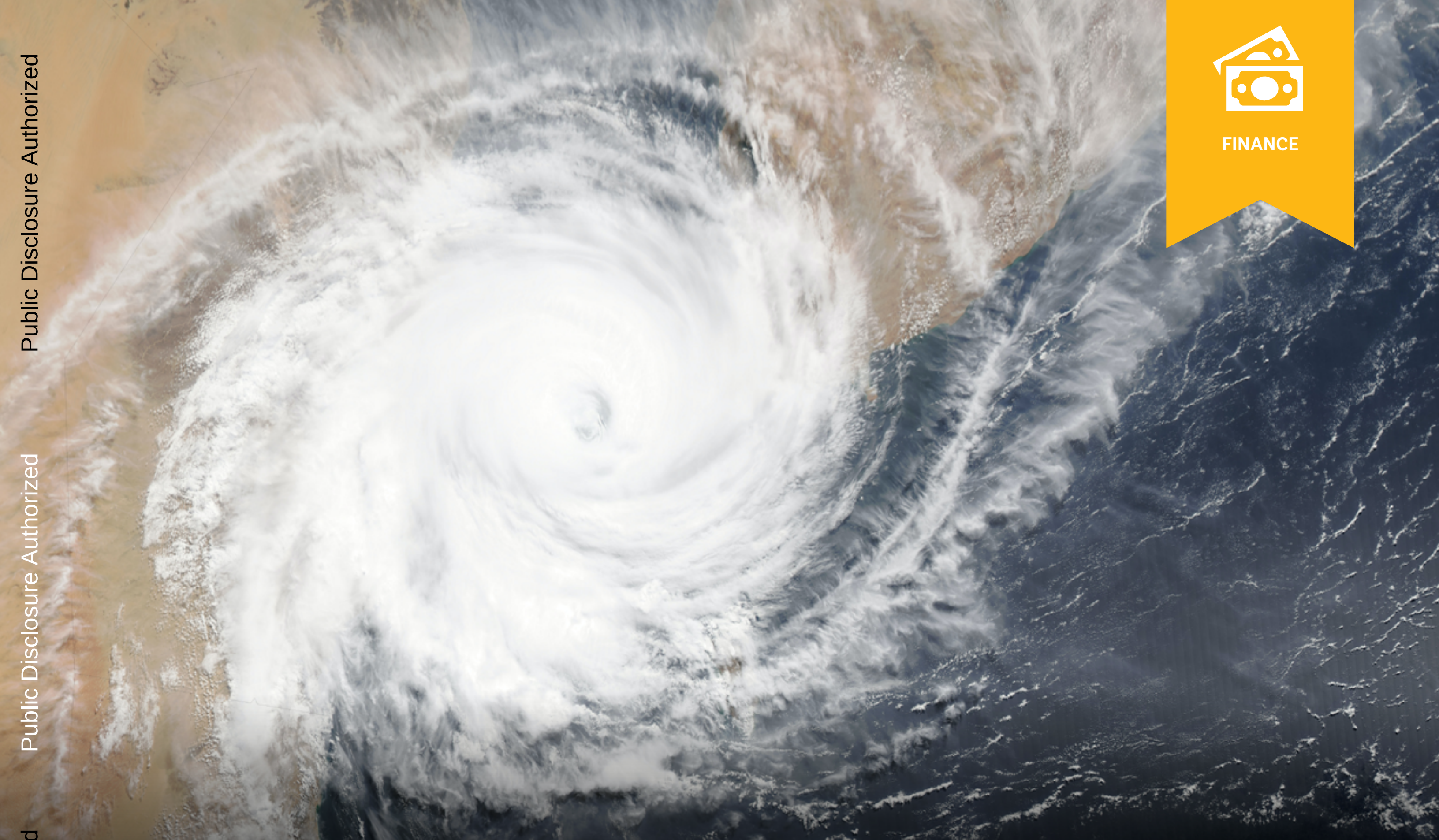

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Assessing Financial Risks from Physical Climate Shocks: A Framework for Scenario Generation

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Abstract

Climate change has become a main concern of ministries of finance, central banks, and financial regulators. In response, a suite of scenarios and tools have been developed to assess the financial risks from physical climate shocks (for example, hurricanes, droughts, wildfires, flooding). However, those scenarios do not fully capture such shocks, which could lead financial institutions to underestimate the potential scale of climate risks and underprice investments in resilience. This is particularly important for emerging markets and developing economies where exposure to physical climate risks is already high and is expected to further increase with climate change. The paper identifies five areas, or risk drivers, that make a material contribution to physical climate risks to the financial sector and that are not consistently included in current scenarios and tools: (1) extreme weather events, (2) uncertainties in climate models, (3) compound scenarios, (4) indirect economic impacts of shocks, and (5) feedback between the real economy and the financial sector. We derive a framework for generating scenarios to assess acute physical climate-related financial risks, which is inspired by the "Realistic Disaster Scenarios" that are used in risk management and supervision in the insurance sector. The framework is illustrated through an application of the EIRIN macroeconomic model. This framework aims to complement recent work by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) and the Financial Stability Board (FSB) to inform ministries of finance, central banks, financial regulators, and financial institutions on climate financial risk assessments, both for micro- and macroprudential risk management, and to incorporate climate risks into wider financial decision making and disclosures.

Keywords: physical climate risk; climate-related financial risk scenarios; risk drivers; macrofinancial feedbacks, macroprudential supervision; risk management; low-income countries.

Acronyms

AAL	Average Annual Loss
BAU	Business as usual
BIS	Bank for International Settlements
BoE	Bank of England
CAR	Capital Adequacy Ratio
CBES	Climate Biennial Exploratory Scenario
CGE	Computable general equilibrium
CMIP	Climate Model Intercomparison Project
DRF	Disaster risk finance
DSGE	Dynamic stochastic general equilibrium
ECB	European Central Bank
EU	European Union
FSAP	Financial Sector Assessment Program
FSB	Financial Stability Board
GCM	Global Climate Models
GDP	Gross domestic product
GVA	Gross Value Added
IAM	Integrated Assessment Models
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
LAC	Latin America and the Caribbean
MFI	Microfinance institution
NGFS	Network of Central Banks and Supervisors for Greening the Financial System
NPL	Nonperforming Loan
NRB	Nepal Rastra Bank
RCP	Representative Concentration Pathways
SACCO	Savings and Credit Cooperatives
SFC	Stock-flow consistent
SIDS	Small island developing states

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Contents

Figure

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Introduction

Climate change is becoming a main concern of ministries of finance, central banks, and financial regulators. More than 50 ministries of finance have endorsed the Helsinki Principles, which include commitments to take action to account for climate change within macroeconomic policy, fiscal planning, budgeting, and public investment (Principles 4 and 5[1]). To date, 100 central banks and financial regulators have become members of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), with its central goal to contribute to climate and environmental risk management in the financial sector. Managing the systemic risks for financial stability is a core part of the mandate of central banks. Financial regulators play a central role in assessing and managing idiosyncratic risks as well as ensuring the development of sound financial markets for the long term. A growing chorus of central banks and financial regulators have highlighted the potential financial risks associated with climate change and many, including the United Kingdom, the European Central Bank (ECB), France, Singapore, Australia, and the Netherlands, are beginning to put in place supervisory guidance and/or requirements for banks and insurers to disclose, assess, and embed climate risks within risk management frameworks.

Much of the focus to date on climate-related financial risks has been on so-called climate *transition risks*, that is, financial risks associated with the way policies, regulations, changing sentiments, or technological shocks are introduced in the low-carbon transition (Carney 2015). Several central banks and financial regulators have started to assess investors' exposure to transition risks via Climate Policy Relevant Sectors (Battiston et al. 2020, EBA 2020). With regard to climate risk exposure, a growing number of central banks have developed climate stress tests (Vermuelen et al. 2019, Allen et al. 2020, de Guindos 2021) that translate climate scenarios developed by Integrated Assessment Models (IAM) into financial risk metrics, building on the climate stress test approach developed by Battiston et al. (2017).

There has been less focus on physical climate-related financial risks, although recent supervisory statements by central banks place equal emphasis on physical risks (see, for example, BoE 2020). This paper focuses on approaches to assess financial risks from physical climate shocks for central banks and supervisors. Physical risks arise from the changes in weather and climate that impact economies and the financial sector (FSB 2020). Activity in this area is now beginning to ramp up with guidance, scenarios, and analyses becoming available (for example, UNEPFI 2020; Smith 2021; IMF 2021) as well as new research on the financial stability implications of physical climate risks. For example, Mandel et al. (2021) find that in high-end climate scenarios,

1. For more information on the Helsinki Principles, visit The Coalition of Finance Ministers for Climate Action at https://www.financeministersforclimate.org/.

physical climate risks related to flooding could lead to financial impacts that become commensurate with the capital of the major global banking sectors.

Under the NGFS framework (NGFS 2020b), physical climate risks are subdivided into two categories: chronic risks and acute risks. Chronic risks result from gradual shifts in biophysical and climate characteristics over time due to climate change. This includes, for example, changes in labor productivity due to gradually warming temperatures or reductions in agricultural output due to shifting rainfall patterns. Acute risks refer to changing frequencies or severity of shocks, such as natural catastrophes, including flooding, tropical cyclones, wildfire, heat waves or droughts (IPCC 2012). The NGFS framework and its scenarios have provided a basis for central banks and other financial institutions to begin climate risk assessment exercises.

This paper focuses on acute risks, hereafter referred to as physical climate shocks. These sudden and severe shocks, as opposed to more long-term, gradual shifts in climate, are most likely to generate material shocks to the financial sector in the near-term (see Feyen et al. 2020, and Calice and Miguel 2021 for examples). Yet, to date, physical climate shocks have not been explicitly considered within the core NGFS scenarios (NGFS 2021b), though they are beginning to be incorporated in some climate stress testing by central banks (see, for example, de Guindos 2021), the World Bank, and the International Monetary Fund (IMF) (see IMF 2021 for an example). Assessing the financial impacts of physical climate shocks is nontrivial and requires drawing upon expertise from across multiple disciplines, including climate science, earth sciences, engineering, economics, and finance. There is a deep literature and practice on assessing the economic impacts of physical climate shocks that can be drawn upon.

This paper argues that there are gaps in the way acute risks are included within current scenarios for physical climate-related financial risk assessments. This could lead to underestimating the potential scale of those risks within micro- and macroprudential risk assessments as well as potentially mispricing of these risks within wider financial decision making. We refer here to those scenarios made available in the public domain by, for example, the NGFS[2], specifically to support central banks, financial regulators, and financial institutions in climate stress testing and scenario analyses. This paper aims to suggest how these gaps could be filled within subsequent versions of the scenarios as well as those tailored scenarios produced by central banks and financial institutions, including the Bank of England 2021 Climate Biennial Exploratory Scenario (CBES). This paper draws upon existing evidence, tools, and experience from other related sectors such as insurance. It proposes a framework for scenario generation for physical climate-related financial risks to the banking sector to help fill these gaps and give an order of magnitude of the potential underestimate of physical climate risk.

This paper aims to inform global and national discussions on scenarios for acute physical climate financial risk assessment. The primary goal is to inform ministries of finance, central banks, financial regulators, and financial institutions involved in climate financial risk assessments, both for micro- and macroprudential risk management. This includes climate stress testing applications and broader scenario analysis. It also has applications for financial institutions and investors using scenarios to incorporate climate risks into wider financial decision making, disclosures, and risk management.

The starting place for understanding future financial risks from physical climate shocks is to first assess how such shocks affected the financial sector (in particular, the banking sector but also the insurance industry) in the past and to fully map potential transmission channels that could come into play in the future. As such, this paper incorporates a review of the empirical evidence on the impacts physical climate shocks on the financial sector and financial stability. A similar approach is proposed by the Climate Financial Risk Forum of the Bank of England (CFRF 2020) for individual financial institutions as starting point to generating relevant climate scenarios for stress testing (see figure 1.1).

2. Climate scenarios are available at https://www.ngfs.net/ngfs-scenarios-portal/.

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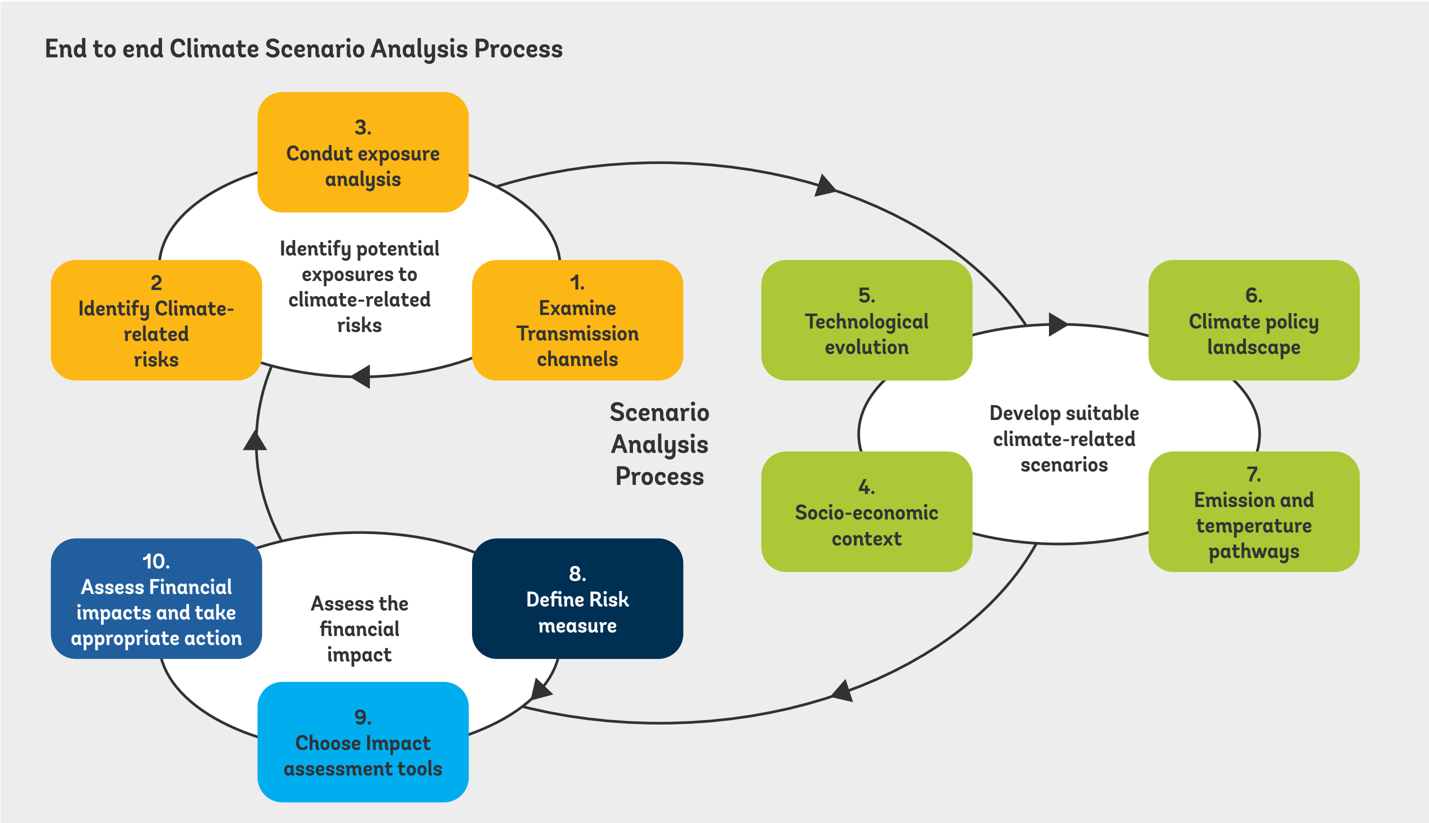
FIGURE 1.1. **Approach to Scenario Generation and Analysis Proposed by the Climate Financial Risk Forum of the Bank of England (a Private Sector Forum for Developing Best Practice)**



Source: CFRF 2020

The paper is organized as follows. Section 2 begins with a review of current scenarios provided in the public domain for climate financial risk assessment by the NGFS and others and compares these with the wider literature on the economics of climate risks and scenario development for stress testing by financial institutions. This section identifies the main gap versus current understanding of physical risks and practice in other analogous areas. Section 3 then reviews the current empirical evidence on the economic and financial impacts of physical climate shocks on the banking sector to identify five specific gaps. Section 4 discusses how these gaps can be better addressed within scenarios for physical climate-related financial risk assessment and proposes a framework for scenario generation based upon this. This section then presents evidence on the scale of the implications for climate-related financial risks. Estimates of scale are provided by reviewing current literature and by presenting a case study for a generic middle-income country that is highly exposed to extreme weather events (for example, typhoons and flooding) based on new analyses using the EIRIN model (Monasterolo and Raberto 2018; Dunz et al. 2021). Section 5 discusses next steps toward implementation of this framework. The paper concludes by drawing recommendations for future research to fill the priority data gaps identified in this study.

