substantially outweigh the positive effects. Although important uncertainties exist that affect our understanding of the timing and magnitude of some impacts, there is *very high confidence* that some effects will very likely lead to changes that are irreversible on human timescales.

Key Message 3

Avoided or Reduced Impacts Due to Mitigation

Many climate change impacts and associated economic damages in the United States can be substantially reduced over the course of the 21st century through global-scale reductions in greenhouse gas emissions, though the magnitude and timing of avoided risks vary by sector and region (*very high confidence*). The effect of near-term emissions mitigation on reducing risks is expected to become apparent by mid-century and grow substantially thereafter (*very high confidence*).

Description of evidence base

There are multiple lines of research and literature available to characterize the effect of large-scale GHG mitigation in avoiding or reducing the long-term risks of climate change in the United States. Recent multisector impacts modeling projects, all of which feature consistent sets of scenarios and assumptions across analyses, provide improved capabilities to compare impacts across sectors and regions, including the effect of global GHG mitigation in avoiding or reducing risks.[2,3,4,5] The results of these coordinated modeling projects consistently show reductions in impacts across sectors due to large-scale mitigation. For most sectors, this effect of mitigation typically becomes clear by mid-century and increases substantially in magnitude thereafter.
In some sectors, mitigation can provide large benefits. For example, by the end of the century, reduced climate change under a lower scenario (RCP4.5) compared to a higher one (RCP8.5) avoids (on net, and absent additional risk reduction through adaptation) thousands to tens of thousands of deaths per year from extreme temperatures,[2,5] hundreds to thousands of deaths per year from poor air quality,[2,72] and the loss of hundreds of millions of labor hours.[2,3,5]

Beyond these multisector modeling projects, an extensive literature of sector-specific studies compares impacts in the United States under alternative scenarios. A careful review of these studies, especially those published since the Third National Climate Assessment, finds strong and consistent support for the conclusion that global GHG mitigation can avoid or reduce the long-term risks of climate change in the United States. For example, mitigation is projected to reduce the risk of adverse impacts associated with extreme weather events,[29,186] temperature-related health effects,[99,100,175] agricultural yields,[187,188,189] and wildfires.[73,190,191]

The finding that the magnitude and timing of avoided risks vary by sector and region, as well as due to changes in socioeconomics and adaptive capacity, is consistently supported by the broad literature base of multisector analyses (e.g., Hsiang et al. 2017, O'Neill et al. 2017, EPA 2017, Houser et al. 2015[2,3,4,5]) and focused sector studies (e.g., Melvin et al. 2016, Neumann et al. 2014[71,77]). Complex spatial patterns of avoided risks are commonly observed across sectors, including for human health effects (e.g., Fann et al. 2015, Sarofim et al. 2016 [100,178]), agriculture (e.g., Beach et al. 2015 [192]), and water resources (e.g., Chapra et al. 2017, Wobus et al. 2017, EPA 2013[167,171,193]).

The weight of evidence among studies in the literature indicates that the difference in climate impact outcomes between different scenarios is more modest through the first half of the century,[2,4,5,9] as the human-forced response may not yet have emerged from the noise of natural climate variability.[6] In evaluating and quantifying multisector impacts across alternative scenarios, the literature generally shows that the effect of near-term mitigation in avoiding damages increases substantially in magnitude after 2050.[2,4,5] For example, mitigation under RCP4.5 is projected to reduce the number of premature deaths and lost labor hours from extreme temperatures by 24% and 21% (respectively) by 2050, and 58% and 48% by 2090.[2] For coastal impacts, where inertia in the climate system leads to smaller differences in rates of sea level rise across scenarios, the effects of near-term mitigation only become evident toward the end of the century (Ch. 8: Coastal).[2,5,19]

Major uncertainties

Quantifying the multisector impacts of climate change involves a number of analytic steps, each of which has its own potential sources of uncertainty. The timing and magnitude of projected future climate change are uncertain due to the ambiguity introduced by human choices, natural variability, and scientific uncertainty, which includes uncertainty in both scientific modeling and climate sensitivity. One of the most prominent sources involves the projection of climate change at a regional level, which can vary based on assumptions about climate sensitivity, natural variability, and the use of any one particular climate model. Advancements in the ability of climate models to resolve key aspects of atmospheric circulation, improved statistical and dynamic downscaling procedures, and the use of multiple ensemble members in impact analyses have all increased the robustness of potential climate changes that drive impact estimates described in the recent literature. However, key uncertainties and challenges remain, including the structural differences between sectoral impact models, the ability to simulate future impacts at fine spatial and temporal resolutions, and insufficient approaches to quantify the economic value of changes in nonmarket goods and services.[85] In addition, the literature on economic damages of climate change in the United States is incomplete in coverage, and additional research is needed to better reflect future socioeconomic change, including the ability of adaptation to reduce risk.

Description of confidence and likelihood

There is *very high confidence* that large-scale reductions in GHG emissions throughout the 21st century are projected to reduce the level of climate change projected to occur in the United States, along with the adverse impacts affecting human health and the environment. Across the literature, there are limited instances where mitigation, compared to a higher emissions scenario, does not provide a net beneficial outcome for the United States. While the content of this chapter is primarily focused on the 21st century, confidence in the ability of mitigation to avoid or reduce impacts improves when considering impacts beyond 2100.

Key Message 4

Interactions Between Mitigation and Adaptation

Interactions between mitigation and adaptation are complex and can lead to benefits, but they also have the potential for adverse consequences (*very high confidence*). Adaptation can complement mitigation to substantially reduce exposure and vulnerability to climate change in some sectors (*very high confidence*). This complementarity is especially important given that a certain degree of climate change due to past and present emissions is unavoidable (*very high confidence*).

Description of evidence base

Global-scale reductions in GHG emissions are projected to reduce many of the risks posed by climate change. However, Americans are already experiencing, and will continue to experience, impacts that have already been committed to because of past and present emissions.[5,9] In addition, multisector modeling frameworks demonstrate that mitigation is unlikely to completely avoid the adverse impacts of climate change.[2,3,4,5,27] These factors will likely necessitate widespread adaptation to climate change (Ch. 28: Adaptation); an expanding literature consistently indicates potential for the reduction of long-term risks and economic damages of climate change.[2,4,5,194] However, it is important to note that adaptation can require large up-front costs and long-term commitments for maintenance (Ch. 28: Adaptation), and uncertainty exists in some sectors regarding the applicability and effectiveness of adaptation in reducing risk.[101]

Because of adaptation's ability to reduce risk in ways that mitigation cannot, and vice versa, the weight of the evidence shows that the two strategies can act as complements. Several recent studies jointly model the effects of mitigation and adaptation in reducing overall risk to the impacts of climate change in the United States, focusing on infrastructure (e.g., Larsen et al. 2017, Melvin et al. 2016, Neumann et al. 2014 [71,77,195]) and agriculture (e.g., Kaye and Quemada 2017, Challinor et al. 2014, Lobell et al. 2013 [108,109,111]). Exploration of this mitigation and adaptation nexus is also advancing in the health sector, with both mitigation and adaptation (such as behavioral changes or physiological acclimatization) being projected to reduce deaths from extreme temperatures[100] in both the higher and lower emissions scenarios that are the focus of this chapter. Similarly, energy efficiency investments are reducing GHG emissions and operating costs and improving resilience to future power interruptions from extreme weather events (Ch. 14: Human Health). While more studies exploring the joint effects of mitigation and adaptation are needed, recent literature finds that combined mitigation and adaptation actions can substantially reduce the risks posed by climate change in several sectors.[2,103,104] However, several studies highlight that mitigation and adaptation can also interact negatively. While these studies are more limited in the literature, sectors exhibiting potential negative co-effects from mitigation and adaptation include the bioenergy–water resource nexus[114] and changes in electricity demand and supply in response to increased use of air conditioning.[2,117]

Major uncertainties

It is well understood that adaptation will likely reduce climate risks and that adaptation and mitigation interact. However, there are uncertainties regarding the magnitude, timing, and regional/sectoral distribution of these effects. Developing a full understanding of the interaction between mitigation and adaptation, with detailed accounting of potential positive and negative co-effects, is an important research objective that is only beginning to be explored in the detail necessary to inform effective implementation of these policies. Quantifying the effectiveness of adaptation requires detailed analyses regarding the timing and magnitude of how climate is projected to affect people living in the United States and their natural and built environments. As such, the uncertainties described under Key Messages 1 and 2 are also relevant here. Further, uncertainty exists regarding the effectiveness of adaptation measures in improving resilience to climate impacts. For some sectors, such as coastal development, protection measures (for example, elevating structures) have been well studied and implemented to reduce risk. However, the effectiveness of adaptation in other sectors, such as the physiological response to more intense heat waves, is only beginning to be understood.

Description of confidence and likelihood

There is *very high confidence* that the dual strategies of mitigation and adaptation being taken at national, regional, and local levels provide complementary opportunities to reduce the risks posed by climate change. Studies consistently find that adaptation would be particularly important for impacts occurring over the next several decades, a time period in which the effects of large-scale mitigation would not yet be easily recognizable. However, further analysis is needed to help resolve uncertainties regarding the timing and magnitude of adaptation, including the potential positive and negative co-effects with mitigation.

This is a tab page.
Please title tab
“S&P”

S&P GLOBAL RATINGS — 5 Dec, 2018

Why It May Make Economic Sense To Tackle Global Warming

Author **Marion Amiot, Michael Ferguson, Noemie De La Gorce**

Theme **Emissions, Governments**

Tags **Global**

HIGHLIGHTS

Global warming of 3 degrees C. is likely to cost us 2% of global output. It is set to affect emerging and developing economies much more than developed ones.

Uncertainty about the costs of climate change and its characteristics of a global public good, which give rise to the free-rider problem, explain why policymakers and market participants have not done enough to cut carbon emissions.

Putting a global price tag on carbon would be the first best solution to fight global warming. Because of coordination problems, our second-best option is therefore change initiated at regional, country, and local levels--as well as by markets.

Capital allocation toward green investment may be considered as a competitive differentiator in portfolios and a strategy to achieve sustainable business models.

Technological hurdles are impeding a quick shift to a low-carbon economy, suggesting investment in this space is set to grow in importance and will likely be met by public support.

Dec. 05 2018 — Climate change is no longer a problem for the future. It has already started to alter the functioning of our world. Every year seems to bring more climate-related shocks--such as floods, hurricanes, harsh winters, and hotter summers--that weigh on economic activity. As temperatures climb, the occurrence of natural disasters is set to rise: Recent research shows that under business-as-usual carbon emissions, the risk of extreme heatwaves and floods is likely to increase by 50% this century (Mann et al., 2018). This means the global economy will increasingly have to cope with the consequences of global warming.

The latest United Nations Climate Change Conference, COP24, is bringing together experts and policymakers over the next two weeks (Dec. 2-14) to assess progress toward implementing the 2015 Paris Agreement and mitigating global warming. A recent report by the U.N.'s Intergovernmental Panel on Climate Change (IPCC) shows that global warming is already affecting our lives and that limiting global warming to 1.5 degrees Celsius is becoming increasingly unrealistic. Here, we look at the economic implications of climate change, why progress in reducing our emissions has been slow, and ways policymakers and markets can still act to mitigate global warming.

The Cost Of Inaction Rises Along With Global Warming

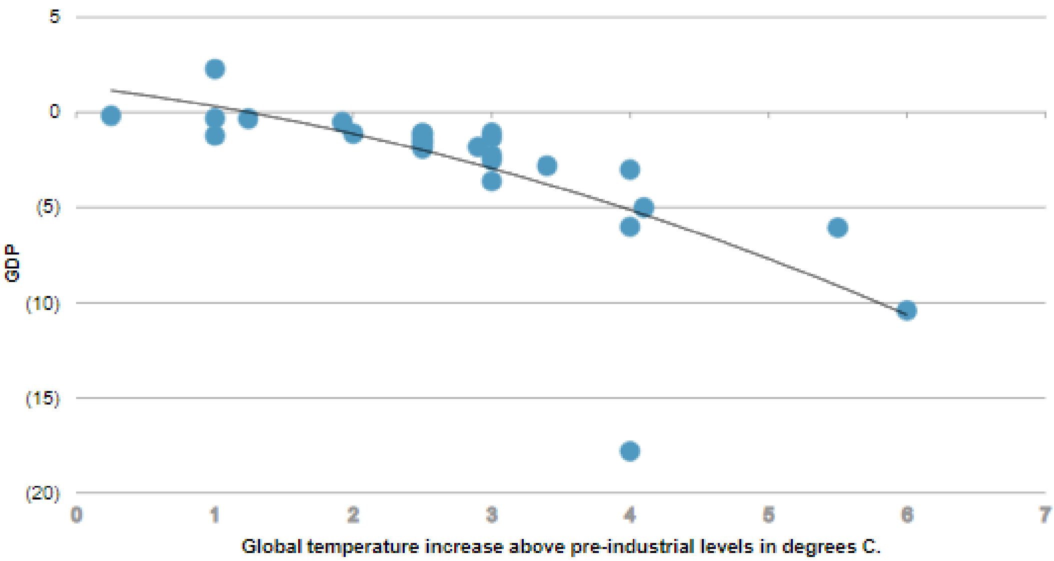
Research shows that global warming is costly. More frequent extreme weather events that damage infrastructure will lead to faster capital depreciation. This will lower the rate of return on these investments and thus the incentives for capital accumulation. Increased temperatures are set to affect the labor supply through higher heat-related morbidity and mortality, as well as weigh on workers' productivity, as hotter days tend to be associated with a reduction in working hours.

Putting all these factors together, studies find that global warming of 3 degrees C., which is the estimated trajectory based on countries' current pledges since 2015, would lower global output by 2%. Warming of 6 degrees C., which is slightly above upper estimates of the business-as-usual carbon emissions scenario, would push global output 8% lower (Nordhaus and Moffat 2017). Granted, current estimates are rough, given the large number of assumptions needed to model climate change. This suggests we might even be underestimating the costs of climate change. Yet, one robust result is that the higher the temperature, the more damaging climate change will be--and in a nonlinear way (see chart 1).

Chart 1 | Download Chart Data

Estimates Of The Impact Of Global Warming On Output Suggest The Cost Of Climate Change Rises With Temperatures

Note: Data points show estimates of the impact of global warming on global output from a number of studies

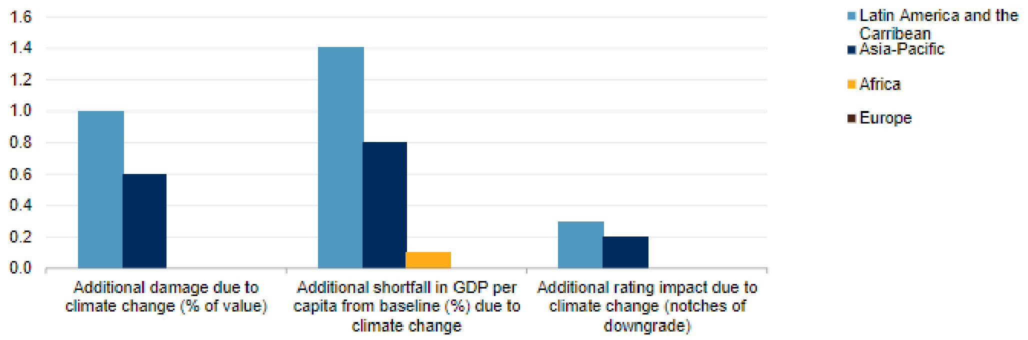


Sources: Nordhaus and Moffat, 2017: "A Survey of Global Impacts of Climate Change: Replication, Survey Methods, And a Statistical Analysis," S&P Global Ratings.

Studies also find that climate change will not be uniform across countries and thus have important distributional effects. Emerging and developing economies in the Caribbean, Asia, and Africa are most exposed to climate change (see charts 2 and 3). By contrast, advanced economies will suffer less from global warming. This is not only because they are better prepared than emerging or developing economies, but also because they are located in colder regions today. This wealth redistribution is likely to exacerbate migration flows to wealthier regions, putting pressure on land use and social systems.

Chart 2 | Download Chart Data

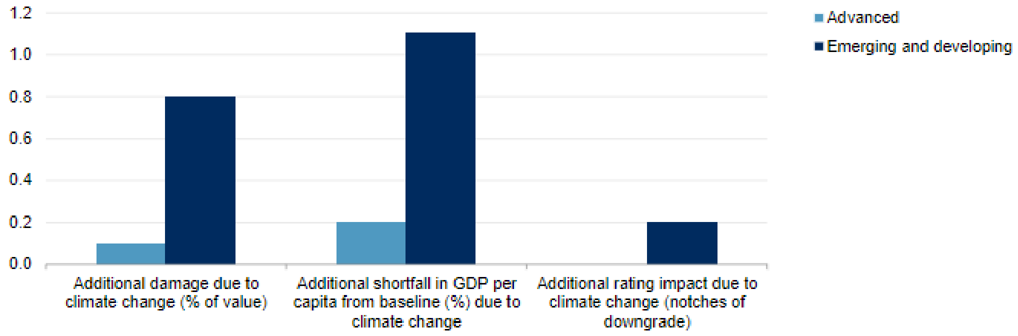
Average Impact Of Climate Change, By Region



Source: "The Heat Is On: How Climate Change Can Impact Sovereign Ratings," S&P Global Ratings, Nov. 25, 2015.

Chart 3 | Download Chart Data

Average Impact Of Climate Change, By Income Group



Source: "The Heat Is On: How Climate Change Can Impact Sovereign Ratings," S&P Global Ratings, Nov. 25, 2015.

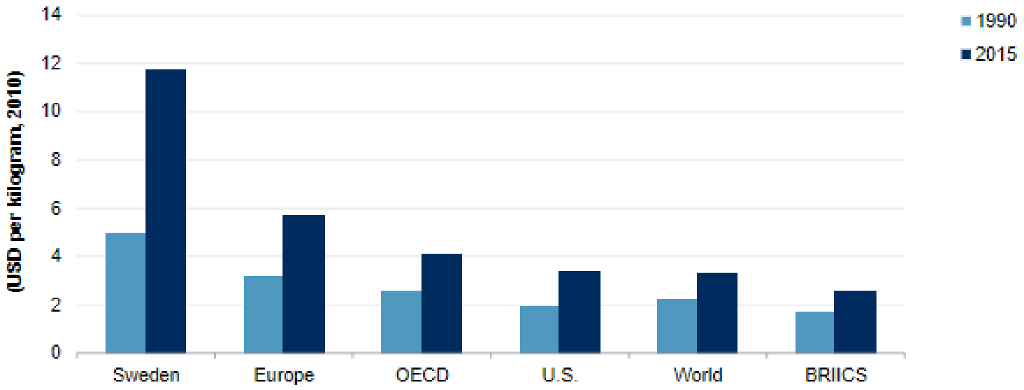
Climate change also represents a challenge for policymaking as it raises uncertainty about the state of the economy. In the long term, its costs are a clear downside risk to growth but also a source of increased volatility. As extreme weather events occur more often, they will also damage economic activity in a nonpredictable way. In the short term, policymakers will have more trouble disentangling the effects of climate change from the effects of other policies on the underlying state of the economy. For example, statisticians have struggled to identify seasonality in first-quarter U.S. GDP numbers linked to colder winters.

So Why Have We Done So Little To Lower Carbon Emissions?

Although it is clear that the cost of inaction rises with higher temperatures, the world has struggled to lower carbon emissions (see chart 4). Limiting global warming to 1.5 degrees C. now seems almost out of reach. According to the latest IPCC report, it would imply lowering carbon emissions to net zero by 2050. So why have we struggled to tackle global warming?

Chart 4 | Download Chart Data

The World's CO2 Productivity Improved Only 46% Over The Past 25 Years, While Output Doubled
Production-based CO2 productivity, GDP per unit of energy-related CO2 emissions



Sources: OECD, S&P Global Ratings. BRIICS--Brazil, Russia, India, Indonesia, China, South Africa.

One big hurdle is that its cost remains uncertain and the worst effects will occur in the future, once they are irreversible. This makes it difficult to compute the opportunity cost for acting now. If we discount the future too much, there is little ground for action today. The Trump Administration's announcement to withdraw from the Paris Agreement even suggests that some see no need to redirect resources toward greener energy to mitigate climate change or lead climate initiatives that carry significant economic benefits.

Another issue, which explains why policymakers have struggled to coordinate globally, is that climate change has all the characteristics of a global public good. A country has little incentive to change its behavior on its own since emissions are diffuse across borders and reducing them is costly, giving rise to the free-rider problem. For some policymakers, the worry is that firms might relocate their activity to countries with weaker environmental standards. Meanwhile, though they are the most affected by climate change, developing countries have less funds available to fight against it and may prefer to target other priorities, such as reducing poverty.

Meanwhile, the market on its own is unlikely to reach an optimal equilibrium, because most consumers and companies do not directly feel or internalize the cost of climate change. Although global warming is increasingly affecting consumers and firms through more frequent floods, hurricanes, and wildfires, it still comes with problems of attribution. It remains unclear that all of the impact is due to climate change. What's more, only a small number bear the costs, which are massive. The others do not feel the consequences of global warming and are more worried that a switch to greener spending may hurt their purchasing power or profits. In short, without a nudge or fiscal incentives, private consumption and activity will not actively seek to mitigate the impact of higher emissions on climate change.

A Few Avenues To Mitigate The Cost Of Inaction

Putting a global price tag on carbon would be the most efficient way to reduce carbon emissions. Taxing carbon or limiting its use would ensure that firms and consumers internalize the cost of global warming today. This is also the recommendation of policy experts (for example at IPCC, OECD, World Bank, and International Monetary Fund). The High-Level Commission on Carbon Prices recommends a carbon price of USD50-USD100 per ton of CO2 by 2030 to achieve the Paris Agreement goal. However, the coordination problems we have outlined above have made it difficult to put that into place.

The second-best approach is to initiate change at other regional, country, or local levels. Importantly, this gives countries more flexibility to design policy in line with their priorities and constraints, and removes the difficulty of reaching a global compromise. In terms of carbon pricing, this is where most progress has happened so far. **Finland** and **Poland** put a carbon tax in place in 1990, the EU created the first Emission Trading System (ETS) in 2005, and other jurisdictions have replicated these efforts since then. With China set to put its ETS in place in 2020, the World Bank estimates that all regional, national, and supranational initiatives will cover about 20% of global emissions. The next step toward a global carbon price would be for countries that have already established an ETS to link them together--similar to the current Swiss-EU initiative. While this is a big improvement, this is far from a global carbon tax.

