Macroeconomic Implications of Catastrophe Bond Adoption

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Abstract

This study analyzes indemnity and parametric catastrophe (CAT) bonds as financial instruments against chronic flooding in emerging economies like Thailand, utilizing a dynamic small-open-economy model with sovereign default risk and Epstein-Zin preferences. Results show both instruments cushion macroeconomic drops, but their welfare impacts differ due to competing forces. Parametric bonds offer superior welfare gains under baseline climate conditions due to a spread-efficiency effect that lowers borrowing costs. Conversely, indemnity bonds excel under severe climate change via a tail-risk-smoothing effect, providing guaranteed payouts that become vital as flood frequencies rise. Although parametric bonds remain more financially efficient, climate change significantly narrows the welfare gap between the two instruments. These findings advocate for a stratified disaster risk framework that strategically layers rapid-paying parametric tranches with exact-match indemnity buffers to balance cost savings against tail-risk protection.

Keywords: Catastrophe Bond, Flood, Climate Change, Sovereign Default
JEL Classification: E44, G22, H12, H63, Q54

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1 Introduction

Climate change increasingly exposes developing economies to a joint macroeconomic and financial-stability problem. Extreme weather events impose especially large costs on economies constrained by limited adaptation and recovery capacities (Noy, 2009; Noy and Nualsri, 2011). Floods remain among the most pervasive and economically disruptive hazards, with exposure rising as population and assets concentrate in high-risk areas (Jongman et al., 2012). The IPCC further highlights that high-emissions scenarios increase the likelihood of intense precipitation and large-scale flooding (Intergovernmental Panel on Climate Change (IPCC), 2023). For vulnerable nations, recurrent flood shocks therefore interact with public capacity constraints and can become a persistent source of instability in output, public finances, and external financing conditions (Winsemius et al., 2016; Klomp, 2015; Di Tommaso et al., 2023; Mallucci, 2022).

Floods affect the macroeconomy through several mutually reinforcing channels. They destroy productive capital, depress output, and disrupt supply chains (Noy, 2009; Fomby et al., 2013; Haraguchi and Lall, 2015). They also weaken private balance sheets, reducing household consumption and welfare through credit and collateral constraints (Kurosaki, 2015; Karim, 2018; Noth and Schüwer, 2023). At the same time, emergency relief and reconstruction spending under tight fiscal constraints can raise public debt burdens and sovereign risk premia (Noy and Nualsri, 2011; Klomp, 2015, 2017; Mallucci, 2022; Schumacher et al., 2020). Higher spreads then tighten borrowing conditions and discourage private investment (Uribe and Yue, 2006; Neumeyer and Perri, 2005). In financially integrated open economies, these effects may be amplified by diminished capital inflows or outright capital flight (Klomp, 2017; Yang, 2008; Anuchitworawong and Thampanishvong, 2015). As a result, reliance on discretionary budget reallocations or post-disaster debt issuance can generate macro-financial feedbacks that compound and prolong aggregate welfare losses (Noy, 2009; Mallucci, 2022).

Insurance-linked securities (ILS), including catastrophe and resilience bonds, offer one way to alter this transmission mechanism by transferring disaster risk to capital markets in exchange for yield-bearing premiums (Schumacher et al., 2020; Song et al., 2024). Focusing on catastrophe (CAT) bonds, this paper studies how state-contingent principal forgiveness can relax fiscal and external financing constraints when predefined disaster triggers are met. The macroeconomic value of these instruments, however, depends on trigger design. Indemnity triggers link payouts to realized losses, providing close loss alignment, but require verification and loss adjustment that can delay or dilute effective relief (Cummins and Weiss,

2009). Parametric triggers instead rely on observable hazard metrics, allowing faster and more transparent payouts, but expose issuers to basis risk when the index does not perfectly match realized economic losses (Cummins et al., 2004). The central economic trade-off is therefore between spread efficiency and tail-risk smoothing: parametric contracts may lower equilibrium borrowing costs by avoiding verification frictions, while indemnity contracts may provide more reliable insurance in severe disaster states. Quantifying how these distinct contract designs operate through macro-financial channels is central to assessing their sovereign policy value.

The core problem motivating this study is that many flood-prone developing economies remain exposed to repeated climate shocks while lacking financing arrangements that can simultaneously stabilize fiscal positions and sustain external funding conditions (Noy, 2009; Noy and Nualsri, 2011; Mallucci, 2022). Although CAT bonds are promising tools to smooth post-disaster public spending and limit ad hoc borrowing, policymakers face uncertainty regarding their broader macroeconomic effectiveness, particularly for chronic hazards such as floods that inflict heavy economic costs without always reaching rare, humanitarian crisis thresholds. This uncertainty matters because flood-induced welfare losses are driven not only by direct physical damages but also by second-round macro-financial spillovers, which are precisely the margins that contingent financing is designed to influence (Mallucci, 2022; Uribe and Yue, 2006).

This paper addresses three related gaps in the literature. First, while prior work stresses the fiscal benefits of CAT bonds in stabilizing post-disaster public spending and borrowing (Suanin and Wattanakoon, 2023; Maran, 2023), their general-equilibrium implications across key macroeconomic welfare determinants remain less well understood. Second, existing macro-focused research concentrates heavily on low-frequency, high-impact disasters such as hurricanes (Mallucci, 2022; Phan and Schwartzman, 2024), leaving uncertain whether these mechanisms extend to chronic, persistent flood risks prevalent in developing economies. Third, despite the centrality of trigger choice and basis risk in practice (Cummins et al., 2004; Cummins and Weiss, 2009), little quantitative guidance exists on how indemnity versus parametric structures alter macroeconomic trajectories. Bridging microeconomic index insurance theory (Clarke, 2016) and asset-pricing models of moral hazard (Lee and Yu, 2002), we characterize conditions under which parametric liquidity can dominate indemnity verification frictions, and show when this ranking is weakened by basis risk and tail-risk concerns.

Against this backdrop, this paper extends the general-equilibrium sovereign climate-finance

framework of Phan and Schwartzman (2024) to evaluate the macroeconomic and welfare implications of sovereign CAT bond adoption in a flood-prone small open economy, using Thailand as a case study. Within this framework, the analysis addresses three related objectives. *First*, it examines how CAT bond adoption influences key macroeconomic and welfare outcomes, including capital accumulation, output, net worth, consumption, sovereign debt dynamics, borrowing spreads, and international capital flows, following exogenous flood shocks. *Second*, it compares alternative CAT bond trigger structures, namely indemnity and parametric contracts, to assess how the trade-off between verification frictions and basis risk affects macroeconomic stabilization and sovereign financing conditions. *Third*, it examines how worsening climate conditions affect the welfare trade-off between spread efficiency and tail-risk smoothing, thereby shaping the relative desirability of indemnity and parametric CAT bonds.

Thailand provides an informative environment for the analysis. First, its chronic exposure to recurrent, economically meaningful flooding makes it a natural laboratory for studying climate shocks as a persistent macroeconomic disturbance rather than an isolated tail event (Darnkachatarn and Kajitani, 2024). Second, Thailand's deep integration with global financial markets ensures that sovereign risk perceptions and external financing conditions serve as primary macroeconomic transmission channels, where yield spreads and capital flows tightly drive domestic fluctuations (Neumeyer and Perri, 2005; Uribe and Yue, 2006; Hutchison and Noy, 2006). Third, as a middle-income economy facing dual fiscal constraints and escalating climate exposure, Thailand represents a broader class of developing nations that must strategically pair structural infrastructure investments with credible sovereign financing instruments to mitigate macroeconomic volatility and aggregate welfare losses (Darnkachatarn and Kajitani, 2024).

Our contribution is twofold. First, building on the sovereign climate-finance framework of Phan and Schwartzman (2024), we extend the analysis to compare alternative CAT bond trigger structures within a unified general equilibrium setting with sovereign default risk and recursive preferences. This framework allows us to trace how differences in contract design propagate through borrowing conditions, investment decisions, default incentives, and welfare outcomes under climate-related disasters. Second, we characterize a non-linear relationship between financial efficiency and aggregate welfare. Under sufficiently low basis risk, parametric bonds generate lower equilibrium borrowing spreads than indemnity bonds because they avoid verification frictions. Nonetheless, this pricing advantage does not necessarily translate into a proportional welfare gain. The welfare ranking depends on the balance

between lower borrowing costs and exposure to basis risk in severe disaster states. When risk aversion is moderate, the spread-efficiency advantage of parametric contracts dominates. When risk aversion is high and climate conditions worsen, the tail-risk-smoothing value of indemnity contracts becomes increasingly important, narrowing the welfare advantage of parametric bonds.

The remainder of the paper proceeds as follows. Section 2 provides an overview of the flooding situation in Thailand and its fiscal implications. Section 3 presents the model, characterizes equilibrium, and explains how CAT bond adoption and trigger design enter the economy's fiscal and external financing constraints. Section 4 provides the quantitative analysis using calibrated parameters consistent with a small open economy like Thailand and reports the macroeconomic and welfare implications across policy regimes. Section 5 concludes with implications for disaster risk finance and climate-resilient macroeconomic policy in Thailand and comparable developing economies.

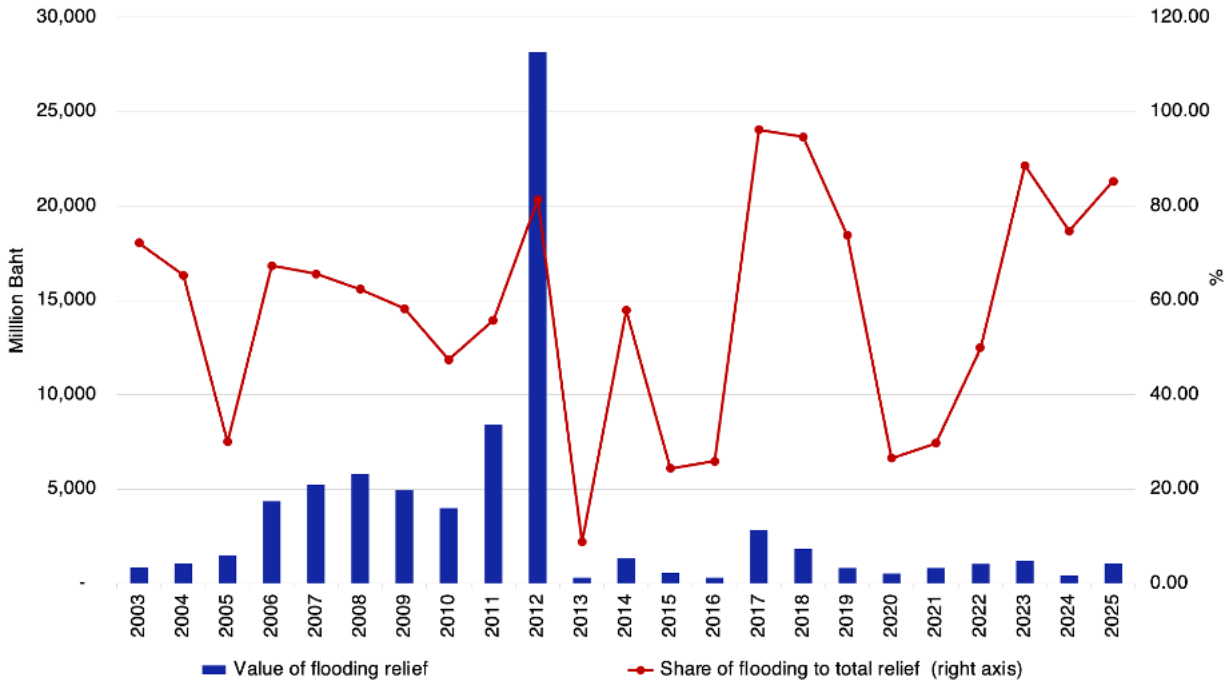
2 First look: Flooding in Thailand

Administrative data on requests for central-budget appropriations to reimburse the government's advance funds for emergency disaster relief in flood cases indicate that flood-related incidents occur every year and that floods account for the largest share of disaster-related emergency compensation over 2003-2025 (Figure 1). On average, flood compensation represents roughly 59% of total reimbursements during this period, rising to more than 80% in 2025. Province-level patterns (Figure 2) further show that, over the past two decades, a substantial portion of flood-related reimbursements has been concentrated in Pathum Thani, Nonthaburi, Phra Nakhon Si Ayutthaya, Bangkok, Nakhon Si Thammarat, Tak, and Sukhothai, in that order.

The 2011 floods provide a stark benchmark episode, illustrating how flood shocks can propagate through production networks, public finances, and market sentiment. The World Bank estimates that the 2011 floods affected more than 13 million people, caused over 680 fatalities, and generated total damages and losses of THB 1.43 trillion (approximately US$46.5 billion), with the manufacturing sector bearing a disproportionate burden around 70% of total damages and losses (World Bank, 2012). The combined damages and losses were equivalent to 12% of Thailand's GDP in 2011.

