Network for Greening the Financial System

Technical document

Acute physical impacts from climate change and monetary policy

August 2024

NGFS

Central Banks and Supervisors
Network for Greening the Financial System

Foreword

Sabine Mauderer
Chair of the NGFS

James Talbot
Chair of the Workstream on Monetary Policy

Global temperatures are rising and, in the absence of further mitigating actions, are likely to reach highs over the next few years. The frequency and severity of extreme weather events resulting from rising temperatures has increased markedly. Annual global damages from weather-related hazards have more than doubled in real terms in the past twenty years, reaching 275 billion USD in 2022[1].

Central banks, therefore, need to assess and understand the economic impact of climate change. In the 2022 NGFS survey, central banks expressed a desire to deepen their understanding of these effects.

This report presents the channels through which the physical impacts of climate change may affect the economy. It provides monetary policymakers with a framework to evaluate the implications for key macroeconomic variables that are relevant for their decision-making.

Physical effects of climate change will affect both the demand and supply side of the economy, which can be amplified through financial channels. These impacts can alter the path of output and inflation in the short-run, which means that they are a relevant consideration for monetary policymakers in the context of their price stability mandates.

This publication is one of a suite of reports being published by the NGFS Workstream on Monetary Policy. They aim to support central banks in assessing and understanding the macroeconomic effects of climate change as well as potential implications for the conduct of monetary policy. While this report focuses on physical impacts, the two reports that will follow cover the influence of the green transition on the economy, and central banks' approaches to modelling the effects of climate change.

We are, as ever, grateful to the NGFS members and observers as well as the NGFS Secretariat for contributing to this work. Given the increase in the frequency and severity of extreme weather events resulting from climate change, we hope this publication contributes to deepening the understanding of the macroeconomic impacts of these shocks and in turn their implications for monetary policy.

1 Banerjee *et al.* (2023).

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Executive summary

As severe weather events (acute physical hazards) intensify, become more frequent and more geographically widespread with progressing climate change, so too will their macroeconomic effects, at both the monetary policy horizon, and in the longer run. Annual global direct damages from these weather-related hazards have more than doubled in real terms from the early 2000s and reached 275 billion USD in 2022[2]. The further increase in the value of these direct damages is expected to stem in part from the compounding of severe weather events and the non-linear relationship between the intensity of the event and the damages caused by it.

The negative impacts from severe weather events are not limited to the destruction of output, capital, and real estate but extend to the broader economy because supply, demand, and financial channels amplify and propagate the effects of the initial shock as substantiated by the microeconomic studies reviewed in this report. The immediate impact of physical hazards is often first experienced on the supply side of the economy encompassing the impacts on the standard determinants of production – capital, labour, and total factor productivity[3]. Output, productive capital, real estate, or infrastructure are destroyed. Workers are dislocated, or their jobs are destroyed. Crop yields and productivity drop.

The demand effects of physical hazards work through household wealth and income, expectations of future climate events as well as consumer and business confidence. The resulting lower aggregate spending acts as an additional drag on economic activity. Effective insurance mechanisms with fast and predictable payouts can limit the economic fallout and speed up the recovery process.

The financial sector propagates the economic effects from severe weather events through asset prices as well as credit conditions and volume[4]. Tighter financial conditions and reduced access to finance slow down the recovery and may result in spillovers to initially unaffected areas of the economy. The destruction of physical assets and the decline in their prices from acute and chronic risks negatively impact the value of firms' collateral, which in turn weakens the balance sheet of financial intermediaries. Weaker bank balance sheets are also problematic given the increased demand for recovery loans in the aftermath of a disaster.

Macroeconomic studies tend to find negative impacts on GDP both in the short- and long-term. Econometric studies find GDP growth rates to decline by more than 0.5 percentage point in the year of the shock, for very severe events, and significantly higher values for the worst events.

For inflation, in theory, the effects of a specific severe weather event depend on whether the demand or the supply effects of the event dominate. The nascent empirical work on inflation suggests that food prices rise after an event with some spillovers into overall inflation. The inflationary effects can be nonlinear as documented for the case of heatwaves.

Monetary policy decisions will likely be affected by the expected increase in the frequency and severity of severe weather events. Severe weather events are largely unpredictable and thus resemble other shocks that unfold over the business cycle and to which monetary policymakers tend to adjust monetary policy. In the aftermath of a severe weather event, near-term movements in the key variables relevant for monetary policy – inflation and measures of resource utilisation or spare capacity – could indicate a need to adjust financial conditions with the direction depending on the relative balance between the supply and demand effects of the event and their persistence. Communication of monetary policy could be complicated, in particular for inflation-targeting central banks, when greater and persistent inflationary pressures from severe weather events call for policy tightening against the backdrop of an

2 Banerjee *et al.* (2023).

3 Severe weather events also inflict damages on ecosystems resulting in the loss of services from these systems. Although this report does not explicitly consider such losses, they are to some degree indirectly reflected in the overall economic costs from severe weather events. For example, the destruction of natural beauty can amplify the economic losses in a tourist region beyond the damages to local housing and other tourist facilities. The NGFS report Nature-related Financial Risks: a Conceptual Framework to guide Action by Central Banks and Supervisors (2023) offers a rich introduction to this topic.

4 In this report, unforeseen economic and financial damages resulting from severe weather events are referred to as *severe weather shocks*.

extensive decline in supply. Further out, policymakers have to wrestle with the question of the long-term implications of physical hazards for potential output and growth and the appropriate longer-run stance of monetary policy. Going beyond the effects of a specific event, the changes in the distribution of severe weather events – an increase in the frequency, intensity, and geographical spread of physical hazards – will alter the investment and savings behaviour of economic actors globally with implications for important policy determinants such as the long-run neutral rate of interest.

The absolute and relative strength of the supply, demand, and financial channels varies by type and intensity of the physical hazard, as well as the socio-economic and environmental characteristics of the affected area. For a specific physical hazard to cause meaningful economic damages, the hazard must affect a location with economic activity that is vulnerable to the specific hazard. The degree of economic exposure to severe weather events depends on the extent of economic activity in disaster-prone areas. The vulnerability of a location depends on factors such as construction quality, building codes, protection measures, as well as disaster preparedness and response capacity. Many of these factors correlate with a country's level of economic development and wealth.

Climate-change adaptation and greater resilience can help limit the projected increase in the economic damages from stronger and more frequent severe weather events associated with ongoing climate change. Currently, expenditures on disaster recovery far exceed those on risk reduction and adaptation, and new risks are created by expanding activity into more disaster-prone, high-risk areas. By lowering the likelihood of large damages and reducing the need for financial protection, adaptation and resilience measures also create space for insurance markets to provide effective risk protection.

Although the literature offers many insights on the economic effects from severe weather events from past events, the **links between severe weather events and the economy are dynamic and subject to change in particular because of climate change.** Questions that require better understanding include the exact shift in the global distribution of severe weather events under different mitigation policies, the compounding of multiple weather events and their interaction with the chronic effects from climate change (rising sea levels, higher average surface temperatures), the extent of successful adaptation and resilience measures, and the policy efforts to mitigate climate change. Considering these and other unresolved questions, **climate change will likely cause greater uncertainty about the economic environment in which monetary policymakers operate** in pursuit of fulfilling their monetary policy and financial stability mandates. More work is needed to adequately prepare central banks to meet this challenge.

Introduction

Climate change poses an increasing threat to the global economy. Severe weather events (or acute physical hazards) such as droughts, floods, and storms destroy crops, production facilities, housing, critical infrastructure and can disrupt global supply chains. Annual global direct damages from these acute physical hazards have more than doubled in real terms from the early 2000s and reached 275 billion USD in 2022[5]. Experts attribute 5% of the damages that occurred in 2022 to the Pakistan floods[6] and over one-third to Hurricane Ian that made landfall in southwest Florida. Disaster-related global losses are not slowing down, with losses recorded in the first half of 2023 similar to those in the first half of 2022[7]. Damages are expected to climb further as severe weather events intensify, become more frequent and more geographically widespread as climate change progresses. The increase in the value of damages is expected to stem in part from the compounding of events and the non-linear relationship between intensity of the event and damages[8].

The negative impacts from severe weather events are not limited to the destruction of output, capital, and real estate but extend to the broader economy because supply, demand, and financial channels amplify and propagate the effects of the initial shock[9]. The indirect costs of extreme weather events include economic losses from unusable infrastructure, lower investment and consumption demand due to declines in wealth, disrupted trade flows, and uncertainty about future climate events. Production of goods and services may decline because of labour shortages if workers are displaced or are diverted to reconstruction efforts. When insurance mechanisms fail to carry a significant share of the costs, the burden placed on government finances limits the space for other productivity-enhancing public investments. Econometric studies on the macroeconomic effects from severe weather events confirm that in the immediate aftermath of a severe weather event, both the level and growth rate of GDP drop. Depending on the study, GDP growth rates decline by more than 0.5 percentage point in the year of the shock, for very severe events, and can reach significantly higher values for the worst events. Over time, GDP growth recovers, but there is no consensus whether the economy returns to its pre-shock path for the level of GDP, as suggested by the neoclassical growth model, or continues at a lower path[10].

While the output effects of severe weather events are now relatively well understood, the inflationary consequences of severe weather events remain understudied. The nascent literature has identified that severe weather events tend to be inflationary, primarily through higher food prices associated with negative supply impacts from temporarily increased temperatures, storms, flood, or precipitation[11]. These findings suggest that the supply-side effects associated with physical hazards dominate for agricultural products whereby an increase in monthly mean temperature results in inflationary effects mainly in summer and autumn. The net impact on inflation remains to be understood because it depends on the relative balance between the demand and supply effects from physical hazards.

Monetary policy decisions will likely be affected by an expected increase in the frequency and severity of severe weather events. Severe weather events are largely unpredictable and thus resemble other shocks that unfold over the business cycle and to which monetary policymakers tend to adjust monetary policy. In the aftermath of a severe weather event, near-term

5 Banerjee *et al.* (2023).

6 World Bank (2022).

7 Munich Re (2023).

8 See IPCC (2023): Summary for Policymakers and the NGFS report Compound Risks: Implications for Physical Climate Scenario Analysis (2023).

9 See Batten (2018) for an early review of the channels through which acute and chronic physical risks as well as transitions risks transmit to the economy.

10 Leading contributions on the GDP effects from physical hazards include Cavallo *et al.* (2013), Felbermayr and Gröschl (2014) as well as Hsiang and Jina (2014).

11 Parker (2018) shows that storms and floods increase food price inflation. Hot summers with extreme temperatures have also been shown to cause increases in food prices, as argued in Faccia, Parker and Stracca (2021). In a related study, Kotz *et al.* (2023) find that temperature increases in hotter months and regions have larger inflationary impacts, both on headline and food inflation.

movements in the key variables relevant for monetary policy – inflation and measures of resource utilisation or spare capacity – could indicate a need to adjust financial conditions with the direction depending on the relative balance between the supply and demand effects of the event and their persistence. Further out, policymakers have to wrestle with the question of the long-term implications of physical hazards for potential output and growth and the appropriate longer-run stance of monetary policy. Going beyond the effects of a specific event, the changes in the distribution of severe weather events – an increase in the frequency, intensity, and geographical spread of physical hazards – will alter the investment and savings behaviour of economic actors globally with implications for important policy determinants such as the long-run neutral rate of interest.

In addition to severe weather events, chronic physical impacts from climate change and the transition to a net zero economy are also likely to leave an imprint on real economic activity and inflation dynamics. Rising sea levels and higher average surface temperatures will impose additional physical damages on the global economy by themselves, and by interacting with the acute physical effects from climate change. For example, coastal flooding associated with a severe storm can be more widespread and damaging in areas that lie below sea-level than in those that lie above. As sea levels rise and more areas of significant global economic activity lie further below sea-level, the expectation is that severe weather will become more damaging in the future. Rising sea levels also prevent rivers from draining into the oceans which increases flood risks after extreme precipitation, including in non-coastal areas. Higher temperatures can intensify chronic water scarcity. Warmer winters imply less snow fall and snow accumulation limiting the amount of water in reserve available for irrigation in droughts and drought-like conditions. In response to growing pressures from the chronic and acute physical impacts of climate change, societies will likely take adaptation measures to lessen the implications for human and economic activity, such as building seawalls or relocating settlements. While mitigation measures and an orderly transition remain the best possible options to curb the impact from severe weather events, even in the 1.5 °C net-zero orderly transition scenario, significant investment and financing by governments and financial markets will be needed for adaptation measures[12]. The fact that these aspects remain largely undiscussed in this document should not be viewed as passing judgment on their importance for economic activity and monetary policy, but simply reflects the decision to focus this work on one aspect of the near-term challenges posed by climate change. Further analysis on these issues should be conducted in the near future.

This work aims to provide a systematic understanding of the implications of physical hazards for the macroeconomy and monetary policy. Financial stability concerns from climate change are not covered in this report. Section 1 sets the stage by laying out the conditions under which severe weather events can lead to significant disruptions in economic activity. This section also provides a brief introduction to and overview of the different kinds of physical hazards and their main characteristics. The channels through which severe weather events affect the economy are discussed in Section 2. In addition to the destruction of current and future economic supply, severe weather events can cause financial conditions to become less favourable and suppress demand. Section 3 turns to the empirical work on the macroeconomic effects from physical hazards on output and inflation. This section continues with a discussion of the implications for monetary policy. The discussions are supplemented by six boxes as listed in the Table of Contents.

