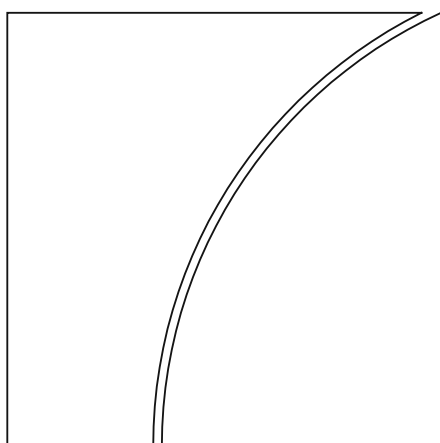


Basel Committee on Banking Supervision



Climate-related risk drivers and their transmission channels

April 2021



BANK FOR INTERNATIONAL SETTLEMENTS

This publication is available on the BIS website (www.bis.org).

© *Bank for International Settlements 2021. All rights reserved. Brief excerpts may be reproduced or translated provided the source is stated.*

ISBN 978-92-9259-472-5 (online)

Contents

Glossaryiv

Executive Summary..... 1

1. Introduction..... 3

2. Climate-related risk drivers 5

 2.1. The evolution of climate-related risks 5

 2.2. Physical risk drivers 6

 2.3. Transition risk drivers 7

 2.4. Uncertainties related to climate risk drivers..... 9

3. Transmission channels 10

 3.1. Usage of traditional financial risk categories to observe risks..... 10

 3.2. Microeconomic transmission channels 11

 3.3. Macroeconomic transmission channels..... 19

4. Geographical heterogeneity, amplifiers and mitigants.....23

 4.1. Geographical heterogeneity.....23

 4.2. Amplifiers26

 4.3. Mitigants27

5. Conclusion32

 5.1. Potential impacts on traditional risk categories32

 5.2. Research across all risk types and increased data availability32

References.....34

Glossary

Acute physical risk	See physical risks
Anthropogenic emissions	Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes, livestock production, fertilisation, waste management and industrial processes.
Basel Framework	The Basel Framework is the full set of standards of the Basel Committee on Banking Supervision (BCBS). As at March 2021 the framework consists of 14 standards as set out at https://www.bis.org/basel_framework/
Business-as-usual (BAU)	A scenario based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted.
Carbon intensity / Emission intensity	Carbon intensity is the amount of carbon dioxide (CO ₂) emissions released per unit of another variable such as gross domestic product (GDP), output energy use or transport. An activity or process is carbon-intensive if it has a high carbon intensity relative to a given benchmark.
Carbon taxation (carbon tax)	A carbon tax (or energy tax) generally refers to a tax levied on the carbon content of some goods and services, typically in the transport and/or energy sectors. The purpose is to reduce CO ₂ emissions by increasing the price of these goods and services. It is one of the main types of tools used in climate change policies around the world.
Chronic physical risk	See physical risks
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate projection	A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised.
Climate-related financial risks	The potential risks that may arise from climate change or from efforts to mitigate climate change, their related impacts and their economic and financial consequences.
Climate sensitivity	The change in the annual global mean surface temperature in response to a change in the atmospheric CO ₂ concentration or other radiative forcing.
Climate vulnerability	Vulnerability is the propensity or predisposition to be adversely affected. It encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. In the context of climate risk drivers, vulnerability refers to the level of damage which can be expected at different levels of intensity of a hazard. For example, when a storm surge hits an area with weak building regulations and few flood mitigation measures, it is more vulnerable to loss compared to an area that has strong flood control infrastructure and strong building regulations. Vulnerability assessments may include secondary impacts such as business interruption.
ESG	ESG (environmental, social and governance) refers to a set of criteria that play a role in the investment decision-making process or in a company's operations. Environmental factors consider how an investment or a company contributes to environmental issues such as climate change and sustainability. Social factors examine the social impacts of an investment or a company on communities. Governance relates to transparency and legal compliance of an investment or a company's operations, for instance in terms of accounting and shareholders' rights.

Feedback loop	An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback loop is one in which the initial perturbation is weakened by the changes it causes; a positive feedback loop is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.
Global mean surface temperature	Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in global mean surface temperature, near-surface air temperatures over both land and oceans are also used.
Global warming	The estimated increase in global mean surface temperature averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.
Greenhouse gases (GHGs)	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 thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H ₂ O), carbon dioxide (CO ₂), nitrous oxide (N ₂ O), methane (CH ₄) and ozone (O ₃) are the primary greenhouse gases in the Earth's atmosphere.
Macro (or macroeconomic) transmission channel	Macroeconomic transmission channels are the mechanisms by which climate risk drivers affect macroeconomic factors, such as labour productivity and economic growth, and how these, in turn, may have an impact on banks through an effect on the economy in which banks operate. Macroeconomic transmission channels also capture the effects on macroeconomic market variables such as risk-free interest rates, inflation, commodities and foreign exchange rates.
Micro (or microeconomic) transmission channel	Mechanism through which climate risk drivers affect banks' individual counterparties, potentially resulting in climate-related financial risk to banks and to the financial system. This includes the direct effects on banks themselves, arising from impacts on their operations and their ability to fund themselves. Microeconomic transmission channels also capture the indirect effects on name-specific financial assets held by banks (eg bonds, single name CDS and equities).
Physical hazard (or hazard)	The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard refers to climate-related physical events or trends or their physical impacts.
Physical risks	Economic costs and financial losses resulting from the increasing severity and frequency of: <ul style="list-style-type: none"> extreme climate change-related weather events (or extreme weather events) such as heatwaves, landslides, floods, wildfires and storms (ie acute physical risks); longer-term gradual shifts of the climate such as changes in precipitation, extreme weather variability, ocean acidification, and rising sea levels and average temperatures (ie chronic physical risks or chronic risks); and indirect effects of climate change such as loss of ecosystem services (eg desertification, water shortage, degradation of soil quality or marine ecology).
Physical risk drivers	Physical risk drivers are the changes in weather and climate mentioned above that lead to physical risks and impacts on economies and banks (eg a flood).
Projection	A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised.
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (eg rate of technological change, prices) and relationships. Scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

Scenario analysis	Scenario analysis is a tool that is used to enhance critical strategic thinking. A key feature of the scenarios analysed is to explore alternatives that may significantly alter the basis for “business-as-usual” assumptions. Accordingly, they need to challenge conventional wisdom about the future.
Stranded asset	Asset that at some time prior to the end of its economic life is no longer able to earn an economic return as a result of changes associated with the transition to a low-carbon economy (adapted from Carbon Tracker).
Stress test	The evaluation of a financial institution’s financial position under a severe but plausible scenario. The term “stress testing” is also used to refer to the mechanics of applying specific individual tests and to the wider environment within which the tests are developed, evaluated and used within the decision-making process.
Tipping point	A level of change in system properties beyond which a system reorganises, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when the global or regional climate changes from one stable state to another stable state.
Transition risks	The risks related to the process of adjustment towards a low-carbon economy.
Transition risk drivers	These drivers represent climate-related changes that could generate, increase or reduce transition risks. They include changes in public sector (generally government) policies, legislation and regulation, changes in technology and changes in market and customer sentiment, each of which has the potential to generate, accelerate, slow or disrupt the transition towards a low-carbon economy.
Transmission channels	The causal chains that explain how climate risk drivers give rise to financial risks that impact banks directly or indirectly through their counterparties, the assets they hold and the economy in which they operate.

Executive summary

This report explores how climate-related financial risks can arise and impact both banks and the banking system. By synthesising existing literature, it illustrates how physical and transition climate risk drivers affect banks' financial risks via micro- and macroeconomic transmission channels. It also explores various factors that may determine the likelihood or size of the impact from climate-related risk drivers. The report's main findings are as follows:

Banks and the banking system are exposed to climate change through macro- and microeconomic transmission channels that arise from two distinct types of climate risk drivers. First, they may suffer from the economic costs and financial losses resulting from the increasing severity and frequency of physical climate risk drivers. Second, as economies seek to reduce carbon dioxide emissions, which make up the vast majority of greenhouse gas (GHG) emissions,¹ these efforts generate transition risk drivers. These arise through changes in government policies, technological developments, or investor and consumer sentiment. They may also generate significant costs and losses for banks and the banking system.

Evidence suggests that the impacts of these risk drivers on banks can be observed through traditional risk categories. The table below summarises the potential effects in each risk type:

Risk	Potential effects of climate risk drivers (physical and transition risks)
Credit risk	Credit risk increases if climate risk drivers reduce borrowers' ability to repay and service debt (income effect) or banks' ability to fully recover the value of a loan in the event of default (wealth effect).
Market risk	Reduction in financial asset values, including the potential to trigger large, sudden and negative price adjustments where climate risk is not yet incorporated into prices. Climate risk could also lead to a breakdown in correlations between assets or a change in market liquidity for particular assets, undermining risk management assumptions.
Liquidity risk	Banks' access to stable sources of funding could be reduced as market conditions change. Climate risk drivers may cause banks' counterparties to draw down deposits and credit lines.
Operational risk	Increasing legal and regulatory compliance risk associated with climate-sensitive investments and businesses.
Reputational risk	Increasing reputational risk to banks based on changing market or consumer sentiment.

Existing literature largely focuses on the impacts of climate risk drivers on those aspects of the economy relevant to banks' credit risk, and to a lesser extent on market risk. There is little work that takes climate risk drivers all the way through to the impact on banks. So far, empirical analysis of realised impacts is largely focused on the wider economic impacts of observed physical risks. Given its forward-looking nature, analysis of transition risks is focused on scenario analysis. To better understand transmission channels going forward, analysis on the realised impact of transition risks on banks across various jurisdictions would be valuable.

This report highlights how the economic and financial market impacts of physical and transition risks can vary according to geography, by sector and by economic and financial system development:

¹ This report essentially focuses on carbon emissions. Carbon dioxide (CO₂) emissions make up about three quarters of all global GHG emissions, with methane (16%), nitrous oxide (6%) and fluorinated gases (2%) making up the remainder. See Center for Climate and Energy Solutions: www.c2es.org/content/international-emissions

- Banks' business models and exposures can increase the severity of any climate-related risk impact. This is because certain economic sectors will have greater sensitivities to acute climate-related physical risks or to the transition to a low-carbon economy;
- Climate-related exposures vary according to the geographic location of a bank and its exposures. This is due to heterogeneity in weather patterns, natural environments, political systems, and consumer sentiment; and,
- Literature suggests that less developed economies are more susceptible to climate risk factors. They might also have lower initial resources to manage resultant losses.

Climate-related events and risks are uncertain, and may be subject to non-linearities.

Physical risks have been categorised into acute and chronic events, and while some aspects of those risks can be predictable, there is increasing uncertainty as to the location, frequency and severity of these events. For transition risks, there is uncertainty as to the future pathways that changes in policies, technology innovation and shifts in consumer sentiment contribute to shaping.

To size climate-related financial risks, banks and regulators require plausible ranges of scenarios to assess the potential impacts of both physical and transition risk drivers on their exposures. These scenarios need to be combined with sufficiently granular data that capture the climate sensitivity of their exposures and are subject to an appropriate methodology as discussed in the companion report *Climate-related financial risks – measurement methodologies*.

There is a limited amount of research and accompanying data that explore how climate risk drivers feed into transmission channels and the financial risks faced by banks. Existing analysis does not generally translate changes in climate-related variables into changes in banks' credit, market, liquidity or operational risk exposures or bank balance sheet losses. Instead, the focus is on how specific climate risk drivers can impact narrowly defined sectors of particular economies, individual markets, or top-down assessments of the macro economy as a whole.

The report concludes that traditional risk categories used by financial institutions and reflected in the Basel Framework can be used to capture climate-related financial risks. To explore this further, a comprehensive analysis could usefully be undertaken on how climate-related financial risks can be incorporated into the existing Basel Framework. Part of the Basel Committee's near-term work would be to identify gaps in the current Basel Framework, where climate-related financial risks may not be sufficiently addressed. This mapping exercise would be comprehensive in nature and could act as a conceptual foundation for the Committee's future work in exploring possible measures to address these gaps where relevant.

A better understanding of risk drivers and their transmission channels across all risk types could be gained from further research by a broader community. In this regard, further work on the impact of climate risk drivers on bank exposures would be valuable. Empirical work to better understand indirect effects would also be informative. Broader steps for data improvements are set out in the companion report on measurement methodologies. To facilitate the research, further steps to improve data availability would be encouraged.

1. Introduction

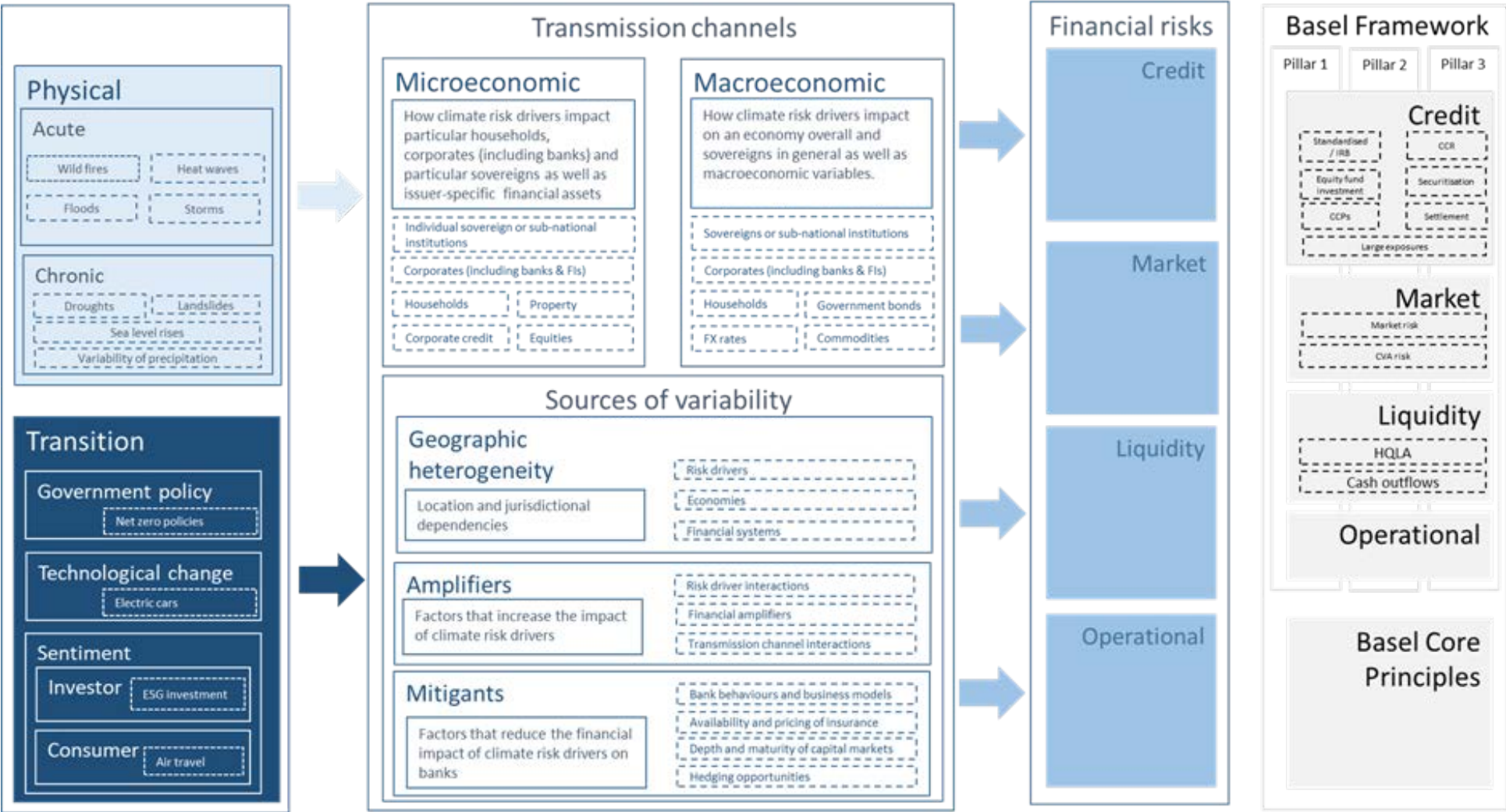
To achieve its mandate,² the Basel Committee on Banking Supervision (BCBS) shares information on developments in the banking sector to help identify current or emerging risks for the global financial system. This includes the potential financial impacts arising from climate change. Climate-related financial risks could impact the safety and soundness of individual financial institutions, giving rise to broader financial stability implications within the banking system (BCBS (2020)). The Basel Committee has established the Task Force on Climate-related Risks (TCFR) to undertake work on climate-related financial risks.