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Review of Current Scenarios for Physical Climate Risks

To frame the context, we first review the scenario generation for physical climate-related risks as embodied by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) (NGFS 2020a; NGFS 2020b; NGFS 2021b). Box 2.1 introduces the six policy scenarios defined by the NGFS. Physical risk scenarios use climate projections from five Global Climate Models (GCMs) driven by the Representative Concentration Pathways (RCPs). The NGFS recommends the use of the climate impact scenarios collected by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) initiative[3] to carry out estimates of climate physical risk for investors. These impact scenarios cover climate impacts such as changes in agricultural productivity, ecosystems, forestry, and water stress.

For economic damages, NGFS climate physical risk scenarios (identified as "damage" scenarios) rely upon damage functions developed in other models (for example, William D. Nordhaus' Dynamic Integrated Climate Economy (DICE) model; Kalkuhl and Wenz 2020). These scenarios are then embedded in process-based Integrated Assessment Models (IAMs)[4] (that is, GCAM, MESSAGE-GLOBIOM, REMIND-MagPie) to provide an estimate of global, aggregate gross domestic product (GDP) loss. Damage functions link climate variables, such as mean temperature, with impact metrics, such as GDP losses based upon econometric analyses and other evidence. The resulting trajectories can be calculated by users in the NGFS scenario explorer[5]. These show that estimates of physical climate losses are very sensitive to the type of damage function and its calibration.

3. To learn more about the ISIMIP initiative, visit https://www.isimip.org/outputdata/.
4. A more recent generation of "process based," large-scale IAM, embeds a granular representation of energy technologies (for example, fossil fuel and renewables) (Weyant 2017). They develop long-term emission projections and socioeconomic scenarios, based on assumptions on carbon pricing and modeling of technology investments that suggest how to reach given targets in terms of cumulative emissions (and thus in terms of carbon budget) by 2100. Emissions translate then into temperature targets with associated probabilities. Process-based IAM do not directly model disaster risk yet focus on the transition to low-carbon futures.
5. See https://data.ene.iiasa.ac.at/ngfs to learn more about the NGFS Scenario Explorer.

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BOX 2.1

Overview of NGFS Scenario Framework

The NGFS has recommended a set of climate scenarios to be used by financial supervisors for climate-related financial risk assessment (including stress test exercises, for example, see guidance document NGFS 2020a); these aim to inform assessments of both transition and physical climate-related risks. These scenarios are based upon process-based Integrated Assessment Models (IAM) that are reviewed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2014; IPCC 2018) and have a high-granular representation of energy technologies to aid in transition risk assessment. Within the dimension of (high) physical risk, the NGFS has identified two high-level scenarios (NGFS 2021b):

1. Hot house world corresponds to the IPCC scenario Representative Concentration Pathways (RCP) 6.0—a scenario in which the global temperature reaches over 3 degrees C by 2100 in comparison with pre-industrial times. This is described as a situation in which output across low/high carbon activities progresses in line with the current NGFS scenarios policies, that is, a continued reliance on fossil fuel energy sources and unabated greenhouse gas emissions. Along this pathway, an increase of physical risk is projected due to increased frequency and intensity of climate-related extreme events (or physical climate shocks) and chronic effects (such as sea level rise and permafrost melting). In this scenario, there is no transition to a low-carbon economy, and hence there is no transition risk.

2. Transition scenarios (orderly and disorderly) (figure B2.1.1) corresponds to scenario RCP2.6—below 2 degrees Celsius (C) by 2100. These scenarios are further subdivided into subscenarios: one considering different temperature targets (1.5 degrees C or 2 degrees C. respectively); another considering the timing of the introduction of climate policy such as a carbon tax (immediate, meaning 2020 versus delayed, say, to 2030); and finally, reliance on carbon dioxide removal.[a]

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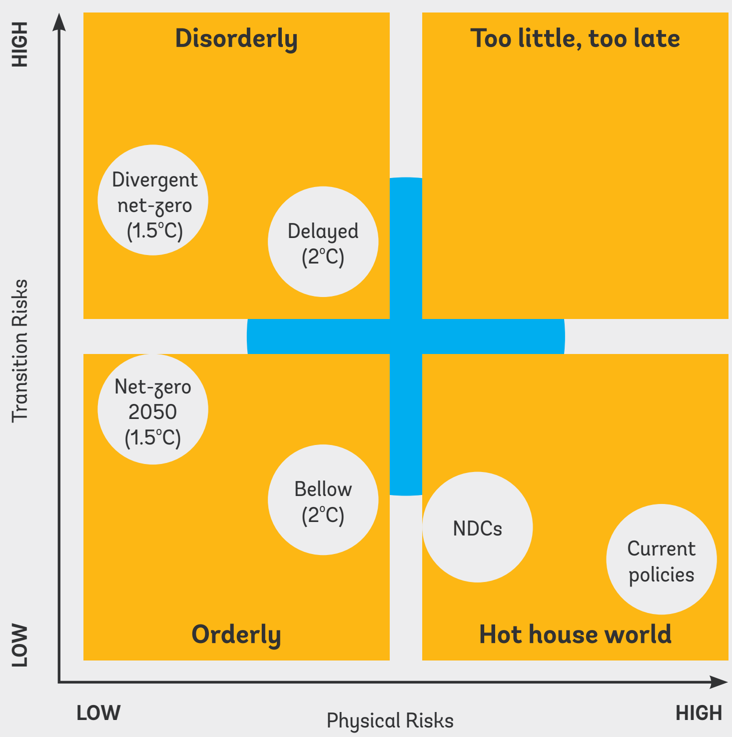
FIGURE B2.1.1. - **Mapping of Investigated Scenarios to the NGFS Classification**



a. Arguably, the assumed mitigation pathway of the transition scenarios may also be optimistic, for example in assuming the full deployment potential of carbon capture and removal technologies (such as from geoengineering, afforestation, soil and water management, etc.) and assuming that countries are on a track on their 2030 policy commitments (including nationally determined contributions). According to the last United Nations Environment Programme (2021) Emissions Gap Report, most countries who reported their progress are still far from their goals. However, in this paper we focus on the quantification of impacts rather than the mitigation paths.

Challenges to using IAMs for this type of assessment are well documented (Farmer et al. 2015; Stern 2016; Hepburn and Farmer 2020). Firstly, such models present an incomplete picture of the impacts of climate change, including missing extreme weather shocks (Stern 2016). In addition, several phenomena induced by climate change—such as migrations, crop yield shocks, and social instabilities in exposed regions—are missing from these models. The potential for cascading and compounding risks or nonlinear effects are also missing (Hepburn and Farmer 2020). The links between climate and ecosystems and natural resources (such as soil, water, forestry) that are known to be an important driver of financial risk (Dasgupta 2021), are excluded. Taken together, this implies that current IAMs and scenarios built upon them could underestimate physical climate risks. Finally, and crucial for climate financial risk assessment, IAM scenarios do not account for the financial sector and investors' expectations, thus missing important feedback between the economy and financial sector (Battiston et al. 2021). Evidence suggests these could be substantial gaps in current physical risk scenarios.

There are also limitations in current climate and impact models that underpin IAMs and the representation of uncertainties, as outlined by Fiedler et al. (2021) and Farmer et al. (2015): the range of possible future outcomes is much wider than implied by current scenarios. Each of these is important to consider when structuring scenarios for the purpose of evaluating the risk of financial outcomes and potential risk management options. Figure 2.1 represents the coverage of risks and uncertainties in current scenarios based on the authors' analysis, using a framework adapted from Watkiss et al. 2005 and Stern 2006.

The scenarios also do not capture the potential policy and financial responses to changing physical risks—for example, the potential for rapid adjustments in asset valuations in coastal and inland flood-exposed regions as investors perceive growing risks related to climate change or shifts in public policy that have widespread impacts on the availability of insurance. Such rapid adjustments are not unheard of today (for example, Keys and Mulder 2020; Kyum Kim and Peiser 2020).

NGFS made available in 2021 a Climate Impact Explorer,[6] with a set of indicators of acute risks such as 1-in-100-year losses and population exposures to extremes (from Climate Analytics). The Bank of England released similar variables for its 2021 Climate Biennial Exploratory Scenario (CBES) (Box 2.2).[7] This is helpful in filling the gaps in the core scenarios, yet this does not fully fill the gaps identified by Fiedler et al. (2021), Hepburn and Farmer (2020) and Stern (2016).

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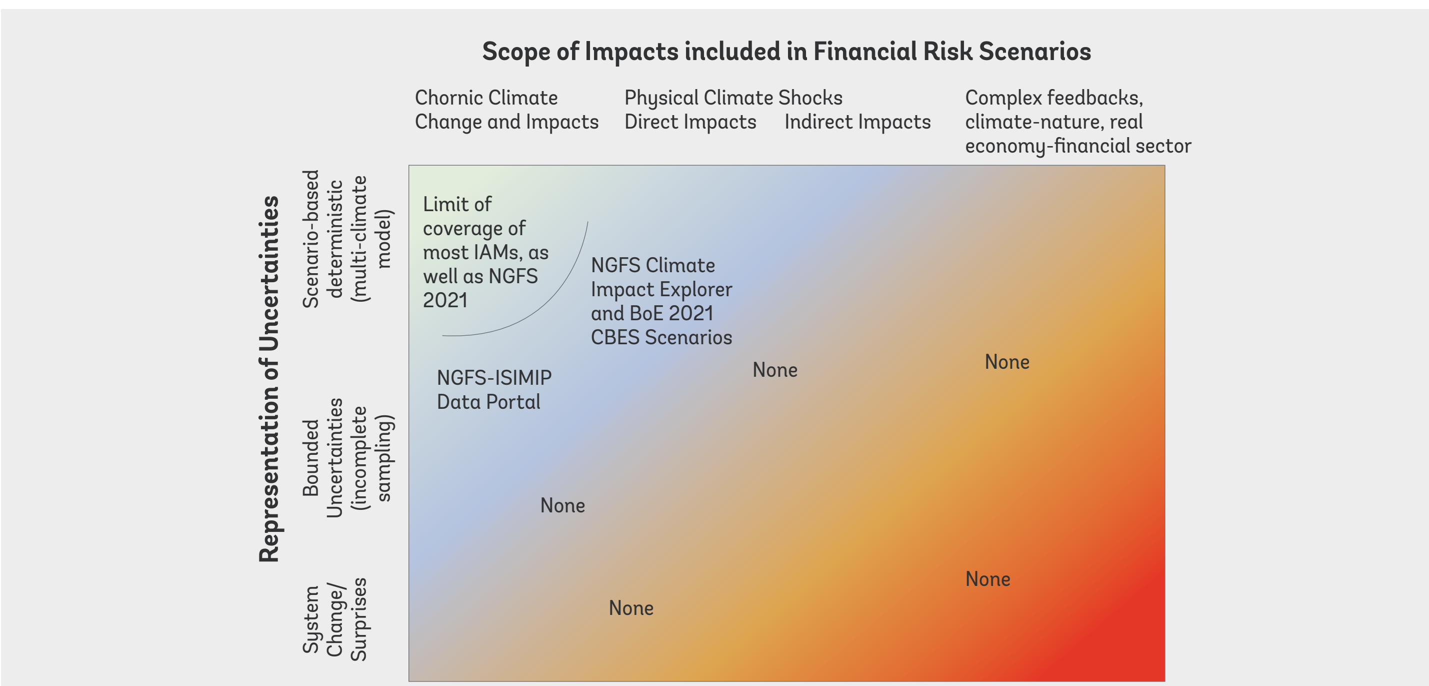
FIGURE 2.1. - **Coverage of Physical Climate-Related Risks in Current Scenarios**



Source: Adapted for this publication from diagram for coverage of risks in IAMs in Watkiss, Downing et al. 2005 and elaborated in Stern 2006. NGFS 2021 = Published scenarios in June 2021 (NGFS 2021b). NGFS-ISIMIP= Data available through the NGFS Scenario Explorer (https://data.ene.iiasa.ac.at/ngfs). BoE 2021 CBES are as outlined in box 2.2. NGFS Climate Impact Explorer (http://climate-impact-explorer.climateanalytics.org/).

6. More information is available at http://climate-impact-explorer.climateanalytics.org/.
7. Key elements of the 2021 biennial exploratory scenario are found at https://www.bankofengland.co.uk/stress-testing/2021/key-elements-2021-biennial-exploratory-scenario-financial-risks-climate-change.

According to the International Monetary Fund (IMF), for stress testing, the priority for central banks and supervisors is to identify and assess macrofinancial vulnerabilities that can trigger systemic risk, or, through the operation of the financial system, create downside risks to growth and so signal the need of systemwide mitigating measures (IMF 2019). Scenarios for bank stress testing should be "forward-looking, severe, consistent, and robust trajectories for a comprehensive set of macro-financial variables that react following the materialization of shocks… Scenario design starts with a narrative about how the realization of tail risks could interact with financial vulnerabilities to generate severe but plausible macro-financial impact" (IMF 2019). The evidence above suggests that the potential for systemic risks is currently not fully captured by the current scenarios made available to central banks and financial institutions. Using scenarios that do not capture important drivers of material financial risk could constitute a source of future systemic risk. For example, the emergence of new risk information over time could lead to rapid devaluations in asset prices and knock-on effects that could create instability. The same argument can be made for stress testing idiosyncratic risks (microprudential regulation) and ensuring the long-term soundness of financial sector development (often the responsibility of financial regulators and ministries of finance).