12 The macroeconomic effects of the transition to a carbon-free economy are analysed in the companion report *The green transition and the macroeconomy: a monetary policy perspective.*

1. From severe weather events to physical risks and disasters

This section sets out the conditions under which a severe weather event has significant economic impacts. The economic effects of any given severe weather event depend on its type and intensity, the vulnerability of the affected area, and the assets and socioeconomic elements that are exposed to the event. Thus, the economic effects from physical hazards vary considerably across economies and geographic locations.

No two physical hazard events have the same macroeconomic effects. Put differently, whether a physical hazard has an outsized economic impact (and turns into a disaster) depends on a variety of factors. This section first establishes the distinction between *physical risks* and *physical hazards* and *disasters.* It then reviews key facts about the main weather-related physical hazards.

1.1 Acute physical risk

The term **acute physical risk refers to the projected impact on the economy or individual economic agents resulting from the realisation of a physical hazard.** When the economic and human toll of a physical hazard exceeds certain thresholds, a realised hazard is commonly classified as a disaster[13]. While physical hazards can have far-reaching effects on societies and natural ecosystems, the focus here lies on their economic implications. The literature distinguishes three dimensions that determine the physical risk impact:

1. physical hazard,
2. exposure,
3. vulnerability.

In the context of climate change, physical hazards are acute severe weather events (such as heatwaves, landslides, floods, wildfires, and storms) **or chronic climate events** such as rising sea levels and higher average temperatures. The frequency and intensity of physical hazards differ by geographic location and vary over time as climatic conditions and other environmental factors change. As a result, areas currently unaffected by severe weather events may experience them in the future.

For a specific physical hazard to cause meaningful economic damages, the hazard must affect a location with economic activity. The exposure dimension of physical risks depends on the total value of assets (such as productive capital, infrastructure and housing) and socioeconomic elements (such as population and jobs) that are exposed to a hazard. The exposure of a specific location to physical hazards is not constant over time because of changing socioeconomic dynamics, for example via population, economic connectivity, and migration.

Finally, the vulnerability dimension describes the degree of damages to the exposed assets and socioeconomic elements that can be expected at different hazard intensities. The extent of a location's vulnerability depends on factors such as construction quality, building codes, protection measures, as well as disaster preparedness and response capacity. Many of these factors correlate with a country's level of economic development and wealth. The magnitude of the economic effects from physical hazards can be amplified further or moderated by the financial and macroeconomic environment, as well as the policy responses, including those of monetary policymakers as discussed in Sections 2 and 3.

As the physical impacts from climate change are determined by geophysical aspects and human actions, mitigation and adaptation measures have the potential to limit damages. Climate change mitigation efforts that drastically reduce greenhouse gas emissions may limit the projected increase in the frequency and intensity of severe weather events and restrain the unfolding of chronic climate hazards. Measures to support adaptation and strengthen resilience to physical hazards can further reduce the expected damages from climate change, because they help to reduce the exposure and vulnerability of specific locations to hazards. Currently, expenditures on

13 EM-DAT, the international disaster database maintained by the Centre for Research on the Epidemiology of National Disasters (CRED), defines disasters as "situations or events which overwhelm local capacity, necessitating a request for external assistance at the national or international level. Disasters are unforeseen and often sudden events that cause significant damage, destruction, and human suffering."

disaster recovery far exceed those on risk reduction and adaptation, while economic activity continues to expand into more disaster-prone, high-risk areas.

The United States' experience with hurricanes illustrates that the damages from climate hazards under current climatic conditions can be reduced through adaptation and resilience measures. According to the National Oceanic and Atmospheric Administration (NOAA) the count of severe hurricanes has significantly increased over the last 40 years and inflation-adjusted damages have increased tenfold[14]. Over the same period, coastal areas have experienced dramatic population growth, and along with it the expansion of urban areas with hard surfaces replacing wetlands and mangroves, and an accumulation of physical assets. The greater exposure and vulnerability of these coastal areas combined with the climate-change-induced rise in hurricane activity have contributed to the increase in damages over time. For example, according to Banerjee *et al.* (2023), Hurricane Ian alone caused between 50-65 billion USD of insured damages, almost half of all insured damages globally in 2022. This hurricane made landfall in Southwest Florida, an area that has seen a staggering rate of population growth (620%) since the 1970s compared with 217% for the State of Florida and 65% for the United States. More generally, Iglesias *et al.* (2021) show that 57% of structures in the 48 conterminous U.S. states are in hazard hotspots and development in these areas is still growing more rapidly than the baseline rates for the nation, indicating larger future potential losses even without the worsening effects of climate change. This phenomenon is not unique to the United States. For instance, Pelli and Tschopp (2017) show a high concentration of firms in storm-prone areas in India and in the Philippines. Coastal regions are attractive to businesses and humans alike because the access to open waters facilitates the transport of goods and the conduct of recreational activities. While it is possible to limit the economic effects from physical hazards by reducing exposure through relocation to less vulnerable locations, this reduction also comes at a loss of the benefits associated with the (disaster-prone/more vulnerable) location.

Without greater adaptation and increased resilience, the economic impacts from physical hazards are more likely to increase when, all else equal, severe weather events become more frequent and intense. The empirical literature discussed in Sections 2 and 3 suggests the presence of a **resilience threshold:** events below this threshold are associated with a significantly lower toll on the human and economic activity than events that surpass this threshold[15]. The resilience threshold is country specific and is dependent on a country's wealth, fiscal capacity, and insurance mechanisms, among other factors. The resilience threshold is likely to be lower in lower-income countries than in higher-income ones, and as a result, lower-income countries already experience relatively larger damages and economic repercussions from physical hazards. When severe weather events become more frequent and intense, the resilience threshold will be surpassed more often in a specific country, and larger economic damages will be experienced. Greater damages take an increasing toll on the country's capacity to cope with future hazards as fiscal capacity is diminished and the insurance sector is impaired. Consequently, the resilience threshold could fall and the economic impact of a physical hazard for a given geophysical strength may increase. Adaptation can help mitigate the impact of current and future physical hazards, and in doing so could raise (or at least stabilise) a country's resilience threshold[16].

1.2 Types of physical hazards and their distribution

Not all hazards are climate or weather related. Conventionally, scientists classify hazards into six groups[17]:

1. **Hydrological hazards** are caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater such as floods, wave action and storm surges.
2. **Meteorological hazards** are caused by short-lived, micro- to mesoscale extreme weather and atmospheric conditions that last from minutes to days such as convective storms, extratropical storms, extreme temperatures, fog, and tropical cyclones.

14 See https://www.ncei.noaa.gov/access/billions/time-series/US.

15 For example, Felbermayr and Gröschl (2014) show that disaster damages caused by events in the 99th percentile of geophysical strength are more than tenfold when compared to the damages cause by events in the 95th percentile of geophysical strength.

16 Auffhammer (2018) discusses the relationship between climate damages and adaptation.

17 See Integrated Research on Disaster Risk (2014) for details.

3. **Climatological hazards** are caused by long-lived, meso- to macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability such as drought, glacial lake outburst and wildfires.
4. **Geophysical hazards** originate from solid earth and include earthquakes, mass movement, volcanic eruption, snow avalanches and landslides.
5. **Biological hazards** are caused by the exposure to live organisms and/or the toxic substances or vector-borne diseases that they may carry.
6. **Extra-terrestrial hazards** are caused by asteroids, meteoroids, and comets as they pass near the Earth, enter the Earth's atmosphere, and/or strike the Earth, or changes in interplanetary conditions that affect the Earth's magnetosphere, ionosphere, and/or thermosphere.

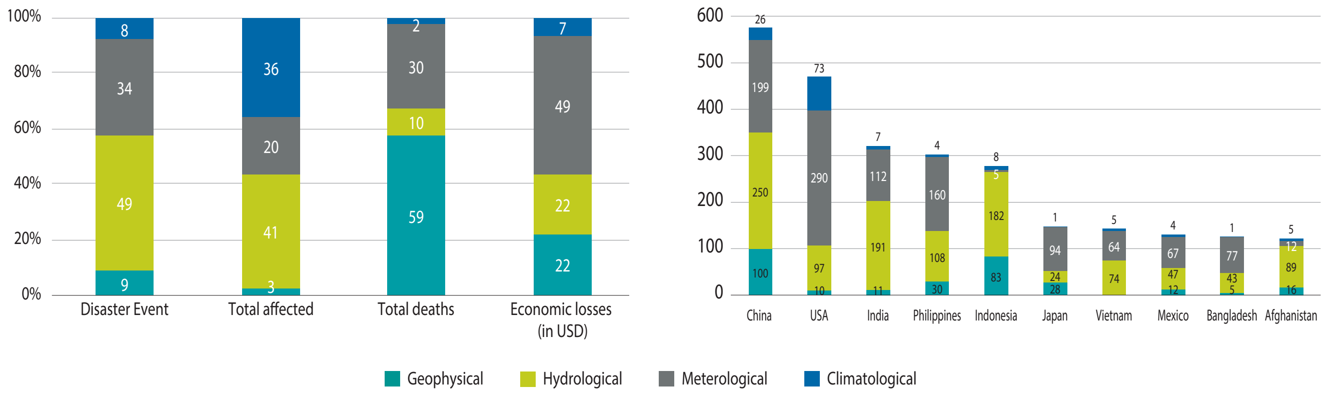
One database that sheds light on the relative importance of different hazards is EM-DAT, which globally records, at the country level, human and economic losses for disasters[18]. This discussion focuses on hydrological, meteorological, and climatological disasters. The left panel of Figure 1 provides information on the relative importance of hazard groups by number of events, total people affected, total deaths and economic losses in USD from 2000 to 2019. The right panel shows the distribution of the hazards in the 10 most disaster-affected countries.

According to EM-DAT hydrological and meteorological hazards are the most common causes of disasters worldwide. Hydrological hazards, of which the vast majority are floods, account for 49% of the total number of recorded "disaster events". However, their shares of the human and economic costs of physical hazards – 10% and 22%, respectively – are significantly lower. By contrast, meteorological hazards, despite accounting for only 33% of the recorded disasters, caused three times as many deaths and imposed twice the economic losses than hydrological disasters. These numbers demonstrate that the impact of a hazard depends on both its geophysical strength and the location the hazard strikes. Meteorological hazards disproportionately affect the United States and take a toll on high-value assets. Hydrological hazards are more concentrated in India, the Philippines, Indonesia, and China where the exposed assets are typically of lower economic value and population density is high (which may explain the high share of "total (people) affected" by hydrological hazards in the left panel of Figure 1).

Figure 1 **Disasters by type and countries in EM-DAT**

Proportion of various types of impacts by disaster subgroup (2000-2019)

Top 10 countries by occurrence of disaster subgroups (2000-2019)



Source: UNDRR report "Human cost of disasters". Data: Emergency Events Database (EM-DAT).

18 To access EM-DAT, follow the link https://www.emdat.be/. EM-DAT is the most comprehensive global disaster database. A hazard is deemed a disaster if at least one of the following occurs: 10 or more deaths, 100 or more people affected/injured/homeless, or some declaration by the country of a state of emergency and/or appeal for international aid. The database also records granular detail on the type of disaster, as well as estimated deaths, damages, and total population affected, amongst other physical and human capital metrics. EM-DAT suffers from some shortcomings regarding geographic coverage and the treatment of some disasters (e.g. droughts). Box 1 points to alternative data sets.

There is broad-based consensus among experts that the economic damages from severe weather events will rise significantly. Climate and Earth systems scientists predict that, even under the assumption that global warming can be limited successfully to 1.5-2 °C, the frequency and intensity of severe weather events will increase[19]. However, the exact magnitude of future damages is uncertain because these damages depend on the uncertain future evolution of a variety of factors. Given the uncertainty about the range, timing, and success of mitigation policies, the exact extent of the future changes in the distribution of severe weather events is uncertain. In addition, it is uncertain which adaptation and resilience measures will be implemented and how these measures will limit the exposure and vulnerability of economic activity to the increased impact from more severe hazards.

Box 1

Data and methods

The literature on assessing the economic effects from physical hazards uses a variety of data sources and methodological approaches. Deciding on the appropriate data and methodology is a key step towards measuring the economic impact of a physical hazard. This box lays out important considerations when making these decisions and describes commonly used data and methods.

Data

It is crucial that the data captures the relevant risk dimensions. The economic impact of a hazard is a measure of not only its geophysical strength, but also the exposure and vulnerability of the affected area. Thus, data from each of these dimensions must be incorporated for an accurate assessment of economic impacts of severe weather events.

Disaster databases incorporate these dimensions by reporting the financial damages of historical disasters, a metric that brings together the hazard and geophysical strength of the event with the exposure and vulnerability of the affected area. Commonly used disaster databases include EM-DAT, GeoMet, NatCatSERVICE, and Sigma.

Alternatively, individual data sets that characterise hazard, exposure, and vulnerability can be combined. The geophysical strength can be measured using hurricane wind speeds, temperature and precipitation, and other variables found in meteorological databases such as the JRC Risk Data Hub and IPCC WGI Interactive Atlas. These metrics must be combined with some measure of exposure or vulnerability, such as population, spatial GDP, capital stock, or granular land cover, for an accurate assessment of economic impact. This is usually done using calibrated or estimated damage and loss functions. The damage assessment typically relies on damage functions that translate the magnitude of extreme events (in physical units like wind speed or water height) to a quantifiable damage in economic terms (Prahl *et al.*, 2016). Damage functions are also a key building block in catastrophe risk (Cat) models that estimate the probability of losses due to severe weather events.