Importantly, flooding has continued to recur in recent years, reinforcing its status as a chronic

Figure 1: Central budget allocations to reimburse the government's contingency (advance) fund for emergency disaster relief in flood cases, fiscal years B.E. 2003-2025



Source: The Department of Disaster Prevention and Mitigation (DDPM)

risk. In late 2024, floods in southern Thailand affected nearly 534,000 households and necessitated the establishment of numerous temporary shelters.[1] Additional monsoon-related flood and landslide episodes in 2024 resulted in 22 deaths and affected about 30,000 households[2]. In 2025, flooding affected 16 provinces and more than 100,000 households, underscoring the frequency with which large-scale events can occur.[3]

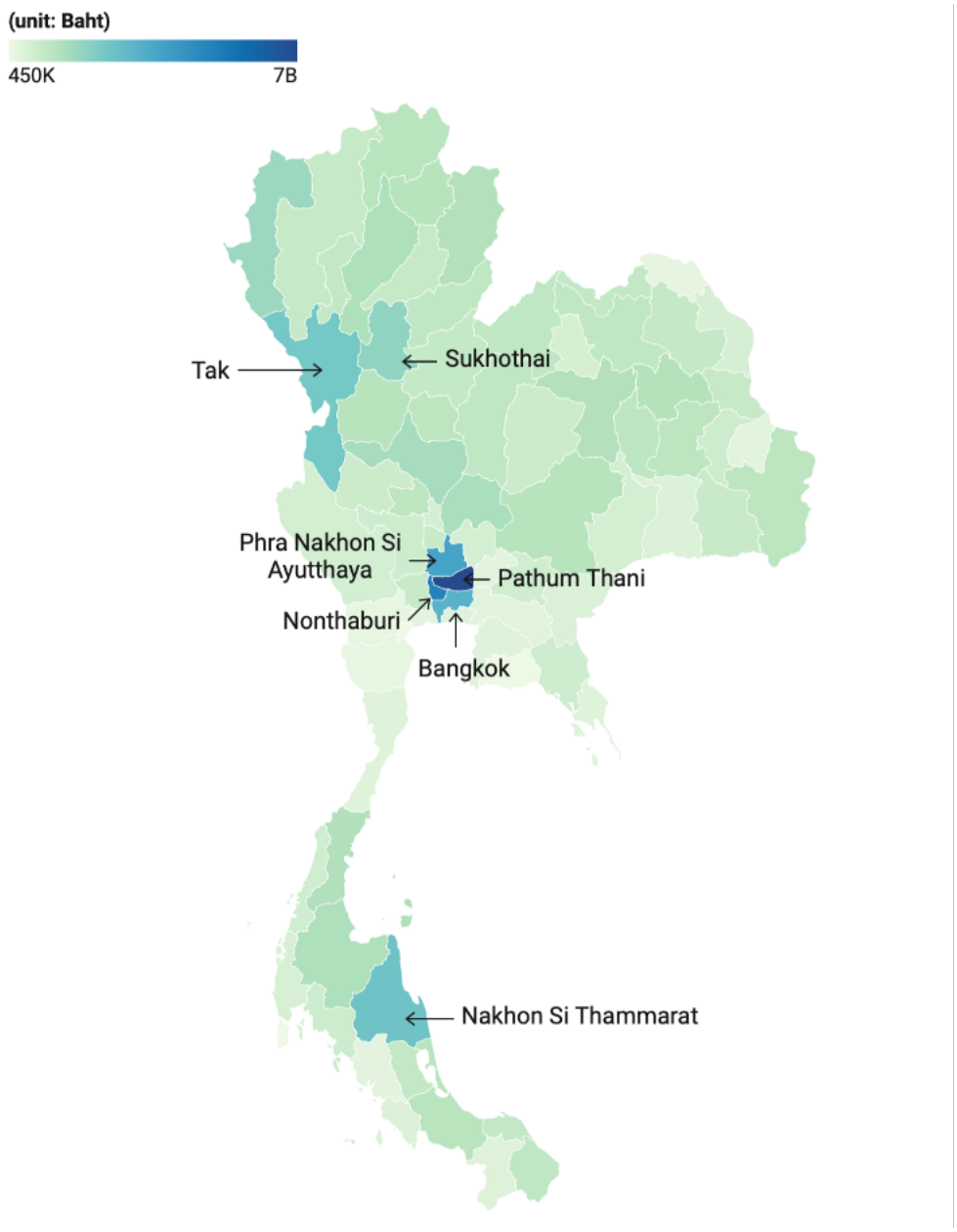
The fiscal burden of flooding extends beyond immediate relief expenditures to encompass sizable reconstruction spending and long-term investments in flood prevention and water management following major events. World Bank (2012) estimates post-2011 recovery and reconstruction needs at approximately THB 1.5 trillion (about US$50 billion), representing a substantial claim on Thailand's fiscal resources. Consistent with this scale, the Cabinet approved an emergency decree authorizing borrowing of THB 350 billion to finance flood

[1]Reuters. Death toll rises to 12 as Thailand and Malaysia face worst floods in decades. November 30, 2024.

[2]Reuters. Thailand warns against severe floods that killed 22. August 26, 2024.

[3]Reuters. Thailand warns against severe floods that killed 22. August 26, 2024.

Figure 2: Central budget allocations to reimburse the government's contingency (advance) fund for emergency disaster relief in flood cases, fiscal years B.E. 2003-2025, by province (unit: baht)



Source: The Department of Disaster Prevention and Mitigation (DDPM)

rehabilitation and prevention, and subsequently increased the fiscal-year 2012 budget deficit ceiling from THB 350 billion to THB 400 billion to accommodate larger reconstruction outlays.[4] The legal basis for this borrowing program is detailed in the emergency decree published by the Public Debt Management Office, which authorizes the Ministry of Finance to borrow up to THB 350 billion for comprehensive water management and related national development objectives, with borrowing permitted through June 30, 2013. Beyond direct fiscal measures, the Bank of Thailand was empowered to support THB 300 billion in soft loans to assist affected firms and households, indicating that flood-related burdens can also be transmitted through financial-stability and monetary-policy channels.

Taken together, these statistics motivate three important points to the study of disaster risk financing instruments. First, flooding in Thailand is frequent and generates cumulative nationwide losses. Second, when severe episodes occur, as in 2011, the macroeconomic scale of damages can exceed 10% of GDP. Third, the associated fiscal response can be large, spanning both reconstruction expenditures and sizable, event-specific borrowing programs. These features provide empirical grounding for why pre-arranged liquidity instruments that reduce reliance on ad hoc post-disaster borrowing (e.g., catastrophe bonds) are of direct policy relevance in the Thai context and potentially any other developing countries in a similar environment.

3 Model

3.1 Baseline Set-up

The small open economy with a representative sovereign government is modeled in the same fashion as Phan and Schwartzman (2024). Only a single consumption good from capital (K_t) and labor, which is supplied inelastically, is produced following a Cobb-Douglas production function:

$$Y_t = (e^{-x_t d_t} K_t)^{\alpha} (A_t)^{1-\alpha}, \text{ where capital share } \alpha \in (0,1)$$

where A_t is total factor productivity assumed to follow a random walk with the identically and independently distributed (i.i.d.) growth shock g_t: $\log \frac{A_{t+1}}{A_t}$ from a distribution Φ_g.

Weather shocks: Flood is modeled as exogenous shocks x_t and d_t, which are the extensive and intensive margins of a stochastic process of disaster. The dummy variable, x_t, appears as 1 if there is a bad weather shock or a flood hits the economy, and 0 otherwise. The

[4]Reuters. Factbox: Thailand's flood management plans and funding. January 19, 2012.

continuous variable, $d_t \geq 0$, represents the level of damage of flood toward the capital stock. The probability of a bad weather shock is a constant $\Pr(x_t = 1) = p$ and the damage d_t follows i.i.d. distribution Φ_d with support over $[0, \infty]$

Preferences: The representative government maximizes Epstein and Zin (1989) recursive preferences as follows:

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

where ι, γ, β are the inverse intertemporal elasticity of substitution, the relative risk aversion coefficient and the discount factor, respectively, while C_t is treated as government consumption in the current period. Following macrofinance literatures i.e. Bansal and Yaron (2004) and Cai and Lontzek (2019), only a relevant range of ι is bounded within 1.

Sovereign borrowing: The government has access to one-period non-contingent bonds issued by risk-neutral international lenders with a promise to repay one unit of consumption good in the subsequent period. The country can decide either to repay the debt or default. If the country decides to default, it needs to bear deadweight loss of a fraction ℓ_t of the country's output in the same version as Aguiar et al. (2016). Following Adam and Grill (2017), we assume that it can regain access to the international credit market immediately after default in the sense that next period bond issuance is possible after mispayment. The government has tendency to default in a low-growth state. The specification of a procyclical fractional loss $\ell_t = \ell(g_t)$ is defined as:

$$\ell(g') = \bar{\ell} e^{\psi g'}, \; \psi \geq 0, \; \bar{\ell} > 0, \tag{3.1}$$

where g' and ψ are next period growth shock and the responsiveness of the default to the loss fraction.

Optimization Problem: After the growth and weather shocks are realized in period t, the government chooses (i) to repay or to default on its outstanding debt, (ii) the value of new bonds issued (b_n), and (iii) new capital investment (k_n). All variables are detrended by the productivity A_t and detrended variables were written in lowercases (i.e. $\nu_t = \frac{V_t}{A_t}$, $k_t = \frac{K_t}{A_t}$). The government has the following optimization problem with one state variable: the country's net worth, m:

$$\nu(m)^{1-\iota} = \max_{k_n \geq 0, b_n} c^{1-\iota} + \beta E \Big[\nu(\max\{m'_R, m'_D\})^{1-\gamma} e^{(1-\gamma)g'} \Big]^{\frac{1-\iota}{1-\gamma}} \tag{3.2}$$

subject to budget constraint:

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

where b_n and k_n are the value of new bond issued and capital investment, and $q(b_n, k_n)$ represents the bond price schedule. The budget constraint reflects that government consumption must not exceed the sum of the country's net worth m and the value of newly issued bond $q(b_n, k_n)b_n$ net new capital investment. The detrended next-period debt (b') and capital stocks (k') after the realized subsequent-period shocks are as follows:

$$\begin{aligned} b' = &\quad e^{-g'} b_n \\ k' = &\quad e^{-x'd'-g'} k_n \end{aligned}$$

The country's net worth in the next period is defined as $m' = \max\{m'_R, m'_D\}$, which is equal to m'_R if the government repays the debt, while m'_D if the government decides to default, is given by:

$$m'_R = (k')^\alpha + (1-\delta)k' - b' \tag{3.3}$$

$$m'_D = (1-\ell(g'))(k')^\alpha + (1-\delta)k', \tag{3.4}$$

where δ is depreciation rate.

The decision to default comes when its debt over GDP is greater than the output lost fraction $\ell(g')$:

$$m'_R < m'_D \Leftrightarrow \underbrace{\frac{b'}{k'^\alpha}}_{\text{debt to GDP}} > \ell(g') \Leftrightarrow \underbrace{g' - \frac{\alpha}{1-\alpha+\psi}x'd'}_{\tilde{g}'} < \underbrace{\frac{1}{1-\alpha+\psi}\ln\frac{b_n}{\ell k_n^\alpha}}_{\bar{g}(b_n,k_n)} \tag{3.5}$$

With a fractional loss of default from equation 3.1 substituted into the above default condition, we find that the country decides to default when the weather-adjusted growth term $\tilde{g}' = g' - \frac{\alpha}{1-\alpha+\psi}x'd'$, which expresses the damage toward capital stock, is less than an endogenous default threshold $\bar{g}(b_n, k_n) = \frac{1}{1-\alpha+\psi}\ln\frac{b_n}{\ell k_n^\alpha}$.

Phan and Schwartzman (2024) found that the difference between $\bar{g}$ and $\tilde{g}'$ is the distance to default. Equation 3.5 indicates the default threshold $\bar{g}$ rises with higher debt level (b_n) and falls with next-period capital stock (k_n), implying that default risk rises with greater debt and falls with higher future capital. The expression also underscores the importance of

cyclical default costs. As the parameter ψ increases, amplifying the responsiveness of default costs to the growth shock g', the sensitivity of the default threshold $\bar{g}$ to changes in debt and capital stock diminishes.

Bond: The equilibrium bond price schedule defines the price per unit of sovereign debt as a function of the country's borrowing decisions. In a competitive credit market with risk-neutral lenders who account for the possibility of default, this schedule is determined by:

$$q(b_n, k_n) = \frac{1 - s(b_n, k_n)}{1 + r}, \forall b_n, k_n, \tag{3.6}$$

where r is the world risk-free interest rate assumed to be constant and taken for a small open economy, and s is the sovereign default spread defined as the probability of default with repayment and default net worth (m'_R and m'_D from equations 3.3 and 3.4) as follows:

$$\begin{aligned} s(b_n, k_n) &= \Pr[m'_R < m'_D] \\ &= \Pr[\tilde{g}' < \bar{g}(b_n, k_n)] \\ &= (1-p)\Phi_g(\bar{g}) + p\mathbb{E}_{d'}\left[\Phi_g\Big(\bar{g} + \frac{\alpha}{1-\alpha+\psi}d'\Big)\right] \end{aligned} \tag{3.7}$$

The function s is the spread between the price of a risk-free bond and the price of a bond issued by the country. Equation 3.7 illustrates how disaster risk influences the bond spread schedule. Conceptually, default is a tail event that occurs when economic conditions deteriorate to the point where the cost of repayment exceeds the output loss from default. The introduction of disaster risk effectively alters the distribution of the growth shock from g' to $\tilde{g}'$. Since the distribution of $\tilde{g}'$ exhibits a fatter left tail compared to that of g', the presence of disaster risk increases the likelihood of adverse economic realizations. Consequently, this raises the probability of default for any given level of debt b_n and future capital k_n.

The shape of the spread schedule s determines how sensitive the economy's borrowing cost is to disaster risk. Phan and Schwartzman (2024) established that equilibrium spreads increase with higher levels of debt issuance and declines with higher next-period capital. This result directly follows from the observation that the default threshold ($\bar{b}$) is decreasing in new capital investment (k_n) hereby reducing the size of the default region as characterized in equation 3.5. Therefore, the interaction between capital, debt, and sovereign spreads generates a vicious feedback loop. A decline in the capital stock from disaster leads to higher spreads, in turn raising the cost of borrowing and constrain further capital accumulation. This self-reinforcing mechanism amplifies economic vulnerability and plays a critical role in the transmission of

weather shocks, as explored in the quantitative analysis presented in Section 4.