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BOX 2.2

Acute risks in the Bank of England 2021 Climate Biennial Exploratory Scenario

The Bank of England (BoE) runs regular stress tests to help assess the resilience of the United Kingdom's financial system and individual institutions. There are two types of exercise within the BoE's concurrent stress testing framework for banks and building societies (hereafter 'banks'): annual solvency stress tests and biennial exploratory scenarios. Running biennial exploratory scenarios allows policymakers to probe the resilience of the United Kingdom financial system to a wide range of risks and is a tool to enhance participants' strategic thinking on how to manage those risks. The 2021 exercise explores the resilience of the largest United Kingdom banks and insurers to the physical and transition risks associated with climate change, including acute physical risks. For the BoE, the intention is that the Climate Biennial Exploratory Scenario (CBES) be a learning exercise. Given that expertise in modeling such risks is in its infancy, the exercise aims to develop the capabilities of both the BoE and CBES participants.

The scenarios provided by the BoE for the CBES are not forecasts of the most likely future outcomes. Instead, the BoE describes that scenarios are plausible representations of what might happen based on different future paths of governments' climate policies (policies aimed at limiting the rise in global temperature). Each scenario is assumed to take place over the period 2021–2050. Participants will measure the impact of the scenarios on their end-2020 balance sheets, which represents a proxy for their current business models. For banks, the CBES focuses on the credit risk associated with the banking book, with an emphasis on detailed analysis of risks to large corporate counterparties. A key metric of that risk will be the cumulative total of provisions against credit-impaired loans at various points in the scenarios.

Chronic physical risk variables[a] are provided at (mainly) the national level for the United Kingdom and seven other countries, including temperature; precipitation rate; wind speed; land area exposed to crop failure and sea level rise in 2020, 2030, and 2050. Acute risk variables include tropical cyclone (category 3–5 frequency and intensity changes) and land area exposed to heat wave and wildfire. Macroeconomic variables are provided, including both transition and (chronic) physical risks. Much of the data comes from the NGFS, with some exceptions.[b] A single value is given for each variable and no uncertainty information is provided. The BoE provides links to additional data provided by the NGFS from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)[c] that includes further model-based projections.

Source: Bank of England 2021, Key elements of the 2021 biennial exploratory scenario located at https://www.bankofengland.co.uk/stress-testing/2021/key-elements-2021-biennial-exploratory-scenario-financial-risks-climate-change.

a. Chronic variables can be found at https://www.bankofengland.co.uk/-/media/boe/files/stress-testing/2021/variable-paths.
b. OASIS Hub for wind speeds and sea level rise, UK Met Office for UK projections and Knutson et al. 2000 for tropical cyclone.
c. The physical impact data collected by the ISIMIP is located at https://www.isimip.org/outputdata/isimip-data-on-the-esgf-server/.

This paper discusses how such gaps can be filled in a way that is feasible and commensurate with the scale of the risks versus other (non-climate) risks faced by financial institutions. It is helpful to briefly compare and contrast the approach to scenario generation taken to standard practice in macro- and microprudential risk management in the insurance sector (including regulatory frameworks such as Solvency II—the prudential framework for insurance firms in the European Union). The insurance industry and its supervisors and regulators are experienced in managing the financial risks of physical climate shocks. The insurance sector typically uses catastrophe risk models that are tailored to assess the direct impacts of physical climate shocks (physical damage) and importantly, are able to represent the volatility (or stochastic nature) of these shocks as well as their correlation/systemic implications for individual firms and the industry globally, rather than just averages. Such extreme scenarios are critical to inform underwriting and portfolio risk management. Under Solvency II, capital requirements are determined on the basis of a 99.5 percent (1-in-200 years) value-at-risk measure over 1 year, meaning that enough capital must be held to cover the market-consistent losses that may occur over the next year with a confidence level of 99.5 percent.[8] The Bank of England's General Insurance Stress Test 2019 required insurers to stress test against extreme weather event scenarios of between 1-in-100 years and 1-in-250 years compounded with an insurance asset price shock (PRA 2019). Lloyd's of London requires all syndicates to report against 16 compulsory "Realistic Disaster Scenarios," including a major hurricane striking New York State and the East Coast of the United States (Lloyd's of London 2021). See Box 2.3 for more on these two approaches. These approaches can draw important lessons for physical climate-related financial risk assessment; specifically, the focus on simple, realistic but extreme scenarios for stress testing and the use of multiple scenarios, with quantitative and qualitative elements, that aim to explore the space of possible outcomes and avoid spurious accuracy that can emerge when attempting to provide projections based on models when there is deep uncertainty.

8. Solvency II (Directive 2009/138/EC) as amended by Directive 2014/51/EU (Omnibus II).

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BOX 2.3

Stress Testing Scenarios for Physical Climate Shocks in the Insurance Industry

Bank of England's General Insurance Stress Test 2019[a]

The 2019 stress test provided a series of scenarios that aimed to stress the asset and liability side of insurers in parallel. On the asset side, the scenario outlines a deterioration in the economic environment, including reduction in interest rates, widening of corporate bond spreads, and fall in asset values. In parallel, insurers are asked to stress test against five liability shock scenarios, four of which are based on natural catastrophes. As an example, scenario five describes a set of two events that generate some £20 billion of aggregate insured loss, both occurring in the United Kingdom. The first event is a windstorm causing significant storm surge losses along the East coast of England that generates approximate half of the overall losses (figure B2.3.1). The second event is for extensive flooding across England and Wales, generating the remainder of the overall losses (figure B2.3.2). The return period for aggregate wind, surge, and flood losses of this size to the United Kingdom is estimated to be approximately 200 to 250 years. Firms are encouraged to develop their own view of risk, including making adjustments for model uncertainty. This stress is superimposed on the insurance asset shock scenario, a compound risk scenario. In 2019, firms were also requested to consider the expected impact under three different climatic states on their assets, liabilities, and business models, assuming that their current exposures and investment profile remain constant. Learning from this exercise fed into the design of the 2021 Climate Biennial Exploratory Scenario.

FIGURE B2.3.1.
United Kingdom Windstorm scenario

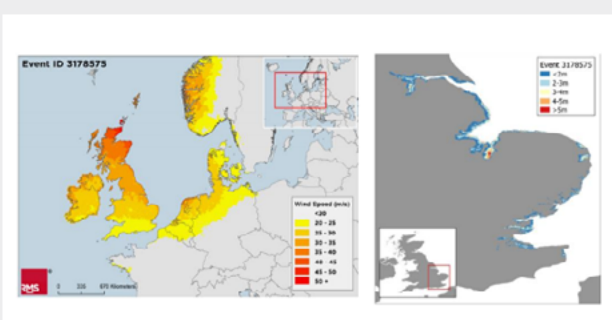
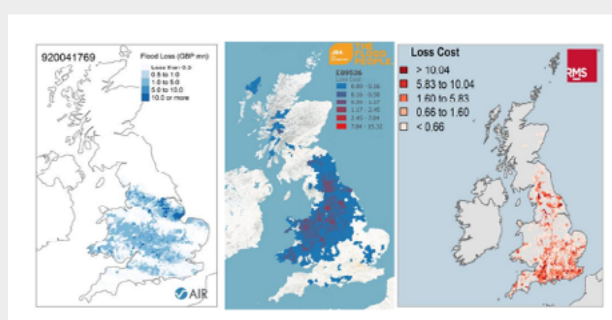


FIGURE B2.3.2.
United Kingdom flood scenario



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Lloyd's of London Realistic Disaster Scenarios 2021b

There are 16 compulsory scenarios that managing agents must complete for all syndicates, with losses of up to US$120 billion. Each scenario outlines an extreme but realistic event, the largest of which is a double hurricane strike to the United States in a year: one causing major damage to the North East United States and the other to South Carolina. Managing agents are provided with detailed loss information for the scenarios, including residential and commercial property losses as well as disruptions to ports and airports. Other scenarios include windstorm strikes to Florida, a United Kingdom flood, Japanese typhoon and earthquakes, and a California earthquake and terrorism scenarios.

FIGURE B2.3.3.
Hurricane Strike to the US Northeast Scenario

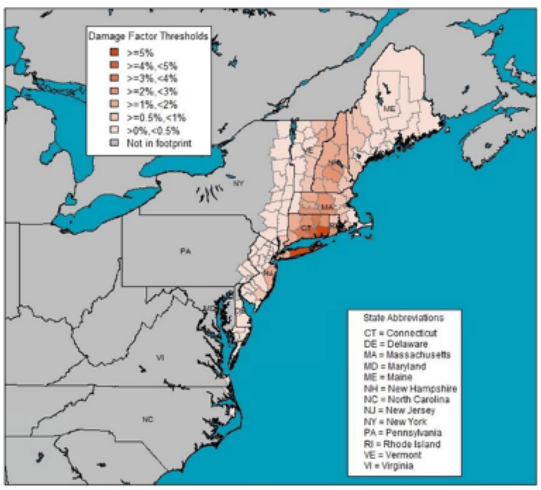
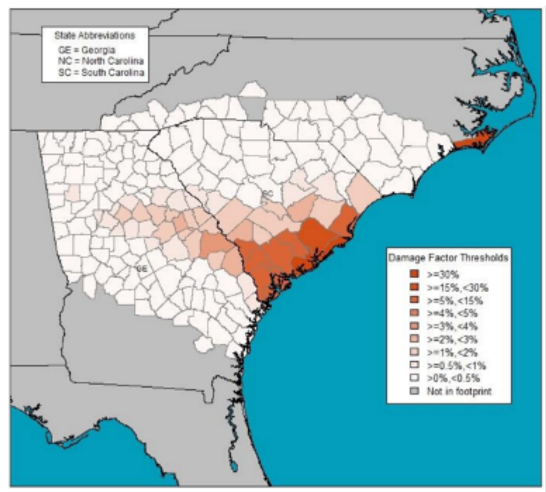


FIGURE B2.3.4.
Second Hurricane Strike to South Carolina Scenario



Source: PRA 2021; Lloyd's of London 2021

a. Information resourced at https://www.bankofengland.co.uk/-/media/boe/files/prudential-regulation/letter/2019/general-insurance-stress-test-2019-scenario-specification-guidelines-and-instructions.pdf.
b. Information resourced at https://assets.lloyds.com/media/e73cc2f7-a535-4eaf-8196-fedcf5e1432c/2%20RDS%20Scenario%20Specification%20%20January%202021.pdf.

One example of a central bank climate stress test that bridged across this standard practice in the insurance industry and approaches for bank stress testing was the 2021 IMF and World Bank Financial Sector Assessment Program for the Philippines (IMF 2021). Similarly, to the 2019 Bank of England General Insurance Stress Test, this climate stress test for the central bank considered a 1-in-250 years typhoon scenario compounded with an economic shock and a pandemic, in a current and future climate (taking an upper bound scenario). The climate stress (Box 2.4) connected a climate model, a catastrophe risk model, and a macrofinancial model to develop scenarios for the stress test. It concluded that physical climate risks are relevant for financial stability, though the infrastructure destruction from typhoon wind alone is not systemic unless extreme tail events materialize. This highlights the importance of considering such tail risks. On the basis of this analysis, it recommended improving information collection, monitoring risk metrics, and stress test capacity for climate change and environmental risks.

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BOX 2.4

IMF 2021 Philippines Financial System Stability Assessment Program

The 2021 Financial Sector Assessment Program (FSAP) developed a new approach for analyzing banks' solvency for physical risks from typhoons, building climate change macroeconomic scenarios using climate science studies, a catastrophe risk model, and a macrofinancial model, in collaboration with the World Bank. The analysis indicated the relevance of typhoon risks, though found that they may not be necessarily systemic except for extreme tail events. Without other shocks, the destruction of physical capital from typhoons' wind alone would reduce bank capital ratio only by 1 percentage point, even in once-in-500-years events in the future (figure B2.4.1). However, the joint shock with a pandemic intensifies the effects of climate change for extremely intense typhoons (figure B2.4.2). For once-in-500-years events, the difference between current and future scenarios with the pandemic rises to 4½ percentage points.

FIGURE B2.4.1.

Impact of Typhoon on Bank Capital – Normal Time

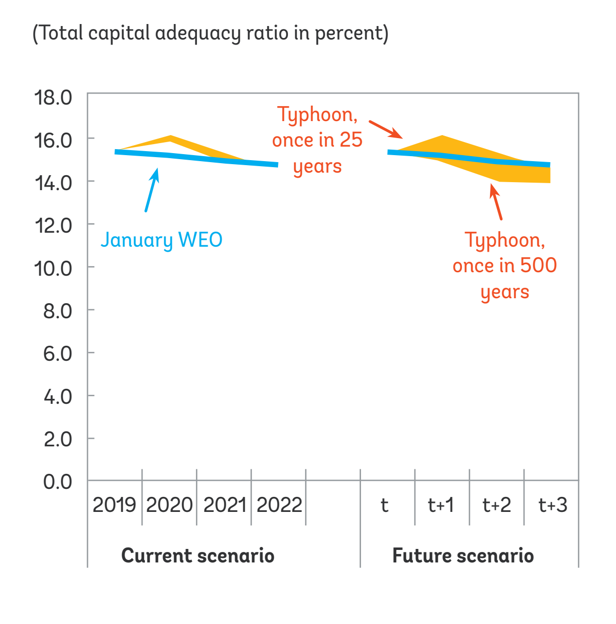
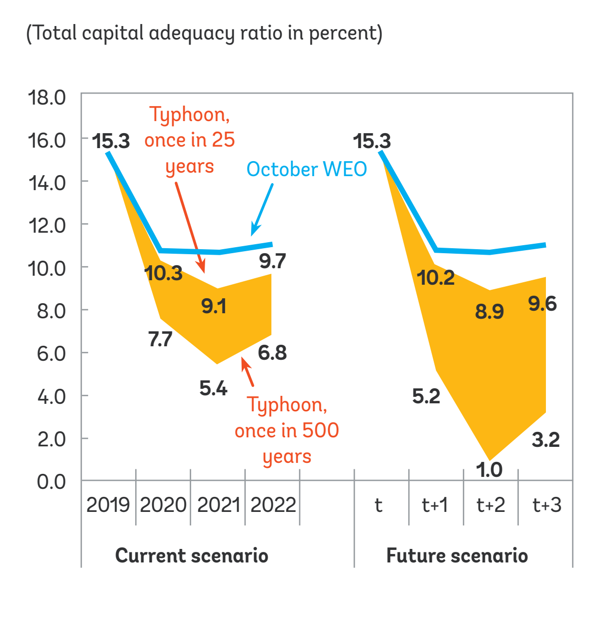


FIGURE B2.4.2.

Impact of Typhoons and Pandemic on Bank Capital



Note: WEO = World Economic Outlook, https://www.imf.org/en/Publications/WEO

3. Empirical Evidence on the Impacts of Physical Climate Shocks to Banks

This section reviews the empirical literature on the impacts of physical climate shocks on the banking sector in order to identify specific gaps in the representation of risks and transmission channels. While there is a well-established literature on the social and economic impacts of weather-related shocks based on empirical analyses and models (for example, review by Botzen, Deschenes, and Saunder 2019), evidence on the impacts on the banking sector itself is more nascent. A number of studies have analyzed historical impacts of disaster-related shocks on the banking sector. For example, Noth and Schüwer (2017) present evidence from the USA that disasters can weaken the stability of banks in the same region measured through lower z-scores, higher probabilities of default and higher nonperforming loan ratios. Klomp et al. (2014) present evidence across 140 countries showing increased probabilities of default for commercial banks following disasters. Calice and Miguel (2021) study empirical evidence on climate risks in Latin America and the Caribbean (LAC) and find that after largescale natural disasters, banks' nonperforming loans increase by up to 1.4 percentage points in affected provinces. They conclude that in terms of physical climate risks, exposure to floods represents the most important source of credit risk for the LAC banking sector, with exposure particularly concentrated around cities. Climate can also affect bank lending decisions; for example, Garbarino and Guin (2021) analyze how lenders account for recent severe flood events in England in 2013–14, finding that lender valuations are biased upward, and lender do not track closely the impact of extreme weather events.

