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Climate Defaults and Financial Adaptation

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Toàn Phan & Felipe Schwartzman*

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Abstract

We analyze the relationship between climate-related disasters and sovereign debt crises using a model with capital accumulation, sovereign default, and disaster risk. We find that disaster risk and default risk together lead to slow post-disaster recovery and heightened borrowing costs. Calibrating the model to Mexico, we find that the increase in cyclone risk due to climate change leads to a welfare loss equivalent to a permanent 1% consumption drop. However, financial adaptation via catastrophe bonds and disaster insurance can reduce these losses by about 25%. Our study highlights the importance of financial frictions in analyzing climate change impacts.

Keywords: climate change; disasters; sovereign default; emerging markets; growth.

JEL classification codes: Q54, F41, F44, H63, H87.

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1 Introduction

Climate change is projected to alter the frequency and severity of weather-related disasters, such as hurricanes, in many economies. How quickly a country can recover from such disasters depends on its ability to attract foreign capital. This is likely to prove challenging for many emerging economies, given their relatively high risk of debt crises and costly access to external finance in times of need. These financial challenges may amplify the costs of rising climate-related risks, but they may also suggest a potential role for financial market developments in helping countries adapt to the changing climate.

To systematically analyze these challenges and opportunities, we develop a tractable and quantifiable growth model of a small open economy with an exogenous climate-related disaster risk and an endogenous sovereign default risk. The framework allows us to quantify the welfare implications of changes in disaster risks and the potential benefits of financial adaptation strategies.

Crucially, the model generates implications that are consistent with several critical empirical observations for emerging economies. First, adverse weather shocks such as hurricanes can cause long-lasting adverse macroeconomic effects, with declines in GDP and national income that are persistent for many years (Mendelsohn et al. 2012; Bakkensen and Mendelsohn 2016; Hsiang and Jina 2014), and the damage tends to be more severe and long-lasting in countries with less financial development and insurance coverage (Bakkensen and Barrage 2022; Von Peter et al. 2012). Second, these shocks have adverse financial effects. Ex-post, natural disasters often lead to increased borrowing costs and a higher likelihood of a subsequent sovereign debt crisis (Klomp 2015, 2017; Asonuma et al. 2018). Ex-ante, countries with greater exposure to climate-related disaster risks generally face higher borrowing costs, all else being equal (Kling et al. 2018; Barnett et al. 2020; Beirne et al. 2020).

Our model can explain these stylized facts through an endogenous propagation mechanism that hinges on the movements of a sensitive default risk, which depends not only on the level of debt issuance, as in standard sovereign debt models, but also on the level of physical capital investment. By destroying a country's capital, a bad disaster shock increases the risk of default and the interest rate spread as functions of debt issuance. This shift forces the country to reduce borrowing, further depressing future output and investment. The lowered borrowing capacity keeps investment low and borrowing costs high, therefore creating a feedback loop that can lead to a persistent reduction in capital stock and output in the aftermath of the disaster. Together, the model generates persistent economic damage from adverse weather shocks. It also predicts that, all else equal, countries with higher exposure to bad weather shocks face higher borrowing costs and that the realization of a disaster raises borrowing costs and the probability of a sovereign debt crisis.

To quantify the economic impacts of weather shocks and the welfare consequences of climate change, we calibrate the weather shock process to cyclones, a critical and well-studied climate-related peril (Nordhaus 2010; Mendelsohn et al. 2012). We calibrate the model economy to Mexico, an important emerging economy with significant cyclone exposure (Juarez-Torres and Puigvert 2021). Our quantitative analysis reveals that after a large cyclone strike, the endogenous default risk can significantly delay the recovery by at least two decades. This finding aligns with the best estimates from the empirical literature (Hsiang and Jina 2014, 2015) and highlights the long-lasting impact of climate-related disasters on vulnerable economies. One key driver of this delay is the looming threat of future default-triggering cyclone shocks, exacerbating borrowing costs and further complicating the post-disaster recovery process.

In addition, we utilize our model to examine how financial frictions affect the welfare implications of climate change. Drawing on the well-known climatology predictions developed by Emanuel et al. (2008), we assume that cyclone activity in the Atlantic basin will increase by 10% by the end of the century under the "business as usual" climate scenario. Our structural model allows us to calculate the welfare loss due to such changes, which we estimate to be equivalent to a permanent drop in consumption of approximately 1%. This value is significant in comparison with, for instance, well-known measures of the benefits of completely eliminating business cycle fluctuations.[1]

[1] See Lucas (1987) for an early version of this calculation, which estimates the cost to be

Finally, we characterize the potential effects of financial adaptation in mitigating the impacts of climate change. We examine two forms of adaptation: the utilization of disaster insurance and the issuance of catastrophe (CAT) bonds. We find that, by combining the different advantages of the instruments, their adoption can recover approximately 25% (a quarter) of the welfare loss from climate change.

Intuitively, adopting insurance allows the country to smooth consumption and net worth across disaster and nondisaster states. The country can then quickly rebuild its capital stock, leading to greater overall wealth and reducing the impact of climate change. However, the gains from insurance are balanced by the fact that the country has to use its already constrained debt capacity to pay the insurance premium in good times. On net, these two forces translate into a slight increase in country wealth and capital over the long run, but not nearly enough to compensate for the losses due to climate change. However, insurance has no direct effect on the country's incentive to default in disaster states as long as the payments from insurance contracts, which are the sovereign country's assets, cannot be seized by foreign creditors in the case of default (Bulow and Rogoff 1989).

In contrast, CAT bonds decrease the debt burden in disaster-stricken states, reducing the default risk for any level of debt. The model produces a "CAT-issuance Laffer curve," whereby expected debt repayment and bond price are nonmonotonic functions of the fraction of bond issuance that is CAT. While a moderate share of CAT bonds can be beneficial for both lenders and the borrowing country, an excessive amount can result in unnecessarily higher borrowing costs.[2]

The two instruments are, therefore, complements rather than substitutes. On the one hand, insurance provides countries with resources to speed up

just 0.05% in consumption equivalent terms for the United States. Jordà et al. (2020) revise the cost to be about 15% in the post-WW2 era, primarily due to disasters and mini-disasters in consumption growth dynamics.

[2]This result is reminiscent of Krugman (1989) discussion of the 1980s debt crisis in Latin America, that "just as governments may sometimes actually increase tax revenue by reducing tax rates, creditors may sometimes increase expected payment by forgiving part of a country's debt."

disaster recovery but does little to help avoid default costs. On the other hand, CAT bonds help the country avoid costly defaults in disaster states but provide little insurance.

Related literature. Our paper adds to the rapidly growing theoretical climate economics literature, pioneered by Nordhaus (1994) and Nordhaus and Boyer (2000), and more recently Golosov et al. (2014) and Hassler et al. (2021), among others. While the importance of studying the economic effects of climate-related disasters has been emphasized in several studies, including Weitzman (2009), Nordhaus (2010), Cai and Lontzek (2019), Bansal et al. (2019), Cantelmo et al. (2020), and Hong et al. (2020),[3] our contribution is the first model to study how climate change affects welfare via the endogenous and dynamic interplay between investment and sovereign default risk. Our paper also integrates best estimates of cyclone damages from the empirical climate economics literature, including Nordhaus (2010), Mendelsohn et al. (2012), Hsiang and Jina (2014), Hsiang and Jina (2015), and Bakkensen and Barrage (2022).[4]

Our paper connects the climate economics literature to the growing literature on sovereign default, including Eaton and Gersovitz (1981), Bulow and Rogoff (1989), Aguiar and Gopinath (2006), Arellano (2008), Yue (2010), Mendoza and Yue (2012), Bai and Zhang (2012), Chatterjee and Eyigungor (2015), Hatchondo et al. (2016), Phan (2016, 2017b), Park (2017), Dovis (2019), Bianchi et al. (2019), Asonuma and Joo (2020), and da Rocha et al. (2022).[5] A related paper is Mallucci (2022), which introduces hurricane risk and CAT bonds into a quantitative endowment economy framework with long-term debt carefully calibrated to a sample of Caribbean countries and provides a refined discussion of the impact of disaster risk on spreads. In studying disaster-contingent bonds, our paper is also related to those that analyze the potential

[3]Also see Ikefuji and Horii (2012) and Müller-Fürstenberger and Schumacher (2015).