The effects of climate risk drivers on banks' financial risks are complex and existing research exhibits a range of approaches for how they should be studied. Research has largely tended to focus on the impact of climate change on economies rather than on banks. Within the bank-focused research, a number of studies have sought to analyse how climate risk drivers give rise to financial risks. Whilst these approaches differ, they often have similar fundamentals. This report synthesises relevant literature to create a single framework that charts how climate risk drivers can give rise to financial risks in banks (see Figure 1). This framework illustrates how climate-related changes can transmit and translate into banks' financial risks through the following key components:

- **Climate risk drivers** (column 1 in Figure 1): These represent climate-related changes that could give rise to financial risks. They are classified into either physical or transition risks. Physical risks arise from the changes in weather and climate that impact economies. Where relevant, physical risk drivers can also be distinguished between acute physical hazards and chronic physical hazards. Transition risk drivers arise as a result of transitioning an economy that is reliant on fossil fuels to a low-carbon economy. Climate risk drivers are explored in Section 2 of this report.
- **Transmission channels** (column 2 in Figure 1): Transmission channels are the causal chains that explain how climate risk drivers impact banks directly and indirectly through their counterparties, assets, and the economy in which they operate. They are explored in Section 3 of this report.
- **Sources of variability – geographical heterogeneity, amplifiers and mitigants** (column 2 in Figure 1): The likelihood and size of the impact of climate risk drivers can be affected by a number of additional variables. These include: the geographic location of the bank, asset or exposure, interactions and interdependencies between transmission channels and climate risk drivers that can amplify impacts, and mitigants that reduce or offset impacts. Sources of variability are explored in Section 4 of this report.
- **Financial risks** (column 3 in Figure 1): The impact of climate risk drivers on banks is illustrated through examples from the literature in terms of the traditional risk categories of credit, market, liquidity and operational risk. The information on transmission channels in Section 3 reflects this structure.
- **Basel Framework** (column 4 in Figure 1): The Basel Framework provides the backdrop to this work, but this report does not explore how it captures climate-related financial risk. For completeness, the Basel Framework is included to frame the analysis set out in this report.

² See www.bis.org/bcbs/charter.htm.

Figure 1: Financial risks from climate risk drivers



2. Climate-related risk drivers

In order to translate climate change into financial risks, this report introduces the concept of climate risk drivers, the climate-related changes that impact economies. There is broad consensus within literature that climate risk drivers can be grouped into one of two categories:

- Physical risks, which arise from the changes in weather and climate that impact the economy; and
- Transition risks, which arise from the transition to a low-carbon economy.

Climate risk drivers have a number of distinct features, including unprecedented frequencies, speeds and intensities and the non-linear form that the risks are expected to take. Together, these factors give rise to a material level of uncertainty as to how climate risk drivers and their impacts will evolve.

2.1. The evolution of climate-related risks

The observed global mean surface temperature of the Earth has increased by 0.87°C since 1900.³ This progressive increase in global warming is expected to continue and will give rise to changes that will impact all economies.

Scientific analysis suggests that the increase in concentration of GHGs in the atmosphere is extremely likely to be the main cause of this global warming (IPCC (2014)). Furthermore, the warming that results from anthropogenic emissions will persist for centuries to millennia in the absence of any action to reduce them (IPCC (2018)). Scientists therefore recommend that to mitigate global warming and the severity of future impacts of climate change, economies need to reduce GHG emissions by transitioning to a “low-carbon” economy (IPCC (2014)).⁴

The continued anthropogenic emission of GHGs will cause further warming. Extreme temperatures around the mean are likely to increase along with more extreme precipitation events (IPCC (2014)). These physical hazards would further develop over long time horizons and include: rises in sea levels (IPCC (2019)); increases in the variability of precipitation (Allen and Ingram (2002) and Solomon et al (2009)), and consequently higher occurrence of landslides (IPCC (2012)); regional increases in drought trends (IPCC (2018)); more frequent wildfires (Jones et al (2020) and Abatzoglou et al (2019)); higher frequency of extreme temperatures (IPCC (2018)); and recurring and increasingly severe floods (IPCC (2018)).

The transition implied by reducing GHG emissions exposes economies to potential disruptions and shocks. Changes to regulation, technologies and sentiment (both consumer and market) may disrupt different sectors of the economy, especially if they take place abruptly and have not been planned and prepared for in advance.

A recent BCBS stocktake (BCBS (2020)) showed that a majority of jurisdictions did not have an explicit mandate to regard climate-related financial risks. However, they consider that such risks could potentially impact the safety and soundness of individual financial institutions and consequently pose risks

³ The mean global temperature for the decade 2006–15 was estimated at 0.87°C higher than the average over the 1850–1900 period (IPCC (2018)).

⁴ IPCC (2014) views mitigation and adaptation as complementary strategies for reducing the impact of climate-related risks.

to financial stability. Accordingly, some jurisdictions and international organisations have already incorporated climate-related risks into their existing supervisory and regulatory frameworks.⁵

2.2. Physical risk drivers

Physical risk drivers are changes in both weather and climate that impact economies. They can be categorised as acute risks, which are related to extreme weather events, or chronic risks associated with gradual shifts in climate (NGFS (2019a) and McKinsey Global Institute (2020)). These drivers may appear with a significant time lag, and the frequency and severity of each type of risk may also vary considerably and become increasingly difficult to predict. While human activity and decisions affect exposure to physical climate risks, the location, timing and magnitude of specific physical events cannot be controlled.

Global natural disasters, of which almost 60% were meteorological and climatological, resulted in losses of around \$5.2 trillion between 1980 and 2018, and these loss numbers are trending upwards (Munich Re (2020)). Studies such as Hinkel et al (2014), Burke et al (2015) and Dietz et al (2016), together with the recently published scenarios developed by the NGFS (NGFS (2020d)), provide complementary analysis that explores the projected⁶ impact of climate change on economies.

Examples of acute and chronic physical risk drivers that are expected to affect, or currently are affecting (see McKinsey Global Institute (2020)), economies and markets in financial assets are set out below.

Acute physical risk drivers

Acute physical risks are generally considered to consist of: lethal heatwaves, floods, wildfires and storms, including hurricanes, cyclones and typhoons as well as extreme precipitation.

For example, an increase in temperatures around the globe has the potential to generate acute changes in climate through heatwaves and, relatedly, wildfires (Jones et al (2020) and Abatzoglou et al (2019)). There is in turn evidence that this contributes to the spread of forest fires (Abatzoglou and Williams (2016)), causing damage to fauna and to local economies. A warmer atmosphere can hold more moisture, which is expected with high confidence to lead to an increase in heavy and concentrated precipitation in several regions (IPCC (2018)). The increase in the severity of rainfall and its concentration over relatively short periods is expected to produce acute climate events such as destructive flash floods that give rise to physical damages to properties, infrastructure and agriculture. When associated with heatwaves, concentrated rainfalls may increasingly result in periods of severe drought followed by periods of flooding in certain regions. This type of climate impact has the potential to generate, and in some cases has generated, significant and recurring financial losses.

⁵ Examples of climate-related supervisory and regulatory efforts directed at the financial sector include: the establishment of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS); the European Central Bank's *Guide on climate-related and environmental risks*; the launch of the Sustainability Agenda by the Central Bank of Brazil; the announcement by the Bank of Canada and the Office of the Superintendent of Financial Institutions (OSFI) of a pilot project on climate risk scenarios; the Bank of England's microprudential approach; the establishment in Mexico of the Sustainable Finance Committee as part of its Financial System Stability Council; and the establishment of climate work programmes within the Financial Stability Board (FSB) and the BCBS.

⁶ Climate projections use models based on a number of assumptions. For an overview of the types of assumptions used in these projections, see NGFS (2020d).

Chronic physical risk drivers

Chronic physical risks are generally considered to include: rising sea levels, rising average temperatures, and ocean acidification. Extended periods of increased temperatures may lead to the further development of chronic climate events, such as desertification. Similarly, extended periods of increased average temperatures might impact the ecosystem, agriculture in particular.

These changes could result in higher levels of migration and the increased risk of humanitarian crises. The World Bank (2018) estimates that by 2050, in Latin America, South Asia and sub-Saharan Africa about 140 million people could migrate within their own countries from areas with less water availability and reduced crop yields. Another study conducted by the McKinsey Global Institute (2020) projects that under a severe increase in temperature, and without adaptation responses, up to 200 million people in India could live in areas with a chance of experiencing deadly heatwaves.⁷ The IPCC also warns that higher temperatures will accelerate the melting of ice sheets and glaciers, raising sea levels (IPCC (2019)). This may generate endemic (or even permanent) inundations of, and erosion of, coastal cities, islands and low-lying regions.⁸

Physical risks and geographical heterogeneity

Climate change is a global phenomenon, but the way in which physical risks impact economies will vary depending on geographical location as different regions exhibit distinct climate patterns and levels of development. Some regions are therefore expected to be more severely affected than others because they are more exposed and also more vulnerable to specific types of weather disasters.

2.3. Transition risk drivers

Transition risk drivers are the societal changes arising from a transition to a low-carbon economy. They can arise through: changes in public sector policies; innovation and changes in the affordability of existing technologies (eg that make renewable energies cheaper or allow for the removal of atmospheric GHG emissions); or investor and consumer sentiment towards a greener environment. While banks have been impacted by, and have therefore closely monitored, these forms of changes, the expected scale and synchronous nature of transition-related changes have the potential to make the impact much greater than previously anticipated.⁹ Transition risk drivers are global, although the specific nature of the risk driver will vary by economy. Examples of transition risk drivers are summarised below.

Climate policies

As part of the Paris Agreement, the parties agreed to take measures to curb GHG emissions through energy transition policies, pollution control regulation, policies on resource conservation, and public subsidies. In order to achieve the Agreement's goal¹⁰ and pave the way to a low-carbon economy, many

⁷ According to the study, under a severe increase in temperature scenario where no adaptation responses are undertaken, by 2030 between 160 and 200 million Indian people could live in areas where there is a 5% annual probability that heatwaves exceed the survivability threshold for a healthy human being.

⁸ See ec.europa.eu/clima/change/consequences_en

⁹ For example, see Netherlands Bank (2018).

¹⁰ As of January 2020, the Paris Agreement was ratified by 190 countries. The Agreement's goal is to limit global warming to well below 2 – and preferably 1.5 – degrees Celsius, compared to pre-industrial levels. See unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

jurisdictions have established a number of policy initiatives. Some parties have proposed climate-related policies to reduce GHG emissions,¹¹ others have introduced subsidies encouraging the use of electric vehicles, increased energy efficiency standards or reduced or removed fossil fuel subsidies.¹² The aim of these measures is to encourage the transition of the economy, or at least of some of its parts, towards activities that produce fewer GHG emissions, and lower carbon emissions in particular.

Technology

Technology represents another important driver of economic change. Technological change relating to energy-saving, low-carbon transportation, and increasing use of non-fossil fuels or other technologies that help reduce GHG emissions are needed to meet policy goals. However, corporates' existing business models may be based on technologies that are likely to become superseded or on the use of energy sources that may become more expensive as a result of policy measures (whether through higher efficiency standards or through the introduction of carbon taxation). This creates a need for them to adapt to minimise the downside impact and to remain competitive.

Separately, there is the potential for technological developments that improve economic resilience to climate change. These developments, such as improvements in energy storage through battery technology and in climate-resilient infrastructure, are expected to change the way in which households, corporates and sovereigns are impacted by climate change.

Investor sentiment

Equity and debt investor awareness and expectations with respect to climate change are increasing. A growing number of investors are incorporating climate risk considerations into their investment decisions, potentially reflecting growing pressure from non-governmental associations and environmental groups. This can be seen in the asset management business, where some of the world's largest asset managers who provide these investment services¹³ have signalled that they are either incorporating, or intending to incorporate, climate change into their investment approach and decision-making. The risk profile and valuation of debt and equity investments of corporates exposed to climate change will be impacted as investors undertake a reassessment of their investment decisions.

Consumer sentiment

A change in human behaviour is required to transition to an economy with lower carbon emissions. A shift in behaviour to climate-friendly consumption would, for example, create a move to more climate-friendly transportation, manufacturing and energy use. There are signs that such changes in consumer behaviours may be starting to take place.¹⁴ In the banking sector, retail clients may request that their savings or investments be directed towards institutions with more climate-friendly policies or projects with a positive environmental impact. The increased awareness of, and explicit demand for, climate-friendly financial products and investment are a potential trigger for corporates and banks to adjust their business strategies, notwithstanding potential regulatory or supervisory approaches. Conversely, expectation of

¹¹ For a summary, see: www.nationalgeographic.com/environment/2019/09/climate-change-report-card-co2-emissions/.

¹² However, according to the International Energy Agency, global fossil fuel subsidies still amounted to \$320 billion in 2019. See www.iea.org/topics/energy-subsidies.

¹³ For instance, in a letter to its clients in January 2020, BlackRock, the world's largest asset manager with ~\$9 trillion in assets under management, announced initiatives to integrate climate risk into its investment approach. See www.blackrock.com/corporate/investor-relations/2020-blackrock-client-letter. PIMCO, another major asset manager, has publicly disclosed that it uses seven proprietary tools to assess, manage, and help mitigate climate-related risks in its portfolios.

¹⁴ See in particular the results of the Ipsos Survey for the World Economic Forum published in January 2020 at: www.ipsos.com/sites/default/files/ct/news/documents/2020-01/report-global-advisor-climate-change-consumer-behavior-final_2.pdf

physical hazards (eg flooding), climate policies or changes in technologies may result in investors and consumers changing their preferences, with consequent impacts on the value of assets. In this way, climate risk drivers can be impacted by investor and consumer sentiment.

2.4. Uncertainties related to climate risk drivers

Climate risk drivers have a number of features that makes their evolution highly uncertain. These include the following:

- Climate-related changes, and the speed with which they are evolving, are unprecedented in human history to such an extent that very little reliance can be placed upon historical experience to assess their magnitude or to identify patterns. This gives rise to a high level of uncertainty when attempting to assess the magnitude and timing of climate risk drivers;
- Climate risk drivers are also likely to be subject to non-linearities (ie tipping points) that exacerbate uncertainty; and
- The impacts of physical and transition climate risk drivers are geographically diverse.

Given the characteristics above, assessments of climate risks must account for elevated levels of uncertainty, even while there is no uncertainty that climate change is under way (Pindyck (2020)). This uncertainty arises from, but is not limited to, assumptions around future emissions pathways and the impact that these have on physical hazards, interactions between natural systems, future paths of policy, technological advances, and consumer and market sentiment.

3. Transmission channels

Transmission channels are the causal chains linking climate risk drivers to the financial risks faced by banks and the banking sector. They can also be viewed as the way through which climate change might materialise as a source of financial risk (NGFS (2020a)). This section explores these transmission channels, along with examples from the available literature.

This report classifies transmission channels as microeconomic or macroeconomic. This split has been utilised as it better allows for an analysis of banks' financial risks in key areas such as: the direct effect felt by banks; the split between the microeconomic impacts on banks' counterparties and their exposures to financial assets; and indirect macroeconomic effects. These groupings are defined as follows:

- Microeconomic transmission channels include the causal chains by which climate risk drivers affect banks' individual counterparties, potentially resulting in climate-related financial risk to banks and to the financial system. This includes the direct effects on banks themselves, arising from impacts on their operations and their ability to fund themselves. Microeconomic transmission channels also capture the indirect effects on name-specific financial assets held by banks (eg bonds, single-name CDS and equities).
- Macroeconomic transmission channels are the mechanisms by which climate risk drivers affect macroeconomic factors (for example, labour productivity and economic growth) and how these, in turn, may have an impact on banks through an effect on the economy in which banks operate. Macroeconomic transmission channels also capture the effects on macroeconomic market variables such as risk-free interest rates, inflation, commodities and foreign exchange rates.

To demonstrate ways in which risk drivers can impact banks, this section includes illustrative examples taken from the literature. Analysis of examples strongly suggests that climate risk drivers can translate into traditional financial risk categories, rather than representing a new type of risk. This report therefore considers climate-related financial risk under the categories of credit risk, market risk, liquidity risk, operational risk and reputational risk. It does not explore how these risks are captured within the existing Basel Framework.

These examples also help to demonstrate how transmission channels could apply to all global banks. The impact of climate risk drivers on specific financial institutions depends on a variety of factors. These include geographical location, sectoral and geographic concentrations as well as business models. Moreover, the role of amplifiers and the extent to which mitigants are in place will be relevant. These factors are discussed separately in Section 4.