Beyond carbon pricing, policymakers have many other ways to support a greener economy. They can foster greener investments and behaviors through fiscal policy, regulation, increased awareness by civil society and more climate-friendly public infrastructure. If well-designed, those policies can provide immediate economic and social benefits. To name a few, decreasing the reliance of an economy on fuel reduces its exposure to oil-price shocks; switching to less-polluting cars provides direct health benefits; and better-insulated homes reduce the energy bill for households.

Investing in resilience to climate change in the most exposed regions can help smooth the distributional effects of global warming. It can also be an immediate source of growth, as those regions tend to be less developed. Given that developing countries have tighter budget constraints, developed countries could think of green development aid.

Markets also have a role to play in climate change mitigation. As the cost of global warming is increasingly visible and rising, it is only rational for markets to start pricing its cost. All other things being equal, companies that integrate environmental goals in their strategy are more likely to achieve sustainable long-term value creation, especially if environmental regulation goes into a similar direction. In some industries, energy also represents an important proportion of operating costs, meaning gaining in energy efficiency may lead to productivity gains. With consumers and investors becoming more aware of the consequences of climate change, there is also a case for providing "environmentally friendly" alternatives. Indeed, we can see that there is increased demand for such instruments from the fast-growing green bonds market, which may surpass $200 billion in 2018, after reaching $160 billion in 2017 (see "**Untapped Potential: How The Green Economy Is Broadening**," published on Nov. 5, 2018). Interestingly, more than 90% of labeled green bonds have been rated investment grade.

Taking Advantage Of Sustainable Investment

As global decarbonization intensifies, so too has awareness about "green" investment--that is, investment considered environmentally beneficial. This kind of capital allocation may be considered a competitive differentiator in portfolios due to the potential for assets with improved cash flow, greater risk mitigation, and a more sustainable business model in the long term.

Against this backdrop, we have seen a plethora of diverse industries--many from traditionally "nongreen" sectors, including metals, mining, petrochemicals, heavy industry, energy, and power--looking to broaden sustainability strategies. What's driving development? In part, greater awareness of climate risks by corporates, investors, and wider society that has been an outgrowth of national and regional climate initiatives.

China's recent surge of investment into clean energy and sustainability initiatives signals an acceleration of the country's agenda to become a green superpower. It already accounts for nearly 71% of global production of solar panel technology and manufactures more lithium ion batteries than any other country in the world. China's greening policies, an integral part of the country's transformative Belt and Road Initiative, could represent an acknowledgement of the role that sustainable investment plays in attracting foreign capital. Indeed, the country's energy and climate goals for 2015 to 2020 are estimated to require between US$480 billion and US$640 billion of investment. And by 2040, China plans to have invested in excess of US$6 trillion into low-carbon power generation and clean technologies, which, if fulfilled, could far exceed that of many EU countries and even the U.S. (see "**Greener Pastures: China Cuts A Path To Becoming A Green Superpower**," published on Nov. 5, 2018).

Such ambitious and publicized targets emanating from **China** have fostered rivalry in other corners of the globe. This, combined with the Trump Administration's announcement to withdraw from the Paris Agreement, have sparked concerns in the U.S. that technological developments will stall in a more isolationist environment. Yet hope for the U.S. remains in the form of state-led initiatives. This September, Jerry Brown, Governor of **California**, formally announced the state's commitment to achieving a carbon-neutral economy. To this end, he signed SB 100, a mandate to set California on a path to deriving 100% of its power from clean sources by 2045, up from today's figure of 35%. California now also boasts a carbon-trading system that includes transport fuels and a low-carbon fuel standard, both of which are likely to promote development of advanced biofuels and associated technologies. California represents the largest state in the U.S. by population and economic output, and other states are following suit, introducing heightened renewable standards, implementing energy efficiency targets, and developing decarbonizing technologies, though, for the moment, these initiatives are largely clustered on the West Coast and in the northeastern part of the country.

The EU-wide goal of reducing CO2 emissions by 40% compared to 1990 levels by 2030 has served to raise the profile of global sustainability efforts. Even oil-rich Norway has been looking to decarbonize further, tightening its standards with a focus on its transportation sector, where there is still room for improvement.

Technological Disruptors And Moving Forward

For both private investors looking to diversify their portfolios and governments looking to fight global warming, investment in low-carbon and renewable energy sources will likely grow in importance. If low-carbon projects and renewables are to proliferate, the energy supply needs to be guaranteed. To provide vital backup to the grid and bridge supply shortfalls during intermittent weather, energy storage via batteries will need to improve and become commonplace. But there is still some way to go, suggesting there might be a case for increased public support for the technology. For example, storage capabilities would have to increase 200-fold to meet California's renewables target. But once capacity increases, growth could be exponential. And as renewables technology advances, forecasts can be benchmarked against real operating performance, providing more clarity and data, and ultimately encouraging increased investor appetite for renewables assets.

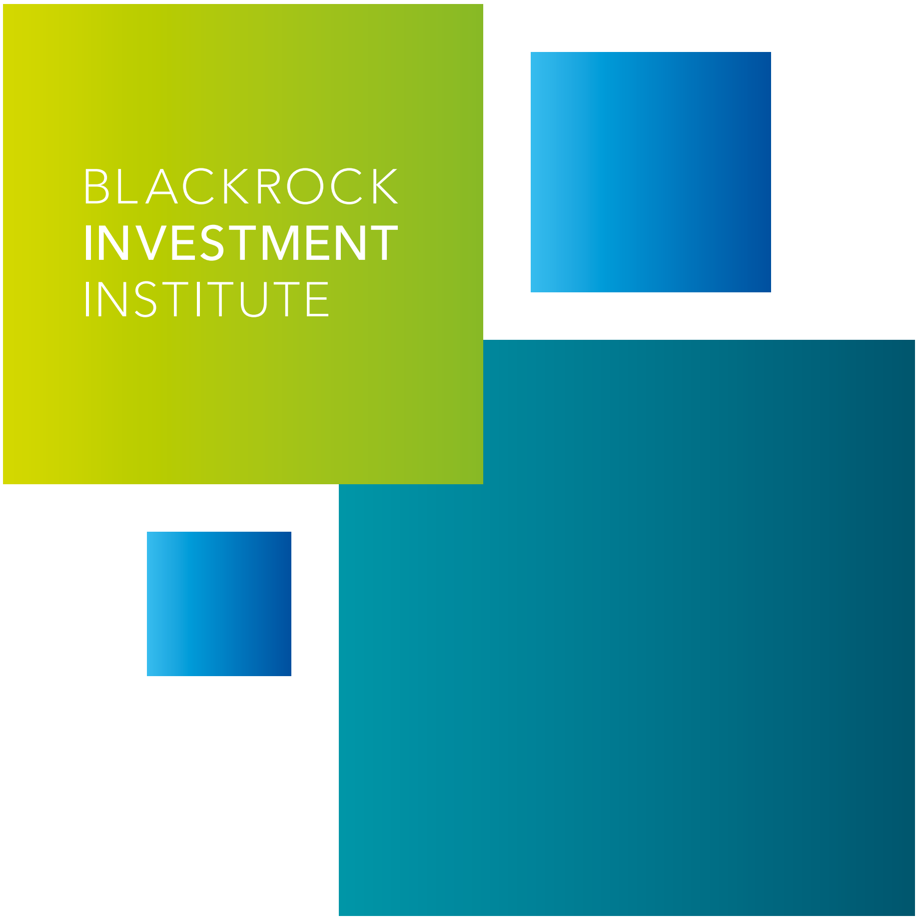
Overcoming technological hurdles and navigating complex political and regulatory environments are imperative for green investment to continue to grow. Low-carbon power projects reside at the intersection of economics and politics, where the continued deployment of energy technologies will require ongoing access to capital markets. Even with improved economics, this will require a higher level of transparency about the performance and cost of these assets. This may be an expensive proposition in the short term but one that may well pay off in the future.

This is a tab page.
Please title tab
“BlackRock”

GLOBAL INSIGHTS • APRIL 2019

Getting physical

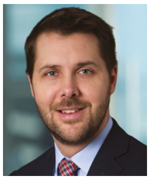
Scenario analysis for assessing climate-related risks



BLACKROCK®

Introduction

Brian Deese
Global Head of
Sustainable Investing



Philipp Hildebrand
BlackRock
Vice Chairman

Rich Kushel
Head of Multi-Asset
Strategies and
Global Fixed Income

Isabelle Mateos y Lago
Chief Multi-Asset
Strategist, BlackRock
Investment Institute

A series of recent extreme weather events – from hurricanes and wildfires in the U.S. to heat waves in Europe and floods in Japan – have put a spotlight on climate-related risks. Yet the implications for investment portfolios – stemming from a rising frequency and intensity of such events – have been notoriously hard for investors to grasp.

Why? First, the effects of slower-moving physical changes such as rising sea levels can seem distant. This causes investors to discount pressing climate-related risks already lurking in portfolios. Second, the risks are hard to model. New climate patterns mean long-dated historical data are a poor guide to the future. Investors using models overly reliant on the past are missing the big picture. Third, the risks have been hard to pinpoint. Drilling down on physical risk to the exact geographical location and asset level is key for investors — think of potential damage to commercial real estate or electric power plant facilities. But analyzing huge amounts of climate data properly and effectively is a challenge.

The good news: Recent advances in climate and data science make it easier to overcome these hurdles and separate the signal from the noise. BlackRock's collaboration with Rhodium Group combines our asset-level expertise with the latest climate science and big-data capabilities. The result – generating some 160 terabytes of data – is a granular picture of investment-relevant physical climate risks. We can now assess direct physical risks to assets on a local level — today and under different future climate scenarios. We can also estimate knock-on effects, such as the impact on energy demand, labor productivity and economic activity.

These tools give us unique insight into the severity, dispersion and trajectory of climate-related risks. This helps us assess whether the risks are adequately priced by markets. Our early findings suggest investors must rethink their assessment of vulnerabilities. Weather events such as hurricanes and wildfires are underpriced in financial assets, including U.S. utility equities. A rising share of municipal bond issuance is set to come from regions facing climate-related economic losses. And many high-risk commercial properties are outside official flood zones.

Understanding and integrating these insights on climate-related risks can help enhance portfolio resilience, we believe. Our first step focuses on assets and companies in the U.S. We plan to extend the analysis across regions, asset classes and sectors as data availability improves. Yet our early work already strengthens our conviction that sustainable investing is increasingly a ***"why not?"*** proposition.

CONTENTS

Summary

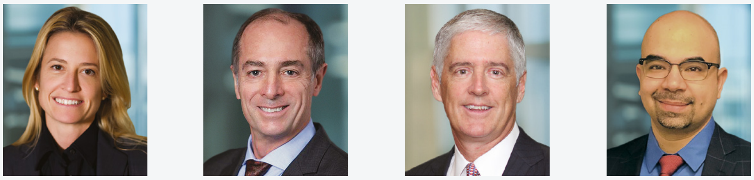
- **We show how physical climate risks vary greatly by region, drawing on the latest granular climate modeling and big data techniques.** We focus on three sectors with long-dated assets that can be located with precision: U.S. municipal bonds, commercial mortgage-backed securities (CMBS) and electric utilities. Hurricanes pose a threat to the finances of southern U.S. states; rising sea levels make coastal real estate vulnerable; and power plants in the Southwest have exposure to extreme heat. A localized assessment of such risks under different climate scenarios can provide investors with 1) a sharp lens for risk management and diversification; and 2) an informed basis for engaging with companies and issuers about their climate resiliency and capital spending plans.

- **Extreme weather events pose growing risks for the credit worthiness of state and local issuers in the $3.8 trillion U.S. municipal bond market.** We translate physical climate risks into implications for local GDP – and show a rising share of muni bond issuance over time will likely come from regions facing economic losses from rising average temperatures and related events. Some 58% of metropolitan areas face climate-related GDP hits of 1% or more by 2060–2080 under a "no climate action" scenario, we find. We zoom in on the highest risk areas – and explain the importance of assessing muni issuers' resolve and financial ability to fund adaptation projects to mitigate climate risks. We see potential to extend this analysis to sovereign issuers, including emerging markets.

- **Hurricane-force winds and flooding are key risks to commercial real estate.** Our analysis of recent hurricanes hitting Houston and Miami finds that roughly 80% of commercial properties tied to affected CMBS loans lay outside official flood zones – meaning they may lack insurance coverage. This makes it critical to analyze climate-related risks on a local level. We show how the economic impacts of a warming climate could lead to rising CMBS loan loss rates over time.

- **Aging infrastructure leaves the U.S. electric utility sector vulnerable to climate shocks such as hurricanes and wildfires.** We assess the exposure to climate risk of 269 publicly listed U.S. utilities based on the physical location of their plants, property and equipment. A key conclusion: The risks are underpriced. Electric utilities with exposure to extreme weather events typically suffer temporary price and volatility shocks in the wake of natural disasters. We find some evidence that the most climate-resilient utilities trade at a premium. We believe this premium could increase over time as the risks compound and investors pay greater attention to the dangers.

AUTHORS



LEFT TO RIGHT

Ashley Schulten – Head of Responsible Investing for Global Fixed Income; **Andre Bertolotti** – Head of Global Sustainable Research and Data; **Peter Hayes** – Head of Municipal Bond group; **Amit Madaan** – Co-head of Commercial Credit Modeling, BlackRock Solutions

Setting the scene

We explain how changes to the climate – and related extreme weather events – pose tangible risks to investment portfolios today, not just years in the future.

The climate is changing, societies are adapting, and technologies are catching up. This dynamic creates risks and opportunities for investors. The implications of climate change are playing out across four key channels: physical, technological, regulatory and social. See BlackRock's ***Adapting portfolios to climate change*** of 2016 for more. Advances in data and analytics now give us growing conviction in our ability to measure and manage these key risks.

In this piece we go deep on physical risk. Increasing global temperatures are leading to measurable changes in our habitat, such as rising sea levels, droughts, wildfires and storms. The trend of rising average temperatures is boosting the frequency at which extreme weather events occur, as well as their intensity. These changes are affecting our economy *today*.

The implications for investors go beyond coastal real estate. Think of agriculture (crop yields), insurance (property and casualty premiums) and electric utilities (risks to plants; peak electricity demand). The damage from storms, floods and heat waves can also disrupt corporate supply chains – and pressure public finances, posing risks to municipal and sovereign bond holders.

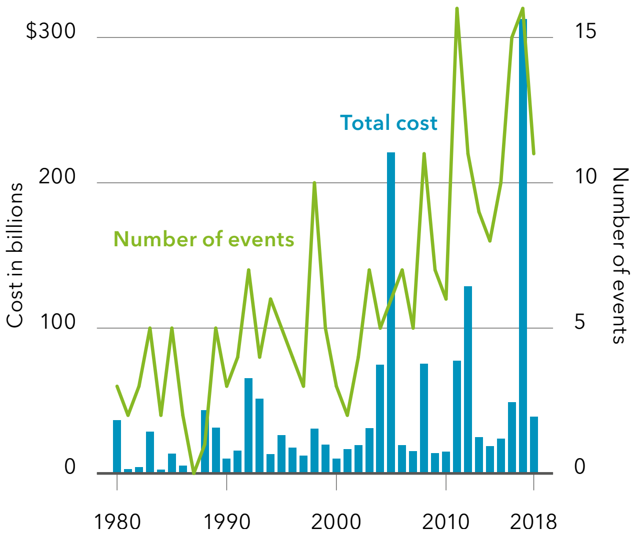
The number of natural disasters causing $1 billion-plus in damages has been on a steady rise, as shown in the *Mounting costs* chart. Related insurance claims hit a record $144 billion in 2017, but with much of the exposure uninsured, losses totaled $337 billion, according to 2018 ***Swiss Re data*****.** The data show wildfires caused a record $21 billion of damage globally in 2017, while a trio of hurricanes – Harvey, Maria and Irma – caused losses equivalent to 0.5% of U.S. GDP. This highlights a risk to investors. The rising incidence of extreme weather events over time could lead to spiking property and casualty insurance premiums, and reduced or even denied coverage if insurers shy away from underwriting risks that have become too great or uncertain. Investors need to get ahead of these risks.

We combine our asset-level expertise and cutting-edge climate modeling from Rhodium's work with a consortium of scientists and data experts to examine how the risks look today – and how they may evolve over time under different climate scenarios. See Rhodium's paper ***Clear, Present and Underpriced: The Physical Risks of Climate Change*** for a summary of its approach.

The climate modeling and data we purchased from Rhodium allow us to assess direct physical risks such as probabilities of flooding and hurricane-force winds – on a localized level across the U.S. This helps us estimate potential direct financial damages, as well as knock-on effects such as the impact of rising temperatures on crop yields or labor productivity. ***See page 7*** for details. We refer to these direct physical impacts and their indirect economic impacts collectively as climate-related risks. Many of the vulnerabilities are local. Example: Infrastructure on the U.S. Gulf Coast is at risk from wind and storm surge damage by hurricanes. Communities in the U.S. West are increasingly at risk from wildfires.

Mounting costs

U.S. billion-dollar disaster events, 1980–2018



Sources: BlackRock Investment Institute, with data from NOAA National Center for Environmental Information NCEI, October 2018. Notes: The line shows the number of climate events with losses exceeding $1 billion. The data include droughts, flooding, severe storms, tropical cyclones, wildfires, winter storms and freezes. The bars show the total cost. The data are adjusted for inflation using 2018 dollars.

Climate complacency

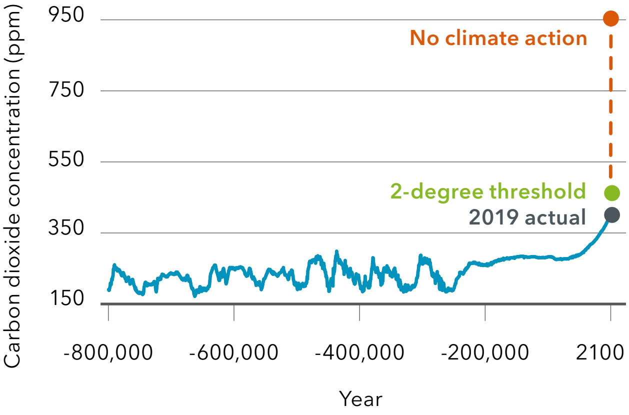
One of the most striking implications of our work drawing on the latest climate research: How much more pronounced the risks are today, compared with just a few decades ago. The risks that hurricanes pose to commercial properties, for example, have increased meaningfully, we find. ***See page 13*** for details. Investors who are not thinking about climate-related risks, or who view them as issues far off in the future, may need to recalibrate their expectations. Some physical changes – such as slowly rising sea levels – can seem outside of a traditional investment horizon. Yet the most pressing risks, such as exposure to hurricanes, wildfires and droughts, are clear and present – and often hidden in investors' portfolios *today*.

Our research suggests many of these risks are not priced in. Why? First, financial markets tend to be short-sighted – and underestimate risks that appear uncertain and distant. This may lead to a discounting of physical risks that are already biting. Second is a lack of tools and data. Example: Risk managers often rely on outdated flood zone maps to assess risks to real estate. Short-sighted policy and regulatory requirements can exacerbate this problem. Hurricane modelers look at 100 years of history to gauge future risks. But data prior to 1980 are patchy. And the past is of limited use as a guide to the future when averages (global temperatures and hurricane probability) are rising over time. Consider that Houston has seen three "one-in-500-year" flooding events since 2015, Houston's Harris County Flood Control District said in 2017. Bottom line: Looking backward over long periods results in underpricing the financial impact of climate-related risks.

Physical climate models can help fill the gap – and provide a more accurate assessment of the probability of a range of extreme weather events occurring in any given year. The challenge: Climate modeling is an evolving science. Different models point to different outcomes, with wide bands of uncertainty. Standard approaches to valuing the effects of rising global temperatures look at average predicted impacts for large regions – sometimes the entire globe. Yet recent computational advances make it possible for us to analyze the risks on a localized level.

Hockey stick

Global atmospheric concentration of CO_2, 800,000 B.C.–2100



Sources: BlackRock Investment Institute, with data from the U.S. Environmental Protection Agency, March 2019. Notes: The chart shows the concentration of carbon dioxide in the atmosphere over time, measured in parts per million (ppm). The data until 1950 are from historical ice core studies from the European Project for Ice Coring in Antarctica project. Post-1959 numbers are direct measurements taken at Mauna Loa, Hawaii. The 2019 actual data point is as of January 31. The 2-degree threshold is the CO_2 concentration at which global average temperatures are predicted to rise by 2°C from pre-industrial levels by end-century, as estimated by the IPCC. The "no climate action" scenario assumes ongoing use of fossil fuels and a CO_2 concentration of 940 parts per million (ppm) by 2100.

Hot today; hotter tomorrow

Scientists have long cited a clear linear relationship between the level of carbon dioxide (CO_2) in the atmosphere and warmer temperatures (the "greenhouse effect"). Temperatures over land and ocean have already gone up an average 1.2°C (2.2°F) since the mid-1800s, and significantly more at the Earth's poles, according to data from the National Oceanic and Atmospheric Administration (NOAA). CO_2 concentrations in the atmosphere are at a higher level than they have been for the past 800,000 years. See the *Hockey stick* chart.

How much warming can the Earth tolerate before experiencing the most destructive effects of climate change? The threshold of 2 degrees Celsius (3.6 °F) above "preindustrial" temperature levels rings alarm bells for many scientists. Recent trends in emissions suggest the 2-degree threshold is unlikely to hold. See the green dot in the chart. A "no climate action" trajectory (the orange dot) assuming ongoing use of fossil fuels would lead to a roughly 4°C (7°F) increase in average global temperatures by 2100, according to the Intergovernmental Panel on Climate Change (IPCC). Uncertainty around the path of carbon emissions means it is prudent to consider alternative scenarios when assessing climate-related risk. ***See page 7*** for more.

Investment applications

We detail our framework for assessing climate-related risks under different scenarios – and pinpoint the potential risks to assets across the U.S.

The physical risks posed by climate change were tough to model until recently. Advances in big data and cloud computing now enable us to zoom in on these risks on a 20 km (12 miles) by 20 km level across the U.S. We present a snapshot of our evolving research in this paper. It draws on Rhodium's work with the ***Climate Impact Lab***, combining historical climate and socioeconomic data with physical climate modeling. This work – a collaborative project between data gurus, econometricians and climate scientists – leverages millions of simulations. Our efforts to apply the data to U.S. assets required 600,000 hours of CPU processing power – and generated 160 terabytes of data – the equivalent of 120 million 1980's-era 3.5 inch floppy disks.