Since weather events often have localised impacts, the ability to make use of spatial data is important. The impacts of hazards such as floods, storms, and wildfires often vary significantly within a few kilometres. Thus, the data sources should capture these variations. One challenge of using individual data sets is that economic exposure and vulnerability data often lack the fine spatial resolution of hazard data. Thus, non-traditional economic variables that are available at a higher spatial and temporal frequency such as industrial output, disposable income, risk premium spreads, night lights (city lights as seen from space), and credit card usage, may be effective in assessing the impact of a disaster. Using these intermediatory variables, however, requires the additional step of connecting these findings to the broader macroeconomic variables of interest for monetary policy.

19 See IPCC (2023): Summary for Policymakers for details.

In recent years, researchers in the climate space have accessed many new data sources. Nevertheless, going forward more investment into both building granular, higher-frequency data sets and expanding data analysis capacity may be needed to improve real-time analysis of the economic impacts from severe weather events.

Methods

Panel regressions, vector auto-regressions (VARs), and local projections are the most common empirical methods used to study the economic impacts of acute physical hazards. By accounting for individual, time, and country fixed effects, panel regressions are commonly used to study various climate risks, from temperature and precipitation changes to hurricanes and earthquakes (Parker, 2018; Johar *et al.,* 2022; Kotz *et al.,* 2023; Kruttli *et al.,* 2023). VARs are useful in tracing the dynamic impact of a weather event through impulse-response functions and have been adapted to include controls for seasonal dependence of shocks and variation over the business cycle (Noy and Nualsri, 2011; Ciccarelli and Marotta, 2021). The local projections method similarly estimates impulse-response functions, with the key deviation from VARs being that local projections are estimated at each period of interest rather than extrapolating into distant horizons (Jordà, 2005; Avri *et al.,* 2022; Faccia *et al.,* 2021; Roth Tran and Wilson, 2020; Natoli, 2023).

Structural models, such as DSGE models, are also used to study natural disasters. DSGE models can incorporate severe weather events such as shocks to capital, technology, infrastructure, and productivity as discuss in Box 6 (Keen and Pakko, 2011; Hashimoto and Sudo, 2022; Kahn *et al.,* 2021). Disaster shocks have been integrated into these models often as shocks to total factor productivity (Cantelmo, 2022) or via a small, time-varying probability of rare events (Isoré and Szczerbowicz, 2017).

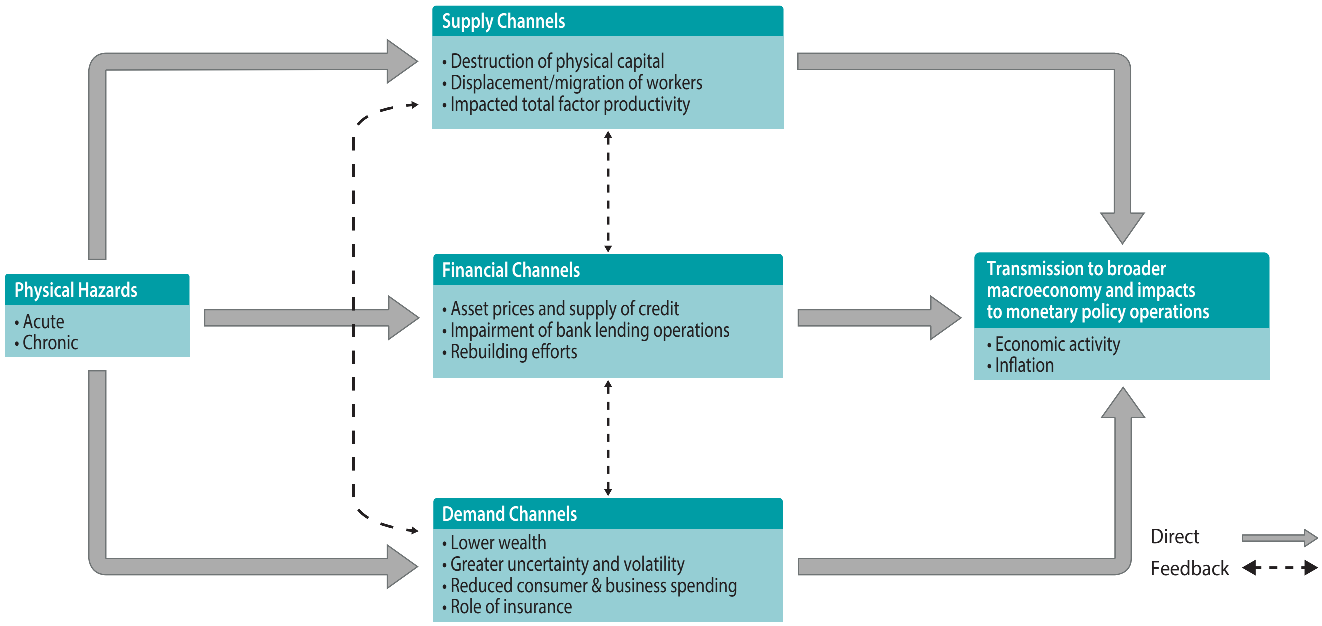
2. Propagation of physical hazards: supply, demand, and financial channels

This section discusses the supply, demand, and financial channels through which severe weather events propagate. Microeconomic studies provide insight on the specific channels at work for different types of severe weather events. The immediate impact from severe weather events is often first felt on the supply side before spilling over more broadly to the domestic economy and possibly even abroad through production, trade, and financial linkages.

The physical impacts from climate change propagate to the broader economy through supply, demand, and financial channels and leave an imprint on the variables relevant for monetary policy (i.e. inflation and resource utilisation, as illustrated in Figure 2). Supply-side channels encompass the standard factors of production – capital, labour, and total factor productivity (TFP) – where TFP encapsulates the role of technology, financing conditions, infrastructure, supply chain disruptions, etc. Demand-side channels include, among others, wealth and income effects associated with the destruction of assets or imperfect insurance, uncertainty over the future price of selected assets, and lower aggregate spending as consumer and business confidence weaken. Financial channels capture the linkages between physical impacts and the financial sector, where the latter plays an important role in the propagation of shocks through changes in asset prices and the supply of credit. This section discusses these propagation channels in detail, as well as linkages between them.

In light of the discussion in Section 1, it should not be surprising that the **propagation of the physical hazards to the broader economy will vary by type of disaster and the socioeconomic characteristics of the affected country.** Some hazards, like storms and floods, are of short duration (just a few days) but can bring massive and long-lasting physical destruction. Other hazards, like droughts, are slow to unfold, and the true extent of the damages may take several months to be fully visible. The overall aggregate effect of a severe weather event will depend on the financial infrastructure that can support reconstruction efforts in the aftermath of that event. Private insurance and fiscal policy space are two pillars of this infrastructure. Increased frequency and intensity of climate events, and therefore damages, can weaken the insurance sector and public finances and thus a country's overall resilience to severe physical hazards in the future.

Figure 2 **Flow chart of potential channels**



In empirical work it is often difficult to distinguish between the theoretical channels because the various hazards operate through all of them, and channel-specific outcome variables are difficult to obtain. Studies that focus on the aggregate effects of physical hazards, such as GDP and inflation, only offer an indirect inference on the existence and strength of these channels. Bakkensen and Barrage (2018) illustrate this issue and point to structural quantitative modelling as one way to address the identification challenge. Alternatively, microeconomic studies are well suited to shed light on specific transmission channels. Thus, the **discussion in this section of transmission channels leans more on microeconomic evidence.** Given the challenges of extrapolating from microeconomic evidence to the macroeconomic effects of physical hazards, Section 3 relies more on macroeconomic studies.

2.1 Supply channels

The immediate impact of physical hazards is often first experienced on the supply side of the economy. Current and future production of goods and services are impaired or may even come to a complete stop in the areas directly affected by the hazard. The discussion of the effects from physical hazards on the supply side is structured around the components of a simple aggregate production function (i.e. the capital stock, labour, and total factor productivity).

2.1.1 Destruction of physical goods, capital, and infrastructure

The destruction of physical goods, capital and infrastructure is an especially salient feature of severe physical hazards and leads to a decline in current and future output. Annual global direct damages from these acute physical risks have more than doubled in real terms from the early 2000s and reached 275 billion USD in 2022[20].

The depth and persistence of the decline in output partly depends on how the physical hazard impairs the use of the physical capital in the affected area[21]. Taking the example of a battery production plant, a hurricane may damage the plant in a way that reconstruction of the asset is needed for it to be usable again. By contrast, a drought that limits access to water needed in the production process impedes the use of the physical asset for the duration of the hazard but not beyond. Moreover, a specific hazard type does not have a uniform impact on output and capital. Returning to the example of droughts, the impact is mostly felt in the agricultural sector and, to a lesser extent, in other sectors that rely on water for cooling or as a direct input. Producers in sectors with low water usage may only be indirectly affected through input-output linkages even if they are located in the drought area[22].

Physical hazards also impair or destroy infrastructure. Stable and high-quality infrastructure is key for the smooth functioning of national economies and international supply chains[23]. Damages to roads, bridges, pipelines, electricity grids, airports, ports, or railways disrupt the flow of goods and materials and may give rise to supply bottlenecks and slow economic activity[24]. As in the case of physical capital, different hazards can have divergent impacts on specific infrastructure and the same hazard can have a divergent impact on different infrastructure (see also the discussion on supply chains and trade in Section 2.1.3.3).

The destruction of residential real estate does not directly reduce the productive capacity of the economy as long as the asset is not an input into the aggregate production function. Nevertheless, the destruction of housing impacts economic activity via the displacement of workers (see Section 2.1.2), the reduction of household wealth (see Section 2.2), and, during the recovery phase from the hazard, the reconstruction of destroyed property.

20 Banerjee *et al.* (2023).

21 Elliott *et al.* (2019) find that typhoons induce a reduction in turnover and profits of around 1% for Chinese manufacturing plants lasting about one year. A nonlinear damage function is used to map wind speeds into a physical impact variable for typhoons. Using Indian firm-level panel data on various components of firm capital Pelli *et al.* (2023) show that the average cyclone destroys about 2% of a firm's fixed assets and decreases its sales by around 3% for one year.

22 Hashimoto and Sudo (2022) measure the impact of floods on the aggregate capital stock in Japan using a DSGE model. Gallic and Vermandel (2020) study the effects of drought conditions on agricultural and aggregate output in New Zealand using both structural vector autoregression (SVAR) and a DSGE model. They report a sizable impact from droughts on agricultural output and negative spillovers to the aggregate economy.

23 See Bom and Ligthart (2014) for a survey of the literature and estimates of the output elasticity to public capital.

24 For example, hurricane Sandy and its associated flooding caused extensive damages to both buildings and infrastructure. In New York City, virtually all subways, commuting trains, buses, and tunnels were shut down due to the hurricane. Close to two million people lost power at some point during the storm. Services were mostly restored within one month of the disaster. See the report NYC Special Initiative for Rebuilding and Resiliency (2013) for details. Grenzeback and Lukman (2008) detail the extent of destruction and failure of transportation infrastructure in the Gulf Coast region due to Hurricanes Katrina and Rita.

While the literature generally acknowledges that the destruction or impairment of productive capacity by a physical hazard has a negative effect on economic activity in the short run, the long-term effects from physical hazards continue to be debated. The extent to which the damaged or destroyed capital stock is rebuilt is a key determinant of the long-term dynamics of the economy. However, other economic factors yet to be discussed also play a role. Hence, the discussion of the long-term effects is postponed until Section 3.

2.1.2 Labour

The destruction of physical capital or the prolonged impairment of its use often go together with job destruction. Facing the loss of jobs and damage to both residential housing and infrastructure, people may consider or be obliged to move out of the area affected by the disaster[25]. Belasen and Polachek (2013) summarise the findings of the literature as (1) natural disasters lead to movement of labour in the short-term and possibly the long-term with the bulk of that occurring in developing countries; and (2) people living in rural areas (especially in developing countries) being less mobile than people in urban areas. A persistent reallocation of workers over the long run can destroy existing agglomeration economies, which reduces growth (Boustan *et al.,* 2020; Desmet *et al.,* 2021; Gandhi *et al.,* 2022; Jia *et al.,* 2022).

In developing countries, large scale movement in labour due to climate disasters or climate change more generally is a well-studied phenomenon. Marchiori *et al.* (2012) estimate that temperature and rainfall anomalies caused a total net displacement of five million people during the period 1960-2000 in sub-Saharan Africa. Robalino *et al.* (2015) argue that on average hydro-meteorological emergencies significantly increased internal labour movement in Costa Rica during 1995-2000. Thiede *et al.* (2016) investigate similar trends in South America due to climate variability. Exposure to monthly temperature shocks has the most consistent effects on the movement of people relative to monthly rainfall shocks and gradual changes in climate over multi-year periods.

