LAPSE OF TIME

SM/20/93

May 1, 2020

To: Members of the Executive Board

From: The Secretary

Subject: **April 2020 Global Financial Stability Report—Analytical Chapter 5**

Board Action:	Further to the Executive Board discussion on April 7, 2020, this Analytical Chapter of the Global Financial Stability Report is being circulated for **Executive Directors' comments** in advance of publication.
Deadline to Provide Comments:	**Friday, May 15, 2020** **12:00 (noon)**
Publication:	Proposed, after Friday, May 15, 2020
Questions:	Mr. Natalucci, MCM (ext. 37108) Ms. Qureshi, MCM (ext. 38942) Mr. Vandenbussche, MCM (ext. 36676) Mr. Suntheim, MCM (ext. 39084)
Additional Information:	The paper will be revised for publication in light of the comments from Executive Directors. If Executive Directors have comments, they should notify Mr. Natalucci (ext. 37108), Ms. Quereshi (ext. 38942), Mr. Vandenbussche (ext. 36676), and Mr. Suntheim (ext. 39084) by **12:00 p.m. on Friday, May 15, 2020.**

Physical Risk and Equity Prices

Chapter 5 at a Glance

- The impact of large climatic disasters on equity prices has been modest in the past.
- Climate change physical risk does not appear to be reflected in global equity valuations.
- Beyond climate change mitigation and adaptation, sovereign financial strength and higher insurance penetration helps to preserve financial stability.
- Stress testing and climate risk disclosure are essential to better assess physical risk.

The projected increase in the frequency and severity of disasters due to climate change is a potential threat to financial stability. Equity markets are a key segment of the global financial system, provide a data-rich environment, and are sensitive to long-term risks, making them a fertile ground to investigate how projected future physical risk affects financial markets and institutions. Looking back over the past 50 years, the impact of large disasters on equity markets, bank stocks, and non-life insurance stocks has generally been modest although country characteristics matter. Higher rates of insurance penetration and greater sovereign financial strength have helped dampen the adverse effects of large disasters on equity markets and financial institutions. While projections of climatic variables and their economic impact are subject to a high degree of uncertainty, aggregate equity valuations as of 2019 do not appear to reflect the predicted changes in physical risk under various climate change scenarios. This suggests that equity investors may not be paying sufficient attention to climate change risks. Beyond policy measures to mitigate and adapt to climate change, actions to enhance insurance penetration and strengthen sovereign financial health will be instrumental in reducing the adverse effects of climatic disasters on financial stability. Moreover, better measurement and disclosure of exposures to climatic disasters is needed to facilitate the pricing of climate-change-related physical risks.

Approved By
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CONTENTS

Introduction ___ 3

Climatic Disasters—Some Stylized Facts ___ 7

Large Climatic Disasters and Equity Returns ___ 10

The Role of Insurance Penetration and Sovereign's Financial Strength in Cushioning the Equity Market Effects of Climatic Disasters ___ 11

Equity Pricing of Future Climate Change Physical Risk ___ 14

Equity Investors' Attention to the Effect of Temperature on Pricing ___ 19

Conclusion and Policy Recommendations ___ 20

BOX

5.1. Stress Testing for Physical Risk in the Financial Sector Assessment Program ___ 26

FIGURES

5.1. Projected Changes in Climatic Hazards ___ 3
5.2. Climate Change Physical Risk and Financial Stability ___ 5
5.3. Climatic Disasters and Related Damage ___ 9
5.4. Equity Market Returns Immediately before and after Large Climatic Disasters ___ 12
5.5. Insurance Penetration and the Protection Gap ___ 13
5.6. The Effect of Insurance Penetration and Sovereign Financial Strength on Equity ___ 14
5.7. Growth in the Sustainable Equity Fund Market ___ 15
5.8. Climate Change Physical Risk and Equity Valuations ___ 17
5.9. Equities' Temperature Sensitivity ___ 20

References ___ 22

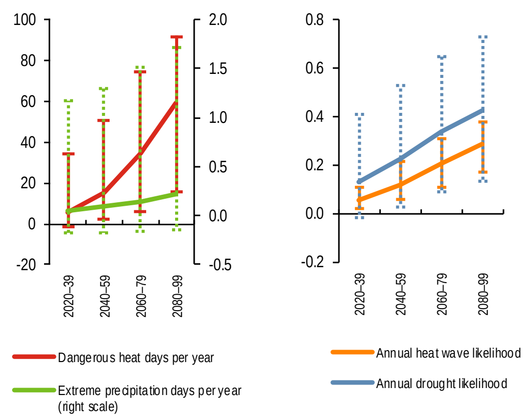
Introduction

1. Global temperatures have increased by 1.1 degrees Celsius relative to pre-industrial levels, and climate scientists have almost unanimously attributed this change to man-made (anthropogenic) greenhouse gas emissions. The path of global temperatures over the next several decades will depend in large part on mitigation actions that help reduce the amount of emissions. Based on currently stated mitigation policies, future anthropogenic greenhouse gas emissions are predicted to lead to a warming of about 3 degrees Celsius by the end of the century (IPCC 2018). Climate change induced by this level of warming is, in turn, expected to adversely impact the world's stock of natural assets, lead to a significant rise in sea level, and increase the frequency and severity of extreme weather events (IPCC 2014 and Online Annex Table 5.1.3). The impact is subject to a significant degree of model uncertainty (Figure 5.1), is likely to vary considerably across economies and may be non-linear as a result of thresholds in the climate system beyond which the effects accelerate or become irreversible (DeFries and others 2019).

Figure 5.1. Projected Changes in Climatic Hazards

The size of the future increase in climatic hazard occurrence is large and uncertain.

Sample Economies: Latest Projected Changes in Extreme Weather Events, Relative to 1985–2005
(Various horizons)



Sources: The World Bank Group, Climate Change Knowledge Portal; and IMF staff calculations.
Note: The figure shows the equally-weighted average across all sample economies of the median projection—from up to 35 models included in the fifth phase of the Coupled Model Intercomparison Project (CMIP5)—of four climate variables, defined as anomalies relative to historical simulations over the period 1986–2005. The extremities of the vertical bars show the equal weighted average of the 90th and the 10th percentiles of the projections. Projections are based on the high-emissions scenario Representative Concentration Pathway (RCP) 8.5. See Online Annex 5.1 for the list of sample economies, as well as a definition of the RCP scenarios, and the future climate variables.

2. Extreme weather events—or climatic hazards—can turn into disasters that cause loss of life and capital stock, as well as disruptions to economic activity. As a result, they are a source of so-called "physical risk" for economic agents. Some climatic hazards have wrecked cities and even entire economies. New Orleans was devastated by Hurricane Katrina in 2005, while Dominica suffered damages amounting to over twice its GDP when Hurricane Maria struck in 2017. As the frequency and severity of climatic hazards rise, the resultant socioeconomic losses could be significantly higher than in recent history.

3. The magnitude of the change in physical risk will depend not only on how future emissions (and therefore mitigation policies) translate into global warming, and on how this warming, in turn, translates into more frequent and more severe climatic hazards, but also on nonclimatic factors—that is, the reactions of economic agents (including governments) to these changes, in particular through adaptation.[1] For example, a study of predicted flood losses in the world's 136 largest coastal cities concluded that global annual average losses would exceed $1 trillion in 2050 in a scenario without adaptation versus only $60 billion in a scenario with adaptation investments that maintain constant flood probabilities despite a higher sea level (Hallegatte and others 2013).

4. Given the climatic trends, financial stability authorities have become concerned that the financial system may be underprepared to cope with this potentially large increase in physical risk, as well as with the so-called "transition risk" resulting from policy, technology, legal, and market changes that occur during the move to a low-carbon economy. Transition risks include assets becoming stranded, reputational damage, and financial distress of polluters. The Network for Greening the Financial System, a group of central banks and financial supervisors, has expressed concern that financial risks related to climate change are not fully reflected in asset valuations and has called for integrating these risks into financial stability monitoring (NGFS 2019). In its Financial Sector Assessment Program, the IMF is paying increasing attention to financial stability risks related to climate change and aims to push forward efforts around climate change stress testing across economies (see Box 5.1).

5. From the perspective of physical risk, climate change can affect financial stability through two main channels (Figure 5.2). First, a climatic hazard can turn into a disaster if it happens in an area where the exposure is large and vulnerability is high.[2] Such a disaster affects households, nonfinancial firms, and the government sector through the loss of physical and human capital, thereby causing economic disruptions that can possibly be significant. Financial sector firms are exposed to these shocks through their underwriting activity (insurers), lending activity (mostly banks), and portfolio holdings of affected securities (all financial firms). Financial institutions could also be exposed to operational risk (such as in cases in which their structures, systems, and personnel are directly affected by an event) or to liquidity risk (such as if a disaster triggers sizable withdrawal of customer deposits). Insurers play a special role in absorbing shocks. The provision of insurance concentrates the impact of the shock on the insurance sector and reduces the impact on other economic agents.[3] Governments also generally play an important cushioning role by providing some forms of insurance, as well as relief and support in the aftermath of a disaster. The strain on government balance sheets after a disaster could potentially have financial stability implications given the strong sovereign-bank nexus in many economies.

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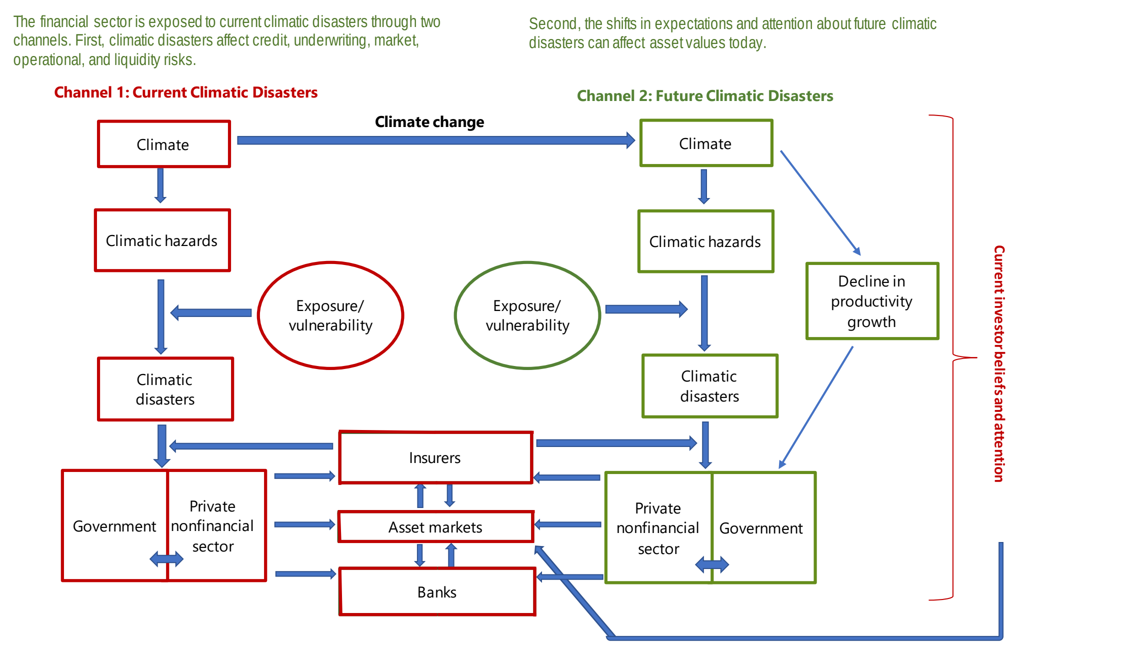
[1]Mitigation addresses the causes of climate change, whereas adaptation addresses the impacts of climate change.

[2]The chapter uses the same terminology as climate change research, where exposure is defined as "the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected" and vulnerability is defined as "the propensity or predisposition to be adversely affected" (IPCC 2012). Resilience is the opposite of vulnerability.

[3]Insurers can transfer portions of their risk portfolios to reinsurers. Yet, anecdotal evidence suggests that some large disasters had a sizable impact on insurers' solvency. For example, Hurricane Andrew led to the failure of at least 16 US insurers in 1992–93 (Insurance Information Institute 2020).

6. Second, investors form beliefs about physical risk—the result of a combination of climatic hazards, exposures, and vulnerabilities—as well as insurance coverage (and risk-sharing more broadly, including through the government) at various time horizons in the future. Standard asset pricing theory suggests that investors should demand a premium for holding assets exposed to a future increase in physical risk induced by climate change. In other words, these assets should have a lower price compared to assets with similar characteristics but not exposed to this change in physical risk. However, because the nature of the risk is long term, and depends on complex interactions between climate variables and socioeconomic developments that are difficult to model, markets may not price future physical risk correctly, potentially leading to capital misallocation and economic inefficiency. Perhaps more importantly from a financial stability perspective, a sudden shift in investors' perception of this future risk could lead to a drop of asset values, generating a ripple effect on investor portfolios and financial institutions' balance sheets.[4]

Figure 5.2. Climate Change Physical Risk and Financial Stability



Source: IMF staff.

[4]As shown in Figure 5.2., the climate economics literature suggests that climate change could lead to a decline in productivity growth, which may also not be reflected adequately in asset prices. Under a scenario of no further mitigation action on climate change, most estimates suggest a loss of global economic output of less than 5 percent in 2050 and 10 percent in 2100 (Kahn and others 2019). While this implies that the average productivity growth decline due to climate change would be small, the historical relationship between temperature and GDP growth may not be an accurate guide to the future in the presence of tipping points in the climate system.

7. Against this backdrop, the chapter analyzes the financial stability implications of the anticipated increase in the frequency and severity of climatic hazards over the next several decades.[5] To do so, it focuses on equity markets, which play a central role in the financial system and provide a useful avenue to explore the two channels described. This is so because, relative to other financial markets, equity markets provide readily available high-frequency information on investors' perception of the impact of a shock on the future performance of a broad range of financial and nonfinancial firms. Equity markets are thus well suited for an event-study type of analysis to investigate the first channel. Moreover, because equities are perpetual claims on firms' cash flows, their price should reflect the long-term risks facing firms, including those associated with changes in physical risk, allowing an investigation of the second channel.

8. The chapter focuses on 68 economies with available aggregate stock market data[6] and asks the following key questions: (1) What has been the trend in frequency and severity of climatic disasters in these economies? (2) How have aggregate equity prices, bank equity prices, and insurance equity prices reacted to large climatic disasters in the past? (3) Can better insurance coverage and sovereign financial strength enhance the resilience of equity markets and financial institutions? (4) Acknowledging the informational challenges faced by investors, are climate change risks reflected in equity prices—that is, do equity valuations as of 2019 correlate negatively with the predicted changes in physical risk? (5) Are equity investors paying attention to temperature, a climate variable that—in contrast to future climatic hazards—is not predicted or model-dependent but can actually be observed at high frequency? The sample used in the analysis comprises 34 advanced and 34 emerging market and developing economies and covers the past 50 years. The data sources and econometric methodologies, as well as robustness tests of the key findings are described in the online annexes.

9. The chapter's main findings are as follows: Climate change is a source of financial risk for investors that could lead to adverse consequences for financial stability. However, over the past several decades, the reactions of aggregate equity prices, bank equity prices, and insurance equity prices to large climatic disasters have generally been modest, in particular in economies with high rates of insurance penetration and sovereign financial strength. Pricing future climate risks is extremely challenging, given the large uncertainties around climate science projections and the economic cost of predicted hazards. That acknowledged, current economy-level equity valuations as of 2019 are generally not statistically significantly associated with the currently available proxies of future changes in physical risk. Furthermore, equity investors do not seem to have paid full attention to temperature, which could suggest that they do not pay full attention to climate change either. The analysis implies that, in the current baseline scenario, where climate change mitigation policies are projected to remain weak globally, domestic financial stability will be best protected if governments preserve or enhance their financial strength, reduce barriers to non-life insurance penetration while ensuring adequate capital in the insurance sector, and encourage adaptation. Soberingly, preserving or

[5]An in-depth exploration of the impact of transition risk is left for future issues of the *Global Financial Stability Report*. For a comprehensive discussion of financial stability risks related to climate change, including transition risk, see Carney (2015); Bank of England Prudential Regulatory Authority (2018); European Central Bank (2019); and Network for Greening the Financial System (2019), among others. Chapter 6 of the October 2019 *Global Financial Stability Report* also discusses these risks as part of a broad analysis of sustainable finance.

[6]All economies for which aggregate stock market data are available have been included in the sample. These represent about 95 percent of world GDP in 2018. See Online Annex 5.1 for the list of economies.

enhancing financial strength appears challenging as public debt ratios continue to increase (see Chapter 1). In addition, better measurement and increased disclosure of exposure and vulnerability to climatic hazards would help reduce investors' informational challenges and facilitate risk pricing.