[4]For a review of the empirical climate-economics literature in general, see Dell et al. (2014). Also see Greenstone et al. (2013), Auffhammer (2018), Colacito et al. (2019) and references therein.

[5]For a comprehensive literature review, see Aguiar et al. (2016).

effects of making sovereign debt more state-contingent, such as Grossman and Van Huyck (1988), Alfaro and Kanczuk (2005), Adam and Grill (2017), and Borensztein et al. (2017).[6] Our paper's relative contribution to this literature is a tractable model that allows for (analytical and quantitative) characterizations of how disaster risks affect debt, default risk, *and investment dynamics*. Our framework offers a practical approach to simplifying the complex dynamics between endogenous investment and sovereign default, which have posed significant challenges in the existing literature (Gordon and Guerron-Quintana 2018).

Our paper is organized as follows. Section 2 provides the model environment and several analytical characterizations. Section 3 provides the calibration exercise and several numerical results. Section 4 analyzes financial adaptation strategies. Section 5 concludes.

2 Model and analytical characterizations

Consider a small open economy with a representative sovereign government. The economy produces a single consumption good from capital K_t and labor—which is supplied inelastically and normalized to be one—using a Cobb-Douglas production function:

$$Y_t = (e^{-x_t d_t} K_t)^\alpha (A_t)^{1-\alpha}, 0 < \alpha < 1,$$

where A_t is total factor productivity (TFP). We assume for simplicity that A_t follows a random walk, i.e., the growth shock $g_t := \log \frac{A_{t+1}}{A_t}$ is identically and independently distributed (i.i.d.) according to a distribution Φ_g.[7]

[6] See also Grossman and Van Huyck (1993), Braun et al. (1999), Phan (2017a), Asonuma et al. (2018), and Hatchondo et al. (2022).

[7] It is straightforward to extend the model to allow the growth shocks to follow a Markov process. We keep the simpler process as it captures the most salient quantitative facts with significant gains in terms of tractability.

Weather shocks. Exogenous variables x_t and d_t represent the extensive and intensive margins of a stochastic process for weather shocks. The dummy x_t is one if there is a bad weather shock (e.g., a cyclone strike) and zero otherwise. The continuous variable $d_t \geq 0$ denotes the intensity of the damage to the capital stock. In the baseline analysis, we assume that the probability of a bad weather shock in each period is a constant $\Pr(x_t = 1) = p$ and that the damage d_t is i.i.d. according to a distribution Φ_d with support over $[0, \infty)$. (We will later consider how climate change alters the distribution of weather shocks.)

Preferences. To more fully capture the welfare effects of the weather jump process, we assume that the representative government maximizes Epstein and Zin (1989) recursive preferences:

$$V_t = \left(C_t^{1-\iota} + \beta E_t \left(V_{t+1}^{1-\gamma} \right)^{\frac{1-\iota}{1-\gamma}} \right)^{\frac{1}{1-\iota}},$$

where ι is the inverse intertemporal elasticity of substitution and γ is the relative risk aversion coefficient (if $\iota = \gamma$, then the preferences collapse to the constant relative risk aversion specification). Following the macrofinance literature (e.g., Bansal and Yaron 2004; Cai and Lontzek 2019), we focus on the relevant parameter range where $\iota < 1$.

Sovereign borrowing. The country can borrow from risk-neutral international lenders by issuing one-period noncontingent bonds. Each unit of bond is a promise to repay one unit of the final consumption good in the subsequent period. However, the country cannot commit to this promise. We assume that default is costly: it leads to a deadweight loss of a fraction ℓ_t of the country's output Y_t. Following Aguiar et al. (2016), we assume a procyclical fractional loss $\ell_t = \ell(g_t)$, where

$$\ell(g') = \bar{\ell} e^{\psi g'}, \quad , \psi \geq 0, \bar{\ell} > 0. \tag{1}$$

This specification implies that the country has more incentive to default in low-growth states. Such a cyclical cost of default is a standard assumption in the sovereign debt literature as it helps the model match the cyclical movements of spreads observed in data (Aguiar et al. 2016).

As in Adam and Grill (2017), we assume that the defaulting country can immediately regain access to the debt market. An important advantage of this assumption is that it greatly enhances the tractability of the model, allowing us to characterize the equilibrium bond price in closed form and numerically solve the optimization problem with both capital accumulation and strategic default without the traditional curse of dimensionality (Gordon and Guerron-Quintana 2018). A potential disadvantage is that we may miss the quantitative implications of the cost of credit exclusion; for example, we may underestimate the level of debt that can be sustained in equilibrium. However, it has been well known in the literature that credit exclusion alone plays a limited role in sustaining debt in equilibrium (Bulow and Rogoff 1989; Aguiar et al. 2016).[8]

Optimization problem. In each period t, after the realization of the growth shock and the weather shock, the country chooses (i) to repay or to default on its outstanding debt obligation, (ii) the value of new bonds issues, and (iii) new capital investment. We detrend all variables by the productivity level A_t and denote the detrended variables with lowercase letters (e.g., $v_t := \frac{V_t}{A_t}$, $k_t := \frac{K_t}{A_t}$). The recursive optimization problem can be written concisely with just one state variable—the country's net worth:

$$v(m)^{1-\iota} = \max_{k_n \geq 0, b_n} c^{1-\iota} + \beta E\left[v(\max\{m'_R, m'_D\})^{1-\gamma} e^{(1-\gamma)g'}\right]^{\frac{1-\iota}{1-\gamma}}, \tag{2}$$

subject to a budget constraint:

$$c = m - k_n + q(b_n, k_n)b_n,$$

[8] Alternatively, we can interpret the cost as a reduced form for various sources of default costs, including the effects of temporary exclusion from international credit markets. This interpretation is arguably reasonable in our context, since in the calibration we make each period five years, which is close to the average duration of exclusion.

where b_n and k_n denote the new bond issuance and next period capital, and q denotes the bond price schedule (determined below). The detrended debt and capital positions in the subsequent period (after the next period's shocks have been realized) are given by:

$$b' = e^{-g'} b_n \tag{3}$$
$$k' = e^{-x'd'-g'} k_n. \tag{4}$$

The country's net worth, conditional on either debt repayment or default, is given by:

$$m'_R = (k')^\alpha + (1-\delta)k' - b' \tag{5}$$
$$m'_D = (1-\ell(g'))(k')^\alpha + (1-\delta)k' - 0. \tag{6}$$

The country's net worth next period is then simply $m' = \max\{m'_R, m'_D\}$. It is straightforward from (5-6) that the country chooses to default if and only if its debt over GDP exceeds the output lost fraction $\ell(g')$:

$$m'_R < m'_D \iff \frac{b'}{(k')^\alpha} > \ell(g').$$

Given specification (1), the country defaults if and only if the *weather-adjusted growth* term $\tilde{g}' := g' - \frac{\alpha}{1-\alpha+\psi}x'd'$, which captures the damage from the weather shock, is below an endogenous *default threshold* $\bar{g}(b_n, k_n) := \frac{1}{1-\alpha+\psi}\ln\frac{b_n}{\bar{\ell}k_n^\alpha}$:

$$\text{default} \iff \underbrace{g' - \frac{\alpha}{1-\alpha+\psi}x'd'}_{\tilde{g}'} < \underbrace{\frac{1}{1-\alpha+\psi}\ln\frac{b_n}{\bar{\ell}k_n^\alpha}}_{\bar{g}(b_n,k_n)}. \tag{7}$$

The difference between the $\bar{g}$ and $\tilde{g}'$ can be interpreted as the distance to default. Note from (7) that the default threshold $\bar{g}$ is increasing in b_n and decreasing in k_n. This implies that the default risk increases with more debt and decreases with the next period's capital stock. The expression also highlights the role of cyclical default costs. As ψ increases (so that default costs increase more rapidly with the growth shock g'), the default threshold $\bar{g}$ becomes less sensitive to changes in debt and capital stock.

Figure 1 illustrates how the disaster risk affects the tail of the distribution of growth shocks. It plots the histograms associated with the probability distributions of g' and $\tilde{g}'$ (when the TFP growth shock g' follows a normal distribution and the damage intensity d' follows a Weibull distribution). It is immediate to see that for a given threshold $\bar{g}$ (illustrated by the dashed vertical line), the tail event $g' < \bar{g}$ has a smaller probability than the tail event $\tilde{g}' < \bar{g}$, implying that the presence of the bad weather shocks increases the likelihood of default.