3.1. Usage of traditional financial risk categories to observe risks

Over recent years, a number of institutions have started to explore how climate risks impact banks. Responses from industry participants summarised in Box 1 of the companion report *Climate-related financial risks – measurement methodologies* suggest that there is broad agreement that while climate risks have distinctive elements, they can be reflected through the traditional financial risk categories. Reports from a range of supervisory authorities further suggest that the existing Basel risk categories could also be used to reflect climate-related risks (ACPR (2019); PRA (2018); Netherlands Bank (2018); NGFS (2020b)).

Based on a review of a broad set of examples of how climate risk drivers can impact banks, this report has not found any evidence that would suggest an additional risk category needs to be developed to address banks' climate risks.

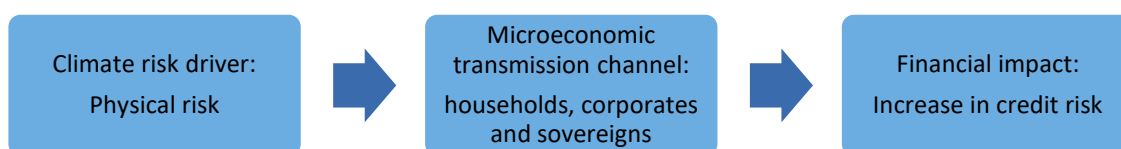
3.2. Microeconomic transmission channels

Microeconomic transmission channels are those that allow climate risk drivers to impact banks' financial risks either directly or indirectly, for example through their counterparties or financial assets. This section summarises how climate risk drivers can affect a bank's credit risk through its counterparties, its market risk through the value of financial assets, its liquidity risk through its deposits, funding costs and drawdowns of credit or liquidity lines and risk to banks' operations. These descriptions focus on the gross risk, the role of mitigants is discussed in Section 4.3.

3.2.1 Credit risk

Climate risk drivers can impact household, corporate, or sovereign income and/or wealth. Physical and transition risk drivers increase a bank's credit risk as soon as they have a negative effect on a borrower's ability to repay and to service debt (the income effect) or on a bank's ability to fully recover the value of a loan in the event of default because the value of any pledged collateral or recoverable value has been reduced (the wealth effect). This credit risk impact takes many forms, which are explored in the examples drawn from the literature.

Physical risk drivers



Physical risk drivers mainly impact banks' credit risk indirectly through their counterparties. The physical capital (housing, inventory, property, equipment or infrastructure¹⁵) of households, corporates and sovereigns can be damaged or destroyed by physical hazards. This damage reduces the value of assets and, consequently, a counterparty's wealth. Physical risk drivers can also negatively impact cash flows of the affected entities as damaged physical capital, such as impaired rental properties and factories, will generate less income.¹⁶ The damage may be caused by acute physical risks, such as tropical storms, and also by chronic physical risks, such as rising sea levels. This section explores examples of how physical climate-related financial risks may crystallise in households, corporates and sovereigns.

Households

Studies that assess the impact of climate risk drivers on households typically focus on wealth effects from damage to real estate caused by acute or chronic physical risks. There is empirical evidence of property value declines resulting from damage caused by severe weather events, or chronic flooding (Bin and Polasky (2004); Ortega and Taspinar (2018)), although the magnitude of the effect, and how long it persists, vary. Moreover, Noth and Schüwer (2018) find that weather-related disaster damage increases the predicted probability of default as well as increasing non-performing asset ratios and lowering bank equity ratios.

For those households exposed to acute flood risk, evidence suggests that severe weather events have an effect on home prices. Banks could face greater losses than anticipated if mortgage customers

¹⁵ Damage to infrastructures is also likely to have knock-on effects as other agents use them as a means for production. OECD (2018), for instance, notes how physical risks may directly impact infrastructure networks. The report mentions the OECD's modelling of a major flood in Paris, showing that 35–85% of business losses would be caused by disruption to the transportation and electricity supply, not by the flood itself.

¹⁶ See, for instance, Collier et al (2020), Koetter et al (2020) and Berg and Schrader (2012).

default and values of collateral are reduced. Bin and Polasky (2004) find evidence of a sudden decrease in the price of homes in floodplains following a severe weather event. Ortega and Taspinar (2018) find that prices for flooded neighbourhoods dropped nearly 20% in New York City after Hurricane Sandy, and three years later, homes in those neighbourhoods were still valued 10% lower than those in unflooded neighbourhoods, suggesting that asset prices can reflect the expectation that severe weather events will continue taking place in these areas.

Sea level rise and repeated flooding could damage property in coastal areas and lead to large devaluations of residential real estate. Banks with residential property as mortgage collateral in impacted regions could see their credit risk increase. Research that forecasts the total cost of sea level rise and chronic flooding to US residential real estate finds that around \$0.5 trillion and \$1.75 trillion in homes will be inundated frequently by 2050 and 2100, respectively (Zillow Research (2019)).

Corporates

Evidence shows that acute physical risks in the form of severe weather events reduce corporate profitability and potentially increase credit risk to lenders. Studies based on historical data find that natural disasters can result in short-term moderate decreases in corporate sales. For example, US corporates have been shown to experience an average drop of 2 to 3 percentage points in sales growth following a major natural disaster that affects their suppliers, ultimately causing a 1% drop in corporates' equity value (Barrot and Sauvagnat (2016)). An extensive body of literature and news articles have documented the impact of natural disasters on global supply chains, often referencing natural disasters in Japan and/or Thailand as case studies (Abe and Ye (2013); Park et al (2013); Bland and Kwong (2011)).

Global supply chains increase the potential for physical risks to impact banks' counterparties. This impact of climate change on corporates across countries is difficult to quantify, given the complexity of the global economic system, data gaps and methodological challenges (Andreoni and Miola (2014)). However, the effects may be significant as developed countries are increasingly reliant on long supply chains and on supplies and services provided by countries vulnerable to climate risk. Companies in the S&P 500 index, for example, own physical assets across 68 countries globally, and 60% of these entities hold assets that are at high risk of at least one type of physical risk (Mattison (2020)).

Chronic physical risks, not necessarily reflected in historical data, are projected to negatively impact corporate credit portfolios primarily through income effects. A number of bank and industry scenario analyses project that incremental climate change, such as rising temperatures, drought and flood risk, may pose a greater risk to the financial health of borrowers than climate-related natural disasters (UNEP-FI (2018a,b)). While severe droughts could increase bank corporate credit risk, the projected impact could vary by sector, geography, and reliance on hydropower (NCFA and GIZ (2017)).¹⁷ The unprecedented nature of these changes increases the importance of climate-relevant data to better understand the ways in which chronic physical risks might impact economies and banks' financial risks.

Studies project that the agricultural sector will be hit by higher temperatures and changes in precipitation, the effects of which will vary by crop and by geographical location. The resultant impacts on profitability could affect creditworthiness. Changes in temperature and precipitation in some countries are projected to drive declines in yields of corn, soybeans and cotton by the end of the 21st century (Schlenker and Roberts (2009)), and the impact on farmland value is predominantly negative under a range of global warming scenarios (Fisher et al (2012)). By contrast, Deschênes and Greenstone (2007) project almost no

¹⁷ Using an analytical tool based on the catastrophe modelling framework used by the insurance industry, a consortium of banks assessed the potential impact of drought on credit quality. The authors projected default rates more than doubling in Brazil, Mexico and China, driven by water-dependent industry such as power generation, water distribution, agriculture, food production and water-intensive manufacturing. In the United States, however, this analysis suggests that drought would lower corporate profitability and drive credit rating downgrades indirectly for certain sectors like petroleum refineries and production, through a reduction in aggregate demand.

potential downside effect of temperature and precipitation on US agricultural yields of corn and soybeans and estimate that US agricultural profits would increase 4% over the long run. This work suggests that details of corporates' climate exposure are important for understanding the ways in which chronic physical effects can impact economies.

Sovereigns and subnational institutions

For sovereigns, the income effects from physical risk events may primarily arise through tax and spending channels. Lower tax revenues may result from impaired corporates, reduced household income and an overall reduction in output. Higher government spending is likely to take place in an effort to address – and partly compensate for – negative economic impacts and cover adaptation costs. As a result, sovereigns, including subnational institutions, could be confronted with higher borrowing costs or limited access to debt markets, increasing the risk of default and the loss-given-default. This in turn could give rise to heightened credit risk within banks' sovereign and municipal exposures.

Analysis suggests that countries more vulnerable to climate change face higher sovereign bond yields and spreads relative to more resilient countries.¹⁸ For example, extreme weather events and chronic physical risks have been shown to restrict some Caribbean governments' access to financial markets, with governments facing worse borrowing conditions when extreme weather becomes more frequent and more intense (Mallucci (2020)).

Transition risk drivers



While governments, consumers, and investors are becoming more cognisant of transition risk, banks have not yet suffered material losses arising from transitioning away from a carbon-intensive economy. Whether these losses will materialise in the future, and to what degree, will be determined by the path of carbon emissions over the coming decades. Empirical evidence of the impacts of transition risk drivers, as with physical risk drivers, is limited. Instead, researchers and supervisors have relied upon scenario analysis to establish the range of these path-dependent economic effects.

Government policy

Corporates may be affected through changes in production, sales and profitability in the transition towards a low-carbon economy (UNEP-FI (2018a)). Current and future expectations of profitability in turn affect creditworthiness. For instance, firms may face higher operating expenses because of a higher tax on GHG emissions. The impact of this tax could reduce earnings and therefore also reduce the corporation's creditworthiness. In turn, this could limit its access to funding and increase the cost of such funding. Additional information on the relative impact of governments' climate policies on corporates' profitability would be useful to better understand this transmission channel.

Increases in credit costs for corporates in certain sectors may curtail their ability to repay outstanding debts to banks. Empirical evidence suggests that the 2015 Paris Agreement resulted in a higher cost of credit for corporates in polluting industries, for example fossil fuel companies (Seltzer et al (2020)); Delis et al (2019)). UNEP-FI estimates that assets associated with the utilities, transportation, agriculture, mining and petroleum sectors are most at risk of suffering climate-related losses, while the

¹⁸ Cevik and Tovar Jalles (2020) find that climate vulnerability has a highly significant positive effect on sovereign bond spreads. This indicates that countries more vulnerable to physical climate risk face higher borrowing costs.

value of manufacturing assets should decline by less but could pose a greater risk to banks' portfolios given their higher portfolio contribution (UNEP-FI (2019)).

Transitions to lower-carbon economies may make extracting a large proportion of fossil fuel reserves uneconomical, creating so-called "stranded assets" that are no longer able to earn an economic return as a result of changes associated with the transition. For example, McGlade and Ekins (2015) suggest that, in order to limit average global warming throughout the 21st century to 2°C above pre-industrial levels, one third of global oil reserves, half of gas reserves and over 80% of coal reserves should remain underground from 2010 to 2050. If countries agree to this objective, corporates that own rights to extract fossil fuel reserves would become vulnerable to significantly reduced values for those reserves on their books. Devaluation of carbon-sensitive assets and the resulting hit to corporate balance sheets and income may increase their propensity to default. Moreover, if the fossil fuel reserve assets are used as collateral for loans, their devaluation could result in a significant reduction in the credit risk mitigation provided by that collateral. Going forward, further information on the impact of stranded assets on banks' balance sheets could help to improve understanding of this transmission channel.

Technological change

Efforts to manage climate change are expected to facilitate technological innovations that enable transition to lower-carbon economies. These could make existing carbon-intensive technologies relatively more expensive if carbon taxes or more stringent regulations are introduced. Consequently, corporates that rely on carbon-intensive technologies may become less competitive if they fail to adopt newer technology. For example, automobile manufacturers who are unable to produce electric vehicles efficiently may suffer from lower profitability in carbon-neutral economies.¹⁹ Banks with exposures to corporates that are unable to successfully adapt to carbon-neutral economies may experience higher credit-related losses. Empirical data that inform on the relationship between technological change and credit risk would be useful to gain a better insight into this transmission channel.

Sentiment

Transitioning to lower-carbon economies may also trigger shifts of consumer and market sentiment to less carbon-intensive products or investments. One possible way such shifts could manifest is through rising expectations of detrimental future climate events making individuals more aware of climate change as physical risks materialise. Consequently, they may act in ways that would contribute to reducing the impact of climate change. For example, in the automobile industry, consumers may increasingly prefer cars with lower GHG emissions. As a result, traditional automobile manufacturers who continue to produce high GHG emission cars may see the future of their brands compromised, regardless of regulatory or technical initiatives. Additional research on the income and wealth effects of sentiment on corporates would help to enhance understanding of the nature of this transmission channel.

Stakeholder sentiment and action is a potentially important transition climate risk driver for households, corporates and sovereigns. Activist measures, changes in consumption patterns or consumer awareness and behaviour may drive corporates, including banks, towards more environmentally friendly business, production or investment models. For banks in particular, retail and wholesale clients may manage their savings or investments – or require that these be managed on their behalf – towards projects with a positive environmental impact. As noted above, cost of capital and funding for some corporates may increase as equity and debt investors and rating agencies include climate-related or environmental factors in their investment and rating decisions. Rating agencies have already initiated negative rating actions in response to climate risk factors such as drought and hurricane losses (S&P Global (2018)).

¹⁹ The United Kingdom, for example, has announced a ban on the sale of new gasoline and diesel cars beyond 2030 in an effort to transition to a carbon-neutral economy.

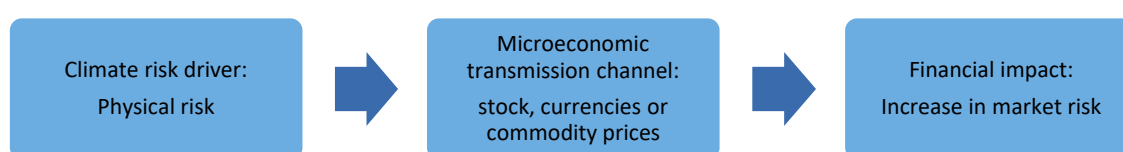
There is evidence of shifting market preferences affecting firms' funding conditions. For instance, the Principles for Responsible Investment (PRI), a United Nations-supported international network of investors who aim to incorporate environmental, social and governance (ESG) factors into investment, was launched in April 2006. The number of signatories has been increasing since and has, at the time of writing, reached more than 3,000. Rising environmental awareness has also led many institutional investors to divest from firms and projects with environmental concerns.²⁰ Some of the literature suggests that certain investors take into account carbon emissions when providing funding to firms.²¹ Higher costs associated with climate regulation changes could dampen firms' profitability and eventually increase banks' credit risks.

Both corporates and governments may face higher litigation costs, for example where they are perceived to have caused environmental harm. These increased expenses could result in a deterioration in credit quality of assets held by banks. A notable recent example of this is the bankruptcy of PG&E, a gas and power company which was judged liable for wildfires in California linked to its equipment (Baker and Roston (2019)). Overall, climate change lawsuits, particularly against governments and fossil fuel producers, have increased in recent years in both the number of cases and the number of countries where cases have been filed (UNEP (2017)). In total, more than 1,500 cases of climate litigation were brought between 1986 and May 2020: 1,213 cases in the United States and 374 in 36 other countries and eight regional or international jurisdictions, mostly notably Australia, the United Kingdom and EU bodies and courts (Setzer and Byrnes (2020)).²² Successful litigation against banks' counterparties has a wealth effect that could elevate credit risk through increases in the client's loss-given-default or by precipitating default itself to the extent that the counterparty may no longer be able to meet its payments as and when due.

3.2.2 Market risk

Climate risk drivers can have a significant impact on the value of financial assets. Specifically, physical and transition risks can alter or reveal new information about future economic conditions or the value of real or financial assets, resulting in downward price shocks and an increase in market volatility in traded assets. Climate risk could also lead to a breakdown in correlations between assets, reducing the effectiveness of hedges and challenging banks' abilities to actively manage their risks. However, where climate risk is already priced in, the potential for unexpected price movements may be reduced.

Physical risk



Uncertainty about the timing, intensity and location of future severe weather events and other natural disasters may lead to higher volatility in financial markets. Analysis of the impact of physical risks on financial markets is limited. However, Wachter (2013) shows that the risk of a consumption shock similar to one following a natural disaster explains high levels of stock price volatility. Kruttli et al (2019) show that stock options of firms located in the forecasted trajectory or eventual landfall region of a hurricane experience an increase in implied volatility. There is little research on the impact of physical risk drivers on

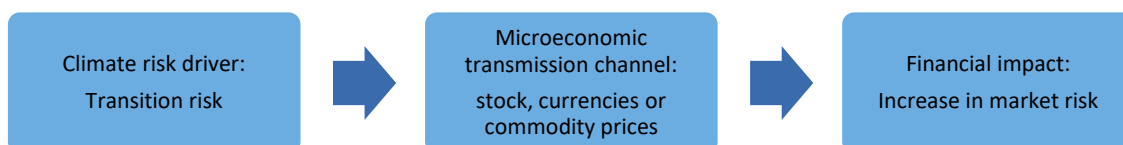
²⁰ See, for instance, FT (2019).