Although less studied, physical hazards also lead to the movement of people in developed economies. For example, the Internal Displacement Monitoring Centre (2020) reports that the 2019-2020 wildfires in South-Eastern Australia displaced around 65,000 people, potentially leading to longer-term displacement of more than 8,000 people. The American Dust Bowl led to a mass movement of people: between 1935 and 1940 about 7% of the residents in the Great Plains moved to a place more than 200 miles away. Hornbeck (2020) argues that those who move out of areas with greater soil erosion had lower education and struggled economically in their new homeland. Sheldon and Zhan (2022) study household post-disaster choices in the United States after hurricanes and floods and argue that natural disasters increase households' propensity to move to safer destinations.

Regarding the labour market conditions in the affected area, Belasen and Polacheck (2008) find a negative short-run impact on employment for Florida counties after a hurricane. Groen and Polivka (2008) argue that evacuees from Hurricane Katrina experienced a temporary but noticeable decline in both their labour force participation and employment rate. Barattieri *et al.* (2023) report similar findings for counties in Puerto Rico in response to hurricane landfalls. However, when accounting for sectoral differences, these authors find that not all industries are weakened by natural disasters. Employment in construction and industries with strong linkages to construction are temporarily strengthened by the disaster.

Since the people who have moved enter the labour market in their new location of settlement, **severe weather events can spill over to unaffected regions via the labour market.** De Silva *et al.* (2010) and McIntosh (2008) argue that the movement of Hurricane Katrina evacuees to Houston lowered wage growth in the Houston area because of the increase in labour supply.

High temperatures and heatwaves impact labour supply and labour markets quite differently than storms and floods. High temperatures not only impact labour productivity, but they can also affect labour supply through

25 It is worthwhile to note that rising sea-levels or higher average temperatures can cause similar migration effects, not the least because the chronic effects from climate change interact with its acute physical impacts.

work absenteeism or reducing the time allocated to work as shown in Graff Zivin and Neidell (2014) and Somanathan *et al.* (2021). The effects on labour can differ across sectors if labour laws limit outside work in high temperatures. At a higher level of aggregation, Zhang *et al.* (2018) find that the labour inputs of industrial firms in China almost do not respond to temperature, except when the temperature is extremely high.

2.1.3 Total factor productivity

In an aggregate production function total factor productivity (TFP) captures technological aspects and inputs that are not explicitly modelled, including infrastructure and supply chains. Productivity can also be negatively affected when attention and resources are devoted to reconstruction efforts rather than optimising production processes and innovation.

It is often difficult to isolate the TFP effects of severe weather events. One attempt of doing so is by Bakkensen and Barrage (2018). Starting from an aggregate production function, the authors derive time series of TFP for 40 cyclone-vulnerable countries (hurricanes and typhoons). They then regress their TFP series on cyclone intensity and other controls. Cyclones are shown to have a negative impact on their derived TFP measure.

2.1.3.1 Labour productivity

More narrowly restricting attention to labour productivity – as opposed to TFP or labour supply effects – and temperature variation, labour productivity declines during heatwaves. Zhang *et al.* (2018) report that the impact of more frequent heatwaves has reduced Chinese manufacturing productivity by 12%. Somanathan *et al.* (2021) find that, in addition to an increase in absenteeism, high temperatures lower worker productivity in the Indian manufacturing sector. Cai and Wang (2018) find that extreme cold and heat reduce productivity of workers in a Chinese paper cup factory by around 9-10%. Using weekly production data from 64 automobile plants in the United States over a ten-year period, Cachon *et al.* (2012) find that adverse weather conditions lead to a significant reduction in production. For example, a week with six or more days of heat exceeding 32 °C (90 °F) reduces production in that week by 8% on average and it is unclear whether the production losses can be recovered over time. Relatedly, using personal income data at the U.S. county level, Deryugina and Hsiang (2014) find that productivity of individual days declines roughly 1.7% for each 1 °C (1.8 °F) increase in daily average temperature above 15 °C (59 °F). Colacito *et al.* (2019) find an effect from temperature on economic activity, particularly for the summer: a 0.55 °C (1 °F) increase in the average summer temperature is associated with a reduction in the annual growth rate of state-level output of 0.15 to 0.25 percentage points. Changes in labour productivity appear to be the main driver behind the temperature induced variations in GDP[26].

Using data from 1960-2018 on productivity measures and severe weather events for a cross section of countries, Dieppe *et al.* (2021) finds a contemporaneous reduction in labour productivity of 0.5% that builds up over time to several percent. Although these effects are largely attributable to weaker TFP, capital misallocation can also weigh importantly on labour productivity (Hallegatte and Vogt-Schilb, 2019).

2.1.3.2 Agriculture productivity

Agriculture is another area of the economy for which it is important to distinguish shocks to land productivity from other aspects that impact food production such as the supply of farmland and its quality. During the catastrophe of the 1930s Dust Bowl, which was the result of severe dust storms in the North American prairies, agricultural productivity declined substantially due to soil erosion (see Hornbeck, 2012). Wang *et al.* (2018) examine the patterns of productivity changes and weather variations across regions and over time in the United States. Gallic and Vermandel (2020) analyse the effects of drought conditions on agricultural productivity in New Zealand and the aggregate economy. Using panel regressions on New Zealand data, Pourzand and Noy (2019) conclude that droughts have a negative impact on the agricultural productivity[27].

26 Natoli (2023) also provides evidence of how extreme temperatures impact labour productivity.

27 Studying severe weather events, Costinot, Donaldson and Smith (2016) report that climate change has the potential to reduce the productivity yield of crops by around 0.26% of world GDP, which corresponds to around 1/6th of world agricultural output.

Box 2

Heatwaves in Egypt

Egypt is highly vulnerable to heatwaves, water scarcity, rising sea levels, and other adverse impacts of climate change (Al-Mailam *et al.,* 2023). Heatwaves – domestically and in key trading partners – are of particular concern given key features of the Egyptian economy:

1. Agriculture is one of Egypt's main sectors, accounting for 12% of GDP and 19% of employment in the fiscal year 2022/2023.
2. Water scarcity already threatens productivity in the agricultural sector (and others) via reduced availability of groundwater and its increased salinity. In addition, dissolved oxygen levels decrease with higher temperature harming fish population (Barania, 2021).
3. Increased electricity demand for cooling raises demand for domestic natural gas and increases energy prices. Export revenue from natural gas drops as extracted gas is diverted back into the domestic market.
4. As a net importer of agricultural products, Egypt is vulnerable to global food price shocks.

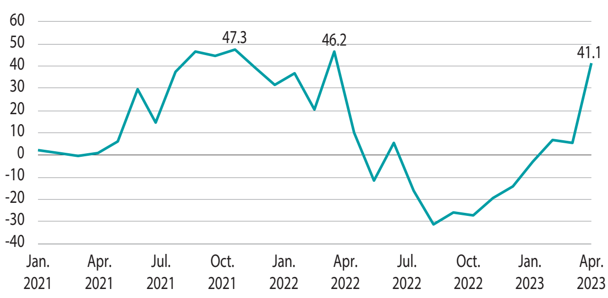
Research using the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) suggests that crop yield will decline due to climate change which would cause Egyptian agricultural output to contract by more (–5.7%) than in the rest of the world (–4.4%) by 2050. Related research by Ahmed *et al.* (2020) suggests that production of different agricultural commodities may drop between 10% and 18% as temperature increases reduce crop yields and raise water demand with strong effects on consumer prices which increase by up to 16% on average under the assumptions of the study.

The impact from heatwaves on agricultural production and prices can be well illustrated by the examples of mangos and olives, two of Egypt's most important, climate sensitive crops. Since 2018, the temperature-sensitive mango crop has been exposed to unusual temperature volatility with both the warmest summer in the last 140 years and the longest/coldest winter (winter of 2019) occurring within a short period. In 2021, the average summer temperature exceeded its long-term average by 3 to 4 °C, mango production fell by around 20-25% driving year-on-year price increases to 40-50% (Box Figure 1). Recent research shows that the productivity of mango production declined by 1% and 1.8% in response to an increase in minimum and maximum temperatures by 1% (see Rania *et al.,* 2023).

Olive production has also suffered in recent years as a direct result of temperature variability. Estimates for the 2020/2021 crop year suggest that Egyptian production of olive oil shrank by 33% compared to the previous year because the cold winter was followed by a sudden temperature surge and a heatwave, which damaged olive trees and subsequently, production. The substantial production losses were reflected in price fluctuations of olives, with prices growing more than 165% year-on-year (Box Figure 2).

Figure 1 **Annual Inflation of Mango**

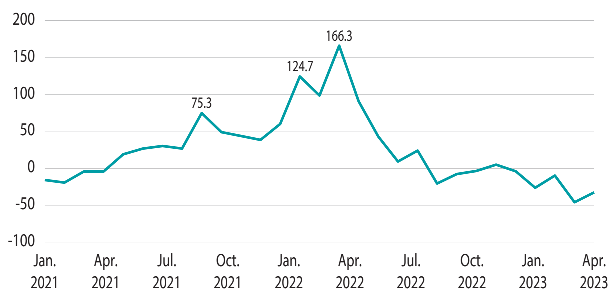
(in %, y/y)



Source: Central Bank of Egypt and CAPMAS.

Figure 2 **Annual Inflation of Olives**

(in %, y/y)



Source: Central Bank of Egypt and CAPMAS.

2.1.3.3 Supply chains and trade

Disasters can impact national and international supply chains and trade beyond the reduction in current and future output produced in the affected area. Through production networks and supply chains the drop in production by upstream manufacturers directly limits output of factories downstream[28]. Di Giovanni *et al.* (2018) and Caliendo *et al.* (2018) analyse the propagation of shocks across space and stages of the production process. Here, two examples focus on how severe weather events can limit the use of waterways for trade via their impacts on coastal infrastructure and river navigation.

Historically, hurricanes have caused sizable damages to coastal infrastructure. In the United States, Hurricane Katrina caused 1.7 billion USD in damages to Southern Louisiana ports (Santella *et al.,* 2010), Hurricane Ike caused 2.4 billion USD in damages to Texan ports (FEMA, 2008), and Hurricane Sandy resulted in 2.2 billion USD damages to the Port of New York and New Jersey (Port Authority of New York and New Jersey, 2013[29]). Sytsma (2020) analyses the indirect effects from hurricanes on trade using data on wind speeds and export shipments and finds a significant negative effect from hurricanes on international bilateral trade flows. Sytsma (2019) documents the persistent fall in export values in port locations affected by a hurricane as some volumes can be picked up by unaffected ports. This diversion of trade flows accounts for the small aggregate effects of hurricanes on trade. Indeed, Friedt (2021) finds similar results following the impact of Hurricane Katrina in the United States. Specifically, port-level data showed that Hurricane Katrina resulted in a sizable and persistent decline in activity in the affected ports while activity in unaffected neighbouring ports picked up. Gassebner *et al.* (2010) take a more aggregate approach by assessing the impact of disasters on imports and exports of disaster-affected countries. They find that the marginal effect of a disaster is to reduce imports on average by 0.2% and exports by 0.1%.

The navigation of internal waterways can be affected by both excessive rainfall and drought conditions. In late 2022, the Mississippi River, which moves 60% of soy and corn crop volumes in the United States, experienced extremely low water levels resulting in transportation costs soaring by more than 300%. The Rhine River in Europe has also experienced extremely low water levels in recent summer droughts. Ademmer *et al.* (2020) find that in a month with 30 days of low water, industrial production in Germany declines by about 1%. Although shipping on inland waterways accounts only for a small share of the total volume of transportation in Germany, it is responsible for a significant share of the transportation of industrial goods such as coal, crude oil, coke oven products and chemical products – all goods usually used far upstream in the production chain. More generally, these cases illustrate the possibility that severe weather events in a small region can have disproportionate impacts on aggregate activity because of supply chain disruptions.

2.1.4 Public financing conditions

The fiscal implications of disasters can be far-reaching due to the costs associated with replacing damaged assets and infrastructure, social transfers, and relief aid. In addition to these explicit liabilities, governments may also face implicit contingent liabilities from disasters. Political and social pressures may cause governments to assume responsibility for damages and costs outside their standard area of responsibility. Finally, the fall in output and tax write-offs for destroyed physical capital have a negative impact on tax revenues. The financial burden associated with physical hazards may weaken the fiscal position of a country, worsen financing conditions, and eventually – in extreme circumstances – prevent policymakers from having the resources to stabilise the economy[30]. In terms of assessing the direction and magnitude of the policy response after a disaster, Deryugina (2017) estimates the fiscal costs of hurricanes in the United States, taking into account both direct costs (i.e. through the disaster aid channel) and indirect

28 One such example are the severe floods in Thailand in 2011 which disrupted the Japanese automobile industry. Although unrelated to severe hazards, the 2011 Tohoku Earthquake, studied in Carvalho *et al.* (2016), caused disruptions upstream and downstream along supply chains, affecting the direct and indirect suppliers and customers of disaster-stricken firms.

29 Strunsky, S. "Port Authority puts Sandy damage at $2.2 billion, authorizes $50 million to power wash PATH tunnels". NJ.com, 16th October 2013. Retrieved 3rd April 2024.

30 See Gagliardi *et al.* (2022) for more detailed discussion.

costs (i.e. through other social safety net programmes). While disaster aid averages around 160 USD per capita per hurricane in the affected areas, non-disaster social insurance programmes average about 1,000 USD per capita following a hurricane in present value terms. Hence, the total fiscal burden from physical disasters is far more extensive once the indirect costs are accounted for.