3.2 Catastrophe Bond Adoption

We explore the use of CAT bonds, which function similarly to traditional bonds but include an important contingency feature: their face value is automatically reduced if a predefined trigger event occurs, typically when a natural disaster surpasses a specified intensity threshold. We consider two different trigger types for CAT bond: indemnity loss and parametric triggers. An indemnity loss trigger pays out based on the actual damages (d') if such loss is above the threshold ($\bar{d}$). The issuer then obtains the compensation equal to the excess damages incurred by the issuer ($d' - \bar{d}$). In contrast, a parametric trigger releases payouts when pre-defined physical measures, such as flood depth or rainfall intensity (ω), exceed a set threshold ($\bar{\omega}$), despite of the actual monetary losses. The issuer will then receive a fixed compensation (μ_{pt}).

Regardless of CAT bond triggers, we set the country's optimization problem as follows: The representative government need to decide the composition (θ) of debt issuance between regular and CAT bonds. Denote $\theta \in [0, 1]$ as a fraction of CAT bond in total debt portfolio. The optimization problem for the country is given by:

$$\nu(m)^{1-\iota} = \max_{k_n \geq 0, b_n, \theta} c^{1-\iota} + \beta E\Big[\nu(\max\{m'_R, m'_D\})^{1-\gamma} e^{(1-\gamma)g'}\Big]^{\frac{1-\iota}{1-\gamma}} \tag{3.8}$$

subject to

$$c = m - k_n + q(b_n, k_n, \theta) b_n \tag{3.9}$$

$$b' = (1 - T'_j \theta(1-\tau)) e^{-g'} b_n, \text{ for } j = it, pt \tag{3.10}$$

$$k' = e^{-x'd' - g'} k_n \tag{3.11}$$

$$m'_R = k'^{\alpha} + (1-\delta)k' - b' \tag{3.12}$$

$$m'_D = (1 - \ell(g'))k'^{\alpha} + (1-\delta)k' \tag{3.13}$$

Next period bond issuance equation (3.10) is modified to include CAT bond. If T'_j is equal to 1, it means that the condition for CAT bond to pay out is met and the issued CAT bond will default, which result in a lower level of new bond issuance in the next period. While indemnity triggers ($j = it$) minimize basis risk by linking payouts to actual losses, this precision comes at a cost. Following the costly state verification from Townsend (1979) and Gale and Hellwig (1985), investors cannot costlessly observe the sovereign's true loss. They demand a verification process such as audits and loss adjustment to prevent moral hazard.

This process introduces a friction $\tau \in [0, 1)$, which can be interpreted as either direct loss, adjustment expenses, or the time-value erosion of delayed payouts (World Bank, 2014). In contrast, parametric triggers ($j = pt$) rely on publicly observable data (e.g., rainfall), eliminating the verification wedge ($\tau = 0$) but introducing basis risk, which will be discussed in the next section. The rest of the set-up is similar to the baseline case.

Recall the endogenous default threshold $\bar{g}(b_n, k_n)$ derived in Equation 3.5. The sovereign defaults when the realized weather-adjusted growth $\tilde{g}'$ falls below this threshold. With CAT bond issuance, the repayment obligation b' is reduced, which lowers the default threshold. We denote the effective default thresholds for indemnity-trigger CAT Bond ($\bar{g}_{it}$) as follows:

$$\bar{g}_{it}(b_n, k_n, \theta) = \bar{g}(b_n, k_n) + \frac{1}{1 - \alpha + \psi} \ln(1 - \theta(1 - \tau)) \tag{3.14}$$

Note that q now represents the price of the entire bond portfolio. This price depends on θ, not only because lenders demand an insurance premium for disaster coverage, but also because the use of CAT bonds affects the country's default incentives as follows.

$$q(b_n, k_n) = \frac{1 - s(\bar{g}_j(b_n, k_n), \theta)}{1 + r}, \text{ for } j = it, pt \tag{3.15}$$

Next, we consider the details of two different triggers i.e. indemnity loss and parametric ones and their subsequent results on spread functions.

3.2.1 Indemnity Loss Trigger

We define T'_{it} as the dummy for the indemnity loss trigger for CAT bond. T'_{it} is 1 when the disaster hit ($x' = 1$), the damage is big enough ($d' > \bar{d}$), and there are newly bond issued ($b_n > 0$).

$$T'_{it} = x' \mathbf{1}_{d' > \bar{d}} \mathbf{1}_{b_n \geq 0} \tag{3.16}$$

Then, s denotes the spread for the entire bond portfolio issued by the sovereign government, expressed as a function of the endogenous default threshold $\bar{g}$ defined in equation (3.5) and

the CAT bond fraction θ. If $\bar{d} > 0$, spread takes the following form:

$$
\begin{aligned}
s_{it}\left(\bar{g}, \theta, \bar{d}\right) \; &= (1-p)\,\Phi_g(\bar{g}) + p \int_0^{\bar{d}} \Phi_g\big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\, d'\big)\, f_{d'}(d')\,\mathrm{d}d' \\
&\quad + p(1-\theta) \int_{\bar{d}}^{\infty} \Phi_g\Big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\, d' + \underbrace{\tfrac{1}{1-\alpha+\psi}\, \ln\big(1-\theta(1-\tau)\big)}_{<0,\ \text{reduced default risks.}}\Big)\, f_{d'}(d')\,\mathrm{d}d' \\
&\quad + \underbrace{p\theta \int_{\bar{d}}^{\infty} f_{d'}(d')\,\mathrm{d}d'}_{>0,\ \text{indemnity CAT bond premium}}
\end{aligned}
\tag{3.17}
$$

The spread $s_{it}(\bar{g}, \theta, \bar{d})$ in equation 3.17 is the risk-neutral expected loss per unit of face value that lenders suffer next period, so it equals the bond's price discount relative to a risk-free bond. The first term represents the probability of sovereign default when no disaster occurs. The second part captures default risk in disaster states whose loss (d') is below the indemnity trigger ($\bar{d}$), so the debt is not written down and the face value remains 1. The third term measures default risk in disasters above the trigger, but now the country's repayment obligation has been reduced to $(1-\theta(1-\tau))$ which lowers the default threshold by the constant $\frac{1}{1-\alpha+\psi}\ln(1-\theta(1-\tau)) < 0$. The final term is CAT bond or insurance premium: even if the country repays after a severe disaster, creditors still lose the fraction θ that is automatically written off, which results in higher spread.

The comparative statics of the indemnity spread reflect three competing channels, formalized in proposition 1. First, increasing the indemnity trigger ($\bar{d}$) changes the classification of marginal disaster states around $d' = \bar{d}$. These states move from the insured region into the uninsured region. This has two opposite effects on lenders' expected losses. On the one hand, lenders no longer lose the CAT-bond haircut (θ) in these marginal states, which lowers the premium component of the spread. On the other hand, the sovereign no longer receives the debt write-down, so its residual repayment burden is higher and the probability of outright default rises. The net effect is therefore not unconditionally positive or negative. It depends on the CAT-bond share (θ). For small positive CAT-bond shares, the default-risk channel can dominate if the marginal relief effect is sufficiently strong. For CAT-bond shares close to one, the premium-saving channel dominates, so raising the trigger lowers the spread.

Second, the verification friction (τ) weakens the effective relief delivered by an indemnity-triggered CAT bond. A higher τ reduces the sovereign's effective debt write-down from θ to $\theta(1-\tau)$, leaving the sovereign with a larger post-disaster repayment burden in trig-

gered states. Risk-neutral lenders anticipate the resulting increase in residual default risk and therefore require a higher spread. This effect is strict for interior CAT-bond shares, $\theta \in (0,1)$. At $\theta = 0$, there is no CAT-bond relief to attenuate; at $\theta = 1$, the default-risk term for triggered states is multiplied by $1-\theta$, so the derivative with respect to τ is zero under the spread specification in equation 3.17.

Third, changing the CAT-bond share (θ) also produces two opposing effects. A marginal increase in θ strengthens post-disaster debt relief, shifts the repayment threshold downward, and reduces the probability of outright sovereign default in triggered disaster states. At the same time, it increases the expected CAT-bond premium because investors forfeit a larger fraction of principal whenever the indemnity trigger is met. If the marginal default-risk reduction dominates the marginal premium cost at $\theta = 0$, the spread initially falls as the CAT-bond share rises. However, when the CAT-bond share becomes sufficiently large, the premium effect eventually dominates. Under a single-crossing condition, this generates a unique spread-minimizing CAT-bond share (θ^*). Thus, the indemnity spread is generally U-shaped in θ.

Proposition 1. Suppose the growth-shock distribution $\Phi_g \in C^1$, with positive, continuous, and bounded density $\phi_g = \Phi_g'$, and $\Phi_g(x) < 1$ at every finite argument, and suppose the damage density f_d is continuous with $f_d(\bar{d}) > 0$. Writing $\eta \equiv \frac{\alpha}{1-\alpha+\psi}$, $\lambda \equiv \frac{1}{1-\alpha+\psi}$ and $C(\theta,\tau) \equiv \lambda \ln(1-\theta(1-\tau))$, consider $\theta \in [0,1]$ for each $\tau \in (0,1)$. The equilibrium indemnity spread satisfies:

(i) *Trigger threshold.*

$$\frac{\partial s_{it}}{\partial \bar{d}} = p\, f_d(\bar{d}) \Big[\Phi_g(\bar{g} + \eta\bar{d}) - (1-\theta)\Phi_g(\bar{g} + \eta\bar{d} + C(\theta,\tau)) - \theta \Big] \equiv p\, f_d(\bar{d})\, G(\theta).$$

The sign is share-dependent: $G(0) = 0$ and $G(1) = \Phi_g(\bar{g} + \eta\bar{d}) - 1 < 0$. Hence, s_{it} is strictly decreasing in $\bar{d}$ at $\theta = 1$, and by continuity also for θ sufficiently close to one. Under the threshold–relief condition

$$\lambda(1-\tau)\phi_g(\bar{g} + \eta\bar{d}) > 1 - \Phi_g(\bar{g} + \eta\bar{d}),$$

we have $G_\theta(0) > 0$, so $G(\theta) > 0$ for sufficiently small $\theta > 0$. If in addition G has a unique zero in $(0,1)$, then there exists a unique cutoff $\theta^\dagger \in (0,1)$ such that

$$\frac{\partial s_{it}}{\partial \bar{d}} > 0 \quad \text{for } \theta \in (0, \theta^\dagger), \qquad \frac{\partial s_{it}}{\partial \bar{d}} < 0 \quad \text{for } \theta \in (\theta^\dagger, 1].$$

(ii) *Verification friction.* For $\theta \in (0,1)$ the spread is strictly increasing in τ, $\partial s_{it}/\partial\tau > 0$; the derivative is zero at the endpoints $\theta \in \{0,1\}$.

(iii) *CAT-bond share.* If the marginal relief benefit dominates the marginal premium cost at $\theta = 0$,

$$\lambda(1-\tau)\int_{\bar{d}}^{\infty} \phi_g(\bar{g}+\eta d')f_d(d')\,\mathrm{d}d' > \int_{\bar{d}}^{\infty} \left[1-\Phi_g(\bar{g}+\eta d')\right] f_d(d')\,\mathrm{d}d',$$

then

$$\left.\frac{\partial s_{it}}{\partial\theta}\right|_{\theta=0} < 0.$$

Together with

$$\left.\frac{\partial s_{it}}{\partial\theta}\right|_{\theta=1} = p\left[(1-F_d(\bar{d})) - J(1,\tau)\right] > 0,$$

provided $1-F_d(\bar{d}) > 0$, the intermediate value theorem implies the existence of at least one interior $\theta^* \in (0,1)$ satisfying

$$\frac{\partial s_{it}}{\partial\theta} = 0.$$

If in addition $\partial s_{it}/\partial\theta$ has a unique zero in $(0,1)$, then θ^* is unique.

Proof: Appendix A.1

Proposition 1 shows that indemnity-triggered CAT bonds involve a non-monotonic pricing trade-off. Their advantage is that payouts are tied to realized losses, so the sovereign receives relief precisely in states where disaster damages exceed the contractual threshold. However, this precision is costly because verification frictions reduce the effective relief received by the sovereign, and because larger CAT-bond shares raise the expected haircut priced by investors. The resulting spread schedule depends on the balance between lower sovereign default risk and higher CAT-bond premium costs. This conditional structure motivates the comparison with parametric triggers in the next section. Parametric contracts avoid the verification wedge by relying on publicly observable physical indicators, such as rainfall, flood depth, or flooded area, but they introduce basis risk because payouts may not perfectly match realized economic losses.