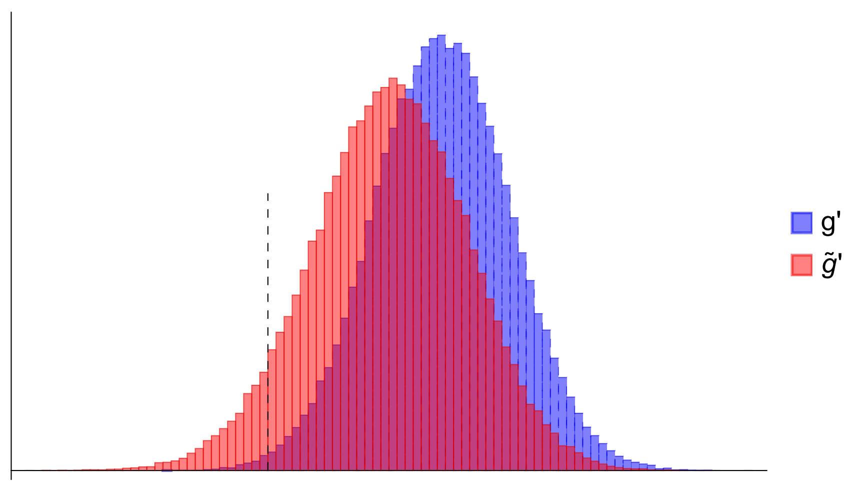


Figure 1: *Effects of weather shocks on growth.* Histograms of growth shock g' (blue) and of weather-adjusted growth shocks $\tilde{g}' := g' - \frac{\alpha}{1-\alpha+\psi}x'd'$, which captures the damage of the weather shock (red).

Bond price schedule. The equilibrium bond price schedule is a function that specifies the price per unit of bonds issued by the country given its choices. In the competitive credit market with risk-neutral lenders, where lenders rationally expect the possibility of default, the schedule is given by:

$$q(b_n, k_n) = \frac{1 - s(b_n, k_n)}{1 + r}, \forall b_n, k_n, \tag{8}$$

where r is the world risk-free interest rate (assumed to be a constant for simplicity), and s is the sovereign default spread, defined as the probability of default:

$$s(b_n, k_n) = \Pr[m'_R < m'_D],$$

with repayment and default net worth values m'_R, m'_D as specified in (3-6).

The function s, which is key to our analysis, is the spread between the price of a risk-free bond $(1/(1+r))$ and the price of a bond issued by the country. A nice feature of the tractability of our model is that we can derive a closed-form expression for s by using the default decision specified in (7):

$$\begin{aligned} s(b_n, k_n) &= \Pr\left[\tilde{g}' < \bar{g}(b_n, k_n)\right] \\ &= (1-p)\Phi_g(\bar{g}) + pE_{d'}\left[\Phi_g\left(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d'\right)\right]. \end{aligned} \tag{9}$$

Equation (9) shows how the disaster risk affects the spread schedule. Intuitively, default is a tail event, which happens when the economic conditions are sufficiently bad, making the burden of repaying larger than the output loss of default. The presence of the disaster risk effectively changes the growth shock from g' to $\tilde{g}'$. Since the distribution of $\tilde{g}'$ has a fatter left tail than the distribution of g', it follows that the disaster risk raises the probability of default (for any given choice of debt b_n and next period capital k_n).

The shape of the spread schedule s determines the sensitivity of the economy's borrowing cost to disaster risk. The following proposition analytically characterizes the elasticity of s:

Proposition 1. *The equilibrium spread schedule s is positively elastic in debt issuance b_n:*

$$\frac{b_n}{s}\frac{\partial s}{\partial b_n} = \frac{1}{1-\alpha+\psi}h(\bar{g}) > 0,$$

and negatively elastic in investment k_n:

$$\frac{k_n}{s}\frac{\partial s}{\partial k_n} = -\frac{\alpha}{1-\alpha+\psi}h(\bar{g}) < 0,$$

where the ratio $\tilde{h}(\bar{g})$ *is defined as:* $\tilde{h}(\bar{g}) = \frac{(1-p)\phi_g(\bar{g})+pE_{d'}\phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')}{(1-p)\Phi_g(\bar{g})+pE_{d'}\Phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')}$.

Proof. Appendix A.1. □

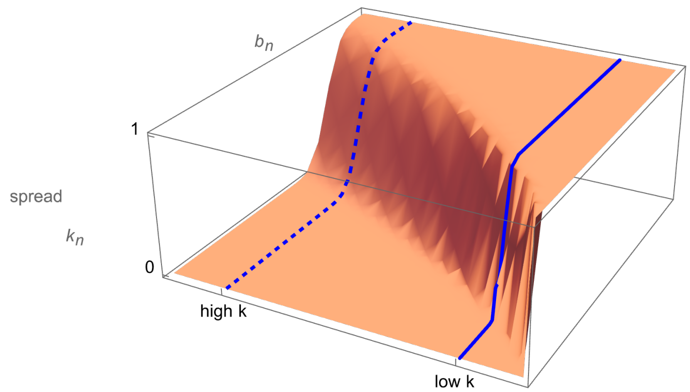
The first claim of Proposition 1 confirms a standard result in the sovereign debt literature: the equilibrium spread increases in debt issuance. The newer part is the second claim, which states that the spread *decreases* in the next period capital. This is a direct corollary of the fact that the default threshold $\bar{b}$ is decreasing in k_n (leading to a smaller default region according to (7)).

Figure 2 illustrates the dependence of the spread on capital (for a simple case where the TFP growth shock g' follows a normal distribution, and the damage intensity d' is deterministic). Figure 2a plots s as a function of b_n and k_n, with two cross-sectional cuts at two different levels of next-period capital. Figure 2b plots the two curves associated with these two cross-section cuts, showing s as a function of debt issuance conditional on two different levels of next-period capital. The solid line is associated with a higher capital level and the dashed line with lower capital. It is clear how the spread curve shifts to the right as k_n moves from the low level to the high level, meaning that for each amount of debt issuance b_n, the spread is higher when there is less capital in the next period. Furthermore, note how the spread function is steeper (the default probability is more sensitive to an increase in debt issuance b_n) when investment k_n is lower.

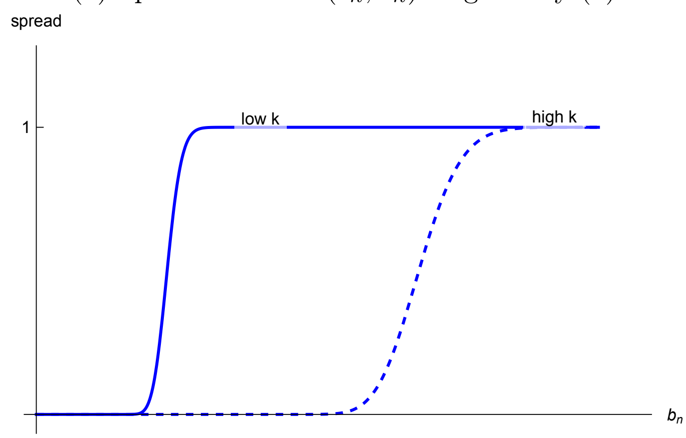
The interplay among capital, debt, and spreads gives rise to the vicious feedback loop, illustrated in Figure 2c. As the capital stock falls, spreads increase, making debt more costly, and limiting capital accumulation. This vicious cycle will play an important role in the propagation of weather shocks in our quantitative analysis in Section 3.

Finally, we can use the framework to derive the qualitative impact of climate disasters on spreads. This provides a qualitative sense of the role of disasters and the effects of their increased frequency. This is summarized in the following proposition:

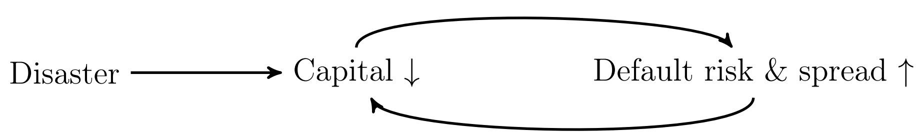
Proposition 2. *The spread schedule increases in the weather shocks' frequency*



(a) Spread surface $s(b_n, k_n)$ as given by (9).