A first conclusion from such studies is that the impact of physical climate risks on the banking sector is highly dependent on the level of resilience of the financial sector overall (to any shock) and the vulnerability of their borrowers. For example, countries with weaker supervision and regulation and with more concentrated and less interconnected banking sectors will see greater risks, while more advanced and resilient financial sectors will be less affected. Smaller economies will be more vulnerable, particularly small island states where economic losses can constitute a significant proportion of their gross domestic product (GDP). This is an intuitive result, yet one that is important to explicitly recognize because it underlines the importance of tailoring scenarios to the circumstances of the country. This moderating (or amplifying) factor needs to be accounted for when assessing climate-related financial risks and is not explicitly captured in current scenarios. Central banks and supervisions would typically account for this within their own top-down stress tests, but there is limited guidance on the implications for climate scenario construction or analysis.

The evidence available also points toward a complex web of transmission channels between the direct impacts of shocks (such as capital destruction or loss utilities such as power), the real economy, and the financial sector. Figure 3.1 below maps the main transmission pathways based on the literature and describes the main types of impact in the context of the International Monetary Fund's (IMF's) Financial Soundness Indicators (IMF 2006) (capital adequacy, asset quality, earnings and profitability, liquidity, and sensitivity to market risk). It is consistent with that provided by the Bank for International Settlements (BIS) (BIS 2021) and the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) (NGFS 2021a) as well as the analysis of transmission channels provided by Feyen et al. 2020.

Disasters cause damage to physical assets and other productive capital, as well as business interruption (for example, due to disruptions to power) and reduced demand or reduced production (for example, in the case of agricultural firms and drought), potentially leading to reduced return on assets for the firm and reduced *asset quality* for banks (higher nonperforming loans or impairments). This can have knock-on effects throughout the real economy that can slow growth, including through impacts on supply chains, demand, and households (impacts on income and consumption). At the same time, demand for credit increases postdisaster for recovery and reconstruction, and in some cases, withdrawals may increase, tightening *liquidity* of banks.

Where financial resilience of banks is relatively low, this can lead to a depletion of capital, and, if liquidity is insufficient, can threaten the survival of the bank. Reserves may be depleted due to a large write-off of loan losses or a reduction in risk-weighted asset values. Asset risk may be increased by the destruction of collateral of borrowers. *Profitability* (return on assets) may decrease as a result of write-offs. Banks may also experience damage and operational disruption from physical damages to their own buildings or critical services.

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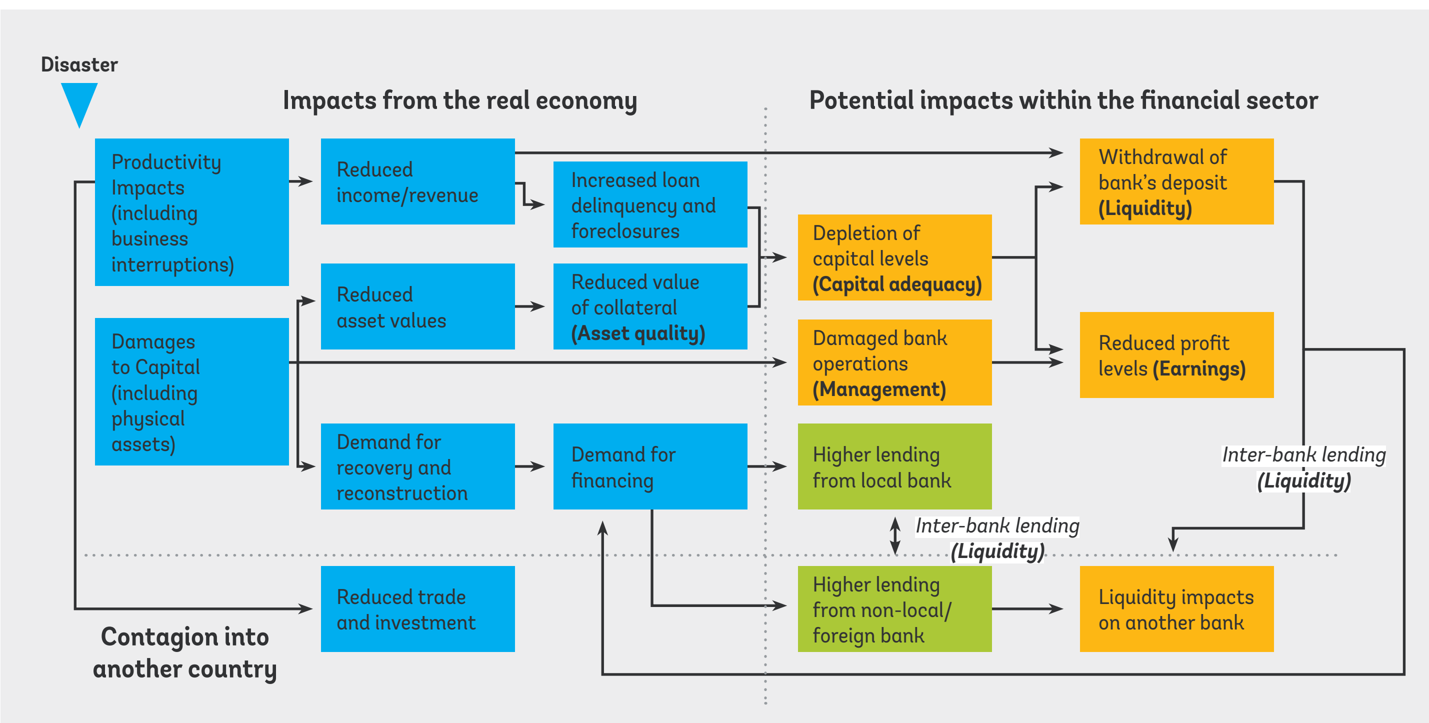
FIGURE 3.1. - **Illustration of the Transmission Channels for Shocks from the Real Economy to the Financial Sector**



Source: Original figure for this publication.

Where predisaster financial resilience and health of the banking sector is high, the impact of such shocks on the financial sector is minimal. In addition, even in developing countries, typically the government and central bank will act quickly postdisaster to protect stability. For example, to help ease the impact of the 2015 earthquake, the central bank, Nepal Rastra Bank (NRB), put in place regulatory relief for banks to enable them to continue to extend credit despite heavy impacts on the economy, including time-bounded measures covering loan-loss provisioning, loan rescheduling, grace periods, and regulatory forbearance on asset classification (IMF 2015). Impacts on financial stability were avoided. Likewise, in the 2011 Thailand floods, 4–13 percent of loans by value were in affected areas, and the Bank of Thailand responded by relaxing asset classifications (TCG 2016; World Bank 2012; IMF 2012; Ramcharram 2017) and providing a (partial) credit guarantee facility to support recovery. This, combined with strong existing capital buffers, avoided major impacts. These responses are one reason why it is difficult to find empirical evidence of impacts of disasters on, for example, nonperforming loans.

Arguably, this risk is being absorbed somewhere in the system, and this should be considered by ministries of finance and central banks when projecting future climate-related financial risks. In some cases, for example, the risk is being absorbed by the public sector in the form of partial credit guarantee schemes and so is relevant to fiscal risk assessments.

Feyen et al. (2020) demonstrate that countries with the greatest physical climate risks also tend to be those with the greatest macrofinancial risks. They find that a significant number of countries, particularly emerging and developing countries, face a double jeopardy due to the simultaneous presence of climate-related and macrofinancial risks. These countries have limited macrofinancial capacity to act, meaning that as physical climate risks materialize, high macrofinancial risks mean low macrofinancial resilience and a high risk of prolonged crisis.

Even where national (systemic) financial stability may be minimally affected, the impacts on local banks and financial institutions serving more vulnerable affected groups can be significant. For example, while Typhoon Haiyan (Yolanda) in the Philippines in 2013 had a minimal and short-lived impact on national GDP, the impact on the local economy and local banks was significant (Gonzalez Pelaez 2019); in the worst-hit areas of Leyte Province, damage to the main sugar cane and rice industries was estimated at over US$300 million (World Bank Group 2014), and the wider Eastern Visayas region overall suffered 2.3 percent contraction in GDP in 2014 from a 4.5 percent growth in 2013 mainly due to the lingering effects of the typhoon (Perez 2015). In Nepal, while overall financial sector stability was unaffected by the 2015 earthquake due to swift action by the NRB, many microfinance institutions (MFIs) and savings and credit cooperatives (SACCOs) serving more deprived areas suffered increases in NPLs and liquidity issues (Government of Nepal 2015). This suggests that subsectors serving more vulnerable groups, such as agribanks, MFIs, and SACCOs may face much higher climate-related financial risks. More work is required to understand any potential contagion affects to financial stability overall as well as the implications for financial inclusion, economic development, and poverty alleviation.

The indirect impacts of physical climate shocks on the banking sector through transmission through the wider macroeconomy, could be larger than the financial risks associated with the direct impacts on firms. This effect is also highly dependent on economywide vulnerability factors. For example, for the most high-income countries, the overall economic impact of disasters is typically small compared with GDP, and indeed, reconstruction can boost output, creating increased demand for credit. But for small island developing states (SIDS) and other small or highly vulnerable states, the impacts of climate shocks on the economy can be significant and long-lasting. For example, in the Caribbean, a one-off hurricane strike can cause damages equivalent to more than 100 percent of GDP, creating, on average, a reduction in output growth of just under 1 percent since 1950 or 7.6 percent for the most destructive hurricanes (Stobl 2009; Alleyne et al. 2017). The 2019 Financial System Stability Assessment Program for the Bahamas found a relationship between NPLs and hurricanes and concluded that the most significant impacts of hurricanes on the banking sector are mediated through the impacts of hurricanes on economic growth and employment rather than direct credit exposure (IMF 2019).

Physical climate-related financial risks become more material when compounded with other economic shocks. For example, evidence from the Caribbean showed that when growth is weak, the impact of hurricanes on NPLs can be amplified and more nonlinear (IMF 2019; Brei, Mohan, and Strobl 2019). This is an important finding, particularly in a COVID-19 context when economies are under strain. For instance, the compounding of physical climate risk (hurricanes) and the pandemic in Mexico contributed to amplify the initial macroeconomic shock, with implications for banks' financial stability and sovereign debt sustainability (Dunz et al. 2021). This points to the importance of considering compounding risks within a physical climate risk assessment (Ranger, Reeder, and Lowe 2021).

Finally, empirical evidence shows that feedback effects between the financial sector and the real economy can amplify or dampen the financial risks to banks (and the wider economy). Firstly, banking-related services play a critical role in economic recovery postdisaster; this includes withdrawals of deposits, restructuring lending, new lending to finance postdisaster reconstruction, or remittance flows. Any disruption to these services can have a major impact on the scale of impacts on firms and households and recovery times. For example, evidence from 1995 Kobe and 2011 Tohoku earthquakes in Japan suggests that physical damage to banks negatively affected investment by firms in those regions (Miyakawa and Hosono 2017). Empirical analyses over 178 countries from 1979 to 2007 found that lack of credit can compound the effects of a disaster, and countries with lower financial sector development tend to suffer more persistent negative impacts of disasters on economic growth over the medium term (McDermott, Barry, and Tol 2014). This feedback could create greater vulnerability over time as asset quality increasingly erodes, particularly in the context of more frequent, intense climate-related shocks.

In conclusion, the review of the empirical evidence suggests a number of factors that should be considered by ministries of finance, central banks, financial regulators, and financial institutions in physical climate financial risk assessment for climate-related financial risk management, including stress testing. Those factors include:

- The importance of representing the feedback between the real economy and the financial sector, which will be specific to the circumstances of the country.
- The need for a tailored approach to developing scenarios that fully capture the risk transmission channels of greatest relevance to the financial sector.
- The links between public and private financial institutions; risk is always absorbed somewhere and often the public sector absorbs some of the private financial risk in times of crises.
- The importance of representing the full economic and social impacts of physical climate shocks, including extreme events and their short-term and long-term indirect economic impacts.
- The need to map subnational risks and risks to financial institutions serving the most vulnerable groups to understand potential contagion effects (and impacts on financial inclusion).
- Consideration of global cascading and national compounding risks.

4

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Revisiting the Development of Physical Climate Financial Risk Scenarios

From the review in the sections above, we can draw out five important areas to consider within a physical climate-related financial risk assessment and scenario design.

1. Representing the **current and future risks of climate extremes, such as hurricanes, droughts, and floods**—or disaster scenarios—in the analysis. This includes representing the direct impacts of extreme weather on natural and human systems, for example on agricultural production, critical infrastructure services, or ecosystem services.

2. Fully accounting for **uncertainties** in climate and impact models to ensure that scenarios span the space of potential future climate outcomes (rather than model averages).

3. Including **compounding scenarios** of physical climate shocks with other shocks and stressors. Climate change will not happen in isolation, and physical climate risk assessments cannot ignore the compounding impacts with other factors that amplify risks, including economic cycles and socioeconomic vulnerabilities, as well as the potential for climate to compound with other shocks like pandemics and climate transition risks.

4. Representing the **indirect impacts** of weather extremes on households and firms and the macroeconomic impacts in addition to the direct impacts in terms of physical capital destruction or production loss. These can create an amplification factor on the risk to the banking sector. This could also include indirect effects related to regional or global impacts of weather extremes.

5. Representing the **financial sector** adequately to capture both the level of resilience of the financial sector to shocks and the complex feedbacks that can amplify risks by prolonging reconstruction and recovery. This includes considering more vulnerable parts of the financial sector, such as microfinance institutions (MFIs) and savings and credit cooperatives (SACCOs) where these are material.

It should be noted that in the first three areas of concern, the exogenous shock is represented within scenarios, that is, the external driver associated with physical climate change. In the latter two areas of concern, the representation of endogenous (internal to the economy) factors might amplify or suppress the impacts of the shock within scenarios and/or within models used to simulate the impact on the real economy and financial sector. Any standard framework for stress testing physical climate risks should be redefined to include consideration of these five factors. It should fully capture the nature of the exogenous shock and particularly the tail risks, which means the volatile nature of weather extremes, the range of possible climate outcomes, their physical impacts on natural systems, and the potential for compounding risks, all of which are known from empirical analyses to be important to banks in determining the financial risks associated with physical climate (see Section 2). A framework should also capture the interaction of these tail risks with the real economy and financial vulnerabilities, which can be a critical amplifier of physical climate-related financial risks (Mandel et al. 2021). As noted above, current scenarios do not capture consistently some of those important risk drivers.

It is necessary to take a proportionate approach. The important question is then how material are these risk drivers compared with drivers considered in the current scenarios, and how can these be included in scenario development in a simple way? The following subsections provide evidence on the potential materiality of each of these risk factors in turn, including new modeling on the interaction of physical climate shocks with financial sector vulnerabilities and the potential amplification from compound shocks. They also review the tools and approaches available to characterize the risks. While we take each factor in turn, the examples builds across each subsection, such that the results shown for the final subsection include each of the five factors to demonstrate how they can be combined.