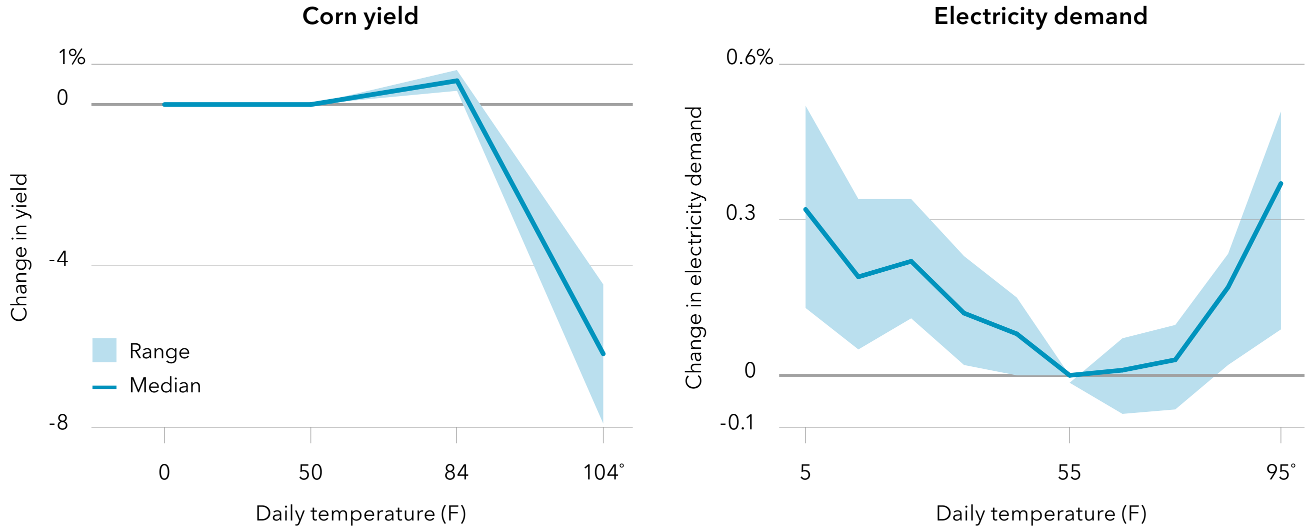
The analysis includes knock-on impacts of rising average temperatures. Many such effects are non-linear. Corn yields, for example, start to drop sharply when daily high temperatures exceed 84°F (29°C). And electricity demand tends to follow a U-shape, rising at extreme low and high temperatures. See the *Turning points* charts.

The focus of our initial work is U.S. municipal bonds (***pages 10-12***), CMBS (***pages 13-14***) and electric utility equities (***pages 15-17***). The reason: These asset classes are backed by long-duration physical assets of known location. We start by assessing the risks to these asset classes today. Too often, assessments of physical climate risk start by looking decades into the future. This overlooks risks that are already present.

How to gauge the related risks on assets? Our process:

1. Determine which assets have a readily identifiable physical location (e.g., properties of CMBS loans).
2. Overlay the asset locations with climate data to assess exposures to relevant direct physical risks such as hurricanes – today and in the future.
3. Link climate data to relevant second-order financial and socioeconomic implications.
4. Analyze if these risks are priced in and/or insured, and determine if the company/issuer has the resolve and financial capacity to adapt.

Turning points



Changes in corn yields and electricity demand as a function of daily maximum temperatures

Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The ranges shown are the 95% confidence interval (two standard deviation range). All analysis is from Rhodium Group. Corn estimates draw on county-level U.S. agricultural production data from the U.S. Department of Agriculture over 1950–2005 to identify the relationship between temperature changes and average yields, using the methodology of *Schenkler and Roberts (2009)*. Electricity demand draws on two studies measuring the effect of climate variables on energy demand: *Deschenes and Greenstone (2011)* examine state-level annual electricity demand from 1968 to 2002 using data from the U.S. Energy Information Adminstration. *Auffhammer and Aroonruengsawat (2011)* study monthly building-level electricity consumption for California households.

Plotting paths

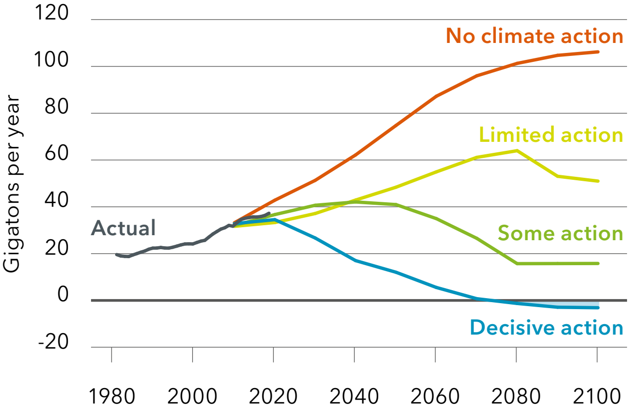
Global climate scenarios are central to our analysis. The climate modeling community has settled on several plausible pathways for the future path of carbon emissions. To account for uncertainty around these future pathways, we consider four scenarios, reflected in the *Plotting paths* chart below: These range from the "no climate action" scenario (orange line) that assumes continued burning of fossil fuels; to a "decisive action" scenario (blue line) that assumes aggressive policy actions to curb emissions.

The latter is the goal of the 2015 Paris Climate Agreement, which aims to keep the average increase in global temperatures to well below 2°C by the end of the 21st century. Actual emissions growth (gray line in the chart) has the world on a path to higher-warming scenarios, posing risks to assets.

Rhodium draws on 21 advanced global climate models to calculate probability-weighted indicators of physical climate changes – such as temperature, rainfall and hurricane risk – for each of these emissions scenarios. See ***Rhodium's article*** in the Journal of Applied Meteorology and Climatology (Oct 2016) for details. The goal: to answer what we know both about the physical risks today, and how those risks may evolve in the future.

Plotting pathways

Scenarios for fossil fuel-related CO_2 emissions, 1980–2100



Sources: BlackRock Investment Institute, with data from Rhodium, March 2019. Notes: CO_2 emissions include fossil fuel combustion and cement production. The chart lays out the four representative concentration pathways (RCPs) commonly used as scenarios in climate modeling, as defined by the Intergovernmental Panel on Climate Change. "No climate action" (known as RCP 8.5) assumes ongoing fossil fuel use, with atmospheric CO_2 concentrations reaching 940 ppm by 2100. "Limited action" (RCP 6.0) sees CO_2 concentrations rising to around 670 ppm by 2100. In "some action" (RCP 4.5), CO_2 concentrations stabilize at around 550 ppm. Decisive action (RCP 2.6) sees aggressive policy action resulting in negative net emissions (see shaded blue area) by late in the century, with CO_2 concentration of 384 ppm by 2100.

SCENARIO ANALYSIS

How can governments, companies and investors best incorporate climate risks into their decision making? Scenario analysis plays a key role. The Financial Stability Board's ***Task Force on Climate-Related Financial Disclosures*** has resulted in a hearty pick-up in analysis. The TCFD, of which BlackRock is a member, separates climate risks into two categories.

- **Transition risks:** The risks to businesses or assets that arise from policy, legal, technological and/or market changes as the world seeks to transition to a lower-carbon economy. See ***Sustainability: the future of investing*** for details on our approach.
- **Physical risks:** The risks to entities or assets from the climate changes already occurring and expected to continue in the years ahead under different greenhouse gas emissions scenarios.

Physical risks pose the greatest threat in the "no climate action" or "limited action" scenarios, both of which likely lead to significant increases in average global temperatures. Transition risks take on greater relevance in a "decisive action" scenario that involves tough regulatory actions to curb emissions, breakthroughs in clean energy, and a more limited rise in temperatures.

Given our focus on physical risks in this piece, we concentrate on the "no climate action" scenario. We see this as a tough, but plausible, scenario for stress-testing investment portfolios. This is in line with the TCFD's recommendation that entities consider "challenging" scenarios for risk management. Scenarios are not forecasts. And they do not equal sensitivity analysis (to a particular factor). The idea is to challenge conventional wisdoms about the future.

Scenarios draw attention to key factors that will drive future developments. This, in turn, can help in assessing how resilient an organization is against potential disruptions. Does it have the ability to adapt to the changes – and take advantage of related opportunities? Does it have plans in place to mitigate the risks? Scenarios can provide investors with a framework for answering such questions.

A glimpse into the future

How might some of the risks play out? Average temperatures show some striking potential changes under a "no climate action" risk scenario of ongoing fossil fuel use.

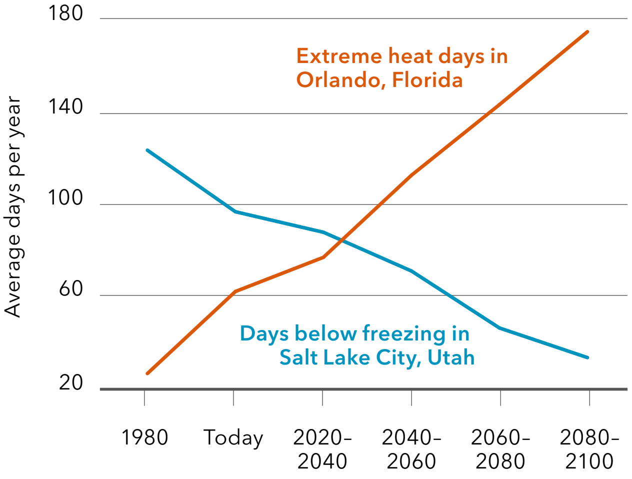
Example: The number of freezing days in Salt Lake City, Utah, could fall by as much as 75% by the end of the century from 1980 levels. By contrast, Disney World in Orlando, Florida, could see the average number of annual days with extreme heat spike to almost half the year. See the *A tale of two cities* chart below.

Up to 26% of U.S. metropolitan areas would likely see more than 100 days a year of 95°F (35°C) heat by 2060–2080, versus around 1% today, the estimates show. This would have important knock-on implications:

- Lower productivity in regions that rely on outdoor labor such as agriculture and construction work;
- Rising mortality rates as the incidence of extreme heat rises in hotter states such as Texas;
- Greater energy expenditure to cool buildings, particularly in the U.S. South West;
- Lower agricultural output due to declining crop yields in hotter states such as Arizona.

A tale of two cities

Average number of cold and hot days in two U.S. cities, 1980–2100



Sources: BlackRock Investment Institute, with data from Rhodium, March 2019. Notes: The chart shows the average annual number of cold days in Salt Lake City, Utah, when the temperature falls below 32°F (0°C), and the number of hot days in Orlando, Florida above 95°F (35°C). 1980 data are actual. "Today" represents the 2010–2030 estimate. Estimates are from Rhodium and assume a "no climate action" scenario. We show the upper bound of the 66%, or "likely" range. Rhodium's estimates draw on 21 general circulation models to assess probabilities of temperature, precipitation and other climate variables.

Changing world

Estimated "no climate action" impacts vs. 1980, 2019–2100

	Today	2020–2040	2040–2060	2060–2080	2080–2100
Sea level rise (feet)					
Houston	1.2	1.6	2.5	3.6	4.9
New York	0.9	1.2	1.9	2.9	4.0
Hurricane damage (annualized % GDP loss)					
New York	0.2	0.2	0.2	0.4	0.6
Miami	2.5	2.5	2.8	3.3	3.9
Change in agricultural output (annualized % GDP gain/loss)					
Pine Bluff, Ark.	-0.9	-1.2	-2.7	-3.7	-3.8
Jamestown, N.D.	1.0	2.4	5.2	6.5	5.0
Change in energy expenditure (annualized as % of GDP)					
Tucson, Ariz.	0.3	0.5	0.8	1.2	1.6
Minneapolis	-0.11	-0.12	-0.13	-0.14	-0.14

Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: All estimates are from Rhodium Group and assume a "no climate action" scenario. We show the upper bound of the 66%, or "likely" range of outcomes to illustrate a plausible risk scenario. Sea level rise (in feet) is from 1980. Hurricane damage, agricultural output and energy expenditure show annualized GDP gains/losses as a result of physical changes in the climate since 1980. For details on Rhodium's methodology see *Estimating economic damage from climate change in the United States*, Science (June 2017).

How large are the potential effects? Pretty big, under a "no climate action" scenario. Tucson, Arizona, for example, would be spending more than 1% of GDP annually on additional energy costs by late century. See the *Changing world* table above. Declining potential for agriculture, as extreme heat reduces crop yields, would be shaving up to 4% annually off the GDP of Pine Bluff, Arkansas. By contrast, Jameston, North Dakota, for example, would gain a GDP boost from warming.

Sea levels are set to rise meaningfully, exposing much coastal property to potential losses. Rhodium's work shows that sea levels in Houston are more than a foot higher today than in 1980. This rise is likely to swell to as much as five feet by the end of the century under current emissions trends, the estimates show. New York City would see likely sea level rises of up to three feet by 2080, exposing roughly $73 billion of property to potential losses. Hurricanes are a key driver. We can estimate potential damages by combining historical loss rates with building-level exposure data and cutting-edge hurricane modeling. The result: Potential annualized storm hits of as much as 3% of GDP to Miami and other coastal cities.

Net impacts

How to gauge the overall economic impact of climate-related risks on a region? Rhodium's work allows us to estimate this under different scenarios. To illustrate, the *Mapping the damage* graphic below visualizes the expected changes to GDP across the U.S. under a "no climate action" scenario in 2060–2080.

The biggest likely losers: the Gulf Coast region, the South Atlantic seaboard and much of Arizona. See the orange tones in the map. A handful of colder states see potential for modest GDP gains. Yet the risks are asymmetric: Some 58% of U.S. metro areas would see likely GDP losses of up to 1% or more, with less than 1% set to enjoy gains of similar magnitude, we estimate. Florida tops the danger zones, with Naples, Panama City and Key West seeing likely annual GDP losses of up to 15% or more, mostly driven by coastal storms. Note these are average annual estimates; losses would likely come in big weather-driven shocks that could be much larger for a given year. The losses are not baked in: Decisive action could mitigate carbon emissions and cities can spend on adaptation measures to increase their resiliency. But the vulnerabilities revealed in the analysis have important implications for municipal bond issuers and investors, as discussed in the next chapter.

58% Estimated share of U.S. metro areas with 1%-plus climate-related GDP losses by 2080

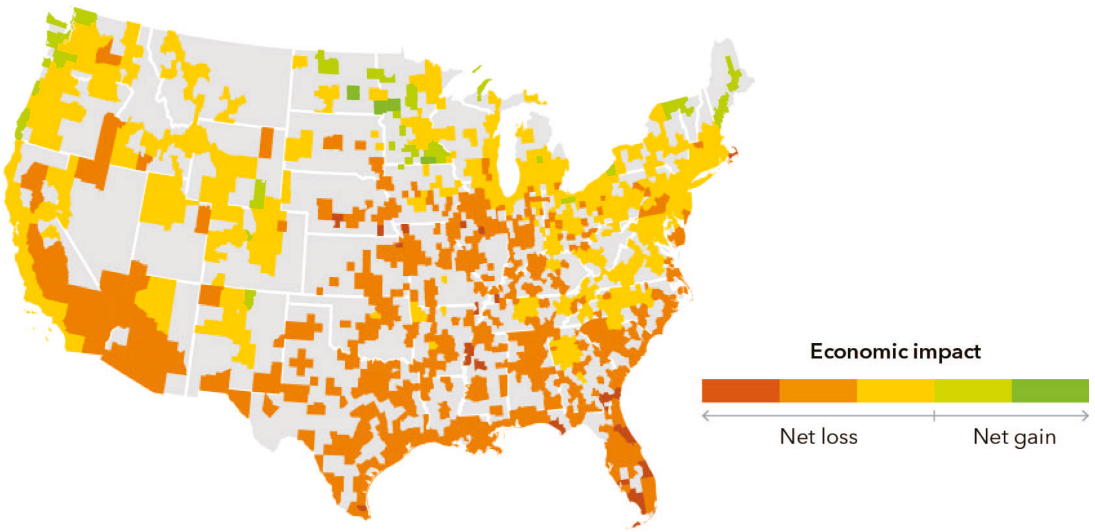
Getting a better handle on physical climate risk, down to the asset level, can add an important tool to an investor's toolkit. This is particularly valuable for portfolios of assets that are geo-locatable – and have decades-long lifespans. This is why we initially focus on U.S. municipal bonds, CMBS and electric utilities.

Our analysis is just a first step. We aim to extend the work to other regions, asset classes and sectors. Future challenges include applying the methodology to multinationals with complex supply chains, as well as to services companies. The latter requires assessing how exposed a company's key markets are to climate risks.

There is inherent uncertainty in climate modeling and weather scenarios. This means there is uncertainty in our estimates of that risk today – and even more so in the future. Yet we believe our work to better measure physical risks today – and under different scenarios in the future – is an important starting point. It can help reveal risks that may be mispriced in portfolios today, and how those risks may change over time.

Mapping the damage

Estimated net economic impact on U.S. regional GDP under "no climate action" scenario, 2060-2080



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The map shows the projected GDP impact in 2060–2080 on U.S. metropolitan areas under a "no climate action" scenario. Climate changes are measured relative to a 1980 baseline. The analysis includes the effect of changes in crime and mortality rates, labor productivity, heating and cooling demand, agricultural productivity for bulk commodity crops, and expected annual losses from coastal storms. It accounts for correlations across these variables and through time – and excludes a number of difficult to measure variables such as migration and inland flooding. See Rhodium Group's March 2019 paper *Clear, Present and Underpriced: The Physical Risks of Climate Change* for further details on its methodology. Forward-looking estimates may not come to pass.

Municipal bonds

We show how climate-related risks threaten the economies – and creditworthiness – of many U.S. state and local issuers, and provide a framework for assessing these risks.

Climate-related risks are underappreciated in the U.S. municipal bond market. Hurricanes, floods and other extreme weather pose a host of financial challenges for state and local issuers. A lot is at stake: The market has $3.8 trillion of outstanding debt, according to late-2018 Federal Reserve data. Consider the following:

- The cost of cleanups after extreme weather, funding mitigation projects to forestall future damages, and rising flood insurance premiums can lead to higher debt levels. This has big implications for general obligation (GO) bonds – those backed by the credit and tax power of states and cities.
- The tax base of a municipality could shrink if large-scale natural disasters lead to a population drain (such as that experienced by Puerto Rico in the wake of Hurricane Maria in 2017) and declining property prices. Some municipalities offer property tax relief in the aftermath of natural disasters, exacerbating the hit to their revenues.
- Gradual changes to the climate – such as rising temperatures and sea levels – can change patterns of land use, employment and economic activity. Businesses may relocate to other regions, also eroding the local tax base.
- Revenue bonds tied to specific projects – such as those issued by water and sewer utilities – may suffer direct harm from sea level rise, floods or droughts.

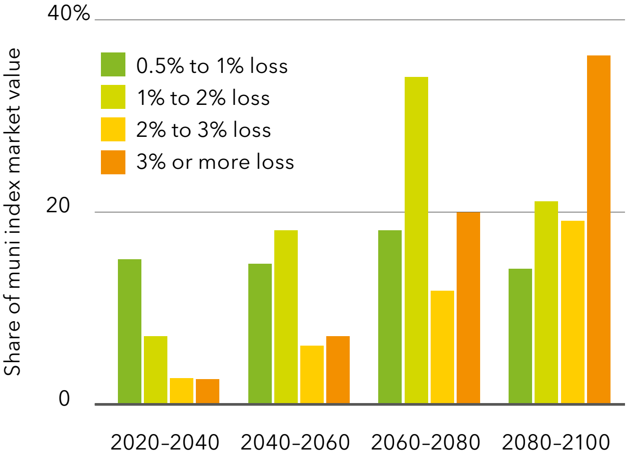
Credit rating agencies are paying increased attention to these risks. Moody's in 2017 warned that climate change would have a growing negative impact on the creditworthiness of U.S. state and local issuers – particularly those without sufficient adaptation and mitigation strategies. Yet such strategies can be costly. One example: Florida's governor in January said the state wanted to spend $2.5 billion over four years to address environmental issues, including the effects of rising sea levels.

Climate models suggest such financial challenges are only set to intensify. Our work shows a rising share of U.S. metropolitan statistical areas (MSAs) will likely face escalating climate-related risks in the coming decades. This analysis breaks down the potential net economic impact – relative to where GDP would have been absent the effects of climate change – on each of the 383 U.S. MSAs under a "no climate action" scenario. It includes estimates of direct impacts, such as the expected losses from hurricane damage, as well as second-order effects such as changes in mortality rates, labor productivity, energy demand and crop yields.

Within a decade, more than 15% of the current S&P National Municipal Bond Index (by market value) would be issued by MSAs suffering likely average annualized economic losses of up to 0.5% to 1% of GDP. See the *A growing burden* chart. This would have big implications for the creditworthiness of MSAs – and their ability to fund adaptation projects. The impacts are set to grow more severe in the decades ahead, as the chart shows.

A growing burden

Muni index share at risk of climate-related GDP loss, 2020–2100



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: We use the S&P National Municipal Bond Index to represent the muni market. The chart shows the estimated market value share of the muni market exposed to GDP losses of various magnitude through 2100 under a "no climate action" scenario. For example, roughly 20% of the market value of the current muni index is expected to come from regions suffering annualized average losses of up to 3% or more of GDP from climate change by 2060–2080. We use the upper bound of the 66%, or "likely," range of losses to illustrate a plausible risk scenario.

Location, location, location

The impact of climate-related risks varies widely, with coastal and southern states hit hardest. The *What's the damage?* chart shows the range of projected effects over time for the 15 largest MSAs, which make up almost 40% of the muni market. Our work suggests all major MSAs are already suffering mild to moderate losses today – the result of cumulative changes to the climate since our 1980 baseline year. Topping the list of damages: Miami, Florida, with estimated annualized GDP losses of more than 1% today – and potential for these losses to grow to an annualized 4.5% of GDP by the end of the century. These would be mostly driven by hurricanes and rising sea levels. Note this is a high-risk scenario; aggressive global efforts to curb carbon emissions would put projected losses on a more moderate path.

Seattle, with its relatively temperate climate, shows the most resilience with little projected damage to GDP over time. The New York City region faces annual losses equivalent to roughly 1% of GDP by late century. The projected losses are not set in stone. Larger, more diversified MSAs such as New York are in a better position to fund adaptation and mitigation projects. The city has pledged to spend $20 billion over 10 years to make buildings and infrastructure more climate resilient.

Blissful ignorance?