Climatic Disasters—Some Stylized Facts

10. Climatic hazards range from acute (storms, floods, heat waves, cold waves, wildfires, and landslides) to chronic (droughts). Hazards that result in large scale damage to human life, physical assets, and economic activity are defined as disasters.[7] The transformation of a climatic hazard into a disaster depends not only on the physical magnitude of the hazard (for example, the windspeed during a storm event), but also on the economic exposure of the region where it strikes (especially the value of assets and the population size) and its vulnerability (for example, the quality of buildings and infrastructure, and disaster preparedness). Given that disasters are more economically meaningful than hazards, the focus here is on disasters, especially on large disasters.[8] The sample includes more than 6,000 disasters, about 60 percent of which have occurred in emerging market and developing economies. The annual number of disasters has increased considerably in the past few decades, from slightly more than 50 in the early 1980s to around 200 since 2000, though it has remained stable over the past 20 years (Figure 5.3, panel 1). Floods and storms have been the most frequent climatic disasters, constituting about 80 percent of the sample. While part of the rise in the frequency of disasters may be related to better reporting over time, a large part of it is also due to increased frequency of the occurrence of hazards and increased exposure of assets and population to hazards (IPCC 2012).

11. In general, emerging market and developing economies have been much harder hit by climatic disasters than advanced economies, suffering almost twice as much average damage relative to the size of their economies (0.13 percent of GDP compared to 0.07 percent of GDP). The difference is even starker when looking at the 10 largest disasters over 1970–2018: emerging market and developing economies incurred damages in the range of 2.9 percent of GDP to 10.1 percent of GDP versus 1 percent of GDP to 3.2 percent of GDP in advanced economies (Online Annex Table 5.1.4). Moreover, the number of people affected by climatic disasters in emerging market and developing economies also tends to be much higher than in advanced economies.

12. The distribution of the damage-to-GDP ratio is asymmetric and strongly positively skewed (Figure 5.3, panel 2). While the median disaster damage amounts to only a small fraction of GDP (0.01 percent), the largest disasters tend to be costly, with the 95th percentile of the distribution corresponding to a damage of about 0.5 percent of GDP.[9] Despite an increase in hazard strength and exposure, the average damage from

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[7]Disaster data are sourced from the Emergency Events Database (EM-DAT). Disasters conform to at least one of the following three criteria: 10 or more deaths; 100 or more people affected; the declaration of a state of emergency and/or a call for international assistance. Reported damages from disasters are measured imperfectly and generally cover only direct costs from damages to physical assets, crops, and livestock.

[8]The chapter defines a disaster as "large" if the rate of affected population is greater than 0.5 percent, or the damage is greater than 0.05 percent of GDP.

[9]Some of the largest disasters in the sample have unfolded over a relatively long period of time. An example is the drought in Australia—the costliest disaster in an advanced economy—that started in 1981 and lasted for two years. However, most other

disasters (including from the largest disasters) in terms of GDP, has not increased much over time (Figure 5.3, panel 3). This is consistent with a concomitant reduction in vulnerabilities.[10]

13. In absolute terms, the total annual average damage from climatic disasters (measured in constant 2018 US dollars) has been increasing in the sample of economies considered here—rising nearly six-fold and surpassing $120 billion in 2010–18 compared to $22 billion in 1980–89. As a share of world GDP, however, it has remained broadly constant at about 0.2 percent over the past 30 years (Figure 5.3, panel 4).

disasters have been acute and have unfolded in a period of a month or less. In the subsequent analysis, the costs of a disaster are attributed to the year of onset.

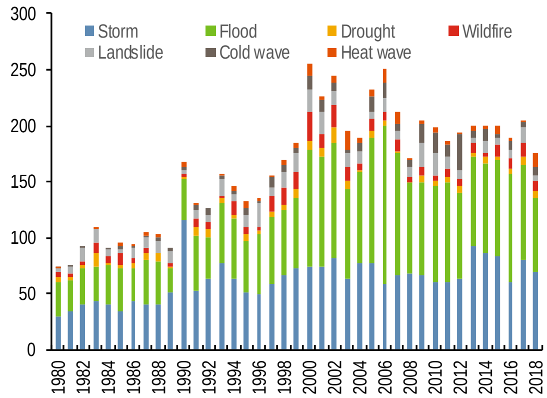
[10]Controlling for hazard size and exposure, the number of deaths from disasters decreases with GDP per capita and institutional quality (Kahn 2005). Some studies find that hurricane damages in the United States have not increased in line with exposure (Estrada, Botzen, and Tol 2015).

Figure 5.3. Climatic Disasters and Related Damage

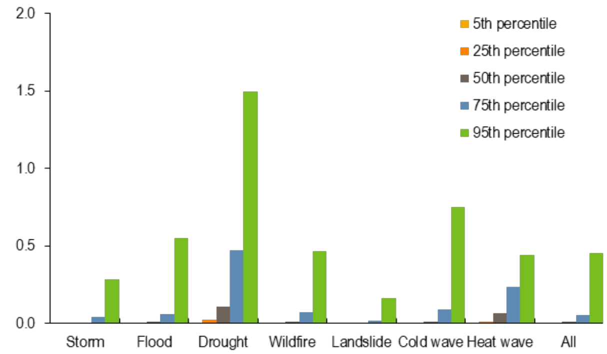
After rising until 2000 the number of climatic disasters has been stable over the past 20 years, with storms and floods accounting for most occurrences.

Only large disasters cause sizable damages relative to domestic GDP.

1. Sample Economies: Annual Number of Climatic Disasters, 1980–2018



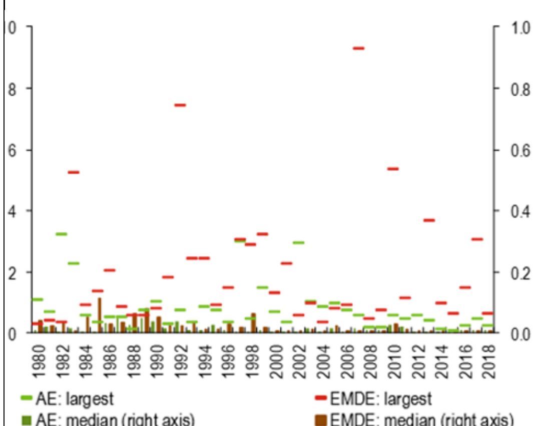
2. Sample Economies: Damages-to-GDP Ratio, by Disaster Type and Percentile of the Distribution, 1980–2018
(Percent)



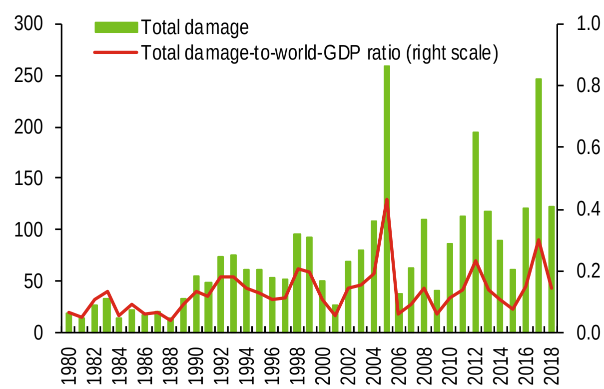
The damage from disasters has been stable over the past 30 years …

… as have total damages relative to the world GDP.

3. Sample Economies: Median and Largest Annual Damage-to-GDP Ratio,1980–2018
(Percent)



4. Sample Economies: Total Annual Damages and Total Annual Damages-to-World-GDP Ratio, 1980–2018
(Left scale = 2018 US dollars; right scale = percent)



Sources: EM-DAT; IMF, World Economic Outlook database; and IMF staff calculations.
Note: In panels 2–4, ratios are calculated based on nominal GDP in the start year of the disaster. In panel 4, conversion to 2018 US dollars is based on the US GDP deflator. AE = advanced economies; EMDE = emerging market and developing economies.

Large Climatic Disasters and Equity Returns

14. The reported damages reflect the loss of physical capital stock and do not capture the disasters' full impact on economic activity. Overall, large climatic disasters can significantly adversely impact GDP for several quarters, especially in low-income economies, as discussed in the recent literature (Felbermayr and Gröschl 2014).

15. The adverse impact of large climatic disasters on economic growth prompts the question: Do such events trigger a response in equity markets that could lead to financial stability concerns? The impact on equity prices can inform financial stability assessments for at least two reasons. First, large disasters could expose financial institutions to market risk if they lead to a large drop in equity prices because of a widespread destruction of firms' assets and productive capacity, or a drop-in demand for their products. To this end, the analysis focuses on aggregate stock market indices to understand the impact that disasters would have on diversified equity portfolios.[11] Second, the reaction of the stock prices of financial institutions provides a summary measure of the extent to which these institutions are affected by disasters. For banks, for example, disasters are a source of credit risk, market risk, operational risk, and liquidity risk. For insurers, disasters are a source of underwriting risk, market risk, credit risk, and operational risk (while they may also be an opportunity to increase underwriting volumes and premiums, as the demand for insurance is likely to rise following a disaster).

16. The analysis indicates that, on average, there has been only a modest response of stock prices to large climatic disasters. The cumulative average abnormal returns (defined as the actual returns minus the returns predicted by a pricing model with a global stock market factor, averaged over disasters) are about –1 percent from 21 trading days before the disaster (to incorporate possible anticipation effects) to 40 trading days after the disaster (Figure 5.4, panel 1). Results, however, vary considerably across the disasters. For example, Hurricane Katrina, which resulted in the largest damage in absolute constant US dollar terms in the sample (of about 1 percent of US GDP; nearly 2,000 lives lost; and half a million people affected), triggered only a modest stock market reaction, with no discernible drop in the US stock market index (Figure 5.4, panel 2). By contrast, the 2011 floods in Thailand, which resulted in the largest damage in the sample relative to the size of the economy (amounting to 10.1 percent of GDP; 813 deaths; and 9.5 million affected people), resulted in a drop in the Thai stock market index of more than 8 percent soon after the onset of the disaster, and a cumulative drop of about 30 percent after 40 trading days (Figure 5.4, panel 2).[12]

17. Among financial sector firms, large disasters have a statistically significant effect on the returns of non-life insurers in advanced economies: the cumulative average abnormal returns trend down for about 50 trading days after a large disaster and reach a trough of about –2 percent (Figure 5.4, panel 3). In emerging market and

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[11] Clearly the impact of disasters is highly firm-specific, as it depends on whether a firm's production facilities, suppliers' production facilities, or customers are significantly hit by the disaster (see Barrot and Sauvagnat 2016). Thus, a disaster may have significant consequences for firms listed in an economy where the disaster did not hit. It is also possible that some firms might benefit from the disaster, such as firms in the construction sector. By looking at the reaction of stock market indices the analysis intends to capture the systemic impact of disasters on equity prices.

[12] It is worth noting that the floods in Thailand caused repercussions not only for firms listed in Thailand, but also for foreign firms with supply chains depending on businesses located in the affected areas.

developing economies, however, there is no significant reaction of insurers' stock prices. What can explain these different outcomes? Such a difference could arise for several potential reasons, such as if a large share of insurance in emerging market and developing economies is provided by subsidiaries of insurers listed abroad; if insurers listed domestically do not or barely cover climatic disasters; or if they reinsure a large share of their exposures to climatic disasters. In fact, the stocks of global re-insurance companies react negatively in response to disasters happening in both advanced economies and emerging market and developing economies (Online Annex 5.2). For banks in both groups of economies, there is a small negative contemporaneous stock market reaction. Cumulative average abnormal returns of banks reach a trough of about –1.5 percent 25 trading days after the onset of a disaster (Figure 5.4, panel 4).[13, 14]

The Role of Insurance Penetration and Sovereign's Financial Strength in Cushioning the Equity Market Effects of Climatic Disasters

18. The United Nations' Sendai Framework for Disaster Risk Reduction emphasizes several economy-wide characteristics that matter for resilience in the face of disasters (UNDRR 2015).[15] The academic literature also finds that economy-level institutional strength and financial development level can help mitigate the impact of disasters on GDP growth (Melecky and Raddatz 2011; Felbermayr and Gröschl 2014; Hsian and Jina 2014).

19. This chapter focuses on the effect of two key economy-wide characteristics that can increase resilience: insurance penetration and sovereign's financial strength. Risk-sharing mechanisms offered by financial markets, such as insurance, weather derivatives, or catastrophe bonds reduce the losses incurred by nonfinancial sector firms (as well as some financial firms) in times of disasters, and thus can be expected to limit the impact on equity prices (see Online Box 5.1 for a discussion of catastrophe bonds).[16] Yet economies vary widely in insurance penetration, measured by the ratio of non-life insurance premiums to GDP, with the ratio ranging from 0 to 5 (Figure 5.5, panel 1). The variation in protection gap (share of uninsured losses) with respect to climatic disasters is also large, as shown in Figure 5.5, panel 2. Even in advanced economies, only two-thirds of losses related to climate disasters are covered by insurance. The sovereign's financial strength is also likely to matter as it affects both the ability of the government to respond to disasters through some financial relief and reconstruction efforts, as well as to offer some forms of explicit insurance schemes.

[13] Klomp (2014) finds that disasters have an adverse impact on bank soundness in emerging markets.

[14] US banks reported only $1.3 billion in loan impairment charges due to Hurricane Katrina and Hurricane Rita (Bauerlein 2005), while insured losses amounted to more than $50 billion.

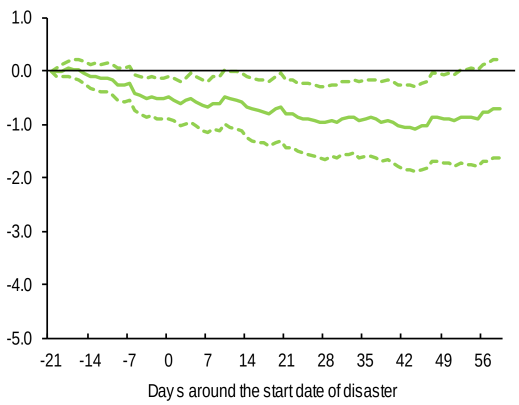
[15] The framework emphasizes: (1) understanding disaster risk; (2) strengthening disaster risk governance to manage disaster risk; (3) investing in disaster risk reduction for resilience; and (4) enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation, and reconstruction. https://www.undrr.org/implementing-sendai-framework/what-sf.

[16] Financial risk-sharing solutions have evolved in reaction to the occurrence of large disasters. For example, catastrophe bonds were created and first used in the aftermath of Hurricane Andrew in the mid-1990s. Hurricane Andrew also revealed that Florida's vulnerability to hurricanes had been seriously underestimated, leading to large changes in the US property insurance market and US insurers' risk management practices (McChristian 2012). Looking ahead, further financial developments along these lines could help to contain the macro-financial impact of disasters.

Figure 5.4. Equity Market Returns Immediately before and after Large Climatic Disasters

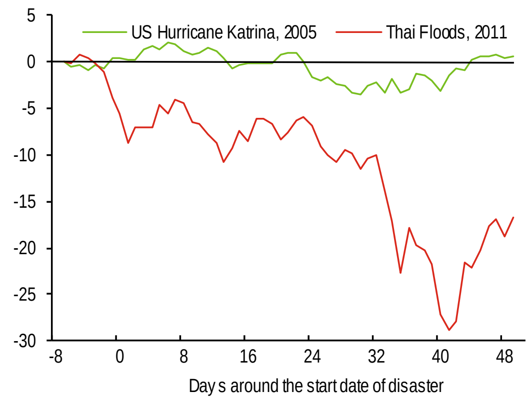
The impact of large climatic disasters on aggregate stock prices has been modest …

1. Sample Economies: Cumulative Average Abnormal Market Returns around Large Disasters, 90 Percent Confidence Interval
(Percent)



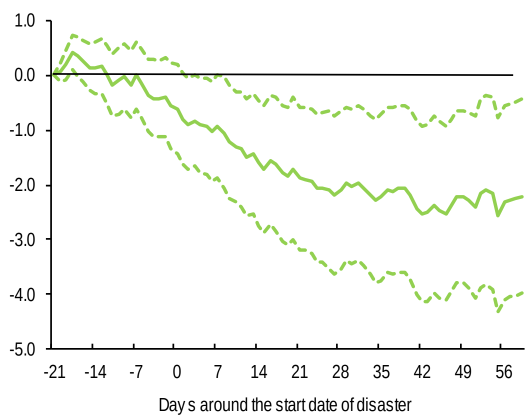
… but varied.

