Compound Risks: Implications for Physical Climate Scenario Analysis

On the necessity for climate financial risk management to integrate compound events in physical climate risk scenario analyses

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Contents

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Executive Summary

The notable confluence of extreme climate-related events amid macroeconomic instability stemming from other crises, including COVID-19 and the Russian war in Ukraine, highlights the presence of polycrises[1] (World Economic Forum 2023). These shocks[2] have both a deep direct human, environmental and economic impact, as well as substantial implications from a financial risk perspective. In this context, it is important that climate scenario analysis of physical risks[3] goes beyond considering climate-related shocks in isolation. Instead, there is a need to consider potential compound risks. In this context, compound risks are defined as "a combination of multiple drivers[4] and/or hazards that contribute to societal or environmental risk" (Zscheischler et al. 2018). Physical climate-related compound shocks[5] include at least one physical climate-related shock compounding with at least one other shock (which may or may not be climate-related). Depending on the nature of the relationships between the constituent shocks (in terms of their modulators, drivers, and hazards), compound shocks can be classified as preconditioned, multivariate, temporally compounding and/or spatially compounding. Along a second dimension of classification based on the systems that they originate from, physical climate-related compound shocks can further be characterized as "Physical climate" ↔ "Physical climate", "Transition climate", "Other environmental" or "Non-environmental" (economic, societal, geopolitical or technological) compound shocks. Compound risks are characterised by their non-linear[6], complex, and often unpredictable effects on society and the economy. As such, the impacts of compound shocks cannot be simply deduced by the sum of the impacts of their constituent shocks. These complex nonlinearities can amplify the impacts of climate-related shocks and pose potential challenges for financial stability. The objective of this note is to provide evidence on the materiality of compound shocks and to review approaches for incorporating them within climate scenario analysis for physical risks.

Physical climate risk analysis is important to identify and evaluate risk, and ultimately inform risk management decisions to contribute to strengthening financial stability. As such, it is important that such analyses capture the potential materiality of physical climate risk,

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[1] Polycrises are defined in the Global Risks Report (World Economic Forum 2023) as "a cluster of related global risks with compounding effects, such that the overall impact exceeds the sum of each part", based on Tooze (2022).

[2] In this note, we refer compound shocks or events as a specific instance, whereas risk refers to the convolution of the respective distributions of, or more simply the multiplication of, the likelihood and impact of compounding events.

[3] The focus of this note is on physical climate risk analysis, however some of the conclusions may be relevant for transition climate risk analysis as well.

[4] For each shock, *modulators* influence the frequency, intensity, and location of *drivers*, which in turn affect the occurrence and severity of *hazards* (the proximate cause of impacts) (Zscheischler et al. 2020).

[5] In this note, for brevity, the terminology "compound climate shocks" (or "physical climate-related compound shocks") are used to refer to compound shocks involving at least one physical climate shock.

[6] In the context of compound shocks, non-linearity refers to the potential for the impacts of events to deviate from (typically by exceeding) the additive impact from single shocks alone.

including from compound risks which may substantially increase materiality. Based on a survey of twenty-six Network for Greening the Financial System (NGFS) members conducted in July 2023 in the context of this note, there is a broad consensus on the urgency of considering compound risks when analyzing climate change impacts. A review of existing evidence on the materiality of compound climate shocks shows the need for additional empirical analysis on the economics of compound shocks and their impacts on the financial sector. A review of the state of practice in incorporating compound shocks within scenario analysis, based on the survey results and publicly available literature, highlights that some central banks and supervisors are starting to incorporate compound shocks into climate scenario analysis and stress testing. A broad range of different types of compound shocks are represented among the scenarios being considered.

A practical toolkit for central banks and supervisors is needed to support the incorporation of compound risks into climate scenario analysis. Many of the existing modelling approaches used for physical climate risk, including those utilized for the NGFS scenarios, do not yet capture compounding effects, which may contribute to a potentially severe underestimation of losses. Recent advances in climate, catastrophe risk, network, and macroeconomic modelling show promise in filling the gaps in modelling compound risks. However, further work is needed to develop appropriate methods for incorporating compound shocks within financial risk assessment. Specifically, it is important to understand where existing tools are useful and if and where a change in approach is warranted.

Providing initial guidance towards an operational framework for incorporating compound risks in climate scenario analysis, we take stock:

- **Compound climate shocks should be considered within climate scenario analysis.** There is a need for further data collection and empirical analysis on the economic impacts of compound shocks. Yet already the collected evidence suggests that compounding may be material and supports the incorporation of compound shocks as a recommended practice within climate scenario analysis.

- **Central banks and supervisors should work closely with the scientific community to help identify the most relevant plausible compound climate shocks** as well as to provide further and robust empirical evidence on the economics of compound shocks and their impacts on the macroeconomy and financial sector.

- **Which compound shocks to consider will depend on the characteristics of the country(ies) of analysis.** There is a broad range of compound shocks. The evidence suggests that at least some of these compound shocks are likely to be relevant and financially material for many countries, even in the short-term. The identification of the most relevant shocks for inclusion in a scenario analysis can be based on historical analyses, identification of climate-related economic vulnerabilities, expert consultations, and analyses of future climate projections.

- **When incorporating compound shocks into climate scenario analysis, central banks and supervisors might consider a three-stage approach:** Firstly, the development of narrative scenarios or storylines in collaboration with experts. Secondly, working with the scientific community to add quantification to scenarios to make them usable and useful for climate scenario analysis; including drawing upon the types of models described in this note. Thirdly, incorporating these scenarios within the existing toolbox of financial institutions. While some non-linearities may be missed (particularly with the current generation of models), incorporating some information on compounding effects would be beneficial. There is no need to wait until 'perfect' models and scenarios are developed to begin to incorporate compound shocks, though results from existing models should be interpreted and communicated with full recognition of current model limitations.

- **In parallel, there is a need for further development of models to capture compound shocks.** The current generation of macroeconomic models used by central banks and supervisors are unable to capture the non-linear effects of compound climate shocks, likely resulting in the underestimation of risks. Continued research and development is also required across the other key models used to characterize compound risks (e.g., climate and catastrophe risk models). Close collaboration between researchers and practitioners should be prioritized to ensure swift integration of methodological developments into the toolkits of central banks and supervisors.

Given the novelty and systemic nature of these risks, organisations like the NGFS are well positioned to advance knowledge, best practice and capability on this area globally,[7] particularly in the area of global compound risks, and to thus support central banks and supervisors to bridge gaps related to the understanding and modelling of compound risks. Such initiatives can complement ongoing work by the NGFS on other aspects of the development of the NGFS scenarios, including efforts to further refine methodologies to capture physical risks, increase usability of scenarios, and develop short-term scenarios. The following next steps for collective action are recommended:

- Update guidance on physical climate financial risk assessment to highlight the relevance of compound climate shocks, identify a set of shocks that are likely to be particularly relevant for the financial sector, and recommend that compound climate and macroeconomic shocks be incorporated within climate scenario analyses.
- Explore how the NGFS, central banks and supervisors could work with the scientific community to advance research on:
    - Development of guidance materials around how scenarios can be developed by central banks and supervisors to incorporate compound risks today, based upon current evidence, both qualitatively and quantitatively.
    - Exploring how compound climate shocks can be incorporated into macroeconomic models commonly used by central banks and supervisors, including studying the potential limitations of the current generation of models in this context, understanding the drivers of non-linear amplification effects, identifying the dominant transmission channels and the drivers of feedbacks to be considered, and developing a roadmap for exploring solutions.

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[7] As discussed in a joint report from the FSB and NGFS (2022), collaboration across jurisdictions could help to facilitate sharing of good practices and advance the development of common frameworks and methodologies, balancing the needs for standardisation with the needs for tailoring scenario analyses to local specificities, particularly in EMDEs.

1. Introduction

In 2023, the world has experienced unprecedented temperatures and an El Niño event that is expected to drive concurrent floods and droughts around the world, with implications for economic growth and global patterns of trade. This unprecedented confluence of events comes at a time of macroeconomic and financial instability across many countries from high inflation associated with energy price increases triggered by the invasion of Ukraine in 2022, volatile markets, supply chain disruptions and tightening financial conditions, as well as fiscal constraints and rising costs of capital for many developing countries in the aftermath of COVID-19 (IMF 2022). World Economic Forum (2023), as well as other authors, have described this as 'polycrisis': *"Concurrent shocks, deeply interconnected risks and eroding resilience are giving rise to the risk of polycrises – where disparate crises interact such that the overall impact far exceeds the sum of each part."* This interaction of risks is referred to as "compounding", highlighting the relevance of compound risks in this era of polycrises. Developing countries are particularly affected by such shocks as they are facing multiple crises, including the lingering effects of the COVID-19 pandemic, growing impacts of climate change, economic imbalances and rising debt distress, commodity price shocks and food insecurity, and persistent fragility and conflict (e.g., World Bank, 2022). These shocks have a deep direct human and economic impact on all countries but particularly long-term adverse spillovers for developing countries, threatening to reverse decades of development gains.

Following Zscheischler et al. (2018), we define compound risks as "*a combination of multiple drivers and/or hazards that contribute to societal or environmental risk".* As outlined later in this note (Section 3), physical climate-related compound shocks include at least one physical climate-related shock compounding with at least one other shock (which may or may not be climate-related). Compound risks are characterised by their non-linear, complex and hard-to-predict effects on society and the economy. As such, the impacts of compound shocks cannot be simply deduced by the sum of the impacts of their constituent shocks. These complex non-linearities can amplify the impacts of climate-related shocks and pose potential challenges for both financial stability and monetary policy. Compound risks are not currently included within the guidance and scenarios of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). Yet, they are expected to become more common with climate change and environmental degradation (Oppenheimer et al. 2014; World Economic Forum, 2023) and the potential scale of impacts is large.

There is an urgent need to address compound physical climate shocks as evidence on their relevance is mounting. There is growing evidence on the increasing likelihood of compounding weather shocks with climate change (Ridder et al. 2020; Weber et al. 2020), with the Intergovernmental Panel on Climate Change highlighting that the probability of compound weather or climate events has already likely increased due to climate change (IPCC 2021). The impacts of unprecedented temperatures and extreme weather events observed around the world are compounding with ongoing macroeconomic and fiscal pressures. There is a 66% chance that global temperature increases[8] will exceed 1.5°C for at least one year between 2023 and 2027. Moreover, there is a 98% chance that at least one of the next five years, and the five-year period as a whole, will be the warmest on record (World Meteorological Organisation, 2023). These climatic changes, in combination with the multitude of macroeconomic and broader risks facing global civil society, underscore the need to consider compound physical climate risks within financial risk management today, including in short-term scenarios.

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[8] Annual average near surface global temperature increase relative to pre-industrial levels.

While there is growing evidence on the increasing likelihood of compounding weather shocks, there is little evidence on how these shocks combine (including with other types of shocks), and the economic and financial implications of these combinations of shocks. There are also no widely accepted frameworks for assessing and quantifying compounding risks associated with climate, environment and social drivers in economic terms suitable for integrating them into financial risk management frameworks used by financial institutions, central banks and supervisors. Many of the existing modelling approaches used for physical climate risk, including those utilized for the NGFS scenarios, do not yet capture compounding effects, which may contribute to a potentially severe underestimation of losses. This underestimation of losses may have harmful implications as external observers may not be aware of the underestimation, and may thus think that climate-related physical risks are likely to produce only negligible impacts on financial institutions and systems on the basis of existing analyses that do not (fully) capture compound risks.[9]

The objective of this note is to provide evidence on the materiality of compound shocks and to review approaches for incorporating them within climate scenario analysis for physical risks. In a survey of twenty-six central banks and supervisory bodies conducted as part of this work, twenty-five agreed that it is important to consider compound risks for climate change, and one third strongly agreed. This note aims to provide practical evidence-based steps for central banks and supervisors to assess these risks that can build on and complement the existing scenario analysis guidance and tools provided by the NGFS.

The note is organized as follows. Section 2 reviews the evidence on the materiality of compound climate shocks based on empirical analysis and modelling. Section 3 then introduces the key concepts and definitions in understanding compound risk and offers a typology of compound shocks for financial institutions. Section 4 reviews the state of practice in incorporating compound shocks within scenario analysis, including drawing upon a survey of NGFS members conducted in July 2023. Section 5 then reviews if and how the current suite of models can be used to model the impacts of compound shocks and Section 6 provides some initial guidance towards an operational framework for incorporating compound risks in climate scenario analysis. Finally, Section 7 provides recommendations on next steps.