3.2.2 Parametric Trigger

Consider T'_{pt} as the dummy for the parametric-triggers CAT bond as follows

$$T'_{pt} = x'\mathbf{1}_{\omega'>\bar{\omega}}\mathbf{1}_{b_n\geq 0} \tag{3.18}$$

$$\omega' = \chi d' + \epsilon \tag{3.19}$$

We denote ω' as the cumulative intensity index of flood events (measured in square kilometers of area-weighted intensity) in the next period, $\chi > 0$ denotes the sensitivity of the index to damage, and ϵ is served as the basis risk, assumed to follow a normal distribution, $N(0, \sigma_\epsilon^2)$ with CDF Φ_ϵ.[5] The parametric CAT bond triggers when the index exceeds the threshold: $\omega' > \bar{\omega}$, yielding the trigger condition as $\epsilon > \bar{\omega} - \chi d'$. We define $H(d') = \mathbb{P}(\omega' > \bar{\omega}|d')$ as the probability of parametric trigger.[6]

The fundamental friction of a parametric CAT bond is basis risk, which arises from the imperfect correlation between the observable index and the actual but unobservable economic damages (d'). By formalizing the trigger probability as a continuous distribution, $H(d') = \Phi_\epsilon(\chi d' - \bar{\omega})$, we isolates the two primary sources of uncertainty. The baseline default risk is governed by Φ_g, while the reliability of the financial payout is governed by Φ_ϵ. The argument $(\chi d' - \bar{\omega})$ acts as the effective signal strength of the disaster. When the variance of the basis risk (σ_ϵ^2) is high, the Φ_ϵ curve flattens. This flattening explicitly quantifies how imperfect calibration generates two distinct statistical errors that govern the equilibrium sovereign spread, as derived in Equation 3.20.

$$
\begin{aligned}
s_{pt}\big(\bar{g}, \theta, \bar{\omega}\big) = (1-p)\,\Phi_g(\bar{g}) + p \int_0^\infty \underbrace{\big[1 - H(d';\bar{\omega})\big]}_{\text{Prob. of No Trigger}} \Phi_g\big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\, d'\big)\, f_{d'}(d')\,\mathrm{d}d' \\
+\, p(1-\theta) \int_0^\infty \underbrace{H(d';\bar{\omega})}_{\text{Prob. of Trigger}} \Phi_g\Big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\, d' + \underbrace{\tfrac{1}{1-\alpha+\psi} \ln\big(1-\theta\big)}_{\text{Maximized relief } (\tau=0)}\Big)\, f_{d'}(d')\,\mathrm{d}d' \\
+\, \underbrace{p\,\theta \int_0^\infty H(d';\bar{\omega})\, f_{d'}(d')\,\mathrm{d}d'}_{>0,\ \text{Parametric CAT bond premium}} .
\end{aligned}
\tag{3.20}
$$

Equation 3.20 defines the equilibrium sovereign spread for a parametric CAT bond, explicitly incorporating the continuous probability of the trigger activating. The first term captures the baseline default risk when no natural disaster occurs. The second term represents the Type II error (false negative) scenario: a disaster strikes, but the localized index fails to reach the trigger threshold. In this state, occurring with probability $[1 - H(d')]$, the sovereign suffers physical capital destruction (d') but receives zero debt relief, leaving it exposed to default.

The third term captures the successful activation of CAT bond. Crucially, because para-

[5] If $\sigma_\epsilon^2 = 0$, the index is perfect (indemnity-like), while if σ_ϵ^2 is large, the parametric index is a poor proxy.

[6] The probability of parametric trigger is given by $H(d') = \mathbb{P}(\omega > \bar{\omega}|d') = 1 - \Phi_\epsilon(\frac{\bar{\omega} - \chi d'}{\sigma_\varepsilon}) = \Phi_\epsilon(\frac{\chi d' - \bar{\omega}}{\sigma_\varepsilon})$ since the normal distribution is symmetric around mean 0.

metric bonds rely on observable indices rather than lengthy loss-adjustment processes, the verification friction is eliminated ($\tau = 0$). This frictionless mechanism provides the sovereign with maximized debt relief, reflected by the full $\ln(1-\theta)$ term, which pushes the default threshold down more effectively than in the indemnity case.

Finally, the fourth term represents the expected haircut loss, or the ex-ante CAT bond premium demanded by investors. Because the trigger is probabilistic, risk-neutral investors must price in the likelihood of the bond paying out across all possible damage states. This includes Type I errors (false positives), where the index triggers a payout despite actual damages being relatively mild. These unwarranted payouts act as a deadweight loss, forcing lenders to charge a higher ex-ante premium to compensate for the false alarms.

Therefore, the macroeconomic viability of the parametric bond is governed by the variance σ_ε^2, mathematically formalizing the trade-off between the speed of parametric liquidity and the precision of indemnity coverage. As the basis risk approaches zero ($\sigma_\varepsilon^2 \to 0$), the trigger probability $H(\cdot)$ converges to a deterministic indicator function. In this limit, the parametric design effectively reduces to an indemnity contract, but crucially, one that retains the macroeconomic advantage of zero verification frictions.

Conditions for Parametric Dominance. Comparing the parametric spread (s_{pt}) in equation (3.20) to the indemnity spread (s_{it}) in equation (3.17) illuminates the central theoretical trade-off: basis risk versus verification costs. In the indemnity equation, the trigger mechanism is deterministic and perfectly correlated with actual damage, represented by the rigid integration bounds from 0 to $\bar{d}$ (no payout) and $\bar{d}$ to ∞ (guaranteed payout). There is zero basis risk, so investors never suffer Type I errors and the sovereign never suffers Type II errors; this precision, however, comes at the cost of the verification friction τ, which reduces the effective relief in the third term of s_{it} to $\frac{1}{1-\alpha+\psi}\ln\big(1-\theta(1-\tau)\big)$ and keeps the sovereign's residual default risk above the maximized relief embedded in s_{pt}. Whether the parametric bond strictly dominates ($s_{pt} < s_{it}$) therefore turns on a single per-state object: the change in lenders' risk-neutral expected loss when the parametric tranche pays out rather than not at a given damage realization,

$$m(d') \equiv (1-\theta)\,\Phi_g\Big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\,d' + \tfrac{1}{1-\alpha+\psi}\ln(1-\theta)\Big) + \theta - \Phi_g\Big(\bar{g} + \tfrac{\alpha}{1-\alpha+\psi}\,d'\Big). \tag{3.21}$$

A payout in states where $m(d') > 0$ raises lenders' expected loss which is an unwarranted transfer priced ex ante as premium, whereas a payout where $m(d') < 0$ lowers it, because

the debt relief outweighs the forfeited haircut. For frictionless parametric relief to outweigh the combined costs of Type I and Type II errors, the contract must be structured so that payouts fall predominantly in this latter, beneficial region. We formalize the requirement in three assumptions.

Assumption 1: Sufficiently low basis risk. The variance of the basis risk σ_ε^2 is bounded near zero in the small-noise limit.

Assumption 2: Symmetric, mean-preserving noise. The observation noise ε is drawn from a symmetric continuous distribution for which an increase in σ_ε constitutes a mean-preserving spread.

Assumption 3: Threshold alignment and single crossing. The index is centred at the trigger, $\bar{\omega} = \chi\bar{d}$, and is aligned so that the incremental trigger cost $m(d')$ in (3.21) single-crosses zero precisely at $\bar{d}$, namely $m(d') > 0$ for $d' < \bar{d}$ and $m(d') < 0$ for $d' \geq \bar{d}$.[7]

The theoretical spread dominance of the parametric CAT bond over its indemnity counterpart hinges on these three assumptions, which together ensure that its frictionless payout mechanism outweighs the inherent costs of basis risk. First, for the parametric bond to strictly dominate, the initial variance of the basis risk must be sufficiently low, rendering the parametric index a highly reliable proxy for actual damages. In this small-noise limit, the probabilities of both trigger failures and unwarranted payouts approach zero, allowing the parametric bond to attain the exact, state-contingent precision of an indemnity contract while uniquely retaining its superior macroeconomic advantage of zero verification frictions.

Second, we assume the index noise follows a symmetric distribution, so that basis risk acts as pure noise around true economic damages without systematically biasing the trigger up or down. Formally, raising σ_ε rotates the trigger-probability schedule $H(d')$ about its centre $\bar{\omega}/\chi = \bar{d}$, increasing the payout probability for sub-threshold damages and decreasing it for super-threshold damages. This symmetric structure clarifies that any increase in noise variance unambiguously penalizes the bond by simultaneously inflating the probability of costly false alarms (Type I errors) and uninsured default risks (Type II errors).

Finally, the trigger threshold must be aligned to satisfy the single-crossing property, ensuring the instrument functions as genuine disaster insurance rather than an inefficient,

[7]The numerical calibration in section 4 recenters the index with the noise, $\bar{\omega}(\sigma_\varepsilon) = \chi\bar{d} + \Phi^{-1}(0.7)\,\sigma_\varepsilon$, so as to fix the trigger probability at the cutoff to $H(\bar{d}) = 0.3$. The comparative statics in Proposition 2 instead hold the contractual threshold $\bar{\omega}$ fixed, as is appropriate for a bond priced at issuance.

unconditional cash transfer. Concretely, the index is centred at the damage level $\bar{d}$ where the incremental trigger cost changes sign: the bond delivers an expected net loss in minor nuisance events ($m > 0$), where the ex-ante premium outweighs the marginal debt relief, and an expected net gain in severe catastrophes ($m < 0$), where liquidity is critical to averting default. Because Assumption 2 places the rotation point of the trigger probability at this same damage level, every increment of basis risk shifts payout probability away from the catastrophic states where it is valuable and toward the nuisance states where it is costly, so the parametric spread rises monotonically in σ_ε. We formalize this dominance and its eventual reversal in Proposition 2.

Proposition 2. Given assumptions 1 to 3, the equilibrium spread of the parametric CAT bond has the following properties:

(i) For sufficiently low basis risk, the parametric bond has a strictly lower spread than the indemnity bond:

$$s_{pt}(\sigma_\varepsilon) < s_{it}(\tau).$$

(ii) The parametric spread is strictly increasing in basis risk:

$$\frac{\partial s_{pt}(\sigma_\varepsilon)}{\partial \sigma_\varepsilon} > 0.$$

(iii) If the large-basis-risk penalty is sufficiently large, there exists a unique threshold $\sigma_\varepsilon^* > 0$ such that

$$s_{pt}(\sigma_\varepsilon) < s_{it}(\tau) \quad \text{for } \sigma_\varepsilon < \sigma_\varepsilon^*,$$

and

$$s_{pt}(\sigma_\varepsilon) > s_{it}(\tau) \quad \text{for } \sigma_\varepsilon > \sigma_\varepsilon^*.$$

Proof: Appendix A.2

From the fundamental trade-offs between verification frictions and basis risk of CAT bond, it is crucial to recognize that the underlying distribution of natural disasters is rapidly evolving. To capture this reality, Section 3.3 extends our theoretical framework to analyze the results of climate change. By modeling this phenomenon as a rightward shift in the flood damage distribution, where catastrophic tail-risk events become both more frequent and severe, we evaluate how a worsening climate regime dynamically alters the equilibrium pricing, basis risk penalties, and ultimate welfare dominance of the competing CAT bond structures.

3.3 The Effect of Climate Change

Within our framework, the macroeconomic threat of climate change extends beyond a simple increase in disaster frequency (p). It also changes the severity distribution of disaster damages. We model climate change as a rightward shift in the damage distribution, where the new climate distribution ($\tilde{f}(d')$) dominates the historical distribution ($f(d')$) in the monotone likelihood-ratio order. This means that high-damage states become relatively more likely than low-damage states.

This distributional shift changes how risk-neutral lenders price the two CAT-bond designs. The indemnity contract provides payouts based on realized losses, but its relief is reduced by verification frictions such as auditing, loss adjustment, or payment delays. The parametric contract avoids these verification frictions, but it is exposed to basis risk. In low-damage states, basis risk may generate false payouts, making the parametric contract relatively costly. In damage states above the trigger, however, the parametric contract becomes relatively less costly because it delivers frictionless relief.

Therefore, when climate change raises the relative likelihood of trigger-relevant severe damage states, it places more probability weight on states where the parametric contract has a pricing advantage over the indemnity contract. Under the low-basis-risk and trigger-alignment conditions stated in proposition 3, this shift strictly widens the indemnity-minus-parametric spread premium.

Proposition 3. Let climate change be defined as a shift in the disaster-severity distribution from $f(d')$ to $\tilde{f}(d')$, where $d' \geq 0$ denotes next-period disaster damage. Suppose that $\tilde{f}$ dominates f in the monotone likelihood-ratio order: $r(d') \equiv \frac{\tilde{f}(d')}{f(d')}$ is increasing in d', so climate change places relatively more probability weight on severe damage states. Let $\Delta L(d') \equiv L_{it}(d') - L_{pt}(d')$ denote the state-contingent lender-loss differential between the indemnity and parametric contracts. Assume the following:

1. The condition for parametric dominance holds, namely basis risk is sufficiently small so that, under the baseline distribution,

$$s_{pt} < s_{it}.$$

   Equivalently, the baseline expected loss differential satisfies $E_f[\Delta L(d')] > 0$.

2. The loss differential is aligned with the trigger threshold $\bar{d}$: $\Delta L(d') < 0 \quad \text{for } d' < \bar{d}$, and $\Delta L(d') > 0 \quad \text{for } d' > \bar{d}$. Below the trigger, the parametric contract may be relatively

more costly because of false payouts, while above the trigger it is relatively less costly because it avoids the verification friction of the indemnity contract.

3. The climate shift increases the relative likelihood of trigger-relevant severe damage states: $r(\bar{d}) \geq 1$

Then the worsening of the damage distribution strictly widens the equilibrium spread differential between indemnity and parametric CAT bonds:

$$\Delta s \equiv s_{it} - s_{pt}$$

strictly increases when the damage distribution shifts from f to $\tilde{f}$.

Proof: Appendix A.3

Proposition 3 shows that climate change can strengthen the spread advantage of parametric CAT bonds when the worsening distribution increases the relative likelihood of trigger-relevant severe damage states. The intuition is that basis-risk costs are most problematic below the trigger, where false payouts may occur, while the verification friction of indemnity contracts is most costly above the trigger, where disaster relief is needed. As probability weight shifts toward these severe trigger-relevant states, lenders place greater weight on the frictionless relief advantage of the parametric contract. This does not mean that parametric basis risk disappears. Rather, under sufficiently low basis risk, its pricing cost becomes less important relative to the verification cost embedded in the indemnity contract.

We examine the welfare implications of CAT bond adoption in Corollary 1. Let $\Delta W(f_d; \gamma) \equiv W_{pt}(f_d; \gamma) - W_{it}(f_d; \gamma)$ denote the ex-ante welfare differential between the parametric and indemnity contracts, where $W_j(f_d; \gamma)$ is ex-ante welfare under contract $j \in \{it, pt\}$ when next-period disaster damage d' follows density $f_d(d')$. We decompose this welfare differential using a hybrid benchmark h, which is priced at the parametric spread $s_{pt}(f_d)$, triggers deterministically as $T'_h = \mathbf{1}\{d' > \bar{d}\}$, and delivers frictionless relief. This benchmark isolates two welfare channels. The difference between h and the indemnity contract captures the spread-efficiency gain from lower borrowing costs and the absence of verification frictions. The difference between the parametric contract and h captures the tail-risk-smoothing penalty from basis risk, since the parametric trigger may fail even in severe damage states. Thus, climate change affects the parametric-minus-indemnity welfare gap through two opposing forces: it increases the value of parametric spread efficiency, but it also increases the welfare cost of uninsured tail states when the parametric trigger fails.