2. Cumulative Market Returns in the United States around Hurricane Katrina (2005) and in Thailand around the 2011 Thai Floods
(Percent)



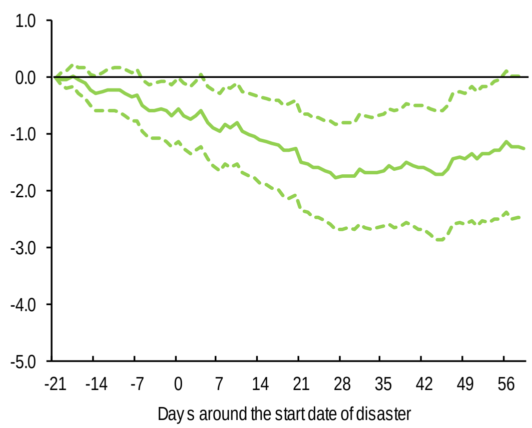
Following a disaster, stock prices of non-life insurers in advanced economies drop modestly …

3. Sample Advanced Economies, Non-Life Insurance Sector: Cumulative Average Abnormal Returns around Large Disasters, 90 Percent Confidence Interval
(Percent)



… as do stock prices of banks in both advanced economies and emerging market and developing economies.

4. Sample Economies, Banking Sector: Cumulative Average Abnormal Returns around Large Disasters, 90 Percent Confidence Interval
(Percent)

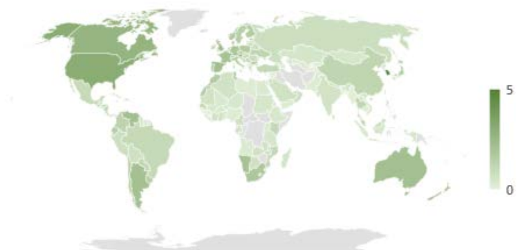


Sources: EM-DAT; Refinitiv Datastream; and IMF staff calculations.
Note: In panels 1, 3, and 4, all large disasters with a precise start date are included in the analysis. The x-axis represents trading days surrounding the events. Time 0 is the start day of the events. Cumulative average abnormal returns are relative to 21 trading days before the start day to incorporate any potential anticipation effects of disasters. Dashed lines represent the 90 percent confidence intervals. Abnormal returns are computed based on estimates from a one-factor model (global factor) using daily returns of the one year before the disaster. Panel 2 plots the cumulative returns of the aggregate stock market for the United States during the days before and after Hurricane Katrina in 2005 and for the floods in Thailand in 2011.

Figure 5.5. Insurance Penetration and the Protection Gap

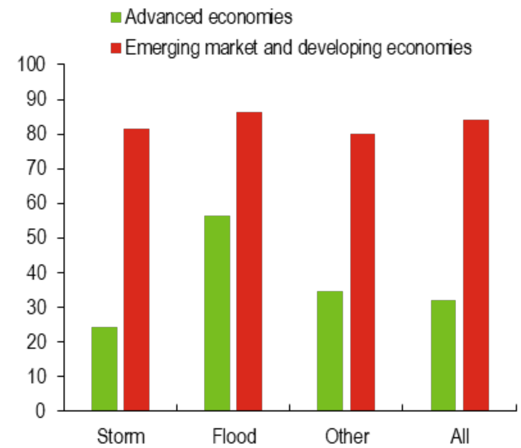
Non-life insurance penetration varies considerably across economies …

1. Insurance Penetration
(Non-life insurance premium, percent of GDP, 2017)



… and the protection gap for climatic disasters is large, particularly in emerging market and developing economies.

2. Protection Gap, 2009–18 Average
(Percent)



Sources: EM-DAT, World Bank, and IMF staff calculations.
Note: Insurance penetration is defined as the ratio of the non-life insurance premium volume to GDP. Protection gap is defined as the share of uninsured losses from disasters.

20. Consistent with such expectations, econometric analysis confirms that a higher rate of insurance penetration and greater sovereign financial strength (proxied by sovereign credit rating) dampen the impact of a large disaster on equity returns. Specifically, focusing on the impact of these two characteristics on cumulative abnormal returns 40 trading days after disaster onset for the aggregate stock market, as well as for the banking, non-life insurance, and industrial sectors, the results show a generally statistically significant association between greater insurance penetration and higher returns in the immediate aftermath of a disaster. Perhaps unsurprisingly, the effects are quantitatively larger and statistically stronger when looking at the left tail of the equity return distribution—that is on those disasters that had the largest negative impact on returns.[17] A 1 percentage point increase in non-life insurance penetration improves banking and industrial sector returns by about 1.5 percentage points on average. In the left tail—that is when returns are particularly low—the improvement is about 3–4 percentage points (Figure 5.6, panel 1). Similarly, sovereign financial strength has a positive and generally statistically significant impact on returns. A one-notch improvement in sovereign rating (on a scale from 1 to 21) boosts aggregate market returns by 0.2 percentage point, and banking and industrial sector returns by 0.3 percentage point on average. When returns are low, the improvement is about 0.6–1 percentage point for the aggregate market and these two sectors, and 1.6 percentage points for the non-life insurance sector (Figure 5.6, panel 2).[18] These effects are large relative to the size of cumulative average abnormal returns around disasters (between 1 percent and 2 percent, as discussed above).

[17]The analysis controls for the damage-to-GDP ratio.

[18]The correlation between insurance penetration and sovereign's financial strength is high. When the two characteristics are considered jointly in the analysis, the effect of the sovereign's financial strength appears more robust.

21. As mentioned in the introduction, climate scientists have warned that some climatic hazards will become more frequent and severe in the future (IPCC 2014). Even though much progress has been made toward a better understanding of these hazards, substantial uncertainties remain, especially over long-time horizons. The results presented in this section indicate that regardless of the size of future climatic shocks, insurance coverage and sovereign's financial strength will be key factors in maintaining financial stability.

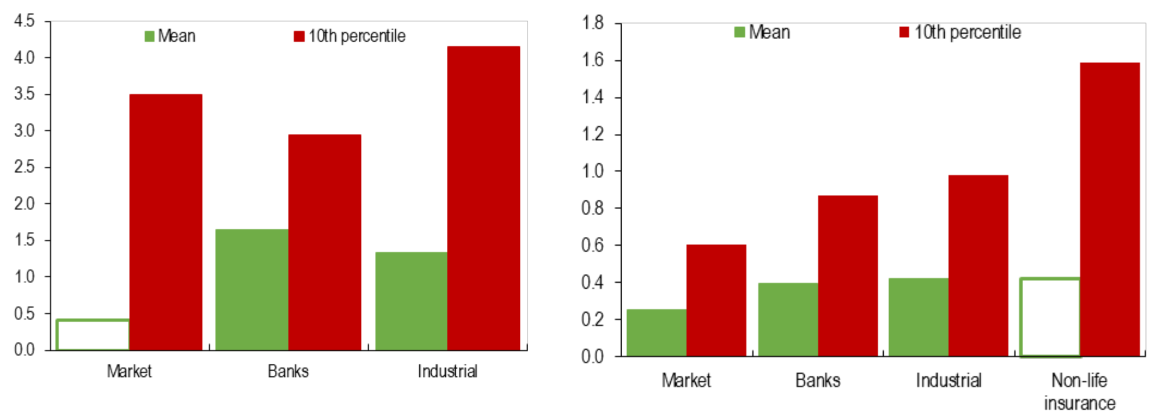
Figure 5.6. The Effect of Insurance Penetration and Sovereign Financial Strength on Equity Market Performance Immediately before and after Large Disasters

Greater insurance penetration cushions the negative impact of large disasters on equities and banks, especially when the impact is large …

… as does greater sovereign financial strength.

1. Effect of Greater Insurance Penetration on Cumulative Average Abnormal Market Returns
(Percentage points)

2. Effect of Sovereign Rating Upgrade on Cumulative Average Abnormal Market Returns
(Percentage points)



Sources: EM-DAT; Refinitiv Datastream; World Bank; and IMF staff estimates.
Note: Panel 1 shows the impact of increasing the non-life insurance-premium–to–GDP ratio by 1 percent on the cumulative average abnormal returns (CAAR) (mean and 10th percentile of the distribution) 40 trading days after large climatic disasters relative to 20 trading days before disasters. Panel 2 shows the impact of increasing sovereign rating by one notch (on a scale of 1 to 21) on the cumulative abnormal returns (mean and 10th percentile) 40 trading days after large climatic disasters relative to 20 trading days before disasters. CAARs are computed at the sector level based on a single global factor model using daily returns in the year proceeding each disaster. In both panels, solid bars indicate significance at the 10 percent level or less.

Equity Pricing of Future Climate Change Physical Risk

22. With climate change predicted to increase physical risk, financial market participants appear to have started to place a greater focus on physical risk as a potential source of financial vulnerability (BlackRock 2019; Institute of International Finance 2019; Moody's Analytics 2019; McKinsey 2020). Still, only a very small proportion of global stocks are held by sustainable funds (Figure 5.7), which are likely to pay greater attention to climate risk and tend to have a more long-term view.[19] A 2018 survey of institutional investors found that beliefs in the lack of financial materiality of physical risk were more pronounced among short- and medium-

[19]There is no single definition of what constitutes a sustainable fund. This chapter relies on the Morningstar classification of sustainable funds.

term investors, while investors with a larger share of sustainable funds ranked climate risk higher in terms of its overall relevance for performance (Krueger, Sautner, and Starks 2019).

23. Equity investors face a daunting informational challenge in pricing the anticipated increase in physical risk into equity portfolios. Based on climate science, expected climate change mitigation policies, and adaptation actions, they need to form views on the likelihood of various climate scenarios and their implications for physical risk across the world.[20] For each firm, they then need to form a granular view on the future location of its production sites, supply chain and suppliers' location, and geographical distribution of customers, under these climate risk scenarios. In addition, even if investors had the ability to correctly price the change in physical risk, the time horizon over which this change is likely to unfold may be longer than the investment horizon of most investors, including institutional investors.

Figure 5.7. Growth in the Sustainable Equity Fund Market

The share of assets under management by sustainable equity funds relative to the overall market capitalization has been increasing but remains small.

Ratio of Total Global Assets Held by Sustainable Equity Funds to Total Global Stock Market Capitalization
(Percent)

Sources: Morningstar; Refinitiv Datastream; and IMF staff calculations.
Note: The figure shows global assets under management by sustainable funds as classified by Morningstar.

24. To test whether climate change is a risk factor priced into equities, the standard empirical asset pricing approach would require a time-varying measure of future physical risk. Given the difficulties in precisely measuring future physical risk—after all, even insurance companies rarely offer contracts over multiple years, and catastrophe bonds have a maximum maturity of only five years—and the scarcity of firm disclosures

[20]Barnett, Brock, and Hansen (2020) distinguish among three forms of uncertainty: (1) risk—what probabilities does a specific model assign to events in the future? (2) ambiguity—how much confidence to place in each model? and (3) misspecification—how to use models that are not perfect?

regarding their exposure to physical risk (both present and future), it is hardly surprising that empirical evidence on whether the valuation of equities (or other types of financial assets) today reflects future physical risk is scant.

25. An alternative, albeit more complicated, approach would be to develop a comprehensive asset pricing model that takes into account the projected impact of climate change on each economy, and compare the model-implied equity risk premium—defined as the financial compensation above the risk-free rate an equity investor should require to hold equity risk—with the market implied equity risk premium.[21] A stylized version of such a model is presented in Online Box 5.2. It suggests that market-implied equity risk premiums as observed in 2019 are in line with those obtained in a scenario with no further warming (possibly implying that climate risk is not being factored in). Moreover, it shows that the premiums in a no-further-warming scenario are significantly smaller than those obtained under a high-warming scenario, suggesting that equity valuations should be lower in case the high-warming scenario were to materialize.

26. In the absence of granular firm-level information and time-varying measures of future physical risk, the approach here is to use simple cross-country econometric analysis to determine whether aggregate equity valuations as of 2019—captured by the price-to-earnings ratio of the stock market index—are sensitive to current proxies for future changes in physical risk under various climate change scenarios.[22] All else equal, economies where these changes are predicted to be smaller would be expected to have higher valuations if future physical risk were financially material and markets were pricing it correctly.[23]

27. To conduct the analysis, economy-specific projections of hazard occurrence from the World Bank Climate Change Knowledge Portal are used. These projections, each corresponding to the change between 1986–2005 and 2020–39, cover the number of extreme heat days, drought likelihood, heat wave likelihood, and the number of extreme precipitation days. Each projection is available for the four emission scenarios presented by the Intergovernmental Panel on Climate Change (labeled RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, where a higher number is associated with a higher level of emissions over multiple time horizons). In addition, measures of projected sea level rise by 2100, and a Climate Change Hazard Index capturing several climate hazards, both current and future (under RCP 8.5), are used.[24]

28. Overall, there is no evidence to suggest that equity valuations in 2019 were negatively associated with these projected changes in hazard occurrence.[25] This can be seen in a simple scatter plot of the composite Climate Change Hazard Index and price-to-earnings ratios (Figure 5.8, panel 1) as well as the association between predicted changes in hazard occurrence and price-to-earnings ratios based on econometric analysis. The association is in fact positive—the opposite of what would be expected were hazards priced into equity

[21]Asset pricing models that incorporate climate-related disasters imply risk premiums that are positive and increasing over time due to climate change (Bansal, Kiku, and Ochoa 2019; Karydas and Xepapadeas 2019).

[22]Findings are similar when equity valuations are measured by price-to-book ratios or dividend yields.

[23]The econometric analysis always controls for three financial variables: mean annual growth rate of earnings per share; standard deviation of annual growth of earnings per share; and the three-month Treasury bill rate.

[24]The Climate Change Hazard Index assesses the degree to which economies are exposed to the physical impacts of climate extremes and future changes in climate over the next three decades. The Climate Change Physical Risk Index captures not only hazard risk, but also exposure and vulnerability.

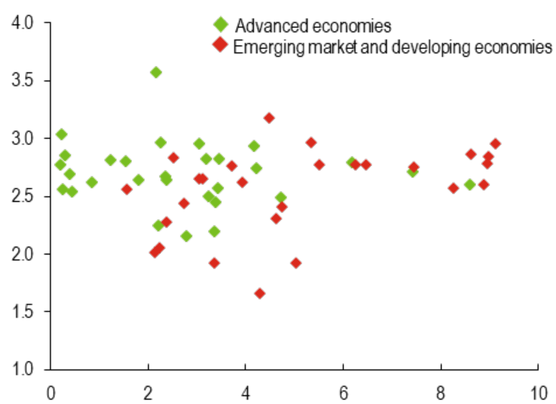
[25]See Online Annex 5.3 for a description of the econometric methodology and additional robustness tests.

valuations—across five of the six types of hazard measures, regardless of the climate change scenario considered (Figure 5.8, panel 2). The association is negative only for the change in drought likelihood but is not statistically significant.

Figure 5.8. Climate Change Physical Risk and Equity Valuations

There is no association between measures of predicted changes in climatic hazard occurrence and equity valuations …

1. Price-to-Earnings Ratio (y-axis) and Climate Change Hazard Index (x-axis).



… even when controlling for fundamentals.

2. Sign of Coefficients from Regressions of Price-to-Earnings Ratio on Indicators of Predicted Changes in Climatic Hazard Occurrence (Various climate change scenarios)

Sign consistent with the pricing of climate change physical risk but the coefficient is not statistically significant

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Δ Extreme Heat Exposure	+	+	+	+
Δ Extreme Precipitations	+	+	+	+
Δ Drought Likelihood	-	-	-	-
Δ Heat Wave Likelihood	+	+	+	+
Sea Level Rise Index				+
Climate Change Hazard Index				+

A greater projected increase in hazard risk combined with a greater sensitivity to climate change is not associated with lower valuations …

3. Sign of Coefficients from Regressions of Price-to-Earnings Ratio on the Interaction Term between Predicted Changes in Climatic Hazard Occurrence and Climate Change Sensitivity Index (Various climate change scenarios)

Sign consistent with the pricing of climate change physical risk but the coefficient is not statistically significant

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Δ Extreme Heat Exposure X Climate Change Sensitivity	-	-	-	+
Δ Extreme Precipitations X Climate Change Sensitivity	+	-	-	-
Δ Drought Likelihood X Climate Change Sensitivity	+	+	-	+
Δ Heat Wave Likelihood X Climate Change Sensitivity	+	+	+	+
Sea Level Rise Index X Climate Change Sensitivity				-
Climate Change Hazard Index X Climate Change Sensitivity				+

… neither is a greater projected increase in hazard risk combined with a lower capacity to adapt to climate change.