4.1. Scenario Generation for Extreme Weather Events Under Current and Future Climate Change

The 2020 and 2021 Network of Central Banks and Supervisors for Greening the Financial System (NGFS) scenarios did not include acute physical climate shocks, albeit in 2021 a set of separate risk indicators were provided.[9] The 2021 Bank of England Climate Biennial Exploratory Scenario (CBES) scenarios similarly included some scenarios of future acute risks, specifically for tropical cyclone. Smith (2021) reviewed approaches taken by commercial providers and financial institutions.

In the climate financial risk literature, two approaches have begun to be explored: (1) to use average annual (direct) losses and (2) to develop a risk rating based on exposure to hazards[10] (for example, Smith 2021). There are challenges in both approaches for the assessment of financial risks. The generation of probabilistic risk data and scenarios of extreme weather to inform financial decision making is well developed, in particular in the insurance industry. From this experience, the financial risks from physical climate shocks cannot be approximated by considering only average annual costs of weather extremes, even on long timescales. Larger, rarer events can cause significant damage and disruption and have long-lived impacts. Vulnerability to such shocks, and in particular indirect damages, can be strongly nonlinear. This means that using measures of average direct losses over time can mask events (and tail risks) that could create significant damage. This is illustrated in figure 4.1. Simple exposure mapping also fails to capture these nonlinear and diffuse impacts. In addition, the past is not a good guide to future risk; using only catalogs of historical events can lead to underestimates of the risk; particularly where considering the risks associated with rare, more severe shocks that may not yet have been observed in recorded history and in the context of a changing climate. These lessons have been learned at high cost by the insurance industry. For example, when Hurricane Andrew struck Florida and Louisiana in 1992 it caused (at that time) unprecedented losses that drove some insurers into insolvency as a consequence of underestimating risk within pricing and portfolio risk management.

9. Future vintages of NGFS scenarios plan to be extended to the analysis of expected economic damages of climate change, based on the probabilistic natural catastrophe impact model CLIMADA. See https://wcr.ethz.ch/research/climada.html for more on CLIMADA.
10. For example, is a particular asset located in a flood plain.

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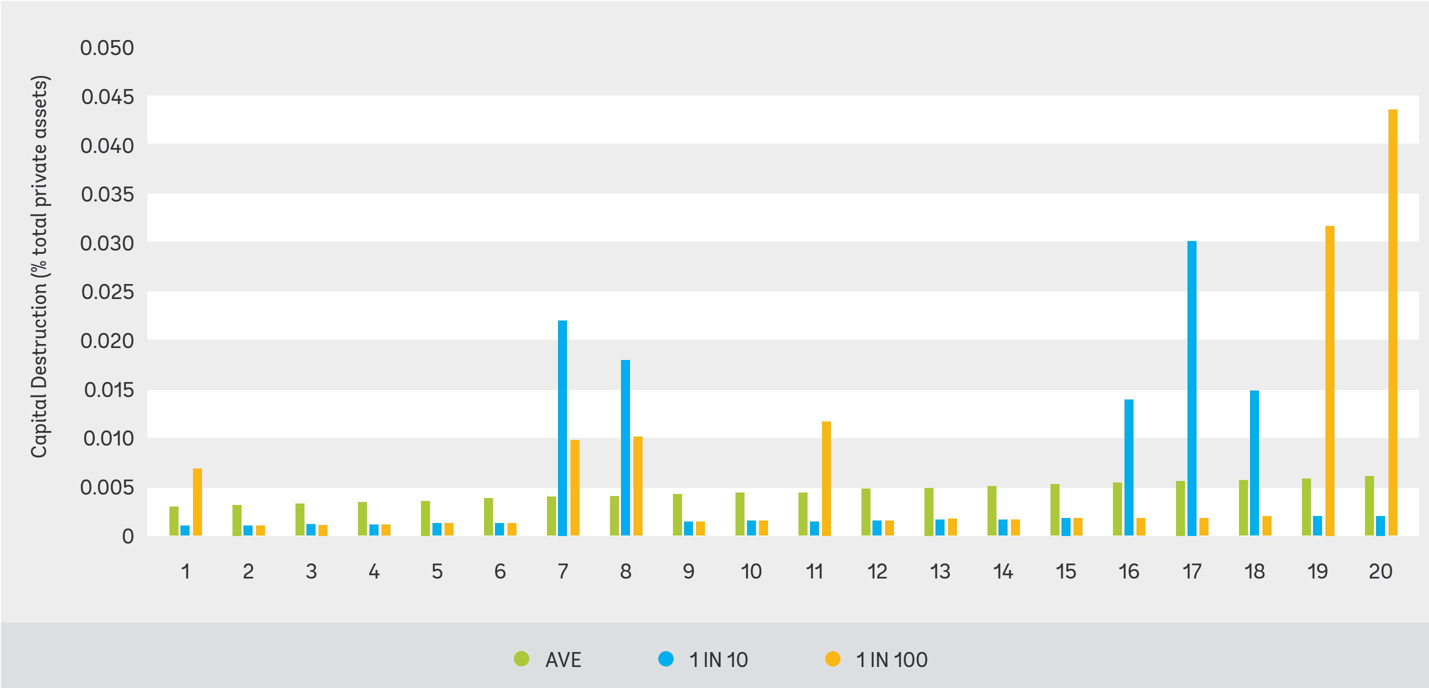
FIGURE 4.1. - **Cumulative loan losses for transition scenarios per bank (percentage of total assets)**



Source: Original calculations for this publication.
Note: Two possible versions of a 20-year period are shown and compared with the average annual loss (each have roughly the same average annual loss). The economic and financial sector impacts associated with these three timeseries would be different given the nonlinearities in indirect impacts and the more prolonged reconstruction and recovery times associated with larger events.

Disaster risk finance (DRF) analytics is a toolkit that has been used in practice for more than two decades to support ministries of finance, insurance supervisors and the insurance industry to strengthen their financial resilience to climate-related and other shocks. Core to this toolbox is the catastrophe risk model, the workhorse analytical tool of the insurance industry since Hurricane Andrew in 1992, to price and manage the financial risks associated with a wide range of catastrophe events, from pandemics to natural hazards, terrorism risks, and climate change. There are many types of catastrophe risk models, from the simplest probabilistic models based upon historical losses and exposure analysis to more complex and spatially resolved models -used for insurance underwriting - that use the latest high-resolution climate models to simulate large catalogs of realistic events in probabilistic terms and overlay with detailed exposure data.

At their core, catastrophe risk models provide a probabilistic view on the financial impacts of weather and climate to particular assets, sectors, or economies. They combine science, engineering, economics, and finance to simulate, in probabilistic terms, the potential financial impacts of disasters to a given portfolio. As noted in Section 1, such tools are used routinely today by insurance supervisors and firms as part of stress testing exercises to ensure the stability and solvency of insurers and are increasingly used by ministries of finance to design strategies to reduce financial risks from disasters to government balance sheets (World Bank 2019).

A further advantage of more sophisticated catastrophe risk models is their ability to assess risk at a granular scale (up to individual buildings) and so assess potential concentrations of risk or distributional factors that can have significant implications for public policies. For banks, which may have geographically concentrated exposures—for example a mortgage portfolio concentrated in cities—this granularity can be particularly important. With this, risk can be underestimated. For highly location-specific hazards such as flooding, a high level of spatial resolution in both the hazard and exposure data is essential to avoid significant biases in risk estimation.
Where such models do not exist, for example, for many developing countries or where is it not feasible to build or obtain such models from proprietary sources, it is common to develop risk profiles using public empirical data on natural hazard and disaster risk and losses databases (examples include EM-DAT, DesInventar, and UNEP-GRDP). Various open access catastrophe risk models are also now becoming available and could play an important and growing role in coming years.

The use of catastrophe risk models for assessing the financial risks of climate change is not new. Such models are already being used to respond to supervisory requirements for climate change stress testing of insurance companies in several countries (PRA 2019). Indeed, so-called climate-conditioned catastrophe risk models have been used by both the insurance industry and government to assess economic and financial impacts of climate change since circa 2005 (see ABI 2005 for example). There is a significant amount of experience in the use of climate and catastrophe risk models to develop climate change scenarios (for example, see Golnaraghi 2021). Like all models, catastrophe risk models come with uncertainty (Aerts et al. 2014), but there is substantial knowledge about how to manage uncertainties in these models in decision making (see Dietz and Niehörster 2020).

In summary, to generate probabilistic scenarios of extreme weather impacts toolkits are available that are tried and tested within decision making in the financial sector and commonly applied within adaptation decision making and climate risk management in other sectors. This existing knowledge, particularly that which has been developed by the insurance industry over several decades, can be readily deployed to support the development of acute risk scenarios for banks. For the reasons described above, probabilistic risk assessment or risk profiles, including catastrophe risk models, should become an important part of the arsenal of ministries of finance and central banks to assess the future financial risks from climate change.

4.2. Fully Capturing the Uncertainty in Current Climate and Impact Projections

A further challenge to be addressed is how to represent the uncertainties in climate (and catastrophe risk) models within scenario development. With climate change, the frequencies and intensities of weather extremes are expected to shift, often toward more frequent intense events (IPCC 2012). However, the scale (and sometimes direction) of changes with climate change is deeply uncertain; this means that it is currently not possible to attach probabilities to such scenarios.

As noted by Schinko et al. (2017) in the context of deep uncertainty, models and scenarios that allow to "explore rather than predict" can better help understand the drivers of individual and system-level responses to shocks in comparison with forecasting models. This approach—which aims to develop plausible but severe scenarios to explore vulnerabilities and risk mitigation options—is well developed in other areas of climate risk management (Kunreuther et al. 2014; Lempert et al. 2013; Hallegatte et al. 2012). It is also consistent with the standard requirements for stress testing and vulnerability assessment by central banks (IMF 2019). As such, it is proposed here as the basis of a framework for scenarios to explore future physical climate-related financial risks. This is a different approach to that encapsulated in current scenarios that provide deterministic projections of future climate risks based purely on models. An approach that more explicitly recognizes deep uncertainty is more akin to the Realistic Disaster Scenarios employed by the insurance industry (Lloyd's of London 2021; PRA 2019).

Substantial literature exists on scenario development under conditions of deep uncertainty (Lempert et al. 2013). This concludes that uncertainty should not be ignored, but instead that scenarios be developed to represent the range of possible outcomes. Model intercomparison initiatives, like the Climate Model Intercomparison Project (CMIP[11]) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), attempt to put bounds on model uncertainty through comparing multiple models run with the same scenarios. However, as noted by Fiedler et al. (2021), ranges generated through such exercises should not be interpreted as the bounds of future outcomes. To account for deep uncertainties, scenario generation exercises will often include model-based projections alongside scenarios developed through expert judgment and the best available science. In the physical climate literature, scenarios that aim to explore the space of possible future outcomes are referred to as story lines (Jack et al. 2020).

The use of such scenarios is commonplace in climate change adaptation planning; for example, such an approach was adopted in the development of scenarios of sea level rise to inform the construction of the Thames Barrier that protects London from flooding (see review by Ranger, Reeder, and Lowe 2013). In this case, scenarios included not only mean projected changes in sea level over the coming decades from climate models, but also a "high+" and "high++" scenario that represented the potential for low probability but high-impact outcomes based upon expert judgment and the best available science on ice sheet melt.

Such approaches have been applied to generating scenarios of extreme weather events with climate change to inform decision making (for examples, see Ranger and Niehörster (2012) for hurricanes in the Atlantic and Daron et al. 2018 and Gallo et al. 2018 for typhoons in the Philippines). Such scenarios have been used to explore the range of impacts of climate change on the insurance industry (Kunreuther, Michel-Kerjan and Ranger 2013). This type of scenario development ap-

11. For more on CMIP see https://www.wcrp-climate.org/wgcm-cmip.

proach appears well aligned with practice in the development of scenarios for stress testing. This is similar to the approach taken by the International Monetary Fund (IMF) in the Philippines (IMF 2021), which built upon those studies noted above.

In summary, uncertainties should not be ignored but rather scenarios developed that span the range of plausible outcomes. There is an established literature and practice to draw upon. Scenario generation exercises that combine model-based projections with expert judgment and the best available science could also be important in ensuring scenarios fully represent tail risks.

4.3. Representing the Indirect Impacts of Physical Climate-Related Shocks

Most existing physical climate risk assessments, including, for example the NGFS Climate Impact Explorer, provide estimates of the direct impacts of physical climate shocks (Smith 2021), but miss the indirect impacts. In many cases these can be at least as large or larger. The differences between direct and indirect impacts can be thought of as damage to stock within an economy (capital stock, for example) versus impact on flows, including supply chains and production.

The direct impacts of an event can be defined as the direct cost of repairing or replacing (at the pre-event price level) assets that have been damaged or destroyed (Hallegatte 2008).[12] Such costs are routinely estimated by insurance companies and are output of traditional catastrophe risk models. But importantly, the direct cost of a disaster is often only part of the overall economic cost and in some cases, can constitute only a fraction of the overall costs to a particular firm and the overall economy. The remainder is the indirect loss, which was defined by Hallegatte (2008) as "the reduction of total value added by the economy because of the disaster; (the indirect loss is) the reduction in production of goods and services, and can include business interruption in the event aftermath, production losses during the reconstruction period, and service losses." Indirect losses refer to changes in economic activity that follow the disaster and include any positive spillover effects due to the substitution of production and the demand for reconstruction (Botzen, Deschenes, and Saunders 2019). This captures both the short- and long-term economic losses in economic production and consumption and any related economic recovery paths (Kousky 2014).

Empirical studies and modeling demonstrate that the indirect impacts can be at least as large as, if not larger than, the direct impacts of physical climate shocks (Hallegatte, Hourcade, and Dumas 2007; Hallegatte 2019; Colon, Hallegatte, Rentschler, and Rozenberg 2019; Dunz et al. 2021). The scale of the indirect impacts versus the direct impacts is dependent on a number of factors, including the level of preparedness and resilience of the economy to shocks. Factors include, for example, insurance penetration, investments in contingency planning, and access to labor and credit postdisaster (Koks and Thissen 2016; Ranger et al. 2011). Botzen, Deschenes, and Saunders (2019) conclude that while the net macroeconomic (that is, indirect) losses are overall negative, they are likely to be small for high-income economies, as they are better able to cope with negative production shocks and generally more severe for low-income countries and smaller, less-diversified economies.

Indirect effects of physical climate shocks can be quantified using computational macroeconomic models. Such models predict the impacts of shocks on a variety of economic indicators, such as GDP level and growth, trade, and employment. Botzen, Deschenes, and Saunders (2019) provide a review of modeling approaches and find that research on the indirect impacts of natural disasters builds on the predictions of input–output (Hallegatte 2008), computable general equilibrium (CGE) models, and most recently, structural econometric models (Burns, Jooste, and Schwerhoff 2021). Integrated Assessment Models (IAMs) have been developed that estimate the impacts of climate change in GDP terms. As described by Botzen, Deschenes, and Saunders (2019), most IAMs estimate the aggregate economic impacts of climate change, so they do not explicitly represent physical climate shocks. Some IAM applications have, however, focused on natural disasters (for example, Narita, Tol, and Anthoff 2010). More recently, scholars started to recognize the need for bottom-up and out-of-equilibrium models rooted on complex system science to understand complex and interconnected sources of systemic risk emerging from the interaction between climate change, the real economy, and the credit and financial markets (Farmer et al., 2015; Battiston, Farmer, et al. 2016). Rezai and Stagl (2016) called for the development of a new generation of models in ecological macroeconomics—models that are able to integrate the microfoundations of the models with a meso- and macroeconomic level of analysis to better understand the feedback loops between the ecosystem, the real economy, and the financial sector. Agent-based models and stock-flow consistent models are two families of models that contributed to address these concerns (Monasterolo and Raberto 2018; Monasterolo and Raberto 2019). An illustrative application of a stock-flow consistent model, EIRIN, to calculate indirect impacts is shown in section 4.4.