2. Materiality of Compound Shocks: State of Evidence

Compound risks are not unique to the past few years nor are they particularly uncommon. For example, in 2020, many countries saw record breaking extreme weather concurrent with pressures on health systems and economies related to COVID-19, leading to compounding climate, health and economic crises (WMO, 2021). Take, for example, the wildfires, hurricane damage and the cold wave in southern US states and Typhoon Vamco in the Philippines. A further historical example is the interplay between drought and oil prices that drove the food price shocks in 2007-08 and 2010 (IEG 2013), or the combination of drought, economic change post WW1 and the Great Depression that led to severe economic and social impacts in the US during the 1930s Dust Bowl. Clearly, compounding risks are not limited to climate-related shocks, for example central banks and supervisors in recent

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[9] This, in turn, could undermine ongoing efforts by financial institutions, central banks, and regulators to advance the analysis of climate-related physical risks and develop risk management measures.

years are managing compounding effects of global shocks and stresses such as the aftermath of COVID-19 lockdowns and the invasion of Ukraine compounding with local shocks.

Compound risks should concern central banks and supervisors because they are a potential source of systemic financial risk[10]. A growing body of literature highlights the importance of considering compound risks within risk assessment (Zscheischler and Seneviratne, 2017; Zscheischler et al. 2019; Ranger et al. 2021; Dunz et al. 2021; Pitman et al. 2022).

Non-linear effects of compound shocks arise due to the complex interactions within the environment and among households, firms, government, and the financial system, all of which can cascade across economic, environmental, societal, geopolitical, and technological systems, at multiple spatial and temporal scales (Figure 1). These interacting mechanisms can significantly amplify the compound impacts (Raymond et al., 2020). Zscheischler et al. (2018) and Pescaroli and Alexander (2018) review historical instances of compound events related to weather extremes and concluded that indeed many major crises bear the hallmark of being caused by compounding events.

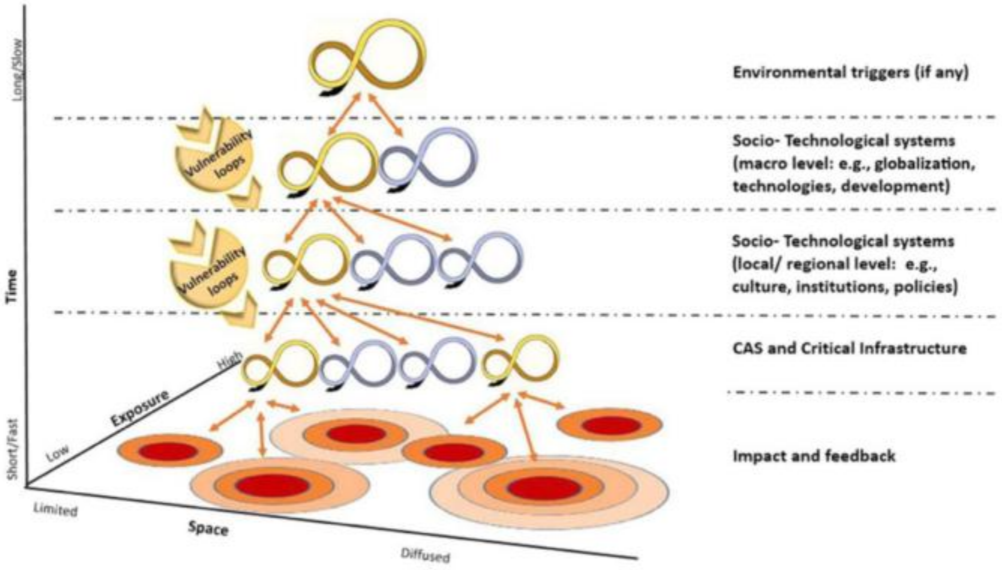

Figure 1: Illustration of complex feedbacks between systems that can generate systemic risks. CAS = complex adaptive systems. Source: Pescaroli and Alexander (2018)

Despite this, the empirical evidence on the economic and financial implications on compound shocks involving at least one physical climate shocks is limited. An important question for those responsible for economic and financial resilience is: are the impacts of compound shocks greater than the sum of the parts (and what are the causes of these non-linearities)? Or alternatively, from a risk management perspective, can shocks be treated in isolation, or is there some inherent non-linearity in how shocks

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[10] Pescaroli and Alexander (2018) describe how when shocks combine, or interact with existing vulnerabilities (i.e., compounding), this can amplify the impacts and lead to complex, cascading effects, increasing the potential for systemic, long-term implications. In the context of financial crises, systemic risk is defined as "*the risk of widespread disruption to the provision of financial services that is caused by an impairment of all or parts of the financial system, which can cause serious negative consequences for the real economy*" (Haldane and May 2011; BIS 2021; Jobst et al. 2013). More broadly, it can be defined as an event that can trigger a severe instability or collapse of an entire economy with significant economic losses and developmental impact (Schweizer and Renn 2019). Compound shocks are one possible source of systemic risk.

interact warranting the need to explicitly consider compound shocks? Zscheischler et al. (2018) suggests this is the case based on historical events. Ranger et al. (2021) seek to explore this explicitly through simulation and propose a metric for this compounding effect: the compound risk multiplier (CRM; Figure 2). The CRM is computed as the ratio between the impact (e.g. GDP loss) in the compound risk scenario and the sum of the impacts across individual shock scenarios. A CRM greater than 100% indicates non-linearities associated with the compound shock having a greater impact than the sum of the impacts of its constituent individual shocks. Based on macroeconomic model simulations for two countries for illustrative compound shock scenarios involving climate-related shocks, they find that the CRM can peak at over 130%; that is, impacts of two compounding shocks can be 30% larger than the scale of the sum of the individual shocks. This suggests that it is indeed important to consider the potential for compound shocks, including within risk analysis and risk management. Compounding effects could result in some climate-related shocks becoming particularly relevant triggers for systemic financial risk, even if such shocks may not be considered material when considered in isolation as individual shocks.

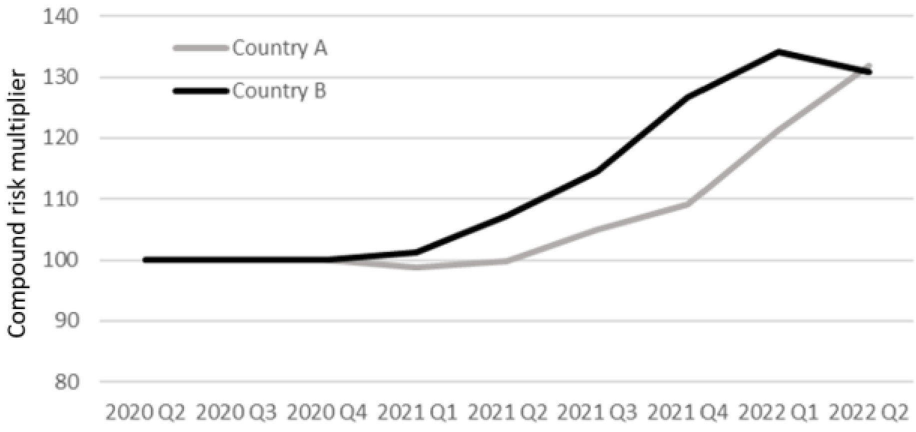

Figure 2: Compound risk multiplier for two example middle-income countries, where one is exposed to a flood shock (Country A) and the other a typhoon shock (Country B) during a pandemic. The compound risk multiplier is computed as the ratio between the GDP loss in the compound risk scenario and the sum of GDP loss in individual pandemic and climate risk scenarios. When the compound risk multiplier is higher than 100, this indicates non-linearities emerging that cause the shock triggered to be higher than the sum of the individual shocks. Source: Ranger et al. (2021).

Ranger et al. (2021) demonstrate that compound risk represents a structural change in the economy and its implications cannot be simply deduced by the sum of individual risks. They show that when risks interact, they can give rise to non-linear dynamics in the economy and financial systems, generating a prolonged out-of-equilibrium state of the economy. This is consistent with empirical understanding of the impacts of compounding events. Individual 'agents', people, firms, and investors, behave differently in these circumstances. Uncertainty about the outcomes makes individual and policy decision making more difficult. This, in turn, contributes to an increase in uncertainty for firms and investors. When agents are uncertain about the impacts of compound shocks, and about the outcomes that will prevail, their expectations are not well defined. Ambiguity averse firms will delay the investment decisions until they can form a better view of the future, and banks will tighten firms' access to credit, by revising the cost of debt upwards. This means that public policies aimed at restoring economic and financial stability will be less effective because the credibility of their economic signal may be weaker in the face of uncertainty. This leads to an amplification of the impacts of compound shocks, which is not captured in standard models.

For many types of compound shocks, the non-linear compounding effects originate mainly within the indirect effects of shocks (rather than direct damages[11]), in particular through impacting the ability of households, businesses, government and the financial sector itself to withstand the shock, respond and recover. Shocks can cascade through an economy with complex feedbacks leading to non-linear effects (Figure 1). For example, in the case of COVID-19 and weather-related shocks, households, businesses and governments' resources were already depleted by the pandemic and economic shutdowns so the impacts from weather-related events on economic growth were larger. Conversely, in an economy where the labor market, investment and capital stock are not already working at capacity, it can be easier to respond during crises and rebuild. Accordingly, Ranger et al. (2021) concluded that the multiplier effect is not one size fits all. This was evident even from comparing the findings from two countries in Figure 2, both of which were large middle-income countries of a similar size and structure. They observed that the dominant transmission channels and drivers of feedbacks are hazard-specific and country-specific and can combine in different ways, leading to vastly different compounding impacts between countries and hazards. The scale and timing of the indirect loss amplification looks different between different countries depending on the structure of the economy, the timing and nature of the shock and different vulnerabilities, leading to heterogeneous impacts on economies and financial systems. Similar risk amplification behavior was observed for Mexico in Dunz et al (2021b). 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. 2021b).

3. Compound Risks: Definition and Typology

To integrate compound risks within financial risk management, this note proposes an operational definition and typology. The literature contains multiple definitions. We adopt the commonly used definition provided by the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), based on Zscheischler et al., *"the combination of multiple drivers and/or hazards that contributes to societal and/or environmental risk"*. In our proposed definition (in the context of compound shocks involving at least one physical climate shock), these *hazards* can include at least one climate-related hazard, alongside hazards emerging from other environmental, economic, societal, geopolitical, and technological systems, and can include, for example, pandemics, economic recessions, wars or financial crises.[12] We further refer to compound *shocks* or *events* as a specific instance, whereas *risk* refers to the *likelihood* multiplied[13] by *impact*[14] of compounding events. Pescaroli and Alexander (2018) describe how such risks could be: *"(a) extremes that occur simultaneously or successively; (b) extremes combined with background conditions that amplify their overall impact; or (c) extremes that result from combinations of "average" events".*

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[11] Direct damages are the physical impacts caused by a shock (e.g., the physical destruction of assets). Indirect effects are the subsequent or secondary impacts of the shock (e.g., disruption to productive activities), and can extend beyond the direct damages in both space and time.

[12] This differs from, e.g. Pescaroli and Alexander (2018), which refer only to hazards in the natural environment.

[13] More generally, risk represents a convolution of the respective distributions of likelihoods and impacts.

[14] The impact is a function of hazard, exposure, and vulnerability. See later sections for details.

Box 1: Definitions from the Intergovernmental Panel on Climate Change

Compound risk:

Arise from the interaction of hazards, which may be characterised by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors.

Compound weather/climate events:

The combination of multiple drivers and/or hazards that contributes to societal and/or environmental risk (Zscheischler et al., 2018). The terms 'compound events', 'compound extremes' and 'compound extreme events' are used interchangeably.

Source: IPCC AR6[15]

There are many diverse types of compound shocks, distinguishable by their origin and how they combine over space and time. "Compounding" effects may occur amongst different elements of compound shocks. For example, compounding can occur through the various processes underlying physical hazards (e.g., the El Niño-Southern Oscillation or other large-scale modes of climate variation can result in spatially compounding droughts and extreme heat in multiple regions of the world) (Anderson et al., 2019). Compounding effects can also occur "downstream" of the hazard itself, for example, if an economy is impacted by a shock, its vulnerability to (and hence the impact of) subsequent shocks might be increased. Likewise, compounding effects can occur when considering indirect impacts on the economy and financial sector.

A typology of compound events has been developed for climate events (Zscheischler et al. 2020) and many parallels can be drawn also for compound shocks relevant to climate financial risk management. Such a typology is a first step toward operational implementation with climate scenario analysis, stress testing and risk management. We propose an operational taxonomy for financial institutions, central banks and supervisors below. Whilst this taxonomy is intended to be helpful for *scenario design* for physical climate scenario analyses, it is important to highlight that another critical element for physical climate scenario analyses is the *impact modelling* for the scenarios that are included.[16]

Four main categories of compound shocks can be distinguished based on the nature of the relationships between the constituent shocks (based on Zscheischler et al., 2020):

- **Preconditioned shocks** are those where hazards have an amplified impact because of a pre-existing condition.
- **Multivariate compound shocks** are those where multiple (spatially and temporally) co-occurring drivers or hazards cause an impact.
- **Temporally compounding shocks** are characterized by a sequence and/or recurrence of hazards in a given geographical region. The temporal horizon over which such sequences of events may occur could be sub-seasonal or may be several years (e.g., in the case of sequences of events that gradually erode the resilience of communities, the economy, and the financial sector).