4. Sign of Coefficients from Regressions of Price-to-Earnings Ratio on the Interaction Term between Predicted Changes in Climatic Hazard Occurrence and Climate Change Adaptive Capacity Index (Various climate change scenarios)

Sign consistent with the pricing of climate change physical risk but the coefficient is not statistically significant

	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Δ Extreme Heat Exposure X Adaptive Capacity	+	-	-	-
Δ Extreme Precipitations X Adaptive Capacity	-	-	+	-
Δ Drought Likelihood X Adaptive Capacity	+	-	-	+
Δ Heat Wave Likelihood X Adaptive Capacity	-	-	-	-
Sea Level Rise Index X Adaptive Capacity				+
Climate Change Hazard Index X Adaptive Capacity				-

Sources: Verisk Maplecroft; The World Bank Group, Climate Change Knowledge Portal; and IMF staff calculations.
Note: In panel 1, the index ranges from 0 to 10. Panels 2–4 show the coefficients from cross-sectional regressions of price-to-earnings ratio on climate change physical risk indicators. Each regression controls for expected future earnings, the equity risk premium, and interest rates. Representative Concentration Pathways (RCP) 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 are International Panel on Climate Change (IPCC) emission scenarios, where a higher number is associated with a higher level of emissions. Extreme heat exposure, extreme precipitation, drought likelihood, and heat wave likelihood are projections for the horizon 2020–39. The sea level rise index is based on projections for the year 2100 under RCP 8.5. The Climate Change Hazard Index is based on projections up to 2050 under RCP 8.5. None of the coefficients in panels 2–4 is significant and has a sign consistent with pricing of climate change physical risk.

29. However, looking simply at predicted changes in hazard occurrence may be misleading. As explained, physical risk is the result of an interaction among climatic hazard, exposure, and vulnerability. To proxy for the combination of exposure and vulnerability, the analysis relies on two readily available indicators: a Climate Change Sensitivity Index and a Climate Change Adaptive Capacity Index.[26] A higher value of the Sensitivity Index would be expected to amplify the adverse effects of climatic hazards, resulting in greater physical risk, while a higher value of the Adaptive Capacity Index would be expected to dampen them, resulting in lower physical risk. If equity valuations were responsive to predicted changes in physical risk, one would expect to find a negative association between valuations and the interaction between hazards and the Sensitivity Index, and a positive association between valuations and the interaction between hazards and the Adaptive Capacity Index. No such associations are found when conducting a similar econometric exercise as above—reinforcing the earlier results that climate change physical risk are not being factored into equity valuations. For the Sensitivity Index, the association is generally positive, and is not statistically significant when it is negative (Figure 5.8, panel 3). The opposite is true for the Adaptive Capacity Index, regardless of the climate change scenario envisaged (Figure 5.8, panel 4).

30. There is a further twist. The preceding analysis of the reaction of equity prices to large climatic disasters concludes that insurance penetration and sovereign financial strength cushion equity markets from the adverse effects of disasters. This suggests that the analysis of equity valuations as of 2019 should consider these two characteristics. Yet, results are equally inconclusive when the exercise is augmented with an interaction between proxies of changes in physical risks and any of the two characteristics.

31. Overall, notwithstanding data and measurement limitations, the evidence in this section does not indicate that equity investors are pricing climate change physical risk.[27] By contrast, there is some evidence for the pricing of climate change physical risk in other asset classes. In the United States, counties projected to be adversely affected by rising sea level face higher costs when issuing long-term municipal bonds (Painter 2020). Similarly, Online Box 5.3 documents that sovereigns facing a greater projected change in physical risk—at least for some available proxies—pay higher spreads for long-term bonds relative to short-term bonds, all else equal.[28] One reason for this apparent difference in pricing of climate change risk between equity and bond investors might be that there is a closer geographical match between the climatic disasters and issuers' assets and sources of income in the case of sovereigns than in the case of listed firms, reducing the informational challenge that investors face.[29] Investors' investment horizon may play a role as well. Another reason could be that equity investors expect governments to bear a greater share of the costs of future climatic disasters than

[26]The Climate Change Sensitivity Index assesses the human population's susceptibility to the impacts of extreme climate-related events and projected climate change. The Climate Change Adaptive Capacity Index assesses the current ability of a country's institutions, economy, and society to adjust to, or take advantage of, existing or anticipated stresses resulting from climate change. See Online Annex 5.1 for details.

[27]It may be that climate change physical risk is heavily discounted by equity investors because of its long-term nature. Bolton and Kacperczyk (2019) provide evidence that equity investors demand a premium for transition risk, elements of which are arguably easier to model, and which could materialize at a shorter horizon than physical risk.

[28]There is no consensus in the literature on whether real estate markets price climate change physical risk. Bernstein, Gustafson, and Lewis (2019) and Baldauf, Garlappi, and Yannelis (2020) find that coastal homes vulnerable to sea level rise are priced at a discount relative to similar homes at higher elevations, but Murfin and Spiegel (2020) find no such effect.

[29] Firms' location of listing, production facilities, customers, and supply chains can be in multiple economies.

listed firms. In addition, it remains a possibility that long-term government bond investors discount less and pay more attention to long-term risks than equity investors.

Equity Investors' Attention to the Effect of Temperature on Pricing

32. Another, more indirect, way to assess whether equity investors have been paying attention to climate change is to focus the analysis on temperature, a climate variable that is observable at high frequency and does not suffer from the same measurement challenges as climate change variables. This section builds on Kumar, Xin, and Zhang (2019), which documents a temperature-related pricing anomaly by showing that returns of a portfolio of US firms with a high sensitivity to temperature underperform relative to other stocks, after controlling for standard equity pricing factors. The discussion here extends that study's analysis to a sample of 27 economies over 1998–2017.[30] A firm's temperature sensitivity is defined as the absolute value of the "temperature beta," which captures how firms' stock return comoves with temperature extremes.[31] A finding that these risk-adjusted returns are different from zero—in other words that a portfolio of firms with high temperature sensitivities would generate returns that cannot be explained by a standard asset pricing model—can be interpreted as a violation of the efficient market hypothesis.

33. The analysis not only confirms the findings in Kumar Xin, and Zhang (2019) for the United States, but also documents a similar temperature-related pricing anomaly in more than half of the economies considered (Figure 5.9). In 10 of the economies, a portfolio composed of the top 20 percent of stocks most sensitive to temperature underperformed by at least 0.5 percent a month, on average, over the sample period, controlling for standard risk factors. The presence of such a pricing anomaly indicates that equity investors in most economies have not paid enough attention to climate variables and suggests that they may not be paying sufficient attention to climate change risk either.[32]

[30]The multifactor equity pricing model is known as the Fama-French three-factor model. See Online Annex 5.4 for methodological details.

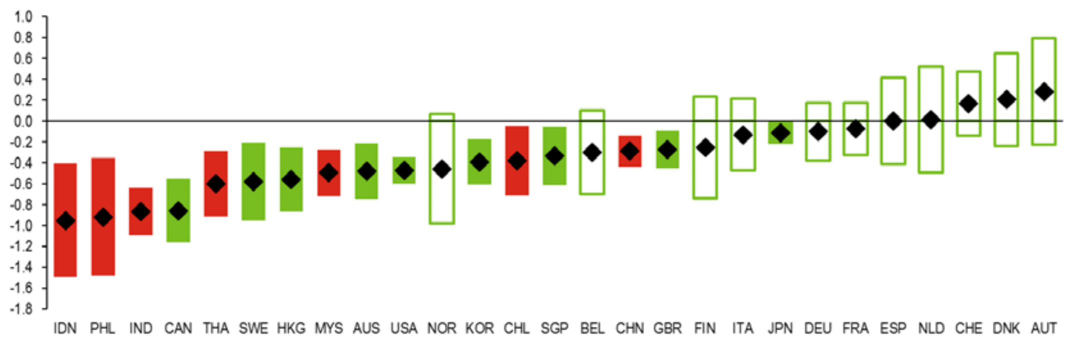
[31]More specifically, the analysis measures the co-movement with the so-called temperature anomaly, defined as the difference between the temperature in a given month and the average temperature over the past 30 years in the same month. By taking the absolute value, the pricing of firms with both high and low sensitivities is considered. The sensitivity is measured over rolling windows of 60 months.

[32]The chapter's finding echoes that of Hong, Li, and Xu (2019), which documents that global stock markets underprice drought risk in the food sector. Bansal, Kiku, and Ochoa (2019), however argues that there is a pricing factor related to temperature that is priced.

Figure 5.9. Equities' Temperature Sensitivity

In many economies, stocks with the highest sensitivity to temperature earn lower returns than the others, after controlling for standard risk factors, suggesting mispricing and lack of attention to temperature-related variables.

Abnormal Equity Returns of Firms with the Highest Sensitivity to Temperature
(Percent, 1998–2007)



Sources: Refinitiv Datastream; and IMF staff calculations.
Note: Black diamonds show the difference in stock return performance between firms with high temperature sensitivity (top quintile) and all other firms. Red (emerging market and developing economies) and green (advanced economies) bars show the 90 percent confidence intervals of the differences. Solid bars indicate significance at the 10 percent level or less. Data labels use International Organization for Standardization (ISO) country codes. See Online Annex 5.4 for a definition of temperature sensitivity.

Conclusion and Policy Recommendations

34. Climate change is a source of physical and transition risks for the financial sector and could have significant implications for financial stability. Pricing the impact of future climatic hazards into asset prices is a challenging task because it requires an understanding of the future behavior of climatic and nonclimatic variables, which are both subject to a large degree of uncertainty. Focusing on climate change physical risk, the analysis and evidence provided in this chapter suggest that the aggregate equity valuations as of 2019 did not reflect this risk; thus, equity investors may be paying insufficient attention to climate variables.

35. The chapter documents that the reaction of equity prices to large climatic disasters has been modest over the past 50 years. However, country characteristics matter. Insurance penetration and sovereign financial strength can lessen the impact of climatic disasters on equity prices, including of the financial sector. These findings imply that, regardless of the magnitude of future climatic hazards, financial stability will be better preserved in economies that score well along these dimensions:[33]

- Non-life insurance is a source of financial resilience because it increases the economies' ability to recover from disasters. Yet the protection gap (the share of uninsured losses) remains significant, especially in emerging market and developing economies. For private insurance markets to thrive, a sound legal and regulatory system is essential. Policymakers may also consider mandating coverage for climatic disaster risks for some assets (such as those used as loan collateral), subsidizing climatic disaster insurance, or enabling insurer-of-last-resort solutions where economic agents find it challenging to become insured. Awareness of the benefits of insurance could be encouraged by increasing financial and risk literacy. Other

[33] These findings are consistent with those of IMF (2019a), which discusses physical and financial resilience in developing economies vulnerable to large natural disasters.

protection gap challenges related to lack of information and expertise in modelling underinsured areas or types of risk can be addressed through the establishment of risk-sharing arrangements between the public and private sectors, such as Protection Gap Entities.[34]

- The sovereign's financial strength allows it to respond forcefully to disasters and reduce the economic and financial impact of the shock. Building fiscal buffers, establishing contingent lines of credit, and developing a sound public financial management system are important in this regard. State contingent debt instruments can also be useful to allow for greater policy flexibility in bad times (IMF 2017).

36. To help the public, including market participants, better understand future physical risk, policymakers should consider strengthening climate change literacy by enhancing the visibility of relevant findings in climate science, climate economics, and climate finance.

37. Granular, firm-specific information on current and future exposure and vulnerability to climate change physical risk would help lenders, insurers, and investors to better grasp these risks. An increasing number of firms have begun to voluntarily disclose climate change risk information, in line with the recommendations set out by the Taskforce on Climate-related Financial Disclosures (TCFD). However, going further by developing global mandatory disclosures on climate change risk would be an important step to sustain financial stability. In the short term, mandatory climate change risk disclosure could be based on globally agreed principles. In the longer term, climate change risk disclosure standards could be incorporated into financial statements compliant with International Financial Reporting Standards.

38. It would be useful for these standards and disclosures to be anchored in proper measurement of financial exposure to climate risk and to be based on adequate taxonomies. For financial firms, climate change stress testing, and scenario analysis more broadly, can play a potentially important role in providing a better sense of the size of the exposures at a highly granular level.

39. Although not explicitly analyzed in the chapter, adaptation and risk reduction measures that decrease (or at least limit) the exposures and vulnerabilities of economies to climate hazards are highly desirable. These include the enhancement of early warning systems and the management of population density in areas at risk, as well as the implementation of regulation (such as land-use regulation) and investment in infrastructure that help boost physical resilience, such as through "build back better" programs.[35]

40. Of course, strong policy actions to mitigate climate change would reduce greenhouse gas emissions and future physical risk in the first place, conferring benefits to mankind that extend well beyond the realm of financial stability. Yet, from a financial stability perspective, this transition to a lower-carbon economy needs to be carefully managed to avoid an abrupt and unanticipated re-pricing of portfolios, and economic dislocation.[36] These issues will be explored further in future issues of the *Global Financial Stability Report*.

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[34]See the discussion in Jarzabkowski and others (2019).

[35]A recent report finds that a global $1.8 trillion investment in adaptation measures over the next decade could generate $7.1 trillion in total net benefits (Global Commission on Adaptation 2019).

[36]The benefits of gradual but ambitious, clear, and predictable mitigation policies for the transition path are discussed in the October 2019 *Fiscal Monitor*. Krogstrup and Oman (2019) provides an overview of available policy tools.

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Box 5.1. Stress Testing for Physical Risk in the Financial Sector Assessment Program

The IMF pioneered the use of stress tests for assessing financial stability in the Financial Sector Assessment Program (FSAP) 20 years ago. Every year, under the FSAP, the IMF carries out in-depth financial stability assessments for 12–14 economies. Stress testing using confidential supervisory data is a cornerstone of the FSAP's risk analysis. The tests capture physical risks related to climatic disasters, such as storms, floods, and droughts, whenever relevant. Over the past decade, one in five FSAPs contained an examination of such risks. Most related to small island states and other economies prone to climatic disasters with economy-wide impacts, but FSAPs for advanced economies with systemically important financial sectors (such as France, Sweden, and the United States) also covered physical risks in insurance stress testing.

The 2019 FSAP for The Bahamas provides an example of a stress test that incorporates a climatic disaster. The country was hit by 11 hurricanes with average costs of 4.3 percent of GDP in the 20 years before the FSAP. The analysis examined the effects of hurricanes on tourism, employment, and financial sector assets, showing how more frequent and more severe hurricanes amplify risks to economic growth. Domestic banks typically required catastrophic risk insurance, and domestic insurance companies reinsured abroad—so growth and employment were the main channels of hurricanes' impact on the financial system. Banks' direct credit exposures to tourism were small, mitigating the risk of large business loan losses, though hotel and infrastructure damage could lead to unemployment and bank losses on mortgages and consumer loans. A key finding was that the financial stability effects of hurricanes were nonlinear and dependent on the broader macroeconomic context: a US recession combined with a hurricane would significantly amplify macrofinancial losses. Three months after the FSAP concluded, The Bahamas were hit by Hurricane Dorian, the worst climatic disaster in the country's history. The financial sector appears to have weathered the hurricane well, thanks to limited exposures to uninsured assets and adequate reinsurance of domestic insurance companies abroad. At the same time, insurance penetration, especially in the residential segment, remains low, leaving many homeowners in dire straits. The IMF therefore suggested new approaches to extend insurance coverage as part of a broader disaster risk management strategy.

Stress tests for climate-related risks are evolving. The FSAP has already been moving from narrow exercises concentrating on non-life insurance to stress tests that incorporate broader macrofinancial feedback effects. While the focus so far has been on "acute" manifestations of physical risk, future assessments may also consider stability implications of slow-moving consequences of climate change, such as migrations due to water shortages and crop failures. Forthcoming FSAPs that are expected to consider physical risk are, for example, those for the Philippines and South Africa.

Ongoing assessments, such as the FSAP for Norway, have started, on a pilot basis, examining consequences of changes in public policy and technology related to the transition to a low-carbon economy. These transition risks are potentially relevant for all economies, with many country authorities recognizing that the transition may not be smooth, and that changes in policies and technology may lead to abrupt changes in asset valuations. Leverage and interconnectedness in the financial system could exacerbate these shocks.

IMF staff has engaged with the World Bank, central banks, and other stakeholders on these issues. In emerging market and developing economies, the IMF carries out FSAP assessments jointly with the World Bank. The joint work provides an opportunity to leverage the World Bank's expertise in financial sector development, catastrophe risk modeling, and sustainable finance.

This box was prepared by Martin Čihák.

APRIL 2020—GLOBAL FINANCIAL STABILITY REPORT

PHYSICAL RISK AND EQUITY PRICES—ONLINE BOXES 5.1–5.3

The following three Online Boxes provide additional analyses that complement Chapter 5 of the April 2020 Global Financial Stability Report:

- **Online Box 5.1. Insuring against Climate Change Physical Risk: The Role of Catastrophe Bond Markets**

  CAT bonds are an important risk sharing mechanism for issuers such as insurers or sovereigns. Online Box 5.1 describes the development of the market for CAT bonds over the past two decades.