(b) Spread as a function of debt issuance b_n at a low and a high level of investment k_n.



(c) Feedback loop between declined investment and heightened default risk, which slows down the post-disaster recovery.

Figure 2: *The dependence of spread on capital.*

p:

$$\frac{\partial s}{\partial p} = -\Phi_g\left(\bar{g}\right) + E_{d'}\Phi_g\left(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d'\right) > 0,$$

and increases (in the first-order stochastic dominance sense) in the distribution of the shock's damage:

$$\hat{\Phi}_d \overset{fosd}{\geq} \Phi_d \Rightarrow s(\cdot, \cdot|\hat{\Phi}_d) \geq s(\cdot, \cdot|\Phi_d).$$

Proof. Appendix A.2. □

Intuitively, an increase in the frequency or intensity of the weather shock raises the thickness of the left tail of the weather-adjusted growth shock $\tilde{g}'$ and thus leads to an increase in the default risk.

3 Quantitative analysis

We now examine the implications of the model in a quantitative setting. The disaster type we have in mind is a cyclone, which not only is an important source of climate-related risk, but also has been extensively studied in both the climate science literature (Emanuel et al. 2008) and the economics literature (Hsiang and Jina 2014; Bakkensen and Barrage 2022). The country that we calibrate the model to is Mexico, an emerging economy that is subject to substantial cyclone risk and whose business cycles are well studied in the macroeconomics literature.

3.1 Calibration

Basic parameters. We take each period to equal five years, which is appropriate for our focus on the recovery dynamics from large disasters. The use of five-year periods affords us a degree of tractability. At such horizons, capital adjustment costs are less likely to be an important part of the dynamics. Furthermore, the implied five-year maturity of the model's one-period debt is a better approximation of the average maturity of EMs' sovereign bonds than that in a quarterly or annual model. The five-year period also allows us to abstract from autocorrelation in TFP growth rates, further reducing the state space.

Given that disasters destroy both physical and human capital (Bakkensen and Barrage 2022), we follow Mankiw et al. (1992) and set $\alpha = 2/3$ as a simple way to capture both types of capital jointly. More recently, Dietz and Stern (2015) also adopted this parametrization to reflect the capital damage due to climate shocks.

We set $\beta = 0.96^5$; namely, the discount factor is 0.96 per year, which is a standard value in business cycle models (but higher than typical values in endowment-economy sovereign debt models without disaster risks such as Arellano 2008). We set depreciation rate δ to a standard value of 10% per year. We set the foreign risk-free interest rate to 1% per year, in line with recent global trends. As usual, the fact that $\beta(1 + r) < 1$ implies that the sovereign in the model is impatient relative to the market and will seek to borrow to tilt consumption and investment forward in time. For the Epstein-Zin preference parameters, we set $\iota = 0.5$ and $\gamma = 4$ as in Gourio (2012).

We choose the parameters μ_g and σ_g governing the mean and standard deviation of TFP growth shocks based on the quarterly values employed by Aguiar and Gopinath (2006, 2007). For the fractional output loss from default, based on Aguiar et al. (2016), we set the level parameter $\bar{\ell}$ at 0.07% and the curvature parameter ψ at 7. These parameter values imply that in the ergodic steady state of the model, the average debt-to-annual-GDP ratio is about 35%, and the average annual spread is about 1.6%, which are reasonable estimates for Mexico during the 2010s.

Weather shock parameters. In order to calibrate the risk and size of the weather shock, we rely on Hsiang and Jina (2014, 2015)'s well-known analysis of an extensive and carefully constructed global data set of exposure to tropical cyclones/hurricanes/typhoons during 1950-2008.[9]

On the extensive margin, we interpret the model's weather shock dummy x as corresponding to whether a country experiences a cyclone landfall in any period. We set the strike probability p (which determines the Poisson rate of

[9]Tropical cyclones are also known as "tropical storms" or "hurricanes" in the Atlantic Ocean, "typhoon" in the Pacific Ocean, and "cyclones" in the Indian Ocean. As in the empirical climate literature, we will refer to all of them simply as *cyclones*.

arrival for cyclone landfall) to match the average annual probability of 58% that at least one cyclone (of any size) makes landfall.[10] Since a model period is five years, the implied value for p is

$$p = 1 - (1 - 0.58)^5 = 0.9869.$$

This number implies that the country is almost guaranteed to be hit by at least one cyclone (big or small) over a five-year period.

On the intensive margin, we interpret the damage parameter d as corresponding to the country's cumulative damage from cyclone activity over a five-year period. Specifically, we assume that $d = \omega \times \mu$, where ω is the cumulative intensity (measured in the unit of wind speed, m/s) of the cyclones that make landfalls in a period, and μ is the marginal damage to the capital stock of each additional m/s of wind speed, normalized by the area of the country. Specifically, we set

$$\mu = 0.0895\%/\alpha = 0.1343\%,$$

to match Hsiang and Jina (2014)'s estimate that each additional m/s of wind speed per unit area causes a cumulative output loss of 0.0895% after five years.[11]

We assume that the maximum wind speed of a cyclone follows a Weibull distribution, which is known to be a good empirical approximation (Bakkensen and Barrage 2022). From Hsiang and Jina (2014)'s cyclone statistics, we set the scale parameter to 6.579, in order to match Mexico's current annual average cyclone activity of 6.6 m/s per unit area. We set the shape parameter to 0.993, in order to match the ratio of 19.5/39.2 between the strength of a 90th percentile cyclone and that of a 99th percentile cyclone. We then get the distribution of ω by the convolution of the Weibull distribution for the intensity of each cyclone that makes landfall in a period. Thus, the distribution of ω

[10] This probability is derived from Hsiang and Jina (2014)'s estimate that the annual probability of a top 10th percentile cyclone is 5.8%.

[11] We use this global average estimate since Hsiang and Jina (2014) do not report country-specific estimates. They argue that the global estimate is very robust and applies to various subsamples of countries in their data.

represents the distribution of the cumulative cyclone activity over a five-year period.

Table 1 summarizes our parameter choices.

	Parameter	Value	Source
	period length	5 years	
α	capital share	2/3	Mankiw et al. (1992)
β	discount factor	0.96^5	Standard RBC values
δ	depreciation	$1 - 0.9^5$	Standard RBC values
r	world interest rate	$1.01^5 - 1$	Standard RBC values
ι	inverse elasticity of substitution	0.5	Gourio (2012)
γ	risk aversion	4	Gourio (2012)
μ_g	mean TFP growth	$1.006^{20} - 1$	Aguiar and Gopinath (2007)
σ_g	std of TFP growth	$0.0213\sqrt{20}$	Aguiar and Gopinath (2007)
$\bar{\ell}$	default cost constant	0.07	Aguiar et al. (2016)
ψ	default cost curvature	7	Aguiar et al. (2016)
p	cyclone strike probability	0.58	Hsiang and Jina (2014)
	marginal output damage	0.000895	Hsiang and Jina (2014)
Φ_d	shape of Weibull distribution	0.993	Hsiang and Jina (2014)
	scale of Weibull distribution	6.579	Hsiang and Jina (2014)

Table 1: Calibrated parameters.

3.2 Numerical results

We now show the quantitative implications of the calibrated model: long-lasting economic effects of cyclone shocks and significant welfare consequences of increased cyclone activity due to climate change.

3.2.1 Propagation of cyclone shock

We examine the impulse responses of the economy to a one-time one-standard-deviation shock to cyclone activity. We generate the responses from the average of one million simulation paths where, in each path, we simulate the economy until it reaches the ergodic steady state. Then in a period labeled 0, there is a one-time unanticipated shock that raises the period's cumulative area-weighted cyclone activity from its ergodic steady-state average value of 24m/s by one standard deviation to 39m/s. We interpret this shock as representing the increased cyclone activity in period $t = 0$ due to the strike of a large cyclone.[12]

Figure 3 plots the impulse in the first panel and the responses of aggregate detrended variables in the remaining panels. To facilitate interpretation, given that each period of the model is five years, we divide the spread and default frequency by five and multiply the debt-to-output by five to report them in annual terms.