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[15] IPCC Glossary: https://apps.ipcc.ch/glossary/

[16] For compound shocks, non-linear amplification compounding effects are a defining feature which impact modelling should aim to capture, as discussed further in Section 5.

- **Spatially compounding shocks** are characterized by occurrence of several hazards at the same time but in multiple different locations.

In the context of climate financial risk assessment, we explicitly expand this categorization differentiating between four categories of physical climate-related compound risks along a second dimension:

- **"Physical climate" ↔ "Physical climate"** compound shocks. This category includes compounding acute physical shocks. It also includes the combination of chronic changes and acute shocks, where weather-related or other shocks happen alongside chronic physical climate impacts (e.g., sea level rise or changing agricultural productivity due to average changes in precipitation and temperatures) and combine either temporally or spatially to generate non-linear impacts for society, the economy, financial sector and society. Compounding effects arising from the interaction of chronic and acute physical risks may manifest via a range of different risk drivers, transmission channels, and feedback effects, which may differ from the main mechanisms governing compounding shocks involving acute physical risks only. Compounding shocks involving chronic physical risks may evolve over long time horizons, as the impacts of chronic changes become more prominent.
- **"Physical climate" ↔ "Transition climate"** compound shocks. This category includes the combination of climate-related physical and transition shocks.
- **"Physical climate" ↔ "Other environmental"** compound shocks. Environmental shocks include broader nature-related shocks beyond climate-related shocks (Almeida et al., 2023), including both physical nature-related risks (arising from degradation of nature and loss of ecosystem services) and transition nature-related risks (arising from misalignments with actions aimed at protecting, restoring and/or reducing negative impacts on nature) (NGFS 2023a). There is increasing recognition that climate change and biodiversity loss are inextricably interconnected (INSPIRE 2022) and that neglecting these interconnections may lead to misestimates of systemic financial risk (Kedward et al. 2022). Capturing nature-related shocks can bring additional complexities beyond those of purely climate-related shocks, due to the complexities of ecosystems and their dynamics, and the need for improved understanding (and modelling) of the limited substitutability of nature and ecosystem services (NGFS 2023a).
- **"Physical climate" ↔ "Non-environmental"** compound shocks. Non-environmental shocks can include geopolitical (e.g., interstate conflict), societal (e.g., infectious diseases, employment crisis), economic (e.g., debt crisis), and technological (e.g., cyber insecurity incidents) risks, following the categories used in the World Economic Forum Global Risks Report (WEF 2023).

Table 1 gives examples of these types of shocks relevant to climate financial risk management. These examples, whilst illustrative, are only a small subset of the plethora of plausible shocks. While we have tried to include some illustrative historical examples, it is important to highlight that forward-looking plausible scenarios could be much more severe, particularly given changing risk profiles both for climate-related risks and other types of risk. Some compound shocks may span across multiple categories and further compound with other shocks given systemic interconnections in this era of polycrises, inducing additional pressure on existing vulnerabilities.

Table 1: Examples of different forms of physical climate-related compound shocks. Source: authors

	"Physical climate" ↔ "Physical climate" compound risks	"Physical climate" ↔ "Transition climate" compound risks	"Physical climate" ↔ "Other environmental" compound risks	"Physical climate" ↔ "Non-environmental" compound risks
Pre-conditioned shocks	Drought predisposing vegetation to burn, exacerbating wildfire severity (e.g., Australia 2019-2020, Squire et al. 2021)	Transition to electricity interacting with high electricity demand and supply outages during extreme heat events	Degradation of forests, wetlands, mangroves and other ecosystems providing natural flood management functions resulting in amplified flood severity (Bradshaw et al. 2007)	Pandemic weakening resilience to climate-related extreme events (e.g., COVID-19 pandemic weakening economy and disrupting response and recovery to disasters, e.g., drought in Madagascar (World Bank 2022) and typhoons in Philippines (World Bank 2020))
Multivariate compound shocks	Concurrent heat and humidity extremes (Raymond et al. 2020b, Powis et al. 2023)	Agriculture affected by drought alongside consumer shift to plant-based protein, increased regulation and carbon border adjustment mechanism in key export markets (e.g. New Zealand scenarios (RBNZ, 2021; Adams-Kane et al. 2023)	Widespread conversion of tropical forests to savannah due to timber extraction, fire, extreme drought (e.g., Amazon ecosystem collapse, Johnson et al. 2021, Lapola et al. 2023)	Climate-related disasters (e.g., severe flood) coinciding with financial crisis (e.g., 1997-1998 El-Nino flooding in Peru compounded with Peru 1997 financial crisis, Callahan and Mankin 2023)
Temporally compounding shocks	Sequence of drought and flood events (e.g., Ethiopia and Kenya 2016-2018 drought followed by widespread flooding[17], World Bank 2022)	Economy dependent on coal exports and coal-generated electricity impacted by transition policy shock subsequently impacted by drought affecting	Coral reef degradation event (e.g., driven by pollution, high ocean temperatures) followed by hurricane impacting tourism- and	Sequence of local conflict, pandemic, and climate-related shocks (e.g., Ethiopia 2020-2023 COVID-19 pandemic, Northern Ethiopia conflict, drought, reduction

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[17] Impacts of these events were further compounded by conflict, political disruption and crop pest infestation (World Bank, 2022).

		other sectors of economy	fisheries-dependent economy	in aid, and Ukraine war, UNDP 2022)
Spatially compounding shocks	Multiple breadbasket failure due to concurrent heat and rainfall extremes in major crop-producing regions (Kornhuber et al. 2023), affecting global food security and trade	Sudden implementation of climate policy by key trading partner affecting export-dependent economy alongside climate-related disaster locally	Concurrent significant stress on food system in key crop-producing regions (e.g., due to pollination collapse (Latty and Dakos 2019) and climate-related extreme events)	War in another region impacting global food, energy, and fertilizer prices, remittances, and tourism flows, alongside local drought/climate-related stresses (e.g., compounding shock of war in Ukraine in North Africa, Belhaj 2022)

Figure 3 illustrates how shocks across these different categories can interact as compound shocks. For each shock, *modulators* influence the frequency, intensity, and location of *drivers*, which in turn affect the occurrence and severity of *hazards* (the proximate cause of impacts). Modulators, drivers, and hazards may be associated with different systems (economic, environmental, societal, geopolitical, and technological)[18], with these systems also governing exposure and vulnerability (which together with hazard define impacts). Interactions and feedbacks between these different systems can contribute to compounding effects. The economy and the financial system can drive changes in environmental systems (including climate change and nature loss) as well as changes in geopolitical, societal and technological systems. The feedback loop between the economy and these systems can be either positive or negative. For example, in the case where economy is the driving factor of climate change in biodiversity loss, the amplification of impacts on the economy will likely prevail; while the nature-positive economy and financial flows would mitigate climate change as well as reduce pressures on biodiversity. That, in turn, would lead to reduced risks of compound shocks on the economy and financial systems.

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[18] In the case of physical climate shocks, the focus is on climate-related systems (as a subset of environmental systems) in the first instance. However, the other systems may be relevant for other shocks that compound with the physical climate shock(s), and these systems may also affect the impacts of the physical climate shocks.

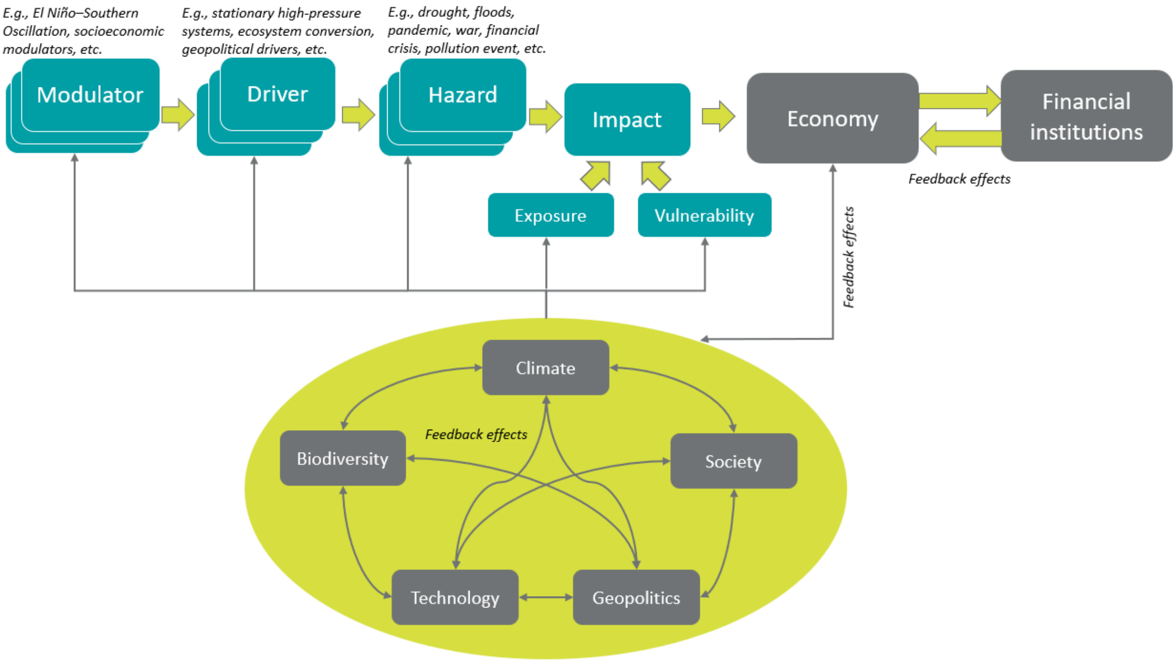

Figure 3: Typology of compound shocks to the financial sector. Modulators influence the frequency, intensity, and location of the drivers, with potential effects on hazard occurrence and severity. Modulators, drivers, and hazards may be associated with different systems (economic, environmental, societal, geopolitical, and technological), which can also affect exposure and vulnerability, and create compounding shocks across multiple interacting systems. Depending on the nature of the relationships between the constituent shocks (in terms of their modulators, drivers, and hazards), compound shocks can be classified as preconditioned, multivariate, temporally compounding and/or spatially compounding. Depending on the systems that they originate from, physical climate-related compound shocks can be characterized as "Physical climate" ↔ "Physical climate", "Transition climate", "Other environmental" or "Non-environmental" (economic, societal, geopolitical or technological) compound shocks Adapted from Zscheischler et al. (2020).

These different types of compounding risks may be relevant for both short-term and long-term scenarios, however the most relevant time horizon may differ between different types of shocks. The time horizon of the scenario analysis has implications for, inter alia, how key variables are modelled and projected, how impacts are calculated and, more specifically for compound risks, the way the compounding effects could unfold. As outlined above, longer time horizons may be relevant for "Physical climate" ↔ "Physical climate" compound shocks involving the combination of acute physical risks and chronic physical risks, as chronic changes become increasingly pronounced over future decades.[19] For scenario analysis involving long-term scenarios, it is important that the modelling methodologies reflect this time horizon, e.g., by considering how the (multivariate) distributions of risk, including the probabilities of co-occurrence of shocks, may evolve over time (see Section 5). Many other types of compound shocks, including examples of "Physical climate" ↔ "Non-environmental" shocks, may be relevant on short time horizons, particularly given the cocktail of

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[19] The relevance of inclusion of chronic physical risks in short-term scenarios is an unresolved point of discussion. Currently, the focus of the NGFS physical risk short-term scenarios is on acute physical risks (NGFS 2023b).

shocks that many countries (particularly EMDEs) are already currently facing. Indeed, as outlined above, there are already examples of compound climate shocks that have materialized. The potential relevance of short-term scenarios is also highlighted in recent work by the NGFS on short-term climate scenarios (NGFS 2023b).Importantly, none of these types of compounding risks are included in the current generation of NGFS scenarios (and guidance). Whilst the NGFS scenarios and methodologies are continuing to be developed, modelling approaches currently utilized for the NGFS scenarios do not yet capture compounding effects and this is one reason that they are likely to underestimate losses, particularly for physical risk. A barrier is that such risks are challenging to assess quantitatively, in both likelihood and scale, and these types of events are deeply uncertain, making it challenging to fully address them through the current generation of models. These issues are discussed in Sections 5 and 6.