12. Botzen, Deschenes, and Saunders 2019 provide a slightly broader definition of direct economic losses to include "the destruction of residences, businesses, productive capital, infrastructure, crops, livestock, and (monetized) physical and mental health impacts"

Three conclusions emerge relevant to physical climate-related financial risk assessment. Firstly, the indirect loss from physical climate shocks are a very material component of financial risk, particularly for emerging and developing economies; ignoring this could lead to a systematic underestimation of the risks. Secondly, a set of well-tested tools are available to assess the indirect impacts of physical climate shocks, applicable at local, national, or global scales. Thirdly, this will typically require macroeconomic models that can identify and quantify the complex transmission channels and feedbacks involved. Importantly, these macroeconomic models should be forced with climate and/or catastrophe risk models that fully represent uncertainties and tail risks as outlined in the previous two sections. Using only AALs for example, will lead to underestimates.

However, there are challenges. First, there is not yet a clear consensus on which models should be used for this type of application, and there is no comprehensive model intercomparison (similar to a CMIP or ISIMIP) that allows decision makers to assess the uncertainties. A second challenge is that the dependence of indirect impacts on the specific characteristics of the economy and the shock mean that it would be difficult to draw out some simple relationship, such as an 'indirect impact vulnerability curve,' or generate generic scenarios that could be easily applied to any country to avoid the need for tailored, country-specific analyses.

It is also important to note that all the macroeconomic models commonly used in climate stress testing do not yet capture all those indirect factors known to be important to physical climate risk assessment. For example, recently there has been significant work on the economic impacts of infrastructure systems disruption associated with physical climate shocks that shows that this contributor to indirect economic cost alone can be far larger than the direct impacts on buildings and infrastructure. Koks et al. (2019) find that 27 percent of all global road and railway assets are exposed to at least one physical climate hazard. Hallegatte, Rentschler and Rozenberg (2019) conclude that altogether, infrastructure disruptions impose costs between $391 billion and $647 billion a year on households and firms in low- and middle-income countries alone. Physical climate-related shocks can also send ripple effects through global supply chains and patterns of trade, as observed, for example, during the global food price shock of 2008/10, partly driven by extensive droughts (IEG 2013).

In summary, there is a large evidence base available on the indirect impacts of physical climate shocks nationally and globally, yet this is not captured in current physical climate scenarios designed for central banks and supervisors. The evidence points toward the materiality of these impacts versus the direct impacts normally considered within physical, climate-related risk assessment as well as the substantial additional layer of uncertainty introduced. A challenge is that no one modeling approach captures the full range of indirect impacts. For physical, climate-related, financial risk scenarios, most critical will be to identify those factors most material in terms of financial risks, based on the evidence and knowledge of the context and analyses of transmission channels, and ensure these are adequately reflected in scenario generation and model selection.

As outlined in CFRF 2020, the starting point will be to understand key drivers of risk to the area and actors of interest and to explore the risk transmission channels. From this, it is possible to develop scenarios that stress test the key relevant financial vulnerabilities and to base this upon a combination of macroeconomic models, empirical data, and quantitative and qualitive scenario-based approaches as appropriate.

4.4. Impacts on the Financial Sector and Economy-Financial Sector Feedbacks

To take the final step from a physical climate shock to estimate the impact on the financial sector requires an additional layer of analysis. The available evidence here is limited. One approach taken is to apply empirical relationships between shocks and variables such as nonperforming loan ratios or z-scores to estimate future impacts of climate change on the financial sector (see Klomp 2014). A strong limitation of such approaches is that current financial risk mitigation measures, such as forbearance, can mask the impacts of shocks in historical data. Another approach is to model the impacts on firms from a reduction in revenues or return on assets associated with a physical climate shock and the consequent increase in debt at risk (Feyen et al. 2017) or probability of default (Merton, 1974). However, these approaches do not take full account of the complex feedbacks between the real economy and the financial sector. These feedbacks can act to amplify or dampen the impacts of physical climate shocks on the banking sector (see Section 2); in large higher-income countries with well-diversified financial markets, the impacts of historical disasters on the banking sector has been generally limited compared to smaller economies and those with more concentrated financial sectors. The interconnectedness of the real economy and financial sector (for example, firms' borrowing and banks' lending, foreign households' remittances and domestic households' disposable income) could contribute to reverberate and amplify the original shock in the economy (Battiston, Caldarelli, et al. 2016; Bardoscia et al. 2021).

For instance, in the 2008 financial crisis, the shock stemming from mortgages in the US market spread fast to the European financial sector and the rest of the world due to the exposure of European and extra European financial actors to the derivative contracts and institutions hit by the crisis. Then, due to the large role that finance plays in today's economy, the shock fast spread in the real economy causing cascading, nonlinear effects, in particular on private and public debt sustainability. COVID-19 showed that a major global systemic shock to the financial sector can also originate from exogenous factors: in that case, a global pandemic and the policy measures imposed to control the health impacts. Here, unlike the global financial crisis, the shock to the financial sector originated in the real economy. This has similarities with what one might expect from future physical climate shocks (that is, exogenous drivers of macrofinancial risks). Such strong financial feedbacks driven by an exogenous shock were demonstrated by Mandel et al. (2021) in the context of flood risk. Missing such feedbacks within scenario development and macrofinancial modeling could lead to under- or overestimating financial risks.

It is also important to note that many countries have financial 'shock absorber' mechanisms in place designed to dampen the impacts of shocks on firms and the financial sector, including partial credit guarantees schemes or other mechanisms, such as forbearance, adjusting provisioning requirements, interest rates, or quantitative easing by central banks. It will be important to build such mechanisms into scenarios. However, notably such mechanisms often imply risk being taken onto the government balance sheet that would have implications for macrofiscal risks as well as imply limits on what risks could be mitigated in the future with climate change.

Capturing the main transmission channels and feedbacks as well as representing any financial shock absorber mechanisms requires a macrofinancial model, that is, a macroeconomic model with sufficient resolution of the financial sector. Macrofinancial models are now regularly applied to assess the impacts of transition scenarios on the financial sector (Battiston et al. 2017; Roncoroni et al. 2021), but examples of their application to physical climate-related financial risks is limited. Current physical climate-related financial risk assessments usually do not incorporate these financial sector feedbacks.

Given the scarcity of evidence, we provide an illustration of macrofinancial modeling of the impact of a physical climate shock on a highly exposed middle-income country. We also use this model to illustrate the importance of such feedbacks by turning on and off credit constraints. We utilize the EIRIN model (Monasterolo and Raberto 2018; Monasterolo and Raberto 2019), which is an open economy macrofinancial model composed of heterogeneous agents and sectors of the real economy and finance represented as a network of interconnected balance sheets. EIRIN is stock-flow consistent (SFC): every agent is represented by its balance sheet items, calibrated on real data (when possible), making it possible to trace a direct correspondence between stocks and flows in the economy and finance and changes as a result of exogenous shocks (natural disasters, for example) and endogenous shocks (change in policy and financial regulation, change in investors' expectations). As a difference from most macroeconomic models used for climate and disaster risk assessment, EIRIN embeds a financial sector, financial market, and a central bank in charge of conventional and unconventional monetary policies. In contrast, in traditional macroeconomic models—such as real business cycles, computable general equilibrium (CGE), and dynamic stochastic general equilibrium (DSGE) models—the role of money and finance is either absent or treated as a friction (Galí 2018; Jakab and Kumhof 2019), thus preventing analysis of endogenous building up of financial crises and their effects on the economy and policy decisions (Monasterolo 2020).

A further advantage of using the EIRIN model in this context is that it is not constrained to solve to equilibrium, thus allowing the analysis of the causes and consequences of nonlinearity of impacts on economic and financial investments and policy decisions. These emerge endogenously from agents' reaction to shocks, considering the interactions among economic and financial agents and sectors. The model allows to account for the richness of risk transmission channels and impacts, considering how the nature of risk affects agents' heterogeneous beliefs, intertemporal preferences, formation of expectations, and decision making in response to the shocks. In this case, the EIRIN model is initiated with scenarios with and without a direct physical climate shock. The direct loss simulation serves as a 'shock' to the economic system, causing economic interruption and diversion of economic flows, hence a potential loss amplification in the aftermath of a disaster. In Gourdel et al. (2021), the EIRIN model was advanced to include a stronger representation of the financial sector and market to allow the integration of macrofinancial dynamics into full financial network models (Battiston et al. 2017; Roncoroni et al. 2021) that analyze direct and indirect losses (such as second, third round impacts) due to financial interconnectedness. The transmission channels between the real economy, the financial sector, and the public sector are illustrated in figure 4.2 and is further described in Gourdel et al. (2021).

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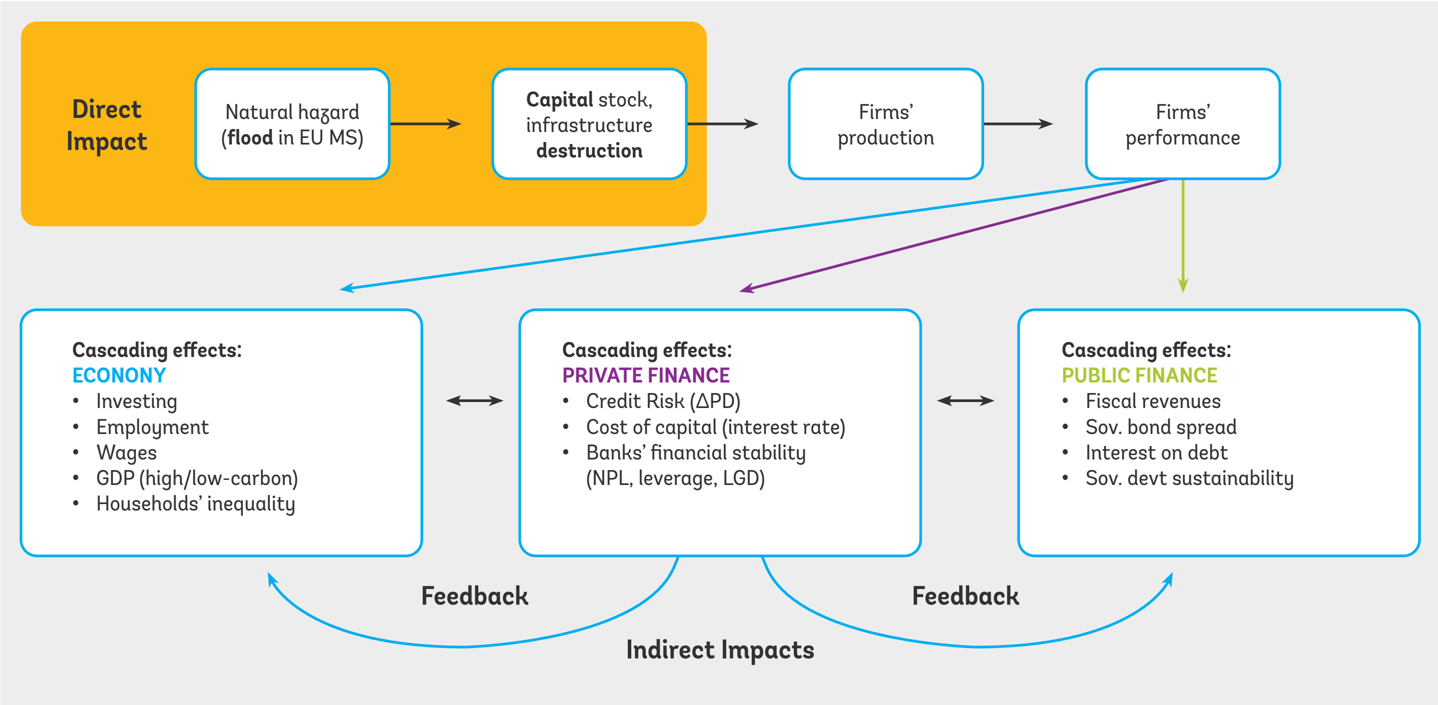
FIGURE 4.2. - **Transmission Channels Between the Real Economy, the Financial Sector, and the Public Sector**



Source: Original for this publication.
Note: Channels of natural disasters (tropical storm) risk transmission to the economy (blue) and its macroeconomic (light red shadow) impacts on the real economy, financial sector (private finance) and government (public finance) within the modified EIRIN model used in this study. Sov = sovereign. LGD = loss given default. PD = probability of default. GDP = gross domestic product. NPL = nonperforming loans. EU MS = EU Member State.

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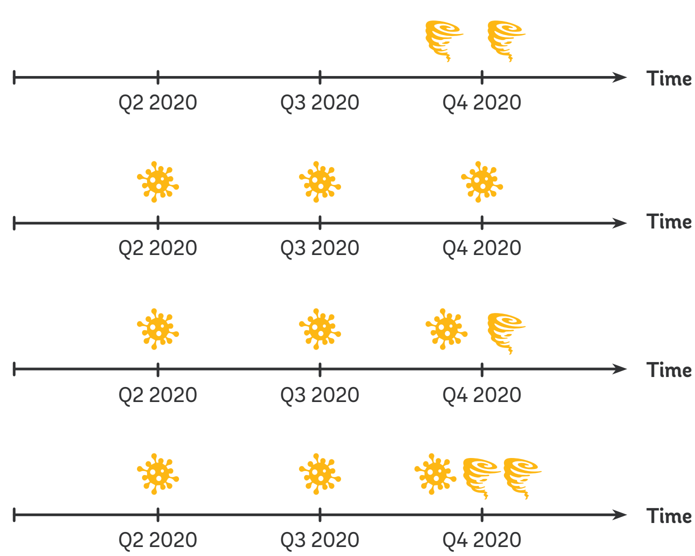
BOX 4.1.
Illustrative Scenarios Developed for the EIRIN Model

FIGURE B4.1.1. - **Four Scenarios Considered in This Study.**

Scenario No	Natural Hazard Occurrence
1 Strong hazard (typhoon)	**Timing:** Q4 2020 **Impact Size:** ς_H = 1.63% **Agriculture** = 0.147% **Industry** = 0.5058% **Service** = 0.978%
2 COVID-19 emergency	**No**
3 Compound COVID-19 and mild hazard	**Timing:** Q4 2020 **Impact Size:** ς_L = 0.46%
4 Compound COVID-19 and strong hazard	**Timing:** Q4 2020 **Impact Size:** ς_H = 1.63%

Graphical Representation



The figure above illustrates the four scenarios considered in this illustrative study. Scenario 1 (SC1) is characterized by the occurrence of typhoons that hit late in the typhoon season. Scenario 2 (SC2) is characterized by the COVID-19 shock (no typhoon). Scenario 3 (SC3) considers the case of the COVID-19 shock followed by a low-impact (mild) typhoon that occurs late in the typhoon season. Scenario 4 (SC4) considers the case of the COVID-19 shock followed by a high-impact (strong) typhoon that occurs late in the typhoon season. The impact of natural hazard is estimated as relative loss of capital stock by economic sector, based on a fitted Findex damage function relevant to the country, calculated using World Bank in-house catastrophe risk models.

