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Abstract

This study explores catastrophe (CAT) bonds as a financial instrument against chronic flooding in emerging economies like Thailand. We embed indemnity and parametric CAT bonds into a dynamic small-open-economy model featuring sovereign default risk and Epstein-Zin preferences. Both instruments cushion macroeconomic drops relative to an uninsured benchmark, but their welfare implications are governed by two competing forces. A spread-efficiency effect favors parametric bonds, whose frictionless design yields lower borrowing costs in all states. A tail-risk-smoothing effect favors indemnity bonds, whose guaranteed payouts eliminate the welfare cost of uninsured catastrophic states where the parametric trigger fails. Under baseline climate conditions, spread efficiency dominates: parametric bonds deliver superior welfare gains while indemnity bonds impose a slight welfare drag. Under severe climate change, the balance shifts. Although parametric bonds remain the most financially efficient instrument, the indemnity contract transforms into a robust welfare-enhancing tool as its certain consumption smoothing becomes increasingly vital for a risk-averse sovereign facing frequent catastrophic floods. The net balance depends on risk aversion, and our calibration confirms substantial narrowing of the welfare gap under climate change. These findings advocate for a stratified framework layering rapid-paying parametric tranches with exact-match indemnity buffers to balance borrowing cost savings against rigorous 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 is increasingly amplifying the frequency and severity of extreme weather events, with particularly acute consequences in developing economies that face structural constraints in adaptation and post-disaster recovery (Noy, 2009; Noy and Nualsri, 2011). Floods are among the most pervasive and economically disruptive hazards, with rapidly rising exposure driven by population and asset concentration in flood-prone areas (Jongman et al., 2012). The IPCC Sixth Assessment Report highlights that under high-emissions scenarios, the likelihood of intense precipitation and large-scale flooding rises markedly ((Intergovernmental Panel on Climate Change (IPCC), 2023)). For many developing economies, this evolving risk profile is not only an environmental challenge but also a macroeconomic one, as repeated flood shocks interact with socio-economic development patterns and constraints on public capacity, turning climate risk into 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 impose macroeconomic costs through multiple, mutually reinforcing channels. They destroy productive capital and depress output (Noy, 2009; Fomby et al., 2013), and can disrupt supply chains in ways that amplify real-sector losses (Haraguchi and Lall, 2015). Flood shocks also weaken private balance sheets and reduce household consumption and welfare, including through credit and collateral channels (Kurosaki, 2015; Karim, 2018; Noth and Schüwer, 2023). Governments typically respond by scaling up emergency relief and reconstruction spending, often under tighter fiscal constraints in developing economies (Noy and Nualsri, 2011; Klomp, 2017). This response can raise debt burdens and increase sovereign risk premia or spreads as investors reassess default risk (Klomp, 2015, 2017; Mallucci, 2022), which in turn tightens financing conditions and discourages private investment (Uribe and Yue, 2006; Neumeyer and Perri, 2005). In open economies, these dynamics can also be accompanied by reduced capital inflows and/or capital outflows, further amplifying the contraction (Klomp, 2017; Yang, 2008; Anuchitworawong and Thampanishvong, 2015). When post-disaster financing relies heavily on discretionary budget reallocations or costly debt issuance, the resulting macro-financial feedback can make welfare losses larger and more persistent (Noy, 2009; Mallucci, 2022).

These challenges have renewed interest in disaster risk financing instruments that can deliver rapid, pre-arranged liquidity and reduce the need for disruptive fiscal adjustments after shocks. This paper focuses on catastrophe bonds (CAT bonds), a class of insurance-linked securities that transfer disaster risk to international capital markets in exchange for yield-bearing premiums. CAT bonds provide contingent financing. When a predefined trigger is met, principal repayment is partially or fully forgiven, injecting resources precisely when they are most valuable for stabilization and recovery. Importantly, the design of the trigger matters. Indemnity triggers are linked to realized losses and thus align payouts closely with damages, but delayed payments may occur because loss verification and assessment can be time-consuming (Cummins and Weiss, 2009). Meanwhile, parametric triggers depend on observable hazard metrics such as rainfall intensity or flooded area offering speed and transparency but exposing issuers to basis risk when payouts diverge from actual economic losses (Cummins et al., 2004). Understanding how CAT bonds operate through macroeconomic and financial channels, and how trigger choice changes those channels, is therefore central to assessing their 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 the fiscal position, and sustain external funding conditions (Noy, 2009; Noy and Nualsri, 2011; Mallucci, 2022). Although CAT bonds are frequently discussed as a promising tool to smooth post-disaster public spending and limit ad hoc borrowing, policymakers still face uncertainty about their broader macroeconomic effectiveness particularly for hazards like floods that can be economically costly even when they do not constitute rare, catastrophic humanitarian crises. This uncertainty is consequential because the welfare impact of floods is shaped not only by direct damages but also by second-round macro-financial spillovers, which are precisely the margins that contingent financing may influence (Mallucci, 2022; Uribe and Yue, 2006).