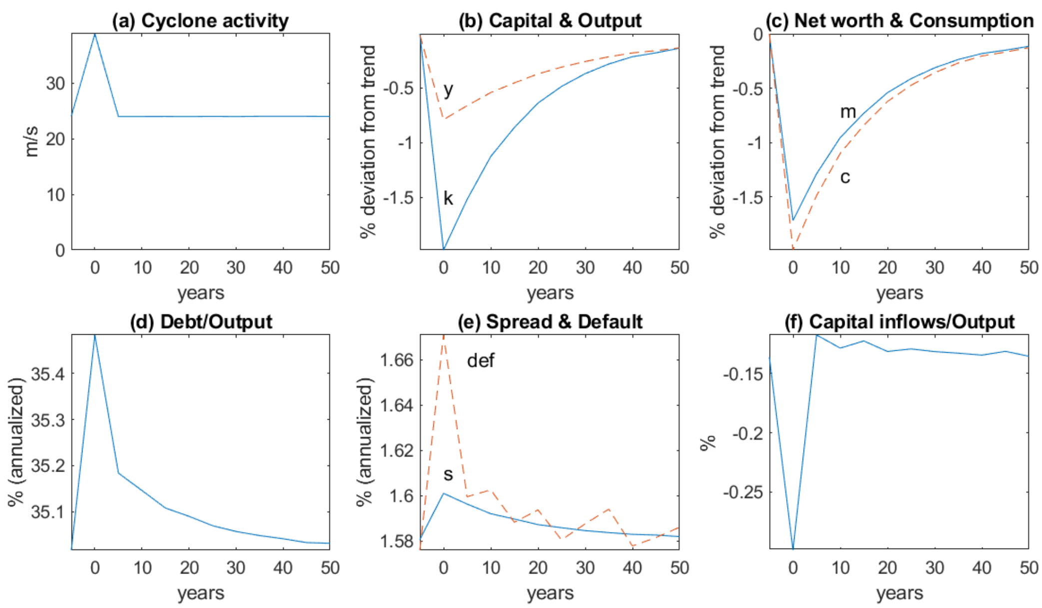


Figure 3: *Impulse responses of detrended variables to an unanticipated one-standard-deviation shock to cyclone activity.* Responses are generated from an average of one million simulation paths. In each path, the economy first reaches the ergodic steady state. Then in a period labeled 0, there is a one-time unanticipated shock that raises the period's cumulative area-weighted cyclone activity by one standard deviation. Variables on the bottom row have been annualized for easy interpretation.

[12]For comparison, the maximum sustained wind speed of a category 5 hurricane is 70m/s or higher.

Panels two and three plot the impulse responses of the detrended capital stock k_t, output flow y_t, net worth m_t, and consumption c_t. All the aggregate economic variables dip at $t = 0$, due to the damaging impact of the cyclone activity shock on the capital stock. Importantly, the model's internal propagation mechanism predicts that the economy will slowly recover in the aftermath ($t \geq 1$), with the half-life of the recovery path toward the steady state of about 20 years. This slow recovery endogenously arises due to the vicious feedback loop between the increased demand for borrowing to rebuild the damaged capital stock and the heightened default risk discussed in Section 2.

To see this further, panel four plots the impulse response of the debt over output ratio, and panel six plots the response of the spread. The ratio increases mechanically upon impact at $t = 0$, as the output denominator decreases. However, the ratio remains elevated for many years afterward, reflecting the need to issue more bonds to rebuild the capital stock. The increase in bond issuance leads to a lower bond price, as reflected by the widening spread. This is a vicious cycle at work: the increase in borrowing to raise funds to rebuild increases the default risk and reduces the revenue per bond issued, which then necessitates more bond issuance, further exacerbating the cycle.

Panel six also plots the response of the frequency of realized sovereign defaults (shown by the dashed line), which jumps upon impact at $t = 0$ due to the unexpected nature of the shock, but remains persistently high afterwards.[13] The predictions of the persistent increases in the spread and the default frequencies are consistent with the aforementioned empirical evidence (Klomp 2015, 2017).

Note that in a counterfactual environment without financial frictions, foreign credit would flow more into the country in the immediate aftermath of the cyclone shock (due to the increase in the marginal product of capital), and the economy would converge back to the steady state trend after just one period. Instead, our model predicts the opposite: foreign capital flows would *decrease*,

[13] The path of the spread is smoother than the path of the default frequency because the former is the expectation of the latter.

as shown by the decline in the capital inflows over output ratio depicted in panel six.[14] Also note that this procyclical capital inflows over output ratio (or equivalently, countercyclical trade balance over output ratio) is consistent with well-known empirical patterns of business cycles in emerging economies (Uribe and Schmitt-Grohé 2017). The decline in the capital inflows also helps explain why consumption drops more than net worth as shown in panel three.

Overall, the impulse responses underscore the importance of financial frictions in explaining the delayed recovery from cyclone strikes as well as the increased spreads and frequencies of debt crises as documented in the empirical literature.

3.2.2 Welfare cost of increased cyclone risk

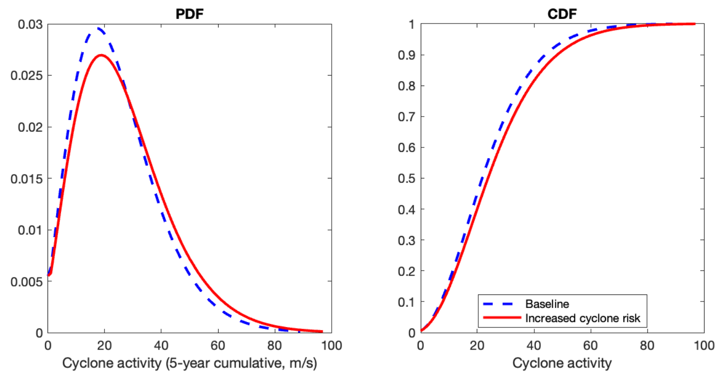
We examine the potential welfare implications of a shift in the distribution of cyclone activity due to climate change. According to projections based on the Intergovernmental Panel on Climate Change (IPCC)'s A1B scenario, the intensity of cyclone activity in the Atlantic basin that contains Mexico is expected to increase by an average of 10.3% by 2090 (Emanuel et al. 2008). We model this shift by increasing the scale parameter of the Weibull distribution for cyclone intensity by 10%. Figure 4a shows the resulting first-order stochastic shift in the distribution of cyclone activity in our model. The blue dashed lines show the probability density function and the cumulative density function for the cyclone activity in the baseline scenario (Table 1), while the red solid lines show those in the increased cyclone risk scenario (Emanuel et al. 2008).

We measure the implied welfare change for the representative agent in the country by

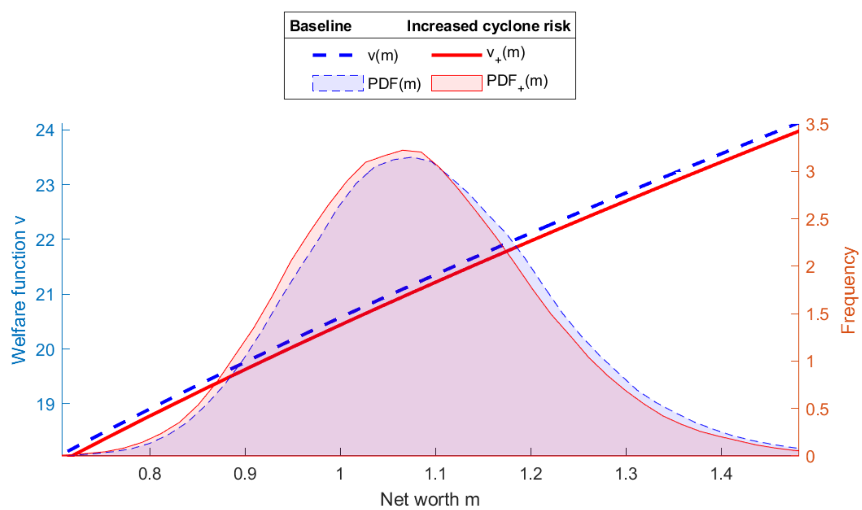
$$\Delta w := 1 - \frac{E_+[v_+(m)]}{E[v(m)]}.$$

Here, $v(m)$ denotes the lifetime utility for a given net worth level m (as defined in (2)), and $E[v(m)]$ denotes the expected lifetime utility given the distribu-

[14] We define the capital inflows as $q_t b_t^n - b_t$, where recall that b_t^n is the debt issuance at t. Hence, the capital inflows are simply the negative of the trade balance or net export.