²¹ See, for instance, Hsu et al (2020), Bolton and Kacperczyk (2020).

²² "Climate change litigation" here means judicial cases and targeted adjudications involving climate change presented to administrative entities and a few international bodies; it does not include commercial disputes.

other aspects of capital markets and further work, including considerations of how physical risk impacts property-related securities, would be welcomed.

Transition risk



Transition-related changes in official sector policy, technological advances and investor sentiment could lead to changes in borrowing costs and an abrupt repricing of financial assets. Investors in financial markets could reward borrowers they believe will be resilient through, or may stand to gain from, the transition away from a carbon-intensive economy. At the same time, investors could increase the risk premia they demand from carbon-intensive borrowers. However, work performed by academics and financial institutions to analyse potential risk differentials between assets that are more or less sensitive to transition risks is limited and is generally inconclusive.²³

Analyses of overall transition-related losses on financial assets give rise to a range of estimates. The commonality across these estimates is the materiality of the expected outcomes that could give rise to a downside wealth effect. To illustrate this:

- UNEP-FI considered a portfolio of 30,000 listed companies under a 1.5°C scenario by 2100, and estimated that the portfolio could lose 13.16% of its value as a result of the transition to a low-carbon economy (UNEP-FI (2019));
- Dietz et al (2016) analysed a representative path to 2100, within which emission reductions limit global mean temperature increases to no more than 2°C at all times. Under this path, the 99th percentile climate value-at-risk would represent 9.2% of global financial assets.²⁴

Holding periods for banks' financial assets are short compared to the time horizons over which transition-related effects are projected to crystallise. This might affect the impact of climate risk drivers on market valuations. Financial assets used as financial collateral may indirectly expose banks to climate risk drivers over longer time horizons. Further work on climate risk drivers' impacts on price as well as market liquidity would be useful.

Pricing-in and management of climate risks within markets

Markets that price in climate risk may be less sensitive to abrupt climate-related price shifts in the future following severe weather events or a rapid transition to a less carbon-intensive economy. Evidence described below suggests that the prices of municipal bonds, corporate debt and some equities have begun to reflect transition risk. Market pricing, however, may be hampered by a lack of consistent methodologies, standardised metrics, and comparable disclosures around climate risk (Giuzio et al (2019)). Further work is needed to better understand the extent to which climate risk is priced into fixed income and equity markets, as well as how sensitive banks' market risk is to abrupt changes arising from climate-

²³ NGFS (2020c).

²⁴ Note that according to this analysis losses under a business-as-usual scenario – corresponding to an expected increase in global mean surface temperature of 2.5°C in 2100 – are higher, at 16.9% of global financial assets.

related information. The section below summarises existing empirical work to quantify the extent to which climate risks are already priced into assets.

Where researchers have found some evidence of municipal bonds pricing in climate change, the effects are generally small, and specific to longer-maturity bonds. Painter (2020) finds that municipal bonds issued by US counties exposed to climate risk require higher initial yields compared to counties unlikely to be affected by climate change, and that results are driven by lower-rated bonds.²⁵ However, Painter finds no significant differences between short-term municipal bonds with differing exposure to climate risk. Goldsmith-Pinkham et al (2021) find statistically significant but small differences in yields on municipal bonds exposed to sea level rise, particularly on the east coast of the United States, after 2013.²⁶

There is mixed evidence, with some suggesting that financial markets may be beginning to price in transition risks for corporates. For example, evidence suggests that the cost of option protection against downside tail risks is larger for firms with more carbon-intensive business models, and this is magnified when the public's attention to climate change spikes (Ilhan et al (2020)). Evidence also suggests that the market is currently starting to penalise oil exploration firms in the United States for growing their undeveloped oil reserves and tends to discount their future value, therefore suggesting that these investments are expected to have lower returns than existing production or even that they may not be expected to pay off over the long run (Atanasova and Schwartz (2019)). Analysis by the BlackRock Investment Institute (2019), however, suggests that investors in general do not require a climate risk premium for municipal bonds.

While some studies seem to indicate that equity prices for some corporates with carbon-intensive activities may partially reflect climate risk, there is little empirical evidence to confirm that climate risk is priced in more broadly. Bolton and Kacperczyk (2020) find that equities of higher-emitting corporates earn higher returns, after controlling for several return-predictive factors. The carbon premium cannot be explained through differences in unexpected profitability or other known risk factors, suggesting that investors may already be demanding compensation for their exposure to these carbon-intensive companies. The IMF (2020) found that the impact of large disasters on equity markets, bank stocks and non-life insurance stocks has been modest over the past 50 years, and that in the aggregate, market-implied equity risk premiums as observed in 2019 did not reflect predicted changes in physical risk under various climate change scenarios, suggesting that investors were not factoring the effects of climate change into asset pricing. Further research on the extent to which climate change is incorporated into equity prices on a forward-looking basis is necessary.

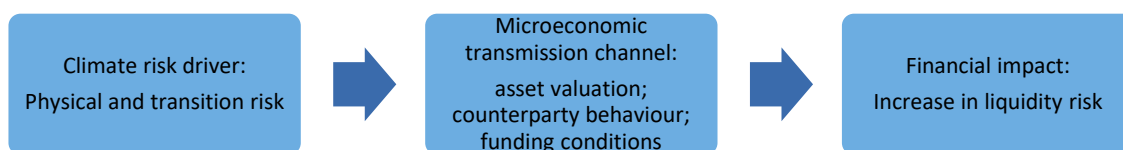
Some studies find evidence that flood risks and rises in sea levels may already be partially priced into selected residential real estate valuations. Bernstein et al (2019) report that some US properties exposed to sea level rise currently sell with a 7% discount, and this discount is driven by sophisticated buyers in communities concerned about global warming. Baldauf et al (2020) come to similar empirical estimates and present a theoretical model that can explain differences in the discount given sea level rise for properties in communities that believe in climate change versus communities that do not. Hallstrom and Smith (2005) find that households update their expectations following exposure to climate event news, and that even a "near miss" hurricane can lead to reductions in prices. However, Murfin and Spiegel (2020), using a methodology that accounts for the variation in the expected time to inundation due to sea level rise for a selected set of residential real estate properties of similar elevation and distance from the coast, find no effect of sea level rise risk being priced into residential real estate valuations.

²⁵ The paper's measure of climate risk uses US cities' expected mean loss from sea level rise as a percentage of GDP. It finds that a 1% increase in climate risk is associated with a 33.3 basis point increase in the total annualised issuance cost of a bond, significant at the 1% level. This represents a 7.1% increase from the mean annualised issuance cost.

²⁶ The paper's estimates imply that a 10 percentage point increase in the fraction of properties exposed to sea level rise is accompanied by a 2 basis point (~3%) increase in municipal bond credit spreads after 2013.

Banks typically manage market risk and limit their exposure to systemic shocks based on historical data. However, the unprecedented nature of climate risk drivers and the opacity of climate-vulnerable exposures makes asset mispricing and the risk of downward price shocks particularly salient. It is currently unclear if, how and to what extent markets price in climate risks when determining the market value of a financial asset. It is also unclear how banks' market risk is affected by the extent to which climate risk is priced into the asset value. In both cases, more research would be both useful and necessary. There is also a lack of information on the extent to which banks' market risk management assumptions could be undermined by the impact of climate risk drivers. For example, banks make assumptions about asset price correlations when hedging with similar, but not equivalent, positions. Moreover, assumptions about the market liquidity of financial assets used to hedge positions are also made. There is limited information on the effect of climate change on these assumptions and further research would be welcome.

3.2.3 Liquidity risk



Climate risk drivers may impact banks' liquidity risk directly, through their ability to raise funds or liquidate assets, or indirectly through customers' demands for liquidity. There is little research on the direct impact of climate risk drivers on banks' liquidity but some related work exists on the indirect impact of natural disasters.

There is some evidence that natural disasters can lead to liquidity risk within banks. These effects could impact the ability of a bank to fund increases in its assets and meet obligations as they come due without incurring unacceptable losses. Available research focuses on physical risk-related liquidity risk, and there is limited analysis of the potential effects of transition risk drivers on banks' liquidity risk. Further research on the effects of climate risk drivers on banks' liquidity risk would be welcomed.

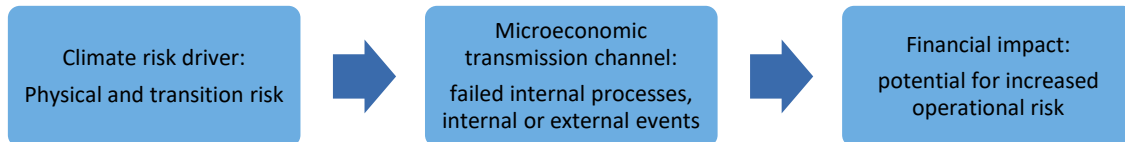
Some evidence suggests that post-disaster lending has a significant and negative effect on liquidity buffers. Severe natural disasters can trigger a sharp increase in precautionary demand for liquidity by financial institutions, households and corporates and the central bank may have to intervene in order to preserve financial stability. After the Great East Japan Earthquake in March 2011, the Bank of Japan (BoJ) offered record amounts of liquidity to Japanese banks to ensure stability in the markets. On the first business day after the earthquake, the BoJ offered funds totalling 21.8 trillion yen, a record high in terms of daily offer equivalent to nearly three times the maximum daily liquidity during the 2007–09 financial crisis. The BoJ continued to provide ample liquidity after the earthquake, and within a month the outstanding balance of current accounts at the BoJ had reached a record high of 42.6 trillion yen (BoJ (2011)). In a separate analysis, Koetter et al (2020) use bank-level data to isolate risk and return implications for two sets of banks located in different German counties. One set was domiciled in regions affected by the 2013 Elbe river flood and the other was not. Both sets of banks increased their lending to counterparties in flood-affected areas, albeit by different amounts. The authors find a negative effect on liquidity buffers for both sets of banks, with the effect persisting during the two years following the flood. This finding highlights the importance of liquidity buffers in absorbing local shocks and puts into context observed bank behaviours in the face of severe natural disasters.

Physical risks to banks' counterparties may have impacts on banks' liquidity. If households and corporates affected by physical risks need liquidity to finance recovery and other cash flow needs, they may withdraw deposits or draw on credit lines. These withdrawals could put the bank's own liquidity under pressure and lead to crystallised liquidity risks within banks. Brei et al (2019) find that the banks in their study faced deposit withdrawals following a hurricane in the Caribbean, but Steindl and Weinrobe (1983) find the opposite: an increase of deposits following natural disasters in the United States. While studies

have analysed the effects of transition risks on the liquidity and funding of corporates, the subsequent effect on bank liquidity has not been studied.

Whilst the above examples of behaviours in response to severe natural disasters may be valuable in aiding understanding of climate-related liquidity risk, they also demonstrate the need for further research in this area.

3.2.4 Operational and reputational risk



Operational risk is defined in the Basel capital Framework as the risk of loss resulting from inadequate or failed internal processes, people and systems or from external events. This definition includes legal risk, but excludes strategic and reputational risk. Where appropriate, strategic and reputational risks should be considered by banks' operational risk management.²⁷

Physical hazards can affect banks directly as operational risks. There is little public research on the operational risks faced by banks and arising from physical risk drivers, but there are parallels to be found in other natural disasters. For instance, if physical hazards disrupt transportation facilities and telecommunications infrastructure, banks' operational ability may be reduced.²⁸

Corporates, as well as banks, may also be exposed to an increasing legal and regulatory compliance risk as well as litigation and liability costs associated with climate-sensitive investments and businesses. Furthermore, climate-related lawsuits could target corporations, as well as banks, for past environmental conduct whilst seeking to direct future conduct. For example, climatic changes caused prolonged droughts in California that increased the risk of fires from the operations of PG&E. The company estimated the cost of settlements to claimants in excess of \$13 billion.²⁹ Indirect reputational risks may also arise for banks providing financing to corporates or activities that are held responsible for negative climate impacts (Migliorelli and Dessertine (2020)).

Publicly available information regarding climate-related operational risks is scarcer than for other risk types, and therefore the whole risk category would benefit from more data and research. Relevant information is most likely to be held by banks themselves. In particular, banks may be required to record information relevant to understanding the "damage to physical assets" from natural disaster losses and "business disruption and system failures" arising from utility outage/disruptions. Studies quantifying operational risk faced by banks as a result of climate risk drivers are extremely limited, and are rarely made public.

3.3. Macroeconomic transmission channels

The previous sections on microeconomic transmission channels provide examples of ways in which climate risk drivers can impact banks both directly and indirectly through their exposures to counterparties and financial assets. Banks can also be affected indirectly through the effect of climate risk drivers on the

²⁷ See <https://www.bis.org/bcbs/publ/d515.pdf>

²⁸ Hosono et al (2016), using data from the 2011 Tōhoku earthquake in Japan, find that firms outside the earthquake area that borrowed from banks in affected regions faced borrowing constraints possibly due to the banks' operational constraints (eg managerial capacity to process loans). This example provides a concrete illustration of how physical destruction events may lead to operational risks for banks.

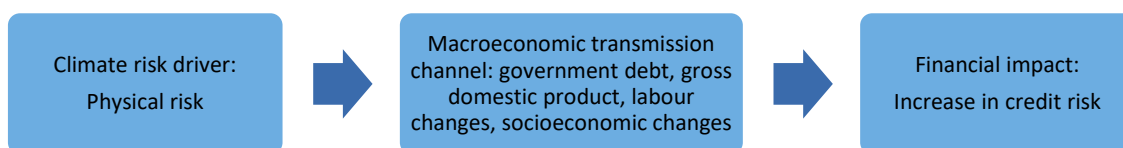
²⁹ See www.bloomberg.com/news/articles/2019-12-07/pg-e-reaches-13-5-billion-settlement-with-wildfire-victims

economy. Evidence at a country level is limited, but work on regional impacts provides insights into potential effects. This section includes some key examples identified in the literature.

The following largely focuses on credit and market risk, where the macroeconomic impacts are expected to be the greatest. Impacts from liquidity and operational risks could also occur, but there is currently very limited research exploring this. Further investigations, which would draw out the connections between climate-related macroeconomic changes and banks' financial risks, would be useful to better understand the macroeconomic transmission channels. Research into knock-on effects of climate-related sovereign downgrades on banks' and bank counterparties' credit ratings would be of particular interest.

3.3.1 Credit risk

Physical risk drivers



Climate-related increases in human mortality and declines in labour productivity are projected to be key drivers of reductions in output. Carleton and Hsiang (2016) quantify climatic influence on economies and find evidence that increases in temperature adversely impact mortality, morbidity, agricultural yields, labour supply, and productivity. Hsiang et al (2017) find that, in aggregate, the greatest direct cost in the United States for global mean surface temperature changes larger than 2.5°C is the burden of excess mortality, followed by changes in labour supply, energy demand and agricultural production. Reductions in labour productivity from climate change could result in a global economic cost of more than \$2 trillion by 2030 and a decrease in output of over 30% in the second half of the 21st century (Kjellstrom et al (2016); UNDP (2016)). Further research to map these projected effects and their impact on banks' credit risk would be useful to better understand this transmission channel.

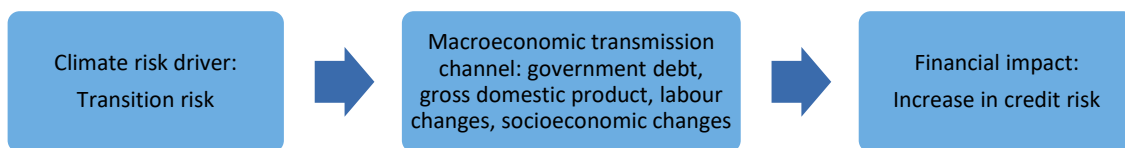
The cost of recovery following a natural disaster can be significant, particularly for poorer municipalities. Hsiang et al (2017) project that the poorest third of US counties will experience damages of up to 20% of county income as a result of climate change under a business-as-usual carbon emissions scenario. In addition to the costs inflicted by physical damages, evidence suggests that exposure to climate risk can increase local government borrowing costs. US counties that are more likely to be affected by climate change pay more in underwriting fees and initial yields for their bonds (Painter (2020)), as a higher likelihood of large negative shocks impacts their repayment capacity. A one standard deviation increase in sea level rise exposure is associated with a 2 to 5% decline in the present value of cash flows supporting debt repayment for municipal bonds (Goldsmith-Pinkham et al (2021)). In some cases, these dynamics might be expected to hold at the sovereign level as well.