Government responses to severe physical hazards reflect their fiscal capacity in addition to the severity of the underlying disaster. Using U.S. data at the state and federal level, Canova and Pappa (2021) show that countercyclical fiscal policy reduces the severity of the economic downfall. Both federal and state governments respond to disaster shocks by increasing expenditures, welfare transfers, and intergovernmental transfers. Following the panel-data evidence in Noy and Nualsri (2011), the response at the aggregate level appears to be counter-cyclical in developed economies, but pro-cyclical in developing economies. The latter finding may be reflecting the limited ability of disaster-prone developing countries to borrow and access finance more broadly as discussed in Mallucci (2022) and Phan and Schwartzman (2023).

2.2 Demand channels

Severe weather events negatively impact the demand side of the economy. Destruction and loss of assets impact household (and firm) income and wealth, which puts downward pressure on consumption and investment demand for goods that are unrelated to reconstruction and replacement efforts[31]. The extent of these downward pressures is amplified by absent or insufficient public or private insurance. In addition, physical hazards can alter demand patterns through changes in the perceived future damages from climate change events (expectations) and through general confidence effects and shifts in consumer preferences.

2.2.1 Wealth and income

An extensive literature in economics has investigated the impact of changes in household wealth on consumption and economic activity. **Empirically, the consumption rate strongly correlates with aggregate household wealth** (both measured relative to disposable income), as discussed in Cooper and Dynan (2013). Using housing wealth and micro data on consumption in the United Kingdom, Campbell and Cocco (2005) show higher house prices cause higher consumption. Thus, to the extent that physical hazards destroy or reduce households' wealth – e.g. destruction of residential real estate or declines in house prices – consumption demand by impacted households is expected to drop after a severe weather event.

Ample evidence suggests that house prices are negatively affected by physical hazards. Even prices of undamaged houses can fall if neighbourhood infrastructure is harmed by the event, enjoyment of the property is negatively impacted by surrounding destruction (e.g. destroyed woodlands around a cabin), or if demand characteristics and preferences for housing change. House prices can also fall if the materialisation of the hazard raises the perceived risk of future extreme events and damages in the same location.

Physical hazards may disrupt the flow of wage and business income because damaged and destroyed physical capital, such as impaired rental properties and factories, will generate lower cash flows or may result in job destruction. The decline in income will in turn lower consumption and investment demand for goods and services that are unrelated to reconstruction efforts[32].

2.2.2 Expectations

Physical hazards may lead economic actors to change their perception of the risk of future extreme events and damages. Greater uncertainty about economic growth and income prospects may cause firms to scale back or hold off on investment, and households to increase (precautionary) savings and consume less, if insurance options are insufficient[33]. These expectations may also depress selected asset prices.

31 The effects of asset destruction and changes in asset prices on household and corporate balance sheets are discussed here under demand effects. The effects from credit conditions and volume are discussed separately under the header financial channels in Section 2.3.

32 This latter aspect has received considerable attention for developing economies. For example, Nguyen *et al.* (2020) use panel data from 4,000 rural households in Thailand and Vietnam and find negative effects on household income and consumption from droughts, floods, and storms.

33 Phan and Schwartzman (2023) illustrate this theoretical point in a simple quantitative model.

Extensive analysis on house prices suggests the emergence of a price penalty after an extreme event. McCoy and Walsh (2018) show that wildfires in Colorado lead to short-run declines in house prices of that area which led them to argue that these declines stemmed from increased risk perception associated with future fires. Bin and Landry (2013) find that hurricane flooding causes temporary declines in house prices in affected areas. Ortega and Taspinar (2018) analyse house prices in New York City in the aftermath of Hurricane Sandy and the flooding that came with it. They find large negative price effects following the event. In addition, they find the gradual emergence of a price penalty associated with properties located in areas affected by flooding but not directly damaged by Hurricane Sandy. The authors provide support for the hypothesis that this price penalty reflects a persistent increase in the perceived risk of extreme events in flood-prone areas[34].

2.2.3 Confidence

In the wake of physical destruction and erosion of balance sheets, increased uncertainty about economic prospects may depress consumer and business confidence which in turn via lower consumer and investment spending reduce economic growth and slow the recovery from the physical hazard[35]. Aladangady *et al.* (2016) use data of transaction volumes to examine how consumers reacted to Hurricane Matthew, which struck the East Coast of the United States in October 2016. Consumer spending fell significantly in the affected states after the hurricane. Spending returned to normal quickly, without making up the earlier shortfall, implying that the hurricane had a negative overall effect on spending. Similar spending effects were observed following Hurricane Sandy in 2012, but the magnitudes were considerably larger and more persistent than those that followed Hurricane Matthew, leaving a larger imprint on the aggregate data.

2.2.4 Insurance

Effective insurance can limit the economic fallout from severe weather events. Because insurance payouts provide post-disaster liquidity to affected (and insured) households and firms in a timely and predictable manner, they cap the deterioration of balance sheets and the knock-on effects to financial institutions from defaults of loans that were previously extended to affected households and firms. Fast payouts provide the necessary resources to begin and speed up the recovery process. Using information on the share of insured versus uninsured direct damages from natural disasters, von Peter *et al.* (2012 and 2024) find that the GDP effects from insured losses are insignificant but are negative and significant from uninsured losses. In addition, faster rebuilding reduces disaster-caused consumption losses (Hallegatte and Vogt-Schilb, 2019). Rousová *et al.*(2021) lay out the theoretical argument and provide empirical evidence for the protective role that insurance can play in dampening the macroeconomic effects from physical hazards while protecting public finances. However, in the wake of massive disasters, the insurance sector may become a concern for financial stability if disaster risks are not properly managed[36].

Given the general stabilisation benefits derived from insurance and the expectation that severe weather events will increase further in frequency and intensity, greater attention has been drawn to the fact that 55% of global losses from physical hazards are currently not insured. Efforts to narrow protection gaps are high on national and international policy agendas[37]. Yet, for some highly exposed regions, a number of private providers have either stopped the provision of certain insurance products or significantly increased their price, feeding concerns that private insurance markets may increasingly need to be supplemented by public initiatives[38].

34 Adaptation investment may partially undo such price declines as argued in Benetton *et al.* (2022) using the example of seawalls in Venise (Italy).

35 For example, the Consumer Sentiment Index of the University of Florida regularly declines after hurricane landfalls in the state. See https://bebr.ufl.edu/florida-consumer-sentiment/.

36 In 1992 Hurricane Andrew caused unprecedented damages on the U.S. Gulf Coast. Eight insurance companies failed, and others were pushed to the brink of insolvency. To tap into new sources of capital, the insurance industry created CAT bonds in 1997 which allowed transferring risks to a wider set of investors.

37 Initiatives like Disaster Risk Financing and Insurance Programme (DRFIP), the G20-V20 InsuResilience Global Partnership, and the Caribbean Catastrophic Risk Insurance Facility are examples of such efforts. The ECB and EIOPA (2023) discussion paper suggests possible actions to reduce the climate insurance protection gap, incentivise risk mitigation and adaptation measures, and lower the share of economic losses from major disasters borne by the public sector. Regulators have also highlighted the importance of addressing the protection gap to support the resilience of the financial system (see IAIS statement, April 2023, www.iaisweb.org/uploads/2023/04/IAIS-statement-on-natural-catastrophe-protection-gap-2023.pdf).

38 In the United States, big national insurance companies have already scaled back their home insurance business in California to avoid the damages from wildfire. Colorado, Florida and Louisiana, and areas along the U.S. Atlantic coast have witnessed similar developments. In Australia, home insurance premia have risen much faster in the north than in the rest of the country reflecting the greater destructive power of natural hazards in that region (ACCC, 2020).

The lack of broad insurance coverage and the declining coverage of selected risks highlight the importance of adopting damage-reducing practices and limiting risk exposure through investments. Insurance mechanisms (both public and private) cannot protect against all climate-change-related hazards, in all locations, and at all times, as discussed in detail in Warner *et al.* (2009). Greater adaptation and strengthened resilience in conjunction with continued mitigation can reduce future damage increases, thereby lowering the need for reliance on insurance mechanisms in the first place.

Despite its key role in managing the economic impacts from physical hazards, in particular in advanced economies, insurance arrangements are part of the broader class of disaster risk finance instruments. UNU-EHS (2021) distinguishes between different insurance programmes (including sovereign risk and public assets), CAT bonds, government revenue and budget measures, and other ex-ante and ex-post instruments.

Box 3

The insurance challenge

Insurance is an important building block of a comprehensive strategy to manage climate-related damages. Adaptation and resilience can lower the likelihood of large damages and reduce the need for financial protection. Protection of physical assets, investments in nature-based solutions (such as wetlands, mangroves), assessing vulnerabilities of business partners to strengthen supply chains, and contingency planning are powerful risk-reducing measures.

Insurance and related compensation mechanisms address those residual risks that cannot be eradicated by adaptation and resilience measures. Given the design of the insurance instrument – the transfer of risk of losses from one party to the other in exchange for a premium – there are limits to what can be insured. Formal (private or public) insurance contracts incentivise risk-reducing behavior, implement risk-based pricing, provide clarity on damage coverage, lead to (timely) payouts in the event of damages. Damages from severe weather events (flood, storms, droughts) can in general be insured. Although insurance is not well suited to manage foreseeable damages from the chronic impacts of climate change (desertification, sea-level rise, loss of habitat and biodiversity), other compensation mechanisms may be used to provide financial relief (see Linnerooth-Bayer *et al.,* 2019).

As physical hazards increase in frequency and intensity due to climate change, the insurance sector has reevaluated its operations to remain profitable. Increases in premia or termination of coverage have raised concerns on how to provide adequate financial protection to firms and households at affordable prices at times when increased physical hazards may call for expanding the provision of insurance.

In advanced economies, the protection gap (the share of uninsured losses) is generally below the global average, but rarely falls below 40%. Most insurance covers private property, but infrastructure is generally not covered despite the sensitivity of critical infrastructure such as ports, airports, and the power sector to physical hazards. Non-pecuniary damages to nature (such as coastal erosion, soil degradation, loss of natural habitat or wetlands) are not included in the protection gap even though these damages may increase the likelihood of severe damages to property and business activities.

In emerging market and developing economies, protection gaps are significantly larger. Swiss Re (2023) reports a protection gap of 95% for China and 92% for India, despite both countries recording massive annual damages following a suite of extreme weather events. As a result, primary disaster relief is often provided by the government which diverts funds from important economic and social development activities. In recent years, Asian economies have undertaken efforts to install new risk transferring schemes, often in the form of microinsurance (Surminski *et al.,* 2019). Focusing on low-income countries, Golnaraghi *et al.* (2016) find that 95% of losses from physical hazards are uninsured and the few insured losses concentrate in the agriculture sector.

What will the future hold for the insurance sector? In response to major historical events, the insurance sector has taken steps to improve its risk modelling and assessment over recent years and have also explored new financial instruments (reinsurance and CAT bonds) to transfer risk to a broader set of risk investors. Given the changing nature of physical hazards, the insurance industry and the public sector may benefit from greater collaboration in reducing risk, as discussed in Warner *et al.* (2009). Examples of collaboration include sharing available data and information systems to raise awareness, incentivising risk reduction through accurate risk pricing, regulating the insurance sector, expanding direct financing or risk reduction measures by insurers, or introducing risk reduction as a prerequisite for insurance. The International Association of Insurance Supervisors analyses the role of insurance supervisors in addressing the protection gap for example through supporting disaster risk assessment and risk management practices (IAIS, 2023).

2.3 Financial channels

The financial sector propagates severe weather shocks through asset prices as well as credit conditions and volume. Tighter financial conditions and reduced access to finance make it more difficult to rebuild the economy after a disaster thereby prolonging the effects of the shock and magnifying its impact. In addition, the change in financial conditions softens economic activity more broadly. Physical hazards also weaken the resilience of the financial sector and reduce financial intermediation[39].

2.3.1 Asset prices and credit conditions

The destruction of physical assets (land, capital, real estate) and the decline in their prices from acute and chronic risks negatively impact the value of the collateral that borrowers can pledge to a lender for securing loan repayment[40]. Given the decline in collateral, not only will the borrower qualify for smaller loans from the lender but, as the external finance premium of the loan rises, the costs per dollar borrowed will also increase[41]. The decline in cash flows that stems from the diminished productive capacity adds to the increase in the external finance premium. This financial accelerator mechanism amplifies the negative impact from physical hazards.

Beyond its effects on lending and external financing, physical hazards can also impact equity prices in a similar manner. For instance, both holders of debt and equity experience a negative wealth effect, decreased creditworthiness, and compressed spending, following an extreme event (as set out in the discussion of the demand channels).

The balance sheets of banks are also impacted through lower value of equity portfolios, increases in non-performing loans (Dafermos *et al.*, 2018), and the withdrawal of deposits used for emergency spending and reconstruction (Brei *et al.*, 2019). With bank liquidity reduced, and default risks increased, banks face higher funding costs, which they may ultimately pass on to firms. This is the bank capital channel discussed, for example, in Levieuge (2009).

As already discussed, **natural disasters are likely to increase government spending for emergency assistance and rebuilding efforts.** In some cases, sovereign debt risk may increase as pointed out in Klomp (2017), Mallucci (2022), and Phan and Schwartzman (2023). The problems could potentially be exacerbated by a "diabolic loop" between the banking sector and sovereign debt of the kind discussed in Brunnermeier *et al.* (2016). The loop refers to a situation where a decline in sovereign creditworthiness

39 Avril *et al.* (2022) show that a strong macroprudential regulation improves countries' ability to cope with the financial impact of natural disasters.