- **Online Box 5.2. Assessing the Impact of Climate Change Physical Risk on the Equity Risk Premium with a Long-Run Risk Model**

  Online Box 5.2 complements the analysis of the chapter by comparing the equity risk premiums implied by a stylized asset pricing model (that takes climate change physical risk into account) with the market implied equity risk premiums.

- **Online Box 5.3. The Pricing of Climate Change Physical Risk into Sovereign Bonds**

  While the Chapter does not find evidence for climate change physical risk being priced in equities, it may be priced in other asset classes. Online Box 5.3 looks at the sensitivity of sovereign bond issuance costs to climate change physical risk by comparing long- and short-term sovereign bond spreads at the time of issuance.

Online Box 5.1. Insuring against Climate Change Physical Risk: The Role of Catastrophe Bond Markets

Catastrophe (CAT) bonds are specialized securities that allow issuers to transfer natural disaster risk to capital markets. They are usually short- to medium-term, high-yield instruments with low turnover, issued primarily by insurance and reinsurance companies. CAT bonds come with specified triggers attached to them, most often related to the size of insurance claims following a particular natural disaster. If the bond is triggered, the principal is either partially or fully forgiven. Demand for CAT bonds has increased over the past 10 years, driven by the search for high-yield assets uncorrelated with other types of financial risk.[1] CAT bonds are a major component of so-called "alternative reinsurance capital," which accounted for 16 percent of the total amount insured by global reinsurance capital in 2019 (Aon 2019).

The most important single peril covered by CAT bonds is hurricanes and other storms (such as cyclones, typhoons, and windstorms), followed by earthquakes (Online Box Figure 5.1.1, panel 1). More than one-quarter of CAT bonds insure against multiple perils, most of which also cover hurricane risk. By volume, almost 75 percent of CAT bonds issued between 2009 and 2018 were exposed to hurricane risk.

The CAT bond market has grown from an annual issuance of about $3 billion in 2008 to a peak of nearly $12 billion in March 2018 (Online Box Figure 5.1.1, panel 2). As of February 2020, more than $41 billion in CAT bonds were outstanding (Artemis 2020). Most CAT bonds offer only short-term protection from catastrophe risks, with maturities between two to four years (Online Box Figure 5.1.1, panel 3). Consistent with search-for-yield behavior, CAT bond primary market spreads have been declining since the global financial crisis, even though the expected losses from CAT bonds have been increasing on average over the past 20 years (Online Box Figure 5.1.1, panel 4).

In light of increasing uncertainty due to climate change, investors might demand a greater risk premium for taking on exposure to climatic disasters relative to other forms of disasters. Regression analysis shows that in a sample of 656 CAT bonds, controlling for expected losses and other factors, exposure to hurricane disasters was associated with around a 90 basis points higher premium on average, relative to CAT bonds with no exposure to hurricanes.[2] Part of this premium might be due to additional uncertainty about future climatic conditions.[3] Going forward, understanding the way climate change affects the pricing of CAT bonds will be crucial for the market to grow.

Given the high costs of insuring against natural disasters, and particularly disasters related to climate change, greater use of CAT bonds could benefit the most vulnerable countries. In developing countries, where the protection gap is largest and a substantial fraction of the population and economy is exposed to climatic disaster risk, government insurance could help reduce this gap (Cebatori and Youseff 2020). CAT bonds can offer an effective avenue for sovereigns to insure against disasters, as seen in the case of Colombia, Chile, and Peru, which issued sovereign CAT bonds equivalent to $1.1 billion in 2018 alone.

This box was prepared by Manuel Perez Archila in collaboration with Alan Feng and Peter Windsor.

[1] CAT funds and institutional investors now comprise 75 percent of total buyers in the CAT bond market (Aon 2019).

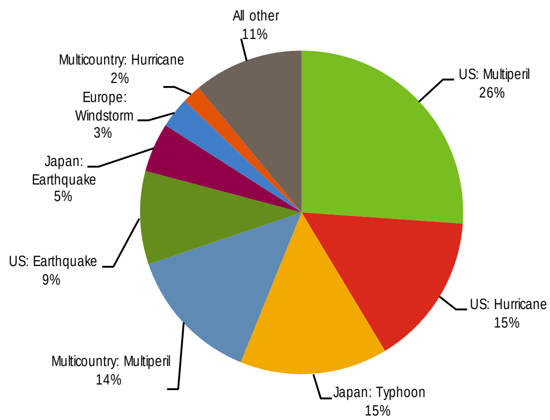
[2] The literature also finds that premiums increase in the immediate aftermath of natural disasters, even though the magnitude of this effect has decreased over time (Froot and O'Connell 1999; Tomunen 2019). A recent study points toward market segmentation and the relatively limited availability of capital in the market as a driver of premiums (Tomunen 2019).

[3] See Online Annex 5.5 for a detailed description of the empirical methodology.

Online Box Figure 5.1.1. Developments in the Global Catastrophe Bond Market

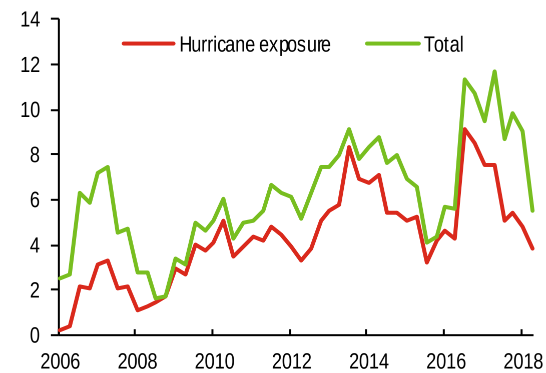
A large proportion of CAT bonds cover hurricanes and other storms

1. CAT Bond Exposure
(Percent of volume issued, 2009–18)



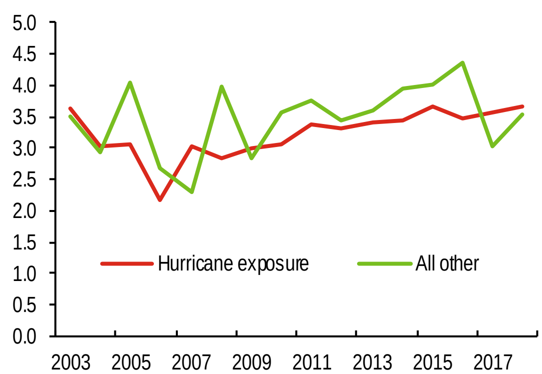
Issuance of CAT bonds has grown since the mid-2000s…

2. CAT Bond Annual Issuance Volume
(Billions of US dollars, past 12 months, 2006–18)



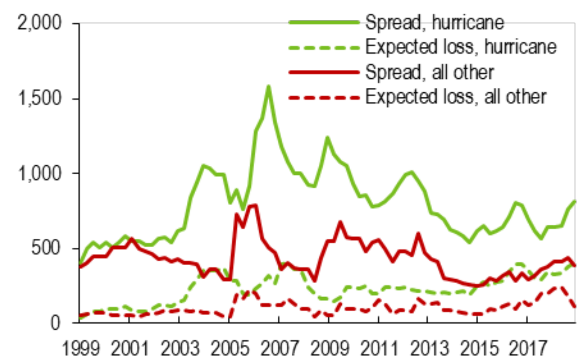
…but most CAT bonds offer only short-to-medium term protection from catastrophe risks

3. CAT Bond Maturity at Issuance
(Years, annual average, 2003–17)



While expected losses have been increasing, spreads have been declining since the global financial crisis.

4. CAT Bond Expected Loss and Spreads
(Basis points, four-quarter rolling average, 1999–2017)



Sources: Refinitiv Datastream; Dealogic; Artemis Deal Directory; Lane Financial; Bloomberg L.P.; Tomunen (2019); and IMF staff calculations.
Note: Panel 1 shows the percent of the volume of CAT bonds issued between 2009 and 2018 with the peril that triggers them. Multicountry bonds are exposed to risks from multiple countries, while multiperil bonds are triggered by multiple catastrophes. In panel 2, the volume of issuance is computed at the end of each quarter as the sum of the face value of all the tranches issued in the previous 12 months. Hurricane exposure bonds include all bonds that are triggered by hurricanes, windstorms, cyclones, or typhoons, although they might also protect against additional perils (multiperil bonds). In panel 3, the maturity is computed by taking the average of the difference in years between the maturity date and the issuance date for all bonds issued in the previous four quarters. "All other" refers to all bonds that are not exposed to any hurricane risk (including the risks of windstorms, cyclones, or typhoons). In panel 4, the expected loss from each bond is taken from a forecasting model and should be interpreted as the annualized expected loss expressed as a fraction of the bond's face value.

Online Box 5.2. Assessing the Impact of Climate Change Physical Risk on the Equity Risk Premium with a Long-Run Risk Model

As large climatic disasters adversely affect the economy and increase market tail risks, a future rise in the frequency and severity of such events should be reflected in equity valuations. Building on a stylized macrofinancial model with long-run risks (LRR), this box illustrates how future climatic disasters can affect the equity risk premium (ERP): that is, the return over the risk-free rate equity investors require for holding equity risk.

In the standard LRR model, time-varying uncertainty about long-run growth is a key factor driving equity prices.[1] To account for the potentially severe consequences of climate change, the model used in this box further incorporates temperature-induced climatic disasters. The model is calibrated using consumption, equity prices, and market dividends data, discount rates found in the literature, a future temperature scenario running until 2100, and a reduced-form mapping between temperature and disasters.[2] Based on data for the United States, a version of the model is estimated for each of four temperature scenarios. The four model-generated equity risk premiums are then compared to one another.

The four scenarios are the following: [3]

- A no warming scenario, in which climatic disasters remain at their current level.
- A low warming scenario corresponding to the RCP 2.6 scenario, in which climate change mitigation actions are implemented forcefully.
- A medium warming scenario corresponding to the RCP 6.0 scenario, in which some climate change mitigation actions are undertaken but emissions rise quickly up to 2060.
- A high warming scenario corresponding to the RCP 8.5 scenario, in which no mitigation action is implemented (see the Online Annex 5.1 for a description of the RCP scenarios).

Model simulations, based on mean temperature projections, deliver ERPs of 5.9 percent, 8 percent, and 11.6 percent, and 13.4 percent respectively, suggesting that a scenario with no mitigation would result in much higher risks for equity investors (Online Box Figure 5.2.1, panel 1).

Based on a similar model for a representative advanced economy, the climate-augmented ERP is then constructed for a sample of advanced economies. When comparing ERPs across economies the risk premiums in the high warming scenario are consistently higher than the current market implied risk premiums with no apparent relationship between the two—suggesting that equity markets may not currently price climate change risk (Online Box Figure 5.3.1, panel 2). Under the high future warming scenario, the model delivers equity risk premiums that are on average more than twice as large as what they are under the no warming scenario.

Overall, the analysis highlights that climatic disasters could be a key source of long-run economic risks and underscores the importance of timely policy action to mitigate climate change and avoid possible market dislocations.

This box was prepared by Andrea Deghi.

[1] See Bansal and Yaron (2004); Bansal and others (2016); and Beeler and Campbell (2012).

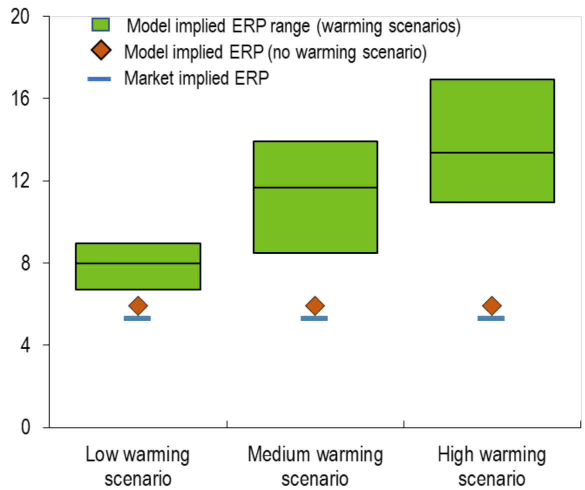
[2] Details on the estimation and calibration are provided in Online Annex 5.6.

[3] See Online Annex Table 5.1.3 for the temperature projections under the different Representative Concentration Pathways (RCPs).

Online Box Figure 5.2.1. The Effect of Climate Change Physical Risk on the Equity Risk Premium

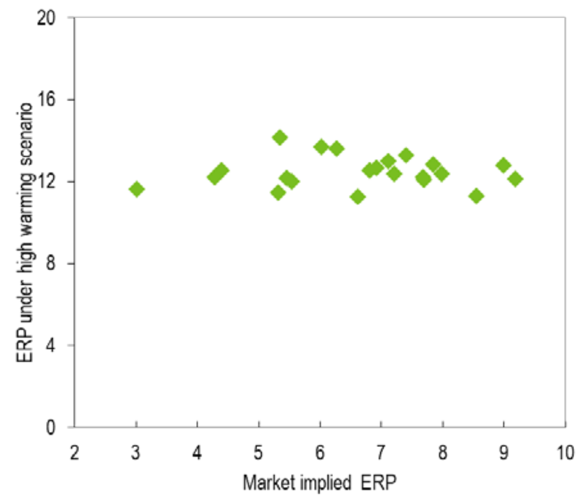
A climate change scenario with no mitigation would result in much higher risk for equity investors in the United States…

1. United Sates: Equity Risk Premiums under Different Climate Scenarios
(Percent)



… and in other advanced economies.

2.Advanced Economies: Market Implied Equity Risk Premiums and Equity Risk Premiums Under High Warming Scenario
(Percent)



Sources: EM-DAT disaster dataset; KNMI Climate Explorer; Haver Analytics; Refinitiv Datastream; and IMF staff calculations.
Note: Panel 1 shows risk premiums for different climate risk scenarios compared to a counterfactual scenario with no future climate risk and the market-implied risk premia based on a standard discounted cash-flow valuation model. Mid-line in the boxplots corresponds to the equity risk premium estimated using the average temperature projection in each scenario. The outer lines in the boxplots correspond to the equity risk premiums estimated at the 5th and 95th percentile of temperature projections in each scenario. Simulation and estimation of the long-run risk model is performed using bootstrapped simulated data until 2100. Disaster shock probability is mapped to the temperature level in each climate scenario. In panel 2, each dot represents an advanced economy and the ERP under the high warming scenario is estimated using model calibrations from a representative advanced economy and the average temperature projection in the RCP 8.5 scenario. ERP = equity risk premium.

Online Box 5.3. The Pricing of Climate Change Physical Risk into Sovereign Bonds

Sovereign risk can be directly affected by climatic disasters, such as through damages to government-owned infrastructure, an increase in expenditures related to the sovereign's role as the economy's ultimate insurer, or loss of fiscal revenue. Budget deficits tend to increase after climatic disasters, especially in countries with low levels of financial development and insurance penetration, often resulting in a higher level of public debt that can increase the cost of debt issuance for the sovereign (Melecky and Raddatz 2011).

Rating agencies have started to recognize that climate risk may affect the creditworthiness of sovereigns (Moody's 2017; Standard & Poor's 2014). In the United States, there is evidence that borrowing costs of municipal bond issuers have become sensitive to risks from rising sea levels (Painter 2020), a trend that is expected to continue (BlackRock 2019).

Based on a global sample of more than 40,000 sovereign bonds issued between 1990 and 2018, this box looks at the sensitivity of issuance costs to climate change risk by comparing long- and short-term sovereign bond spreads at the time of issuance.[1] Long-term bond prices would be expected to have a higher sensitivity to climate change risk than short-term bonds, given the long time frame over which these risks are expected to materialize.[2]

The main findings are as follows: Projected changes in the occurrence of individual climate hazards—extreme heat and precipitation, heat waves and droughts, and sea level rise—are not associated with higher issuance costs for long-term bonds compared to short-term bonds. However, a different picture emerges when focusing on broader, readily available composite measures of climate change hazard risk that take into account both current and future climate extremes. A rise of the Climate Change Hazard Index by 1 point increases spreads by about 8 basis points (Online Box Figure 5.3.1, panel 1).[3] More importantly, the effect is also significant when considering the effect of an index that captures not only hazard, but also exposure and vulnerability: namely, the Climate Change Physical Risk Index. A 1-point increase in this index, which can take values between 0 and 10, is associated with an increase in spreads by 11 basis points.