The effect of climate change on economic growth appears to be more pronounced in developing countries. Empirical evidence suggests that exposure to climate risk has raised the average cost of debt by 117 basis points in a sampling of developing countries, translating into more than \$40 billion in additional interest payments on government debt over the past 10 years (Buhr et al (2018)). Increased borrowing costs could lead to higher taxes, lower government spending and reduced economic activity, which may indirectly impact banks' credit risk. Dell et al (2012) also find evidence that, in poorer countries, an increase of 1°C in a given year reduces economic growth in that year by 1.3 percentage points. In rich countries, however, changes in temperature do not have a robust, discernible effect on growth. Diffenbaugh and Burke (2019) posit that climate change has already driven substantial declines in economic output in hotter, poorer countries and increases in economic output in cooler, wealthier countries. The contrast is more apparent when looking at the 10 largest disasters between 1970 and 2018. While emerging markets incurred damages between 2.9 and 10.1% of gross domestic product (GDP),

advanced economies experienced damages equivalent to 1–3.2% of GDP (IMF (2020)). These reductions in GDP may impact the country-level assessment of credit risk by banks.

There is evidence that climate change leads to socioeconomic changes that could impact economic growth, although the size of these impacts is especially difficult to quantify. Studies show that changes in the climate, including extreme weather, sea level rise, drought and desertification, can deplete resources or cause damages that can lead to an increase in violent conflicts (Hsiang et al (2013)), a substantial relocation of households out of an affected area (Deryugina et al (2018)) or mass migration (Tacoli (2009); McLeman and Smit (2006); and Barbieri et al (2010)). These socioeconomic changes could affect banks indirectly, by driving changes in economic growth and the macroeconomic environment, and ultimately impacting borrower creditworthiness.

Transition risk drivers



A global shift away from fossil fuels to meet the targets of the Paris climate accords is projected to result in the majority of fossil fuel reserves (around 80%) becoming stranded resources, including as much as 90% of Africa’s coal reserves, implying material losses for many countries (Bos and Gupta (2019)). Such a shift could have significant implications for government revenues and spending in some of the poorest countries reliant on fossil fuel revenues. Climate-related income effects on sovereigns could hamper their ability to service their debts, in turn impacting the value of their bonds, their credit ratings and the credit ratings of those institutions associated with the sovereign. In turn, this is expected to increase the credit risk of banks facing these counterparties.

As noted above, transition risk drivers can affect the income of banks’ counterparties, which, in aggregate, could have macroeconomic effects. For example, the income effect could result from carbon emission taxes, increased prices in carbon-intensive supply chains or changed consumer preferences. Higher costs of production reduce profitability, which lowers investment and equity prices. Firms could respond to higher production costs by raising prices, in turn curtailing household disposable income and lowering consumption. The combination of lower consumption and investment reduces GDP. Households could then suffer diminished income, as a result of slower GDP growth or higher unemployment due to structural shifts in the economy caused by climate change impacts or mitigation efforts. A contraction in households’ wealth and income could lead to a deterioration in their ability to service their debts, increasing the credit risk of their banks.

3.3.2 Market risk

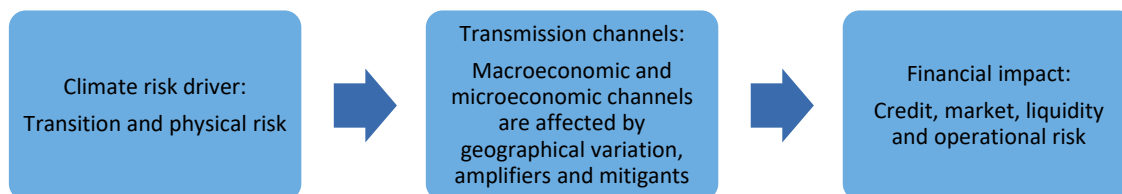
There is little research that seeks to make a connection between macroeconomic effects and banks’ climate-related market risk. The distinction between microeconomic and macroeconomic transmission channels is less pronounced when analysing markets for other risks. As a result, some of the examples set out in the microeconomic section above have elements of macroeconomic channels within them. For example, changes in asset values may be driven by a policy change that affects an individual borrower, or by the effect that policy change may have on the economy more broadly.

Some specific research exists, for example analysis that suggests that sovereigns exposed to physical risk drivers may find their access to debt markets restricted or that their borrowing costs have increased. These studies have focused on the extent to which physical risk drivers can impact a country’s fiscal position and possibly trigger sovereign defaults. In particular, Mallucci (2020) analyses a sample of seven Caribbean countries hit frequently by hurricanes and shows that extreme weather events and chronic physical risks restrict governments’ access to financial markets. Rises in sovereign risk and perceived

deterioration in the creditworthiness of the sovereign may affect home banks through losses on holdings of government debt; by reducing the value of collateral that banks can use to secure funding and access liquidity; or by driving rating downgrades and thereby increasing banks' wholesale funding costs.

The relative absence of research on how macroeconomic channels impact market risk may suggest that this is an area where more analysis would be valuable.

4. Geographical heterogeneity, amplifiers and mitigants



While climate risk drivers may impact banks through transmission channels, several different factors may determine the likelihood or the size of the impact from both physical and transition risk drivers. These factors include geographical heterogeneity, amplifiers and mitigants. Further analysis and research into these factors would help increase understanding of how risk drivers impact banks' financial risks.

Variation in the effects of climate risk drivers may arise from their geographic location, from the nature of banks' particular businesses, and from exposures to particular sectors and counterparties. Studies suggest that the economic and financial market impacts of both physical and transition risks vary significantly by geography, by sector and by jurisdiction.

A large body of research provides evidence of differentiation in risk outcomes both across and within countries and sectors. These differences can be driven by a broad set of geographic factors, from variances in weather patterns through to differences in political systems. The range of outcomes is also driven by differences in the structure of local economies and financial systems, which determine the size and nature of the channels through which climate risk drivers transmit to the banking system.

The effects of climate change may be amplified by interactions between different climate risk drivers, between different transmission channels and the climate-related aspects of amplification arising from the financial system itself. Understanding of the nature and materiality of these effects remains relatively limited.

Banks may also use mitigating actions to reduce financial risks. Financial mitigants can reduce or offset banks' exposure to climate-related financial risks but their reliability, efficacy and cost are highly uncertain. There are a wide range of mitigants that include: changes in bank behaviour and business models; the availability and price of insurance; and the depth and maturity of capital markets, including opportunities for securitisation.

4.1. Geographical heterogeneity

While the microeconomic and macroeconomic transmission channels described in Section 3 may be applicable to all banks, the extent to which individual banks are exposed to particular transmission channels varies significantly across and within geographies. Geographical heterogeneity is driven by several factors: differences in the likelihood and severity of climate risk drivers themselves; structural differences in economies and markets that affect the relative importance of various transmission channels; and differences in financial systems that may impact banks' exposures to climate-related risks. These drivers of geographical heterogeneity are explored below.

The wide variation in climate-related financial risks across and within jurisdictions highlights the importance of granular information and bottom-up analysis, in conjunction with top-down approaches, to better understand and assess bank exposures to climate-related financial risk. Banks with similar portfolios may face very different levels of climate-related financial risks depending on where those assets – and the banks themselves – are located. This geographic heterogeneity creates a need for more granular information to better quantify climate-related financial risks.

4.1.1 Geographical heterogeneity of climate risk drivers

As average global temperatures rise, the incidence and severity of physical hazards, both acute and chronic, are very likely to increase. Variations in climate systems result in large and widespread differences in temperature changes across locations (IPCC (2014, Chapter 21)). Differences in factors such as geographical location, topography and proximity to water mean some regions are expected to experience more severe storms, more frequent droughts or greater and more concentrated precipitation in response to rising temperatures. Chronic physical risk events are also more prevalent in certain regions. This heterogeneity in physical risk drivers translates into elevated levels of climate-related financial risks for banks operating in higher-risk areas. Analysis has suggested that since the 1950s, as a result of climate change, southern Europe has experienced longer, more intense droughts (Vicente-Serrano et al (2014)); and the Caribbean and East Asian and Pacific region countries, many of which are island nations, are particularly vulnerable to sea level rises (Dasgupta (2018)). Analysis suggests that Puerto Rico, Myanmar and Haiti were the countries most affected by extreme weather events in the 20-year period from 1999 to 2018 (Germanwatch (2020)).³⁰

Similarly, countries, regions and sectors are exposed to different levels of transition risk depending on the likelihood of policy action, technological innovation or broad shifts in sentiment within a particular jurisdiction. The speed and nature of transition within a country will reflect the idiosyncratic characteristics of that jurisdiction, including its political system and institutions, economic system and energy mix. Jurisdictions that take early action to facilitate the transition to a low-carbon economy may be less susceptible to an abrupt shift at a later date (ESRB (2016)). Moreover, the likelihood of an abrupt transition may depend in part on the severity and frequency of physical risk events in a particular location. Differences in the likelihood of a policy shift, technological innovation or shift in sentiment across geographies are not widely discussed in the available literature due to the limitations of historical data from which to draw and as the evolution of transition risk drivers is uncertain.

4.1.2 Geographic heterogeneity in economic and market structure

The structure of a country's economy and financial markets influences its sensitivity to physical and transition risks. Even when exposed to similar climate risk drivers, countries may experience disparate microeconomic and macroeconomic consequences driven largely by differences in economic policies, economic and financial systems and insurance availability. More comparative analysis on differences in the impact of climate risks arising from variations in economies and market structure would inform our understanding of transmission channels.

As highlighted below, the overall effect of climate change on economic growth appears to be dependent on a country's economic structure. Climate vulnerability is due to multiple factors – including a tendency towards higher initial temperatures and more frequent physical hazards, as well as economic systems that are less resilient³¹ to the impact of climate change. The IMF finds evidence that emerging market and developing economies have been hit much harder by climatic disasters than advanced economies, suffering almost twice as much damage relative to the size of their economies over recent decades.

Differences in economic and social policies across and within countries may drive variation in the economic impact of climate risk drivers. Studies have illustrated that country characteristics, including economic and structural policies, can mitigate to some extent the negative relationship between temperature shocks and output. For example, Mejia et al (2019) find that low public debt to GDP, foreign aid and remittances may help in the short run, while exchange rate flexibility, high financial sector

³⁰ Puerto Rico is not an independent nation state but an unincorporated territory of the United States. It is considered separately for this analysis.

³¹ Financial resilience is measured by insurance penetration and sovereign financial strength in IMF (2020).

liberalisation, good infrastructure and low inequality tend to help mitigate the impact of temperature shocks on output over the long run.

Variations in the economic impact of climate risk drivers may also be driven by differences in sectoral concentration across and within countries. As noted in previous sections, studies that quantify climatic influence on societies and economies find evidence that increases in temperature adversely impact mortality, morbidity, labour supply and productivity (Carleton and Hsiang (2016); Hsiang et al (2017)). This suggests that countries that are highly dependent on labour-intensive industries and/or outdoor activities, for example, may face greater economic consequences as a result of an increase in temperatures. Higher global temperatures are also expected to have an outsize impact on agriculture and tourism, resulting in larger adverse effects in countries with activity concentrated in these sectors, while transition risk drivers may have an outsize impact on economies that are heavily reliant on the production of fossil fuels.

The availability of insurance varies significantly across countries and may contribute to variation in the economic impact of climate risk drivers. The role of insurance in dampening the income and balance sheet effects of physical hazards on bank counterparties is discussed separately in this section. However, insurance coverage of natural disaster risk varies greatly across countries and within certain countries.

4.1.3 Geographic heterogeneity in financial systems

Differences in the structure of financial systems across and within countries have the potential to contribute to geographical heterogeneity in climate-related financial risk. Differences in the structure of a country's banking system as well as the maturity of capital markets may impact a bank's exposure to climate-related risks and its ability to transfer or offset that risk. More analysis on the role that different financial systems play in banks' climate-related financial risks would increase understanding of transmission channels.

Empirical evidence suggests that the structure of the banking sector within individual jurisdictions has implications for the impact of climate risk drivers on banks' credit risk. Where small, local banks account for a greater share of the banking sector than large banks, banks are more likely to increase credit exposures to retail and corporate borrowers in affected areas following a severe weather event. In this way they play an important role in the economic recovery from natural disasters (Chavaz (2016); Cortés and Strahan (2017); Koetter et al (2020)). Whilst it is not clear that recovery lending necessarily increases bank credit risk (Koetter et al (2020)), it could increase concentration risk especially when the additional lending is directed to a small number of specific sectors. At the same time, local banks in the United States are more likely than diversified banks to securitise climate-exposed assets, ultimately reallocating credit to agents with various degrees of diversification (Chavaz (2016)). These differences in small and large bank behaviour could be salient for countries that host robust small bank sectors and further work in this area would be welcome.

Well developed capital markets may allow market participants to effectively price climate-related financial risks and/or to transfer them to third parties. Capital markets differ substantially across jurisdictions in terms of development, depth, breadth and liquidity. While developed countries tend to have financial markets that are more or less liquid and a range of instruments that allow investors to hedge their risk exposure, financial markets in developing countries can be substantially less liquid (Lesmond (2005), Domowitz et al (2001)). The research presented here is predominantly focused on capital markets in developed countries, particularly the United States, which is the most liquid of all. However, conclusions can differ significantly across countries that have less developed capital markets. Further, capital markets across jurisdictions vary greatly in terms of how developed their derivatives markets are. A derivatives market is crucial to hedging climate change risks affecting corporations or commodities (and agricultural commodities in particular). There is evidence that some derivatives markets in the United States are sensitive to transition risks (see Ilhan et al (2020), who show that the US options market is sensitive to climate regulation uncertainty) and physical risks (see Kruttli et al (2019), who show that stock options are sensitive to hurricane forecasts). This suggests that investors are starting to explore how they can hedge

their climate risk exposures to specific corporations and/or sectors. Engle et al (2020) find that investments in companies that score high on ESG ratings can provide a hedge against climate risk drivers.

4.2. Amplifiers

The impacts of the climate-related financial risks described in Section 3 can be amplified in a number of ways. This includes through interactions and interdependencies between climate risk drivers, through feedback of financial risks, and through the combined impact of risk drivers transmitted through more than one channel. There is little literature examining the role of climate-related amplifiers, in particular financial amplifiers. Accordingly, additional analysis of this area would be valuable.

4.2.1 Risk driver interactions

Interactions exist across both physical and transition risk drivers and, as noted in the companion report on measurement methodologies, a joint consideration of risks may be necessary. Physical risk drivers do not need to occur in isolation. Examples of interactions among transition risk drivers can also be seen in the simultaneous introduction of climate mitigating policies (eg carbon tax and/or transport policies) and technological breakthroughs.

While the future path of each physical climate risk driver is itself uncertain, the dynamics and interaction – such as tipping points and non-linearity – create additional uncertainty and can be accretive. This can also be seen in climatic tipping points, which create uncertainty on the financial impact from climate risks for banks and can result from multiple climate events occurring at more or less the same time (Carney (2015)).

Moreover, interactions between physical and transition risk drivers can reinforce each other (Bolton et al (2020)). However, NGFS (2020a) and ESRB (2020) note that most existing empirical literature focuses on either physical or transition risk drivers. As a consequence, the ESRB calls for work to estimate the costs of policy inaction on intensified physical risk drivers.

4.2.2 Financial amplifiers

Financial amplifiers have the potential to increase the impact of climate-related financial risks to banks. The materialisation of climate-related risks on bank balance sheets might be amplified by behavioural actions taken within the financial system and interaction with the real economy. These amplifying effects may increase losses in the financial system. There is a lack of research on financial amplifiers related to climate change. Further work to consider existing studies of financial amplifiers in a climate context or to examine climate-related financial amplifiers would be useful.

Amplifiers of climate-related financial risks are similar to traditional amplifiers often discussed in the context of financial stability. These include “feedback loops” that arise within the financial system or between the financial system and the real economy. Amplification mechanisms are explored in more detail by the Financial Stability Board (FSB (2020)). In particular, the potential for market participants’ behaviours to reinforce negative effects, for instance through self-reinforcing reductions in bank lending or in the provision of insurance, and the interaction of financial institutions’ and sovereigns’ creditworthiness are cited as potential sources of financial amplification. While these amplifiers are not unique to climate, the lack of information about financial institutions’ exposure to climate risk could further contribute to the amplification of risks.