4. State of Practice on Incorporating Compound Shocks into Scenario Analysis

The state of practice on incorporating compound shocks into climate and regular (non-climate) scenario analysis varies significantly across countries. As a contribution to this note, the authors surveyed NGFS members in July 2023. 32 responses were gathered from 26 central banks and supervisory bodies, plus three responses from multilateral development banks and international organisations. The regional distribution of respondents demonstrates coverage across both high- and middle-income countries (no low-income) across North America, Central and South America, Asia-Pacific and Europe.[20] Importantly, all but one of the respondents agreed that it is important to consider compound risks as part of climate financial risk assessment, and ten (34%) strongly agreed. Many respondents noted the potential for significant underestimation of risk when compound risks are excluded from scenario analysis, for example: *"Not accounting for compound shocks could lead to a severe underestimation of climate shocks' impacts on the macroeconomy and for financial stability".*

Only a quarter of respondents reported having incorporated compound climate shocks within climate-related scenario analyses, while around sixty percent reported that considering compound shocks was a routine part of regular (non-climate) scenario analyses and stress testing (Figure 4). Those that responded positively to both questions about incorporating compound shocks were relatively evenly spread across economic income groups and geographical regions. Written responses (Appendix 1) indicated that compound shocks in non-climate scenario analyses include combinations of credit, market, and liquidity shocks, including the simultaneous occurrence of multiple shocks. Examples of shocks mentioned by respondents include regional economic slowdown, deep recession in local economy, and global interest rate shock, fluctuations in stock prices, and operational risk events. For climate-related scenario analyses, written responses cited several examples, including: a bank solvency stress test scenario of drought, global recession, and depressed agricultural output prices, also including additional operational risk events; compound

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[20] Responses were received from respondents in Bahrain, Belgium, Brazil, Canada, China, Finland, France, Germany, Hong Kong, Iceland, India, Indonesia, Italy, Japan, Latvia, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Peru, Poland, Portugal, Singapore, Spain, and the United States of America. Whilst the responses received are useful to develop an understanding of the state of practice on incorporating compound shocks into scenario analysis, it is important to note that the responses received may not be fully representative of the entire population of central banks and supervisors globally. For example, no responses were received from central banks and supervisors in low-income countries.

drought and emissions pricing risks for agricultural borrowers in credit risk models; combinations of extreme flood events; and scenario including more restrictive external financial conditions, high inflation persistence, a decrease in private consumption and private investment due to political instability, and effects of El Niño phenomenon. What is clear from the survey results is that most of those central banks and supervisors that are considering climate-related compound risks are focusing on the interaction between (non-climate) macroeconomic risks and physical (or transition) risks (i.e., "Physical climate" ↔ "Non-environmental" compound risks based on the typology used in this note). However very few are considering the potential for "Physical climate" ↔ "Physical climate" compound risks or "Physical climate" ↔ "Transition climate" compound risks and none "Physical climate" ↔ "Other environmental" compound risks.

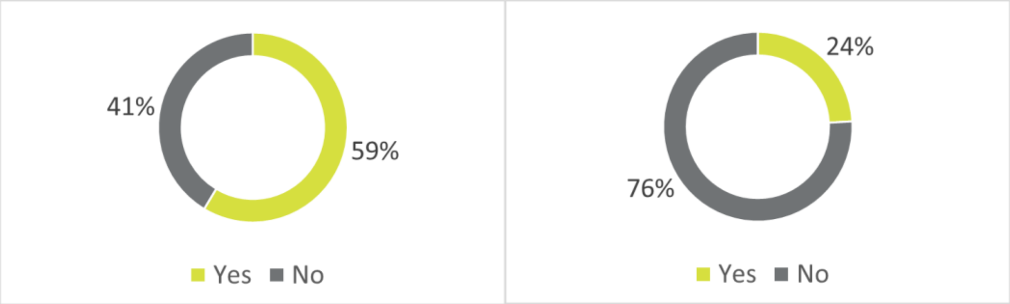

Figure 4: Responses to yes/no questions: (left) Would you consider compound shocks to be a routine component of scenario analyses or stress testing conducted (or supervised) by your institution? (right) Have you incorporated compound shocks in any previous or ongoing climate-related scenario analyses or stress tests?. Results counted across all thirty-two responses to survey conducted by NGFS in July 2023

Consistent with current guidance and practice on regular (non-climate) stress testing, the incorporation of compound risks in climate scenario analysis should be a recommended practice. For regular (non-climate) stress testing, from reviewing literature and responses from NGFS members, it is widely considered to be established practice to apply compound shocks for conducting stress test on banks, commonly in the form of macroeconomic shocks. This is consistent with best practice articulated by the International Monetary Fund (IMF). According to the IMF, for stress testing, the priority for central banks and supervisors is to identify and assess macro-financial 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). Therefore, 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). Compounding risks are explicitly included within their guidance on how to construct appropriate scenarios using a narrative approach similar to that of the PRA (2019). Given this, a recommended practice for climate scenario analysis should be to incorporate compound risks.

There are several publications (and forthcoming publications) with examples of approaches to incorporating climate-related compound risks into scenario analysis and stress testing by NGFS members and observers. Some examples of scenario designs from such analyses, including in EMDEs, are highlighted in Table 2, with further details in Appendix 2. There are geographic and sectoral heterogeneities in the distribution of compound climate risks, as with many types of risks to economies and financial systems. As such, the most relevant scenarios to consider are likely to differ depending on country specificities. The examples in Table 2 highlight how several NGFS members and observers are already considering compound risks in their scenario design for climate risk analysis. The examples cover a range of different types of scenarios, with some examples covering multiple "Physical climate" ↔ "Physical climate", "Transition climate", and "Non-environmental" compounding shocks. However, whilst these examples demonstrate how compound risks are being considered in *scenario design*, in many cases it is unclear to what extent potential non-linear amplification effects associated with these compound risk scenarios are captured in the *impact modelling* for these scenarios (e.g., the analysis of sequence of tropical cyclone and flood scenarios in Mexico by Dolk et al. (2023) does not explicitly capture non-linear compounding effects in the impact modelling).

Table 2: Publicly available examples of climate-related compound risks scenarios in scenario analysis and stress testing

Reference	Scenario design	Scenario classification[21]
Banco de Mexico: Banco de Mexico 2023	Multiple physical climate-related shocks	"Physical climate" ↔ "Physical climate"
Bank of England: PRA 2019	Deteriorating economic environment (reduced interest rates, widening corporate bond spreads and fall in asset values) and liability shocks (including storm surge event and an extensive flooding event)	"Physical climate" ↔ "Non-environmental"
European Central Bank: ECB/ESRB, publication forthcoming	Combination of adverse macroeconomic shocks and transition-related shocks	*(not physical climate)* "Transition climate" ↔ "Non-environmental"
Hong Kong Monetary Authority: HKMA 2023	Several extreme climate events, accelerated transition, and macroeconomic downturn (global economic downturn, Hong Kong recession, and slowdown in mainland China)	"Physical climate" ↔ "Physical climate", "Transition climate", and "Non-environmental"
Latvijas Banka: Ozolina and Petrovska 2023	Multiple physical climate-related shocks	"Physical climate" ↔ "Physical climate"
Reserve Bank of New Zealand: Adams-Kane et al., 2023	Several scenarios, e.g.: physical climate hazards affecting trading partners (impacting exports and tourism) during period with damaging weather events domestically (affecting property values); high transition risk (linked with more stringent carbon pricing) alongside physical climate hazards, including two flood events in the Auckland region	Several scenarios, e.g.: "Physical climate" ↔ "Physical climate"; "Physical climate" ↔ "Transition climate"
World Bank and IMF: Mexico: Dolk et al. 2023	Sequence of tropical cyclone and flood scenarios	"Physical climate" ↔ "Physical climate"
World Bank and IMF: Philippines: Hallegatte et al. 2022	Compound typhoon and pandemic shocks	"Physical climate" ↔ "Non-environmental"

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[21] Based on second dimension of classification of physical climate-related compound risks outlined in Section 3 of this note. For some publications there was insufficient information to classify the scenarios based on the first dimension of classification (i.e., preconditioned, multivariate, temporally compounding and/or spatially compounding).

World Bank: Colombia: World Bank 2021	1-in-500-year flood with a credit risk shock calibrated to the 1998-2000 banking crisis	"Physical climate" ↔ "Non-environmental"
World Bank: Georgia: World Bank, publication forthcoming	Compound pandemic and 1-in-200-year flood shock	"Physical climate" ↔ "Non-environmental"

Many survey respondents noted their intention to consider compound shocks in the near future as climate scenarios developed. *"I am concerned that the potential impacts the compound shocks are much larger and could have significant regional implications"* noted one respondent and another: *"Stress testing should look at 'worst case' severe but plausible scenarios, and in the case of climate risks this means when multiple climate risks materialise at once, and when they coincide with non-climate shocks as well*". Indeed, the experience of the Ukraine crisis was cited multiple times as an example of why considering compound shocks is so important from a financial resilience perspective.

However, the lack of scenarios (in particular, short-term scenarios), data (e.g., geolocated asset data), capability and tried and tested methodologies were noted as a barrier by most respondents to incorporating compound shocks in physical climate scenario analyses. The lack of empirical data on the impacts of compound shocks was noted by two respondents, leading to fear that including compound shocks could put central banks at risk from making substantial factual errors: "*The biggest barrier and difficulty is access to data that could be used to calibrate shocks".* One respondent commented *"the risk is underestimated when not considering compound shocks. But the barriers to conduct such scenarios are multiple: the models have to be adapted to these new compound shocks which is not an easy task".* The compounding impacts of nature and climate risk were particularly noted. Yet as highlighted by the examples presented in this section, it is evident that several NGFS members and observers are already considering compound risks in their scenario design for physical climate scenario analysis. This is in spite of the data, methodology, and modelling challenges associated with modelling the impacts of such shocks (including capturing the non-linear compounding effects characteristic of compound shocks). The following section looks specifically at the challenges and opportunities for modelling compound risks.

5. Modelling the Impacts of Compound Shocks

This section reviews the state of modelling relevant to understanding and quantifying compound risks. To understand the impacts of compound shocks on the financial sector, it is important to understand: firstly, the underlying physical drivers and hazards of physical climate-related shocks; secondly, direct damages associated with these shocks; and thirdly, the indirect impacts on the economy and financial sector, as well as also the impacts of other shocks (e.g., transition climate-related shocks, other environmental and non-environmental shocks). Compounding effects can be introduced at every stage of this impact chain. The extent of understanding of each of these varies, with several gaps in our current knowledge of compound shocks and their impacts on the financial sector. Our understanding is informed by multiple different disciplines and approaches. For example, whilst physical science and climate models give insight into the drivers and hazards of physical climate-related shocks, catastrophe risk models can help to estimate direct impacts of these physical climate-related shocks, macroeconomic models can inform estimations of indirect impacts across both physical climate-related shocks and other types of compound shocks, and financial sector impact models can translate these into estimates of financial sector outcomes. Some models may be particularly important for capturing particular types of compound shocks. For example, physical science and climate models are particularly important for understanding potential "Physical climate" ↔ "Physical climate" compound shocks, though they can also give insights into individual physical climate shocks. To fully understand compound risks, it is necessary to also understand the complex feedbacks at the intersections of, and within, each component, particularly since non-linear amplification associated with compounding effects might arise through these feedbacks. A challenge is the lack of empirical data to date to calibrate and validate the models for the case of compound shocks.

This section discusses how compound shocks are or could (and could not) be captured within these four main types of models that are generally used within physical climate-related financial risk assessment: climate models; catastrophe risk models; macroeconomic models, and financial sector impact models. We also briefly discuss several additional types of modelling approaches: (i) network models (which are emerging in the discourse on compound risks as an alternative method to capture indirect impacts by explicitly modelling the physical interconnections between systems that are important in the transmission of shocks – e.g., infrastructure networks and trade networks); (ii) two approaches that directly link direct damage estimates with banking sector impact estimates (i.e., "bypassing" the explicit modelling of indirect impacts on the economy; and (iii) integrated assessment models (IAMs) that attempt to capture the entire impact chain from climate to economy, albeit in a simplified way versus those models mentioned above.

5.1 Physical Climate Models

There is a large, and growing, body of scientific research related to understanding the physical hazards underlying climate-related compound shocks. This literature provides insights into: the hazards themselves, which can be considered the proximate causes of direct impacts (e.g., floods, droughts); the climate drivers that govern the occurrence and severity of these hazards (e.g., weather systems such as storms, and tropical cyclones); and the modulators that affect the frequency, intensity, and location of the drivers (e.g., climatic variations such as the El Niño-Southern Oscillation) (Zscheischler et al., 2020). Physical climate models play a central role in this research, particularly for forward-looking climate analyses for a range of projection timescales. Yet an important challenge in modelling compound shocks, and in particular understanding the future likelihood, spatial distribution, and intensity of these shocks, is that the granularity of most global climate models is still insufficient to fully capture weather extremes.