(a) Change in the distribution of cyclone activity. The dashed lines plot the PDF and CDF of cyclone activity in the baseline calibration (Table 1). The solid red lines plot those when the scale parameter of the Weibull distribution for cyclone activity increases by 10%.



(b) Changes in the welfare functions $v(m)$ and the ergodic distributions of net worth m. The thick blue dashed line and the thick red solid line plot the sovereign country's welfare functions $v(m)$ and $v_+(m)$ in the baseline calibration and in the increased cyclone risk scenario, respectively. The blue shaded area (with a thin dashed border) labeled $PDF(m)$ and the red shaded area (with a thin solid border) labeled $PDF_+(m)$ plot the kernel density estimation of the ergodic distributions of m in the baseline calibration and in the increased cyclone risk scenario, respectively.

Figure 4: *Welfare implications of the increase in cyclone activity due to climate change.*

tion of net worth over the ergodic steady state, *under the baseline scenario*. Similarly, $v_+(m)$ and $E_+[v_+(m)]$ denote those *under the increased cyclone risk scenario*. Note that by taking into account the ergodic distributions of the state variable m, Δw measures the long-run welfare changes, hence appropriately taking into account the long-term nature of the shift in cyclone risk due to the gradual process of climate change. Furthermore, given the Epstein-Zin preference specification, Δw is also equal to the measure of welfare change in consumption equivalent units that is standard in the macroeconomics literature since Lucas (1987). That is, Δw is equal to the fraction of consumption that the representative agent in the country is willing to permanently give up (i.e., in all time periods and in all states of the world) in order to avoid the increase in cyclone activity.

There are two components of the welfare effect of the increase in cyclone risk. First, there is a downward shift of the value function from v to v_+ at any given level of net worth m. And second, there is a leftward shift in the distribution of m in the ergodic steady state.

To visualize the first component, the thick lines in Figure 4b plot v and v_+ over the relevant range of m (three standard deviations around the ergodic averages). The figure clearly shows that the welfare function shifts from the thick blue dashed line representing v to the thick red solid line representing v_+.

Figure 5 provides a closer look at this shift in v. There, the red solid line plots the loss term $1 - \frac{v_+(m)}{v(m)}$ as a function of the net worth state variable m (shown over the same range of m as in Figure 4b). The plot shows that, for any given net worth m, an increase in cyclone activity leads to a shift in the welfare function that is equivalent to about a 0.6% to 0.7% permanent loss in consumption.

However, the downward shift in the welfare function is only part of the story. This is because the wealth of the country (measured by net worth m) will endogenously adjust over time to the change in cyclone activity, which also will lead to a change in the ergodic distribution of m. Since more intense cyclones make it harder for the country to accumulate assets, the ergodic distribution of m experiences a first-order stochastic dominance shift for the worse. Visualizing this distributional shift, the blue and red shaded areas in Figure 4b plot the ergodic distribution of m in the baseline scenario and in the increased cyclone risk scenario, respectively.

Hence, over the long run, the welfare effect consists of not only the shift in v, but also the shift in the distribution of m, as appropriately captured in the definition of Δw. The first row in Table 2 reports the long-run changes. The first column shows that the leftward shift in the ergodic distribution of m due to increased cyclone activity leads to a reduction of the average net worth by nearly one percentage point (0.93%). The second column shows that, by taking into account the distribution shift in m, the change in long-run welfare Δw is about 1%. In other words, our calibrated model suggests that *the representative agent in the country is willing to permanently give up more than 1% of consumption in order to avoid the increase in cyclone activity.*

To get a sense of the economic magnitude, a welfare loss of 1% in consumption equivalent terms is significantly greater than the conventional benchmark estimate of merely 0.05% for the cost of business cycle fluctuations in the United States (Lucas 1987, 2003). This is because the increased cyclone risk not only amplifies the short-run fluctuations of consumption, but also results in larger cumulative output losses from cyclone shocks, due to the model's propagation mechanism with financial friction as shown in Section 3.2.1. Therefore, the welfare effects of increased cyclone activity are qualitatively comparable to the "mini" economic disasters that Jordà et al. (2020) account for in their revised measurement of the cost of business cycles. In particular, when taking such disasters into account, they revise the impact of fluctuations to be about 15% in consumption equivalent terms in the post-World War II era.

Finally, it is worth emphasizing that our welfare analysis solely considers the cost of heightened cyclone risk and does not incorporate other facets of climate change, such as rising average temperatures, sea level rise, or increased risks associated with heat waves, droughts, flooding, and so on. Conversely, our current calculation does not account for potential physical or financial adaptations to climate change, the latter of which we will now explore further.

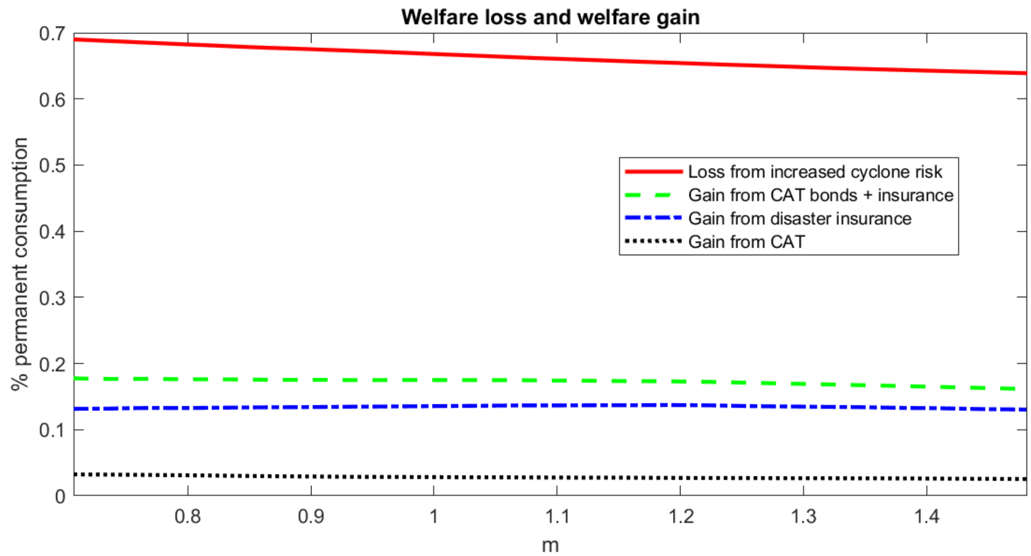


Figure 5: *Shifts in welfare functions* due to increased cyclone risk and due to financial adaptation, measured in consumption equivalent terms. The red solid line plots the loss term due to increased cyclone risk $1 - v_+(m)/v(m)$ over the relevant range of net worth m. The other lines plot the gain term due to financial adaptation $1 - v_i(m)/v_+(m)$, where $i \in$ {insurance, catastrophe bond, or both} represents different forms of financial adaptation.

	Change in the ergodic average of	
	Net worth m	Lifetime utility v
Due to increased cyclone risk		
	-0.93%	-1.07%
Due to financial adaptation		
Insurance	+0.14%	+0.20%
CAT bond	+0.04%	+0.05%
Both	+0.19%	+0.26%

Table 2: *Long-run changes in ergodic steady-state averages of net worth m and lifetime utility v.* The changes from increased cyclone risk are calculated as percent changes relative to the corresponding averages in the baseline calibration (Section 3.1). The changes from financial adaptation are calculated as percent changes relative to the corresponding averages in the calibration with increased cyclone risk (Section 3.2.2).

4 Financial adaptation

As climate change increases the strength of cyclones, we should expect adaptation to occur. One form of adaptation, which has been the focus of much of the literature, is *physical adaptation*, such as building or retrofitting structures to be more resilient to flooding (see, e.g., Barrage 2015; Fried 2022 and references therein). Another form of adaptation, which we focus on here, is *financial adaptation*, meaning the use of more sophisticated financial instruments in order to better cope with the change in climate-related risks.[15] We consider two relevant forms of financial adaptation.

4.1 Disaster insurance

We first consider disaster insurance. Bakkensen and Barrage (2022) report significant differences across countries in the insurance coverage for disaster damages, with developed countries having close to 55% of damages covered, whereas low- and middle-income countries have coverage below 12%. Von Peter et al. (2012) show that countries with higher insurance coverage suffer smaller output losses and experience faster recovery from disasters.