Climate change may in itself affect the future availability and affordability of insurance, making reduced insurance availability an amplifier. Insurance companies typically adjust the insurance coverage they provide and/or the premium they require for such coverage based on both their observed payouts and expected costs. In the medium to long term, these losses could shift towards households, and non-financial sectors more generally, as more risks become uninsurable and/or unaffordable. An example of

such shifts includes the retreat of insurers from some areas of the Caribbean after severe weather events drove declines in mortgage lending and home prices (Carney (2015)). In a case study, the Bank of England's Prudential Regulation Authority (PRA) investigated the pricing implications of climate change for flood insurance in the United Kingdom. Without government intervention, the market risk premium for flood insurance is projected to nearly double in a "high impact of climate change" scenario compared to the market premium under current climate conditions (PRA (2015)). Specific compensation schemes for natural disasters associating private and public sector participants exist already in a number of countries.³² The connections arising from sovereigns' role as backstop providers of insurance that banks rely on is an area that could be explored further. This concern about future insurability against natural catastrophes is not shared by all though. According to the Swiss Re Institute (2019), yearly reviews of risk coverage and pricing alongside constant efforts to upgrade risk assessments should help and suffice to provide risk-based pricing and adequate coverage.

The loss of insurance, or its unaffordability, can act as a financial amplifier. Additional analysis would usefully examine to what extent, for how long and up to what level insurance can act as a mitigant for the financial impact of climate risks to banks. It is unclear to what extent banks know whether and to what degree their exposures and counterparties are covered by insurance and further work in the area would be welcomed. While some banks require clients to purchase insurance as a condition of credit extension, insurance tends to be renewed annually and banks may not always have clear sight on whether policies continue to be in place. Moreover, and in particular for long-term real estate lending, a bank would need to make assumptions about the future coverage, availability and affordability of insurance to take it into account as a mitigant in estimates of climate-related financial risks associated with some of its credit exposures.

4.2.3 Risk drivers transmitted through multiple channels

A given risk driver may impact a bank through more than one transmission channel, therefore amplifying the effect of climate-related financial risks. In particular, there is potential for interactions between microeconomic and macroeconomic transmission channels. An example of this would be where a microeconomic channel directly affected the creditworthiness of a bank's customers while a macroeconomic channel had a more diffuse effect that resulted in a less favourable economic environment. Capturing the specific impact of scenarios across physical and transmission climate risk drivers is noted as a challenge in the companion report on measurement methodologies and remains an area for further research.

The NGFS (2019b) contends that traditional feedback loops between macroeconomic and financial shocks can also create amplification in the context of climate change. As an example, it notes that physical risk drivers can damage houses, and thereby negatively impact individuals' household wealth and – in turn and in aggregate – impact banks' credit risk. Moreover, Feyen et al (2020) note that a vicious cycle may arise where physical risk drivers magnify macro-financial risks for a country. This in turn might limit the country's scope to implement effective transition risk policies. More work on the relative importance of interactions between different transmission channels would be welcomed.

4.3. Mitigants

Financial mitigants can moderate or offset banks' exposure to climate-related financial risks through both proactive and reactive actions. Proactive actions include those that banks take to pre-emptively reduce their vulnerability to climate-related financial risks, eg through diversification. Reactive actions include those taken to respond to climate risks that are already embedded in balance sheet exposures. They might include the use of financial products that transfer climate risk to other parts of the financial system (eg

³² A comparison between some European regimes can be found in Bruggeman and Faure (2018).

hedging). Insurance and reinsurance markets play a critical role in mitigating climate change's impact on businesses, households and banks. Similarly, securitisation and asset sales allow banks to reduce their exposures to high-risk assets.

The future reliability, effectiveness and cost of some financial mitigants, such as insurance, may be uncertain. Accordingly, measuring their effectiveness in reducing gross climate-related financial risks poses several challenges. Different financial mitigants may result in varying degrees of climate risk transfer, and not all risk transfers are necessarily permanent. For example, climate risk hedges may be available today and deployable fairly quickly. That said, they must eventually be rolled over and the specific climate risk hedges that may be needed may be less available or more expensive in future. Insurance, similarly, must be renewed, and policies could be discontinued or premiums rise significantly for a given risk over time. While securitising loans or disposing of climate-vulnerable assets result in permanent risk transfer, counterparties may be less likely to take on these risks in future, challenging business models that rely on such an approach.

As with other areas discussed in this report, different countries may have structures that are more amenable to mitigating climate risks than others. It is noted that while the mitigants set out below may allow individual banks and the banking sector as a whole to reduce climate-related risk, they may shift the risk to less regulated parts of the financial system that may be less resilient. This could give rise to heightened financial stability risks:

- Financial losses from climate disasters can be limited or even prevented if a country's physical infrastructure is resilient. Damages that may result from extreme weather events may be minimised with stronger buildings, facilities, roads, airports and a comprehensive grid of levees and dams. These assets help reduce direct losses and the indirect costs of disruption (OECD (2018)).
- The state of a country's financial infrastructure and levels of openness can affect the availability of mitigants. Access to capital markets can increase climate resilience as it allows borrowers to access greater amounts of funding from more diverse sources, possibly at a lower cost, increasing inflows and allowing for faster reconstruction (Bowen et al (2012)).

The sections below explore the effects of the following financial risk mitigants: bank behaviour and business models; availability and pricing of insurance; depth and maturity of capital markets and opportunities for securitisation; and hedging opportunities.

4.3.1 Bank behaviour and business models

Investment strategies may allow a bank to manage its portfolio against some aspects of climate risk, as shown in recent research (Andersson et al (2016); Engle et al (2020)). Physical risks, in particular, are generally thought to affect companies idiosyncratically, and investors can thus diversify their portfolios to mitigate the impact of these risks. However, diversification strategies may become less effective as increasing global temperatures lead to more widespread and/or correlated extreme weather events. A report by the US Commodity Futures Trading Commission highlights that asset allocation strategies can provide possible mitigation, for example through increasing investment in sustainable companies, but only if investors have sufficient information on which to act (CFTC (2020)).

While bank balance sheets are sensitive to physical and transition risk drivers, studies tend to show that the magnitude of effects varies depending on the nature of the climate event and on specific business models. For example, transition risks could be expected to be higher in sectors with higher levels of GHG emissions such as fossil fuel-based industries, energy-intensive manufacturing and transportation activities. As a result, these sectors could be particularly impacted in a scenario where there is an abrupt and disorderly transition to a low-carbon economy (TCFD (2017)) and underlying assets become stranded as existing infrastructures are retired. Banks may proactively reduce their climate-related exposures through shifts in their business models and balance sheet exposures over time, particularly as they adjust

and calibrate their credit models to better capture climate risk. A gradual reduction in climate-sensitive assets may ultimately reduce the size of potential losses associated with severe weather events or with an abrupt transition to a lower-carbon economy. Alternatively, banks may seek to increase their financial resources in order to continue operating at a similar level in a heightened risk environment.

Empirical work suggests that banks reduce exposures to climate-sensitive assets once identified. Multiple studies demonstrate that banks reduce or transfer exposures to higher-risk assets, typically through securitisations. This often happens following natural disasters or when the exposures are located in areas considered long-term flood risks (Faiella and Natoli (2018); Ouazad and Kahn (2019); Keenan and Bradt (2020)). There is also evidence that banks tightened credit standards for corporates negatively affected by Hurricane Sandy, charging higher interest rates and requiring more collateral for new loans (Collier et al (2020)).

Evidence shows that some banks improve their capital positions following repeated natural disasters, suggesting that this is achieved through reduced lending to the most exposed areas. Schüwer et al (2019) find that banks improved their resilience by strengthening capital buffers after Hurricane Katrina in the United States. Compared to the control group, independent banks improved risk-based capital ratios by 1.87 percentage points of Tier 1 capital in the aftermath of Hurricane Katrina, while banks under a holding company increased Tier 1 capital by 0.39 percentage points.

There is some evidence to suggest that banks are starting to mitigate their exposure to transition risk drivers. Ivanov et al (2020) analyse how banks adjust their loan exposure to US firms as cap-and-trade policies move through the legislative process. They find that corporates affected by these policies are subject to shorter loan maturities, lower access to permanent forms of bank financing, and higher participation of shadow banks in their lending syndicates. This behaviour reflects a gradual process whereby banks may be limiting their exposure to climate-related financial risk, as they minimise new climate exposures and allow old exposures to roll off.

At the same time, banks play an important role in supporting the economy, potentially limiting the economic impact of disasters. Whilst evidence of reduced bank lending exists after isolated and severe weather events, there are also cases of banks increasing lending in disaster-affected areas. For example, a significant body of research suggests that immediately following severe weather events in their areas, US banks rush into the void as credit demand increases, and reallocate credit away from unaffected areas in order to do so (Cortés (2014); Cortés and Strahan (2017); Chavaz (2016)).

4.3.2 Availability and pricing of insurance

Insurance acts as a mitigant and strengthens the financial resilience of banks to physical hazards. Insurance can entail a bank insuring itself against losses from physical hazards (eg losses from a borrower's default or operational outages) or a bank's counterparty insuring itself against losses from physical hazards (eg flooding damage to a house). Insurance results in strengthened financial resilience, because the insurer compensates the insurance taker for covered financial losses. Information on the degree to which banks implicitly or explicitly rely on insurers to manage their climate-related financial risks would be a useful input to a better understanding of transmission channels.

Empirical studies contend that insurance can reduce the financial impact of natural catastrophes. Natural catastrophe insurance comes in many forms, covering damage to a variety of assets (from property to crops) and from a variety of sources (such as floods, storms and tornadoes). Von Peter et al (2012) find that macroeconomic costs from natural catastrophes are driven by uninsured losses. Where sufficiently insured, the impact of natural catastrophes on economic growth can be inconsequential (in the case of earthquakes and volcanic eruptions) or even positive (in the case of storms and flooding), as insurance payouts help to fund reconstruction efforts.

Moreover, US studies find that risk perception and making insurance compulsory for exposed households can increase insurance coverage, suggesting that this strengthens the resilience of exposed

banks. In the United States, households that take out a mortgage from a bank must buy flood insurance coverage if their property is located in a region that has at least a 1% chance of flooding.³³ Looking at this mandatory flood insurance coverage, Kriesel and Landry (2004) find that demand for flood insurance in US coastal areas is price inelastic and responsive to mortgage lender requirements. An analysis of flood insurance purchasing behaviour (Atreya et al (2015)) finds that risk perception, education and age are important determinants in whether an individual will buy sufficient insurance coverage. Petrolia et al (2013) find that perceived exposure to loss and whether governments have tied eligibility for disaster assistance to insurance coverage are also important determinants.

However, insurance coverage is limited and historical data shows only part of economic losses from natural catastrophes is covered. According to Swiss Re (2020), <https://www.swissre.com/media/news-releases/nr-20200408-sigma-2-2020.html> global economic losses from natural catastrophes were \$137 billion in 2019 and \$166 billion in 2018. Of these economic losses stemming from natural catastrophes, 38% and 51% respectively was covered by insurance. In addition, global averages do not reflect differences across countries. In emerging and less developed countries the protection gap is wider; insured losses are less than 10% of total damages (Munich Re (2020)). Uninsured losses are borne by the asset owner, with the potential to impact banks via the transmission channels discussed above.

To find alternative sources of capital to bear potential losses, insurance-linked securities (ILS) and in particular catastrophe bonds have been developed. These transfer the risks associated with natural disasters to investors through global capital markets. According to Polacek (2018), catastrophe bonds are generally issued by insurance companies, reinsurers and state catastrophe funds. The investments from the proceeds as well as insurance premiums are then used to make coupon payments to the investors (World Bank (2020)). A prominent form of ILS is those with parametric payouts, where payouts are based on a trigger event, for example a measure of wind speed or rainfall, rather than a measure of loss. The total size of the outstanding catastrophe bond and ILS risk capital is estimated at around \$40 billion in 2020 (FSB (2020)). While the number of parametric catastrophe bonds is limited, their triggers can be determined quickly and with reduced technical expertise (Polacek (2018)). This allows their issuers to pay out quickly and cover the financial impact, making them relevant in the context of transmission channels to banks.

4.3.3 Depth and maturity of capital markets, and opportunities for securitisation

Where there are opportunities for securitisation, banks with exposure to vulnerable sectors or geographies could reduce on-balance sheet risk. Evidence suggests that, in some jurisdictions, lenders may transfer risk by originating loans in climate-vulnerable areas and securitising them. It also shows that this practice is most prevalent in the United States and among local lenders because these hold geographically concentrated portfolios and benefit from local knowledge (Keenan and Bradt (2020)).³⁴ Chavaz (2016) and Cortés (2014) find that after natural disasters, concentrated lenders that maintain relationship lending and expand lending growth during post-disaster recovery also sell those loans in the secondary market. Schüwer et al (2019) find that banks seeking to shore up their capital positions after Hurricane Katrina decreased loan exposures to non-financial firms via loan sales or securitisation.

The opportunity to originate loans and sell mortgages in the secondary market results in banks extending credit that they might not have originated otherwise. Ouazad and Kahn (2019) find that after a billion-dollar natural disaster, banks are more likely to increase the share of mortgages originated and securitised right below the conforming loan limit (ie the dollar threshold for mortgage purchase by GSEs). The probability of securitisation for conforming and jumbo loans increases by up to 19.3 percentage

³³ See **Error! Hyperlink reference not valid.** www.fdic.gov/regulations/compliance/manual/5/V-6.1.pdf

³⁴ Studies that examine securitisation of climate-sensitive assets tend to focus on the United States, where more than half of residential mortgages are originated and sold to US government-sponsored enterprises (GSEs) "Fannie Mae" and "Freddie Mac".

points. Conforming loans originated following a natural disaster are unsurprisingly riskier since the borrower's creditworthiness is likely to have been affected – the foreclosure probability is 4.9 percentage points higher three years after a natural disaster, and the probability of a 90-day delinquency after origination is 2.4 percentage points higher. Their results suggest that “bunching” at the conforming loan limit is a function of perceived disaster risk. Further work on how and to what extent relevant climate-related information is incorporated into these securitisations would be useful.

4.3.4 Hedging opportunities

Weather derivatives are used by banks and their counterparties – most commonly by the agricultural, entertainment, tourism, energy and insurance sectors – to hedge localised risk associated with unexpected weather conditions and seasonal fluctuations. While these products may be effective in managing localised exposure to weather, they may be more limited in their ability to provide protection against broader climate risk (CFTC (2020)). Recent years have seen innovation in climate-related derivative instruments, such as ESG futures and carbon derivatives based on equity indices, as well as water derivatives,³⁵ to provide greater hedging possibilities in various markets. Additional research into the extent and effectiveness of climate-risk related hedging products is needed to better understand their role in transmission channels.

³⁵ See September 2020 announcement of the launch of water futures, www.cmegroup.com/media-room/press-releases/2020/9/17/cme_group_to_launchfirst-everwaterfuturesbasedonnasdaqvelescalif.html.

5. Conclusion

This report has surveyed existing literature to explore how climate risk drivers impact the financial risks of banks and banking systems via a range of transmission channels. It concludes with two recommendations for areas of focus in future public, private and academic work.

5.1. Potential impacts on traditional risk categories

This report suggests that the impacts of climate risk drivers on banks can be observed through the traditional risk categories. The table below summarises the potential effects in each risk type:

Potential effects of climate risk drivers

Table 1

Risk	Potential effects of climate risk drivers (physical and transition risks)
Credit risk	Credit risk increases if climate risk drivers reduce borrowers' ability to repay and service debt (income effect) or banks' ability to fully recover the value of a loan in the event of default (wealth effect).
Market risk	Reduction in financial asset values, including the potential to trigger large, sudden and negative price adjustments where climate risk is not yet incorporated into prices. Climate risk could also lead to a breakdown in correlations between assets or a change in market liquidity for particular assets, undermining risk management assumptions.
Liquidity risk	Banks' access to stable sources of funding could be reduced as market conditions change. Climate risk drivers may cause banks' counterparties to draw down deposits and credit lines.
Operational risk	Increasing legal and regulatory compliance risk associated with climate-sensitive investments and businesses.
Reputational risk	Increasing operational risk including reputational risk changing market or consumer sentiment.

To explore these linkages further, consideration could be given to how climate-related financial risks can be incorporated into the existing Basel Framework. Part of the Basel Committee's near-term work on climate change would be identifying gaps in the current Basel Framework, where climate-related financial risks may not be sufficiently addressed. This mapping exercise would be comprehensive in nature and could act as a conceptual foundation for the Committee's future work in exploring possible measures to address these gaps where relevant.