Physical climate models are particularly important for analyzing "Physical climate" ↔ "Physical climate" shocks. Recent research has produced promising results in terms of the robustness of current physical climate models for understanding the high-level characteristics of compounding hazards today and in the future, suggesting that such models could be usefully deployed within physical climate risk assessment. For example, Ridder et al. (2020) examined globally the co-occurrence of windstorms, heavy precipitation, heatwaves, and droughts across models to study both the likelihood of co-occurrence and the ability of the current generation of models to provide decision-relevant information given the uncertainties (Figure 5). The authors show a high co-occurrence of strong winds, heavy rainfall, drought and heatwaves that (for most of the world) is consistent with what has been observed. Other studies have conducted more detailed analysis for one or more regions, for example, demonstrating the strong co-occurrence of flood and windstorms in the UK and across Europe, albeit on different timeframes (Bloomfield et al. 2023) (Figure 6).

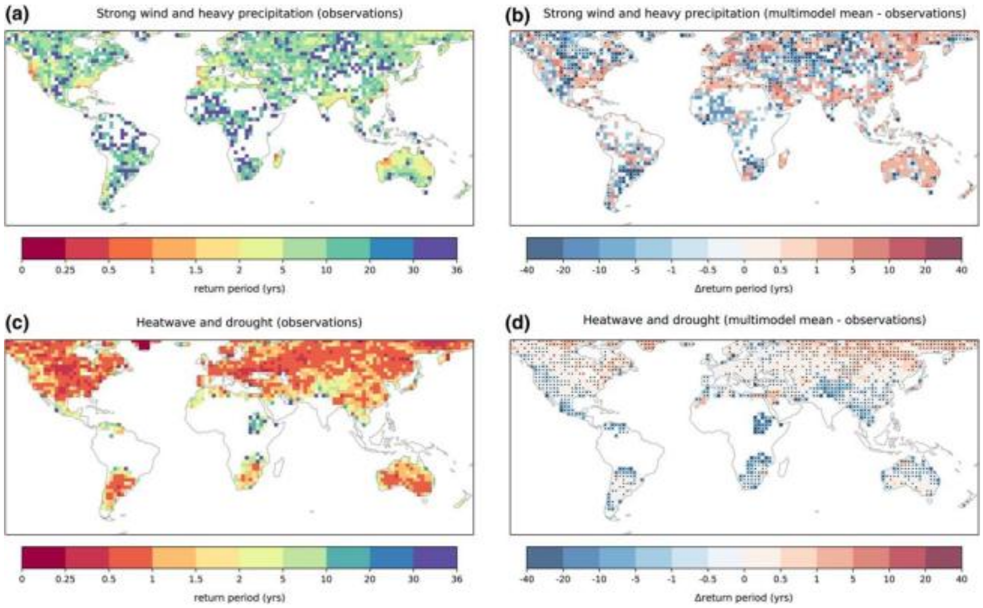

Figure 5: (a) Joint return periods of compound events consisting of strong daily mean winds and high daily precipitation sums in observations. (b) Multimodel mean bias in joint return periods for the co-occurrence of strong winds and heavy precipitation. (c and d) As (a and b) but for compound events consisting of heat waves and meteorological drought. In panels (b and d), stippled regions indicate grid cells where at least 75% of the CMIP6 models agree on the sign of bias. CMIP6, sixth phase of the Coupled Model Intercomparison Project. Source: Ridder et al. 2020

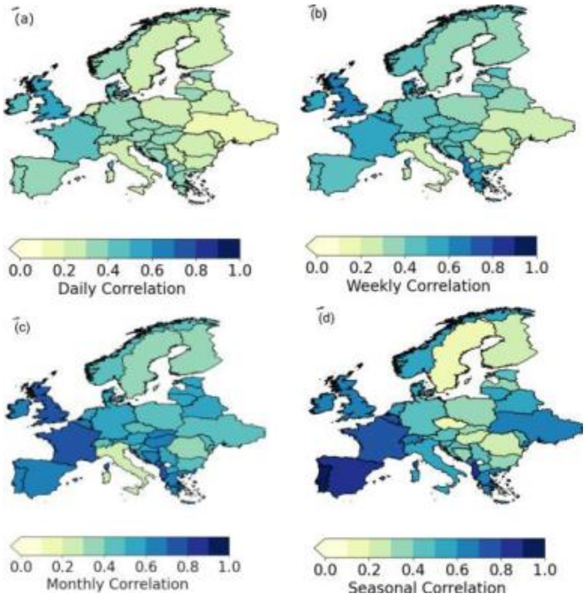

Figure 6: Spearman’s rank correlation between national-aggregate total river flows (GLOFAS) and mean maximum daily 10 m wind gusts (ERA5) over (a) daily (b) weekly, 7 days (c) monthly, 30 days (d) seasonal, 180 days timescales. Source: Bloomfield et al. 2023

As an example of the state of the use of physical climate models for exploring compound physical climate-related risks, consider the state of research on understanding the risk of multiple breadbasket failure scenarios. Globally concurrent extreme climatic events such as droughts (Singh et al., 2022) or heatwaves (Rogers et al., 2022) can have outsized global impacts in particular on the global food sector (Puma et al., 2015). Simultaneous harvest failures in major global crop producing regions are a high-risk scenario in particular for countries that rely heavily on imports. Concurrent extremes occur on an increasing rate under future emission scenarios, mostly driven by mean warming (Raymond et al., 2022; Zhou et al., 2023). Future risks of concurrent breadbasket failures[22] thus far have been estimated based on purely statistical analyses (Gaupp et al., 2019). Concurrent extremes and crop yields are further modulated on annual and seasonal timescales by dominant modes of variability such as the El Niño Southern Oscillation (ENSO) and other modes of variability (Anderson et al., 2023). Thus, for an estimate of future risks of concurrent extremes it is necessary for models to accurately reproduce natural cycles and project their changes in a warmer climate. Recent evidence suggests that ENSO has become more intense due to anthropogenic influences (Cai et al., 2023) which might continue under future emission scenarios (Shin et al., 2022). However, some models seem to fail to reproduce the observed trends (Lee et al., 2022). Several of the globe's major crop producing regions are located in the moderate climate zones of the mid-latitudes where day to day weather and its extremes are driven by the fast-flowing winds of the Jetstream. A strongly meandering jet can generate concurrent extreme weather events with significant effects on harvests in the affected regions (Kornhuber et al., 2020). Analyses suggest that state of the art climate models are underestimating the magnitude of extreme weather events from such weather regimes and their impacts on crop yields (Kornhuber et al., 2023). As such, the authors of these analyses argue that estimates for complex risks such as concurrent breadbasket failures, based on model experiments need to be considered conservative.

Given the recent and ongoing scientific advancements in the understanding of compound climate shocks, the establishment of stronger channels for knowledge sharing between scientists and central banks and supervisors could be helpful to ensure that physical climate shocks are appropriately included within climate scenario analyses and guidance provided to financial institutions. Organizations such as the NGFS could play an intermediary role to facilitate knowledge sharing and disseminate relevant scientific research, including through guidance materials, as discussed in Section 7.

5.2 Catastrophe Risk (Cat) Models

Catastrophe risk (Cat) models have been shown to be useful to estimate the direct impacts associated with climate-related shocks for climate financial risk assessment, but they are currently limited in their ability to capture compound shocks. The strength of Cat models (versus for example integrated assessment models) is their ability to quantify the impacts of extreme weather events. This makes them particularly well suited to physical climate financial risk assessment. The CLIMADA model that underpins some variables in the NGFS Climate Impact Explorer, and is used for modelling flood and tropical cyclone risk in the phase IV NGFS scenarios, is an example of a Cat model. Cat models were also used in the Philippines and Mexico climate financial risk assessments (World Bank and IMF, 2022; Hallegatte et al. 2022; IMF 2021).

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[22] A 'breadbasket failure' is an event of low agricultural production (e.g., due to a drought) in a major food-producing region.

Cat models have originally been developed for use by the (re)insurance industry and are used extensively in insurance to model, in granular detail, the damages and insured losses associated with extremes, including weather extremes but also non-weather-related extreme events (e.g., earthquakes), pandemics and cyber risks. They typically consist of four core modules:

- **A hazard module,** which typically consists of an event catalogue which describes the frequency and severity of plausible events (e.g., tropical cyclone tracks) combined with hazard maps which are used to characterize the local hazard intensity (e.g., flood depth or wind speed);
- **An exposure module**, which characterizes the geographic distribution and attributes of assets and populations in the modelled region;
- **A vulnerability module** which relates hazard intensity to an estimate of direct damage (to exposed assets or populations), and in some cases business interruption losses (though usually based on simplified assumptions); and
- **A financial module** which can translate the estimated direct damage into a financial loss estimate (e.g., considering insurance policy conditions in the case of insured loss estimates).

Each of these modules potentially has a role to play in capturing compounding effects in direct damage estimates of climate-related shocks. However, there are some substantial gaps in the extent to which they currently do so:

- **The hazard module** can capture some forms of compounding effects but is constrained in that it generally only considers individual events at country or region level. For example, flood models may capture antecedent conditions in a catchment (e.g., soils that are saturated due to previous rainfall), which could correspond to Zscheischler et al.'s (2020) concept of a "preconditioned" compound event. In addition, tropical cyclone models are increasingly considering not only wind hazards, but also other hazards associated with tropical cyclones, including flooding from heavy rain and storm surges – corresponding to a "multivariate" compound event. Catastrophe risk models typically have a catalogue of events. While these events can be assigned a timestamp (allowing sequences of events to be considered, and metrics such as annual exceedance probabilities to be computed), they are typically considered independently of each other when direct damages are calculated. As such, there are typically no non-linear compounding effects between the events in the event catalogue in the calculation of direct damages – rather the estimated damage of the sequence of events each year is simply the sum of the damage of the individual events.[23] However, even if the direct impacts are not compounded, there can be value in considering potential sequences of shocks for understanding the potential materiality of shocks in climate scenario analysis (Box 3). Catastrophe risk models do not generally have event sets at a global scale and so, to date, do not consider the potential co-occurrence of events between different regions (e.g., due to the El Niño-Southern Oscillation). This could limit their application for some types of spatially compounding shocks that may occur at a global scale – e.g., multiple breadbasket failures.

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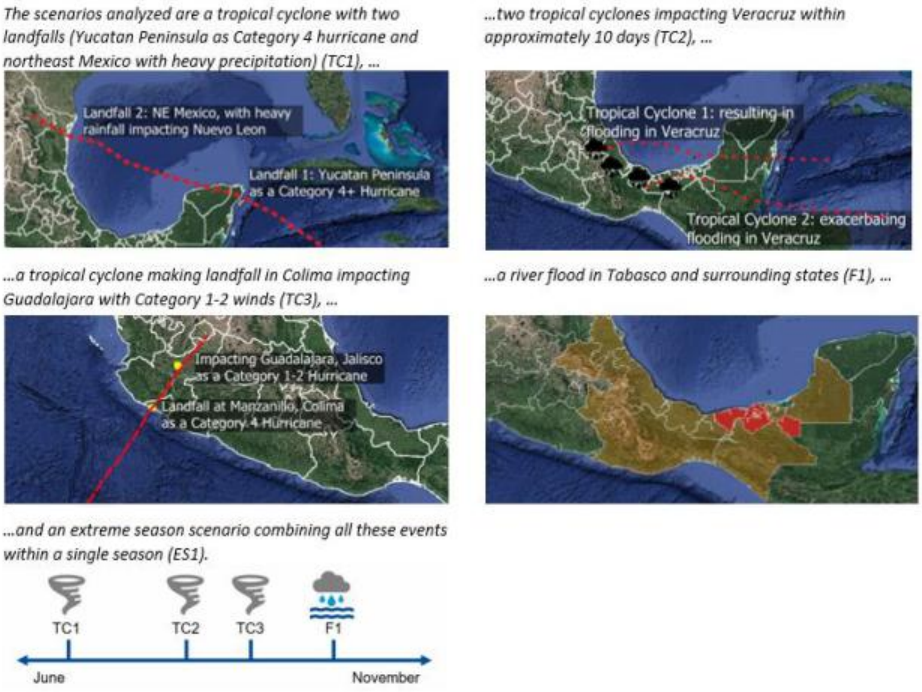
[23] In the case of (re)insurance contracts with features such as annual aggregate deductibles, the occurrence of multiple events may be considered in the financial module of the catastrophe risk model, and thus the sequencing of events might affect the estimated impacts (but more so in terms of the financial loss estimate rather than the direct damage estimate).

Box 3. Applying catastrophe risk models to sequences of natural disasters in Mexico

As part of joint World Bank and IMF climate physical risk analysis for the 2022 Mexico Financial Sector Assessment Program (FSAP) (World Bank and IMF, 2022; Dolk et al. 2023), the team defined and analyzed a sequence/cluster of geographically non-overlapping tropical cyclone and flood events occurring during an "extreme season" scenario impacting Mexico. The definition of these scenarios was based on evidence of clustering of tropical cyclones in the region, with periods of high activity interspersed with periods of relatively low activity, in part linked to large-scale patterns, such as those of sea surface temperatures. The scenario analysis highlighted that even if the scale of individual events may not be material at an aggregate national scale, considering a series of events could lead to potentially significant macro-financial impacts, despite none of the individual events directly affect the region with highest concentrations of banking sector exposures (i.e., Mexico City).