We consider an ideal scenario of a complete disaster insurance market, where the country can purchase disaster insurance contracts within each period *at actuarially fair prices* from competitive foreign insurers. We allow the country to purchase insurance after it observes the realized value of the period's TFP growth, but before the weather shock realizes and before the default decision (Figure 6 illustrates the timing of events within each period t). One interpretation of this timing assumption is that insurance contracts are relatively short-term compared to debt contracts.

[15]Such a form of adaptation may be a natural development to consider since, as hypothesized by Frame and White (2004), one might expect financial innovation to follow greater demand for a particular financial product. For example, the Government Accounting Office (2003) reports an interview with a mutual fund manager where they state that "given the small size of the catastrophe bond market, it did not make sense to hire experts in hurricanes or earthquakes to monitor the market" but that "if the market for catastrophe bonds expanded, the company would reconsider employing experts to better understand these securities."

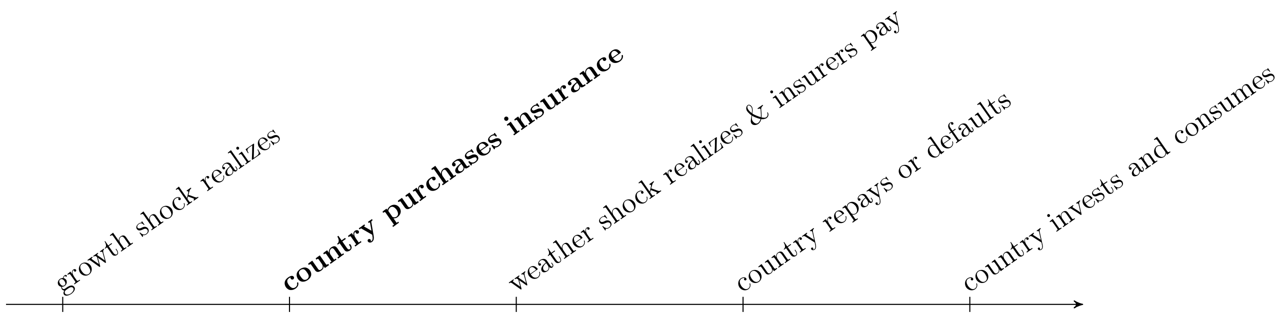


Figure 6: *Timing of events within each period.*

Importantly, we also assume that the country receives insurance payments regardless of its default decision. This assumption reflects the fact that an insurance contract is a financial asset, and it is legally complicated for foreign investors to seize the defaulting countries' assets (Bulow and Rogoff 1989).

Since the representative agent in the country is risk averse (the value function v is concave in m), and insurance is actuarially fair, the country will optimally choose full insurance. That is, the country will choose to purchase insurance so that its net worth is the same in disaster and nondisaster states (m' is the same across different realizations of x' and d'). This then leads to a simplified recursive optimization:

$$v(m)^{1-\iota} = \max_{k_n, b_n} c^{1-\iota} + \beta E\left[v\left(E[\max\left\{m'_R, m'_D\right\}|g']\right)^{1-\gamma} e^{(1-\gamma)g'}\right]^{\frac{1-\iota}{1-\gamma}},$$

subject again to equations (3) through (6). Note that the continuation value term $v(E[m'|g'])$ (where $m' = \max\{m'_R, m'_D\}$) reflects the facts that the country can insure against the weather shocks but not against the TFP shocks (i.e., while the net worth is the same across different realizations of the weather shock, it still differs across different realizations of the TFP shock g').

As in Section 3.2.2, there are two components of the welfare effects of the adoption of disaster insurance. First, there is a shift in the welfare function. Figure 5 again visualizes this shift. There, the blue dash-dotted line plots $1 - v_{insurance}(m)/v_{+}(m)$, which is the difference between the welfare function

$v_+(\cdot)$ under the increased cyclone risk scenario (as studied in Section 3.2.2) and the new welfare function $v_{insurance}(\cdot)$ under the scenario of increased cyclone risk with a complete disaster insurance market that we are studying. For any given level of m within the relevant range, the welfare gain is a little over 0.1% of permanent consumption. In other words, under the increased cyclone risk scenario, the representative agent is indifferent between having access to a complete disaster insurance market and having their consumption permanently increase by a tenth of a percentage point.

Second, the adoption of disaster insurance also implies a change in the distribution of net worth in the ergodic steady state. The second row in Table 2 shows the changes in the ergodic steady states in the increased cyclone risk scenario with and without disaster insurance. In particular, on average, net worth m is 0.14% larger in the long run thanks to disaster insurance, leading to a gain in the long-run welfare measure of approximately 0.2% (i.e., $1 - E_{insurance}[v_{insurance}(m)]/E_+[v_+(m)] = 0.2\%$). Compared to the first row in the same table, the welfare gain from disaster insurance can undo about 20% of the welfare loss due to increased cyclone risk.

Why isn't the welfare gain from having access to an actuarially fair disaster insurance market more substantial? The main reason is that while it allows for a faster recovery after a bad cyclone shock, insurance is not free—the country pays a premium to foreign insurers in each period. The insurance premium payment reduces the country's net worth and hence its ability to borrow and invest in states without a bad cyclone shock. Nevertheless, on average, disaster insurance still yields output gains due to the production function's concavity, resulting in a modest increase in wealth accumulation (and thus a slight increase in average net worth) over the long term.

4.2 Catastrophe bonds

Next, we examine the utilization of catastrophe (or CAT) bonds. These bonds operate like traditional bonds, except that their face values are automatically reduced upon the occurrence of a trigger event, typically the onset of a natural disaster exceeding a predetermined intensity threshold. The market for CAT bonds has experienced substantial growth in the last decades (Artemis 2020). However, with few exceptions such as Grenada, which issued bonds with explicit hurricane clauses following the extensive destruction of its capital stock by Hurricane Ivan, CAT bonds have yet to be widely adopted by vulnerable countries (Asonuma et al. 2018).

For simplicity, we model CAT bonds as bonds that have a face value of zero if a cyclone hits and the realized damage is above a certain (exogenous) threshold ($x = 1$ and $d > \bar{d}$). We maintain the assumption that the country loses a fraction of its output as long as *any* of its debt is defaulted upon. Hence, should the country want to default, it will always default on all the bonds and not just CAT or non-CAT bonds.

In each period, the country can choose how many regular bonds and how many CAT bonds to issue. Let $\theta \in [0, 1]$ denote the fraction of CAT bonds in total debt issuance. Then, the problem of the country becomes:

$$v(m)^{1-\iota} = \max_{k_n, b_n, \theta} c^{1-\iota} + \beta E \left[v(\max\{m'_R, m'_D\})^{1-\gamma} e^{(1-\gamma)g'} \right]^{\frac{1-\iota}{1-\gamma}},$$

subject to

$$\begin{aligned}
c &= m - k_n + q(b_n, k_n, \theta) b_n \\
b' &= (1 - T'\theta) e^{-g'} b_n, \ k' = e^{-x'd' - g'} k_n \\
m'_R &= k'^{\alpha} + (1 - \delta) k' - b', \ m'_D = (1 - \ell(g')) k'^{\alpha} + (1 - \delta) k' - 0,
\end{aligned}$$

where T' is the dummy for a "trigger event":

$$T' = x' \ 1_{d' > \bar{d}} \ 1_{b^n \geq 0}.$$

In words, the trigger event will be activated (and hence the next-period debt b' will be reduced by a fraction θ) if a sufficiently strong disaster hits ($x' = 1$ and $d' > \bar{d}$) and if debt issuance is nonnegative ($b^n \geq 0$).