This paper addresses a clear research gap in the existing literature. Prior work has often emphasized the fiscal and public debt implications of CAT bond issuance highlighting how contingent payouts can help stabilize government spending and borrowing needs after disasters (e.g., Suanin and Wattanakoon (2023); Maran (2023)). Nonetheless, the broader general-equilibrium implications have not been systematically quantified across key macroeconomic variables that jointly determine welfare, including capital stock, output, country's net worth, consumption, the debt-to-output ratio, sovereign spreads, and net capital inflows relative to output. In addition, much of the macro-focused evidence has concentrated on infrequent, high-impact disasters (such as major cyclones or hurricanes) in a limited set of regions (Mallucci, 2022; Phan and Schwartzman, 2024), leaving open the question of whether the stylized benefits of CAT bonds extend to chronic flood risk which is a more common and persistent threat across many developing economies. The literature also provides limited quantitative guidance on how alternative trigger structures (indemnity versus parametric) translate into different macroeconomic trajectories and welfare outcomes, despite the centrality of this design choice in practice and the presence of basis risk (Cummins et al., 2004; Cummins and Weiss, 2009). Drawing on microeconomic theories of index insurance (Clarke, 2016) and asset pricing models of moral hazard (Lee and Yu, 2002), our framework introduces a mathematical decomposition of CAT bond triggers. We explicitly weigh the verification frictions of indemnity structures against the Type I and Type II basis risk errors of parametric structures, formalizing the exact conditions under which parametric liquidity dominates.

Against this backdrop, the paper develops and quantifies a general-equilibrium framework to evaluate the macroeconomic and welfare implications of adopting CAT bonds in a flood-prone small open economy, using Thailand as a case study. The analysis is organized around three objectives. *First,* it examines how CAT bond adoption alters the dynamics of key macroeconomic variables (i.e., capital stock, output, country's net worth, consumption, debt-to-output, sovereign spreads, net capital inflows-to-output, and welfare), following exogenous flood shocks. *Second,* it compares how different trigger designs, specifically indemnity versus parametric triggers, shape these macroeconomic responses by trading off alignment with realized damages against speed, transparency, and basis risk. *Third,* it investigates how the rise of intensity of flooding from climate change affects welfare, contrasting economies that adopt CAT bonds with those that do not, and further distinguishing between trigger structures, thereby clarifying whether CAT bonds remain welfare-improving under more intense shock environments.

Thailand provides an especially informative setting for three reasons. First, it has chronic exposure to flooding that is economically meaningful and recurrent, making it a natural laboratory for studying disaster risk that is not merely tail risk but a persistent macroeconomic disturbance (Darnkachatarn and Kajitani, 2024). The 2011 floods serve as a stark reference point while the broader pattern of recurring flood events underscores the policy relevance of financing arrangements that can be deployed repeatedly and predictably. Second, Thailand's degree of financial development and integration with global capital markets makes sovereign risk perceptions and external financing conditions a first-order macroeconomic channel. Changes in spreads and capital flows can be tightly linked to domestic macro fluctuations in developing economies (Neumeyer and Perri, 2005; Uribe and Yue, 2006; Hutchison and Noy, 2006). Third, as a middle-income economy with both fiscal constraints and growing climate exposure, Thailand is representative of a larger set of developing countries for which adaptation policy must combine infrastructure investment with credible financial instruments that reduce macroeconomic volatility and welfare losses (Darnkachatarn and Kajitani, 2024).

The primary contribution of this study is to provide a unified, quantitative assessment of catastrophe bonds as a macroeconomic stabilization tool against severe flood risk. By embedding these instruments into a dynamic small open economy model with recursive preferences, we systematically link flood-induced capital destruction to sovereign borrowing, yield spreads, and capital flows. This structural framework enables a comprehensive analysis of how contingent disaster financing impacts aggregate welfare through multiple transmission channels, rather than through public debt dynamics alone. Furthermore, by explicitly contrasting indemnity and parametric triggers, the paper provides critical, policy-relevant evidence on how contract design shapes macroeconomic resilience. We clarify the exact conditions under which the rapid, frictionless liquidity of parametric payouts trades off against the precise, state-contingent relief of indemnity contracts, and establish that parametric bonds yield strictly lower equilibrium spreads when basis risk is sufficiently contained, while this spread advantage widens as climate change intensifies the damage distribution.