Corollary 1. Let the sovereign maximize Epstein–Zin preferences with relative risk aversion $\gamma > 1$ and inverse IES $\iota \in (0, 1)$. Assume the conditions of Proposition 3 hold, so that $\Delta s(f_d) \equiv s_{it}(f_d) - s_{pt}(f_d) > 0$, and $\Delta s(\tilde{f}_d) > \Delta s(f_d)$. Define

$$\begin{aligned} SE(f_d;\gamma) &\equiv W_h(f_d;\gamma) - W_{it}(f_d;\gamma), \\ TRS(f_d;\gamma) &\equiv W_{pt}(f_d;\gamma) - W_h(f_d;\gamma), \\ \Delta_{CC}W(\gamma) &\equiv \Delta W(\tilde{f}_d;\gamma) - \Delta W(f_d;\gamma). \end{aligned}$$

Assume further that:

1. The expected tail-risk-smoothing penalty becomes larger under the climate-change distribution, $TRS(\tilde{f}_d;\gamma) - TRS(f_d;\gamma) < 0$, and
2. The net climate-change welfare effect $\Delta_{CC}W(\gamma)$ satisfies a single-crossing condition in risk aversion: it is continuous and strictly decreasing in γ, with $\Delta_{CC}W(\gamma) > 0$ as $\gamma \to 1^+$ and $\Delta_{CC}W(\gamma) < 0$ for sufficiently large γ

Then the change in the ex-ante welfare differential under climate change admits the exact decomposition

$$\Delta_{CC}W(\gamma) = \underbrace{\left[SE(\tilde{f}_d;\gamma) - SE(f_d;\gamma)\right]}_{\text{Spread-efficiency gain}} + \underbrace{\left[TRS(\tilde{f}_d;\gamma) - TRS(f_d;\gamma)\right]}_{\text{Tail-risk-smoothing penalty}}.$$

Moreover,

$$SE(\tilde{f}_d;\gamma) - SE(f_d;\gamma) > 0, \qquad TRS(\tilde{f}_d;\gamma) - TRS(f_d;\gamma) < 0.$$

Finally, there exists a unique threshold $\gamma^* > 1$ such that

$$\operatorname{sign}(\Delta_{CC}W(\gamma)) = \begin{cases} +1, & \text{if } \gamma < \gamma^*, \\ 0, & \text{if } \gamma = \gamma^*, \\ -1, & \text{if } \gamma > \gamma^*. \end{cases}$$

Climate change widens the parametric welfare advantage when $\gamma < \gamma^*$, but narrows it when $\gamma > \gamma^*$.

Proof: Appendix A.4

Corollary 1 shows that the welfare comparison between parametric and indemnity CAT bonds under climate change is governed by two opposing forces. The first is a spread-efficiency effect that favors the parametric design under the maintained low-basis-risk conditions. Because

parametric bonds avoid verification frictions, they can carry a lower equilibrium spread than indemnity bonds, raising the bond price (q_{pt}) and relaxing the sovereign's current-period budget constraint for a given level of issuance. In addition, when the parametric trigger does pay out, it delivers frictionless debt relief because it bypasses the loss-adjustment process ($\tau = 0$). Proposition 3 implies that climate change strengthens this pricing advantage by shifting probability weight toward severe damage states in which frictionless parametric relief is relatively more valuable than verification-adjusted indemnity relief.

The second force is a tail-risk-smoothing effect that works in the opposite direction. This channel arises in disaster states where the two trigger mechanisms diverge. When a severe flood occurs, the indemnity bond triggers with certainty once realized damages exceed the contractual threshold, whereas the parametric bond triggers only with probability $H(d')$. Thus, with probability $1 - H(d')$, the sovereign receives no debt relief despite facing severe disaster losses. Under Epstein-Zin preferences with $\gamma > 1$, these uninsured catastrophic states receive greater welfare weight as risk aversion rises, making the basis-risk penalty more important. Climate change amplifies this penalty by increasing the likelihood of severe damage states in which trigger failure is especially costly. Under the maintained single-crossing condition, the corollary implies a unique threshold γ^*: for moderately risk-averse sovereigns ($\gamma < \gamma^*$), the spread-efficiency gain dominates and climate change widens the parametric welfare advantage; for highly risk-averse sovereigns ($\gamma > \gamma^*$), the tail-risk-smoothing penalty dominates and climate change narrows that advantage.[8]

Having formally established the theoretical trade-offs between the verification frictions of indemnity coverage and the basis risk of parametric triggers, we next evaluate the model quantitively. In Section 4, we calibrate our dynamic small-open-economy framework to match the macroeconomic and hydrological profile of Thailand, an emerging economy highly vulnerable to catastrophic flood risk. Through numerical simulations, we test the bounds of our theoretical propositions specifically measuring how the adoption of different CAT bond structures mitigates post-disaster drops in capital, output, and consumption, while simultaneously analyzing their effects on sovereign spreads and capital inflows. This quantitative exercise allows us to rigorously assess the conditional dominance of parametric CAT bonds and evaluate the macroeconomic welfare implications of these instruments under the intensifying threat of climate change.

[8]In the quantitative calibration with $\gamma = 4$, Table 2 shows that the parametric welfare advantage narrows under climate change, which is consistent with the latter regime and supports the policy relevance of combining parametric and indemnity layers in a stratified disaster risk financing framework.

4 Quantitative Result

We perform a quantitative simulation of the impact of the exogenous shock. The disaster risk under consideration is that of flood, an important and recurrent source of climate-related shocks for emerging economy. For our calibration, we focus on Thailand, an emerging market economy that faces significant exposure to flooding risk.

4.1 Calibration

We set each period to five years, which is well-suited to our focus on recovery dynamics following major disasters. Using five-year periods enhances the model's tractability, as capital adjustment costs are less likely to play a significant role over such horizons. Additionally, the implied five-year maturity of the model's one-period debt aligns more closely with the average maturity of sovereign bonds in emerging markets compared to models calibrated at quarterly or annual frequencies. This choice also allows us to abstract from the autocorrelation typically observed in TFP growth rates, further simplifying the state space.

In our baseline analysis, we follow Phan and Schwartzman (2024) except capital share and flooding-related parameters. Bank of Thailand reported that labor income share is around 44-47% from 2003 to 2021 and thus we employ capital share $\alpha = 1/2$ to reflex the state of the Thai economy. For weather shock parameter, we need to calibrate flood probability, marginal output damage, and the distribution of flood.

On the extensive margin, we interpret the model's weather shock dummy x_t as indicating whether a country experiences a flood within a given period. We calibrate the strike probability p which governs the Poisson arrival rate of rain, to match the observed average annual probability of 30% (Worawiwat et al., 2021).

On the intensive margin, we interpret the damage parameter d_t as representing the country's cumulative economic damage from flood events over a five-year period. This captures the aggregate impact of flood intensity and frequency within each model period. We assume that $d' = \omega' * \mu_{pt}$ where ω' represents the cumulative intensity of flood events (measured in square kilometers of area-weighted intensity) within a given period, and μ_{pt} denotes the marginal damage to the capital stock per additional flooded area[9]. We set the marginal damage for

[9]For indemnity-loss-trigger CAT bond, we apply damage $\bar{d}$ as a trigger and thus the compensation for the flooded victims is calculated from the actual damage and the trigger $d' - \bar{d}$, while parametric-trigger one uses $\bar{\omega}$ as a trigger, and therefore a constant fixed payout μ_{pt} is compensated to the victim. We set $\chi = \frac{1}{\mu_{pt}}$.

output as 4.81%, following the estimated economic loss found in Tanoue et al. (2020)

We assume that maximum flood depth follows a Gamma distribution, which has been shown to provide a good empirical fit for modeling hydrological events with its shape and scale parameters set to 0.3391 and 148.7617, following Suanin and Wattanakoon (2023). Table 1 shows the parameter used in our analysis.

Table 1: Calibrated parameters.

	Parameter	**Value**	**Source**
	period length	5 years	
α	capital share	$1/2$	Bank of Thailand
β	discount factor	0.96^5	Standard RBC values
δ	depreciation	$1-0.9^5$	
r	world interest rate	1.01^5-1	
ℓ	inverse elasticity of substitution	0.5	Gourio (2012)
γ	risk aversion	4	
μ_g	mean TFP growth	$1.006^{20}-1$	Aguiar and Gopinath (2007)
σ_g	std of TFP growth	$0.0213\sqrt{20}$	
ℓ	default cost constant	0.07	Aguiar et al. (2016)
ψ	default cost curvature	7	
p	flood probability	0.30	Worawiwat et al. (2021)
μ_{pt}	marginal output damage	0.0481	Tanoue et al. (2020)
Φ_d	shape of Gamma distribution	0.3391	Suanin and Wattanakoon (2023)
	scale of Gamma distribution	148.7617	
τ_{it}	verification cost	0.1	
$\bar{d}$	Indemnity Loss Trigger	90th percentile of d	Standard CAT Bond Contract
$\bar{\omega}$	Parametric Trigger	$\chi\bar{d}+\Phi^{-1}(0.7)\sigma_\epsilon$	

Note: Most of the basic parameters are similar to Phan and Schwartzman (2024)

The expected compensation parametric-trigger CAT bond issuers is $\mu_{pt} \times \mathbf{1}_{\omega>\bar{\omega}}$. We also set the standard deviation of basis risk: $\sigma_\varepsilon = 0.2\chi d'$, and calibrate the index threshold $\bar{\omega}$ so that the trigger probability at the damage threshold equals 30 percent: $H(\bar{d}) = 0.3$, achieved by setting $\bar{\omega} = \chi\bar{d}+\Phi^{-1}(0.7)\sigma_\varepsilon$, where Φ^{-1} is the standard normal quantile function. The resulting calibration implies substantial basis risk at the trigger boundary when flood damage is exactly severe enough to warrant a payout, the parametric index fails to trigger 70 percent of the time, while ensuring that the trigger fires with near-certainty for catastrophic events well above $\bar{d}$

4.2 Numerical Analysis

4.2.1 Propagation of flood shock

We examine the impulse responses of the economy to a one-time, one-standard-deviation shock to flood. The responses are generated by averaging across one million simulated paths, where in each path the economy is simulated until it reaches its ergodic steady state. Then, in period $t = 0$, we introduce an unanticipated shock that raises the period's cumulative area-weighted flood intensity from its ergodic steady-state average value of 58,000 to 144,000 square kilometers[10], representing a one-standard-deviation increase. We interpret this shock as capturing the impact of an exceptionally severe flood event occurring in period $t = 0$.

Figure 3 illustrates the impulse in the first panel and the responses of aggregate detrended variables in the subsequent panels under three policy regimes: (i) a Baseline without disaster insurance (solid line), (ii) an Indemnity CAT bond (dashed line), and (iii) a Parametric CAT bond (dotted line). To aid interpretation, we adjust the reported values to annual terms by dividing the spread and default frequency by five and multiplying the debt-to-output ratio by five, reflecting the fact that each model period represents five years.

The second and third panels of the first row confirm that the flood shock inflicts a sharp, one-period loss of productive capacity: capital stock falls by about -8 percent in the uninsured economy, an indemnity CAT bond, and a parametric bond[11]. The same trajectory carries over to output, which contracts by roughly -4 percent across regimes, and the gap persists for roughly a decade.

The second row traces the government's balance sheets. Net worth and consumption contract most severely in the uninsured economy, with these losses noticeably milder under CAT bond coverage. Among the two instruments, the indemnity trigger generally provides the strongest stabilization benefit on impact, reflecting its certain, state-contingent payout in disaster states. Consumption recovers faster than wealth in both insured cases, illustrating how external transfers smooth inter-temporal allocations when domestic assets are impaired. Notably, both CAT bonds reduce the peak debt-to-output ratio relative to the baseline, as

[10] The ergodic steady-state average flooded area is simulated from the Gamma distribution calibrated from Suanin and Wattanakoon (2023) over one million simulated samples