When differentiating across bonds based on their maturity structure, the results show that both long-term bonds (that mature between 2025 and 2040) and very-long-term bonds (that mature after 2040) are cheaper when issued by countries with low climate change risk, and that the effect is larger for very-long-term bonds. This suggests that markets expect risks to materialize over the very long term (Online Box Figure 5.3.1, panel 2).

Overall, these findings suggest that investors demand a premium when purchasing sovereign bonds exposed to climate change physical risk. However, results are sensitive to the choice of climate change risk proxies. Further research is required to better understand the sensitivity of sovereign bonds to such risks.

This box was prepared by Felix Suntheim.

[1] The sample includes 41,211 bonds, issued in 121 economies from 1990 to 2019. The economies and the time period covered in this analysis do therefore not correspond to those in the main chapter. The sample is dominated by advanced economies, with more than half of the observations pertaining to the United States, though the results are robust to excluding the United States from the sample. See Online Annex 5.7 for methodological details.

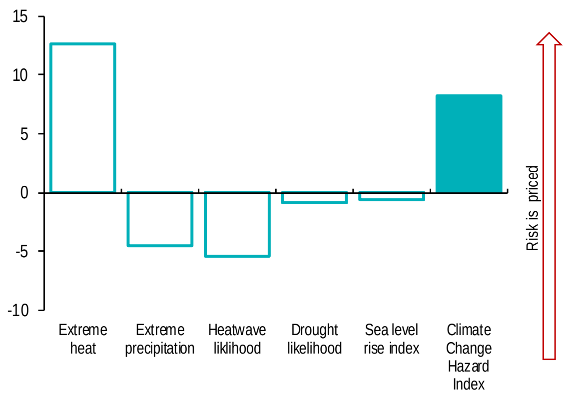
[2] Long-term bonds are defined as bonds that mature after 2040. The analysis is robust to different maturity thresholds.

[3] The indices are defined from 0 = low risk to 10 = high risk.

Online Box Figure 5.3.1. Climate Change Physical Risk and Sovereign Bond Spreads

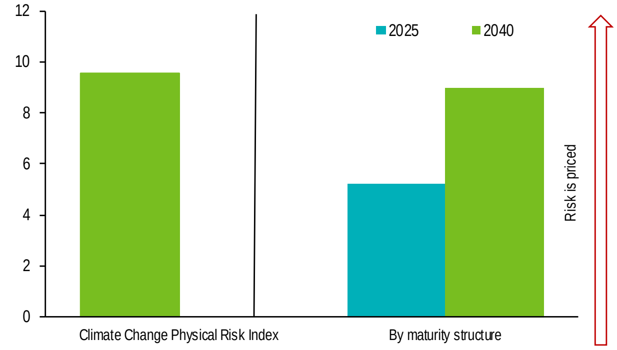
Sovereign bond spreads at issuance are generally not associated with single measures of projected changes in the occurrence of climate hazards.

1. Marginal Effect of an Increase in Climatic Hazard Occurrence on Long-Term Bond Spreads
(Basis points)



However, long-term and very long-term bonds of economies exposed to an increase in composite physical risk indices are issued at a discount.

2. Marginal Effect of an Increase in Physical Risk on Long-Term and Very Long-Term Bond Spreads
(Basis points)



Sources: Refinitiv Dealogic; World Bank; Verisk Maplecroft; and IMF staff calculations.
Note: Panels 1 and 2 show the coefficient of the interaction term of climate risk measures with a dummy for bonds with maturities longer than 2040. Climate hazards 1–4 are projected anomalies over the period 2020–39 under RCP 8.5 relative to historical simulations over the period 1986–2005. Coefficients 1–4 are multiplied by the standard deviation of the variable; The sea level rise index and the Climate Change Hazard Index range from 0 to 10. Panel 2 shows on the left-hand side the coefficient of the interaction term of the Climate Change Physical Risk Index with a dummy for bonds with maturities longer than 2040. The right-hand side the panel shows the coefficients from the interaction of the Climate Change Physical Risk Index with bonds that mature between 2025 and 2040, and from an additional interaction between the climate risk measures and a dummy for bonds that mature after 2040. All regressions include economy-year fixed effects. In both panels, solid bars indicate significance at the 10 percent level. See Online Annex 5.7 for variable definitions and methodological details.

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5

CLIMATE CHANGE

APRIL 2020—GLOBAL FINANCIAL STABILITY REPORT

PHYSICAL RISK AND EQUITY PRICES—ONLINE ANNEXES 5.1–5.7

CONTENTS

Data Sources, Climate Science Overview, Descriptive Statistics ____ 2

Large Climatic Disasters and Equity Returns ____ 10

The Pricing of Physical Risk: Cross-Economy Evidence ____ 12

Temperature Sensitivity and Predictable Equity Returns ____ 14

The Pricing of Hurricane and Storm Risk in the Catastrophe Bond Market ____ 16

Long-Run Risk Model With Climatic Disasters ____ 17

The Pricing of Physical Risk Into Sovereign Bonds ____ 22

References ____ 23

Online Annex 5.1. Data Sources, Climate Science Overview, Descriptive Statistics

Online Annex Table 5.1.1 Data Sources

Variable	Description	Source
Macroeconomic Variables		
Real Gross Domestic Product	Gross domestic product, constant prices in national currency	IMF, World Economic Outlook
Nominal Gross Domestic Product	Gross domestic product, current prices in national currency	IMF, World Economic Outlook
Nominal Gross Domestic Product, World	Gross domestic product, world, current prices in US dollars	IMF, World Economic Outlook
Gross Domestic Productor Deflator	Gross domestic product, current prices in national currency	IMF, World Economic Outlook
Consumer Price Index	Consumer price index, percent	IMF, World Economic Outlook
Nominal Private Consumption Expenditure	Private consumption expenditure, current prices	IMF, World Economic Outlook
Real Private Consumption Expenditure	Private consumption expenditure, constant prices	IMF, World Economic Outlook
Short-Term Nominal Interest Rate	Three-month treasury bill or interbank rate	Refinitiv Datastream; and Haver Analytics
Long-Term Government Bond Yield	Ten-year government bond yield	Refinitiv Datastream; and Haver Analytics
Government Debt	Public debt, percent of GDP	IMF, World Economic Outlook
Demographic Variables		
Population	Total population in millions	IMF, World Economic Outlook
Population, gridded	Grid-level population estimates for the year 2000	NASA Socioeconomic Data and Applications Center (SEDAC)
Aggregate Financial Variables		
Market Capitalization	Market values calculated from the constituents of the sector/market lists (US dollars). Index market value on Refinitiv Datastream is the sum of share price multiplied by the number of ordinary shares in issue for each index constituent. The amount in issue is updated whenever new tranches of stock are issued or after a capital change.	Refinitiv Datastream

Online Annex Table 5.1.1 Data Sources (continued)

Stock Market Price Index	The price as a percentage of its value on the base date, adjusted for capital changes. Sector and market aggregations are weighted by market value and are calculated using a representative list of shares.	Refinitiv Datastream
Price-to-Earnings Ratio	Derived by dividing total market value by total earnings, thus providing an earnings-weighted average of the price-earnings ratios of the constituents.	Refinitiv Datastream
Total Return Index	The return index for a sector or market expresses the theoretical growth in value of a share holding over a specified period, assuming that dividends are re-invested to purchase additional units of the stock. The calculation method used is determined by the source index agency.	Refinitiv Datastream
Dividend Yield	The dividend yield for an index is the total dividend amount for the index, expressed as a percentage of the total market value for the constituents of that index.	Refinitiv Datastream
Firm-level Variables		
Book Value per Share	Represents the book value (proportioned common equity divided by outstanding shares) of a company.	Refinitiv Datastream
Market Capitalization	Represents the current total market value of a company based on current price and current shares outstanding (US dollars).	Refinitiv Datastream
Stock Price	The most recent closing price of a company within the last sixty days available in the database (local currency).	Refinitiv Datastream
Total Return Index	The return index for a stock expresses the theoretical growth in value of a share holding over a specified period, assuming that dividends are re-invested to purchase additional units of the stock. The calculation method used is determined by the source index agency.	Refinitiv Datastream
Price-to-Book Ratio	The ratio of market price to book value per share of a company.	Refinitiv Datastream

Online Annex Table 5.1.1 Data Sources (continued)

Climate Variables		
Observed temperature and precipitation, gridded	Grid-level monthly temperature and precipitation time-series data from 1900 to 2017.	University of Delaware, Department of Geography
Projected temperature and precipitation	Model projections of future temperature and precipitation under different Representative Concentration Pathways (RCPs) by economy.	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Climate Change Atlas
Δ Extreme heat	Number of Days with Dangerous Heat (Heat Index > 35°C). Anomaly to the baseline period of 1986-2005.	World Bank Group, Climate Change Knowledge Portal
Δ Extreme precipitation	Average count of days per month or year with at least 50mm of daily rainfall. Anomaly to the baseline period of 1986-2005.	World Bank Group, Climate Change Knowledge Portal
Δ Heatwave probability	The daily probability of observing such a heat wave, which is a 3 or more-day sequence where the daily temperature is above the long-term 95th percentile of daily mean temperature. Anomaly to the baseline period of 1986-2005.	World Bank Group, Climate Change Knowledge Portal
Δ Drought likelihood	Annual probability of experiencing at least severe drought conditions (Standardized Precipitation Evapotranspiration Index <-2). Anomaly to the baseline period of 1986-2005.	World Bank Group, Climate Change Knowledge Portal
Climate Change Related Indices		
Climate Change Hazard Index	Defined as 10 minus the Verisk Maplecroft Climate Change Exposure Index. The index assesses the degree to which economies are exposed to the physical impacts of climate extremes and future changes in climate over the next three decades. Ranges from low risk = 0 to high risk =10.	Verisk Maplecroft
Sea level rise index	Defined as 10 minus Verisk Maplecroft Sea Level Rise index. Ranges from low risk = 0 to high risk =10. The Sea Level Rise Index quantifies the physical threat of inundation of coastal areas due to projected sea level rise between the present and end-century.	Verisk Maplecroft

Online Annex Table 5.1.1 Data Sources (continued)

Climate Change Adaptive Capacity Index	The Climate Change Adaptive Capacity Index assesses the present abilities of an economy's institutions, economy and society to adjust to, or take advantage of, existing or anticipated stresses resulting from climate change. (ranges from 0 = low adaptive capacity to 10 = high adaptive capacity).	Verisk Maplecroft
Climate Change Sensitivity Index	Defined as 10 minus Verisk Maplecroft Climate Change Sensitivity Index: The Index assesses the susceptibility to the impacts of extreme climate related events and projected climate change. Sensitivity is a function of a population's existing physical, social and livelihood circumstances, with the index examining aspects of sensitivity related to health, poverty, knowledge, infrastructure, conflict, agriculture, and population and resource pressure. (ranges from 0 = low risk to 10 = high risk).	Verisk Maplecroft
Climate Change Physical risk index	Defined as 10 minus Verisk Maplecroft Climate Change Vulnerability index. Ranges from low risk = 0 to high risk =10. The index evaluates the susceptibility of human populations to the impacts of climate extremes and changes in climate over the next three decades. It combines exposure to climate extremes and change with the current human sensitivity to those climate stressors and the capacity of the economy to adapt to the impacts of climate change.	Verisk Maplecroft

Disaster Variables

The data on climatic disasters are sourced from the EM-DAT database. All recorded disasters conform to at least one of the following three criteria: 10 or more deaths; 100 or more people affected; the declaration of a state of emergency and/or a call for international assistance.
Non-climatic disasters such as geophysical disasters (e.g. earthquakes, volcanic activity), biological disasters (e.g. epidemics), extra-terrestrial disasters, and technological disasters (e.g. industrial accidents) are excluded from the analysis.
Reported damages from disasters are measured imperfectly and generally cover only direct costs from damages to physical assets, crops and livestock. Indirect costs from the disruption of economic activity (including through supply chain effects) are not directly observable and are generally excluded. Furthermore, costs associated with vulnerability reduction, such as investments in infrastructure and research and development for risk reduction, which materialize with a lag and are not necessarily be incurred at the location of the disaster, are not considered.

Disaster damages	The amount of damage to property, crops, and livestock in US$ ('000). For each disaster, the figure corresponds to the total damage value over the full duration of the event.	EM-DAT: The Emergency Events Database

Online Annex Table 5.1.1 Data Sources (continued)

Large disaster	A disaster is defined as "large" if the rate of affected population is greater than 0.5 percent, or damages are greater than 0.05 percent of GDP.	EM-DAT; IMF staff calculations
Bond Market Data (Online Box 5.4)		
Spread to benchmark	Spread between coupon rate of security and US Treasury or Benchmark (bps)	Dealogic
Maturity	Years to maturity	Dealogic
Size	Deal Value (Face) in USD	Dealogic
VIX	CBOE Volatility Index	Refinitiv Datastream
CAT Bond Data (Online Box 5.2)		
CAT Bond Issuance Volume	Face value in USD for bonds issued between 1997 and 2019	Dealogic, Bloomberg and Artemis
CAT Bond Original Maturity	Maturity measured as the difference between the pricing and the final maturity dates	Dealogic, Bloomberg and Artemis
CAT Bond Spreads	Floater spread from quoted benchmark rate	Dealogic, Bloomberg and Lane Financial
CAT Bond Expected Loss	Annualized expected loss based on actuarial model	Lane Financial
CAT Bond Hurricane Exposure	Dummy variable denoting whether a bond is exposed to risk from hurricanes, windstorms, typhoons and other tropical storms based on tranche notes and perils covered	Dealogic and Artemis
Other Indicators		
Worldwide Governance Indicators	An indicator that reports on six dimensions of governance for over 200 economies and territories over the period 1996 to 2018.	World Bank Group
Insurance penetration	Reported insurance premium volume as percent GDP	World Bank Group, Global Financial Development Database
Sovereign Rating	Annual average of foreign currency long-term sovereign debt ratings by Moody's, Standard & Poor's, and Fitch Ratings	Kose and others 2017 (World Bank Group, fall 2019 version)
Assets Held by Sustainable Equity Funds	Fund size in USD of all equity funds labeled as "Sustainable Investment – Environmental"	Morningstar

Online Annex Table 5.1.2. Sample Economies, and Time Period
(Percent)

Economy	Period	Economy	Period
Advanced Economies		**Emerging Market and Developing Economies**	
Australia	1973–2019	Argentina	1988–2019
Austria	1973–2019	Bahrain	2003–2019
Belgium	1973–2019	Brazil	1994–2019
Canada	1973–2019	Bulgaria	2000–2019
Cyprus	1992–2019	Chile	1989–2019
Czech Republic	1995–2019	China	1993–2019
Denmark	1973–2019	Colombia	1992–2019
Estonia	1997–2019	Croatia	2005–2019
Finland	1988–2019	Egypt	1996–2019
France	1973–2019	Hungary	1991–2019
Germany	1973–2019	India	1990–2019
Greece	1988–2019	Indonesia	1990–2019
Hong Kong SAR	1973–2019	Jordan	2006–2019
Ireland	1973–2019	Kuwait	2003–2019
Israel	1993–2019	Malaysia	1986–2019
Italy	1973–2019	Mexico	1988–2019
Japan	1973–2019	Morocco	1994–2019
Korea	1987–2019	Nigeria	2009–2019
Lithuania	1998–2019	Oman	2005–2019
Luxembourg	1992–2019	Pakistan	1992–2019
Malta	2000–2019	Peru	1994–2019
Netherlands	1980–2019	Philippines	1987–2019
New Zealand	1988–2019	Poland	1994–2019
Norway	1980–2019	Qatar	2003–2019
Portugal	1990–2019	Romania	1996–2019
Singapore	1973–2019	Russia	1998–2019
Slovak Republic	2006–2019	Saudi Arabia	2005–2019
Slovenia	1998–2019	South Africa	1973–2019
Spain	1087–2019	Sri Lanka	1987–2019
Sweden	1982–2019	Thailand	1987–2019
Switzerland	1973–2019	Turkey	1988–2019
Taiwan Province of China	1987–2019	United Arab Emirates	2003–2019
United Kingdom	1970–2019	Venezuela	2012–2019
United States	1973–2019	Vietnam	2007–2019

Online Annex Table 5.1.3. Climate Change Scenarios and Past Changes in Extreme Weather Events (IPCC 2014)

Climate Scenarios

The Representative Concentration Pathways (RCPs) describe four different 21st century pathways of greenhouse gas (GHG) emissions. RCPs are labeled by the radiative forcing (in W/m2) that will occur in 2100.

Emission scenario	Likely Increase of Global Mean Surface Temperature by the End of the 21st Century (2081–2100) relative to 1986–2005
RCP 2.6	0.3°C to 1.7°C.
RCP 4.5	1.1°C to 2.6°C.
RCP 6.0	1.4°C to 3.1°C.
RCP 8.5	2.6°C to 4.8°C.