A key theoretical insight of the paper is that this widening financial advantage does not translate mechanically into a widening welfare advantage. We show that the welfare comparison between the two instruments is governed by two competing forces: an unconditional spread-efficiency channel through which cheaper parametric borrowing raises consumption in all states, and a conditional tail-risk-smoothing channel through which indemnity's guaranteed payouts eliminate the welfare cost of catastrophic floods where the parametric trigger fails to fire. The relative strength of these forces depends on the sovereign's degree of risk aversion. For moderately risk-averse governments, spread savings dominate and parametric bonds are unambiguously superior. For highly risk-averse governments facing escalating climate risks, the welfare penalty from uninsured tail events grows disproportionately, transforming the indemnity bond from a net cost into a vital complement. This decomposition provides the theoretical foundation for our central policy recommendation: a stratified disaster risk financing framework that layers rapid-paying parametric tranches with exact-match indemnity buffers, with the optimal mix shifting toward indemnity as climate risks intensify.

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.

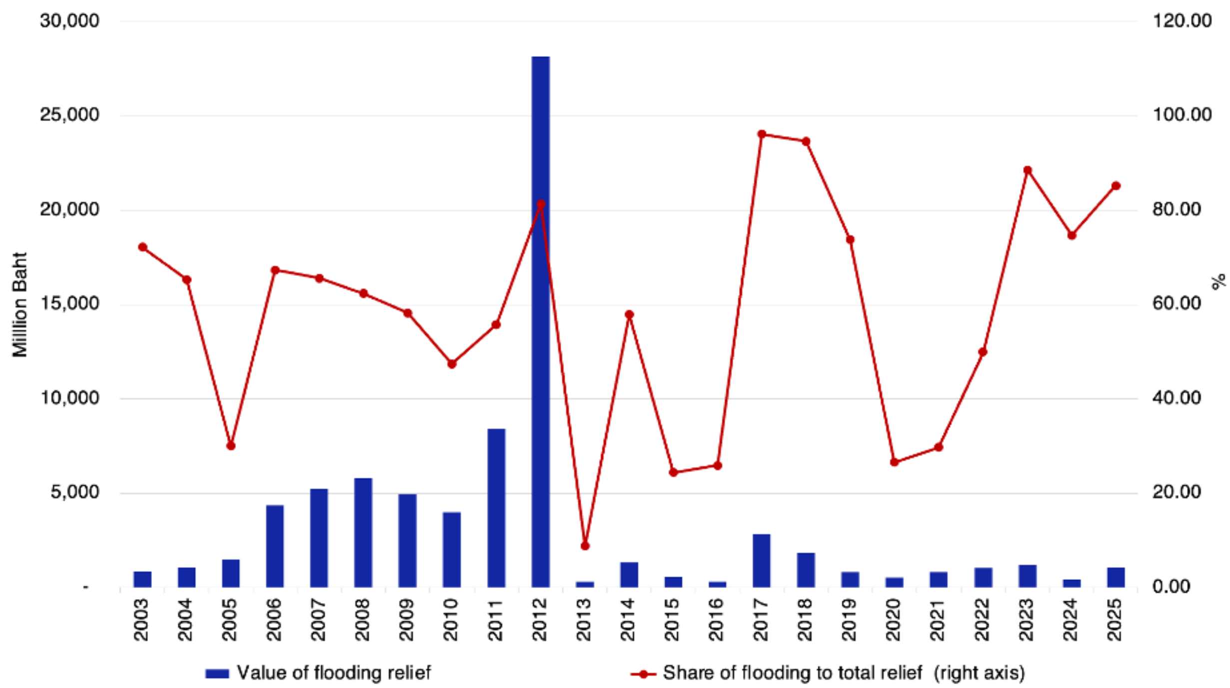
Importantly, flooding has continued to recur in recent years, reinforcing its status as a chronic risk. In late 2024, floods in southern Thailand affected nearly 534,000 households and necessitated the establishment of numerous temporary shelters.[1] Additional monsoon-related flood and landslide episodes 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]

[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 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