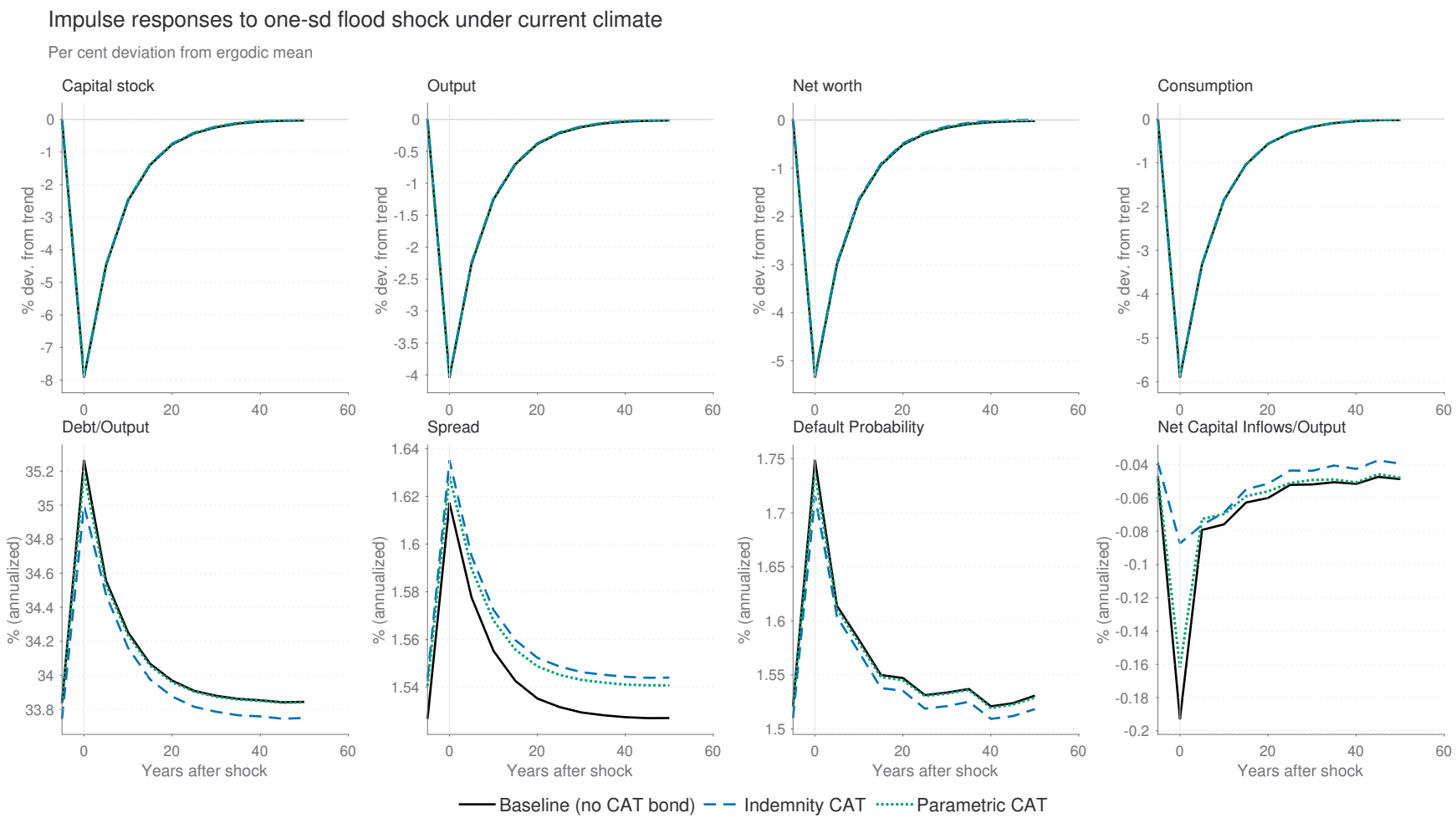
[11] While the level responses in Figure 3 appear nearly identical across regimes, Figure 6 isolates the marginal stabilization benefit of each instrument, revealing that the indemnity CAT bond improves capital retention around 0.02 percentage points relative to the uninsured baseline on impact, and provides even larger stabilization benefits in subsequent periods.

insurance payouts mitigate the immediate need for post-disaster borrowing, with the indemnity bond containing the debt spike more effectively than the parametric bond owing to its guaranteed activation above the trigger threshold.

These debt dynamics feed into the bottom-row financial indicators. Sovereign spreads widen to roughly 1.635 percent under the indemnity bond and about 1.625 percent under the parametric bond, compared to 1.615 percent in the baseline scenario. However, the default-probability panel reveals that insurance effectively lowers the actual default risk: the hazard rate peaks at approximately 1.74 percent in the baseline, but is suppressed to roughly 1.69 percent with the indemnity cover and 1.72 percent with the parametric cover. Consequently, net capital inflows ($q_t b_t^n - b_t$) fall sharply by about -0.19 percent of output without insurance, but this contraction is heavily buffered under the indemnity design (falling only to about -0.08 percent) and moderately under the parametric bond (falling to -0.16 percent), reinforcing how the instruments alleviate the sudden tightening of external finance.

All in all, the figure highlights a fundamental trade-off. CAT bonds, especially parametric ones, deliver swift macro-stabilization by curbing flood damage and accelerating the rebound of production and welfare. Yet, the ex-ante increase in gross debt, coupled with higher required spreads, raises sovereign risk metrics and crowds out capital inflows. Optimal contract design must therefore weigh the short-run benefits of faster recovery against the medium-term costs of a heavier debt burden and tighter external financing.

Figure 3: Impulse responses of detrended variables to an unanticipated one-standard-deviation shock of flood

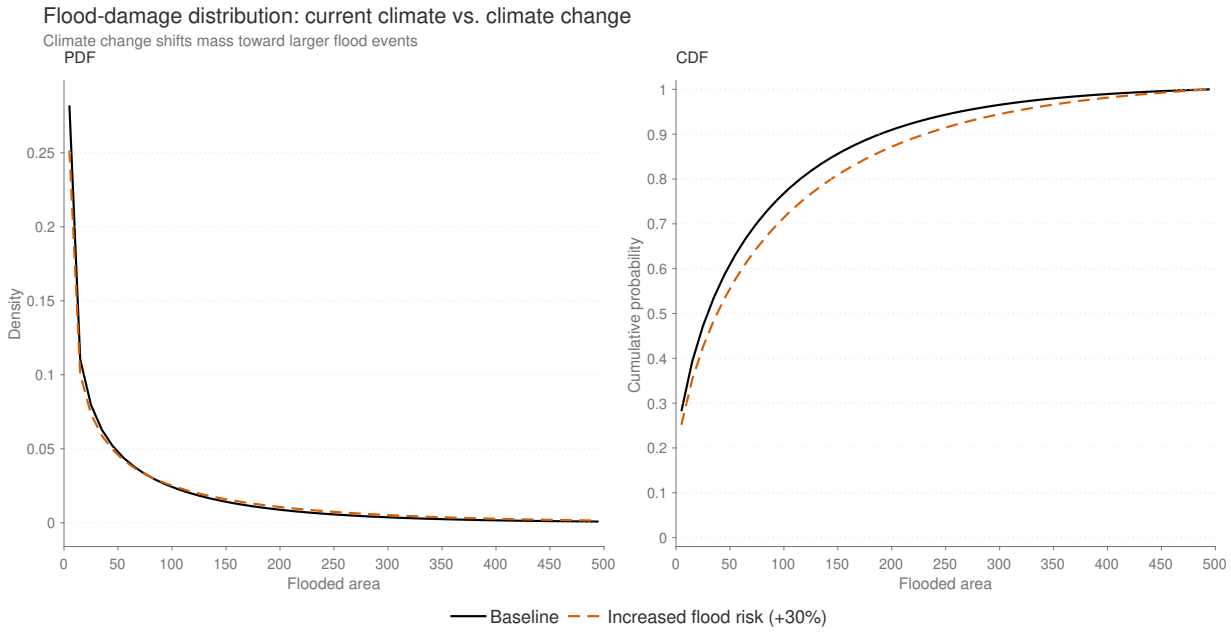


Note: Impulse responses are drawn from one-million simulated samples.

4.2.2 Welfare Analysis with Climate Change

We investigate the welfare implications of a shift in the distribution of flood intensity due to climate change. According to projections based on Intergovernmental Panel on Climate Change (IPCC) (2023), flood intensity in regions such as Southeast Asia including Thailand is expected to increase by an average of 30% in the next ten years. We model this shift by increasing the scale parameter of the Gamma distribution governing flood intensity by 30% from the baseline set-up and plot the probability and cumulative density functions in figure 4.

Figure 4: Change in the distribution after an increase in 30% of flood risk



Note: Authors' computation

To evaluate the long-run welfare implications of CAT bond adoption, we define two complementary metrics. First, we measure the welfare cost of climate change. Denote $E[\nu(m)]$ as the lifetime utility for a given net worth level, m, under the baseline flood distribution, and $E[\nu_+(m)]$ as the corresponding value under the intensified climate-change distribution. The welfare cost of climate change is then

$$\Delta w = 1 - \frac{E_+[\nu_+(m)]}{E[\nu(m)]}, \tag{4.1}$$

which captures the fraction of permanent consumption the representative sovereign would

forgo to avert the projected escalation in flood intensity. Under Epstein-Zin preferences, this metric coincides with the standard consumption-equivalent welfare measure (Lucas, 1987; Barro, 2009). Second, to isolate the value of each CAT bond instrument, we measure the welfare gain from bond adoption relative to the uninsured economy under the same climate regime:

$$\Delta w_j = \frac{E[v_j(m)]}{E[v_0(m)]} - 1, \tag{4.2}$$

where $\nu_j(m)$ is lifetime utility under bond $j \in \{it, pt\}$ and $\nu_0(m)$ is lifetime utility without insurance, both evaluated under the same flood distribution. A positive Δw_j indicates that bond adoption is welfare-improving. By evaluating both metrics over the ergodic distribution of the state variable m, we ensure that the welfare comparisons reflect long-run effects, appropriately capturing the persistent nature of climate risk.

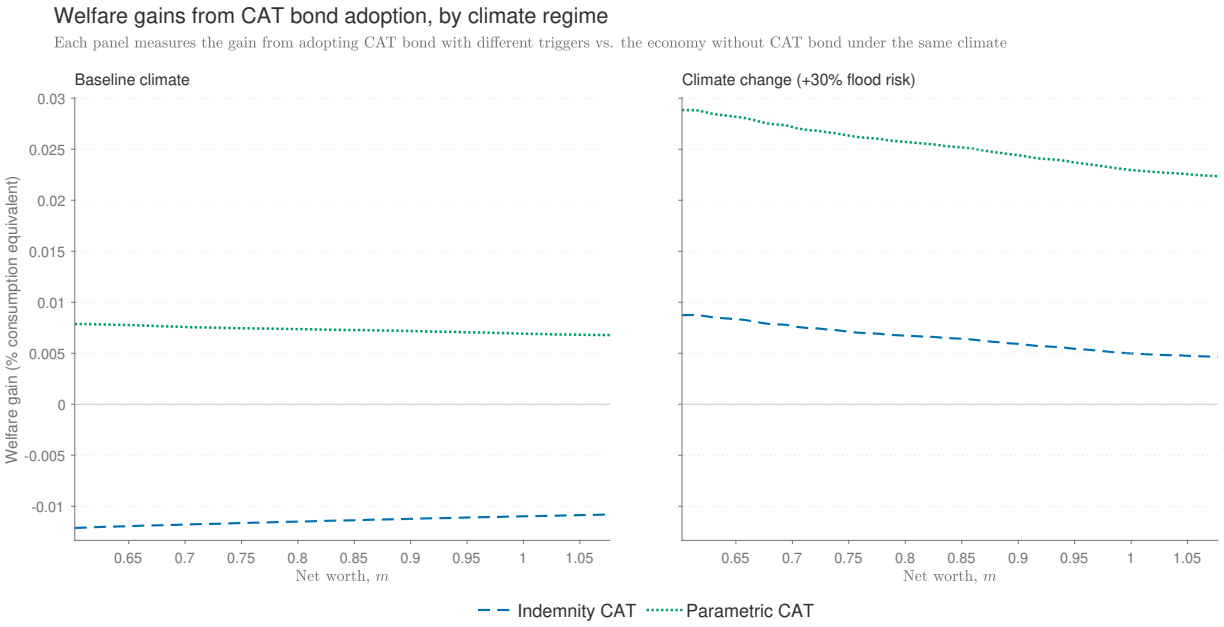
Figure 5 plots Δw_j against the distribution of government net worth under two climate regimes. Each panel measures the gain relative to the uninsured economy under the same climate regime, so the vertical gap between the two lines directly reveals the parametric bond's welfare advantage over the indemnity bond within that regime.

The left panel reports welfare gains under the current baseline climate. The parametric CAT bond (dotted green) generates a substantial positive welfare gain across the relevant range of net worth, reflecting the high value of its frictionless, rule-based liquidity: the absence of verification costs yields a lower equilibrium spread that cheapens borrowing in every period, not just when disasters strike. In contrast, the indemnity CAT bond (dashed red) hovers near zero, with a slight welfare drag at most net worth levels. Although the indemnity design provides a theoretically perfect hedge since state-contingent payouts that trigger with certainty when damage exceeds the threshold, the verification friction imposes a persistent cost through higher spreads that offsets the insurance benefit. Under baseline climate conditions, the spread-efficiency channel dominates, and the wide vertical gap between the two lines confirms the parametric bond's clear superiority.

The right panel reports welfare gains under climate change, where flood intensity increases by thirty percent. Two shifts are immediately visible. First, both lines rise: the indemnity bond transforms from a net welfare cost into a robust welfare-improving instrument, as its guaranteed payouts become increasingly valuable when catastrophic states occur more frequently. Second, the vertical gap between the two lines narrows substantially compared to the left panel. This narrowing is the tail-risk-smoothing effect identified in Corollary 1:

as climate change pushes probability mass toward severe damage states, the welfare cost of uninsured exposure under the parametric trigger, in which the index fails to fire despite devastating floods, grows disproportionately for a risk-averse sovereign. While the parametric bond remains the most financially efficient instrument overall, the indemnity bond's certain consumption smoothing closes much of the welfare gap, increasingly justifying its higher issuance cost as climate risks intensify. Table 2 confirms these patterns at the ergodic steady state.

Figure 5: Welfare Gains from CAT Bond Adoption over Uninsured Economy



Note: Authors' computation

Table 2: Long-run changes in steady-state averages of lifetime utility

	Indemnity Trigger	**Parametric Trigger**
Δ Welfare	-0.001%	0.020%
Δ Welfare after Climate Change	0.011%	0.017%

Note: The changes from increased flood damages are calculated as percent changes relative to the corresponding averages in the baseline calibration with each corresponding CAT bonds.

5 Conclusion

This study examines how sovereign catastrophe (CAT) bonds affect macroeconomic adjustment and welfare in a flood-prone small open economy. Building on a dynamic framework with sovereign default risk and Epstein-Zin preferences, we compare indemnity and parametric trigger designs and trace how these contracts operate through borrowing costs, default incentives, capital accumulation, and post-disaster stabilization.

The analysis highlights a trade-off between spread efficiency and tail-risk smoothing. Under sufficiently low basis risk, parametric CAT bonds can offer lower equilibrium spreads because they avoid verification frictions. This advantage improves financing conditions and supports macroeconomic stabilization after flood shocks. However, lower spreads do not necessarily imply proportionally higher welfare. As climate risks intensify, the welfare cost of parametric basis risk rises in severe states where the index may fail to trigger. In these states, indemnity contracts provide more reliable state-contingent relief, which becomes more valuable for highly risk-averse sovereigns.