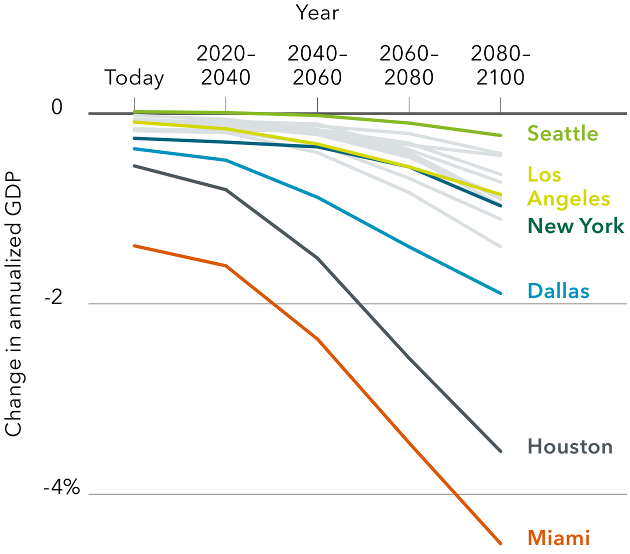
Are markets pricing in any of these future risks? One approach to finding out is to compare similar bonds located in climate-sensitive and non-climate-sensitive areas and review their prices (spreads). Such comparative spot-checks of municipal bonds do not reveal significant differences in valuation, we find.

For example, we considered two bonds with similar characteristics: Jupiter, Florida is an area beset by the hurricanes that affect the greater Miami region. Jupiter's location and its numerous waterways make the city especially vulnerable to tropical storms and hurricanes. By contrast, Neptune, New Jersey is far more insulated against severe storms.

We compared a Jupiter water revenue bond against a Neptune bond with fairly similar characteristics (taking coupon, maturity, callability, and the sector into account). The result: They had almost identical yields after adjusting for the credit quality of the two bonds (AA vs A rating). If climate-related risks were being considered as a key factor, we would have expected the Neptune bond to carry a lower yield (higher price) than the Jupiter bond. We found similar results for other spot checks of bonds in areas of high and low climate risk.

What's the damage?

Estimated climate impact on GDP of top-15 U.S. MSAs by economic weight, 2018–2100



	GDP ($ bln)	Debt ($ bln)	Share of muni index
New York	1,718	203	9.5%
Los Angeles	1,044	86	3.9%
Chicago	680	74	3.3%
Dallas	535	64	3.0%
Washington D.C.	530	45	2.0%
San Francisco	500	71	3.3%
Houston	490	51	2.4%
Philadelphia	445	25	1.2%
Boston	439	67	3.2%
Atlanta	385	34	1.6%
Seattle	356	30	1.4%
Miami	345	33	1.5%
San Jose	275	13	0.6%
Detroit	261	12	0.6%
Minneapolis	260	25	1.2%

Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The cities shown represent the top-15 U.S. metropolitan statistical areas (MSAs) by GDP. The chart shows projected annualized GDP losses (upper bound of the 66%, or "likely," range) due to cumulative changes in the climate since 1980 under a "no climate action" scenario. Today is represented by a 2010–2030 estimate. The table shows the GDP, total outstanding municipal bond issuance, and each MSA's weight in the S&P National Municipal Bond Index. The MSAs shown are greater urban areas; for example, Los Angeles includes Long Beach and Anaheim, California.

The FEMA put

How to explain the municipal bond market's apparent complacency around climate-related risks? We offer a handful of possible explanations:

- **Lack of attention:** Investors have been slow to give serious consideration to climate change, partly due to a lack of granular data for modeling the risks. This mindset is slowly changing. Credit analysts often note that they do consider the location of revenue sources but don't quantify their concerns by building an additional risk premium into spreads.
- **Time horizon:** The most dire projected impacts will come in future decades, beyond the traditional time horizon of most investors and credit rating agencies – and the duration of the average muni bond (16 years). This may lead to a discounting of risks that are already present today.
- **Insurance:** Bonds in climate-sensitive regions are often insured, thus diminishing investor concerns about storm hits. This is a key reason why muni bond prices tend to fall after heavy storm damage, but recover quickly after.
- **The "FEMA put:"** Areas devastated by storms have typically been rebuilt with funding from the Federal Emergency Management Agency (FEMA). Investors assume the bonds are insulated from climate-related risks, with FEMA providing something akin to a put option that preserves the bonds' par value.

We find little evidence that climate-related risks are priced into the municipal bond market today. Yet this dynamic should change over time, in our view. Insurance coverage in climate-affected areas is likely to become more costly – if still available.

The "FEMA put" could become less reliable if mounting disaster costs were to overwhelm FEMA's financial capacity or political will to respond. Political uncertainty around FEMA's structure and mandate only exacerbate this risk. And large-scale extreme weather events such as recent U.S. hurricanes could jolt investor sentiment. As these trends intensify and some of the risks play out, we could see a climate-proof premium emerging. We believe bonds issued by climate-resilient states and cities are likely to trade at a premium to those of vulnerable ones over time.

Assessing resilience

Our analysis shows climate-related risks are real and growing for the municipal bond market. This suggests long-term climate predictions should be taken into account when assessing an issuer's debt structure. And it makes it increasingly important for investors to look at the preparedness of states and municipalities when assessing their creditworthiness.

Some issuers are tapping the green bond market to fund mitigation efforts. Columbia, South Carolina, for example, recently issued the first tranche of a $95 million project to shore up its stormwater drainage system. How to gauge if such efforts are sufficient? Among the key questions we believe investors should be asking:

- Does the issuer have long-term plans – and the financial capacity to finance projects that increase resilience against climate risks?
- Do local ordinances or policies encourage inefficient rebuilding (in vulnerable areas) after storm hits?
- Is insurance coverage adequate for the most relevant risks?
- Do water and sewer utilities have plans in place for droughts and floods?
- Is the local economy diversified enough to absorb climate-related shocks?

Limited disclosure on such plans is one of the challenges investors face. This challenge cuts across asset classes. Providing a disclosure framework is a key goal of the TFCD described on page 8.

We believe our work connecting climate data and assets forms a starting point for assessing the risks. Pinpointing areas that are likely to expect the greatest climate impacts in coming decades can inform asset allocation and security selection decisions. And we see potential to use similar techniques to shine a light on climate risks faced by sovereign issuers, including emerging markets. Bottom line: Climate risk exposure analysis can help assess vulnerabilities of U.S. municipal issuers. We see this as a useful risk-management tool – and a valuable starting point for institutional investors to engage with issuers about their mitigation and adaptation measures.

Commercial real estate

Extreme weather and other climate-related events pose a risk to commercial real estate. We zoom in on hurricane and flood risk and estimate potential losses to the sector.

Climate-related risks are a growing concern for owners of commercial mortgage backed securities. Assets underlying CMBS loans – such as office buildings, retail properties and lodging – can have lifespans of several decades, subjecting them to climate risks that are set to intensify over time. Many assets underpinning CMBS portfolios are located in regions that are vulnerable to the increasing incidence of severe storms. Case in point: New York, Houston and Miami alone made up one-fifth of CMBS properties by market value in the Bloomberg Barclays Aggregate Index, as of March 2019.

Two hurricanes in 2017 illuminated these risks:

- Hurricane Harvey, a Category 4 storm that hit the Houston area, affected over 1,300 CMBS loans. This was roughly 3% of the market as of late 2017, based on our estimates that overlaid impacted properties on to FEMA flood zone maps. Irma, a Category 4 storm that made landfall in Florida, affected almost 1,000 CMBS loans, or 2% of the CMBS universe.
- Some 80% of the commercial properties damaged in both storms, according to our analysis, lay outside official flood zone maps. This indicates they could have had insufficient flood insurance.

Hurricanes pose big risks to commercial property in the form of extreme winds (from blown windows to structural damage) and flooding (damage to basements and electrical systems). Category 4 and 5 wind speeds, in particular, can create outsized damage to properties. These risks are already a reality.

To illustrate, we overlaid Rhodium's hurricane modeling onto the U.S. CMBS market, as proxied by roughly 60,000 commercial properties in BlackRock's proprietary CMBS database. The median risk of one of these properties being hit by a Category 4 or 5 hurricane has risen by 137% since 1980, we found. Within three decades, the risk of being hit by a Category 5 hurricane is projected to rise 275% under a "no climate action" scenario. See the *Stormy weather* chart.

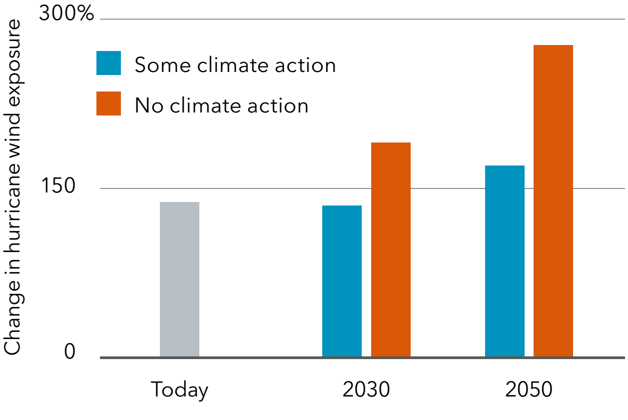
275% Rise in Category 4/5 hurricane risk by 2050

The risks to the CMBS market posed by rising average temperatures are varied, and go beyond the direct physical damages from storms and floods. They include:

- Higher insurance premiums or decreased insurance coverage.
- Rising operational costs such as energy use for air cooling systems.
- Greater capex needs to make buildings more resilient (think of backup generators, water-pumping systems and reinforcement of building exteriors).
- Increased delinquencies as tenants default or walk away from properties after extreme weather events.
- Potential hits to valuations and declining liquidity of properties in vulnerable areas.

Stormy weather

Change in Category 4/5 hurricane wind exposure since 1980



Sources: BlackRock Investment Institute, with data from Rhodium Group, March 2019. Notes: The chart shows the change in median hurricane wind exposure in the CMBS market, represented by around 60,000 commercial properties in BlackRock's CMBS database. The bars represent the estimated change in the median probability of Cat 4 or 5 hurricane winds touching properties relative to 1980 under "no climate action" and "some climate action" scenarios. "Today" is a 2010–2030 estimate. We use the Saffir-Simpson Wind Scale ("Cat" 1–5) to rate hurricane wind speed. Wind fields are estimated by Rhodium using the LICRICE wind field model. For details see S. Hsiang and A. Jina, *"The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones,"* NBER Working Paper, Jul. 2014.

Focus on flooding

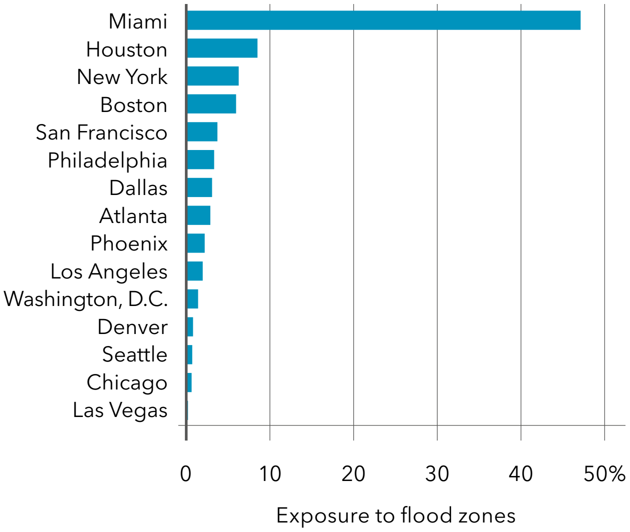
Borrowers contributing assets to CMBS deals are required to have wind insurance as part of their broader "hazard insurance." This does not cover flood risk. Flood insurance is required only if the commercial property is located within FEMA-designated flood zones.

To estimate the official footprint of the flood hazard, we mapped 60,000 properties in our CMBS universe onto FEMA flood maps, using an algorithm that sorted through 830,000 geospatial blocks across the U.S. Based on our analysis, around 6% of the properties in the CMBS market lie in FEMA flood zones. This percentage varies greatly by region. Miami tops the exposures, with almost half of commercial properties situated in flood zones. See the *Flood water* chart.

Recent hurricanes hitting cities such as Houston suggest FEMA flood maps understate true risks. And flood risk is set to intensify. Based on our mapping of the CMBS universe onto Rhodium's data, the number of properties subject to 1% or more storm surge risk per annum would rise by 1800% by 2060–2080 under "no climate action." To be sure, many commercial real estate sponsors take out flood insurance even when properties lie outside flood zones. Yet such insurance may not always be available, and "uninsured" flood exposure is set to rise.

Flood water

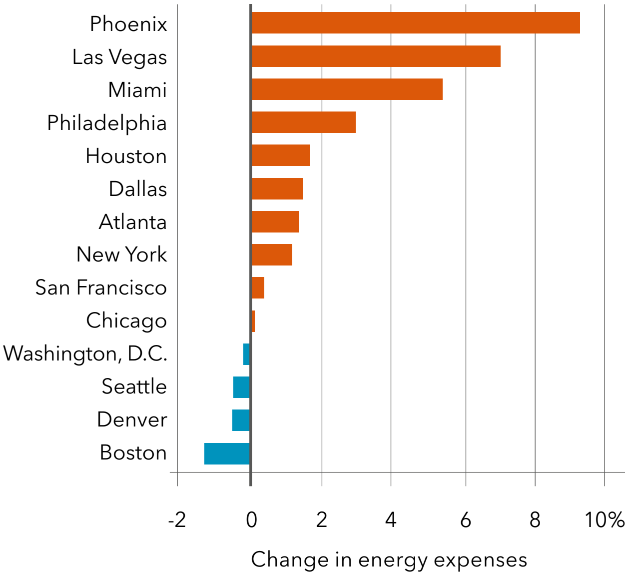
U.S. CMBS market exposure to official flood zones, 2019



Sources: BlackRock Investment Institute, with data from FEMA and BlackRock's CMBS property database, March 2019. Notes: The chart shows the market value share of properties in the U.S. CMBS market that lie within FEMA-designated flood zones in selected U.S. urban centers. We use BlackRock's CMBS property database, containing around 60,000 underlying commercial properties, as a proxy for the CMBS market.

Rising bills

Impact of climate change on energy expenses, 2060–2080



Sources: BlackRock Investment Institute, with data from Rhodium Group, 2019. Notes: The analysis assumes a "no climate action" scenario and takes the upper bound of the 66%, or "likely" range, to illustrate a plausible risk scenario.

Energy or utility expenses make up around 15% of operating expenses for commercial buildings, according to our analysis of 100,000 property financial records. Rising temperatures could inflate these bills. Based on Rhodium's data, energy expenses would rise by up to 9% (Phoenix) under "no climate action." See the *Rising bills* chart. These estimates likely underestimate the costs, as they do not account for electricity rate rises.

What impact could this have on property cash flows and commercial loan defaults? We used an illustrative CMBS model to estimate changes in default rates on commercial mortgages in the Bloomberg Barclays Aggregate Index. Our inputs: CMBS properties' current financials and Rhodium's estimated GDP changes by MSA over 2060–2080 under "no climate action." We then projected the impact on key real estate metrics such as vacancies, rents and tenant renewals. The result: The average expected loss rate on CMBS deals would rise to 3.8% from 3.2% absent the climate-related impact. Defaults and losses would be higher in areas of greatest impact. The estimates do not include the direct financial damages caused by storm hits. More frequent storms may also inflate building maintenance and insurance costs, which by our calculation average roughly 20% in CMBS properties. Bottom line: Climate-related risks are significant today – and set to grow in the future.

Electric utilities

We find extreme weather events are not priced into the equities of U.S. electrical utilities – and introduce a climate risk exposure framework that can help uncover such risks.

Climate-related risks pose big challenges for the electric power sector. Aging infrastructure and older design standards leave power generating assets vulnerable to extreme weather events such as wildfires and hurricanes. Power outages as a result of such incidents pose broader risks to the economy – via lost productivity. They can also trigger capital losses for investors. Utilities can mitigate some of the risks via insurance, disaster recovery plans and physical hardening of facilities, but many companies are likely underprepared.

Are climate-related risks priced into the equities of electric utilities? We sought to find out. Our analysis starts by examining the geolocation of every U.S. electric power plant, as well as planned generation as reported to the U.S. Department of Energy. We plot the locations below, by fuel source, with the size of the bubbles indicating generation capacity. We then traced the ownership of the 4,500 power plants that were publicly owned, aggregating them into a hypothetical portfolio of 269 traded utility companies.

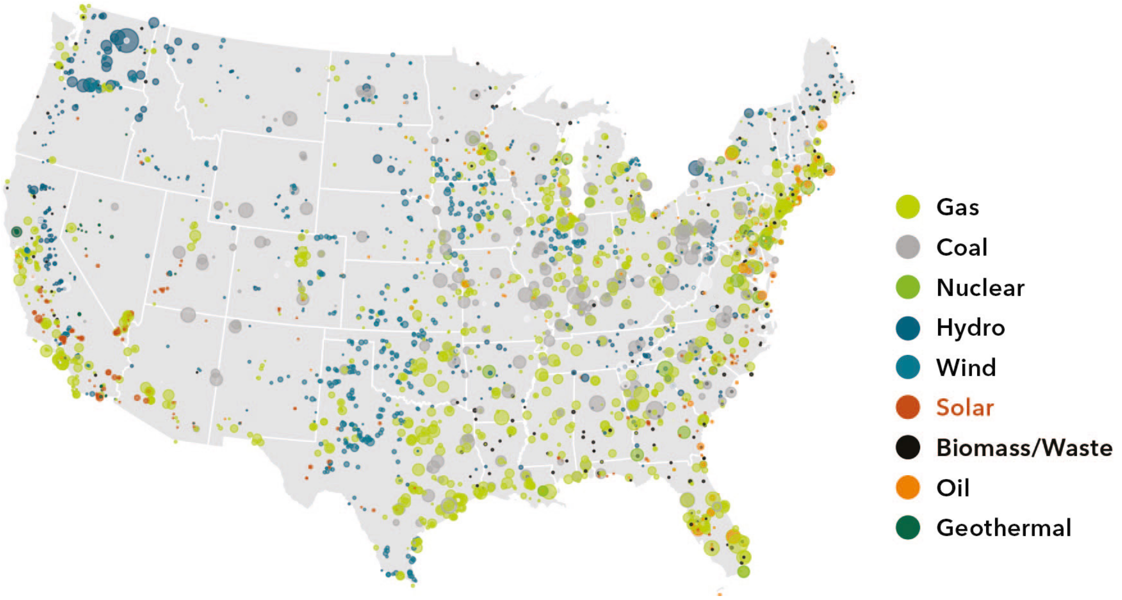
Our analysis divides weather events into two types of shocks: acute shocks with immediate impact, such as hurricanes and wildfires; and chronic events such as high temperatures, flooding and droughts.

Acute climate shocks have the most severe direct physical impact, such as damage to generating facilities. Chronic events tend to play out over longer time periods and wider areas of impact. Droughts, for example, affect thermal coal-fired or nuclear plants that require cooling water drawn from rivers or reservoirs. Declining intake water levels can hurt plant efficiency, or even trigger temporary shutdowns that cause financial losses.

Our historical study included 233 extreme weather events across the United States – those causing more than $1 billion in damages as estimated by the NOAA – dating back as far as 1980. We choose first to zoom in on hurricanes. These made up roughly 15% of these historical events – and have typically caused the most damage.

Sources of power

U.S. electric utility plants by fuel source, 2019



Sources: BlackRock Investment Institute and BlackRock Sustainable Investing, with data from EIA, March 2019. Notes: The chart plots the location of more than 8,000 U.S. electric power plants, as well as planned generation as reported to the U.S. Department of Energy. The bubbles are sized in proportion to each site's power generation capacity.

Not priced

Our hypothesis: Extreme weather risks already threaten utility stocks – and are set to rise in frequency and intensity over time – but are not fully priced in. To measure this embedded risk, we evaluate the impact on company valuation that results from an extreme weather event. If investors believe utilities have fully mitigated their exposure to climate-related risks, then stock prices should not react to the event. Our methodology:

1. Determine an "epicenter" location and the day of occurrence ("day zero"). For hurricanes, this was the date and location where the storm made landfall.
2. Establish a zone of influence; this is 300 kilometers for a hurricane (the average radius).
3. Isolate the power plants operating in the affected zone and the listed parent companies that own them. Calculate the megawatt capacity of each affected power plant as a share of that utility's total generative capacity. This gives us a proxy for the revenue of each company that may be disrupted.
4. Create a hypothetical portfolio of the affected companies, weighted in proportion to the percentage of revenues affected.
5. Study the financial impact of the weather event on stock prices and volatility.

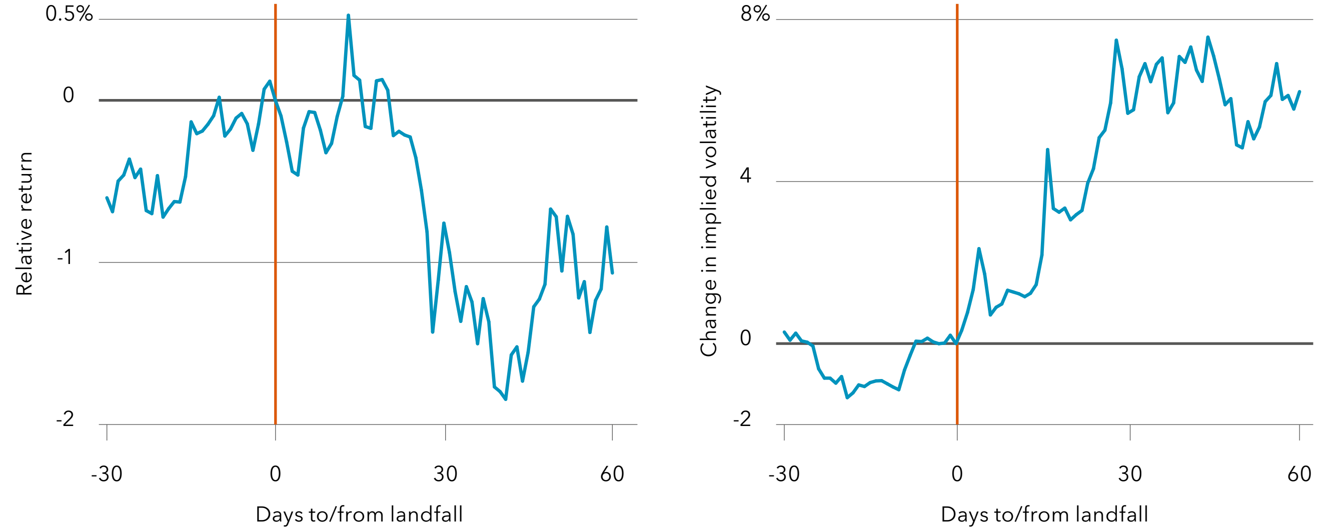
We first investigated if hurricane impacts had a broad effect on the utility sector by analyzing the price response of the S&P Utility Index around such events. We found no discernable impact on prices. Next, we studied the price and volatility impacts from hurricanes on the affected utilities and found the following results:

- Stock prices typically come under pressure for a period of about 40 days after the event – and incur a loss of about 1.5% relative to the sector index.
- The implied volatility of options on impacted utilities increases by about 6 percentage points in the 30 days after impact.
- After a short period, stock returns tend to converge back toward industry averages, while volatility eases from peaks. See the *Storm shock* charts.