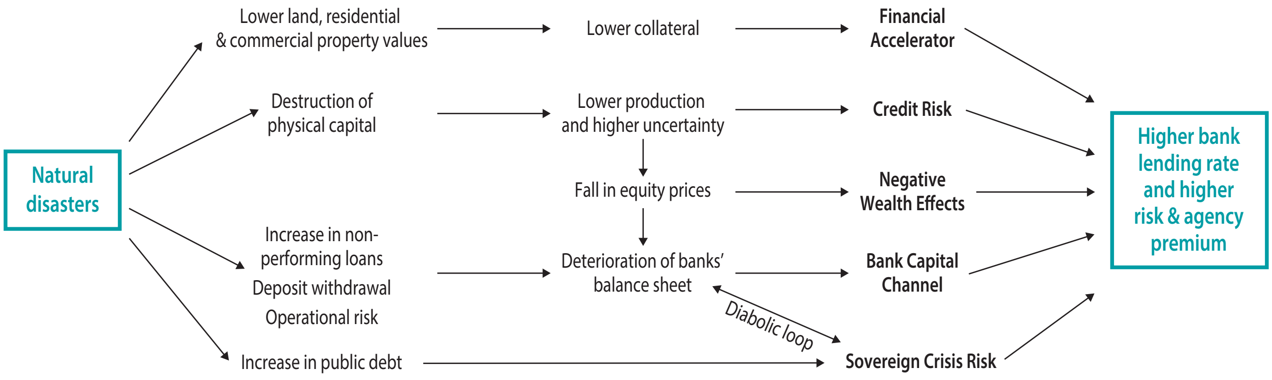
40 Bernstein *et al.* (2019) examine how markets price long-run uncertain cash flows in the face of rising sea levels.

41 In Bernanke and Gertler (1989) an information asymmetry between the borrower and the lender gives rise to the external finance premium. In principle, the financial accelerator effect applies to any shock that affects borrowers' balance sheets and cash flows. Hashimoto and Sudo (2022) illustrate the effects of floods on GDP in Japan via this mechanism. With parts of the capital stock destroyed firms produce less output which in turn reduces firms' ability to pay back their loans. The balance sheets of firms and financial intermediaries deteriorate and further disrupt financial intermediation which in turn weakens GDP further. As the authors stress, because the downward pressure on GDP endogenously deteriorates the corporate balance sheets, this effect is present even if direct damages are insured.

causes bank distress and raises the likelihood of bank bailouts by the sovereign. In turn, these events lower the sovereign's creditworthiness further. Beyond the effects for sovereign debt, Ferriani *et al.* (2023) document that in developing countries disasters can result in a significant reduction in foreign portfolio investment which may further hinder momentum of the economy.

Figure 3 illustrates the channels and the interaction between them. Physical hazards tighten credit conditions, in particular by raising the external finance premium as shown in Avril *et al.* (2022). Insurance is likely to attenuate the strength of these channels by cushioning the negative impact of natural disasters on agents' net wealth.

Figure 3 **Representation of the financial transmission channels of natural disasters**



Source: Avril et al. *(2022).*

2.3.2 Credit volume

It is widely recognised that demand for credit increases in the wake of a severe weather shock to finance reconstruction (Berg and Schrader, 2012). The volume of credit distributed – or recovery lending – depends on the banks' willingness and ability to lend, given that natural disasters also impact their balance sheets.

Recovery lending acts as a substitute for insurance. Empirical evidence suggests that recovery lending is not systematic (Noy, 2009; Hosono *et al.,* 2016), but depends on the characteristics of the banking sector:

1. *Relationship lending:* This occurs when recovery lending is provided by small local banks that have long-term relationships with their clients (Koetter *et al.,* 2020). Local anchorage of banks with a good knowledge of local economic and natural risks, and informational advantages dampen the economic impact of weather shocks through relationship lending (Avril *et al.,* 2023).
2. *Market diversification:* Multi-market banks are likely to protect their core markets by reallocating capital when local demand for credit increases after a natural disaster. They primarily reduce lending in unaffected non-core areas (Cortés and Strahan, 2017).
3. *Concentration of the banking sector:* As credit supply may have positive externalities on local economic activity, local banks may be more prone to continue lending into an area where they have a high share of outstanding loans (Favara and Giannetti, 2017).
4. *Soundness of the banking sector:* Profitable and well-capitalised institutions are more likely to provide recovery lending (Schuwer *et al.,* 2019; Duqi *et al.,* 2021).

Recovery lending could also come from governments, especially in developed countries (Noy and Nualsry, 2011) and in the absence of insurance coverage, albeit at the cost of a possible rise in sovereign risk.

Box 4

Reserve Bank of New Zealand response to the Canterbury Earthquakes

This box describes how the Reserve Bank of New Zealand (RBNZ) reacted to the Canterbury Earthquakes, focusing on monetary policy considerations at that time. This discussion draws on materials in Bollard and Ranchhod (2011), Parker and Steenkamp (2012) and Wood *et al.* (2016).

While unrelated to climate change, the experience of dealing with a major earthquake holds lessons for climate-related disasters. The Canterbury Earthquake swarm affected New Zealand's South Island from September 2010, with more than 50 earthquakes above 5.0 on the Richter scale occurring within a two-year period, leading to a combined damage estimate of just under 20% of GDP. The most devastating earthquake in February 2011 caused widespread destruction in Christchurch, New Zealand's second-largest city.

The policy reaction of the RBNZ took place in several steps. The first measures focused on alleviating the immediate disruptions caused by the event. Because a large share of retail payments in New Zealand are electronic, the loss of electricity reduced the viability of an important payment option. Card transactions in the region fell by around 40% in the days following the February 2011 earthquake. To ensure sufficient cash availability, the RBNZ worked closely with banks to provide an additional 150 million NZD of cash in the following week. The RBNZ also cut its main policy rate in March 2011 by 50 basis points, recognising the uncertainty surrounding the outlook and aiming to prevent a persistent deterioration in economic activity. Against the backdrop of already elevated inflation at the time, the RBNZ's Policy Targets Agreement (PTA) with the New Zealand Treasury provided important support for this rate cut. The PTA states that actual inflation can vary around the medium-term target for inflation in the case of natural disasters affecting a major part of the economy.

The second step involved gathering data on the extent of damages in the region and understanding the likely impact on individual sectors and prices. Because quarterly national accounts are produced with a lag and are subject to revision, the RBNZ leaned heavily on other data sources for its real-time assessment, including high frequency data (e.g. daily electronic card transactions), surveys (e.g. business and household confidence), contacts with government departments, discussions with local councils and consultations with regular business contacts.

The tourism industry was hit particularly hard as the number of available hotel beds plummeted by two thirds in the region. As many New Zealand tourism packages and holidaymakers would typically finish their trips in Christchurch, tourism also dropped in areas that would be visited earlier on in the trip, despite these areas not being directly affected by the earthquakes. Retail sales plunged in Christchurch, as many downtown areas remained inaccessible for a prolonged period. By contrast, the agriculture and manufacturing sectors saw little direct impact, although damages to the port and roads initially required re-routing of exports. The regional rise in rents and housing construction costs pushed up inflation not only in the affected areas but also elsewhere in the country. Insurance premiums increased at the national level.

With a deeper understanding of damages and affected sectors, the third step involved folding the damages and projected rebuilding activities into the RBNZ's economic model and forecasting framework. To do so, staff needed to settle on assumptions regarding the timing and speed of rebuilding efforts, the implications on resources, and the displacement of other activities by the rebuilding efforts. New Zealand has a high rate of earthquake insurance protection in place, with much of the risk ultimately borne by overseas reinsurers. Given this, the rebuilding activities only diverted minor amounts of domestic financing from other activities. Moreover, government debt was low, and the government could easily borrow additional funds on financial markets. Nonetheless, the lack of sufficient construction workers and materials posed some constraints, limiting the speed at which reconstruction efforts could take place. Staff initially assumed that rebuilding activity was unlikely to exceed 2% of GDP in total, with only some crowding out of activity elsewhere.

These initial assumptions proved too optimistic as continued seismic instability delayed rebuilding efforts and the rebound in activity. Continued monitoring of ongoing progress was carried out by Bank staff to understand the impact on overall inflationary pressures in the economy. With more information and further damaging events, the projected total size of the rebuild increased substantially over time.

Overlaying these steps, the RBNZ needed to communicate to the wider public and financial markets and the wider public how their understanding of the impact was evolving, and how it intended to react to developments over time. To this end the September 2010 and March 2011 Monetary Policy Statements explained in detail the RBNZ's considerations and assumptions, with regular communication over time as further information was acquired. Speeches and Bulletin articles provided further opportunity for transparency.

3. Aggregate effects and monetary policy

This section discusses the effects of severe weather events on the key determinants of monetary policy using macroeconomic studies. Some preliminary implications for monetary policy are discussed.

The discussion of the transmission channels in Section 2 leaned heavily on microeconomic studies. However, extrapolating these findings to the aggregate level is not straight forward. Spatial economic models and sectoral detail could bridge the gap between micro and macro aspects. An alternative approach is to **link physical hazards directly to the macroeconomic variables of interest.** The focus lies on the implications for the macroeconomic variables of primary interest for monetary policy, namely output and inflation[42].

3.1 Impact on GDP

Most aggregate studies find negative impacts from severe hazards on GDP both in the short- and long-term[43]. Econometric studies on the macroeconomic effects from severe weather events find that in the immediate aftermath of such an event, both the level and the growth rate of GDP drop. Over time, GDP growth recovers, but there is no consensus whether the economy returns to its pre-shock path for the level of GDP, as suggested by the neoclassical growth model, or continues at a lower path. Depending on the study, (per-capita) GDP growth rates decline by more than 0.5 percentage points, in the year of the shock, for very severe events and reach significantly higher values for the worst events.

The distribution of GDP impacts is highly skewed towards the most severe disasters. Felbermayr and Gröschl (2014) find that a disaster in the top-5 percentile reduces GDP per capita by 0.5%, while a disaster in the top-1 percentile reduces GDP per capita by 6.8%[44]. Hsiang and Jina (2014) show that these significant and disproportionate effects prevail in the long run: a 90th percentile cyclone reduces the level of GDP twenty years later by 7.4%, while one in the 99th percentile depresses it by 15%.

Emerging market and developing economies face much larger shocks to their economies following a disaster of similar magnitude (Noy, 2009) reflecting their lower resilience threshold. A climate disaster results in a cumulative per-capita output loss of 0.5 and 0.25% for middle and high-income countries, while the losses amount to 1% among low-income countries (Raddatz, 2009). However, the smaller effects of weather shocks in higher-income countries do not mean that they are immune to the effects of climate change (Kahn *et al.*, 2021).

However, it is important to highlight that not all studies have found statistically significant negative effects, and some even report positive effects. Kahn *et al.* (2021) find that real per-capita output growth is adversely affected by persistent changes in temperature above or below the historical norm but find no statistically significant effects for changes in precipitation. Roth Tran and Wilson (2023) argue that per capita income is 0.6% higher eight years after a disaster in affected counties in the United States than it would have been without the disaster because of transfers from the government[45]. However, as the U.S. federal government provided financial assistance in most of the disasters included in their sample, their findings cannot be generalised to events that were not directly or indirectly insured. At the country level, Cuaresma *et al.* (2007) argue that only countries with relatively high levels of development benefit from capital upgrading after a natural catastrophe.

42 There are only a few studies offering insight on the response of the unemployment rate (or more broadly labour market conditions), another variable that monetary policymakers pay attention to learn about the degree of economic slack. One example is Barattieri *et al.* (2023) who discuss the aggregate, regional, and sector unemployment response to hurricanes in Puerto Rico.

43 See also Botzen *et al.* (2019) and Parker (2018) for a recent review of the quickly expanding literature. Hsiang and Jina (2014) lay out the range of possible long-term effects of disasters: no-recovery (output does not converge to pre-shock path, only the growth rate of output converges to its pre-shock value); recovery to trend (output converges to its pre-shock path); build-back better (after the initial fall, output is above its pre-shock path); creative destruction (no initial fall, output is above its pre-shock path).

44 See Bodenstein and Scaramucci (2024) for related analysis.

45 Fomby *et al.* (2013) also find positive effects on economic growth from some disasters.

Adaptation, relief policy, and insurance can mitigate the negative effects of severe weather events. Limiting the increase in temperature to 0.01 °C per annum, which corresponds to the December 2015 Paris Agreement objective, may substantially reduce the expected output loss from 7% to 1% by 2100 as conjectured by Kahn *et al.* (2021). Von Peter *et al.* (2012) find that the uninsured part of catastrophe-related losses drives macroeconomic costs, whereas well insured catastrophes can be inconsequential or even positive for economic activity. Lastly, countries with a higher literacy rate, better institutions, higher per capita income, higher degree of openness to trade, and higher levels of government spending are better able to withstand the initial disaster shock and prevent spillovers into the macroeconomy because of the greater ability of mobilise resources for reconstruction (Noy, 2009).