Past Change in Extreme Weather Events

Weather Extreme	Observed Past Changes	Human Contribution
Warmer (and/or fewer cold) days and nights	• Very likely increase (decrease) in frequency over most land areas	• Very likely
Heat Waves	• Medium confidence in increase on global scale • Likely increase in large parts of Europe, Asia, and Australia	• Likely
Heavy Precipitation	• Likely increases over more land areas than decreases	• Medium confidence
River Floods	• Limited to medium evidence for changes in frequency of river floods at the regional level • Low confidence for sign of change of river floods at the global level	• Low confidence
Drought	• Low confidence in change on a global level	• Low confidence
Tropical Cyclones	• Low confidence in increase in activity (intensity and frequency) on timescales of 100 years • Virtually certain increase in activity in North Atlantic since 1970	• Low confidence
Sea-levels	• Likely increase since 1970	• Likely

Sources: IPCC (2014) and Bouwer (2019).

Online Annex Table 5.1.4. Sample Economies—Largest Climatic Disasters

Country	Year	Disaster Type	Disaster Name	Damage-to-GDP Ratio (percent)	Damage insured (percent)	Duration	Number of Deaths	Number of Affected	Market Return (T-5 to T+20; percent)
Advanced Economies									
Australia	1981	Drought		3.2		2 years		80,000	-6.9
Czech Republic	1997	Flood	1997 Central European flood	3.0	17	~ 1 month	29	102,107	5.0
Czech Republic	2002	Flood	2002 European floods	2.9	50	~ 1 month	18	200,000	-1.5
Spain	1983	Flood		2.3		< 1 month	45	506,000	
Denmark	1999	Storm	Anatol	1.5	81	< 1 month	7		3.6
Austria	2002	Flood	2002 European floods	1.1	17	< 1 month	9	60,000	0.4
Canada	1976	Drought		1.1		4 years	0		0.03
Portugal	2003	Wildfire		1.0		2 months	14	150,000	2.5
Greece	1990	Drought		1.0		~ 1 month			6.7
United States	2005	Storm	Hurricane Katrina	1.0	48	~ 1 month	1833	500,000	-0.4
Emerging Market and Developing Economies									
Thailand	2011	Flood	2011 Thailand floods	10.1	25	5 months	813	9,500,000	-6.5
Oman	2007	Storm	Cyclone Gonu	9.3	16.7	< 1 month	76	20,000	4.4
Jordan	1992	Cold wave		7.4		< 1 month	15		
Pakistan	2010	Flood	2010 Pakistan floods	5.4	1.1	< 1 month	1985	20,359,496	-6.5
Peru	1983	Landslide		5.2		~ 1 month	364	700,000	
Philippines	2013	Storm	Typhoon Haiyan (Yolanda)	3.7	7	< 1 month	7354	16,106,870	-8.1
Venezuela	1999	Flood	Vargas tragedy	3.2	12.7	~ 1 month	30000	483,635	6.1
Indonesia	1997	Wildfire		3.1		~ 1 month	240	32,070	7.4
Vietnam	2015	Drought		3.1		1 year		1,750,000	-3.1
China	1998	Flood	Yangtze river flood	2.9	1.0	2 months	3656	239,000,000	-32.9

Sources: EM-DAT; Refinitiv Datastream; and IMF staff calculations.
Note: Missing cells = N/A.

Online Annex 5.2. Large Climatic Disasters and Equity Returns

A standard event study methodology is used to examine the effects of large climatic disasters on equity returns, with a particular focus on the banking and non-life insurance sectors. The analysis also examines how the aggregate stock market and the real sector (industrial sector) stocks react to climatic disasters.

Cumulative Average Abnormal Returns (CAARs) around Disasters

1. Expected returns are estimated for each economy and each sector in an economy based on a pre-event estimation window that starts 12 months before a disaster occurs and ends one month before the disaster.[1] For the excess stock return (excess of the risk-free rate) $r^{e}_{i,c,t}$ in economy *c* and day *t* of each stock index $i \in$ {Market, Banks, Non-life Insurance, Industrial}, the following global factor model is estimated for all disasters:

$$r^{e}_{i,c,t} = \alpha_i + \beta^{global}_{i,c} \cdot r^{e}_{global,t} + \epsilon_{i,c,t}$$

where $r^{e}_{global,t}$ is the excess return for the global stock index (in excess of the risk-free rate of the U.S.), and $\beta^{global}_{i,c}$ is the loading on the global factor. Estimation is conducted at the daily frequency. Returns are calculated using the Stock Market Price Index.

2. For each disaster, using the estimated coefficient $\widehat{\beta^{global}_{i,c}}$, the expected return for time τ after the disaster is estimated to be $E\left(r^{e}_{i,c,\tau}\right) = \widehat{\beta^{global}_{i,c}} \cdot r^{e}_{global,\tau}$ and abnormal return for time τ is $AR\left(r^{e}_{i,c,\tau}\right) = r^{e}_{i,c,\tau} - E\left(r^{e}_{i,c,\tau}\right)$. The cumulative abnormal return (*CAR*) is computed by summing up the abnormal returns starting 21 trading days before the start date of the disaster up to 60 trading days after the disaster start date. The cumulative average abnormal return (CAAR) is the average of the CARs across all disasters in the sample.

Regression Analysis of Equity Market Reaction to Large Disasters

To analyze whether economy characteristics affect the equity market reaction to disasters, the following model is estimated:

$$CAR40_{i,c,d} = \mu_i + \gamma_{1,i} Char_{c,d} + \gamma_{2,i} X_d + \epsilon_{i,c,d}$$

where $CAR40_{i,c,d}$ is the 40-trading-day cumulative abnormal returns for Index $i \in$ {Market, Banks, Non-life Insurance, Industrial} in economy *c* after disaster *d*. $Char_{c,d}$ includes economy characteristics in the disaster economy *c* at the time of disaster *d*, including insurance penetration (ratio of total non-life insurance premiums to GDP, one year lagged), and sovereign financial strength (sovereign bond rating on a scale from 1 to 21, 21 being the highest, and one year lagged). X_d controls for the economic damage to GDP ratio for disaster *d*.

To examine whether economy characteristics play a role in determining the downside risk to CARs after disasters, the following quantile regression is estimated:

$$CAR40^{q}_{i,c,d} = \mu^{q}_i + \gamma^{q}_{1,i} Char_{c,d} + \gamma^{q}_{2,i} X_d + \epsilon^{q}_{i,c,d}$$

[1]Note: Only disasters for which precise start dates are available are included in the analysis.

where *q* is the 10th percentile, capturing the left tail of the distribution of cumulative abnormal returns.

Robustness Analysis

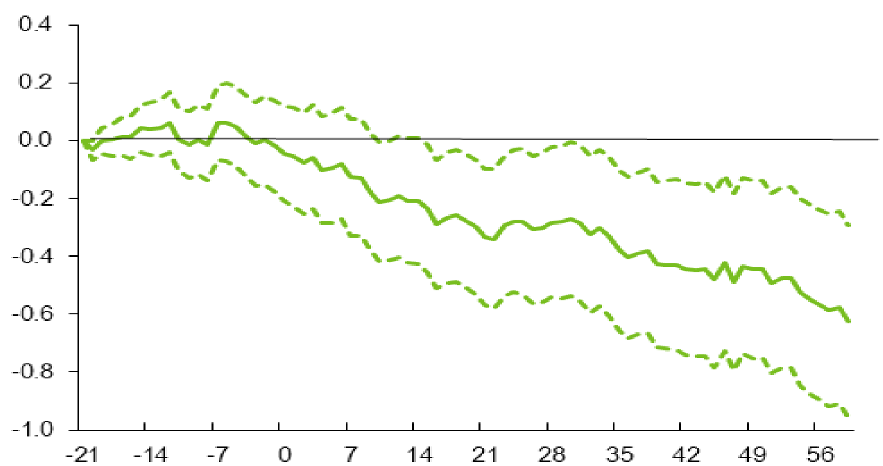
Results remain broadly unchanged for the following robustness checks:

1. To account for business cycle effects and government policy responses, the change in the short-term interest rate (3-month government bond yield) relative to the end of the previous year or the change in the long-term interest rate (10-year government bond yield) relative to the end of the previous year, has been added as an additional control variable.
2. To account for the fact that some disasters such as storms and floods may have more acute effects than other disasters such as droughts and wildfires, the sample is restricted to storms and floods only.

To better understand the role of re-insurers and the global spillovers of disasters, the CAAR analysis is repeated with all globally listed re-insurance companies and all disasters in the sample. Cumulative average abnormal returns are negative and significant as can be seen in Online Annex Figure 5.2.1

Online Annex Figure 5.2.1. Cumulative Average Abnormal Returns for Global Reinsurance Sector

Sample Economies, Reinsurance Sector: Cumulative Average Abnormal Returns (CAAR) Around Large Disasters, 90 Percent Confidence Interval
(Percent)



Sources: Refinitiv Datastream and IMF staff estimates.
Note: This figure plots the cumulative average abnormal returns (CAARs) for the global reinsurance sector during the trading days around large climatic disasters. The global reinsurance sector return is simple average of daily returns of all publicly-traded reinsurance companies globally. Abnormal returns are computed based on a single global factor model and estimation uses historical data one year before each disaster. The x-axis is trading days and time 0 is the start day of disasters. Dashed lines are the 90th percent confidence intervals.

Online Annex 5.3. The Pricing of Physical Risk: Cross-Economy Evidence

Empirical Approach

Using cross-sectional regressions and economy-level measures of predicted changes in hazard occurrence, the following equation is estimated:

$$Valuation_c = \alpha + \beta Hazard_c + \gamma\, Valuation\ Controls_c + \epsilon_c \quad (1)$$

where *c* is economy; $Valuation_c$ is either the log of the price-earnings ratio, of the market-to-book ratio or of the price-to-dividends ratio; $Hazard_c$ is a measure of predicted change in climatic hazard occurrence.[1] $Valuation\ Controls_c$ are proxies for expected future earnings growth, the equity risk premium, and the risk-free interest rate, as in IMF (2019).

Valuation metrics[2]	Climatic Hazard Indicators	Valuation Controls
• Log of Price-to-Earnings per Share Ratio (P/EPS) • Log of Price-to-Book per Share Ratio (P/BPS) • Log of Price-to-Dividend per Share Ratio (P/Div)	• Measures of future changes in hazard occurrence (Maplecroft indicators, World Bank indicators)	• mean annual growth of earning per share (past 5 years) • standard deviation of annual growth of earnings per share (past 5 years) • 3-month govt. bond yield

The estimations are repeated for each of four different representative concentration pathways (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. The sample of economies with available data includes 50 economies in total.

To assess the impact of climate change sensitivity and climate change adaptive capacity, Equation (1) is then augmented as follows:

$$\begin{aligned} Valuation_c = {} & \beta_0 + \beta_1 Hazard_c + \beta_2\, \mathbb{1}\{High\}_c + \beta_3 Hazard_c \mathrm{X}\, \mathbb{1}\{High\}_c \\ & + \beta_4 Valuation\ Controls_c + \epsilon_c \end{aligned} \quad (2)$$

where $\mathbb{1}\{High\}_c$ is an indicator variable equal to one when the Climate Change Sensitivity Index or the Climate Change Adaptive Capacity Index is above the median of the cross-economy distribution.

[1]The climate hazard risks considered are ΔExtreme heat, ΔExtreme precipitation, ΔHeatwave probability, ΔDrought likelihood, Sea level rise index, Climate Change Hazard Index (See Online Annex Table 5.1.1 for data sources and definitions).

[2]Average of monthly observations in 2019.

Robustness Analysis

To control for additional factors that could influence the relationship between future climate hazards and current market valuations, a range of robustness checks have been performed:

- The price-to-book and price-to-dividend ratios have been used as alternative measures of market valuations
- To control for the aggregate state of the economy regressions have been performed using yearly averages of the market valuation metrics as well as averages over longer periods of time (e.g. 5-10 years).
- Possible confounding effects due to the economic and financial cycle have been formally examined by augmenting the baseline specification with the credit-to-GDP gap and Output gap measures. Confounding due to political risk and fiscal capacity have been tested by including interaction terms of the climatic hazard indicators with sovereign ratings. Transition risk proxies have been added as control variables.
- Different projection horizons of the climatic hazard indicators have been used.

The results are robust to these additional tests.

Moreover, there is no change in the pricing of climate change physical risk over time, and no difference in pricing in economies with higher levels of attention to climate change (measured using the Google search index for the topic "climate change" or with the share of sustainable fund investors relative to total market capitalization).

One potential reason for the lack of significance in the pricing of equities might be related to how different agents in the economy trade off immediate costs and uncertain future costs that occur in the very long run. Agents with lower discount rates are also more sensitive to developments expected several years in the future. To test this hypothesis, cross-sectional regressions for different sectors, including the banking sector, insurance, industrials, real estate and utilities were estimated. In line with the previous intuition, insurances and industrials show some degree of pricing of the Climatic Hazard Risk and future Heat Wave likelihoods. The results however do not hold once controls for the financial cycle are included in the baseline specification. The results from the specification with adaptive climate capacity and climate change sensitivity remain unchanged.

ONLINE ANNEX 5.4. TEMPERATURE SENSITIVITY AND PREDICTABLE EQUITY RETURNS

Empirical Approach

This annex summarizes the empirical approach used to calculate the abnormal returns from a portfolio invested in stocks with a high temperature sensitivity.[1]

The 27 economies in the analysis are selected based on the criterion that they have at least 50 listed firms in the first month of 1998. The regressions are conducted based on the same sample period 1993-2017 for all economies.[2]

The analysis follows the two-stage regression approach of Kumar, Xin, and Zhang (2019) and uses the *asreg* command in STATA:

Stage 1: The temperature anomaly is defined as the difference between the current temperature and the average temperature over the past 30 years in the same month. For each month t, the excess return of each firm *i* in economy *c* is regressed on the excess market return and on the temperature anomaly using a rolling window of 5 years (60 months):

$$r_{i,c,t} - r_{f,t} = \alpha_{i,c} + \beta_{i,c}\left(r_{mkt,c,t} - r_{f,t}\right) + \theta_{i,c} TemperatureAnomaly_{c,t} + \epsilon_{i,c,t}, \quad (1)$$

where $r_{i,c,t}$ is firm *i*'s monthly equity return in US dollars, $r_{f,t}$ is the 3-month U.S. treasury yield, $r_{mkt,c,t}$ is monthly market returns in economy *c* in U.S. dollars, and $\theta_{i,c}$ captures the sensitivity of firm *i*'s return to the temperature anomaly in the 5-year window up to month t. Returns are calculated using the Total Return Index. $\theta_{i,c}$ is time-varying since the equation is estimated using rolling windows. The key variable of interest, temperature sensitivity $\theta_{i,c}^{T}$ is the absolute value of $\theta_{i,c}$.

Stage 2: Firms within the same economy are ranked by their temperature sensitivity to the temperature anomaly $\theta_{i,c}^{T}$ in each month and then grouped into quintiles (5 bins), with the top quintile consisting of firms with the highest temperature sensitivity. A dummy variable $HighTS_{i,c,t}$ is created which is equal to 1 if firm *i* belongs to the top quintile in month *t*. The high temperature sensitivity dummy $HighTS_{i,c,t}$ is then used in the following cross-sectional regressions (run for each month *t*):

$$r_{i,c,t+1} - r_{f,t+1} = \mu_{c,t} + \lambda_{c,t} HighTS_{i,c,t} + \gamma'_{c,t} X_{i,c,t} + \xi_{i,c,t+1}, \quad (2)$$

where $X_{i,c,t}$ is the vector of each firm's exposure to three Fama-French factors (excess market returns, the small-minus-big factor, and the high-minus-low factor). The variable of interest is $\hat{\lambda}_c = \left(\sum_{t=1}^{240} \lambda_{c,t}\right)/240$, an

[1] For example, Feng and Peng (forthcoming) show that food sector stock returns may be affected by temperature.

[2] The same pattern of mispricing across economies is present even after allowing earlier starting months for economies that have data for at least 50 listed firms before 1998m1.

average of estimated parameter $\lambda_{c,t}$ over the period 1998m1 to 2017m12. If $\hat{\lambda}_c$ is significantly negative, stocks highly sensitive to temperature anomalies earn abnormal lower returns, indicating mispricing.[3]

Robustness Analysis

To control for any other potential risk exposure three additional standard risk factors are included when estimating equation 2: RMW (robustness minus weak), CMA (conservative minus aggressive) and MOM (momentum).[4]

In addition, following Kumar and others (2019) three additional firm-level characteristics are included in the Fama-Macbeth cross-sectional regressions: lagged firm returns, firm market cap, and firm book-to-market.