In addition, observe that q now represents the price of the entire bond portfolio. It will be dependent on θ, not only because lenders will require an insurance premium for disaster relief, but also because the utilization of CAT bonds influences the country's incentive to default. In particular, q now becomes:

$$q(b_n, k_n, \theta) = \frac{1 - s\left(\bar{g}(b_n, k_n), \theta\right)}{1 + r},$$

where s denotes the spread as a function of the threshold $\bar{g}$ as defined in (7) and of the CAT fraction θ. In the simple case of $\bar{d} = 0$ (i.e., the trigger event is simply the onset of any disaster), s has a straightforward expression:

$$\begin{aligned} s(\bar{g}, \theta) = &(1-p)\Phi_g(\bar{g}) + pE_{d'}\Phi_g\left(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d' + \underbrace{\frac{1}{1-\alpha+\psi}\ln(1-\theta)}_{\text{<0, reduced default risk}}\right) \\ &+ \underbrace{p\theta\left\{1 - E_{d'}\Phi_g\left(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d' + \frac{1}{1-\alpha+\psi}\ln(1-\theta)\right)\right\}}_{\text{>0, "CAT/insurance premium"}}. \end{aligned}$$

The equation implies that increasing the fraction of CAT bonds has two countervailing effects on the equilibrium spread function. On the one hand, it reduces the risk of default in the state with a cyclone shock, generating a net benefit for the lender since they will be able to retain the face value of regular bonds. On the other hand, lenders require an "insurance premium" in exchange for the state contingency of the CAT bonds. In particular,

$$\frac{\partial s}{\partial \theta} = p(1 - \Phi(\bar{g}^d))\left(\frac{\tilde{h}\left(\bar{g}\right)}{1-\alpha+\psi} - 1\right),$$

where $\tilde{h}(\bar{g})$ was defined in Proposition 1. With the growth shocks g normally distributed, the function $h(g)$ starts at zero and increases toward infinity. Therefore, there is a "CAT bond Laffer curve," in the sense that the spread decreases for small values of the CAT fraction θ and increases otherwise. Consequently, the country will not choose to set θ at a very low value, since by increasing it, the country can get more insurance and issue debt at a more favorable price.

Given the increased cyclone risk, what are the welfare implications of the adoption of CAT bonds? As before, Figure 5 plots the shift in the welfare function at any given value of net worth m in the relevant range, and the third row in Table 2 shows the overall welfare change that takes into account not only the shift in the welfare function, but also the shift in the distribution of net worth.[16] Both the figure and the table show that the welfare gain from CAT bonds is smaller than that from disaster insurance. Specifically, Table 2 shows that the long-run gain in welfare from CAT bond issuance is only about 0.05% in consumption equivalent terms (while the gain from disaster insurance is 0.20%). One reason why CAT bonds fall short of insurance is that the bonds only help hedge the risk of a large cyclone if the country does not default. However, the incentive to default is heightened exactly when a large cyclone strikes.[17] A second reason is that the bonds have to be issued one period in advance (while disaster insurance contracts can be purchased within the same period). Since the country is impatient relative to foreign lenders, the country will prefer to hedge the disaster risk using shorter-term disaster insurance contracts than using longer-term CAT bonds. Finally, as pointed out by Mallucci (2022), the introduction of CAT bonds reduces the borrowing cost per unit of bond issuance, leading to more accumulation of debt, which in turn leads to higher consumption in the short run but lower net worth and hence lower consumption and utility in the long run.

Finally, we explore the welfare gain from the combination of having access to a complete insurance market and being able to issue CAT bonds. The green dashed line in Figure 5 plots the change in the welfare function at any given value of m, and the last row of Table 2 shows the overall welfare change in the long run. Table 2 shows that the combination of both forms of financial adaptation can increase the country's welfare by 0.26% in consumption equivalent

[16] In the quantitative exercise, we set the trigger threshold $\bar{d}$ to be at the 90th percentile of cyclone damage (or equivalently, the CAT clause is triggered if the cyclone activity in a period is above the 90th percentile of its distribution).

[17] To see this further, consider an extreme case of a country that always defaults in response to disasters above the CAT bond threshold. For that country, CAT bonds add little insurance benefit.

units. That is, the combination can undo about *a quarter* of the total welfare loss from the increased cyclone risk due to climate change. The fact that the welfare gains from the financial adaptation instruments add up emphasizes the ways in which the two instruments complement each other. On the one hand, disaster insurance allows the country to smooth wealth across states and helps the country rebuild capital after cyclone strikes. However, since the country receives insurance payments regardless of its default decision, the presence of insurance does not affect the default incentive and hence does not affect the borrowing cost. On the other hand, CAT bonds are less useful for insurance but help countries avoid costly defaults in disaster states and help reduce the effect of the disaster risk on raising the country's borrowing costs.

5 Conclusion

In summary, this paper provides a new analysis of the impacts of adverse weather shocks on the debt and investment dynamics in emerging economies, the welfare effects of climate change, and the effectiveness of financial adaptation strategies. We believe that the tractable model and its quantitative assessment can help policymakers better understand the channels through which climate and financial risks interact. This insight, we hope, will enable them to make well-informed decisions on approaches to reduce the impact of climate-related natural disasters. Overall, our calibrated exercise underscores both the nontrivial potential welfare gains and the limitations of financial adaptation.

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A Omitted proofs

A.1 Proof of Proposition 1

Proof. First, let us prove (7). The country defaults if and only if $m'_R < m'_D$. From net worth definitions (5) and (6), we know that this is the case if and only if the debt over GDP is sufficiently high: $\frac{b'}{(k')^\alpha} > \ell(g')$. Given definitions (1), (3), and (4), this is in turn equivalent to:

$$\frac{e^{-g'}b_n}{e^{-\alpha x'd'-\alpha g'}k_n^\alpha} > \bar{\ell}e^{\psi g'},$$

or

$$\frac{b_n}{\bar{\ell}k_n^\alpha} > e^{(1-\alpha+\psi)g'},$$

which yields (7).

Given (7), the spread or probability of default is then given by (9):

$$s(b_n, k_n) = (1-p)\Phi_g(\bar{g}(b_n, k_n)) + p\int \Phi_g\left(\bar{g}(b_n, k_n) + \frac{\alpha}{1-\alpha+\psi}d'\right)d\Phi_d(d').$$

Taking partial derivatives:

$$\begin{aligned}
\frac{\partial s}{\partial b_n} &= \left[(1-p)\phi_g(\bar{g}) + p\int \phi_g(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d')d\Phi_d(d')\right]\frac{\partial \bar{g}}{\partial b_n},\\
\frac{\partial s}{\partial k_n} &= \left[(1-p)\phi_g(\bar{g}) + p\int \phi_g(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d')d\Phi_d(d')\right]\frac{\partial \bar{g}}{\partial k_n},
\end{aligned}$$

where

$$\begin{aligned}\frac{\partial\bar{g}}{\partial b_n} &= \frac{1}{1-\alpha+\psi}\frac{1}{b_n}\\ \frac{\partial\bar{g}}{\partial k_n} &= -\frac{\alpha}{1-\alpha+\psi}\frac{1}{k_n}.\end{aligned}$$

Combining these four equations yields the following expressions for the elasticity of the spread function:

$$\begin{aligned}\frac{b_n}{s}\frac{\partial\bar{g}}{\partial b_n} &= \frac{1}{1-\alpha+\psi}\tilde{h}(\bar{g})\\ \frac{k_n}{s}\frac{\partial\bar{g}}{\partial k_n} &= -\frac{\alpha}{1-\alpha+\psi}\tilde{h}(\bar{g}),\end{aligned}$$

where $\tilde{h}(\bar{g}) = \frac{(1-p)\phi_g(\bar{g})+p\int\phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')d\Phi_d(d')}{(1-p)\Phi_g(\bar{g})+p\int\Phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')d\Phi_d(d')}$, as stated in the proposition. □

A.2 Proof of Proposition 2

Proof. Given (9), the partial derivative of s with respect to p is:

$$\frac{\partial s}{\partial p} = -\Phi_g\left(\bar{g}\right) + \int \Phi_g\left(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d'\right)d\Phi_d(d').$$

Since the support of Φ_d is $[0,\infty)$, it follows that $\frac{\partial s}{\partial p} > -\Phi_g(\bar{g}) + \int \Phi_g(\bar{g})d\Phi_d(d') = 0$, i.e., the spread is increasing in the probability of the bad weather shock, as desired.

Furthermore, suppose $\hat{\Phi}_d$ first-order stochastic dominates Φ_d. Let $\hat{s}$ denote the spread function associated with the damage distribution $\hat{\Phi}_d$. Since $\Phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')$ is increasing in d', it follows that $E[\Phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')|\hat{\Phi}_d] \geq E[\Phi_g(\bar{g}+\frac{\alpha}{1-\alpha+\psi}d')|\Phi_d]$. It then immediately follows that $\hat{s} \geq s$, as desired. □