Our analysis told a similar story for wildfires, albeit with more muted price effects. What does all of this tell us? Investor reaction ahead of forecasted hurricanes is muted because the exact location of landfall – and the power plants that will be affected – are not known with certainty. After the event, investors sell stocks of affected utilities, reflecting concern that the true economic losses are not fully known. The swift recovery of utility stocks suggests investors perceive an "over-reaction" to the hurricane impacts – and eventually "forget" the event.

Storm shock

Stock price and volatility reaction of U.S. electric utility equities around hurricanes, 1980–2019



Sources: BlackRock Investment Institute and BlackRock Sustainable Investing, with data from Bloomberg and NOAA, March 2019. Notes: Our study includes all hurricanes in the NOAA's database since 1980. Day zero is the day of each hurricane landfall. We isolate the power plants within 300 km from the location of the landfall, and identify their parent companies. We then form a hypothetical portfolio of affected companies, weighted in proportion to their revenues affected as implied by their generation capacity as a share of the total capacity of the group. We compare the total return of this hypothetical portfolio to the S&P 500 Utilities Index to arrive at the relative return. Implied volatility is calculated from the OptionMetrics database.

Scoring utilities

Our next step: Developing a framework to estimate the climate risk exposures of publicly traded utilities, in a bid to quantify hidden risks for investors. We do this by combining the exposure to extreme weather at each power plant location with an assessment of the materiality of that exposure, based on historical losses and forward-looking climate modeling. For details, see ***Climate Risk in the U.S. Electric Utility Sector: A case study***, by A. Bertolotti, D. Basu and K. Akallal (2019).

Note: Our analysis is plant-centric. It does not account for potential damages to transmission and distribution networks; liability risks; or increased capex needs over time as increased energy demand for cooling burdens grids with higher peak loads in summertime. We assign each type of weather event a relative impact score on a 1-10 scale. Hurricanes sit at the top of this scale, posing direct physical threats to generating plants and water intake structures. See the *Risk by risk; plant by plant* table below. The potential impact of climate events on power plants varies not only by location but also by the fuel source. Example: Wind energy is vulnerable to variations in wind patterns caused by severe storms. Solar energy, by contrast, is more exposed to extreme heat, which curbs the efficiency of photovoltaic panels.

We reflect these nuances by assigning a weight to each type of weather event by fuel source. We see gas (35% of total U.S. generation capacity according to 2018 EIA data) and coal-fired power plants (27%) as exposed to a broader swath of climate risks, including wildfires, high temperatures, floods and drought.

High temperatures, defined as days with a maximum temperature above 95°F (32°C), pose a meaningful risk to almost all types of fuel sources across the U.S. – and are often associated with other types of weather shocks such as wildfires.

For wind energy (representing around 7% of U.S. generating capacity) we assign a high risk weight to hurricanes – the main material climate risk we see for this fuel source. Wind turbines are typically designed to cut out in extreme wind, to prevent damage to rotors.

For hydroelectric power plants, hurricanes, droughts (drops in reservoir levels reduce generation efficiency) and floods (potential structural damage) are the greatest risks in our framework.

Our work with Rhodium suggests the type of extreme weather events detailed below are likely to intensify in frequency and magnitude in the decades ahead. This means investors need to start assessing the risks today.

Risk by risk; plant by plant

BlackRock's climate risk exposure framework for electric utilities

	Extreme weather event	Hurricanes	Wildfires	High temperatures	Floods	Droughts
	Relative impact (1-10 scale)	10	7	5	4	4
		Weight of extreme weather exposure (%)				
Fuel source	Gas (35% of U.S. generation capacity)	38	13	19	15	15
	Coal (27%)	38	13	19	15	15
	Nuclear (19%)	38	13	19	15	15
	Hydro (7.0%)	26	18	13	21	21
	Wind (6.6%)	63	22	16	0	0
	Solar (1.6%)	49	17	24	10	0
	Geothermal (0.4%)	44	16	22	18	0

Sources: BlackRock's Sustainable Investing and BlackRock Investment Institute, with data from EIA, U.S. Department of Energy, Rhodium Group and Verisk Maplecroft, March 2019. Notes: The table illustrates how we combine plant-level climate exposure scores into a single parent company exposure score. "Relative impact" shows BlackRock's assessment of the financial materiality of each type of extreme weather event, on a scale of 1–10, with 10 being the most material. Impact scores are based on historical loss rates. We then determine which type of weather events are most material for each fuel source. Weather events that pose direct risks to a particular fuel source are assigned a weight of 1; those posing indirect risks are given a weight of 0.5; and those with no impact are assigned a zero weight. We multiply these impact weights by the relative impact score for each event type. The results are translated into percentage exposure weights that sum to 100 for each fuel source. Share of generation capacity figures are based on 2018 EIA data.

Putting it all together

We aggregate the average physical risk across all power plants to arrive at a total climate risk score for each utility. This enabled us to examine another key question: Do utilities with greater climate resilience trade at a premium? We examined the relationship between the climate scores of the utilities in our study with each companies' 10-year average price-to-earnings ratio. The result of this regression analysis: The most climate-resilient utilities tend to trade at a slight premium to their peers, while the most vulnerable carry a slight discount. We found similar results using price-to-book ratios. This gap may become more pronounced over time as weather events turn more extreme and frequent – and more investors factor climate change into their risk/return analysis.

There are limits to our scoring approach. It aggregates the average physical risk across all power plants for each utility. Yet catastrophic losses can occur if the financial impacts caused to or by a single power plant extend beyond the damages to the actual plant. This was the case for a California utility in 2018, when the liabilities from fires caused by its equipment crippled the company. See the *How exposed is my power plant?* map below for a geographic representation of our climate risk scores by power plant.

How can investors use this information? Two potential applications:

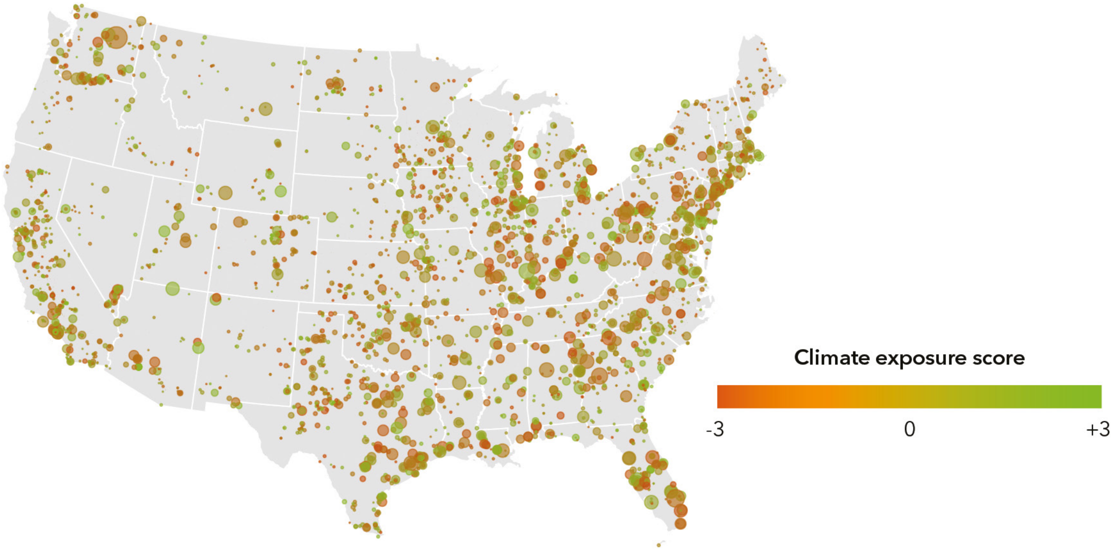
1 **Risk management:** Geolocating power plants and determining their physical climate exposure allows utilities investors to better assess their exposures – and any concentration of risk to a particular type of extreme weather event. Geographic diversification can help offset these risks, since the most acute climate risks tend to strike in specific locations.

2 **Engagement:** Are companies doing enough to mitigate the rising risk of financial damage from climate events? Are their capex plans aligned? Granular analysis of the risks facing a particular utility – reflected in our risk exposure scores – can form the basis for larger investors to engage with corporate management teams on issues of concern.

We conclude that climate-related risks are real for utilities, but mostly not priced in. This has important implications. Overweighting companies with low climate risk exposure and underweighting those with high exposure may pay off as the risks compound over time. Investors also will need to include climate-related risks in their analysis of financial risks and opportunities. This is most relevant for long-term investors, as the probability of experiencing more frequent and intense extreme weather rises the longer a position is held.

How exposed is my power plant?

BlackRock Climate Exposure Scores for U.S. power plants, 2019



Sources: BlackRock Investment Institute, with data from Rhodium Group, Verisk Maplecroft and U.S. Department of Energy, 2019.
Notes: The chart plots the location of each U.S. electric power plant and is color coded according to BlackRock's assessment of its climate exposure, according to the framework presented on page 17. For illustrative purposes only. Risk is expressed in standard deviations. A score of -3 (high climate risk) points to an exposure that is three standard deviations worse than the mean exposure of the plants in our study.

This is a tab page.
Title the tab “Kompas”

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2018EF000922

Special Section:
Resilient Decision-Making for a Riskier World

The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord

Tom Kompas[1,2], Pham Van Ha[2], and Tuong Nhu Che[3]

[1]Centre of Excellence for Biosecurity Risk Analysis, School of Biosciences and School of Ecosystem and Forest Sciences, University of Melbourne, Parkville, Victoria, Australia, [2]Crawford School of Public Policy, Australian National University, Canberra, ACT, Australia, [3]Black Mountain Science and Innovation Park, CSIRO Land and Water, Canberra, ACT, Australia

Key Points:
- The global economic gains from complying with the Paris Climate Accord are shown to be substantial across 139 countries
- With the comparative case of RCP8.5 (4°C), the global gains from complying with the 2°C target (RCP4.5) are US$17,489 billion per year
- The relative damages from not complying with the 2°C target to Sub-Sahara Africa, India, and Southeast Asia are especially severe

Correspondence to:
T. Kompas,
tom.kompas@unimelb.edu.au

Citation:
Kompas, T., Pham, V. H., & Che, T. N. (2018). The effects of climate change on GDP by country and the global economic gains from complying with the Paris Climate Accord. *Earth's Future*, *6*, 1153–1173. https://doi.org/10.1029/2018EF000922

Received 10 MAY 2018
Accepted 3 JUL 2018
Accepted article online 13 JUL 2018
Published online 23 AUG 2018

Abstract Computable general equilibrium (CGE) models are a standard tool for policy analysis and forecasts of economic growth. Unfortunately, due to computational constraints, many CGE models are dimensionally small, aggregating countries into an often limited set of regions or using assumptions such as static price-level expectations, where next period's price is conditional only on current or past prices. This is a concern for climate change modeling, since the effects of global warming by country, in a fully disaggregated and global trade model, are needed, and the known future effects of global warming should be included in forward-looking forecasts for prices and profitability. This work extends a large dimensional intertemporal CGE trade model to account for the various effects of global warming (e.g., loss in agricultural productivity, sea level rise, and health effects) on Gross Domestic Product (GDP) growth and levels for 139 countries, by decade and over the long term, where producers look forward and adjust price expectations and capital stocks to account for future climate effects. The potential economic gains from complying with the Paris Accord are also estimated, showing that even with a limited set of possible damages from global warming, these gains are substantial. For example, with the comparative case of Representative Concentration Pathway 8.5 (4°C), the global gains from complying with the 2°C target (Representative Concentration Pathway 4.5) are approximately US$17,489 billion per year in the long run (year 2100). The relative damages from not complying to Sub-Sahara Africa, India, and Southeast Asia, across all temperature ranges, are especially severe.

Plain Language Summary This work shows considerable global economic gains from complying with the Paris Climate Accord for 139 countries. For example, with the comparative case of a temperature increase of four degrees, the global gains from complying with the 2° target are approximately US$17,489 billion per year in the long run (year 2100). The relative damages from not complying to Sub-Sahara Africa, India, and Southeast Asia are especially severe.

1. Introduction

The cumulative effects of global climate change will depend on how the world responds to increasing emissions. The evidence indicates that climate change has already resulted in extreme weather events and sea level rises (SLRs), with added threats to agricultural production in many parts of the world (United Nations, 2018; World Bank, 2016). However, standard economic forecasts of the impact of climate change very considerably, with early estimates showing mild effects on the world economy (see, e.g., Nordhaus, 1991; Tol, 2002). Some of these views have softened subsequently (Nordhaus, 2007; Tol, 2012), but aggregate damages still remain relatively small for most temperature ranges.

Both Weitzman (2012) and Stern (2016), among others, have warned that current economic modeling may seriously underestimate the impacts of potentially catastrophic climate change and emphasize the need for a new generation of models that give a more accurate picture of damages. In particular, Stern (2016) has pointed out two key weaknesses of the current class of economic models: their limited spatial coverage, including averaged impacts across countries and regions, and unreasonable assumptions on the discount rate, which translate into a relative lack of forward-looking behavior in economic forecasts and resulting negative impacts on future generations.

Indeed, there have been relatively few attempts to examine the full global, disaggregated, and intertemporal effects of climate change on GDP using large-scale economic modeling, modeling that would capture all of the trading patterns, spillover effects, and economic linkages among countries in the global economic system over time. To date, given its computational complexity, computable general equilibrium (CGE) modeling has largely concentrated on individual country effects or on dynamic models with limited numbers of countries or regions and an absence of forward-looking behavior, that is, so-called recursive dynamic models with static or adaptive price-level forecasts. These recursive dynamic models have value, but the assumption that future price-level expectations are based only on current and past values is broadly incongruent with known future projections of various climate change outcomes and resulting trade effects (Kompas & Ha, 2017).

In this work, we extend the results of recent and innovative large-scale economic modeling, Global Trade Analysis Project (GTAP)-INT (Kompas & Ha, 2017), to account for the effects of various Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) on global temperature, which result in a 1–4°C increase in global warming. Our model is fully disaggregated with forward-looking behavior, spanning across 139 countries and 57 broad commodity groups, with full computational convergence over a period of 200 years. In numerical simulations, we show the potential economic gains from following the Paris Climate Accord to the year 2100. It is important to note that we do not calculate the costs of implementing the Accord, but we do carefully measure the avoided damages (as potential losses in GDP) as the benefit of compliance.

As is well known, the Paris Accord targets to hold the increase in the global average temperature below 2.0°C above preindustrial levels and to pursue efforts to limit temperature increases to 1.5°C above preindustrial levels (United Nations, 2015). Following this agreement, United Nations members are committed to *intended nationally determined contributions* (INDCs), which provide estimates of their aggregate greenhouse gas (GHG) emission levels in 2025 and 2030. With the implementation of the INDCs, aggregate global emission levels would be lower than in pre-INDC trajectories (United Nations, 2016). The agreement also aims to further support the ability of countries to deal with the impacts of climate change (United Nations Framework Convention on Climate Change [UNFCCC], 2018a) and is seen as providing an essential road map for the human response to reduce emissions and build in further climate resilience.

Section 2 below provides a brief review of climate change agreements and the international framework. Section 3 highlights some of the previous literature on CGE modeling on the economic effects of climate change. Section 4 details our data, the model approach, and the results. Section 5 evaluates the long-term impacts by RCP scenario and the potential global economic gains of complying with the Paris Climate Accord. Section 6 provides some added discussion and a few closing remarks.

2. Climate Agreement and Scenario Context

Since 1850, the Earth's surface has become successively warmer and especially so over the past three decades. From 1880 to 2012, global average temperature (calculated with a linear trend for combined land and ocean surface temperature) shows a warming of 0.85 [0.65–1.06]°C (Intergovernmental Panel on Climate Change [IPCC], 2014). Emissions grew more quickly between 2000 and 2010, and carbon dioxide (CO_2) levels have increased by almost 50% since 1990. Under the effect of climate change, oceans have warmed, the amounts of snow and ice have diminished, and sea levels have risen. The global average sea level increased by 19 cm from 1901 to 2010 and is predicted to raise 24–30 cm by 2065 and 40–63 cm by 2100 (United Nations, 2018). The IPCC's Fifth Assessment Report (IPCC, 2014) has clearly confirmed human influence on the climate system. The report also indicates that the recent anthropogenic emissions of GHG are the highest in history and have already generated widespread impacts on human and ecological systems.

To counter these impacts, the past two decades have been marked by a sequence of international initiatives and agreements to stabilize GHG emissions. The UNFCCC, for example, was first introduced in 1992 to limit average global temperature increases. The UNFCCC is one of the three intrinsically linked Rio Conventions, adopted at the Rio Earth Summit in 1992. The other two Conventions are the UN Convention on Biological Diversity and the Convention to Combat Desertification (United Nations Framework Convention on Climate Change, 2018b). Since then, other major international climate change frameworks have progressed, including the Kyoto Protocol (1997), along with the Copenhagen Accord (2009), the Durban Platform for Enhanced

Action (2011), the adoption of the Doha Amendment to the Kyoto Protocol (2012), the IPCC Fifth Assessment Report (IPCC, 2014), and the adoption of the Paris Agreement in 2015 (based on United Nations Framework Convention on Climate Change, 2018c, 2018d).

According to the United Nations Framework Convention on Climate Change (2018b), the UNFCCC Convention (1994), developed from the Montreal Protocol (1987; one of the most successful multilateral environmental treaties at that time), binds member states to act in the interests of human safety, facing scientific uncertainty. The Convention aims to stabilize GHG emissions *at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system*. As such, targeted GHG emission levels "should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner" (United Nations Framework Convention on Climate Change, 2018b). Following the Convention, the industrialized country members in the Annex I parties, countries belonging to the Organization for Economic Cooperation and Development, including 12 countries with *economies in transition* from Central and Eastern Europe, which are major sources of GHG emissions, are mandated to do the most to cut emissions. By the year 2000, the Annex I parties were expected to reduce emissions to 1990 levels (United Nations Framework Convention on Climate Change, 2018b).

In addition, the Kyoto Protocol, which was adopted in Kyoto in December 1997 and entered into force for many countries in February 2005, was a major climate change agreement that set internationally binding emission reduction targets. Under the principle of *common but differentiated responsibilities*, the Protocol places a heavier burden on developed nations, which are legally bound to emission reduction targets following two phases of commitment periods, given by 2008–2012 and 2013–2020 (United Nations Framework Convention on Climate Change, 2018e). The Paris Climate Accord (adopted in 2015 to which 175 parties have ratified to date) further intensifies the effort toward sustainable low-carbon development, requiring a worldwide response to climate change. In the Paris Accord, both developed and developing countries have committed to reducing emissions by 2030, using 2005 as the base year. As indicated, the Paris Accord is designed to keep global temperatures in this century to a rise "well below 2 degrees Celsius above preindustrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2018f, 2018a).

To assist with the understanding of future long-term socioeconomic and environmental consequences of climate change, along with the analysis of potential mitigation and adaptation measures, various future scenarios are widely used in climate change research (van Vuuren & Carter, 2014). The IPCC has used climate scenarios from 1990 forward (SA90) following IS92 and the Special Report on Emissions Scenarios in 2007. These scenarios were developed and applied sequentially from the socioeconomic factors that influence GHG emissions to atmospheric and climate processes. As is generally known, the sequential approach led to inconsistency and delays in the development of emission scenarios (Moss et al., 2010). From 2006, the climate research community initiated a new *parallel approach* to developing scenarios, where model development progresses simultaneously rather than sequentially (Moss et al., 2010; van Vuuren et al., 2014). The work of van Vuuren and Carter (2014) provides a summary of the new scenario framework comprising two key elements: (1) Four RCP scenarios representing the possible future development of GHG emissions and concentrations of different atmospheric constituents affecting the radiative forcing of the climate system and (2) five SSP scenarios providing narrative descriptions and quantitative prediction of possible future developments of socioeconomic variables. These two sets of scenarios provide an integrated framework, or a scenario matrix architecture, to account for the various possible effects of global warming (van Vuuren et al., 2014).

Since both sets of scenarios (i.e., the social development and radiative forcing) eventually lead to different surface temperature increases, they can be reconciled into similar groups with comparable temperature increases. As indicated, van Vuuren and Carter (2014) provide suggestions for such reconciliation of the new RCP and SSP scenarios, in which most of the SSP scenarios can be mapped with the four RCP scenarios (see van Vuuren & Carter, 2014, for the detailed discussion of scenarios and reconciliation tables).

The simulations in our own work thus fully examine the impact on the world economy of global warming in the range from 1 to 4°C, which roughly covers all four possible RCP scenarios from RCP2.6 to RCP8.5. Our individual simulations can be further mapped by comparing final temperature increases with the median temperature rise by RCP scenarios in IPCC (2014), using the reconciliation tables in van Vuuren and Carter (2014).

3. CGE Modeling and the Economic Effects of Climate Change

Climate change is a global and long-term phenomenon, which requires global coordination and a forward-looking policy approach. Global dynamic CGE models are, therefore, a natural candidate for climate change impact assessment and policy analysis. Rational, intertemporal responses cannot be made using naive static or adaptive price-level expectations, which are essentially backward looking, or with highly aggregated regional, rather than country-specific, approaches. Unfortunately, due to technical difficulties, current economic and CGE modeling of the effects of climate change lack both adequate time (forward-looking) and spatial (country-disaggregated) coverage.