The quantitative results for Thailand suggest that both CAT bond designs can cushion post-disaster macroeconomic losses, but their relative performance depends on climate conditions and risk preferences. Under the baseline calibration, the parametric design delivers larger welfare gains. Under the climate-change scenario, the indemnity design becomes more valuable and narrows the welfare gap, reflecting the rising importance of tail-risk protection. These results suggest that sovereign disaster-risk strategies should not rely mechanically on a single trigger structure. A layered approach that combines rapid parametric coverage with indemnity protection or fiscal buffers for severe tail events may better balance financing efficiency and insurance reliability.

Several extensions remain useful. Future work could endogenize climate adaptation investment, introduce household heterogeneity to study distributional effects, and estimate sovereign risk preferences or basis-risk parameters more directly. These extensions would help refine the optimal mix of parametric and indemnity coverage for climate-exposed economies.

Statements and Declarations

- Conflict of interest: The authors declare no competing interests.
- Ethics Committee Approval: This project did not involve human subjects research.

- Generative AI and AI-assisted technologies: During the preparation of this work the authors used Claude, ChatGPT and Gemini in order to correct any grammar mistakes. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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A Proofs

A.1 Proof of Proposition 1

Fix $(\bar{g}, p, \alpha, \psi)$ with $1 - \alpha + \psi > 0$, and set $\eta \equiv \frac{\alpha}{1-\alpha+\psi} > 0$, $\lambda \equiv \frac{1}{1-\alpha+\psi} > 0$ (so $\eta = \alpha\lambda$). Assume $\Phi_g \in C^1$ with density $\phi_g = \Phi_g'$ positive, continuous, and bounded, and $\Phi_g < 1$ at every finite argument; assume f_d is continuous with $f_d(\bar{d}) > 0$. Define the verification-adjusted relief shifter

$$C(\theta, \tau) \equiv \lambda \ln\big(1 - \theta(1 - \tau)\big), \qquad \theta \in [0, 1],\ \tau \in (0, 1),$$

so $C(0,\tau)=0$, $C<0$ for $\theta>0$, $C_\theta=-\lambda\frac{1-\tau}{1-\theta(1-\tau)}<0$, $C_\tau=\lambda\frac{\theta}{1-\theta(1-\tau)}>0$, and $C_{\theta\theta}=-\lambda\frac{(1-\tau)^2}{(1-\theta(1-\tau))^2}<0$. With $\bar{F}\equiv F_d(\bar{d})$ and $J(\theta,\tau)\equiv\int_{\bar{d}}^{\infty}\Phi_g\big(\bar{g}+\eta d'+C(\theta,\tau)\big)f_d(d')\,\mathrm{d}d'$, equation (3.17) reads

$$s_{it}=(1-p)\Phi_g(\bar{g})+p\int_0^{\bar{d}}\Phi_g(\bar{g}+\eta d')f_d\,\mathrm{d}d'+p(1-\theta)J(\theta,\tau)+p\,\theta(1-\bar{F}).$$

Since $\tau\in(0,1)$, $1-\theta(1-\tau)\geq\tau>0$ on $\theta\in[0,1]$, so $C, C_\theta, C_{\theta\theta}$ are bounded and continuous there; with $\Phi_g\leq 1$ and ϕ_g bounded, dominated convergence justifies differentiating s_{it} once under the integral sign in τ, and θ.

Part (i): Comparative static in $\bar{d}$. By Leibniz's rule, as C does not depend on $\bar{d}$,

$$\frac{\partial s_{it}}{\partial\bar{d}}=p\,f_d(\bar{d})\Big[\Phi_g(\bar{g}+\eta\bar{d})-(1-\theta)\Phi_g(\bar{g}+\eta\bar{d}+C)-\theta\Big]\equiv p\,f_d(\bar{d})\,G(\theta). \tag{A.1}$$

Since $f_d(\bar{d})>0$, the sign equals that of G. At $\theta=0$, $C=0$ gives $G(0)=\Phi_g(\bar{g}+\eta\bar{d})-\Phi_g(\bar{g}+\eta\bar{d})=0$; at $\theta=1$ the relief term carries weight $1-\theta=0$, so $G(1)=\Phi_g(\bar{g}+\eta\bar{d})-1<0$ because $\Phi_g<1$. Hence s_{it} is strictly decreasing in $\bar{d}$ near $\theta=1$. With $B(\theta)\equiv\Phi_g(\bar{g}+\eta\bar{d}+C(\theta,\tau))$,

$$\begin{aligned}G_\theta(\theta)=&B(\theta)-(1-\theta)\phi_g(\bar{g}+\eta\bar{d}+C)\,C_\theta-1\\ G_\theta(0)=&\lambda(1-\tau)\phi_g(\bar{g}+\eta\bar{d})-\big[1-\Phi_g(\bar{g}+\eta\bar{d})\big].\end{aligned}$$

If the threshold–relief condition

$$\lambda(1-\tau)\,\phi_g(\bar{g}+\eta\bar{d})>1-\Phi_g(\bar{g}+\eta\bar{d}) \tag{A.2}$$

holds, then $G_\theta(0)>0$; combined with $G(0)=0$ this yields $G(\theta)>0$ for sufficiently small $\theta>0$, i.e. $\partial s_{it}/\partial\bar{d}>0$ at small CAT-bond shares. If G has a unique zero in $(0,1)$, and since $G>0$ near 0^+ and $G(1)<0$, then that zero $\theta^\dagger$ satisfies $G>0$ on $(0,\theta^\dagger)$ and $G<0$ on $(\theta^\dagger,1)$.

Part (ii): Comparative static in τ. Only C depends on τ, so

$$\frac{\partial s_{it}}{\partial\tau}=p(1-\theta)\int_{\bar{d}}^{\infty}\phi_g\big(\bar{g}+\eta d'+C\big)\,C_\tau\,f_d\,\mathrm{d}d'.$$

For $\theta\in(0,1)$ one has $1-\theta>0$, $C_\tau>0$, and $\phi_g>0$; moreover, by continuity and $f_d(\bar{d})>0$, $f_d>0$ on a neighbourhood of $\bar{d}$ within $[\bar{d},\infty)$, so the integrand is strictly positive on a set of positive measure. Hence $\partial s_{it}/\partial\tau>0$. At $\theta=0$ there is no CAT bond, and at $\theta=1$ the J term carries weight $1-\theta=0$; in both cases the derivative is 0.

Part (iii): Comparative static in θ. Differentiating,

$$\begin{aligned}\frac{\partial s_{it}}{\partial \theta} &= p\Big[(1-\bar{F}) - J(\theta,\tau) + (1-\theta)J_\theta(\theta,\tau)\Big],\\ J_\theta &= \int_{\bar{d}}^{\infty} \phi_g(\bar{g}+\eta d'+C)\, C_\theta\, f_d\, \mathrm{d}d' < 0.\end{aligned}$$

At $\theta = 0$, $C = 0$ gives $J(0,\tau) = \int_{\bar{d}}^{\infty} \Phi_g(\bar{g}+\eta d') f_d\, \mathrm{d}d'$ and $J_\theta(0,\tau) = -\lambda(1-\tau)\int_{\bar{d}}^{\infty} \phi_g(\bar{g}+\eta d') f_d\, \mathrm{d}d'$, so

$$\left.\frac{\partial s_{it}}{\partial \theta}\right|_{\theta=0} = p\left[\int_{\bar{d}}^{\infty} \big(1-\Phi_g(\bar{g}+\eta d')\big) f_d\, \mathrm{d}d' - \lambda(1-\tau)\int_{\bar{d}}^{\infty} \phi_g(\bar{g}+\eta d') f_d\, \mathrm{d}d'\right], \tag{A.3}$$

which is strictly negative iff the marginal default-risk reduction from a small CAT-bond share dominates the marginal premium cost.

At $\theta = 1$, $(1-\theta)J_\theta = 0$ and, since $\Phi_g < 1$, $J(1,\tau) = \int_{\bar{d}}^{\infty} \Phi_g(\bar{g}+\eta d'+\lambda \ln \tau) f_d\, \mathrm{d}d' < 1-\bar{F}$, hence

$$\left.\frac{\partial s_{it}}{\partial \theta}\right|_{\theta=1} = p\big[(1-\bar{F}) - J(1,\tau)\big] > 0.$$

provided the disaster tail above the trigger has positive probability. $1-\bar{F} > 0$

Because $\tau > 0$ keeps $C(1,\tau) = \lambda \ln \tau$ finite, $\partial s_{it}/\partial\theta$ is continuous on $[0,1]$; with (A.3) negative, the intermediate value theorem yields $\theta^* \in (0,1)$ with $\partial s_{it}/\partial\theta = 0$. If in addition $\partial s_{it}/\partial\theta$ has a unique zero in $(0,1)$, then θ^* is unique with $\partial s_{it}/\partial\theta < 0$ for $\theta < \theta^*$ and > 0 for $\theta > \theta^*$. If, in addition, $\Phi_g \in C^2$ with bounded ϕ_g', then s_{it} is twice differentiable in θ with

$$\frac{\partial^2 s_{it}}{\partial \theta^2} = p\big[-2J_\theta + (1-\theta)J_{\theta\theta}\big], \tag{A.4}$$

$$J_\theta = \int_{\bar{d}}^{\infty} \big[\phi_g'(\cdot) C_\theta^2 + \phi_g(\cdot) C_{\theta\theta}\big] f_d\, \mathrm{d}d', \tag{A.5}$$

and strict convexity ($\partial^2 s_{it}/\partial\theta^2 > 0$) is sufficient for the unique interior zero of $\partial s_{it}/\partial\theta$.

Here, $-2J_\theta > 0$; since ϕ_g' is sign-indefinite, $J_{\theta\theta}$ need not be positive, so (A.5) is sufficient but not necessary, single-crossing of $\partial s_{it}/\partial\theta$ is what the conclusion requires. Under (A.5) the derivative is strictly increasing and θ^* is unique, so the spread is U-shaped in the CAT-bond share.

Note that this comparative static treats τ as a deadweight verification or delay friction that reduces the sovereign's effective relief but does not reduce the contractual haircut borne by CAT-bond investors. The relief term carries the attenuated write-down $\theta(1-\tau)$, while the

premium term still prices the full haircut θ (the $p\theta(1-\bar{F})$ term), so the wedge $\tau\theta$ is pure deadweight that raises residual default risk without compensating investors with a smaller forfeiture. □

A.2 Proof of Proposition 2

Retain $\eta \equiv \alpha/(1-\alpha+\psi) > 0$ and $\lambda \equiv 1/(1-\alpha+\psi) > 0$ from the proof of Proposition 1, the relief shifters $C_{it}(\theta,\tau)$, $C_{pt}(\theta)$, and the trigger probability $H(d';\sigma_\varepsilon) = \Phi\big((\chi d' - \bar{\omega})/\sigma_\varepsilon\big)$ with $\bar{\omega} = \chi\bar{d}$. Collecting the H-terms in the parametric spread (3.20) yields the compact representation

$$s_{pt}(\sigma_\varepsilon) = \text{const} + p\int_0^\infty m(d')\,H(d';\sigma_\varepsilon)\,f_d(d')\,dd',$$

where

$$\text{const} = (1-p)\Phi_g(\bar{g}) + p\int_0^\infty \Phi_g(\bar{g}+\eta d')\,f_d(d')\,dd',$$

$$m(d') \equiv (1-\theta)\Phi_g\big(\bar{g}+\eta d' + C_{pt}(\theta)\big) + \theta - \Phi_g(\bar{g}+\eta d').$$

Since $\Phi_g \le 1$ and ϕ_g is bounded, $|m| \le 2$ and $0 \le H \le 1$; the dominated-convergence theorem therefore justifies passing the limits and differentiating under the integral sign in σ_ε below.

Part (i): Low-basis-risk dominance. By Assumption 1 and dominated convergence, $H(d';\sigma_\varepsilon) \to \mathbf{1}\{d' \ge \bar{d}\}$ pointwise (off the null set $\{d' = \bar{d}\}$), so

$$\lim_{\sigma_\varepsilon\to 0^+} s_{pt}(\sigma_\varepsilon) = (1-p)\Phi_g(\bar{g}) + p\int_0^{\bar{d}} \Phi_g(\bar{g}+\eta d')\,f_d\,dd' + p\int_{\bar{d}}^\infty \Big[(1-\theta)\Phi_g\big(\bar{g}+\eta d'+C_{pt}(\theta)\big)+\theta\Big]\,f_d\,dd'.$$

This is exactly the indemnity spread (3.17) evaluated at the common cutoff $\bar{d}$ and at $\tau = 0$, since the parametric contract carries no verification friction; hence

$$s_{pt}(0) = s_{it}(0).$$

For $\theta \in (0,1)$ and $\tau \in (0,1)$ we have $C_{pt}(\theta) < C_{it}(\theta,\tau) < 0$, so the only difference between $s_{it}(0)$ and $s_{it}(\tau)$ is the relief shifter in the super-threshold term, which enters with positive weight $p(1-\theta)$. By Proposition 1(ii), $\partial s_{it}/\partial\tau > 0$ strictly for $\theta \in (0,1)$ whenever $1 - F_d(\bar{d}) > 0$, whence

$$s_{pt}(0) = s_{it}(0) < s_{it}(\tau).$$

Right-continuity of s_{pt} at 0 then gives $\bar{\sigma} > 0$ with $s_{pt}(\sigma_\varepsilon) < s_{it}(\tau)$ for all $\sigma_\varepsilon \in [0,\bar{\sigma})$.