With all variables included, the pricing anomaly remains.

[3]Same as the Fama-Macbeth test, the t-statistics are calculated using Newey-West adjusted standard errors with 3-month lags.

[4]RMV and CMA are based on the 5-factor model by Fama and French (2015). MOM is based on Carhart (1997).

Online Annex 5.5. The Pricing of Hurricane and Storm Risk in the Catastrophe Bond Market

Data on 778 catastrophe (CAT) bonds issued between 1997 and 2018, including their spreads, expected losses, maturity, and triggers is obtained from Tomunen (2019). Bonds related to mortgage risk are excluded since the focus is on natural disasters. The final sample comprises 656 observations. Bonds are classified depending on whether they are exposed to hurricane and storm risk (including European Windstorms and Pacific Typhoons) or not. OLS regressions based on the following model are performed:

$$Spread_{b,t} = \beta_0 + \beta_1 ExpectedLoss_{b,t} + \beta_2 Hurricane\ Exposure_{b,t} + \beta_3\ USExposure_{b,t} \\ +\beta_4\ Maturity_{b,t} + \beta_5\ \log\left(AmountIssued_{b,t}\right) + \beta_6 TriggerType_{b,t} + \mu_t + \epsilon_{b,t} \quad (1)$$

$Spread_{b,t}$ is the spread over the floating benchmark quoted of bond b issued on day t and is measured in basis points. $ExpectedLoss_{b,t}$ is measured in percentage points, and is the annualized expected loss given the underlying actuarial risk model. $Hurricane\ Exposure_{b,t}$ and $USExposure_{b,t}$ are dummy variables indicating whether the bonds are exposed to hurricane and storm risk and risk in the U.S. respectively. $Maturity_{b,t}$ is the maturity at issuance of the bond in years. $AmountIssued_{b,t}$ is the total face value in U.S. dollars of the bond. $TriggerType_{b,t}$ is a set of dummy variables describing the type of trigger of the bond, including Parametric, Industry Loss Index, Modelled Loss, Indemnity and Multiple Triggers. μ_t are year fixed effects. The coefficient of interest is β_2.

Online Annex 5.6. Long-Run Risk Model with Climatic Disasters

The model builds on the long-run risk (LRR) framework of Bansal and Yaron (2004). It features Epstein and Zin (1989) recursive preferences, a preference for early resolution of uncertainty, and persistent consumption growth shocks. To account for the potentially severe consequences of climate change, temperature-induced very large climatic disasters that affect consumption growth are introduced in the framework, similarly to Barro (2009), Wachter and others (2015) and Bansal and others (2019). In this framework, temperature provides information about the probability of future very large climatic disasters. The main components of the models are described below:

Representative Agent Preferences

The representative LRR agent has recursive Epstein and Zin (1989) preferences, as expressed by the following utility function:

$$\mathrm{U_t} = \left[(1-\delta)\,\mathrm{C_t}^{\frac{1-\gamma}{\theta}} + \delta\left(E_t\left[U_{t+1}^{1-\gamma}\right]\right)^{\frac{1}{\theta}}\right]^{\frac{\theta}{1-\gamma}}, \tag{1}$$

where C_t is consumption at time t, δ reflects the agent's time preference, γ is the coefficient of risk aversion, and $\theta = (1-\gamma)/(1-\frac{1}{\psi})$ where ψ is the elasticity of intertemporal substitution (IES). Utility maximization is subject to the following budget constraint:

$$\mathrm{W_{t+1}} = (W_t - C_t)\,R_{C,t+1} \tag{2}$$

Where W_t is wealth and $R_{C,t}$ is the return on all invested wealth.

Consumption and Dividends Dynamics:

$$\begin{aligned} \Delta c_{t+1} &= \mu_c + x_t + \sigma_t \eta_{t+1} - D_{t+1} \\ x_{t+1} &= \rho x_t + \varphi_e \sigma_t e_{t+1} \\ \sigma_{t+1}^2 &= \overline{\sigma^2} + v\left(\sigma^2 - \overline{\sigma^2}\right) + \sigma_w w_{t+1} \\ \Delta d_{t+1} &= \mu_d + \phi_d x_t + \varphi_d \sigma_t u_{t+1} \end{aligned} \tag{3}$$

where Δc_{t+1} and Δd_{t+1} are the growth rate of consumption and dividends, respectively; μ_c is a positive drift parameter; and x_t is a small but persistent component that captures long run risks in consumption growth. As in the long run risk literature, $\mu_c + x_t$ is the conditional expectation of consumption growth. Volatility of consumption and dividends are driven by a common time-varying component, σ_t . D_{t+1} is a drop in consumption growth due to temperature-induced very large disasters. In addition, the shocks η, e, w and u are assumed to be i.i.d normal and orthogonal to each other.

Model Solutions

The log of the intertemporal marginal rate of substitution (IMRS) can be defined as:

$$m_{t+1} = \theta\, log\delta - \frac{\theta}{\psi}\, \Delta c_{t+1} + (\theta - 1) r_{c,t+1} \tag{4}$$

In order to characterize the intertemporal marginal rate of substitution, one needs to solve for the unobservable return on the consumption claim. Using the linear approximations suggested by Campbell and Shiller (1988), the log return of the endogenously determined aggregate wealth portfolio r_c and the log return of the market portfolio r_m, which constitutes a claim to the dividend stream, can be defined as follows:

$$\mathrm{r_{c,t+1}} = k_0 + k_1 z_{t+1} - z_t + \Delta c_{t+1} \tag{5}$$

$$r_{m,t+1} = k_{0,m} + k_{1,m} z_{m,t} - z_{m,t} + \Delta d_{t+1} \tag{6}$$

where z denotes the log price-consumption ratio, z_m is the log price-dividend ratio and k_* are approximating constants which depend on the unknown mean of z. Accordingly, z is found by numerically solving a fixed-point problem. In so doing, the risk premium for the market asset is then determined by the covariation of the return innovation with the innovation into the pricing kernel:

$$\mathrm{E_t}\left[r_{m,t+1} - r_{f,t}\right] + 0.5\sigma^2_{t,r_j} = -Cov_t\left(m_{t+1} - E_t(m_{t+1}), r_{m,t+1} - E_t(r_{m,t+1})\right) \tag{7}$$

Model Estimation and Calibration

The LRR model, as described above, implies a vector stochastic process for consumption and dividend growth (macro variables), as well as a vector stochastic process for the return of the market portfolio, the risk-free rate, and the price-dividend ratio (financial variables) which depend on the following set of parameters:

$$\Theta = \{ \underbrace{\gamma, \psi, \delta,}_{\text{Preferences}} \quad \underbrace{\mu_c, \rho, \varphi_e, \sigma^2, v, \sigma_w, \mu_d, \phi_d, \varphi_d,}_{\text{Cash flows}} \quad \underbrace{h}_{\text{Time Aggregation}} \} \tag{8}$$

Acknowledging the inherently recursive structure of the LRR model and the challenge posed by the presence of two latent processes, the estimation of the macro parameters is performed using an auxiliary model based on a generalized method of moments-type criterion, which isolates the estimation of the macroeconomic dynamics from that of preferences[1]. In order to do so, a simulation of LRR model-implied data is required to perform the indirect inference estimation. Draws from standard normally distributed random variables are used to obtain realizations of the innovations of the shocks for the macro variables, while the probability of climatic disasters is mapped to the current level of temperature in the simulation. The appropriate time series length for the

[1]Preference parameters are assumed exogenous and their parametrization follows the asset pricing literature.

simulations is then determined by the number of observations, the sampling frequency of the empirical data, the assumed decision frequency of the investor, as well as the length of the projected climate scenario (available until 2100). To overcome possible bias due to small sample dataset the estimation approach is replicated using bootstrap simulations. Given the significant uncertainty surrounding future temperature projections, three main climatic scenarios are considered: RCP 2.6, RCP 6.0 and RCP 8.5. Risk premia reported in the Chapter are estimated using the average, the 5th percentile and the 95th percentile of the temperature projections obtained from the ensemble of models included in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) for each one of the scenarios. These are then compared to a counterfactual scenario with no future climate risk and the market-implied risk premia based on a standard discounted cash-flow valuation model. [2] Details of the calibration of the frequency and size of the disasters are provided below.

Calibration of the Impact of Very Large Climatic Disasters

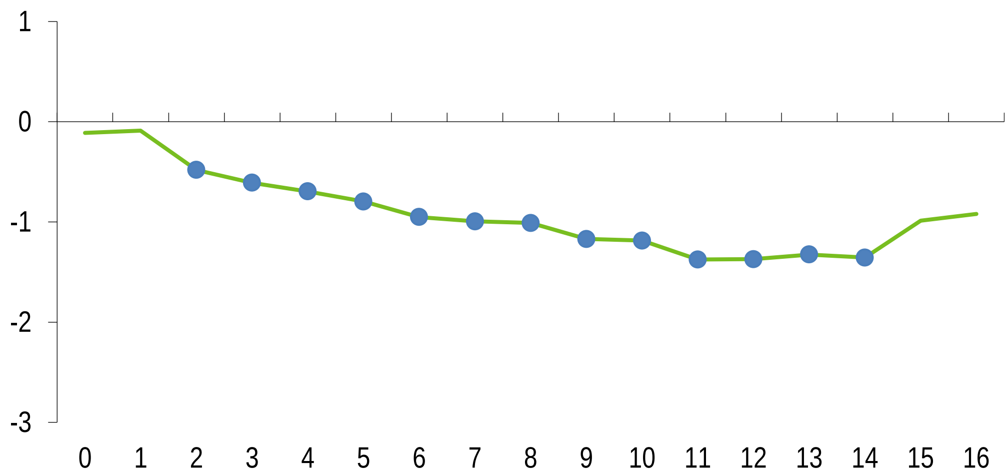
Based on the same sample of the Chapter, the effect of very large disasters on consumption growth is calibrated using the local projections method (Jorda, 2005) with the following specification:

$$y_{c,t+h} - y_{c,t-1} = \beta_0^h + \beta_1^h \mathbb{1}\{Disaster\}_{c,t} + \beta_2^h X_{c,t} + \theta_c + \theta_t + \epsilon_{c,t}^h \quad (9)$$

where *c* is an economy, *t* is a quarter, *h* is a positive integer between 0 and 16, the dependent variable is the log difference in real consumption per capita between time *t-1* to *t+h;* and $\mathbb{1}\{Disaster\}_{c,t}$ is an indicator variable that takes value equal to 1 if economy *c* was hit by a very large disaster in quarter *t*. Economy fixed effects θ_c and quarter fixed effects, θ_t, are included to capture long run differences in growth across economies and the impact of global shocks that are common to all economies in the sample. The residual term $\epsilon_{c,t}^h$ corresponds to an error term that is assumed i.i.d. Net official development assistance and official aid received (percent of GDP) is added as an additional control to the specification ($X_{c,t}$), as in Raddatz (2009). The sample period starts in 1975. The impact of disasters is calibrated based on the estimates for very large disasters reported (β_1^h) in Online Annex Figure 5.6.1.

[2] Implied methods used for the calculations of the equity risk premiums are derived from the standard dividend discount model (DDM) by inverting the discounted cash-flow valuation formulas. Specifically, the market implied equity risk premium is computed as the difference between the 18 months ahead forecasts of earnings per share-to-price ratio and the 10-year government bond yield (inflation adjusted). The measure is then averaged over the last 15 years.

Online Annex Figure 5.6.1. Impact of Very Large Disasters on Consumption
(Deviation from no-disaster scenario, percent)



Sources: EM-DAT, Haver; and IMF staff calculations.
Notes: The figure reports the estimated coefficients measuring the impact of disasters on real per capita consumption. Estimations are based on local projections (Jorda, 2005). The Indicator dummy used in the estimation is equal to one if a very large disaster occurred at time t. A disaster is defined as very large if the ratio of affected population to total population the ratio of deaths to total population, or the damage-to-GDP ratio, are above the 95th percentile of the historical distribution. Blue dots indicate that the coefficients are statistically significant at the 10 percent level or lower.

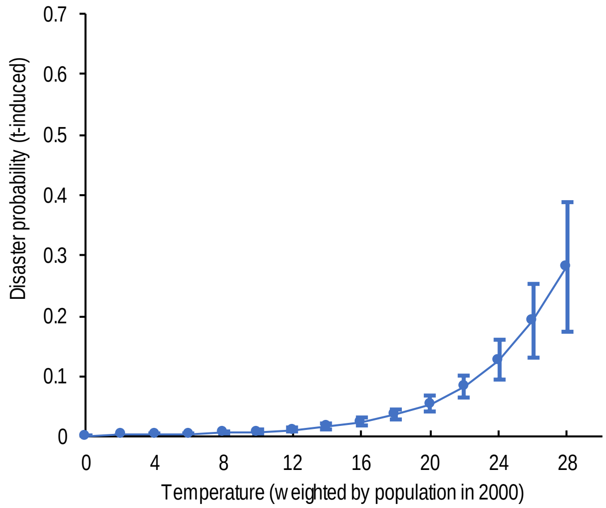
Calibration of the Likelihood of Climatic Disasters

The relationship between temperature and the occurrence of disasters is calibrated using the following panel logit model:

$$\Pr\left(Disaster_{c,t} = 1\right) = \Phi(f(T_{c,t}) + f(P_{c,t}) + \theta_c + \epsilon_{c,t}) \quad (10)$$

where c is economy, t is a quarter, $f(T_{c,t})$ is a quadratic function of temperature, $f(P_{c,t})$ is a quadratic function of precipitations, θ_c are economy fixed effects and $\epsilon_{c,t}$ is the error term. The model is also tested for each disaster type separately. To facilitate the mapping between the temperature level and the likelihood of climatic disasters, the disaster probability calibration is performed only using wildfires, droughts and heat waves events, as arguably these are the most likely to be directly linked to temperature rises. The category of climatic disasters based on these events is then defined, as "T-Induced". The estimates are robust to different fixed effects structures and to the inclusion of economy specific time trends. Within the model simulation, the logit-implied probabilities are scaled by the number of very large T-induced disasters over the total number of T-induced disasters observed in the EM-DAT database, to match the calibration of the size of disasters in the previous section. The (marginal) implied quarterly probability of all T-Induced disasters at different level of temperature is reported in Online Annex Figure 5.6.2.

Online Annex Figure 5.6.2. Model implied Quarterly Probability of ("T-Induced") Disasters
(Probability)



Sources: EM-DAT; University of Delaware (Department of Geography); and IMF staff calculations.
Notes: The figure reports the marginal quarterly probability of all temperature induced ("T-induced") disasters for different levels of temperature. T-induced disasters refer to Heat Waves, Wildfires and Droughts. Vertical lines delineate the 95 percent confidence bounds around the point estimates.

Online Annex 5.7. The Pricing of Physical Risk into Sovereign Bonds

Results are based on the following baseline specification:

$$\begin{aligned} Bond\ Spread\ at\ issuance_{b,c,t} = \alpha_{c,t} + \beta_1\ Climate_c + \beta_2\ longterm_{b,c,t} + \\ \beta_3\ Climate_c X\ longterm_{b,c,t} + \beta_4\ Controls_{b,c,t} + \epsilon_{b,c,t}, \end{aligned} \quad (1)$$

where b is bond, c is economy, and t is year. $Bond\ Spread\ at\ issuance_{b,c,t}$ is the spread between the coupon rate of the security and the US Treasury or another Benchmark bond, and is measured in basis points. Long-term is a dummy for bonds with maturities after 2040. Control variables are log of issue size, log of maturity, VIX, and sovereign credit rating. $\alpha_{c,t}$ are economy-year fixed effects

There is no perfect single measure of climate change physical risk available – one that considers changes in hazard frequency and intensity, and also changes in exposure and vulnerability. The analysis uses the same measures of climate change physical risk as the main text of the Chapter:

$Climate_c$ is one of the following seven variables:

1. projected change in the number of extreme heat days
2. projected change in the number of extreme precipitation days
3. projected change in heatwave likelihood
4. projected change in drought likelihood
5. Sea Level Rise Index
6. Climate Change Hazard Index
7. Climate Change Physical Risk Index

The coefficient of interest is β_3.

Projected changes in climate hazard variables (i.e. variables 1-4) are available for four different projection horizons up to the year 2100, and for four different emission scenarios. The analysis concentrates on the horizon 2020–39 and emission scenario RCP 8.5, but results are robust to other horizons/scenarios.

The sample includes 41,211 bonds, issued in 121 economies. 94 percent of the bonds are issued by advanced economies, and 54 percent by the United States alone. The results are robust to excluding the United States from the sample and to excluding economies not included in the analysis discussed in the main text of the chapter.

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