As a whole, CGE models encompass standard policy analysis and forecasting approaches for GDP growth, incomes, and the global economic system. Since the pioneering work of Johansen (1960), with a basic one country model, CGE models have grown both in size and complexity. Modern CGE models are now (at least potentially) truly global with as many as 140 interactive regional economies (Aguiar et al., 2016; Corong et al., 2017; Hertel, 1997) and can be solved over a long time horizon in a recursive (e.g., Dixon & Rimmer, 2002; Ianchovichina & Walmsley, 2012) or intertemporal framework (e.g., Ha et al., 2017; McKibbin & Wilcoxen, 1999). With the implementation of time (intertemporal) and spacial (regional and country-specific) dimensions, the size of CGE models has grown exponentially posing a serious challenge to current computational methods. Current software packages such as GEMPACK or GAMS, which use a serial direct LU solver (see Ha & Kompas, 2016), are incapable of solving large intertemporal CGE models. Dixon et al. (2005) indeed has shown that with these models, using over 100 industries or commodity groups, it is only possible to solve the system simultaneously for a relatively small number of time periods.

Due to computational constraints, current CGE models are also normally limited to either static or recursive approaches. Static CGE models compare an economy over two discrete time points: the current period before an exogenous shock and either a short-run period or a long-run period after the shock is realized. The main difference between the short- and long-run cases is whether the capital stock is fixed or allowed to freely adjust (in response to an exogenous shock), designated by short- or long-run closure. Hertel et al. (2010) used such a static CGE-GTAP model to simulate the impact of climate change on the world economy in the year 2030 via shocks in agricultural production. Although the model can be used to analyze the impact of climate change in the long run, it cannot provide any intermediate and time path effects from climate change. It is also dimensionally constrained, that is, even with the comparison of only two time periods, Hertel et al.'s (2010) approach can only account for 34 countries/regions. In practice, it is rare to see CGE models, static or recursive, that are solved with a full countrywide database (up to 100 countries/regions or more).

In a search for a more comprehensive approach, recursive models extend the static CGE model beyond a one-period comparative analysis by solving the system recursively, year after year, over an unspecified but extended time horizon. Bosello et al. (2006, 2007), for example, used a variant of the CGE-GTAP model, GTAP-E, to simulate the impact of climate change-induced effects on human health (Bosello et al., 2006) and sea level increases (Bosello et al., 2007) to the world economy up to 2050. (The GTAP-E framework, Burniaux & Truong, 2002, is an extension of the GTAP model, Hertel, 1997, with more detailed energy inputs in the model's production structure.) The model is first run recursively to calibrate the baseline scenario from an initial calibration year to 2050; then shocks to labor productivity, expenditure for health services (public and private), and SLRs are introduced to form comparative effects of climate change-induced effects for human health in particular. For the expenditure on health services, Bosello et al. (2006) impose a shift in parameter values which would produce the required variation in expenditure if all prices and income levels remained constant. The model is simulated for eight regions of the world. An extension of the ICES model (Eboli et al., 2010), another modification of the GTAP-E model, is also a good example of a multiregion recursive dynamic modeling approach to analyze the effects of temperature change on economic growth and wealth distribution globally. In a more elaborate application, Roson and der Mensbrugghe (2012) use the recursive ENVISAGE model to simulate the economic impact of climate change via a range of impact channels: sea level increases, variations in crop yields, water availability, human health, tourism, and energy demand.

A key limitation of these recursive models is their lack of forward-looking behavior, relying instead on static or adaptive price-level expectations, and successive single period calculations. Economic agents, in other words, only respond to shocks in the current year (or past years) and ignore otherwise known future changes in, for example, climate conditions, no matter how severe they may be. In other words, responses in economic behavior only occur once the shocks are realized. In addition, even though recursive models are solved one period at a time, successively, they normally can only solved for a relatively small number of countries, regions, and sectors, given computational constraints. Thus, they cannot use the available and fully disaggregated country data to facilitate computation.

There have been a few attempts to breakout of the traditional recursive dynamic modeling approach, building instead a forward-looking, global intertemporal model for climate change analysis. McKibbin et al. (2009), for example, use their G-CUBED model (McKibbin & Sachs, 1991; McKibbin & Wilcoxen, 1999) to form an intertemporal global economy to predict future CO_2 emissions under different scenarios. The model in Dixon et al. (2005) is another approach, using rational expectations of future prices to model intertemporal behavior. These are valuable methods, but they too suffer from either limited dimension (McKibbin et al., 2009, with only 14 countries and 12 sectors in) or with difficulties guaranteeing convergence to a solution as in the case of the rational expectations approach.

Outside of the context of the CGE modeling of global intertemporal economies, there are a number of examples of economic assessments of the effects of climate change using more basic models, where damage functions range from low to extreme levels. Tol (2002), for example, estimated the impact of a 1°C warming on the world economy based on a suit of existing and globally comprehensive impact studies. Tol, 's estimations are somewhat inconclusive. The impacts on world GDP with a 1°C warming range from +2% to −3% depending on whether a simple sum or a global average value method is used. Using an estimated damage function for the U.S. economy and extrapolated to the world economy, Nordhaus (1991) also finds mild effects from climate change impacts of 1%, or at most 2%, on the global economy. These views have been modified more recently, as indicated above, but total damages are still relatively small.

Alternatively, Weitzman (2012) has warned that we might be considerably underestimating the welfare losses from climate change by using conventional quadratic damage functions and a *thin-tailed* temperature distribution and suggests severe limits on GHG levels to guard against catastrophic climate risks. A study by the Global Humanitarian Forum (2009) also provides a worrisome picture of the social impacts (e.g., on environment and health) of climate change in the developing world. The loss from global warming, here, includes climate-related deaths from worsening floods and droughts, malnutrition, the spread of malaria, and heat-related ailments. According to Global Humanitarian Forum (2009), the current global warming process already causes 300,000 deaths and US$125 billion in economic losses annually.

Our paper addresses the above weaknesses of current economic analysis and CGE modeling of the effects of climate change by applying new solution methods, developed for solving intertemporal CGE models with very large dimension (Ha & Kompas, 2016, 2014; Ha et al., 2017; Kompas & Ha, 2017), modifying and extending the preliminary results of the effects of climate change contained in Kompas and Ha (2017) to different RCP scenarios. As such, we provide the first example of a large-scale and intertemporal computational modeling of the economic effects of global warming, across all 139 countries in the GTAP database, for various temperature changes. The added, large-dimensional precision matters to the final estimates and disaggregation by country is especially important here. Although the effects of climate change on global average GDP may be large or small, depending on RCP scenario, the effects on individual countries can be enormous across various RCPs. Averaging across such countries into regions severely masks these effects.

4. GTAP-INT Model Framework, Data, and Climate Change Results

The modeling approach applied in this study is an intertemporal CGE version of the GTAP model, termed GTAP-INT in Ha et al. (2017). GTAP is a global economic model that estimates the interactions of economic activities and effects among countries or regions under various exogenous shocks (Hertel, 1997).

We use GTAP version 6.2 to be consistent with our previous research (Ha et al., 2017). We are aware of the publication of GTAP version 7, where commodities and activities are separated so that a single producer can produce more than one product (Corong et al., 2017). However, in the most recent GTAP database (version 9), which we employ, a producer can produce only one product (see Aguiar et al., 2016). Therefore, we expect no substantive difference in our work between GTAP version 6.2 and version 7 simulation results with the current database.

The intertemporal version of GTAP model consists of blocks of supply and demand equations for producers, households, investment demand, and governments, indexed by country and at each point in time. Producers use inputs, or factors of production, such as land, labor and capital, and other intermediate goods, to deliver commodities which are sold on international and domestic markets. Households make decisions between savings and the consumption of various commodities, foreign and domestic, from their income, less taxes. In an individual economy, the total demand for a product (from international and domestic sources) equals the supply of that product, with corresponding price linkages and market clearing conditions. Global savings, investment, and transportation is also modeled (Ha et al., 2017; Hertel, 1997).

The GTAP model, in its current form, is run either as a static model or as a recursive dynamic model with assumed static or adaptive price-level expectations (Kompas & Ha, 2017). A key benefit of the GTAP-INT model is that it allows producers, in particular, to look forward, to choose how much to invest in capital stocks over time to maximize profits in the long run. A fully defined intertemporal version of the GTAP model was first developed in Ha et al. (2017), where fixed capital formation and given allocations of investment across regional blocks of countries are replaced by long-run profit conditions. The version of GTAP-INT in Kompas and Ha (2017) extends this work to very large dimensions using a new solution method and allowing for multiple countries and time periods. In the context of climate change, GTAP-INT allows producers to respond to foreseeable climate change impacts immediately, in terms of how they invest and the choice over what they produce, rather than waiting for climate change impacts to be actually realized and then enter their forecasts for prices and other key variables. In recursive models, alternatively, producers only respond to climate change impacts once they actually occur. The structural equations for GTAP-INT are detailed in Ha et al. (2017) and are not repeated here, save for the key intertemporal condition for profit (dividend) maximization, given by two motion equations for capital accumulation and its shadow price:

$$\dot{k}_{r,t} = I_{r,t} - \delta_r k_{r,t} \tag{1}$$

$$\dot{\mu}_{r,t} = \mu_{r,t}[r_t + \delta_r] - \frac{\phi_{r,t}}{2}\left(\frac{I_{r,t}}{k_{r,t}}\right)^2 p^I_{r,t} - p^k_{r,t} \tag{2}$$

where $k_{r,t}$ is the capital stock in region r at time t (hereafter we supress the indices r and t where appropriate for simplicity), r_t is the world interest rate, $I_{r,t}$ is increment in capital (i.e., investment), δ_r is the depreciation rate, $\mu_{r,t}$ is the shadow price of capital, and $\phi_{r,t}$ is the investment coefficient, which shows how much extra money we must invest in order to obtain a dollar increase in the capital stock; $p^I_{r,t}$ is the price of capital goods; and $p^k_{r,t}$ is the rental price of capital. To solve the model, we use the GTAP model equations to link all global economies over time using forward-backward equations (i.e., equations (1) and (2)) for each country in the GTAP model, given an initial condition (fixed initial capital $k_{r,0}$) and one terminal condition: $\dot{\mu}_{r,T} = 0$ (Kompas & Ha, 2017). As usual in intertemporal models, we take a state steady benchmark as the baseline or as *business as usual*. We then compare this baseline path to parametric changes across different climate change scenarios. This is standard in an intertemporal framework and indeed is the only technical option available to facilitate our large-dimensional modeling.

4.1. Database and Climate Change Damage Functions

As indicated, the database employed in this work is GTAP Data Version 9 (Aguilar et. al., 2016; GTAP, 2017), which consists of 140 countries and regions (we drop one country, Benin, for numerical stability) and 57 commodities with 2011 as the base year. The data set requires the addition of damage functions, which aim to estimate the economic impacts of global warming, in general, and, in particular, in CGE and GTAP modeling. The climate change damage functions applied in this paper largely follow, with some qualifications, Roson and Sartori (2016), where climate change parameters for damages are estimated from a series of meta-analyses for each of the 140 countries and regions in the GTAP version 9 data set. The damage functions applied include the effects of SLR, losses in agricultural productivity, temperature effects on labor productivity and human health, energy demands, and flows of tourism (Roson & Sartori, 2016).

The background for all of this is straightforward. For SLR impacts, following the Fifth IPCC Assessment Report (IPCC, 2014), Roson and Sartori (2016) note that a large number of studies find a connection between global warming and sea level increases. SLR affects the total stock of land and causes erosion, inundation, or salt intrusion along the coastline. As a consequence, the share of land which may be lost depends on several country-specific characteristics. In Roson and Sartori (2016), the relationship between SLR (in meters) and the increase in global mean surface temperature (in degrees Celsius), at the time intervals 2046–2065 and 2080–2100, is based on IPCC (2014), with an added emphasis on land losses in agriculture.

Indeed, economic studies of climate change appear to focus predominantly on agricultural impacts. According to Roson and Sartori (2016), climate change is expected to bring about higher temperatures, a higher carbon concentration, and different patterns in regional precipitation, all of which affect crop yields and agricultural productivity. In Roson and Sartori (2016), in particular, the climate change damage function for agricultural productivity is based on a meta-analysis provided in IPCC (2014), which provides central estimates for variations in the yields of maize, wheat, and rice. Roson and Sartori (2016) elaborate on these results to get estimates of productivity changes for these three crops, in all 140 regions and for the five levels of temperature increase, from 1 to 5°C. The estimation distinguishes between tropical and temperate regions and identifies a nonlinear interpolation function for all cases. Roson and Sartori (2016) also apply the work by Cline (2007) for the estimation of productivity changes for the entire agricultural sector in various regions. In this approach, the variation in agricultural output per hectare is expressed as a function of temperature, precipitation, and carbon concentration.

Estimation of labor productivity loss due to heat stress in Roson and Sartori (2016) is based on a study by Kjellstrom et al. (2009), which produced a graph of *work ability* as the maximum percentage of an hour that a worker should be engaged working. Roson and Sartori (2016) define work ability (a proxy for productivity) as a function of *wet bulb globe temperature*. The heat exposure index, using wet bulb globe temperature (units in °C), is a combination of average temperature and average absolute humidity (Roson & Sartori, 2016). As developed from Kjellstrom et al. (2009), Roson and Sartori (2016) estimate the effect of global warming for different increments in temperatures (ranging from 1 to 5°C) for three labor sectors (agriculture, manufacturing, and services) in each of the GTAP countries.

In Roson and Sartori (2016), estimation of the GTAP human health damage function is developed from Bosello et al. (2006), which, based partly on Tol (2002), develops estimates of the association between temperature increments and a number of added cases of mortality and morbidity of selected diseases, considering, in particular, the direct effect of incremental temperatures for vector-borne diseases (e.g., malaria and dengue), heat- and cold-related diseases, and diarrhea. Given the lack of data, supporting evidence and the scope of the analysis, Roson and Sartori (2016) do not include other diseases mentioned in IPCC (2014), such as hemorrhagic fever, plague, Japanese and tick-borne encephalitis, air quality and nutrition-related and allergic diseases, nor other impact categories mentioned in World Health Organization (2014) such as heat-related mortality in elderly people, or mortality associated with coastal flooding, and so on (Roson & Sartori, 2016).

Given our purposes, we disregard the climate damage functions for tourism and energy demand, also estimated by Roson and Sartori (2016). In terms of tourism, Roson and Sartori (2016) estimate travel flows following Hamilton et al. (2005) of which flows of international tourism are regressed as a function of temperature, land area, length of coastline, and per capita income. However, tourism flows in Roson and Sartori (2016) are regressed simply as an exponential function of temperature with a constant term (for a country's specific condition). This seems inadequate for our otherwise nonlinear specifications. Also, Roson and Sartori (2016) did not consider the other key drivers of tourism flows, including the attractions of natural landscapes, cultural and historical attributes, and, most importantly, the distinction between tourism and other forms of migration for climate change-related movements. Moreover, transforming the tourism effect into a CGE framework, which is based on GDP, implies no difference of income spending between nationals and foreigners inside a country's border and therefore is largely inappropriate.

The climate change effect on household's energy consumption in Roson and Sartori (2016) is estimated and adjusted from De Cian et al. (2013) of which the key drivers are season, sources of energy, and a country's climatic condition. However, for GTAP modeling, other drivers such as the elasticity of fuel use and income, the fuel mix in each country, and variations in standards of living among rich and poor nations matter a great deal. Since these are not included, we suspend this effect, for now, pending the development of a GTAP-E version of GTAP-INT. In any case, the temperature elasticities in De Cian et al. (2013), which are estimated for current climate conditions, would change considerably under various global warming scenarios, and this needs to be analyzed separately and comprehensively and not simply adjusted.

From the above damage function estimations, we design shocks to the GTAP-INT model to simulate the climate change impacts. First, the SLR impact will be simulated as a negative shock to the supply of land, a nonmobile factor of production in GTAP-INT. The shock is region specific, as in Roson and Sartori (2016). Next, negative agricultural productivity will be simulated by a percentage change shock to output-augmenting technical change in agricultural sectors. The shock is also sector and region specific. We aggregate and simulate labor productivity loss and human health damages via a negative labor productivity loss. Again, the labor productivity loss will be region and sector specific. With all the shocks, we assume a linear gradual increase from the current year (2017) with the highest shock occurring in 2100. After 2100, the size of the shock is assumed to remain constant (at the 2100 level), and the model is run forward for 200 years to ensure convergence to a new steady state, which the latter interpreted as long-run losses or impacts. With the time horizon of the model at 200 years, we apply a variable time grid to reduce the dimension of the model (see for details on intertemporal solution methods ; Dixon et al., 1992). Nevertheless, with multiple periods and the full regional and country-specific GTAP model, the size of the model is very large, and we solve the model using only the one-step Johansen method (see for details on the Johansen solution method; Dixon et al., 1992).

4.2. The Economic Effect of Global Warming

Following Riahi et al. (2017), different SSP narratives are characterized by assumptions on future economic growth, population change, and urbanization. As indicated above, Riahi et al. (2017) provide an overview of the main characteristics of five SSPs and related integrated assessment scenarios. The scenario analysis in our work, as discussed in section 2, is based on four different scenarios where the world surface temperature increases from 1 to 4°C to 2100, with RCPs (Moss et al., 2010) mapped to our scenarios by using the predictions of global surface temperature increases in IPCC (2014). As SSPs can also be mapped with RCPs (van Vuuren & Carter, 2014), our scenarios can be seen as a potential realization of scenarios from the Scenario Matrix Architecture (van Vuuren et al., 2014) and are valuable for analyzing climate change and mitigation policies.

For our GTAP-INT results, the dynamic effect of global warming is measured as the change in real GDP in all regions for different global warming scenarios in the range from 1 to 4°C. With lower emissions, for example, global warming is approximated by an increase of 0.85°C as in RCP2.6, where the climate change damage parameters for the 1°C case in Roson and Sartori (2016) can be (approximately) applied. In the extreme case of RCP8.5, without mitigation action (i.e., with *Rocky Road* [SSP 3] and strong *Fossil-Fueled Development* [SSP5] scenarios; Ria et al., 2017), global warming could increase temperatures by as much as 4°C, or perhaps more, by 2100.

For our current purposes, we first focus on *Middle of the Road* (SSP2) as the most likely or *business as usual* scenario. In this case, the path of the world's social, economic, and technological trends does not shift markedly from historical patterns (Riahi et al., 2017). As such, climate change is likely to be RCP6.0 and our scenario with a global warming of 3°C by 2100 can be applied. The results from GTAP-INT on GDP are given in percentage changes in Table 1 (which, with Figure 1, qualify and extend the preliminary results in Kompas & Ha, 2017). The value losses in GDP caused by global warming over the medium and long term for selected countries are contained in Table A1. Table A2 also details the global warming effects decomposed by economic sectors. As indicated, it is important to note that the model is run forward for 200 years, our *long run* for convenience and computational convergence. After the year 2100 no additional shocks are introduced to the model so that convergence is guaranteed. GDP estimates in Table A2 and the calculation of the gains from complying with the Paris Accord are based on outcomes to the year 2100 only.

The results clearly show that the effects of global warming vary by time, region, and economic sectors but tend to increase over time and become much worse in relatively poor African and Asian nations, where the loss in GDP here and in all countries near the equator is most severe (see Table 1 and Figure 1). But, indeed, over the medium term, despite some minor gains in a few European countries, the losses from global warming (at 3°C) dominate a major part of the world (Figure 1).

Using the value of GDP in 2017 from IMF (2018) as the base year, our GTAP-INT results, and economic growth forecasts from SSP2 (Crespo Cuaresma, 2017; International Institute for Applied Systems Analysis, 2018), the approximate global potential loss is estimated to be US$9,593.71 billion or roughly 3% of the 2100 world GDP for 3°C global warming (see Table A1). At 4°C, losses from global warming increase significantly to US$23,149.18 billion. The largest losses in all cases, and for all temperature increases, occur in Sub-Saharan Africa, India, and Southeast Asia.