Source: Ranger, Mahul, and Monasterolo (2021) and references therein.

Figure 4.3, panels a, b, and c illustrate three outputs from the EIRIN model relevant to understanding the macrofinancial impacts of physical climate shocks (a strong typhoon represented by the orange line on all three graphs) based on Monasterolo et al. 2021. The four scenarios employed (SC1, SC2, SC3, and SC4) are described in Box 4.1.

Figure 4.3, panel shows a peak 2.5 percent loss of real GDP occurring in the quarter following the shock and then declining. This creates an immediate credit shock, including almost a doubling of credit demand from firms for investment and liquidity purposes. Credit demand recovers quickly as investments align with those of the business as usual (BAU) scenario (figure 4.3, panel b). Finally, the capital adequacy ratio (CAR) represents the ratio between the bank's equity and the banks' risk-weighted assets (in this analysis, we consider loans) (figure 4.3, panel c). Here, the CAR influences the amount that banks can lend to firms, conditioned to the regulatory CAR that considers the risk exposure of the bank via loans. Thus, it represents a maximum credit supply. The CAR falls following the shock, reducing credit supply. This reduction peaks at 10 percent below BAU and persists for several quarters. This analysis demonstrates the materiality of physical climate risks to both economic output and key financial sector soundness indicators, such as the CAR and credit demand. Explicitly modeling these transmission channels is important in assessing the scale of financial risks.

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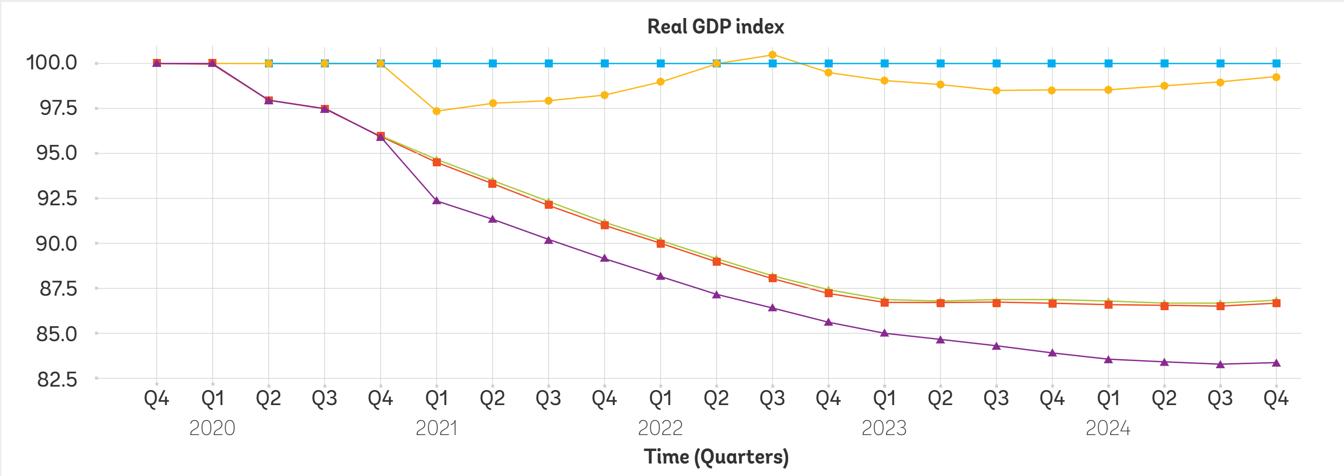
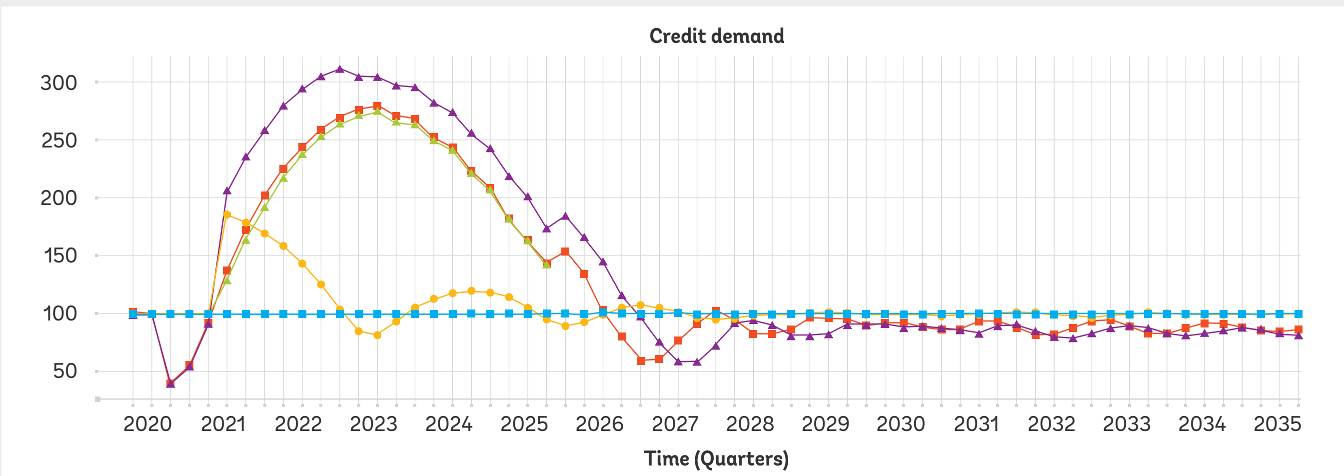
FIGURE 4.3. **Panels a, b, c: Three Outputs from the EIRIN Model Including a Strong Typhoon**

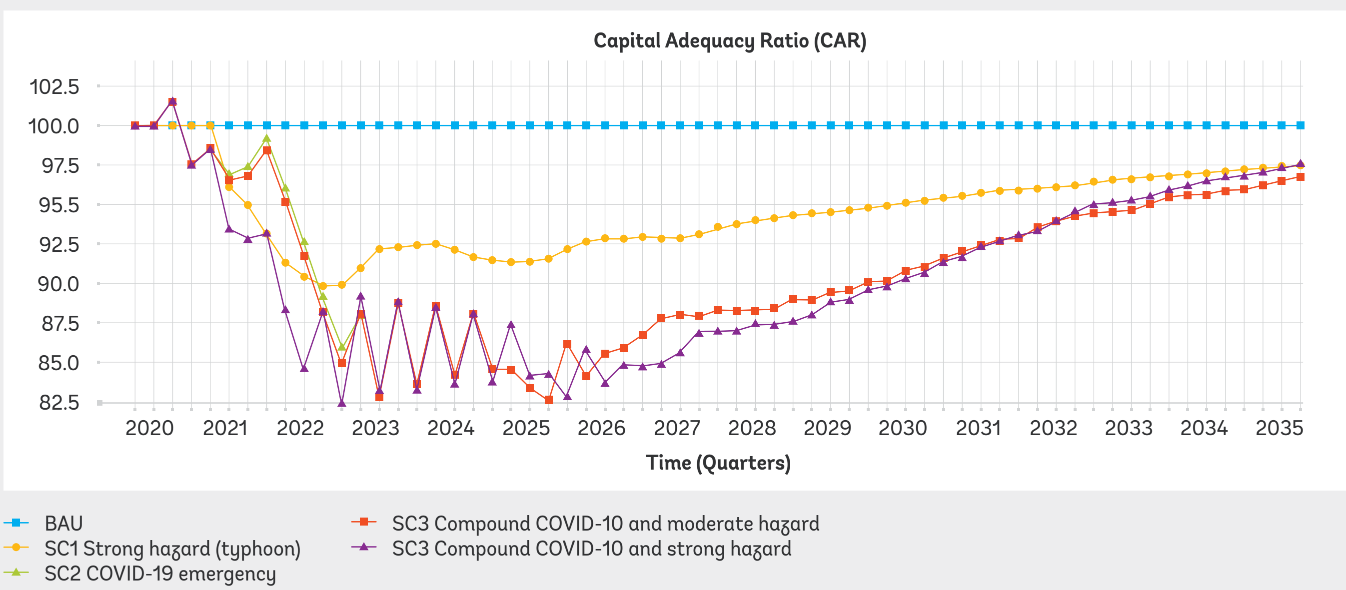
a: Real GDP Indexed Against the Business as Usual (BAU) Scenario



b: Impacts on Credit Demand by Firms



b: Impacts on Credit Demand by Firms



Source: based on Monasterolo et al. 2021

Figure 4.4 illustrates why these feedbacks are important to consider within the development of scenarios to assess physical climate-related financial risks. It shows real GDP for the same shock but under different credit constraints—an important feedback between the real economy and the financial sector. It illustrates that when credit constraints are strong (represented by a high regulatory CAR) the impacts of a physical climate shock on GDP are substantially amplified and more persistent. Such credit constraints could be generated by high demand for credit (particularly the context of compounding shocks illustrated in figure 4.4), changing policies by banks or changes in regulation to protect the financial sector. This illustrates how not representing potential feedbacks between the real economy and the financial sector in scenarios or not allowing these feedbacks in modeling, could cause central banks and other financial institutions to substantially underestimate the potential risks; this undervaluation and pricing of risk could have systemic implications. The feedbacks explored here are national only; yet Mandel et al. 2021 also demonstrate the importance of international financial networks as potential amplifiers of risk.

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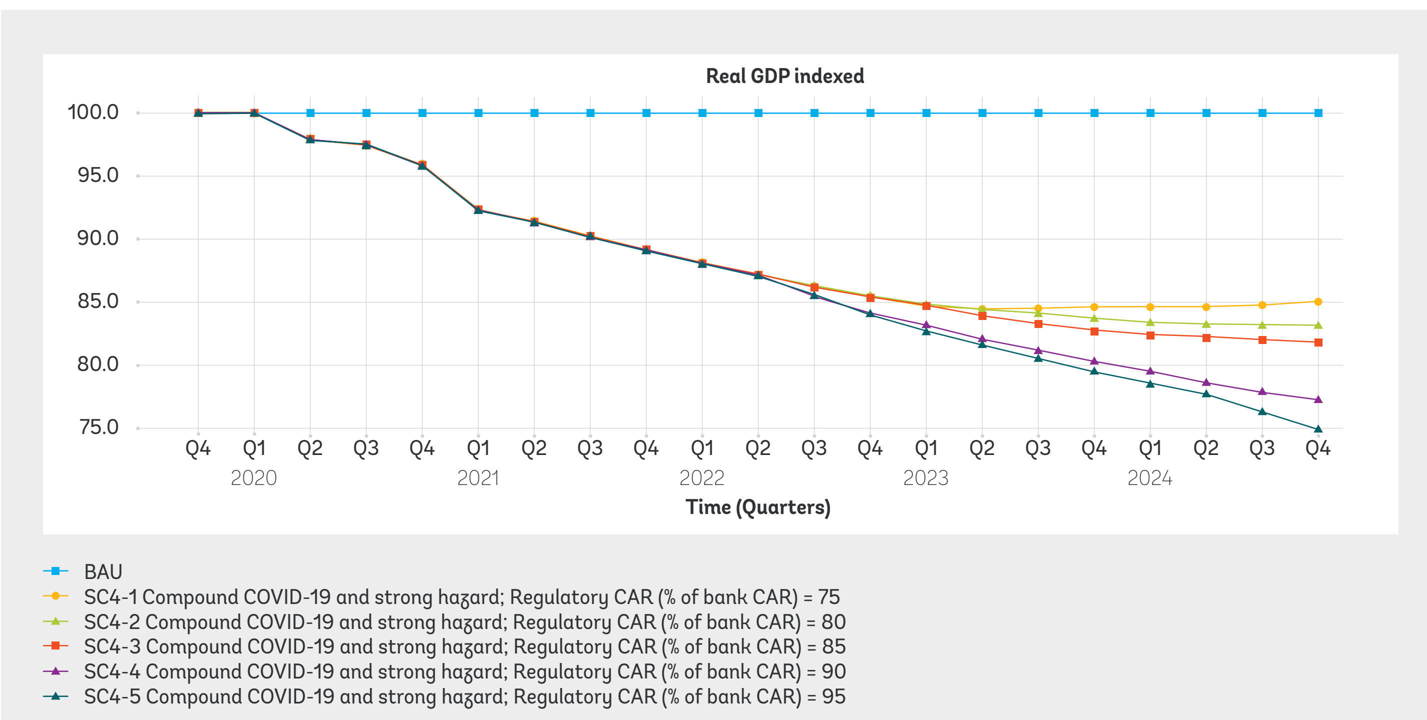
FIGURE 4.4. - **Real GDP Indexed Against the BAU Scenario for a Compound Shock (Typhoon plus COVID-19) in the EIRIN Model with Different Credit Constraints**



Source: based on Monasterolo et al. 2021

Battiston et al. (2021) also noted the importance of accounting for investors' expectations in the realization of the climate scenarios because they affect the cost of capital and thus firms' investment decisions. This finance-climate feedback is currently not included by climate scenarios, but it is crucial to avoid underestimating risk in stress testing exercises. Indeed, research has shown that financial actors' expectations and anticipation of climate risks (the so-called climate sentiments), affect both the viability and performance of investments in high (low) carbon sectors negatively (positively) and thus the success of climate mitigation and adaptation (Dunz et al. 2021). In this context, investments that are considered as crucial for mitigation, could not materialize, leading to scenarios that are not considered by the NGFS. In contrast, investments in climate misaligned activities (or carbon stranded assets) could increase, thus increasing the exposure to physical climate-related financial risks.

Further work is also needed to explore how financial institutions serving more vulnerable groups, such as agribanks, MFIs, and SACCOs are affected by physical climate shocks. In particular, it is important to understand through which channels physical climate risk becomes material and affects such actors and the potential implications for overall financial sector development and stability (including contagion effects). In low-income and emerging countries with an underdeveloped financial sector, the direct implications for financial stability may be limited: major impacts could be expected on financial services on vulnerable communities. Indeed, in some economies, these nonbanks represent an important part of the overall financial sector; there may be a case of 'too many to fail.' This in turn would have important indirect impacts on inequality and on poverty alleviation, with cascading effects on living conditions of rural communities and their socioeconomic development, which over time could have systemic effects.

The analysis demonstrates that including such direct and indirect impacts of climate risks shocks is critical to provide a comprehensive assessment of risk to which specific sectors and segments of society are exposed to and to identify tailored policy response via risk mitigation and adaptation. This analysis suggests that scenarios could otherwise underestimate the scale of the impacts significantly. The approach proposed above is a first attempt to include such direct and indirect economic impacts in a comprehensive climate risk assessment. Few models incorporate such feedback, and this can be a constraint for advancing climate financial risk assessment. Of critical importance is, at a minimum, to recognize this potential gap and explore opportunities to represent this transmission channel through scenario design.