International spillovers from severe weather events can be of considerable magnitude and occur mainly through commodity prices. In the agricultural and energy sectors production tends to be concentrated in a small number of regions some of which are vulnerable to extreme weather conditions. In a panel of 75 countries, de Winne and Peersman (2021) show that a 10% increase in global food commodity prices stemming from weather shocks lowers GDP by 0.5% after six quarters. Given that extreme weather events have triggered price shifts of up to 30% in the data, much larger GDP movements are conceivable. Perhaps surprisingly, the impact is stronger in advanced economies where food expenditures constitute a smaller share in total household expenditures compared to low-income countries, often because these economies tend to be net importers of agricultural products with small domestic agricultural production.

Box 5

The Federal Reserve's forecast after Hurricane Katrina

This box offers an account of how the Federal Reserve staff incorporated the effects from Hurricane Katrina into its projections in real-time based on historical Greenbooks, the main forecast and monetary policy document prepared by Federal Reserve staff in the lead up to each meeting of the Federal Open Market Committee (FOMC) at that time[1].

In August 2005, Hurricane Katrina flooded New Orleans and neighbouring regions, destroyed homes and businesses, and severely damaged oil and gas refinery and production capacity in the Gulf of Mexico with damages of nearly 200 billion USD (in 2023 dollars). The subsequent landfalls of Hurricanes Rita and Wilma in the weeks shortly thereafter compounded these effects.

Staff initially incorporated the effects from Hurricane Katrina in the September 2005 Greenbook by lowering their GDP forecast for the remainder of the year, with a rebound only expected in 2006. Specifically, growth in real GDP was reduced by about 0.75 percentage point (pp) on an annual basis in the third quarter, reflecting the significant disruptions to the production of oil, natural gas, and refined petroleum products in the U.S. Gulf Coast (Box Table 1). Despite the injection of federal emergency aid immediately after the event, the weakening of the economy was projected to last into the fourth quarter because of the persistent decline in consumer spending and employment (Q4 GDP growth was revised lower by 0.5 pp). Staff projected GDP growth to rise by 0.5 pp in 2006 as the recovery efforts, conditional on federal aid financing these activities, were expected to support activity relative to the pre-Katrina baseline. These projections were viewed as very uncertain, and staff entertained the possibility of both significantly larger and smaller damages. See Congressional Budget Office (2005) for a related discussion of uncertainty.

As more information became available, the damages from Hurricane Katrina were assessed to be smaller than originally feared. However, new uncertainty was injected into the forecast as Hurricane Rita and Hurricane Wilma compounded the effects from Hurricane Katrina only a few weeks later. Relief efforts were suspended,

1 These materials are publicly available at www.federalreserve.gov/monetarypolicy/fomchistorical2005.htm.

Table 1 **Forecast adjustments to GDP growth (annualised basis) due to Hurricanes Katrina, Rita, and Wilma between Greenbook vintages**

Greenbook \ Forecast	Q3 2005	Q4 2005	2006
September 2005	-0.75 ppar	-0.50 ppar	+0.5 ppar
November 2005	-1.00 ppar	-0.50 ppar	+0.5 ppar
December 2005	-0.75 ppar	-0.25 ppar	+0.3-0.5 ppar

Source: Federal Reserve Greenbooks (September-December 2005).

new evacuations were carried out, and the energy-related infrastructure was further damaged. Consequently, the outlook was revised down further despite the reassessment of damages from Hurricane Katrina. In the November Greenbook, the additional disruptions to the oil and gas sector were projected to hold back the expansion of GDP by 1 pp in the third quarter and 0.5 pp in the fourth quarter of 2005, relative to what had been expected in September, followed by a recovery boost of 0.5 pp in 2006.

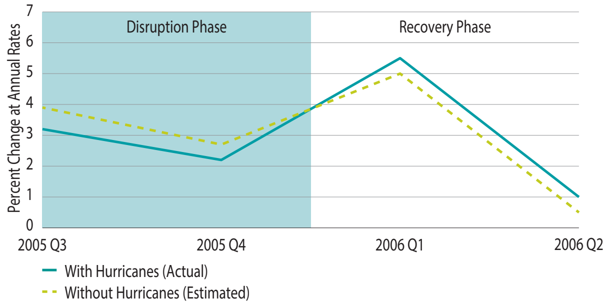
By the time of the December Greenbook, new data showed large production gains in some of the affected industries (chemicals, food, plastics) and stronger-than-expected consumer spending, although the rebuild of the damaged infrastructure in the energy sector remained slow. To reflect these largely positive developments in the forecast, staff revised up its GDP forecast for 2005 and pencilled in the smaller recovery boost for 2006.

The staff real-time forecast in September 2005 turned out to be closest to the historical assessment of the combined impact of the three hurricanes. Later estimates suggest that the hurricanes lowered U.S. real GDP growth by 0.7 pp in the third quarter of 2005 and 0.5 pp in the fourth quarter. The recovery likely stimulated GDP growth by 0.5 pp in the first half of 2006 (see U.S. Department of Commerce, 2006). Box Figure 1 combines these estimates with historical GDP data to graph quarterly GDP growth with and without the hurricanes.

Much of the Greenbook discussion on the inflationary effects from the hurricanes focused on the implications for energy prices and likely spillovers from higher energy prices into overall inflation. In September 2005, consumer energy prices were projected to increase at an annual rate of 49% in the third quarter and 29% in the fourth. As higher energy prices passed through to non-energy goods and services, core inflation was expected to increase by an additional 0.2 percentage points in 2006.

Figure 1 **Real GDP growth in the United States**

With and without Hurricanes Katrina, Rita and Wilma



Sources: Bureau of Economic Analyse (historical data), Council of Economic Advisers and Congressional Budget Office (hurricane effects).

The FOMC acknowledged that the hurricanes set back spending, production, and employment in the near term because of the devastation, dislocation of economic activity, and the boost to energy prices. However, the FOMC concluded that these developments did not pose a persistent threat beyond the near-term, and continued the pre-Katrina policy tightening, which it had started in June 2004 to bring inflation down from well above 2%. The target federal funds rate was raised by 25 basis points at each meeting following Hurricane Katrina until June 2006.

All in all, the Greenbooks document the staff's difficulties in quantifying the macroeconomic impacts of Katrina (and other storms and shocks) given the uncertainty about the magnitude and duration of disruptions, the response of the federal government, and the speed of the recovery. Scenario analysis provided guidance to policymakers with regard to this uncertainty. While better information helped narrow the uncertainty over time, limited experience with disasters of this scale and the compounding effects from Hurricane Rita and Wilma posed additional challenges.

3.2 Impact on inflation

The inflation effects of a specific severe weather event depend on whether the demand or the supply effects of the event dominate. Section 2 illustrated that severe weather events generate negative shocks to both supply (via a destruction of capital and decrease in labour and total factor productivity) and demand (impact on wealth, confidence, and expectations). As supply and demand effects push inflation in opposite directions, the overall inflation effects may be small. To obtain a clear understanding of the magnitude and the direction of the inflation response, the demand and supply components must be clearly identified as discussed in Cantelmo (2022) and Cantelmo *et al.* (2024).

Like in the case of economic activity, the inflationary effects depend on the type of disaster, the sectors exposed, the structure and maturity of the economy, location, seasonality, and time horizon. Parker (2018) analyses the inflationary consequences of severe weather events using panel data for a large set of countries. In the short term, storms increase food price inflation, floods increase headline inflation, and earthquakes reduce inflation excluding food, housing, and energy, but do not affect headline inflation. While the effects tend to be small in advanced economies, developing economies can experience elevated inflation for several years. Focusing on the euro area and food prices, Peersman (2022) documents how shocks to international food prices can spill over into domestic inflation even if the shock originated abroad. His research identifies unanticipated shocks to the harvests of globally traded agricultural commodities imported by the euro area, where shocks stem from changes in weather conditions or crop diseases. In response to a 1% unanticipated increase in food commodity prices, euro area real GDP declines by 0.1% and headline inflation rises by 0.1%.

Hotter-than-usual summers can increase inflation for several months, usually through their impact on food prices. Other components of consumer prices can also be affected but most research tends to find either insignificant or negative impacts over the medium term (see Faccia *et al.* (2021), Ciccarelli *et al.* (2023), and Kotz *et al.* (2023) for details). Using the case of the European Union, Kotz *et al.* (2023) find that temperature increases in hotter months and regions of Europe have larger inflationary impacts, both on headline and food inflation. This nonlinearity of the inflation effects with regard to temperature may reflect a nonlinear effect from greater heat stress on labour productivity and crop yields. The authors also argue that the 2022 extreme summer heat in Europe increased food inflation by around 0.7 percentage point cumulatively after one year. Using their estimates, the authors project that, barring adaptation measures, annual global food price inflation may increase about 1-3 percentage points per year by 2035 while headline inflation is expected to increase by 0.3-1.2 percentage points per year. Ciccarelli *et al.* (2023) find that services inflation can also be affected by hotter summers in southern euro area countries, presumably due to rising food prices and a sensitivity of tourism-related services to hotter temperatures.

In addition, the inflation effects of higher average temperatures may be nonlinear. Kotz *et al.* (2023) provide evidence that upward pressure from warmer temperatures on inflation are larger in warmer months and warmer countries, but the impact can be insignificant in colder months and colder countries. Consequently, this study suggests that the inflationary effects associated with climate change may be more pronounced during extremely hot summers. As a result, inflation could become more volatile, be heterogeneous across regions, and rise in its level. Overall, the emerging literature on the relationship between climate change and inflation suggests a non-linear relationship. The possible existence of "tipping points" adds to the risks surrounding the expected impacts from climate change[46].

Finally, the monetary economics literature assigns an important role to inflation expectations for actual inflation and the effectiveness of monetary policy. Meinerding *et al.* (2023) find that **climate change perceptions matter for inflation expectations.** They find a negative correlation between climate concern and expected inflation (i.e. individuals with lower climate concerns tend to have higher inflation expectations). In a volatile environment due to climate events, steering inflation expectations could become more challenging for central banks.

46 The IPCC defines a tipping point as "a critical threshold beyond which a system reorganises, often abruptly and/or irreversibly" (see IPCC, 2021).

3.3 Implications for monetary policy

When it comes to the implications from physical hazards for monetary policy, it is important to **distinguish between the realisation of a specific hazard** (e.g. the effects on inflation and output from a hurricane making landfall in Florida) **and the changes in the distribution of physical hazards.** When climate-related hazards increase in intensity and frequency, the anticipation of greater future damages may cause an uptick in precautionary savings over time and a decline in aggregate demand and output even without a hazard materialising.

Regarding the effects of a realised hazard, it is important to recognise that both **the direction and magnitude of the impact that a hazard has on the main determinants of monetary policy depends on the characteristics of the specific hazard.** As highlighted in Section 2, the different types of physical climate hazards propagate in very different ways to the broader economy.

Storms operate largely through destroying parts of an economy's capital stock on impact. The lasting output drop associated with the destruction of productive capacity is amplified through financial channels. Recovery of the economy requires rebuilding the lost capital stock. By contrast, **heatwaves affect economic activity primarily through a temporary decline in labour and agricultural productivity** and leave the capital stock largely unaffected. Once the heatwave ends, productivity largely returns to normal without much delay or the need for costly reconstruction. For long-lasting heatwaves, soil deterioration may pose a challenge. Also, the decline in output and cash flows may slow down the recovery if the shock is amplified through financial channels.

While aggregate output is likely to fall following the onset of both storms and heatwaves, the magnitude and direction of the inflation response is harder to predict. With both the demand and the supply sides of the economy being affected, the response of inflation reflects the relative strength of these two channels: quantitative macroeconomic models suggest that inflation rises by less or even falls when the capital stock is impaired but rises when labour factor productivity falls. These theoretical findings for inflation are generally consistent with the econometric results presented in Parker (2018) for storms and floods and Faccia *et al.* (2021) and Kotz *et al.* (2023) for heatwaves.

The empirical evidence suggests that an economy may not fully recover after a climate disaster. **Uncertainty about the longer-term effects of a specific disaster translates into uncertainty about central concepts of monetary policymaking, namely potential output and in turn the output gap.** Theory suggests that a correctly measured output gap can give valuable guidance to monetary policymakers. But if not, mismeasurement in the output gap can lead to policy mistakes and weaken the central banks' stabilisation efforts as illustrated in Orphanides *et al.* (2000) and Orphanides (2003). The uncertainty about the long-term effects on potential output may be exacerbated if repeated shocks lower the supply capacity of the economy because the compounding of events makes it harder to identify the long-term effects of a hazard in the data.

Even if the effects of a realised disaster were fully understood, decision-makers still face policy challenges from the shift in the distribution of disasters. **More frequent and intense disasters alter the consumption, savings, and investment decisions of households and firms.** As discussed in Cantelmo (2020), increased precautionary savings could lower aggregate demand and push down the natural rate of interest (r*), another important concept for monetary policymakers[47]. There is uncertainty over the size of the effect because of the uncertainty about the exact future distribution of severe physical hazards, which will be sensitive to the actual mitigation, adaptation, and resilience measures taken by society among other factors. Surveying the literature, Mongelli *et al.* (2022) highlight the possibility of higher precautionary savings and lower productivity growth due to climate change. If these factors weigh negatively on the natural rate, they limit the space for monetary policymakers to accommodate shocks due to the effective lower bound on interest rates[48].