Table 1
Impacts of Global Warming (3°C) on the World GDP (% Change/Year)

Country	2027	2037	2047	2067	Long run
Australia	−0.051	−0.107	−0.172	−0.326	−1.083
New Zealand	0.043	0.073	0.087	0.073	−0.798
Rest of Oceania	−0.452	−0.924	−1.422	−2.470	−5.171
China	−0.205	−0.438	−0.692	−1.247	−2.918
Hong Kong	−0.356	−0.765	−1.216	−2.205	−5.288
Japan	−0.042	−0.100	−0.173	−0.356	−1.335
South Korea	−0.025	−0.071	−0.136	−0.313	−1.498
Mongolia	−0.214	−0.415	−0.631	−1.105	−2.710
Taiwan	−0.535	−1.121	−1.740	−3.034	−5.978
Rest of East Asia	−0.819	−1.752	−2.752	−4.849	−9.490
Brunei Darussalam	−0.372	−0.815	−1.308	−2.385	−5.563
Cambodia	−1.175	−2.439	−3.758	−6.482	−12.101
Indonesia	−1.242	−2.594	−4.020	−6.973	−13.267
Laos	−1.039	−2.164	−3.342	−5.765	−10.621
Malaysia	−1.091	−2.293	−3.568	−6.229	−12.118
Philippines	−1.206	−2.592	−4.093	−7.275	−14.798
Singapore	−0.905	−1.958	−3.106	−5.562	−11.652
Thailand	−0.766	−1.605	−2.500	−4.401	−9.243
Vietnam	−0.802	−1.636	−2.500	−4.276	−7.959
Rest of Southeast Asia	−1.342	−2.767	−4.237	−7.234	−12.924
Bangladesh	−0.854	−1.671	−2.491	−4.142	−7.591
India	−1.023	−2.099	−3.222	−5.532	−10.351
Nepal	−0.505	−1.012	−1.537	−2.628	−5.731
Pakistan	−0.483	−1.001	−1.557	−2.753	−6.435
Sri Lanka	−1.129	−2.320	−3.569	−6.154	−11.716
Rest of South Asia	−1.081	−2.105	−3.133	−5.206	−9.606
Canada	0.062	0.111	0.151	0.203	−0.218
United States of America	−0.015	−0.037	−0.067	−0.147	−0.622
Mexico	−0.029	−0.076	−0.147	−0.363	−2.277
Rest of North America	0.015	−0.003	−0.033	−0.127	−0.902
Argentina	−0.061	−0.137	−0.228	−0.450	−1.583
Bolivia	−0.194	−0.388	−0.592	−1.028	−2.332
Brazil	−0.319	−0.658	−1.018	−1.782	−3.843
Chile	0.008	0.001	−0.021	−0.112	−1.158
Colombia	−0.452	−0.916	−1.401	−2.425	−5.532
Ecuador	−0.183	−0.380	−0.594	−1.061	−2.599
Paraguay	−0.630	−1.304	−2.012	−3.482	−6.729
Peru	−0.174	−0.348	−0.526	−0.902	−1.934
Uruguay	−0.055	−0.135	−0.234	−0.482	−1.776
Venezuela	−0.309	−0.636	−0.982	−1.712	−3.614
Rest of South America	−0.028	−0.075	−0.141	−0.321	−1.545
Costa Rica	−0.585	−1.277	−2.038	−3.673	−7.871
Guatemala	−0.215	−0.442	−0.684	−1.206	−2.798
Honduras	−1.025	−2.151	−3.337	−5.802	−11.126
Nicaragua	−1.187	−2.449	−3.757	−6.435	−11.673
Panama	−0.870	−1.823	−2.838	−4.958	−9.580
El Salvador	−0.338	−0.719	−1.136	−2.048	−4.957

Table 1 *(continued)*

Country	2027	2037	2047	2067	Long run
Rest of Central America	−1.163	−2.391	−3.665	−6.285	−11.646
Dominican Republic	−0.522	−1.150	−1.855	−3.400	−7.934
Jamaica	−0.616	−1.287	−1.999	−3.492	−6.940
Puerto Rico	−0.458	−0.995	−1.587	−2.870	−6.527
Trinidad and Tobago	−0.503	−1.136	−1.842	−3.371	−7.357
Caribbean	−0.771	−1.610	−2.492	−4.320	−8.207
Austria	0.055	0.107	0.151	0.200	−0.486
Belgium	0.043	0.081	0.108	0.128	−0.540
Cyprus	0.025	0.042	0.049	0.024	−0.816
Czech Republic	0.086	0.165	0.231	0.312	−0.567
Denmark	0.037	0.068	0.092	0.112	−0.393
Estonia	0.018	0.028	0.028	−0.008	−0.750
Finland	0.060	0.117	0.165	0.231	−0.254
France	0.048	0.088	0.117	0.141	−0.455
Germany	0.044	0.083	0.112	0.140	−0.415
Greece	0.108	0.200	0.281	0.402	−0.275
Hungary	0.064	0.122	0.168	0.217	−0.590
Ireland	0.055	0.108	0.152	0.196	−0.748
Italy	0.070	0.136	0.190	0.255	−0.588
Latvia	0.060	0.111	0.152	0.196	−0.394
Lithuania	0.092	0.178	0.251	0.353	−0.394
Luxembourg	0.054	0.101	0.138	0.171	−0.600
Malta	0.066	0.130	0.181	0.225	−1.261
Netherlands	0.054	0.101	0.135	0.169	−0.467
Poland	0.074	0.139	0.192	0.253	−0.514
Portugal	0.044	0.083	0.113	0.140	−0.460
Slovakia	0.100	0.193	0.273	0.382	−0.470
Slovenia	0.041	0.071	0.091	0.097	−0.512
Spain	0.044	0.078	0.102	0.113	−0.575
Sweden	0.039	0.074	0.102	0.131	−0.349
United Kingdom	0.034	0.063	0.085	0.101	−0.422
Switzerland	0.016	0.028	0.034	0.029	−0.355
Norway	0.003	0.008	0.007	−0.022	−0.646
Rest of EFTA	0.057	0.111	0.154	0.205	−0.421
Albania	−0.054	−0.114	−0.185	−0.365	−1.461
Bulgaria	0.063	0.115	0.153	0.187	−0.590
Belarus	0.089	0.147	0.191	0.240	−0.249
Croatia	0.010	0.015	0.015	−0.007	−0.454
Romania	0.041	0.076	0.099	0.112	−0.483
Russian Federation	−0.011	−0.016	−0.027	−0.081	−0.936
Ukraine	0.057	0.107	0.149	0.204	−0.250
Rest of Eastern Europe	0.175	0.311	0.432	0.639	0.370
Rest of Europe	0.104	0.198	0.280	0.401	−0.206
Kazakhstan	−0.031	−0.058	−0.089	−0.173	−0.820
Kyrgyzstan	0.009	0.006	−0.011	−0.083	−0.930
Rest of Former Soviet Union	0.012	0.019	0.017	−0.015	−0.564
Armenia	−0.040	−0.079	−0.126	−0.249	−1.350

Table 1 *(continued)*

Country	2027	2037	2047	2067	Long run
Azerbaijan	−0.174	−0.350	−0.538	−0.953	−2.638
Georgia	−0.025	−0.060	−0.106	−0.231	−1.035
Bahrain	−0.281	−0.630	−1.031	−1.939	−5.138
Iran	−0.167	−0.350	−0.558	−1.047	−3.516
Israel	−0.198	−0.410	−0.632	−1.102	−2.317
Jordan	−0.158	−0.342	−0.555	−1.052	−3.254
Kuwait	−0.218	−0.508	−0.851	−1.639	−4.488
Oman	−0.210	−0.478	−0.786	−1.477	−3.780
Qatar	−0.357	−0.829	−1.387	−2.674	−7.304
Saudi Arabia	−0.378	−0.831	−1.332	−2.422	−5.449
Turkey	0.007	−0.008	−0.045	−0.180	−1.540
United Arab Emirates	−0.457	−1.007	−1.630	−3.024	−7.684
Rest of Western Asia	−0.248	−0.507	−0.783	−1.381	−3.306
Egypt	−0.354	−0.714	−1.086	−1.867	−4.000
Morocco	−0.200	−0.415	−0.640	−1.120	−2.436
Tunisia	−0.227	−0.473	−0.735	−1.303	−3.052
Rest of North Africa	−0.211	−0.417	−0.630	−1.080	−2.394
Burkina Faso	−1.576	−3.278	−5.076	−8.829	−17.058
Cameroon	−0.980	−1.989	−3.031	−5.162	−9.396
Cote d'Ivoire	−1.972	−3.988	−6.034	−10.164	−17.528
Ghana	−2.000	−3.999	−6.028	−10.124	−17.571
Guinea	−0.980	−1.939	−2.932	−4.991	−9.896
Nigeria	−1.674	−3.422	−5.217	−8.874	−15.723
Senegal	−1.270	−2.565	−3.905	−6.666	−13.001
Togo	−2.338	−4.553	−6.787	−11.276	−19.032
Rest of Western Africa	−2.334	−4.091	−5.860	−9.409	−15.566
Central Africa	−0.376	−0.783	−1.223	−2.173	−4.977
South Central Africa	−0.289	−0.587	−0.896	−1.549	−3.320
Ethiopia	−0.759	−1.476	−2.197	−3.656	−6.704
Kenya	−0.744	−1.492	−2.254	−3.813	−7.238
Madagascar	−0.726	−1.486	−2.270	−3.881	−7.212
Malawi	−0.983	−1.995	−3.028	−5.133	−9.266
Mauritius	−0.650	−1.359	−2.113	−3.700	−7.458
Mozambique	−0.837	−1.738	−2.681	−4.639	−8.878
Rwanda	−0.766	−1.531	−2.309	−3.888	−7.047
Tanzania	−0.737	−1.479	−2.237	−3.785	−6.988
Uganda	−0.635	−1.268	−1.912	−3.232	−6.328
Zambia	−0.407	−0.831	−1.272	−2.189	−4.414
Zimbabwe	−0.428	−0.849	−1.283	−2.187	−4.423
Rest of Eastern Africa	−0.874	−1.750	−2.644	−4.461	−8.099
Botswana	−0.148	−0.322	−0.523	−0.993	−3.047
Namibia	−0.088	−0.190	−0.310	−0.610	−2.404
South Africa	−0.130	−0.278	−0.443	−0.823	−2.464
Rest of South African Customs Union	−0.192	−0.407	−0.644	−1.172	−3.045
Rest of the World	−0.078	−0.177	−0.294	−0.577	−1.918

Note. Source: Authors' GTAP-INT calculation.

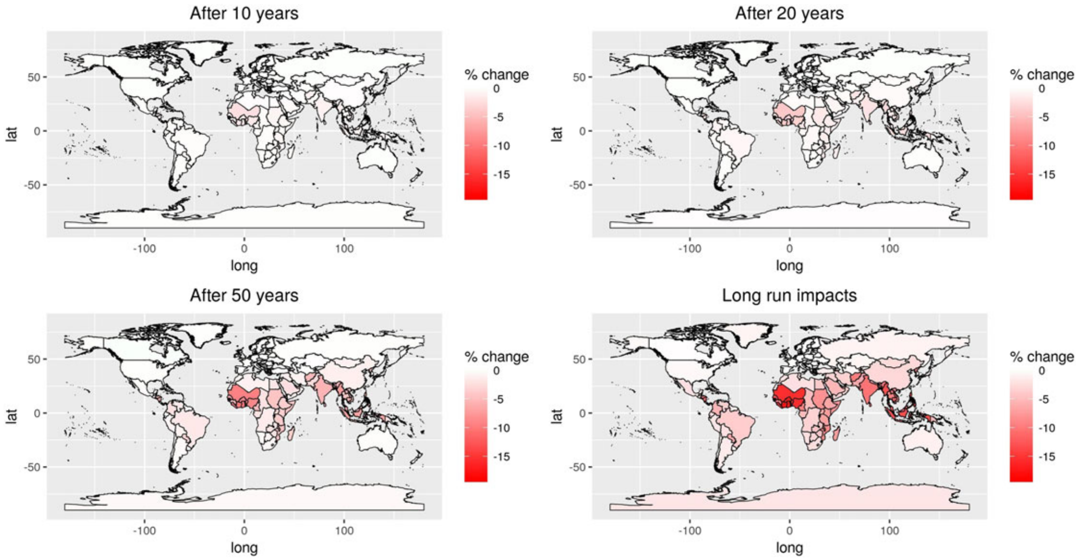


Figure 1. Dynamic impacts of global warming (3°C) on the world GDP (% change/year).

5. Long-Term Potential Impacts by RCP Scenario and Gains From Complying With the Paris Accord

This section compares the long-term impact by different temperature changes from global warming or equivalently different RCPs so that the avoided losses from various responses to climate change can be analyzed and the gains from complying with the Paris Accord can be calculated. Table 2 presents the long-run impacts of different global warming scenarios (1–4°C), which correspond to different RCPs in Moss et al. (2010). The measure is the change in GDP. It is clear that falls in GDP for countries near the equator are especially dramatic.

Indeed, it is interesting to compare our results with the findings of Roson and der Mensbrugghe (2012), using their ENVISAGE model. Although comparable, it is important to note that the model context here is different. Roson and der Mensbrugghe (2012) use a recursive dynamic approach, with adaptive expectations, and their results are only for 15 regions, which will necessarily average outcomes. Our intertemporal approach is dimensionally larger, for 139 countries, and drops the damage functions for tourism and energy use. That said, Roson and der Mensbrugghe (2012) find that the developing and poorer countries in the *rest of Asia* and the *Middle East and North Africa* lose 10.3% to 12.6% of their GDP when the global temperature increases by 4.79°C in 2100. Our larger dimensional model shows, instead, that if global surface temperature increases by 4°C, countries in South East Asia can lose up to 21% of their GDP per year. The picture for developing countries in Africa is even more grim with the GDP losses as high as 26.6% per year (Table 2).

From the above GDP damages, it is possible to calculate the gains from complying with the Paris Climate Accord. Following van Vuuren et al. (2011), we can map our scenarios in terms of their implications for the following climate change policies.

1. The case of 1°C is likely to reflect the lowest emission scenario with the most stringent mitigation policies (or approximately RCP2.6).
2. Implementation of a climate change agreement (e.g., the Paris Accord) would slow global warming to around 2°C by 2100 (or approximately RCP4.5).
3. A medium baseline case with less stringent mitigation policies will push global surface temperatures up to 3°C by 2100 (approximately RCP6).
4. Without any countervailing action to reduce emissions, global warming could increase up to 4°C (or approximately RCP8.5).

The successful achievement of the Paris Accord, which aims to keep global warming at roughly 2°C (or RCP4.5), or less, allows us to calculate the potential benefit of the Accord as the difference in losses between the 4, 3, and 2°C scenarios. Based on the full version of Table 2 from our GTAP-INT simulation results, and Table A1, which represents the value of annual GDP losses in 2100, we can calculate the differences.

Table 2
Long-Run Impacts of Climate Change Scenarios on the World GDP (% Change/Year)

Country	1°C	2°C	3°C	4°C
Australia	−0.287	−0.642	−1.083	−1.585
New Zealand	−0.144	−0.413	−0.798	−1.269
Rest of Oceania	−1.015	−2.627	−5.171	−8.553
China	−0.755	−1.694	−2.918	−4.597
Hong Kong	−1.314	−3.082	−5.288	−7.655
Japan	−0.182	−0.595	−1.335	−2.412
South Korea	−0.211	−0.731	−1.498	−2.666
Mongolia	−0.789	−1.664	−2.710	−3.981
Taiwan	−1.597	−3.560	−5.978	−8.552
Rest of East Asia	−2.389	−5.709	−9.490	−13.710
Brunei Darussalam	−1.202	−3.134	−5.563	−8.173
Cambodia	−3.509	−7.572	−12.101	−17.183
Indonesia	−3.347	−7.980	−13.267	−19.040
Laos	−3.369	−6.795	−10.620	−15.759
Malaysia	−3.084	−7.145	−12.118	−17.339
Philippines	−4.113	−9.185	−14.798	−20.986
Singapore	−2.729	−6.923	−11.652	−16.566
Thailand	−2.541	−5.749	−9.243	−13.269
Vietnam	−2.223	−4.862	−7.959	−11.641
Rest of Southeast Asia	−3.811	−8.110	−12.924	−18.573
Bangladesh	−2.285	−4.755	−7.591	−11.237
India	−2.922	−6.434	−10.351	−14.622
Nepal	−1.012	−2.881	−5.731	−9.859
Pakistan	−1.901	−3.994	−6.435	−9.338
Sri Lanka	−2.989	−6.941	−11.716	−17.437
Rest of South Asia	−2.778	−6.002	−9.606	−13.880
Canada	−0.096	−0.158	−0.218	−0.321
United States of America	−0.182	−0.392	−0.622	−0.885
Mexico	−0.506	−1.178	−2.277	−3.985
Rest of North America	−0.231	−0.539	−0.902	−1.292
Argentina	−0.360	−0.872	−1.583	−2.610
Bolivia	−0.650	−1.442	−2.332	−3.356
Brazil	−0.615	−1.910	−3.843	−6.829
Chile	−0.323	−0.709	−1.158	−1.674
Colombia	−1.104	−2.714	−5.532	−9.325
Ecuador	−0.741	−1.627	−2.599	−3.801
Paraguay	−1.604	−3.873	−6.729	−10.142
Peru	−0.509	−1.169	−1.934	−2.768
Uruguay	−0.471	−1.023	−1.776	−2.785
Venezuela	−0.649	−1.794	−3.614	−6.339
Rest of South America	−0.459	−0.937	−1.545	−2.446
Costa Rica	−1.407	−4.047	−7.871	−12.928
Guatemala	−0.694	−1.553	−2.798	−4.533
Honduras	−2.751	−6.492	−11.126	−16.521
Nicaragua	−3.020	−6.898	−11.673	−17.264
Panama	−2.197	−5.367	−9.580	−14.457
El Salvador	−0.986	−2.498	−4.957	−8.438

Table 2 *(continued)*

Country	1°C	2°C	3°C	4°C
Rest of Central America	−1.675	−5.603	−11.646	−18.231
Dominican Republic	−1.850	−4.406	−7.934	−12.171
Jamaica	−1.485	−3.696	−6.940	−10.813
Puerto Rico	−1.269	−3.297	−6.527	−10.536
Trinidad and Tobago	−1.690	−4.150	−7.357	−10.905
Caribbean	−1.864	−4.529	−8.207	−12.605
Austria	−0.122	−0.287	−0.486	−0.728
Belgium	−0.151	−0.330	−0.540	−0.788
Cyprus	−0.194	−0.462	−0.816	−1.481
Czech Republic	−0.169	−0.352	−0.567	−0.842
Denmark	−0.127	−0.252	−0.393	−0.573
Estonia	−0.230	−0.476	−0.750	−1.087
Finland	−0.067	−0.153	−0.254	−0.383
France	−0.139	−0.285	−0.455	−0.662
Germany	−0.118	−0.254	−0.415	−0.608
Greece	−0.048	−0.149	−0.275	−0.708
Hungary	−0.197	−0.390	−0.590	−0.884
Ireland	−0.184	−0.436	−0.748	−1.125
Italy	−0.144	−0.342	−0.588	−0.906
Latvia	−0.140	−0.259	−0.394	−0.564
Lithuania	−0.179	−0.288	−0.394	−0.587
Luxembourg	−0.137	−0.343	−0.600	−0.896
Malta	−0.275	−0.691	−1.261	−2.083
Netherlands	−0.118	−0.275	−0.467	−0.694
Poland	−0.166	−0.332	−0.514	−0.774
Portugal	−0.120	−0.275	−0.460	−0.684
Slovakia	−0.129	−0.285	−0.470	−0.706
Slovenia	−0.139	−0.310	−0.512	−0.764
Spain	−0.147	−0.341	−0.575	−0.871
Sweden	−0.095	−0.211	−0.349	−0.516
United Kingdom	−0.122	−0.260	−0.422	−0.613
Switzerland	−0.094	−0.214	−0.355	−0.522
Norway	−0.160	−0.377	−0.646	−0.967
Rest of EFTA	−0.097	−0.242	−0.421	−0.634
Albania	−0.395	−0.857	−1.461	−2.360
Bulgaria	−0.090	−0.294	−0.590	−0.999
Belarus	−0.176	−0.214	−0.249	−0.617
Croatia	−0.083	−0.216	−0.454	−0.946
Romania	−0.171	−0.329	−0.483	−0.754
Russian Federation	−0.266	−0.568	−0.936	−1.405
Ukraine	−0.153	−0.219	−0.250	−0.382
Rest of Eastern Europe	0.011	0.160	0.370	0.492
Rest of Europe	−0.089	−0.150	−0.205	−0.318
Kazakhstan	−0.371	−0.592	−0.820	−1.137
Kyrgyzstan	−0.377	−0.614	−0.930	−1.500
Rest of Former Soviet Union	−0.239	−0.392	−0.564	−0.888
Armenia	−0.739	−1.050	−1.350	−1.777
Azerbaijan	−0.756	−1.563	−2.638	−4.025

Table 2 *(continued)*

Country	1°C	2°C	3°C	4°C
Georgia	−0.393	−0.680	−1.035	−1.769
Bahrain	−1.440	−3.192	−5.138	−7.303
Iran	−0.894	−2.044	−3.516	−5.365
Israel	−0.743	−1.514	−2.317	−3.416
Jordan	−0.982	−1.998	−3.254	−4.835
Kuwait	−1.315	−2.795	−4.488	−6.387
Oman	−0.996	−2.248	−3.780	−5.482
Qatar	−2.091	−4.618	−7.304	−10.358
Saudi Arabia	−1.650	−3.457	−5.449	−7.773
Turkey	−0.342	−0.842	−1.540	−2.479
United Arab Emirates	−2.207	−4.799	−7.684	−10.976
Rest of Western Asia	−0.829	−1.879	−3.306	−4.985
Egypt	−1.083	−2.377	−4.000	−6.143
Morocco	−0.770	−1.525	−2.436	−3.487
Tunisia	−0.871	−1.836	−3.052	−4.609
Rest of North Africa	−0.653	−1.415	−2.394	−3.639
Burkina Faso	−5.229	−10.894	−17.058	−23.586
Cameroon	−2.276	−5.528	−9.396	−14.480
Cote dIvoire	−4.710	−10.742	−17.528	−25.252
Ghana	−4.857	−10.815	−17.571	−24.983
Guinea	−2.712	−6.093	−9.896	−14.689
Nigeria	−4.528	−9.689	−15.723	−22.250
Senegal	−3.859	−8.189	−13.001	−18.544
Togo	−5.597	−12.221	−19.032	−26.556
Rest of Western Africa	−4.432	−9.769	−15.566	−21.938
Central Africa	−1.013	−2.430	−4.977	−8.362
South Central Africa	−0.961	−2.066	−3.320	−4.894
Ethiopia	−1.862	−4.238	−6.704	−9.416
Kenya	−2.331	−4.706	−7.238	−10.506
Madagascar	−1.976	−4.286	−7.212	−10.993
Malawi	−2.277	−5.683	−9.266	−13.609
Mauritius	−1.829	−4.399	−7.458	−11.245
Mozambique	−2.411	−5.311	−8.878	−12.989
Rwanda	−2.107	−4.490	−7.047	−9.819
Tanzania	−1.546	−4.130	−6.988	−10.825
Uganda	−1.743	−3.652	−6.328	−10.404
Zambia	−1.097	−2.616	−4.414	−6.720
Zimbabwe	−1.261	−2.726	−4.423	−6.502
Rest of Eastern Africa	−2.112	−4.750	−8.099	−11.862
Botswana	−0.710	−1.659	−3.047	−4.873
Namibia	−0.673	−1.464	−2.404	−3.616
South Africa	−0.740	−1.570	−2.464	−3.433
Rest of South African Customs Union	−0.890	−1.923	−3.045	−4.390
Rest of the World	−0.587	−1.227	−1.918	−2.671

Note. Source: Authors' GTAP-INT calculation.

As indicated above, we calculate world GDP in 2100 using 2017 world GDP in US$ (IMF, 2018, from the World Economic Outlook database) and economic growth from the corresponding SSPs (SSP1 for 2 °C, SSP2 for 3°C and SSP5 for 4°C; Crespo Cuaresma, 2017; International Institute for Applied Systems Analysis, 2018). Because the economic forecasts in the SSPs are for a 10-year period, we apply a linear interpolation method to approximate the missing forecasts for the years between and any two predicted time points (similarly for the GDP damage ratios from our simulation results). The results for GDP damages in US$ are available from 2017 to 2100, but only 2100 results are shown in Table A1.

In total, the avoided global GDP losses for the case of 3°C (or equivalently RCP6.0) compared to 2°C are US$3,934.25 billion a year in terms of 2100 GDP. For the case of RCP8.5, or a global warming of 4°C, the avoided global losses in GDP between 4 and 2°C are much larger or US$17,489.72 billion a year in the long run (also in terms of GDP in 2100).