Part (ii): Monotonicity in basis risk. Differentiating under the integral sign and using $\frac{\partial H}{\partial \sigma_\varepsilon} = \frac{\bar{\omega} - \chi d'}{\sigma_\varepsilon^2}\,\phi\!\left(\frac{\chi d' - \bar{\omega}}{\sigma_\varepsilon}\right)$,

$$\frac{\partial s_{pt}}{\partial \sigma_\varepsilon} = \frac{p}{\sigma_\varepsilon^2}\int_0^\infty m(d')\,(\bar{\omega} - \chi d')\,\phi\!\left(\frac{\chi d' - \bar{\omega}}{\sigma_\varepsilon}\right) f_d(d')\,dd'.$$

With $\bar{\omega} = \chi \bar{d}$ we have $\bar{\omega} - \chi d' = \chi(\bar{d} - d')$, so the integrand's sign equals that of $m(d')\,(\bar{d} - d')$. By Assumption 3, this product is non-negative for almost everywhere d', strictly positive below $\bar{d}$ (where $m > 0$) and above $\bar{d}$ (where $m < 0$) and strictly positive on a set of positive f_d-measure. Since $\phi > 0$ and $\sigma_\varepsilon > 0$,

$$\frac{\partial s_{pt}}{\partial \sigma_\varepsilon} > 0,$$

so s_{pt} is strictly increasing in σ_ε.

Part (iii): Unique reversal. As $\sigma_\varepsilon \to \infty$, Assumption 2 gives $H(d'; \sigma_\varepsilon) \to \frac{1}{2}$ for each finite d', so by dominated convergence

$$\lim_{\sigma_\varepsilon \to \infty} s_{pt}(\sigma_\varepsilon) = \text{const} + \frac{p}{2}\int_0^\infty m(d')\, f_d(d')\, dd'.$$

Define $\Delta(\sigma_\varepsilon) \equiv s_{pt}(\sigma_\varepsilon) - s_{it}(\tau)$, which is continuous and, by Part (ii), strictly increasing. Part (i) gives $\Delta(0) < 0$, while the stated large-basis-risk condition gives $\lim_{\sigma_\varepsilon \to \infty} \Delta(\sigma_\varepsilon) > 0$. The intermediate value theorem yields a crossing, and strict monotonicity makes it unique; denote it $\sigma_\varepsilon^\star$. Then $s_{pt} < s_{it}(\tau)$ for $\sigma_\varepsilon < \sigma_\varepsilon^\star$ and $s_{pt} > s_{it}(\tau)$ for $\sigma_\varepsilon > \sigma_\varepsilon^\star$. □

A.3 Proof of Proposition 3

Let $d' \in [0, \infty)$ denote next-period disaster damage. Define

$$\Delta L(d') \equiv L_{it}(d') - L_{pt}(d')$$

as the state-contingent lender-loss differential between the indemnity and parametric contracts. Since the no-disaster component is common to both contracts, the indemnity-minus-parametric spread premium under the baseline distribution f can be written as

$$\Delta s \equiv s_{it}(\tau; f) - s_{pt}(\sigma_\varepsilon; f) = p\int_0^\infty \Delta L(d') f(d')\,\mathrm{d}d',$$

where $p = \Pr(x' = 1) > 0$ is the disaster-arrival probability. Under the climate-change distribution $\tilde{f}$, the corresponding spread premium is

$$\widetilde{\Delta s} \equiv s_{it}(\tau; \tilde{f}) - s_{pt}(\sigma_\varepsilon; \tilde{f}) = p \int_0^\infty \Delta L(d') \tilde{f}(d') \, \mathrm{d}d'.$$

Let

$$r(d') \equiv \frac{\tilde{f}(d')}{f(d')}$$

denote the likelihood ratio. By the monotone likelihood-ratio property, $r(d')$ is strictly increasing in d', so the climate-change distribution places relatively more probability weight on severe damage states. Since $\tilde{f}(d') = r(d') f(d')$, we have

$$\int_0^\infty \Delta L(d') \tilde{f}(d') \, \mathrm{d}d' = \int_0^\infty \Delta L(d') r(d') f(d') \, \mathrm{d}d'.$$

Subtracting and adding $r(\bar{d})$, this becomes

$$\int_0^\infty \Delta L(d') \tilde{f}(d') \, \mathrm{d}d' = \int_0^\infty \Delta L(d') \big[r(d') - r(\bar{d}) \big] f(d') \, \mathrm{d}d' + r(\bar{d}) \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d'.$$

By the trigger-alignment condition, the state-contingent loss differential satisfies

$$\Delta L(d') < 0 \quad \text{for } d' < \bar{d}, \qquad \Delta L(d') > 0 \quad \text{for } d' > \bar{d}.$$

Since $r(d')$ is strictly increasing,

$$r(d') - r(\bar{d}) < 0 \quad \text{for } d' < \bar{d}, \qquad r(d') - r(\bar{d}) > 0 \quad \text{for } d' > \bar{d}.$$

Therefore,

$$\Delta L(d') \big[r(d') - r(\bar{d}) \big] \geq 0$$

for all d', with strict inequality on a set of positive probability. Hence,

$$\int_0^\infty \Delta L(d') \big[r(d') - r(\bar{d}) \big] f(d') \, \mathrm{d}d' > 0.$$

The low-basis-risk condition implies baseline parametric dominance:

$$s_{pt}(\sigma_\varepsilon; f) < s_{it}(\tau; f).$$

Equivalently,

$$\Delta s = p \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d' > 0.$$

Since $p > 0$, this implies

$$\int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d' > 0.$$

Moreover, by assumption, the climate shift raises the relative likelihood of trigger-relevant severe states, so

$$r(\bar{d}) \geq 1.$$

It follows that

$$r(\bar{d}) \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d' \geq \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d'.$$

Combining the preceding inequalities yields

$$\int_0^\infty \Delta L(d') \tilde{f}(d') \, \mathrm{d}d' > \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d'.$$

Multiplying both sides by $p > 0$, we obtain

$$\widetilde{\Delta s} = p \int_0^\infty \Delta L(d') \tilde{f}(d') \, \mathrm{d}d' > p \int_0^\infty \Delta L(d') f(d') \, \mathrm{d}d' = \Delta s.$$

Thus, the worsening of the damage distribution strictly widens the equilibrium spread differential between indemnity and parametric CAT bonds. □

A.4 Proof of Corollary 1

By definition,

$$\Delta W(f_d; \gamma) = W_{pt}(f_d; \gamma) - W_{it}(f_d; \gamma).$$

Adding and subtracting $W_h(f_d; \gamma)$ gives

$$\begin{aligned} \Delta W(f_d; \gamma) &= \big[W_h(f_d; \gamma) - W_{it}(f_d; \gamma)\big] + \big[W_{pt}(f_d; \gamma) - W_h(f_d; \gamma)\big] \\ &= SE(f_d; \gamma) + TRS(f_d; \gamma). \end{aligned}$$

Applying the same identity under $\tilde{f}_d$ and subtracting yields

$$\begin{aligned} \Delta_{CC} W(\gamma) &\equiv \Delta W(\tilde{f}_d; \gamma) - \Delta W(f_d; \gamma) \\ &= \big[SE(\tilde{f}_d; \gamma) - SE(f_d; \gamma)\big] + \big[TRS(\tilde{f}_d; \gamma) - TRS(f_d; \gamma)\big]. \end{aligned}$$

This proves the exact decomposition.
By Proposition 3, the spread differential

$$\Delta s(f_d) \equiv s_{it}(f_d) - s_{pt}(f_d)$$

strictly widens under the MLRP shift from f_d to $\tilde{f}_d$. Since the hybrid benchmark h is priced at the parametric spread and delivers frictionless relief, while the indemnity contract is subject to the higher indemnity spread and verification frictions, the spread-efficiency component increases:

$$SE(\tilde{f}_d; \gamma) - SE(f_d; \gamma) > 0.$$

For the tail-risk-smoothing component, the hybrid benchmark and the parametric contract share the same pricing schedule and the same frictionless relief conditional on payout. They differ only in trigger certainty. The hybrid benchmark triggers deterministically when $d' > \bar{d}$, whereas the parametric contract triggers only with probability $H(d')$. Thus, $TRS(f_d; \gamma)$ captures the welfare cost of parametric basis risk relative to the hybrid benchmark. By assumption (a), this expected penalty becomes larger under the climate-change distribution:

$$TRS(\tilde{f}_d; \gamma) - TRS(f_d; \gamma) < 0.$$

Finally, suppose the net climate-change welfare effect

$$\Delta_{CC} W(\gamma)$$

satisfies the single-crossing condition: it is continuous and strictly decreasing in γ, positive as $\gamma \to 1^+$, and negative for sufficiently large γ. Then the intermediate value theorem implies that there exists at least one $\gamma^* > 1$ such that

$$\Delta_{CC} W(\gamma^*) = 0.$$

Strict monotonicity implies that this threshold is unique. Therefore,

$$\operatorname{sign}(\Delta_{CC} W(\gamma)) = \begin{cases} +1, & \text{if } \gamma < \gamma^*, \\ 0, & \text{if } \gamma = \gamma^*, \\ -1, & \text{if } \gamma > \gamma^*. \end{cases}$$

This completes the proof. □

A.5 Quantitative Results over Baseline under Current Climate and Climate Change

We document the difference between a CAT-bond economy's impulse response and the no-CAT-bond baseline's impulse response to the same calibrated flood shock, illustrating the extra macro cushion (in percentage points of deviation from trend, or of the annualized level, depending on the variable) that issuing the bond provides at each horizon. Figure 6 isolates what each bond buys the economy conditional on the climate regime that bond was designed for: the current-climate figure measures the cushioning achieved under the flood distribution the bonds were priced against, while Figure 7 measures cushioning after the flood distribution shifts outward but the bonds themselves are already issued at pre-change prices. Comparing the two panels variable by variable is what makes the two-force story visible: where the parametric-minus-indemnity gap widens or narrows as the climate regime changes reveals whether the spread-efficiency advantage of the parametric bond or the tail-risk-smoothing advantage of the indemnity bond dominates for that variable, and by how much.

Figure 6: Marginal improvement of indemnity and parametric trigger CAT bonds over baseline under current climate

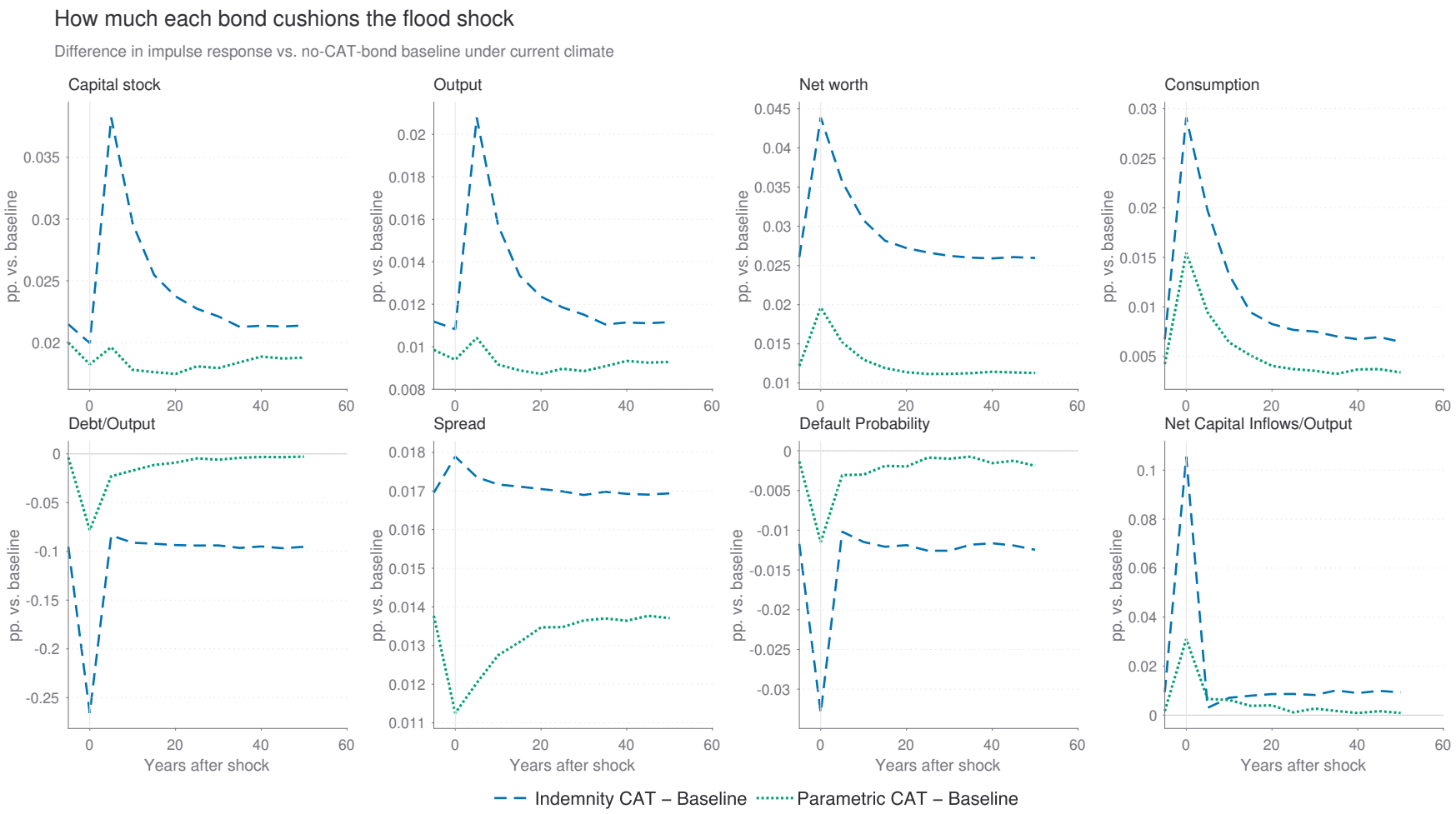


Figure 7: Marginal improvement of indemnity and parametric trigger CAT bonds over baseline under climate change