4.5. Compounding Risks

Physical climate shocks will not happen in isolation. Physical climate shocks will combine with other shocks and stress within the economy, such as economic cycles, pandemics, or financial crises. When different types of shocks compound within an economy, they can generate nonlinear effects that can amplify losses significantly. This is already well recognized within standard approaches to stress testing, for example IMF 2019 and Lloyd's of London 2021. For this reason, it is important to include scenarios that capture compounding risks within physical climate-related financial risk assessment.

In addition, physical climate shocks will interplay with chronic changes and so cannot be treated entirely independently. For example, sea level rise will increase the risks associated with typhoons and storm surges in coastal regions; strain on global food systems resulting from gradual changes in temperatures and rainfall could increase vulnerabilities to droughts. In addition, transition and physical climate-related risks will happen in parallel and will combine.

The compounding of shocks of different nature (such as pandemics, acute and chronic climate changes, economic crises, and financial shocks) represents a new type of risk for macroeconomic and financial research. When risks compound, they can generate nonlinear dynamics in the economy and finance, generating a prolonged out-of-equilibrium state of the economy and potential amplification effects (Monasterolo et al. 2021). The macrofinancial implications of compound risk cannot be simply detected by the sum of individual risks so should be explicitly built into scenarios.

To explore the potential scale of compounding risks in this context, we applied a second set of scenarios to the EIRIN model that included a physical climate shock, pandemic (COVID-19) and associated economic shock (linked to locking down of economic activities).

While different combinations of shocks will lead to difficult compound outcomes, we choose the following for illustration, with referring model simulations shown earlier in figures 4.2 and 4.3.

Pandemics and disasters have different direct impacts and affect respectively demand and supply in the economy. However, by impacting simultaneously on the firms' production and household demand, indirect impacts get amplified by agents' response to the shocks (and to the potential policy measures taken in response to the shock), and by agents' interaction.

For example, both COVID-19 and physical climate risk impact on firms' expectations and investment decisions, yet through different channels. This, in turn, can increase unemployment, reduce wages, and reduce household welfare, creating a reinforcing feedback on demand, so amplifying the indirect economic impact. This can lead to long-lasting negative socioeconomic effects on both firms and people and slowed growth and recovery. We can measure this compounding as a *compound risk multiplier* (figure 4.5) and find that it can peak at over 150 percent in some cases; that is, indirect impacts that can be 50 percent larger than the scale of the sum of the individual shocks.

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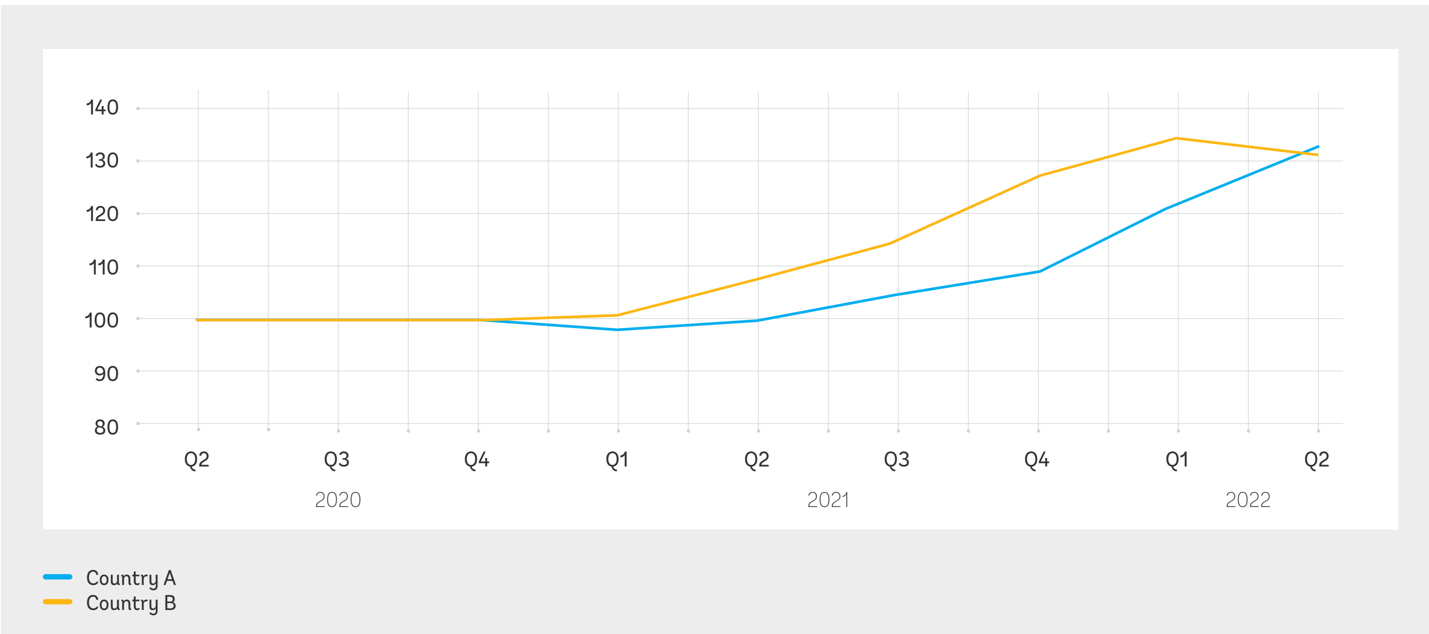
FIGURE 4.5. - **Compound Risk Multiplier for Two Example Middle-Income Countries, Where One Is Exposed to a Flood Shock (Country A) and the Other a Typhoon Shock (Country B) During a Pandemic**



Source: Ranger, Mahul, and Monasterolo (2021)

The transmission channels and drivers of feedbacks for compounding shocks are risk specific and can combine in different ways. As illustrated in figure 4.5 the scale and timing of the amplification looks very different between different middle-income countries depending on the structure of the economy, the timing and nature of the shocks and vulnerabilities to different hazards. In the example above, for both representative country A and B, both large middle-income countries, GDP is strongly related to investment and capital stock is working close to capacity, so shocks can have a large indirect impact by damaging capital stock, disrupting economic activity, and reducing investment. Both a disaster and a pandemic impact on production and investment so the compound effect is large. For country A, the flood shock is more prolonged.

The difference in how the financial sector reacts to these different shocks and the combined effects shown in figures 4.2 and 4.3 are also important to note. The compounding shock has a much greater and more long-lived impact on GDP. Contrary to the physical climate shock, investments drop in the COVID-19 shock scenarios during 2020 due to the direct domestic and external shocks in demand and investment. In the scenario characterized by compound COVID-19 and strong natural hazard displays a further spike in credit demand in Q1 2021 to rebuild the destroyed capital stock. While demand for credit related to the firms' investment plans increases, investments can be impaired by supply side constraints in the form of labor constraints and credit rationing; this amplifies the impact of the physical climate shock both on investment and GDP.

This illustration highlights the importance of including scenarios that explore how physical climate shocks compound with other shocks and stresses within physical climate-related financial risk assessments. It demonstrates that this compounding effect can significantly amplify the impacts of climate change and so is important for central banks and other financial institutions to consider within climate stress tests. The simple approach outlined here could form a model for how compounding risks could be considered within future sets of scenarios for central banks.

Next Steps Toward Implementation

This section suggests an approach to scenario development that aims to take account of the key material risk drivers while remaining practical for real application, particularly in countries where data availability may be constrained. The risk transmission channels are unique to each country and so a tailored approach to scenario development is necessary.

Figure 5.1 below illustrates a set of steps to construct climate scenarios for central banks and financial regulators as well as financial institutions and governments. This could take a set of generic scenarios as one input—such as the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) scenarios—combined with a wide range of inputs to ensure that scenarios represent the space of plausible future outcomes tailored to the key risk drivers and transmission channels of a specific country. This would include probabilistic information on extreme weather events and their physical impacts on key sectors and systems, climate change and other future risk scenarios that represent the range of uncertainties in projections. It would also include estimates of indirect impacts for the key risk transmission channels, compound events, and representation of potential real economy to financial sector feedbacks in line with the five risk drivers outlined in Section 4.

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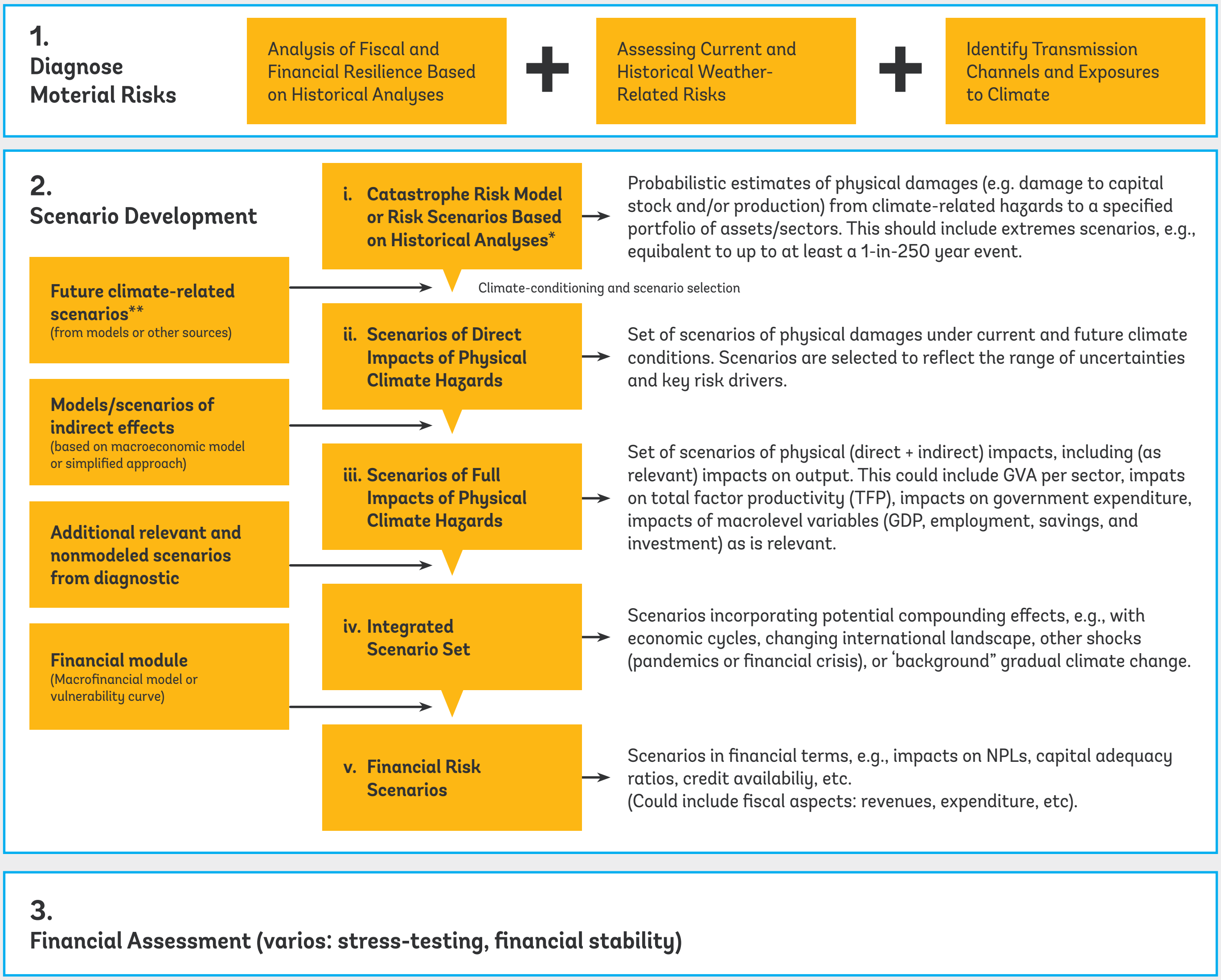
FIGURE 5.1. - **A Framework for Scenario Construction for Physical Climate-Related Shocks**



* It may not be necessary to use a full catastrophe risk model.
** Could in some cases include scenarios of changes to exposure or vulnerability.

Source: Original figure for this publication.
Note: GDP = gross domestic product;

To identify and prioritize the key country-specific risk drivers and transmission channels, the following steps can be followed:

- Understanding the impacts of historical physical climate shocks and analogous exogeneous shocks, such as pandemics, on the real economy and financial institutions and the key transmission channels, including through empirical analysis.
- Reviewing a wide range of evidence on the social and economic impacts of physical climate change to the country, including international dimensions of impacts as well as vulnerabilities and trends in other key factors that influence vulnerability to shocks, such as the structure of the economy and urbanization.
- Mapping the exposures of economic and financial activities from physical climate shocks—for example, by overlaying financial exposures to openly accessible hazard maps.
- Analyzing the largest possible losses for the economy and financial actors, considering the characteristics of the financial network such as financial interconnectedness, and including the role of second and third round exposures (e.g., interbank lending or exposure to the insurance industry).

Based upon this understanding, it is possible to define a set of informative, relevant yet pragmatic climate scenarios that span the space of plausible future outcomes suitable for climate stress testing and scenario analysis. It will also be possible to identify where the materiality and uncertainties in risks justify a greater investment in further analyses, including quantitative modeling such as that presented in this paper.

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Conclusions

This paper identifies potential gaps in current scenarios widely available for physical climate financial risk assessment and aims to improve the understanding and design of physical climate financial risk scenarios, including for climate stress testing. Those gaps represent material financial risks that cannot be ignored within physical climate financial risk assessment. Tools and approaches are readily available and tried and tested to capture these risks within physical climate financial risk assessment.

In order to address those gaps, the paper identifies five important areas to consider within a physical climate-related financial risk assessment and scenario design: (1) extreme weather events, (2) uncertainties in climate models, (3) compound scenarios, (4) indirect economic impacts of shocks, and (5) feedbacks between the real economy and the financial sector. The combination of these five areas within a climate-related financial risk assessment using simple scenarios is illustrated through the EIRIN macroeconomic model.

The complexity and deep uncertainty of climate change, the heterogeneity of channels of countries' (financial) exposure to climate risks, and their socioeconomic and financial characteristics, imply new challenges for macroeconomic analysis and stress testing to inform policy making that require further research. However, such uncertainties are not new or unique to climate stress testing and scenario analysis. A 'Realistic Disaster Scenario' approach that combines model-based projections, expert judgment and the best available science to develop scenarios relevant to stress testing can help overcome challenges in data scarcity and constraints on availability of models, particularly in emerging markets and developing economies. Such scenarios need not be complex, but instead should aim to represent the material risk drivers and risk transmission channels, the range of plausible outcomes, and their interactions.

Some further challenges can be highlighted. They include:

- Strengthening the evidence based on the relationship between the economic impacts of physical climate shocks and the impacts on the financial sector.
- Quantifying key economic impacts that are currently missing from models, such as the impacts of infrastructure disruptions and the potential for regional and global cascading shocks.
- Exploring how physical climate risks interplay with other shocks and stresses, including transition risks, gradual climate change, and feedback with nature and biodiversity as well as economic and financial crises; build this into compound risk scenarios.
- Structuring intercomparison exercises between different macroeconomic and macrofinancial models to understand the uncertainties in current estimates of economic and financial impacts of physical climate shocks.
- Understanding potential contagion effects between larger banks and those serving poor communities that are more heavily affected by physical climate shocks.
- Exploring scenarios that take account of long-term trends in exposure, vulnerable and resilient, as well as feedback between climate action and the financial sector over time (Battiston et al. 2021).

These are left for further research.

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