6. Discussion and Concluding Remarks

GHG emission growth and its global warming consequences are a significant threat to the Earth's future. Assessing climate change impacts to the global economy and national incomes, and the potential benefit of climate change agreements, however, is complex, requiring large-scale modeling to even approach a comprehensive answer. For economists, the standard tool is CGE modeling. But, here, save for a few valuable country studies and some dynamic recursive modeling efforts, current models are either dimensionally too small or bound by myopic forecasting rules to be completely useful or compelling. The extension of the GTAP-INT model used in this work fills that gap, providing estimates of global warming damages on GDP and its rate of change for 139 countries in the GTAP database, by various temperature changes, as well as by measures of the benefits of complying with a trade agreement, such as the Paris Climate Accord.

Although GTAP-INT is country detailed and uses forward-looking approaches to forming price and profit expectations, there are a number of significant caveats to be aware of and considerable scope for future research. First, the model dimension does not computationally allow for random shocks or any of the usual jump-diffusion characteristics of a stochastic process that may impact both technology or living standards in the economy, among many other things. This lack of randomness is a serious shortcoming of all CGE modeling, except those with very small dimensions, and it needs to be worked on. There are ways forward, but it will require very large dimensional modeling and the use of parallel processing techniques, at the least, as in the GTAP-INT model and related work (Ha & Kompas, 2016; Ha et al., 2017; Kompas & Ha, 2017).

Second, given the lack of a random component, it is not possible to include the effects of natural disasters or more extreme weather events that occur year to year in the model. The costs of these can be considerable. For now, all that is captured is the effects of SLR, changes in agricultural productivity, and key health effects. Indeed, some of the significant effects of actions concomitant with global warming, such as the effects of air pollution, losses in biodiversity, the spread of invasive species, changes in energy mix, and the costs of significant migration, are also not included. Capturing natural disaster shocks and these other effects is possible in GTAP modeling, but it has not been done for the global economy to date, and this too needs to be worked on.

Third, and finally, although the extension of GTAP-INT to full climate change effects does allow for forward-looking estimates of the possible effects of global warming, the informational requirements here are profound and will not nearly be met in every circumstance or by every producer and consumer. Practically speaking, some forecasts fail to account not only for projected changes in the local and global economy but also for all of the other unpredictable changes that occur. Including randomness in the model framework would help with this, but as it stands the model is benchmarked to perfect foresight settings as a comparator. Designing models with mixed information requirements, that is, ranges of forward-looking forecasts combined over a set of elements with more myopic forecasting rules, is possible, but that work too needs to be done. It is clear, however, that models with only static price forecasting rules are clearly inadequate when climate change is considered. We know that at least some economic agents look forward and endeavor to incorporate this information in their price forecasting. We also know that economic agents revise their forecasts given exogenous shocks at any moment in time, calling again for some stochastic process in the CGE/GTAP model framework.

With all of the above caveats in mind, the estimates from GTAP-INT do indicate substantial damages and losses in national income from global warming, providing at least a means of comparison across different temperature ranges and countries, regardless of the range of information that is available, perfect or otherwise. The losses in GDP and the gains from complying with the Paris Accord, even in this limited framework, are substantial, as indicated. What is perhaps as equally disturbing is how the percentage fall in GDP varies across the world and is most severe in many of the poorest countries (Table 2). Notable in the list are the dramatic falls in GDP by decade and in the long term, especially, of course, for the 4°C outcome, for Ghana, Nigeria, Cote D'Ivoire, Togo, Honduras, Nicaragua, the Phillipines, Cambodia, and Laos, among others. But Indonesia, Bangladesh, India, Singapore, Central America, East Asia, Thailand, and Vietnam also experience fairly substantial falls. Complying with the Paris Climate Accord would benefit these relatively poor countries, especially so.

It is important to note that the results above also assume that the United States remains in the Paris Accord and that all countries that have agreed to emission reduction targets honor their commitments. This is all questionable.

One final point. The often severe falls in GDP in the long term will put many governments in fiscal stress, since tax revenues are tied to GDP or national income levels. In addition, if global warming is tied to increases in the frequency of weather events and other natural disasters, which invoke significant emergency management responses and expenditures, the pressure on government budgets will be doubly severe. It would be good to form estimates of the extent of these budget pressures.

Appendix A: Impacts of Climate Change on the Global Economy

In this appendix we detail estimates of the long-term losses in GDP per year under various global warming scenarios to the year 2100. We also indicate the long-run impacts of global warming on the economic sectors (or commodity groups) contained in the GTAP database.

Table A1
Estimation of Long-Term GDP Loss per Year Under Global Warming Scenarios (US$ Billion/Year) to the Year 2100

	4°C	3°C	2°C
World total	−23,149.18	−9,593.71	−5,659.47
Sub-Saharan Africa	−8,073.68	−2,889.66	−1,927.78
India	−4,484.96	−2,070.06	−1,149.36
Southeast Asia	−4,158.88	−2,073.09	−1,166.23
China	−1,716.91	−701.75	−394.59
Latin America	−1,371.81	−576.65	−259.82
Rest of South Asia	−1,157.92	−469.98	−283.78
Middle East and North Africa	−1,032.27	−451.96	−241.12
United States of America	−697.77	−223.83	−168.48
Japan	−253.18	−54.43	−23.02
Mexico	−127.70	−55.79	−20.88
Australia	−117.42	−36.87	−23.72
South Korea	−81.44	−14.72	−7.86
Rest of Oceania	−39.65	−14.97	−6.96
Russian Federation	−24.49	−10.88	−6.53
Rest of Former Soviet Union	−9.93	−5.31	−3.85
EFTA	−8.72	−3.01	−2.16
New Zealand	−4.19	−0.77	−0.09
East Asia	−3.35	−1.27	−0.78
Rest of Eastern Europe	1.49	1.28	0.18
Rest of Europe	3.15	1.38	0.63

Table A1 *(continued)*

	4°C	3°C	2°C
World total	−23,149.18	−9,593.71	−5,659.47
United Kingdom	17.78	4.06	0.35
Germany	23.85	5.38	2.46
France	26.92	7.11	1.80
Italy	32.42	12.20	7.26
Canada	45.29	11.40	5.20
Rest of EU25	64.19	18.47	9.68

Note. The numbers are calculated on the value of predicted GDP to 2100 from data in IMF (2018), International Institute for Applied Systems Analysis (2018), and Crespo Cuaresma (2017).

Table A2
Long-Run Impacts of Global Warming (3°C) on the World's Economic Sectors (% Change)

Economic Sectors	2017	2027	2037	2067	Long run
Paddy rice	−0.026	−0.532	−1.056	−2.687	−4.857
Wheat	0.006	−0.339	−0.699	−1.843	−3.582
Cereal grains nec	−0.012	−0.358	−0.718	−1.859	−3.554
Vegetables, fruit, nuts	−0.012	−0.398	−0.797	−2.040	−3.723
Oil seeds	−0.010	−0.501	−1.012	−2.618	−4.875
Sugar cane, sugar beet	0.015	−0.450	−0.939	−2.493	−4.812
Plant-based fibers	0.182	−0.432	−1.081	−3.144	−6.240
Crops nec	0.001	−0.348	−0.720	−1.914	−3.763
Bovine cattle, sheep and goats, horses	−0.015	−0.293	−0.588	−1.539	−3.102
Animal products nec	−0.007	−0.308	−0.625	−1.646	−3.293
Raw milk	−0.017	−0.334	−0.666	−1.720	−3.362
Wool, silkworm cocoons	−0.090	−0.423	−0.772	−1.877	−3.562
Forestry	−0.020	−0.300	−0.608	−1.645	−3.632
Fishing	−0.008	−0.303	−0.616	−1.619	−3.162
Coal	−0.003	−0.162	−0.345	−0.985	−2.365
Oil	0.006	−0.112	−0.253	−0.763	−1.987
Gas	0.018	−0.021	−0.079	−0.347	−1.431
Minerals nec	−0.018	−0.202	−0.418	−1.200	−3.061
Bovine meat products	−0.002	−0.265	−0.539	−1.421	−2.893
Meat products nec	0.002	−0.204	−0.422	−1.130	−2.384
Vegetable oils and fats	−0.006	−0.384	−0.783	−2.052	−3.980
Dairy products	−0.002	−0.170	−0.348	−0.945	−2.141
Processed rice	−0.029	−0.468	−0.926	−2.363	−4.363
Sugar	−0.016	−0.324	−0.649	−1.693	−3.381
Food products nec	−0.001	−0.201	−0.414	−1.113	−2.369
Beverages and tobacco products	−0.003	−0.158	−0.327	−0.900	−2.073
Textiles	0.003	−0.188	−0.398	−1.107	−2.501
Wearing apparel	0.006	−0.131	−0.282	−0.804	−1.942
Leather products	−0.002	−0.167	−0.346	−0.950	−2.176
Wood products	0.013	−0.063	−0.161	−0.563	−1.907
Paper products, publishing	−0.003	−0.104	−0.221	−0.650	−1.767
Petroleum, coal products	0.003	−0.105	−0.233	−0.703	−1.876
Chemical, rubber, plastic products	−0.002	−0.147	−0.315	−0.914	−2.326
Mineral products nec	−0.020	−0.176	−0.360	−1.053	−2.921
Ferrous metals	−0.024	−0.201	−0.409	−1.174	−3.112

Table A2 *(continued)*

Economic Sectors	2017	2027	2037	2067	Long run
Metals nec	−0.028	−0.224	−0.449	−1.252	−3.084
Metal products	−0.028	−0.162	−0.319	−0.909	−2.515
Motor vehicles and parts	0.013	−0.096	−0.230	−0.745	−2.236
Transport equipment nec	−0.025	−0.203	−0.409	−1.148	−2.894
Electronic equipment	0.011	−0.139	−0.319	−0.994	−2.720
Machinery and equipment nec	0.007	−0.118	−0.271	−0.865	−2.561
Manufactures nec	−0.015	−0.190	−0.389	−1.092	−2.700
Electricity	0.000	−0.115	−0.249	−0.740	−2.006
Gas manufacture, distribution	0.018	−0.132	−0.303	−0.920	−2.440
Water	−0.016	−0.143	−0.288	−0.811	−2.093
Construction	−0.007	−0.132	−0.290	−0.917	−2.829
Trade	−0.004	−0.156	−0.327	−0.934	−2.341
Transport nec	−0.006	−0.142	−0.298	−0.861	−2.248
Water transport	−0.004	−0.204	−0.433	−1.238	−2.972
Air transport	0.000	−0.118	−0.255	−0.747	−1.940
Communication	0.001	−0.101	−0.221	−0.668	−1.880
Financial services nec	0.001	−0.108	−0.237	−0.708	−1.927
Insurance	0.000	−0.097	−0.208	−0.606	−1.591
Business services nec	0.012	−0.042	−0.112	−0.407	−1.495
Recreational and other services	0.004	−0.096	−0.210	−0.623	−1.675
Public Administration, Defense, Education, Health	0.000	−0.104	−0.218	−0.603	−1.420
Dwellings	−0.003	−0.068	−0.160	−0.569	−2.158

Note. Source: Authors' GTAP-INT calculation.

Acknowledgments

The following software library package has been used in computations and graphical representation of this paper: Portable, Extensible Toolkit for Scientific Computation (PETSc) at Argonne National Laboratory (Balay et al., 1997; Balay et al., 2016a; 2016b); Message Passing Interface (MPICH) 3.2.7; HSL Mathematical Software Library (HSL, 2013); R (R Core Team, 2018) and its packages: maptool (Bivand & Lewin-Koh, 2017), gplot2 (Wickham, 2009), RColorBrewer (Neuwirth, 2014), reshape (Wickham, 2007), and tidyr (Wickham & Henry, 2018). Special thanks to the developers who shared their work. The views expressed here do not necessarily reflect those of the CSIRO.

References

Aguiar, A., Narayanan, B., & McDougall, R. (2016). An overview of the GTAP 9 data base. *Journal of Global Economic Analysis*, *1*(1), 181–208.

Balay, S., Abhyankar, S., Adams, M. F., Brown, J., Brune, P., Buschelman, K., et al. (2016a). PETSc users manual (Tech. Rep. ANL-95/11 - Revision 3.7). Argonne National Laboratory.

Balay, S., Abhyankar, S., Adams, M. F., Brown, J., Brune, P., Buschelman, K., et al. (2016b). PETSc Web page. Retrieved from http://www.mcs.anl.gov/petsc

Balay, S., Gropp, W. D., McInnes, L. C., & Smith, B. F. (1997). Efficient management of parallelism in object oriented numerical software libraries. In S. Balay, W. D. Gropp, L. C. McInnes, & B. F. Smith (Eds.), *Modern software tools in scientific computing* (pp. 163–202). Birkhäuser Press.

Bivand, R., & Lewin-Koh, N. (2017). Maptools: Tools for reading and handling spatial objects. r package version 0.8-41.

Bosello, F., Roson, R., & Tol, R. (2006). Economy-wide estimates of the implication of climate change: Human health. *Ecological Economics*, *58*, 579–91.

Bosello, F., Roson, R., & Tol, R. S. (2007). Economy-wide estimates of the implications of climate change: Sea level rise. *Environmental and Resource Economics*, *37*(3), 549–571.

Burniaux, J.-M., & Truong, T. (2002). GTAP-E: An energy-environmental version of the GTAP model (GTAP Technical Paper n.16).

Cline, R. W. (2007). Global warming and agriculture—Impact estimates by county, Center for Global Development, Peterson Institute for International Economics, Washington DC.

Corong, E. L., Hertel, T. W., McDougall, R., Tsigas, M. E., & van der Mensbrugghe, D. (2017). The standard GTAP model, version 7. *Journal of Global Economic Analysis*, *2*, 1–119.

Crespo Cuaresma, J. (2017). Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change*, *42*, 226–236.

De Cian, E., Lanzi, E., & Roson, R. (2013). Seasonal temperature variations and energy demand: A panel co-integration analysis for climate change impact assessment. *Climatic Change*, *116*, 805–825.

Dixon, P. B., Parmenter, B., Powell, A. A., Wilcoxen, P. J., & Pearson, K. (1992). Notes and problems in applied general equilibrium economics. In C. Bliss & M. Intriligator (Eds.), *Advanced textbooks in economics* (Vol. 32, pp. 392). Amsterdam, London, New York, Tokyo: North-Holland.

Dixon, P. B., Pearson, K., Picton, M. R., & Rimmer, M. T. (2005). Rational expectations for large CGE models: A practical algorithm and a policy application. *Economic Modelling*, *22*(6), 1001–1019.

Dixon, P. B., & Rimmer, M. T. (2002). *Dynamic general equilibrium modelling for forecasting and policy: A practical guide and documentation of MONASH, contributions to economic analysis* (Vol. 256). North-Holland: Elsevier.

Eboli, F., Parrado, R., & Roson, R. (2010). Climate-change feedback on economic growth: Explorations with a dynamic general equilibrium model. *Environment and Development Economics*, *15*, 515–533.

Global Trade Analysis Project (2017). GTAP 9 database, Global Trade Analysis Project.

Global Humanitarian Forum (2009). The anatomy of a silent crisis, human impact report—Climate change. Retrieved from http://www.ghf-ge.org/human-impact-report.pdf, Accessed date: 22 Apr 2018

HSL (2013). A collection of fortran codes for large scale scientific computation. Retrieved from http://www.hsl.rl.ac.uk

Ha, P. V., & Kompas, T. (2014). Solving the GTAP model in parallel using a doubly bordered block diagonal ordering technique. In *2nd International Workshop on "Financial Markets and Nonlinear Dynamics" (FMND), June 4-5, 2015*. Paris, France.

Ha, P. V., & Kompas, T. (2016). Solving intertemporal CGE models in parallel using a singly bordered block diagonal ordering technique. *Economic Modelling*, *52*, 3–12.

Ha, P. V., Kompas, T., Nguyen, H. T. M., & Long, C. H. (2017). Building a better trade model to determine local effects: A regional and intertemporal GTAP model. *Economic Modelling*, *67*, 102–113.

Hamilton, M. J., Maddison, J. D., & Tol, R. S. (2005). Climate change and international tourism: A simulation study. *Global Environmental Change*, *15*, 253–263.

Hertel, T. W. (1997). *Global trade analysis: Modelling and applications*. Cambridge, New York: Cambridge University Press.

Hertel, T. W., Burke, M. B., & Lobell, D. B. (2010). The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, *20*(4), 577–585.

IMF (2018). World Economic Outlook, IMF Publication. Retrieved from https://www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx, Accessed on 27 April 2108

Intergovernmental Panel on Climate Change (2014). Climate change 2014: Synthesis report. In Core Writing Team, R. K. Pachauri, & L. A. Meyer (Eds.), *Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (151 pp.). Geneva, Switzerland: IPCC.

Ianchovichina, E., & Walmsley, T. L. (2012). *Dynamic modeling and applications for global economic analysis*. New York: Cambridge University Press.

International Institute for Applied Systems Analysis (2018). SSP database (shared socioeconomic pathways)—Version 1.1. Retrieved from https://tntcat.iiasa.ac.at/SspDb, Accessed date: 27 Apr 2018.

Johansen, L. (1960). *A multi-sector study of economic growth*. North-Holland Pub. Co.

Kjellstrom, T., Kovats, R. S., Lloyd, S. J., Holt, T., & Tol, R. (2009). The direct impact of climate change on regional labor productivity. *Archives of Environmental and Occupational Health*, *64*(4), 217–227.

Kompas, T., & Ha, P. V. (2017). The 'curse of dimensionality' resolved: The effects of climate change and trade barriers in large dimensional modelling. *Presented at the 3rd International Workshop on Financial Markets and Nonlinear Dynamics (FMND)*. Paris, France. 1 June 2107, http://www.fmnd.fr/10/program.html, Accessible at: https://ssrn.com/abstract=3222092

McKibbin, W. J., Pearce, D., & Stegman, A. (2009). Climate change scenarios and long term projections. *Climatic Change*, *97*, 23.

McKibbin, W. J., & Sachs, J. D. (1991). *Global linkages: Macroeconomic interdependence and cooperation in the world economy*. Washington, DC: Brookings Institution.

McKibbin, W. J., & Wilcoxen, P. J. (1999). The theoretical and empirical structure of the G-Cubed model. *Economic Modelling*, *16*(1), 123–148.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*, 747–756.

Neuwirth, E. (2014). RColorBrewer: ColorBrewer Palettes, R package version 1.1-2.

Nordhaus, W. D. (1991). To slow or not to slow: The economics of the greenhouse effect. *The Economic Journal*, *101*, 920–937.

Nordhaus, W. D. (2007). A review of the stern review on the economics of climate change. *Journal of Economic Literature*, *101*(407), 920–37.

R Core Team (2018). *R: A language and environment for statistical computing, R foundation for statistical computing*. Vienna, Austria. Retrieved from http://www.R-project.org/

Riahi, K., van Vuuren, D. P., & Kriegler, E. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168.

Roson, R., & der Mensbrugghe, D. V. (2012). Climate change and economic growth: Impacts and interactions. *International Journal of Sustainable Economy*, *4*, 270–285.

Roson, R., & Sartori, M. (2016). Estimation of climate change damage functions for 140 regions in the GTAP 9 database. *Journal of Global Economic Analysis*, *1*(2), 78–115.

Stern, N. (2016). Economics: Current climate models are grossly misleading. *Nature*, *530*, 407–409. https://doi.org/10.1038/530407a

Tol, R. S. (2002). Estimates of the damage costs of climate change—Part 1: Benchmark estimates. *Environmental and Resource Economics*, *21*, 47–73.

Tol, R. S. (2012). On the uncertainty about the total economic impact of climate change. *Environmental and Resource Economics*, *53*, 97–116.

United Nations Framework Convention on Climate Change (2018a). Paris agreement—Status of ratification. Retrieved from https://unfccc.int/process/the-paris-agreement/status-of-ratification, Accessed date: 22 Apr 2018.

United Nations Framework Convention on Climate Change (2018b). What is the united nations framework convention on climate change? Retrieved from https://unfccc.int/process/the-convention/what-is-the-united-nations-framework-convention-on-climate-change, Accessed date: 22 Apr 2018.

United Nations Framework Convention on Climate Change (2018c). UNFCCC process. Retrieved from https://unfccc.int/process, Accessed date: 22 Apr 2018.

United Nations Framework Convention on Climate Change (2018d). UNFCCC—20 years of effort and achievement—Key milestones in the evolution of international climate policy. Retrieved from http://unfccc.int/timeline/, Accessed date: 22 Apr 2018.

United Nations Framework Convention on Climate Change (2018e). KP introduction. Retrieved from https://unfccc.int/process/the-kyoto-protocol, Accessed date: 22 Apr 2018.

United Nations Framework Convention on Climate Change (2018f). What is the Paris agreement? Retrieved from https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement, Accessed date: 22 Apr 2018.

United Nations (2015). The Paris agreement. Retrieved from https://unfccc.int/sites/default/files/english_paris_agreement.pdf, Accessed date: 22 Apr 2018.

United Nations (2016). Aggregate effect of the intended nationally determined contributions: An update—Synthesis report by the secretariat. In *Conference of the Parties Twenty-second session Marrakech, 7-18 November 2016*. Retrieved from https://pfbc-cbfp.org/news_en/items/Unfccc-Synthesis.html, Accessed date: 5 May 2018

United Nations (2018). Goal 13: Take urgent action to combat climate change and its impacts. Retrieved from http://www.un.org/sustainabledevelopment/climate-change-2/, Accessed date: 22 Apr 2018.

van Vuuren, D. P., & Carter, T. R. (2014). Climate and socio-economic scenarios for climate change research and assessment: Reconciling the new with the old. *Climatic Change*, *122*(3), 415–429.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*, 5. https://doi.org/10.1007/s10584-011-0148-z van Vuuren, D., Kriegler, E., O'Neill, B., Ebi, K., Riahi, K., Carter, T., et al. (2014). A new scenario framework for climate change research: Scenario matrix architecture. *Climatic Change*, *122*, 373–386.

WHO (2014). Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s, WHO. Geneva, Switzerland. Retrieved from http://www.who.int/globalchange/publications/quantitativerisk-

Weitzman, M. L. (2012). GHG targets as insurance against catastrophic. *Journal of Public Economic Theory*, *14*, 221–244.

Wickham, H. (2007). Reshaping data with the reshape package. *Journal of Statistical Software*, *21*(12), 1–20.

Wickham, H. (2009). *ggplot2: Elegant graphics for data analysis*. New York: Springer-Verlag.

Wickham, H., & Henry, L. (2018). tidyr: Easily tidy data with 'spread()' and 'gather()' functions, r package version 0.8.0.

World Bank (2016). *Climate change action plan 2016–2020, World Bank group reports*. Washington, DC: World Bank.