Source: Dolk et al. 2023

- **Vulnerability:** The vulnerability functions used in catastrophe models are generally static, that is they do not consider the potential changes in vulnerability due to previous events. This is a limitation when considering compound shocks since vulnerabilities are unlikely to be static. This limits the ability to model 'pre-existing conditions'. For example, vulnerability could be increased if a building is weakened by a previous shock (e.g., a building whose roof is damaged by tropical cyclone winds could be more vulnerable to subsequent rainfall events). Whilst there have been studies to develop damage-dependent vulnerability curves for some risks (e.g., earthquake, Polese et al. 2013), these have not yet been systematically incorporated into catastrophe risk models.

- **Exposure:** For a given model run, the exposure in catastrophe models typically remains fixed over time so these models would require adjustment to incorporate any 'pre-conditioning' impacting exposures, such as damages from past shocks.

In conclusion, while catastrophe risk models do hold promise for capturing some aspects of the direct damages associated with compound shocks, there are currently some critical gaps that remain to be addressed. These gaps are of particular importance for types of compound shocks for which compounding dynamics would be expected to affect the direct damages. However, catastrophe risk models are nonetheless useful tools when combined with other approaches.

5.3 Macroeconomic (and Macro-Financial) Models

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 (Ranger et al. 2022), which often are at least as large. Examples of direct impacts include physical damages to capital stock, whereas indirect impacts may include broader impacts, for example on supply chains and production, as well as macro-economic feedbacks and long-term adverse consequences on economic growth (see Hallegatte 2015). Indirect effects of physical climate shocks can be quantitatively estimated using computational macroeconomic models. Such models assess the impacts of shocks on a variety of economic indicators, such as GDP level and growth, trade, and employment. There are a wide range of macroeconomic models, which may be broadly differentiated based on theoretical (equilibrium/non-equilibrium), methodological (optimisation/simulation) and flow of information (demand-led/supply-led) aspects (Mercure et al. 2019).[24] The most commonly used models by central banks and supervisors are Computable General Equilibrium (CGE) models, Dynamic Stochastic General Equilibrium (DSGE) models (e.g. the EMuSe model described in Hinterlang, Martin, Röhe, Stähler, and Strobel, 2023) and structural econometric models (e.g., Burns, Jooste, and Schwerhoff, 2021).

The current standard economic toolkit is not well suited for analysing the economic and financial impacts of compound shocks. In the last decade, research in macroeconomics and finance has extended to consider climate change and systemic financial risks, as well as their transmission channels and impact on the real economy. However, the compounding of shocks of different nature (e.g., pandemics, climate change, financial instability) represents a new type of risk for macroeconomic research, policy making and financial regulation that requires more investigation and, possibly, new tools. Macroeconomic research on compound shocks is still limited to only a few studies, and not yet well integrated into the toolkit of central banks and supervisors. As discussed in Section 2, compound risk represents a structural change in the economy and its implications cannot be simply deduced by the sum of individual risks (Ranger et al., 2021). Amplification of the impacts of compound shocks are challenging to capture in many models (e.g., Box 4).

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[24] Examples of supply-led models include CGE models and DSGE models. Examples of demand-led models include macro-econometric models and agent-based models. The reader is referred to Mecure et al. (2019) and Monasterolo et al. (2023) for a comparison of these models.

Box 4: Challenges capturing compound shocks in the OECD CatDSGE model

CatDSGE, a New Keynesian DSGE model, was developed by the OECD to understand systematic impacts of catastrophes on economies. The model uses scenarios constructed using catastrophe model methods as model input and transforms scenario damage estimates into macroeconomic shocks. As part of a joint OECD -World Bank project, the team explored how the methodology could be used to analyze individual and compound scenarios, including compound natural disaster and pandemic scenarios. The model results showed that in some cases the damaging effects from a natural disaster and pandemic add up and that a pandemic's constraints on firms and labour can work against a natural disaster's positive effects on demand creation, creating a 'worst of both worlds' effect with increased unemployment and reduced GDP. In one compound drought/pandemic scenario, ongoing shocks from a long-term drought diminished post-pandemic recovery, with GDP prevented from reconverging at the steady pace modelled for the pandemic shock without the compounding drought.

The model results also highlighted potential temporal re-ordering of impacts due to time preferences, with first-year impacts of a compound scenario exceeding the simple sum of two individual scenarios, and later impacts falling below the linear sum.

However, the sum of all shock effects over time remained additive due to the numerical methods employed to solve CatDSGE. The team concluded that further work to capture potential non-linear amplification effects that can occur between shocks is needed as part of future development of CatDSGE to enable it to better capture compound shocks. Other dynamics that the model is unable to capture include epidemiological interactions. For example, for a compound flood/pandemic scenario, the model results showed an increase in hours worked by households, driven by reconstruction needs following the flood. However, increasing work hours amidst a pandemic could further increase disease transmission, an effect which is not captured by the model.

Source: World Bank and OECD

Considering the complex, non-linear dynamics of compound shocks is important because they can lead to economic scarring, i.e., long-lasting effects and a slow recovery (hysteresis). Recent research also highlights the limitations of traditional macroeconomic and financial risk approaches to analyze the non-linearity and complexity of climate-related risks, and the implications of using traditional approaches for policy recommendations (Monasterolo 2020; Krogstrup & Oman 2019). For instance, macroeconomic models commonly used by Ministries of Finance and central banks, such as Dynamic Stochastic General Equilibrium (DSGE) models and Computable General Equilibrium (CGE) models typically assume that agents have rational expectations and that hysteresis plays no role. These models rely on equilibrium assumptions, which may not be valid, particularly in the case of acute physical climate shocks. Whilst CGE models typically have high sectoral granularity, drawbacks of these models include their limited ability to capture short-term dynamics (which are often relevant when evaluating the impacts of disasters). Although some DSGE models have started to incorporate individual actors and more endogenous factors (e.g., money creation by banks, Jakab and Kumhof, 2019), they mostly relegate it to short-term 'financial frictions' (Galí, 2018), without considering the potential for long-term build-up of economic and financial fragility. Recent research shows that embedding investor expectations and risk perception is crucial to avoid underestimating risk and has implications for the growth and transition path (Battiston et al. 2021; Dunz et al. 2021a). This is highly relevant in the context of compounding risk, for which we need integrated economy-finance models that are flexible enough to consider different high-end climate and compound risk scenarios, endogenously generated demand and supply side reactions, and a realistic representation of the role of financial markets (Dunz et al. 2021b). Gourdel et al. 2021 demonstrate these points for European stress testing.

Whilst equilibrium models are widely used, scholars from other schools of thought have recognized 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 et al. 2021, Farmer, et al. 2016). Stock-Flow Consistent (SFC) models and agent-based models (ABMs) have emerged as important classes of models for this type of problem. SFCs represent the economy with detailed balance sheet assessment, and can endogenize the climate-economy-finance feedback. ABMs represent the economy through simulations of the microlevel behaviour of heterogenous individual agents, assuming that these agents use simple heuristics for decision making (Poledna et al. 2023). Whilst these models can be useful for capturing non-linearities, a key drawback for their more widespread use in applications by central banks and supervisors is their data intensiveness. Several studies have now begun to model the impacts of compound shocks using such models. Box 5 gives a case study example from Ranger et al. (2021), using macroeconomic and financial risk analysis of compounding scenarios, using the EIRIN macroeconomic model (Monasterolo and Raberto 2018, 2019), an example of an SFC ABM. A primary conclusion drawn from this analysis is that when pandemic and extreme weather events combine and interact within an economy, they generate non-linear effects that can amplify losses significantly (Figure 2). Indeed, the total impacts can be larger than the sum of the individual shocks. Pandemics and disasters have different direct impacts. However, by impacting simultaneously on the firms' production and household demand, indirect impacts are amplified. For example, both shocks impact on firms' expectations and investment decisions. 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 socio-economic effects on both firms and people and slowed growth and recovery. Dunz et al. (2021b) completed an analogous study for Mexico, using the same scenario framework and model. Whilst these approaches are promising, current drawbacks include limited sectoral granularity,[25] and limited ability to be solved analytically. Other examples of non-equilibrium models applied for analyzing climate shocks include macro-economic simulation models (e.g., E3ME, Mercure et al. 2018)

Further work is needed to compare and refine models to strengthen the toolkit for compound risks, including exploring opportunities to incorporate compound risks robustly within the standard toolkit of central banks. The diverse range of models outlined above can generate very different insights into the impacts of shocks. For example, Bachner et al. (2023) applied a CGE model and an ABM – two very different models – to analyze indirect impacts of flood events in Austria. They highlight that the different model classes considered have different strengths and weaknesses which influence their suitability for different applications (e.g., the ABM used may be suited for describing short to medium-term effects, whereas the CGE model may be used to study long-term effects). They suggest that as a result of the fundamental differences between the models, direct comparison of

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[25] Limited sectoral granularity compared with other models was cited as one of the reasons why EIRIN was note used by the NGFS Macrofinancial Workstream in a pilot when selecting an additional model for increasing the sectoral resolution of the NGFS scenarios (NGFS 2022).

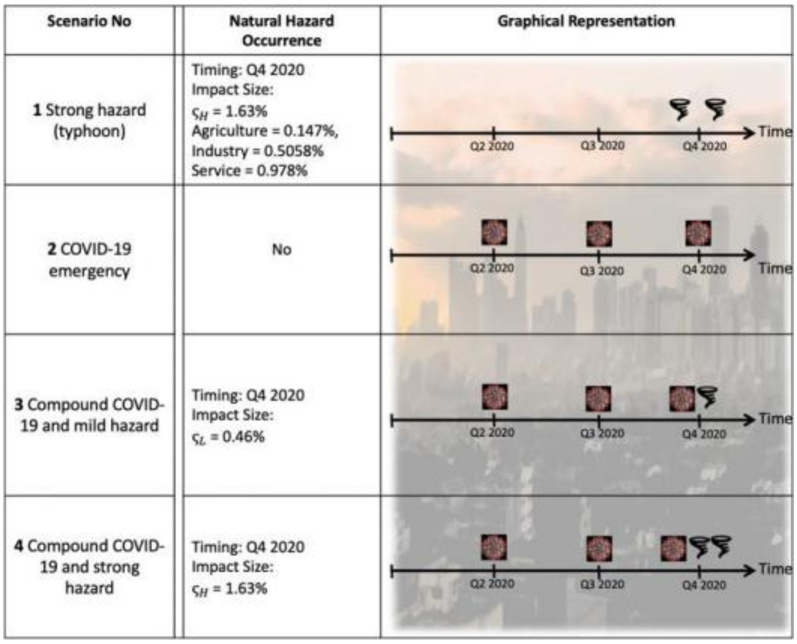
model results may not be meaningful, but nonetheless reveals large modelling uncertainties, and the potential advantages of a "toolbox" approach to modelling shocks.

Despite the limitations of the various existing macroeconomic modelling approaches, there is potential for substantial progress to be made in the analysis of physical risks by applying models from the existing macroeconomic modelling toolkit. This should be encouraged, alongside the ongoing development of modelling approaches that can better capture the non-linear amplification effects characteristic of compound shocks.

Box 5: Case Study: Modelling Compound Shocks

Ranger et al. (2021) proposed a preliminary framework for assessing the economic losses and financial impacts associated with compounding climate, economic and pandemic shocks. They take a three-step approach. First, developing a framework for capturing compound shocks within a macroeconomic risk assessment using a scenario-based approach and propose a new indicator for measuring the compounding effect in economic terms. The scenario-based framework learns from existing approaches to scenario planning and stress testing that are common when dealing with complex, non-linear and potentially systemic risks (e.g., IMF 2020; Schweizer and Renn, 2019). Secondly, map the potential transmission pathways of shocks and identify where they could interact and lead to potential amplifying or cascading effects. Thirdly, simulating the impacts of different scenarios using one macroeconomic model, EIRIN (Monasterolo and Raberto 2018), modified to capture the transmission pathways identified in the analysis described above. This last step enabled the authors to quantitatively assess how climate (physical) shocks are (directly and indirectly) transmitted, and how it compounds with other shocks like a pandemic or economic shock.

As a demonstration, they took the case of a major climate shock occurring during a pandemic and applied it to two middle income countries structurally similar to Southeast Asian or some larger Latin American countries. Scenarios were designed of individual and compounding COVID-19 and natural hazards, i.e. floods, that seasonally hit individual case study countries and that are worsened by climate change. In a similar way to stress-test exercises, they identify severe but plausible scenarios, based on the country's exposure to natural hazards and COVID-19. The figure below illustrates the construction the four scenarios. The four scenarios combine climate shocks of different magnitudes with COVID-19 scenarios based on empirical observations and test different timings of the compounding events. The scenarios are designed to assess risks that could happen tomorrow (rather than a future projection) and therefore are highly relevant to decision makers now and to COVID-19 recovery planning. Some results of this analysis are shown in Figure 2, highlighting the non-linear compounding effects that were observed in the model outputs.