5.2. Research across all risk types and increased data availability

There is a limited amount of research and accompanying data that explore how climate risk drivers feed into transmission channels and the financial risks faced by banks. Existing analysis does not generally translate changes in climate-related variables to changes in banks' credit, market, liquidity or operational risk exposures or to bank balance sheet losses. Instead, the focus is on how specific climate risk drivers can impact: narrowly defined sectors of particular economies; individual markets; and/or a top-down assessment of the macro economy as a whole. Nevertheless, these examples provide insights on transmission channels and help to demonstrate heterogeneity in climate impacts across geographic, sectoral and jurisdictional boundaries.

A better understanding of risk drivers and their transmission channels, across all risk types, would be gained from further research. Research would also benefit from more granular information that is often privately held, for example more granular borrower data for credit risks. The table below summarises the areas where further analysis would be valuable:

Further analysis recommended

Table 2

Risk	Areas where further analysis would be valuable
Credit risk	Whilst existing research is weighted towards credit risk, it is largely focused on aggregate and country-level data. Further research and more granular data would usefully assess the impact of transmission channels on corporates, households and sovereigns for specific types of products.
Market risk	Research suggests that climate risk drivers have impacted the value of certain types of financial assets. Additional research could usefully explore how climate risk drivers undermine or challenge banks' assumptions on market liquidity and price correlations when managing market risk, as well as investigating how climate change impacts a broader set of assets in banks' trading portfolios.
Liquidity risk	Limited research on banks' liquidity risk has been undertaken, with existing research weighted towards wider liquidity impacts of physical risk drivers on the economy. Further research on the impact of physical and transition risk drivers on banks' liquidity would be valuable.
Operational risk	Existing studies suggest the potential for material operational climate losses on banks is small. However, this is based on modelling of idiosyncratic events and limited public information. In addition, liability and/or compliance risks related to climate changes may be significant and are yet to be studied in detail. Further research on bank-relevant operational risks would therefore be valuable.

The lack of research on banks' climate-related financial risks partially arises from a lack of data availability. Researchers interested in quantifying the impacts of climate change may not have access to the exposure data needed to assess these risks. The emergence of national climate-related stress testing exercises may partially address this information gap, but more could potentially be done to create opportunities for collaboration between climate and finance experts.

More research on the importance of different amplifiers and mitigants of climate-related financial risk would help inform where banks and supervisors could usefully focus their resources. Institutions are starting to conduct assessments that estimate the combined effect of climate-related financial risks on bank loan books and trading portfolios. This represents an evolution from the more narrowly focused studies on credit, market, liquidity or operational risk. However, most studies do not model the efficacy of mitigants or the propagation and potential amplification of the impacts that climate risk drivers may have across the financial system. Whilst the literature is increasingly exploring how these channels arise, understanding of this area remains undeveloped. More research is needed on how these effects could result in aggregate impacts that are greater than the sum of the individual parts.

References

- Abatzoglou, J and A Williams (2016): "Impact of anthropogenic climate change on wildfire across western US forests", *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, vol 113, no 42, October, pp 11770–75, www.pnas.org/content/113/42/11770.
- Abatzoglou, J, A Williams and R Barbero (2019): "Global emergence of anthropogenic climate change in fire weather indices", *Geophysical Research Letters*, vol 46, no 1, January, pp 326–36, agupubs.onlinelibrary.wiley.com/doi/10.1029/2018GL080959.
- Abe, M and L Ye (2013): "Building resilient supply chains against natural disasters: the cases of Japan and Thailand", *Global Business Review*, vol 14, no 4, pp 567–86, journals.sagepub.com/doi/abs/10.1177/0972150913501606.
- Allen, M and W Ingram (2002): "Constraints on future changes in climate and the hydrologic cycle", *Nature*, vol 419, September, pp 228–32, www.doi.org/10.1038/nature01092.
- Andersson, M, P Bolton and F Samama (2016): "Hedging climate risk", *Financial Analysts Journal*, vol 72, no 3, pp 13–32, doi.org/10.2469/faj.v72.n3.4.
- Andreoni, V and A Miola (2015): "Climate change and supply-chain vulnerability: methodologies for resilience and impacts quantification", *International Journal of Emergency Services*, vol 4, no 1, July, pp 6–26, www.emerald.com/insight/content/doi/10.1108/IJES-09-2014-0012/full/html.
- Atanasova, C and E Schwartz (2019): "Stranded fossil fuel reserves and firm value", *NBER Working Papers*, no 26497, November, www.nber.org/papers/w26497.
- Autorité de Contrôle Prudentiel et de Résolution (2019): *Climate change: which risks for banks and insurers?*, October, acpr.banque-france.fr/sites/default/files/medias/documents/as_cover_note_en.pdf.
- Baker, D and E Roston (2019): "After PG&E's climate-driven bankruptcy, who's next?", Bloomberg, 22 January, www.bloomberg.com/news/articles/2019-01-22/why-a-pg-e-bankruptcy-could-change-climate-calculus-quicktake.
- Baldauf, M, L Garlappi and C Yannelis (2020): "Does climate change affect real estate prices? Only if you believe in it", *The Review of Financial Studies*, vol 33, no 3, March, pp 1256–95, academic.oup.com/rfs/article/33/3/1256/5735306.
- Bank of Japan (2011): *Responses to the Great East Japan Earthquake by payment and settlement systems and financial institutions in Japan*, Payment and Settlement Systems Department, October, www.boj.or.jp/en/research/brp/ron_2011/data/ron111027a.pdf.
- Barbieri, A, E Domingues, B Lanza Queiroz and R Machado Ruiz (2010): "Climate change and population migration in Brazil's northeast: scenarios for 2025-2050", *Population and Environment*, vol 31, no 5, May, pp 344–70, www.researchgate.net/publication/225699319_Climate_change_and_population_migration_in_Brazil's_Northeast_Scenarios_for_2025-2050.
- Barrot, J-N and J Sauvagnat (2016): "Input specificity and the propagation of idiosyncratic shocks in production networks", *The Quarterly Journal of Economics*, vol 131, no 3, August, pp 1543–92, www.doi.org/10.1093/qje/qjw018.
- Basel Committee on Banking Supervision (2020): *Climate-related financial risks: a survey on current initiatives*, April, www.bis.org/bcbss/publ/d502.pdf.
- Berg, G and J Schrader (2012): "Access to credit, natural disasters, and relationship lending", *Journal of Financial Intermediation*, vol 21, no 4, October, pp 549–68, www.sciencedirect.com/science/article/pii/S1042957312000253.
- Bernstein, A, M Gustafson and R Lewis (2019): "Disaster on the horizon: the price effect of sea level rise", *Journal of Financial Economics*, vol 134, no 2, November, pp 253–72, www.sciencedirect.com/science/article/pii/S0304405X19300807.
- Bin, O and S Polasky (2004): "Effects of flood hazards on property values: evidence before and after Hurricane Floyd", *Land Economics*, vol 80, no 4, November, pp 490–500, le.uwpress.org/content/80/4/490.
- BlackRock Investment Institute (2019): "Getting physical: assessing climate risks", 4 April, www.blackrock.com/institutions/en-gb/insights/blackrock-investment-institute/physical-climate-risks.
- Bland, B and R Kwong (2011): "Supply chain disruption: sunken ambitions", *Financial Times*, 3 November, www.ft.com/content/6b20d192-0613-11e1-ad0e-00144feabdc0.
- Bolton, P, M Despres, L Pereira da Silva, F Samama and R Svartzman (2020): *The green swan: central banking and financial stability in the age of climate change*, Bank for International Settlements, January, www.bis.org/publ/othp31.pdf.
- Bolton, P and M Kacperczyk (2020): "Do investors care about carbon risk?", *CEPR Discussion Papers*, no DP14568, papers.ssrn.com/sol3/papers.cfm?abstract_id=3594189.
- Bos, K and J Gupta (2019): "Stranded assets and stranded resources: implications for climate change mitigation and global sustainable development", *Energy Research and Social Science*, vol 56, 101215, October, www.sciencedirect.com/science/article/pii/S2214629618305383.

- Bowen, A, S Cochrane and S Fankhauser (2012): "Climate change, adaptation and economic growth", *Climatic Change*, vol 113, pp 95–106, link.springer.com/article/10.1007/s10584-011-0346-8.
- Brei, M, P Mohan and E Strobl (2019): "The impact of natural disasters on the banking sector: evidence from hurricane strikes in the Caribbean", *The Quarterly Review of Economics and Finance*, vol 72, May, pp 232–9, www.sciencedirect.com/science/article/pii/S1062976918301613.
- Bruggeman, V and M Faure (2018): "Compensation for victims of disasters in Belgium, France, Germany and the Netherlands", The Netherlands Scientific Council for Government Policy, *Working Papers*, no 30, www.verzekeraars.nl/media/5662/compensation_for_victims_of_disasters_working_paper_30.pdf.
- Buhr, B, C Donovan, G Kling, Y Lo, V Murinde, N Pullin and U Volz (2018): *Climate change and the cost of capital in developing countries*, Imperial College Business School and SOAS University of London, UN Environment and MAVA, June, eprints.soas.ac.uk/26038/1/ClimateCostofCapital_FullReport_Final.pdf.
- Burke, M., Hsiang, S. & Miguel, E. *Global non-linear effect of temperature on economic production. Nature* 527, 235–239 (2015). <https://doi.org/10.1038/nature15725>
- Carleton, T and S Hsiang (2016): "Social and economic impacts of climate", *Science*, vol 353, no 6304, September, science.sciencemag.org/content/353/6304/aad9837.
- Carney, M (2015): "Breaking the tragedy of the horizon – climate change and financial stability", speech given at Lloyd's of London, 29 September, www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability.
- Cevik, S and J Tovar Jalles (2020): "This changes everything: climate shocks and sovereign bonds", *IMF Working Papers*, no 20/79, June, www.imf.org/en/Publications/WP/Issues/2020/06/05/This-Changes-Everything-Climate-Shocks-and-Sovereign-Bonds-49476.
- Chavaz, M (2016): "Dis-integrating credit markets: diversification, securitization, and lending in a recovery", *Bank of England Staff Working Papers*, no 617, September, www.bankofengland.co.uk/-/media/boe/files/working-paper/2016/dis-integrating-credit-markets-diversification-securitization-and-lending-in-a-recovery.pdf.
- CME Group (2020): "CME Group to launch first-ever water futures based on Nasdaq Veles California Water Index", 17 September, www.cmegroup.com/media-room/press-releases/2020/9/17/cme_group_to_launch-first-everwaterfuturesbasedonnasdaqvelescalif.html.
- Collier, B, A Haughwout, H Kunreuther and E Michel-Kerjan (2020): "Firms' management of infrequent shocks", *Journal of Money, Credit and Banking*, vol 52, no 6, September, pp 1329–59, onlinelibrary.wiley.com/doi/epdf/10.1111/jmcb.12674.
- Commodity Futures Trading Commission (2020): *Managing climate risk in the US financial system*, CFTC, September, www.cftc.gov/sites/default/files/2020-09/9-9-20%20Report%20of%20the%20Subcommittee%20on%20Climate-Related%20Market%20Risk%20-%20Managing%20Climate%20Risk%20in%20the%20US%20Financial%20System%20for%20posting.pdf.
- Cortés, K (2014): "Rebuilding after disaster strikes: how local lenders aid in the recovery", Federal Reserve Bank of Cleveland, *Working Paper* no 14-28, November, www.clevelandfed.org/en/newsroom-and-events/publications/working-papers/2014-working-papers/wp-1428-rebuilding-after-disaster-strikes-how-local-lenders-aid-in-the-recovery.aspx.
- Cortés, K and P Strahan (2017): "Tracing out capital flows: how financially integrated banks respond to natural disasters", *Journal of Financial Economics*, vol 125, no 1, July, pp 182–99, www.sciencedirect.com/science/article/pii/S0304405X17300806?via%3Dihub
- Dasgupta, S (2018). "Risk of sea-level rise: high stakes for East Asia and Pacific region countries", World Bank Blogs, 9 March, blogs.worldbank.org/eastasiapacific/risk-of-sea-level-rise-high-stakes-for-east-asia-pacific-region-countries.
- Delis, M, K de Greiff and S Ongena (2019): "Being stranded with fossil fuel reserves? Climate policy risk and the pricing of bank loans," *EBRD Working Paper* no 231, September, papers.ssrn.com/sol3/papers.cfm?abstract_id=3451335.
- Dell, M, B Jones and B Olken (2012): "Temperature shocks and economic growth: evidence from the last half century", *American Economic Journal: Macroeconomics*, vol 4, no 3, July, pp 66–95, pubs.aeaweb.org/doi/pdfplus/10.1257/mac.4.3.66.
- Deryugina, T, L Kawano and S Levitt (2018): "The economic impact of Hurricane Katrina on its victims: evidence from individual tax returns", *American Economic Journal: Applied Economics*, vol 10, no 2, April, pp 202–33, www.aeaweb.org/articles?id=10.1257/app.20160307.
- Deschênes, O and M Greenstone (2007): "The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather", *American Economic Review*, vol 97, no 1, March, pp 354–85, www.aeaweb.org/articles?id=10.1257/aer.97.1.354.
- Dietz, S., Bowen, A., Dixon, C. et al. 'Climate value at risk' of global financial assets. *Nature Climate Change* vol 6, 676–679 (2016). <https://doi.org/10.1038/nclimate2972>
- Diffenbaugh, N and M Burke (2019): "Global warming has increased global economic inequality", *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, vol 116, no 20, May, www.pnas.org/content/116/20/9808.

- Domowitz, I, J Glen and A Madhavan (2001): "Liquidity, volatility and equity trading costs across countries and over time", *International Finance*, vol 4, no 2, pp 221–55, onlinelibrary.wiley.com/doi/full/10.1111/1468-2362.00072.
- Engle, R, S Giglio, B Kelly, H Lee and J Stroebel (2020): "Hedging climate change news", *The Review of Financial Studies*, vol 33, no 3, March, pp 1184–216, academic.oup.com/rfs/article/33/3/1184/5735305.
- European Systemic Risk Board (2016): "Too late, too sudden: transition to a low-carbon economy and systemic risk", ESRB, *Reports of the Advisory Scientific Committee*, no 6, February, www.esrb.europa.eu/pub/pdf/asc/Reports_ASC_6_1602.pdf.
- (2020): *Positively green: measuring climate change risks to financial stability*, ESRB, June, www.esrb.europa.eu/pub/pdf/reports/esrb.report200608_on_Positively_green_-_Measuring_climate_change_risks_to_financial_stability~d903a83690.en.pdf?c5d033aa3c648ca0623f5a2306931e26.
- Faiella, I and F Natoli (2018): "Natural catastrophes and bank lending: the case of flood risk in Italy", *Bank of Italy Occasional Paper* no 457, October, papers.ssrn.com/sol3/papers.cfm?abstract_id=3429210.
- Feyen, E, R Utz, I Zuccardi Huertas, O Bogdan and J Moon (2020): "Macro-financial aspects of climate change", *World Bank Policy Research Working Paper* no 9109, January, openknowledge.worldbank.org/bitstream/handle/10986/33193/Macro-Financial-Aspects-of-Climate-Change.pdf?sessionid=2AB16DC259C66719118262815BE21E0D?sequence=1.
- Financial Stability Board (2020): *The implications of climate change for financial stability*, November, www.fsb.org/wp-content/uploads/P231120.pdf.
- Financial Times (2019): "Sharp rise in number of investors dumping fossil fuel stocks", 9 September, www.ft.com/content/4dec2ce0-d0fc-11e9-99a4-b5ded7a7fe3f.
- Fisher, A, W Hanemann, M Roberts and W Schlenker (2012): "The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather: comment", *American Economic Review*, vol 102, no 7, December, pp 3749–60, www.aeaweb.org/articles?id=10.1257/aer.102.7.3749.
- GermanWatch (2020): *Global Climate Risk Index 2020*, www.germanwatch.org/en/17307.
- Giuzio, M, D Krusec, A Levels, A Melo, K Mikkonen and P Radulova (2019): "Climate change and financial stability", European Central Bank, *Financial Stability Review*, May, www.ecb.europa.eu/pub/financial-stability/fsr/special/html/ecb.fsrart201905_1~47cf778cc1.en.html.
- Goldsmith-Pinkham, Paul S. and Gustafson, Matthew and Lewis, Ryan and Schwert, Michael, Sea Level Rise Exposure and Municipal Bond Yields (January 29, 2021). Jacobs Levy Equity Management Center for Quantitative Financial Research Paper, Available at SSRN: <https://ssrn.com/abstract=3478364> or <https://dx.doi.org/10.2139/ssrn.3478364>.
- Hallstrom, D and V Smith (2005): "Market responses to hurricanes", *Journal of Environmental Economics and Management*, vol 50, no 3, November, pp 541–61, www.sciencedirect.com/science/article/pii/S0095069605000537.
- Hinkel, J. et al "Coastal flood damage and adaptation costs under 21st century sea-level rise". PNAS March 4, 2014 111 (9) 3292–3297 <https://www.pnas.org/content/111/9/3292>
- Hosono, K, D Miyakawa, T Uchino, M Hazama, A Ono, H Uchida and I Uesugi (2016): "Natural disasters, damage to banks, and firm investment", *International Economic Review*, vol 57, no 4, November, pp 1335–70, www.jstor.org/stable/44280155?seq=1#metadata_info_tab_contents.
- Hsiang, S, M Burke and E Miguel (2013): "Quantifying the influence of climate on human conflict", *Science*, vol 341, no 6151, September, science.sciencemag.org/content/341/6151/1235367.
- Hsiang, S, R Kopp, A Jina, J Rising, M Delgado, S Mohan, D Rasmussen, R Muir-Wood, P Wilson, M Oppenheimer, K Larsen and T Houser (2017): "Estimating economic damage from climate change in the United States", *Science*, June, vol 356, no 6345, pp 1362–69, science.sciencemag.org/content/356/6345/1362.
- Hsu, P-H, L Kai and C-Y Tsou (2020): "The pollution premium", SSRN, April, ssrn.com/abstract=3578215.
- Ilhan, E, Z Sautner and G Vilkov (2020): "Carbon tail risk", *The Review of Financial Studies*, forthcoming, ssrn.com/abstract=3204420.
- Intergovernmental Panel on Climate Change (2012): *Managing the risks of extreme events and disasters to advance climate change adaptation*, www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/.
- (2014): *Climate change 2014: mitigation of climate change*, Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, www.ipcc.ch/report/ar5/wg3/.
- (2018): *Global warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, www.ipcc.ch/sr15/.
- (2019): *Special report on the ocean and cryosphere in a changing climate*, www.ipcc.ch/srocc/.