Overall, **physical hazards increase uncertainty about the evolution of key variables for monetary policy.**

47 The natural rate of interest denotes the real interest rate level that would prevail when inflation is at the central bank's target and full employment is reached. See also Isoré and Szczerbowicz (2017), Dietrich *et al.* (2021), and Ojeda-Joya (2022) for an analysis.

48 Mongelli *et al.* (2022) find that the natural rate can be positively affected if transition spurs innovation and raises productivity growth.

The substantial volatility and non-linearities inherent to climate change require enhanced and more sophisticated macroeconomic analysis and modelling. Real-time assessment of the impact of physical hazards is even more challenging for policymakers as illustrated in Box 5. Hence, it could become more difficult to prepare reliable forecasts of inflation and output, within historical error ranges, raising the risk of monetary policy mistakes, that could undermine central bank credibility. To better navigate monetary policy under these challenges, central banks may benefit from transparent communication and engagement with the public about central banks' (evolving) understanding of the links between physical hazards, the economy, and monetary policy.

Box 6

Modelling the aggregate economic effects from physical hazards

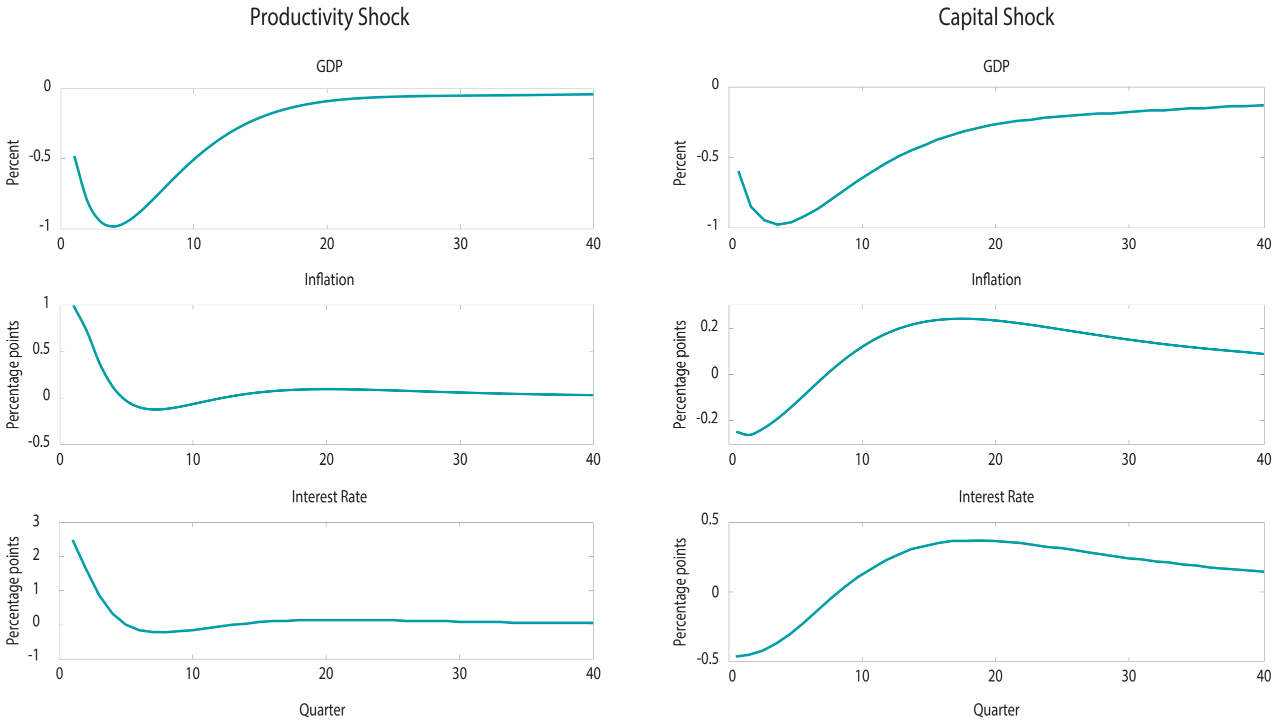
This box illustrates how to map a climate scenario narrative to a Dynamic Stochastic General Equilibrium (DSGE) model and gain insight on the transmission of climate-related shocks to the broader economy to derive guidance for monetary policy. DSGE models are a popular analytical tool used by central banks to communicate economic insight. Scenario design is one application for which DSGE models appear particularly well suited because these models allow economists to assess the relative strength of the forces impacting the economy in a transparent manner. Most DSGE models at central banks incorporate enough detail about the macro economy so that researchers can derive meaningful answers to recurring questions from the models, but they are also flexible to address questions for which they were not originally designed when they are applied in conjunction with other theoretical and quantitative models. DSGE model analysis of the physical effects from climate hazards falls into that latter category. Here this box relies on the model by Gertler and Karadi (2011), henceforth SWGK, which has many features in common with the DSGE models at central banks.

For illustration, consider the narratives of two short-term scenarios proposed in ESRB (2022). These narratives are instructive regarding the choice of shocks to implement for severe weather events in DSGE models:

1. An **extreme flood** substantially impacts properties and other asset classes (households, companies, infrastructures, public buildings). In the SWGK model, the primary flood effect of destroying physical capital is captured by a transitory increase in the capital depreciation rate in the impact period. Additional effects from temporary displacement of workers and factor market disruptions can be thought of as negative shocks to labour supply and total factor productivity (TFP), respectively.
2. A **long heatwave period** takes a toll on the economy via a decrease in productivity, especially for outdoor sectors such as agriculture, construction, and tourism. In the SWGK model, the primary heatwave impact of destroying output (either directly or preventing it from being produced) is captured by a decline in TFP over the duration of the heatwave. A shock to the time preference of consumption can capture the temporary decline in the demand for goods and services related to outdoor activities. Additional effects may include lasting damages to physical capital and infrastructure (captured by an increase in the depreciation rate) and health considerations (captured by a negative labour supply shock).

Box Figure 1 displays the dynamic evolution of selected variables in response to shocks to TFP and capital depreciation. A drop in TFP lowers output even if capital and labour remain at their pre-shock levels. However, with marginal factor products dropping, firms demand fewer inputs at current factor prices. This pullback lowers output beyond the direct effects from the productivity shock. The output effects persist beyond the duration of the shock because the temporary cut back in the demand for capital lowers investment demand and ultimately the capital stock. In the presence of nominally rigid prices and wages, the fall in potential output is faster than in actual output resulting in significant upward pressure on inflation.

Figure 1 **Dynamic evolution of GDP, inflation, and interest rates in response to shocks to TFP and capital depreciation**



Note: Impulse responses to a productivity and a capital destruction shock in the SWGK model.

Qualitatively, a capital depreciation (or destruction) shock induces similar responses of output and inflation as the shock to TFP. However, in this case the drop in the capital stock lowers the marginal productivity of labour while TFP is unchanged. Since rebuilding the capital stock requires resources and time, the output effects of the one-time shock to the capital stock are more persistent than those of the one-time shock to TFP even if both shocks are sized to induce the same initial decline in output. The inflation effects are also considerably more drawn out in response to the capital depreciation shock. Cantelmo *et al.* (2024) conduct a related analysis for a small open emerging market economy.

As this discussion illustrates, DSGE models can capture important aspects of the dynamics that are likely to occur after a severe weather event. Introducing additional shocks can suitably enrich the discussion along several dimensions. For example, a shock to the time preference of consumption can capture the business and consumer sentiment effects of a severe weather event. The decline in consumption demand causes output to drop. Inflation falls as well in this case because potential output is unaffected by the demand shock.

When assessing the quantitative implications from climate-scenario narratives using DSGE models, the selection of shocks (including their magnitude) is key and requires both a clear understanding of how climate-related shocks propagate in the real world and how the various shocks in the DSGE model relate to them. The SWGK model is rich enough to capture the core elements of the two scenarios above. However, ideally, for the narrative on extreme floods, the model would distinguish between productive and non-productive assets. Damages to commercial and private real estate have a significantly smaller impact on the economy's productive capacity than damages to machines. Given the leading role of the construction sector during reconstruction, some sectoral detail may help with understanding the recovery. Greater sectoral detail is also of help when analysing the effects of heatwaves. Weather-sensitive activities like agriculture and construction experience much stronger temporary suppression of activity during a heatwave than manufacturing.

Conclusion

The physical impacts from climate change propagate to the broader economy through supply, demand, and financial channels. The absolute and relative strength of these channels varies by type and intensity of the physical hazard.

The immediate impact of physical hazards is often first experienced on the supply side of the economy. Output, productive capital, real estate, or infrastructure are destroyed. Workers are dislocated, or their jobs are destroyed. Productivity drops. But importantly, **not all hazards affect the supply side in the same way.** The effects of droughts are concentrated on the agricultural sector and droughts suppress production in water-intensive industries. By contrast, the effects of storms are more evenly distributed across the sectors of economy. However, storms may have longer-lasting effects on production if they destroy productive capital.

The demand effects of physical hazards work through household wealth and income, expectations of future climate events as well as consumer and business confidence. Insurance payouts may speed up the rebuilding of destroyed productive capacity and thereby limit the aggregate effects of the physical hazard.

The financial sector propagates severe weather shocks through asset prices as well as credit conditions and volume. Tighter financial conditions and reduced access to finance slow down the recovery and may result in spillovers to initially unaffected areas of the economy. The destruction of physical assets and the decline in their prices from acute and chronic risks negatively impact the value of firms' collateral, which in turn weakens the balance sheet of financial intermediaries. Weaker balance sheets are also problematic given the increased demand for recovery loans in the aftermath of a disaster.

Most aggregate studies find negative impacts on GDP both in the short- and long-term. For inflation, in theory, the effects of a specific severe weather event depend on whether the demand or the supply effects of the event dominate. The nascent empirical work on inflation suggests that food prices rise after an event with some spillovers into overall inflation. The inflationary effects can be nonlinear as documented for the case of heatwaves.

This discussion of how the primary impact from severe weather events unfolds and propagates to the broader economy allows some **preliminary conclusions for the design of short-term scenarios that can support monetary policymakers in their decision making.** First, **scenario narratives have to be specific about the severe weather** event driving the scenario, its impact on different aspects of the economy (real estate, economic sectors), the connection between physical damages and the financial sector (who financed the damaged assets), the extent of insurance against physical impacts, and the assumptions about the recovery process. Second, the **macroeconomic models** used to derive the implications for output and inflation dynamics as well as monetary policy should be **detailed enough to capture the main features of the narrative.** At the minimum, the model should be able to distinguish between the damages to productive assets (machines) and other assets (real estate) as well as some key sectors – either because of their sensitivity to certain physical hazards (agriculture, energy) or their role in leading recovery efforts (construction, insurance, financial intermediaries). Hallegatte *et al.* (2022) propose a model that incorporates many of these elements.

The literature offers many insights on the economic effects from severe weather events by studying past events. Unfortunately, the **links between severe weather events and the economy are dynamic and subject to change in particular because of climate change.** From a geophysical perspective, it is uncertain how the distribution of severe weather events will change both with regard to its mean and its variance even for a given path of climate mitigation policies and carbon emissions. Similarly, the economic effects from the compounding of multiple severe weather events and their interaction with the chronic effects (rising sea levels, higher average surface temperatures) are poorly understood in part because of the uncertainty of countries' resilience and adaptation to climate change.

Considering these many unresolved questions, **climate change will likely cause greater uncertainty about the economic environment in which monetary policymakers operate** in pursuit of fulfilling their monetary policy and financial stability mandates. More work is needed to better describe the range of the climate-change-related uncertainty relevant to monetary policy and financial stability to formulate concrete policy options.

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Acknowledgements

The document *Acute physical impacts from climate change and monetary policy* is a collaborative effort of the members of the NGFS Workstream on Monetary Policy.

This document was prepared under the auspices of the chair of the Workstream, James Talbot (Bank of England). The drafting of the document was supported by the chair's team (Lukasz Krebel, Danae Kyriakopoulou, Theresa Lober and Michelle van der Merwe) and the NGFS Secretariat (Benjamin Alford, Léa Grisey, Daniel Gybas and Li Savelin).

This document relies on the analysis and drafting work of a dedicated team of Workstream members. The NGFS is especially thankful to Rana Abdurrahman (Central Bank of Egypt), Martin Bodenstein (U.S. Federal Reserve Board), Johannes Gross (European Central Bank), Gregory Levieuge (Banque de France), Francis Martinez (U.S. Federal Reserve Board), Angeliki Momtsia (Bank of Greece), Miles Parker (European Central Bank), Johannes Pöschl Ketelsen (Danmarks Nationalbank), Sara Sakr (Central Bank of Egypt), Sherif Shaheen (Central Bank of Egypt), Ifigeneia Skotida (Bank of Greece) and William Yang (U.S. Federal Reserve Board). Other team members included Jesus Bejarano (Banco de la República, Colombia), Alessandro Mistretta (Banca d'Italia), Raghavi Naidu (Central Bank of Seychelles), Jair Ojeda Joya (Banco de la República, Colombia), Haluk Ovali (Central Bank of the Republic of Türkiye) and Shanthessa Ragavaloo (Reserve Bank of South Africa).

The chair of the Workstream and the contributors are also thankful to Gert Peersman (Ghent University) and Swenja Surminski (Marsh McLennan and Grantham Research Institute at LSE) for their insightful discussions of the draft report at the November 2023 meeting of the Workstream in London.

Comments and suggestions by all Workstream members and observers are gratefully acknowledged.

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