Scenario No	Natural Hazard Occurrence	Graphical Representation
1 Strong hazard (typhoon)	Timing: Q4 2020 Impact Size: $\varsigma_H = 1.63\%$ Agriculture = 0.147%, Industry = 0.5058% Service = 0.978%	Q2 2020 Q3 2020 Q4 2020 Time
2 COVID-19 emergency	No	Q2 2020 Q3 2020 Q4 2020 Time
3 Compound COVID-19 and mild hazard	Timing: Q4 2020 Impact Size: $\varsigma_L = 0.46\%$	Q2 2020 Q3 2020 Q4 2020 Time
4 Compound COVID-19 and strong hazard	Timing: Q4 2020 Impact Size: $\varsigma_H = 1.63\%$	Q2 2020 Q3 2020 Q4 2020 Time

Figure: Illustration of scenario framework for one middle-income country. Scenario 1 (SC1) is characterized by the occurrence of typhoons that hit late in the typhoon season, but no COVID-19 shock. 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. COVID-19 scenarios were based upon actual data available for the countries at the time of the study. 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 et al. 2021

5.4 Financial Impact Models

To estimate the impacts on the financial sector, the outputs of the macroeconomic models can be translated into financial sector outcomes. A common way to do this is using the credit and market risk models commonly used by central banks and supervisors. These models are based on empirical estimates of relationships between macroeconomic variables and financial sector variables (e.g., non-performing loans and probability of default). These models typically provide outcomes per unit of exposure. A financial stress test model is then used to link these estimates per unit of exposure to the balance sheets of banks and other financial institutions to estimate bank impacts. While this approach to financial sector impact modelling has been commonly used, a major limitation is that in most cases it does not capture potential feedbacks from the financial sector to the economy,[26] which are capable of amplifying shocks, and thus may be relevant in the context of compound risks. Researchers and central banks and supervisors could further explore the magnitude and relevance of

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[26] Whilst many of the macroeconomic models discussed in Section 5.3 do not capture feedbacks from the financial sector to the economy, some of the approaches that embed financial actors in macroeconomic analyses and endogenize investors' expectations (e.g., SFC models such as the EIRIN model) do allow some finance-economy feedbacks to be analyzed. Such approaches may thus have advantages for capturing compound shocks relative to approaches where macroeconomic model results are unidirectionally translated into financial sector outcomes.

potential compounding effects in these feedbacks between the financial sector and the economy, and whether the materiality warrants them to be better captured and assessed in models.

Borrower-level credit risk models are another financial impact modelling approach that may be used to estimate impacts on the financial sector and may be suited to capturing some of the non-linearities associated with compound shocks. In this more "bottom-up" approach, credit risk is modelled at the borrower level then aggregated across borrowers. For each borrower, default may be considered a binary outcome from the set of shocks they are hit with. In the case of individual shocks, depending on the shock severity, some (perhaps many) borrowers will not default. However, in the case of combined compound shocks, borrowers may be more borrowers may be likely to default. Thus, when estimated individual default outcomes are subsequently aggregated across borrowers (who have a distribution of vulnerabilities and thus a distribution of default thresholds for a given shock or combination of shocks) the aggregate default rate will naturally be non-linear with respect to the magnitude of the shock or sum of the magnitudes of combined compound shocks. Such models are not always fully integrated with the macroeconomic models outlined in Section 5.3. Rather, in some cases, borrow-level credit risk modelling has been applied to directly link damage estimates with banking sector impact estimates (see Georgia example in Section 5.5.2).

5.5 Other Modelling Approaches

While the sections above cover some of the main types of models that are used within a 'modelling chain' to assess physical climate-related financial risks, there are also several other approaches that are of relevance to our discussion of compound shocks modelling. Each of these is briefly discussed here: (i) network models; (ii) models directly linking damage estimates with banking sector impact estimates; and (iii) IAMs.

5.5.1 Network Models

Network models are an emerging class of model that explicitly captures how shocks can transmit across networks, such as infrastructure networks (electricity, telecommunications, transport, water), supply chains and (physical) trade interconnections (ports, airports, roads). This type of model can include infrastructure systems models, but also more traditional global trade models. They would typically complement catastrophe risk models and macroeconomic models through providing the 'missing step' between them that captures the physical transmission of the shock within a country or globally. Network models are useful as they emphasize the 'location' of a node/asset/agent within the economic/financial system, where the location may be geographical or may represent a location within a production network. This could be particularly relevant to assess spatial dynamics of compounding shocks or dynamics within production networks, where the location is the decisive driver for amplifying shock impacts. While this might be also relevant for cascading impact assessments of individual shocks, in the case of compounding shocks it might be relevant where dynamic changes in the network are induced by an initial shock, which could reduce the resilience to subsequent shocks.

This class of model is seen as increasingly important in physical climate risk assessment because disruptions to networks can significantly amplify the initial direct shock. The indirect losses are shown to be potentially significantly larger than the direct effects. An example is the loss of power following a typhoon, or disruption to transport and thus, trade, can lead to closure of businesses that can drive major economic losses, and can impact the financial sector through non-performing loans. Networks are important in the compounding of shocks, for example, through trade and transport networks, shocks can be transmitted globally, thereby playing a role in each of those shock types in Table 1. Shocks to global transport networks can have systemic impacts on global shipping, trade and supply chains with implications for financial centres. For example, by combining estimated climatic-related port downtime at 1,320 ports with a global model of transport flows, Verschuur et al. (2023) estimates a total of US$81 billion of global trade and at least US$122 billion of economic activity being at-risk on average annually (Figure 7). Given the increasing interconnectedness of the global economy and the increasing reliance of economies on digital networks, network-related risks will increase over time.

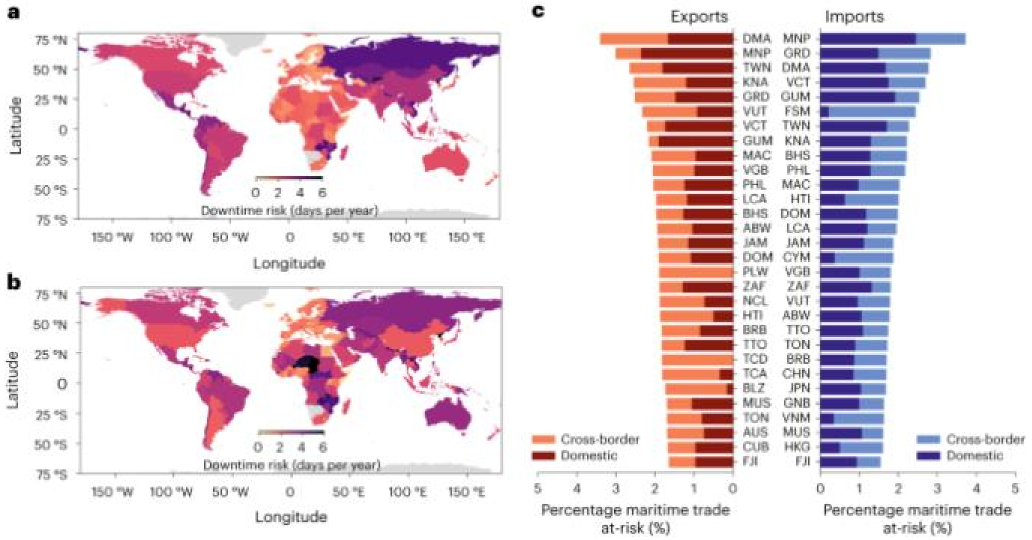

Figure 7: a, Cross-border downtime risk for import flows of countries. b, Same as a but for exports. c, Top 30 countries in terms of maritime trade at-risk (in value terms), including a breakdown between domestic and cross-border downtime risk. The country codes refer to country ISO-alpha3 code. Source: Verschuur et al. 2023

5.5.2 Approaches directly linking damage estimates with banking sector impact estimates

In the 'modelling chain' commonly used for modelling impacts of physical risks on the financial sector, direct damage estimates (e.g., from cat models) are used as inputs to macroeconomic models (which estimate indirect impacts) before generating estimates of financial sector outcomes. However, there are several examples of compound risk analysis approaches that have bypassed explicit indirect / macroeconomic impact estimates, either ignoring indirect impacts (a substantial limitation) or assuming that they are implicitly captured in relationships used to link direct damage estimates to bank impacts.

For example, in an analysis of a compound flood and pandemic scenario in Georgia (World Bank, publication forthcoming), a microeconomic and corporate balance sheet approach was used. First damage to fixed assets and revenue losses are estimated in a firm-level stress testing framework, using output from catastrophe risk models to estimate asset damages combined with proxies and simplified assumptions for estimating revenue impacts. Then the estimated firm-level impacts are linked with bank exposures in a "bottom-up" bank stress testing framework. This approach has the benefits of micro-level analysis (e.g., capturing firm heterogeneities). However, the approach is dependent on the availability of granular firm-level data, and in the case of the Georgia analysis is limited in that it does not capture other indirect shocks including infrastructure and supply chain disruptions.

Another example is an approach based on empirical estimates of the relationships between damages from natural disasters and banking sector impacts, as used in a climate stress test of the Colombian banking system (World Bank 2021). For this analysis, the elasticity of loan loss provisions and the sovereign credit rating to economic damages owing to natural disasters were estimated. A difference-in-difference modelling approach was used to estimate excess credit provisions in areas affected by the La Nina floods of 2010-2011 that cannot be attributed to other cyclical and bank-specific factors. The estimated elasticities to damages were then applied to model a range of scenarios, including a compound flood and banking crisis scenario. This approach however relies on the availability of historical data capturing disaster shocks, and relies on the assumption that the estimated elasticities hold for shocks of different severities (including also in compound shock scenarios) – thus limiting its ability to capture potential non-linear amplifications for compound shocks. As such, this example could be considered to have incorporated compound risks into the scenario design but not to have truly captured compounding effects in the impact modelling for the scenario.

5.5.3 Integrated Assessment Models

Integrated assessment models are a common tool in economic impact assessment for climate change, yet several authors have highlighted their limitations in the context of understanding the impacts of extreme weather events and so physical climate financial related risks (e.g., Ranger et al. 2022 and references therein). 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. In the context of the NGFS scenarios, whilst IAMs are extensively used in the generation of NGFS scenarios (e.g., particularly for transition risk), alternative models based on cat modelling approaches are used for the acute physical risk scenarios, in addition to the damage functions used for chronic physical risks.

IAMs attempt to model the whole impact chain, from climate to economy and so necessarily simplify each component. The current generation of IAMs assume that the impacts of extreme weather events can be represented as damage functions that connect temperatures to economic losses. This significant simplification, while justifiable for some applications, can lead to major misrepresentations of extreme weather and so underestimates of the scale of physical climate financial risks, as illustrated for example by Pitman et al. 2022. This limitation would similarly severely limit the ability of the current generation of IAMs to capture the effects of compounding climate shocks. Such impacts would, in effect, need to be boiled down to one or more damage functions linking temperature to impacts; that is, some amplification of the current damage function. Given the immature status of understanding and quantification of compound risks, both in terms of their impacts and how their likelihood would increase with global warming, such an approach would not be recommended at this stage for application within financial risk assessment.

In summary, recent advances in climate modelling, catastrophe risk modelling and macroeconomic modelling, as well as the new generation of network models, do bring promise in terms of developing a practical toolkit for central banks and supervisors to begin to incorporate compound risks into climate scenario analysis. We describe how, at this stage, approaches combining these types of models is recommended to address compound shocks, rather than attempting to incorporate compounding effects within the damage functions of IAMs. However, further work is needed to develop appropriate tried and tested methods for incorporating compound shocks within financial risk assessment, and to understand where the existing toolkit can be useful and if and where a whole change in approach is warranted.

6. Toward an Operational Framework for Incorporation of Compound Risks in Climate Scenario Analysis

This section provides initial recommendations toward an operational framework for incorporating compounding climate shocks within physical climate financial risk assessment. As noted in previous sections, many NGFS members and observers already include compounding risks within their guidance and practice on stress testing and scenario analysis (beyond climate). IMF (2019), for example, details how appropriate shocks can be identified and provides a framework for scenario analysis. Further, several central banks and supervisors that responded to the July 2023 survey were already considering the compounding of climate and macroeconomic shocks within climate scenario analysis. Given this, the pertinent question is if and where there is a rationale for a different approach to tackle compound climate risks specifically. On this, based on the discussion above, we offer the following conclusions:

- **Compound climate shocks should be considered within climate scenario analysis.** There is a need for further data collection and empirical analysis on the economic impacts of compound shocks. Yet already the collected evidence suggests that compounding may be material and supports the incorporation of compound shocks as a recommended practice within climate scenario analysis by central banks and supervisors.