- International Monetary Fund (2020): "Chapter 5: Climate change – physical risk and equity prices", *Global Financial Stability Report*, no 2020/001, April, www.imf.org/en/Publications/GFSR/Issues/2020/04/14/Global-Financial-Stability-Report-April-2020-49020.
- Ivanov, I, M Kruttli and S Watugala (2020): "Banking on carbon: corporate lending and cap-and-trade policy", SSRN, December, papers.ssrn.com/sol3/papers.cfm?abstract_id=3650447.
- Jones, M, A Smith, R Betts, J Canadell, I Prentice and C Le Quéré (2020): "Climate change increases risk of wildfires", *ScienceBrief Review*, January, sciencebrief.org/briefs/wildfires.
- Keenan, J and J Bradt (2020): "Underwaterwriting: from theory to empiricism in regional mortgage markets in the US", *Climatic Change*, vol 162, June, pp 2043–67, link.springer.com/article/10.1007%2Fs10584-020-02734-1.
- Kjellstrom, T, D Briggs, C Freyberg, B Lemke, M Otto and O Hyatt (2016): "Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts", *Annual Review of Public Health*, vol 37, March, pp 97–112, www.annualreviews.org/doi/full/10.1146/annurev-publhealth-032315-021740.
- Koetter, M, F Noth and O Rehbein (2020): "Borrowers under water! Rare disasters, regional banks, and recovery lending", *Journal of Financial Intermediation*, vol 43, July, article 100811, www.sciencedirect.com/journal/journal-of-financial-intermediation/vol/43/suppl/C.
- Kriesel, W. and Landry, C. (2004), Participation In The National Flood Insurance Program: An Empirical Analysis For Coastal Properties. *Journal of Risk and Insurance*, 71: 405-420. <https://doi.org/10.1111/j.0022-4367.2004.00096.x>
- Kruttli, M, B Roth Tran and S Watugala (2019): "Pricing Poseidon: extreme weather uncertainty and firm return dynamics", Board of Governors of the Federal Reserve System, *FEDS Working Paper* no 2019-054, July, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3423254.
- Lesmond, D (2005): "Liquidity of emerging markets", *Journal of Financial Economics*, vol 77, no 2, August, pp 411–52, www.sciencedirect.com/science/article/pii/S0304405X05000176.
- Mallucci, E (2020): "Natural disasters, climate change, and sovereign risk", Board of Governors of the Federal Reserve System, *International Finance Discussion Papers*, no 1291, July, www.federalreserve.gov/econres/ifafiles/ifa1291.pdf.
- Mattison, R (2020): "The big picture on climate risk", S&P Global, www.spglobal.com/en/research-insights/featured/the-big-picture-on-climate-risk.
- McGlade, C and P Ekins (2015): "The geographical distribution of fossil fuels unused when limiting global warming to 2°C", *Nature*, vol 517, no 7533, January, pp 187–90, pubmed.ncbi.nlm.nih.gov/25567285/.
- McKinsey Global Institute (2020): *Climate risk and response: physical hazards and socioeconomic impacts*, January, www.mckinsey.com/mwg-internal/de5fs23hu73ds/progress?id=aoCkcm-eu6iy2EkYtKoPdpaOKwcmtryTgHZFzqUNzJE&dl.
- McLeman, R and B Smit (2006): "Migration as an adaptation to climate change", *Climatic Change*, vol 76, no 1, June, pp 31–53, www.researchgate.net/publication/225198169_Migration_as_an_Adaptation_to_Climate_Change.
- Mejia, S, C Baccianti, M Mrkaic, N Novta, E Pugacheva, P Topalova (2019): "Weather shocks and output in low-income countries: adaptation and the role of policies", *IMF Working Papers*, no 19/178, August, www.imf.org/en/Publications/WP/Issues/2019/08/16/Weather-Shocks-and-Output-in-Low-Income-Countries-The-Role-of-Policies-and-Adaptation-48554.
- Migliorelli, M and P Dessertine eds (2020): *Sustainability and financial risks: the impact of climate change, environmental degradation and social inequality on financial markets*, www.palgrave.com/gp/book/9783030545291.
- Munich Re (2020): "Risks posed by natural disasters", www.munichre.com/en/risks/natural-disasters-losses-are-trending-upwards.html#-1624621007.
- Murfin, J and M Spiegel (2020): "Is the risk of sea level rise capitalized in residential real estate?", *The Review of Financial Studies*, vol 33, no 3, March, pp 1217–55, academic.oup.com/rfs/article/33/3/1217/5735310.
- National Geographic (2019): "Climate change report card: These countries are reaching targets", 19 September, www.nationalgeographic.com/environment/article/climate-change-report-card-co2-emissions.
- Natural Capital Finance Alliance and Deutsche Gesellschaft für Internationale Zusammenarbeit (2017): *Drought stress testing: making financial institutions more resilient to environmental risks*, naturalcapital.finance/wp-content/uploads/2018/12/NCFA-drought-stress-testing-tool-summary.pdf.
- Netherlands Bank (2018): "An energy transition risk stress test for the financial system of the Netherlands", *Occasional Studies*, vol 16 – 7, www.dnb.nl/media/naiiupcg/persberos_transition-risk-stress-test-versie_web_tcm46-379397.pdf.
- Network for Greening the Financial System (2019a): *A call for action: climate change as a source of financial risk*, April, www.ngfs.net/sites/default/files/medias/documents/ngfs_first_comprehensive_report_-_17042019_0.pdf.
- (2019b): *Macroeconomic and financial stability: implications of climate change*, July, www.ngfs.net/sites/default/files/medias/documents/ngfs-report-technical-supplement_final_v2.pdf.

- (2020a): *The macroeconomic and financial stability impacts of climate change: research priorities*, June, www.ngfs.net/sites/default/files/medias/documents/ngfs_research_priorities_final.pdf.
- (2020b): *Guide for supervisors: integrating climate-related and environmental risks into prudential supervision*, May, www.ngfs.net/en/guide-supervisors-integrating-climate-related-and-environmental-risks-prudential-supervision.
- (2020c): *A status report on financial institutions' experiences from working with green, non green and brown financial assets and a potential risk differential*, May, www.ngfs.net/sites/default/files/medias/documents/ngfs_status_report.pdf.
- (2020d): *Guide to climate scenario analysis for central banks and supervisors*, June, www.ngfs.net/sites/default/files/medias/documents/ngfs_guide_scenario_analysis_final.pdf.
- Noth, F and U Schüwer (2018): "Natural disaster and bank stability: evidence from the US financial system", *SAFE Working Paper* no 167, April, papers.ssrn.com/sol3/papers.cfm?abstract_id=2921000.
- Organisation for Economic Co-operation and Development (2018): "Climate-resilient infrastructure", *OECD Environment Policy Paper* no 14, www.oecd.org/environment/cc/policy-perspectives-climate-resilient-infrastructure.pdf.
- Ortega, F and S Taspinar (2018): "Rising sea levels and sinking property values: the effects of Hurricane Sandy on New York's housing market", *Journal of Urban Economics*, vol 106, July, pp 81–100, www.iza.org/publications/dp/10374/rising-sea-levels-and-sinking-property-values-the-effects-of-hurricane-sandy-on-new-yorks-housing-market.
- Ouazad, A and M Kahn (2019): "Mortgage finance and climate change: securitization dynamics in the aftermath of natural disasters", *NBER Working Papers*, no 26322, www.nber.org/papers/w26322.
- Painter, M (2020): "An inconvenient cost: the effects of climate change on municipal bonds", *Journal of Financial Economics*, vol 135, no 2, February, pp 468–82, doi.org/10.1016/j.jfineco.2019.06.006.
- Park, Y, P Hong and J Roh (2013): "Supply chain lessons from the catastrophic natural disaster in Japan", *Business Horizons*, vol 56, no 1, January–February, pp 75–85, doi.org/10.1016/j.bushor.2012.09.008.
- Petrolia, D, C Landry and K Coble (2013): "Risk preferences, risk perceptions, and flood insurance", *Land Economics*, vol 89, no 2, econpapers.repec.org/article/uwplandec/v_3a89_3ay_3a2013_3a11_3a1_3ap_3a227-245.htm.
- Pindyck, R (2020): "What we know and don't know about climate change, and implications for policy", *NBER Working Papers*, no 27304, June, www.nber.org/papers/w27304.
- Polacek, A (2018): "Catastrophe bonds: a primer and retrospective", Federal Reserve Bank of Chicago, *Essays on Issues*, no 405, fraser.stlouisfed.org/files/docs/historical/frbchi/fedletter/frbchi_fedletter_2018_405.pdf.
- Prudential Regulation Authority (2015): *The impact of climate change on the UK insurance sector: a climate change adaptation report by the Prudential Regulation Authority*, September, www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/publication/impact-of-climate-change-on-the-uk-insurance-sector.pdf.
- (2018): *Transition in thinking: the impact of climate change on the UK banking sector*, September, www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/report/transition-in-thinking-the-impact-of-climate-change-on-the-uk-banking-sector.pdf.
- PwC (2020): "Asset & wealth management revolution", www.pwc.com/jg/en/publications/asset-and-wealth-management-revolution.html.
- S&P Global (2018): "How ESG factors help shape the ratings on governments, insurers, and financial institutions", Standard and Poor's Global, 23 October, www.spglobal.com/en/research-insights/articles/how-environmental-social-and-governance-factors-help-shape-the-ratings-on-governments-insurers-and-financial-institutions.
- Schlenker, W and M Roberts (2009): "Nonlinear temperature effects indicate severe damages to US crop yields under climate change", *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, vol 106, no 37, September, pp 15594–8, www.pnas.org/content/106/37/15594.short.
- Schüwer, U, C Lambert and F Noth (2019): "How do banks react to catastrophic events? Evidence from Hurricane Katrina", *Review of Finance*, vol 23, no 1, February, pp 75–116, academic.oup.com/rof/article/23/1/75/4971559.
- Seltzer, L, L Starks and Q Zhu (2020): "Climate regulatory risks and corporate bonds", SSRN, 17 April, papers.ssrn.com/sol3/papers.cfm?abstract_id=3563271.
- Setzer, J and R Byrnes (2020): *Global trends in climate change litigation: 2020 snapshot*, Grantham Research Institute on Climate Change and the Environment, July, www.lse.ac.uk/granthaminstitute/wp-content/uploads/2020/07/Global-trends-in-climate-change-litigation_2020-snapshot.pdf.
- Solomon, S, G-K Plattner, R Knutti and P Friedlingstein (2009): "Irreversible climate change due to carbon dioxide emissions", *Proceedings of the National Academy of Sciences of the United States of America (PNAS)*, vol 106, no 6, January, pp 1704–09, [www.doi.org/10.1073/pnas.0812721106](https://doi.org/10.1073/pnas.0812721106).

Steindl, F, and M Weinrobe (1983): "Natural hazards and deposit behavior at financial institutions: a note", *Journal of Banking and Finance*, vol 7, no 1, March, pp 111–18, www.sciencedirect.com/science/article/pii/0378426683900596.

Swiss Re (2020): "Socio-economic developments and climate-change effects to drive rising losses from severe weather events, sigma says", Swiss Re Group, 8 April, www.swissre.com/media/news-releases/nr-20200408-sigma-2-2020.html.

Swiss Re Institute (2019): "Climate risk management", *Financial Report*, reports.swissre.com/2019/financial-report/sustainability/climate-risk-management.html#.

Tacoli, C (2009): "Crisis or adaptation? Migration and climate change in a context of high mobility", *Environment and Urbanization*, vol 21, no 2, September, pp 513–25, journals.sagepub.com/doi/abs/10.1177/0956247809342182.

Task Force on Climate-related Financial Disclosures (2017): *Recommendations of the Task Force on Climate-related Financial Disclosures*, June, assets.bbhub.io/company/sites/60/2020/10/FINAL-2017-TCFD-Report-11052018.pdf.

United Nations Development Programme (2016): *Scaling up climate action to achieve the sustainable development goals*, www.undp.org/content/undp/en/home/librarypage/climate-and-disaster-resilience-/scaling-up-climate-action-to-achieve-the-sdgs.html.

United Nations Environment Programme (2017): *The status of climate change litigation – a global review*, May, wedocs.unep.org/bitstream/handle/20.500.11822/20767/climate-change-litigation.pdf?sequence=1&isAllowed=y.

United Nations Environment Programme – Finance Initiative (2018a): *Extending our horizons – assessing credit risk and opportunity in a changing climate: Part 1 – transition-related risks and opportunities*, April, www.unepfi.org/wordpress/wp-content/uploads/2018/04/EXTENDING-OUR-HORIZONS.pdf.

——— (2018b): *Navigating a new climate: assessing credit risk and opportunity in a changing climate: Part 2 – physical risks and opportunities*, July, www.unepfi.org/publications/banking-publications/navigating-a-new-climate-assessing-credit-risk-and-opportunity-in-a-changing-climate/.

——— (2019): "Changing course: UNEP FI and twenty institutional investors launch new guidance to implement TCFD Recommendations", May, www.unepfi.org/news/industries/investment/changing-course-unep-fi-and-twenty-institutional-investors-launch-new-guidance-for-implementing-tcfd/.

Vicente-Serrano, S, J-I Lopez-Moreno, S Beguería, J Lorenzo-Lacruz, A Sanchez-Lorenzo, J García-Ruiz, C Azorin-Molina, E Morán-Tejeda, J Revuelto, R Trigo, F Coelho and F Espejo (2014): "Evidence of increasing drought severity caused by temperature rise in southern Europe", *Environmental Research Letters*, vol 9, no 4, April, iopscience.iop.org/article/10.1088/1748-9326/9/4/044001/meta.

von Peter, G, S von Dahlen and S Saxena (2012): "Unmitigated disasters? New evidence on the macroeconomic cost of natural catastrophes", *BIS Working Papers*, no 394, December, www.bis.org/publ/work394.pdf.

Wachter, J (2013): "Can time-varying risk of rare disasters explain aggregate stock market volatility?", *Journal of Finance*, vol 68, no 3, June, pp 987–1035, doi.org/10.1111/jofi.12018.

Williams, A, J Abatzoglou, A Gershunov, J Guzman-Morales, D Bishop, J Balch and D Lettenmaier (2019): "Observed impacts of anthropogenic climate change on wildfire in California", *Earth's Future*, vol 7, no 8, August, pp 892–910, www.doi.org/10.1029/2019EF001210.

World Bank (2018): *Groundswell: preparing for internal climate migration*, World Bank, openknowledge.worldbank.org/handle/10986/29461.

——— (2020): "What are catastrophe bonds?", treasury.worldbank.org/en/about/unit/treasury/ibrd/ibrd-capital-at-risk-notes#3.

Zillow Research (2019): "802,555 homes at risk of 10-year flood inundation by 2050", 31 July, www.zillow.com/research/homes-at-risk-coastal-flooding-25040/.