- **Central banks and supervisors should work closely with the scientific community to help identify the most relevant plausible compound climate shocks** as well as to provide further and robust empirical evidence on the economics of compound shocks and their impacts on the macroeconomy and financial sector.

- **Which compound shocks to consider will depend on the characteristics of the country(ies) of analysis.** There is a broad range of compound shocks. The evidence suggests that at least some of these compound shocks are likely to be relevant and financially material for many countries, even in the short-term. The identification of the most relevant shocks for inclusion in a scenario analysis can be based on historical analyses, identification of climate-related economic vulnerabilities, expert consultations, and analyses of future climate projections.

- **When incorporating compound shocks into climate scenario analysis, central banks and supervisors might consider a three-stage approach:** Firstly, the development of narrative scenarios or storylines in collaboration with experts.[27] Secondly, working with the scientific community to add sufficient quantification to scenarios to make them usable and useful for climate scenario analysis; including drawing upon the types of models described in this note. Thirdly, incorporating these scenarios within the existing toolbox of financial institutions. While some non-linearities may be missed (particularly with the current generation of models), incorporating some information on compounding effects would be beneficial. There is no need to wait until 'perfect' models and scenarios are developed to begin to incorporate

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[27] Collaborations could include experts from climate science, as well as potentially from other domains relevant for developing compound shock narratives (particularly for "Physical climate" ↔ "Other environmental" and "Physical climate" ↔ "Non-environmental" compound shocks, for which expertise in environmental, geopolitical, societal, economic, and technical risks may be relevant).

compound shocks, though results from existing models should be interpreted and communicated with full recognition of current model limitations.

- **In parallel, there is a need for further development of models to capture compound shocks.** The current generation of macroeconomic models used by central banks and supervisors are unable to capture the non-linear effects of compound climate shocks, likely resulting in the underestimation of risks. Continued research and development is also required across the other key models used to characterize compound risks (e.g., climate and catastrophe risk models). Close collaboration between researchers and practitioners should be prioritized to ensure swift integration of methodological developments into the toolkits of central banks and supervisors.

On the basis of the above, and as experience further develops, we anticipate that we will be able to move towards a more comprehensive operational framework for incorporating compound risks in climate scenario analysis by central banks and supervisors.

7. Recommended Next Steps

Central banks and supervisors could play an important role in supporting new research and the development of best practice in this important area. Given the novelty and systemic nature of these risks, organisations like the NGFS are well positioned to advance knowledge, best practice and capability on this area globally, particularly in the area of global compounding risks, and to thus support central banks and supervisors to bridge gaps related to the understanding and modelling of compound risks. Such initiatives can complement ongoing work by the NGFS on other aspects of the development of the NGFS scenarios, including efforts to further refine methodologies to capture physical risks, increase usability of scenarios, and develop short-term scenarios. The following next steps for collective action are recommended:

- Update guidance on physical climate financial risk assessment to highlight the relevance of compounding climate shocks, identify a set of shocks that are likely to be particularly relevant for the financial sector, and recommend that compound climate and macroeconomic shocks be incorporated within climate scenario analyses.
- Explore how the NGFS, central banks and supervisors could work with the scientific community to advance research on:
    - Development of guidance materials around how scenarios can be developed by central banks and supervisors to incorporate compound risks today, based upon current evidence, both qualitatively and quantitatively. Collaborations between central banks and supervisors and academic researchers should include experts across physical climate science, catastrophe risk modelling, network risk analysis and economic and financial impact modelling. Such collaborations may be useful to inform practitioners at central banks and supervisors about what types of severe compound shock scenarios are plausible from a scientific perspective and relevant to include when designing scenarios for physical climate scenario analyses. Research could include a review the evidence on the main types of compounding shocks and additional research to fill gaps.

- Exploring how compounding climate shocks can be incorporated into macroeconomic models commonly used by central banks and supervisors today, including studying the potential limitations of the current generation of models in this context, understanding the drivers of non-linear amplification effects, identifying the dominant transmission channels and the drivers of feedbacks to be considered, and developing a roadmap for exploring solutions. New research could also assess the potential underestimation of physical climate risks created by the lack of compounding effects within current scenarios. In the short-term, there could be "low hanging fruit" for improving modelling of the impacts of compound shocks (adopting some of the already established macro models that are better suited for capturing disaster-related impacts), alongside longer-term development of models to better capture compounding effects endogenously.

We conclude with two informative statements provided by respondents to the July 2023 survey. "*To resolve these gaps, the economic and financial modelling communities need to step up, and work collaboratively with the scientific communities to develop a framework and appropriate toolkit to assess such risks"* and *"It will be helpful to provide some more examples and data about the types of compound shocks and their potential impacts. Also, it will be helpful to provide some more guidance about how to consider compound shocks in climate scenario analysis, including some qualitative or simple quantitative approaches to start with, for encouraging a broader consideration of compound shocks. I would like to work collaboratively with the NGFS Workstream members to understand and examine in more details the potential impact of compound shocks and the extent of potential underestimation, and contribute to the development of guidance for qualitative and quantitative considerations of compound shocks and their impacts."*

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Appendix 1

Example anonymised responses from the NGFS survey on compound risks in July 2023

Survey question	Example anonymised responses
Would you consider compound shocks to be a routine component of scenario analyses or stress testing conducted (or supervised) by your institution?	*"compound shocks have been considered for stress testing that combine credit, market, and liquidity shocks together"* *"In the context of supervisory banking stress tests we consider (simultaneous) impact from different economic risk drivers, inter alia different market risk as well as credit risk drivers"* *"[solvency stress tests include] extremely stressful scenario with simultaneous occurrence of multiple stress events (such as slowdown in regional economy, deep recession in local economy and global interest rate"* *"Our stress testing incorporates compounding shocks of deterioration of the economy such as decline in GDP and market conditions such as fluctuations in stock prices"* *"In our bank solvency stress testing we regularly include operational risk events on top of the scenario"*
Have you incorporated compound shocks in any previous or ongoing climate-related scenario analyses or stress tests?	*"our approach to the physical risk stress test fits parts (a) and (b) of the compound shocks definitions: (a) extremes that occur simultaneously or successively; (b) extremes combined with background conditions that amplify their overall impact, where we consider the simultaneous occurrence of several severe extreme events, in a context where these shocks are transferred to macrofinancial variables"* *"Considered scenarios with combinations of extreme flood events, also taking into account broader macrofinancial implications"* *"Participating banks were instructed to consider compound risks in their credit risk models, for example when an agricultural borrower faces a drought and emissions pricing at the same time. In our 2021 bank solvency stress test, the scenario included a prolonged drought against a backdrop of a global recession and depressed agricultural output prices. In our bank solvency stress testing we regularly include operational risk events on top of the scenario"* *"For stress testing purposes, we incorporate a macroeconomic scenario that includes the materialization of several shocks, including more restrictive external financial conditions, high inflation persistence, a decrease in private consumption and private investment due to political instability, and the macroeconomic effects of El Niño phenomenon"* *"when analysing natural disaster influence on the insurance sector, we did not account for extra damages in case several catastrophes occur in one year or in consecutive years, as our previous experience suggests that consecutive disaster is less damaging. However, we considered higher impact on the decision to insure properties"*

Appendix 2

This appendix provides further details of the publicly available examples of approaches to incorporating climate-related compound risks into scenario analysis and stress testing, presented in Table 2 in Section 4.

The European Central Bank (ECB) is one example where compound risks were included in a top-down climate scenario analysis, though this case was focused primarily on transition risk rather than physical risk. The ECB analyzed the amplification effects of adverse macroeconomic shocks on transition risk and its transmission to banks' credit risk, using the ECB top-down climate stress test models (ECB/ESRB, forthcoming). The first scenario frontloads transition-related shocks from the NGFS delayed transition scenario from the years 2030-2035 to 2023-2030 and combines them with macroeconomic shocks based on the EU-wide supervisory stress test of 2023. The macroeconomic shocks assume a non-adverse development of the euro area economy for the next three years. The second scenario follows the same approach as the first, but with the difference that the macroeconomic shocks from the EU-wide supervisory stress test incorporate an adverse development of the euro area economy. The amplification effect of adverse macroeconomic shocks on transition risk could be estimated by "subtracting" expected losses in the first scenario from the second scenario.

A further example comes from the Bank of England's insurance stress test in 2019, which provided a series of scenarios that aimed to stress both the asset and liability side of the insurer balance sheet in parallel. A macroeconomic scenario with a deteriorating economic environment, including reduced interest rates, widening corporate bond spreads and fall in asset values, was combined with five types of liability shock, four of which were based on natural catastrophes, including a significant storm surge event causing losses along the east coast of England, and an extensive flooding event across England and Wales (Figure 8). This is an example of a "Physical climate" ↔ "Non-environmental" compound risks scenario. The narrative scenario approach employed here is instructive for future approaches to compound risk estimation for banks (Section 7).

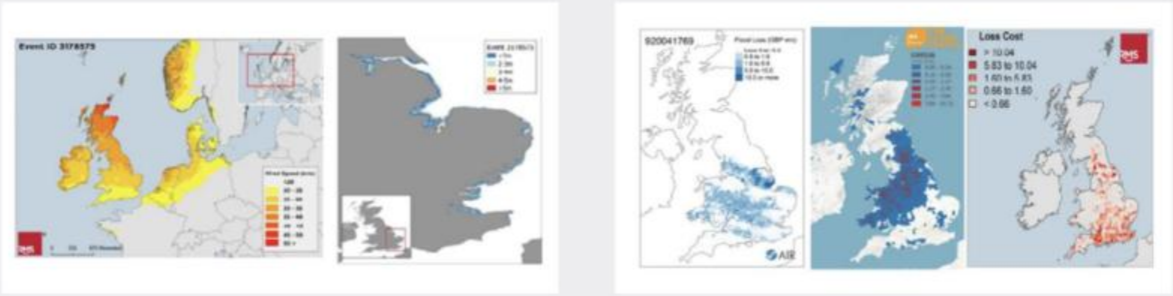

FIGURE B2.3.1.
United Kingdom Windstorm scenario

FIGURE B2.3.2.
United Kingdom flood scenario

Figure 8: Climate shock scenarios considered in the Bank of England's 2019 Insurance Stress Test. Source: PRA 2019

Another example of a compound shocks scenario comes from the Hong Kong Monetary Authority's 2023-2024 climate risk stress test exercise. For example, among the scenarios included is a short-term scenario featuring both climate-related shocks (including a number of extreme climate events and an accelerated transition) and a macroeconomic downturn (comprising global economic downturn, Hong Kong recession, and slowdown in mainland China). This scenario thus represents features of "Physical climate" ↔ "Physical climate", "Physical climate" ↔ "Transition climate", and "Physical climate" ↔ "Non-environmental" compound risks. It also represents elements of spatially compounding and temporally compounding shocks.

The Reserve Bank of New Zealand's 2023 Climate Stress Test Scenario (Adams-Kane et al., 2023) incorporates elements of multiple types of compound shocks. For example, spatially and temporally compounding "Physical climate" ↔ "Physical climate" compound risks are represented with physical climate hazards affecting New Zealand's trading partners (flowing through to exports and tourism) during a period with several damaging weather events domestically (affecting property values in flood zones). "Physical climate" ↔ "Transition climate" compound risks are also represented, for example in the 2030s with high transition risk (linked with more stringent agricultural emissions pricing) alongside physical climate hazards, including two years of agricultural drought, and flood events in the Auckland region.

Scenario analyses from Banco de Mexico (Banco de Mexico 2023) and Latvijas Banka (Ozolina and Petrovska 2023) consider multiple physical climate-related shocks, and thus may be considered examples of "Physical climate" ↔ "Physical climate" compound scenarios. However, it is unclear to what extent potential non-linear amplification effects of compounding are captured by the analyses.

Some other examples from emerging markets and developing economies where compound risks were included within climate scenario analysis include analyses in the Philippines (IMF 2021), Mexico (World Bank and IMF 2022; Dolk et al. 2023), Colombia (World Bank 2021), and Georgia (publication forthcoming). The Philippines and Mexico analyses were completed jointly by the World Bank and the International Monetary Fund under the Financial Sector Assessment Program and explored compound typhoon and pandemic shocks (in the case of Philippines) and a sequence of tropical cyclone and flood scenarios (in the case of Mexico). In Colombia, a double shock scenario consisting of a 1-in-500-year flood with a credit risk shock calibrated to the 1998-2000 banking crisis in Colombia was included in a bank stress test analysis completed as part of a collaboration between the World Bank and the Financial Superintendence of Colombia (SFC). In Georgia, a bank stress testing analysis completed by the World Bank in collaboration with the National Bank of Georgia and Georgia's Service for Accounting, Reporting and Auditing Supervision, considered a compound pandemic and 1-in-200-year flood shock.