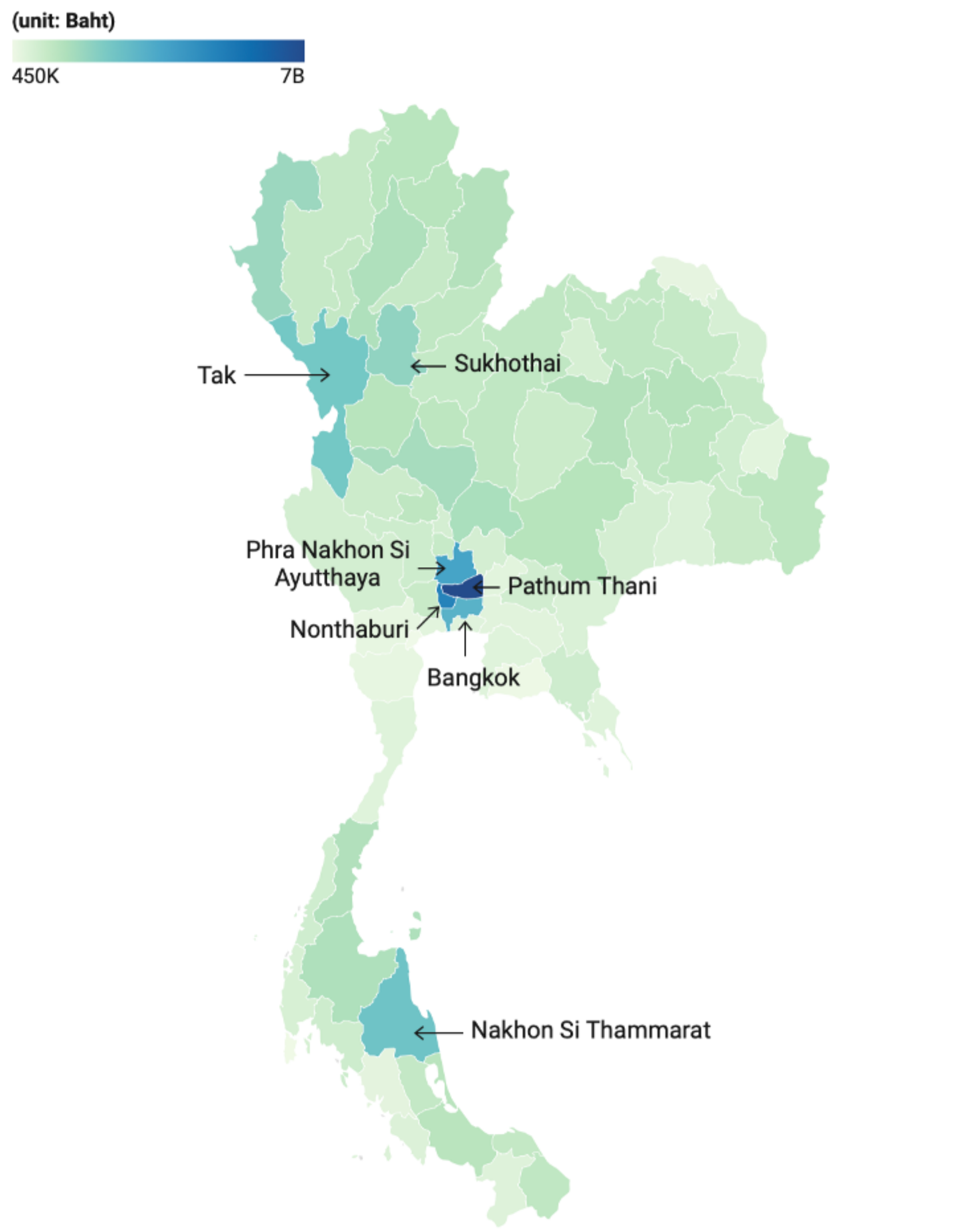


Source: The Department of Disaster Prevention and Mitigation (DDPM)

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 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

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

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) 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 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:

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

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 $\ell(g')$:

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

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 $\bar{g}(b_n, k_n) = \frac{1}{1-\alpha+\psi} \ln \frac{b_n}{\bar{\ell} k_n^\alpha}$.

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:

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

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:

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

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:

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

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.

Intuitively, when a trigger $\bar{d}$ is raised, a slice of disaster states that previously qualified for the automatic write-down ($d' > \bar{d}$). In those states lenders stop paying the insurance premium since they no longer forfeit the fraction θ of face value. Nevertheless, they simultaneously lose the default-risk cushion the CAT bond had provided. Without the write-down, the sovereign must repay the full unit, so the default probability jumps from the lower level $\Phi_g\big(\bar{g} + \frac{\alpha}{1-\alpha+\psi}\bar{d} + \frac{1}{1-\alpha+\psi}\ln(1-\theta(1-\tau))\big)$ with relief to the higher $\Phi_g\big(\bar{g} + \frac{\alpha}{1-\alpha+\psi}\bar{d}\big)$ without relief, and because $\frac{1}{1-\alpha+\psi}\ln(1-\theta(1-\tau)) < 0$ this jump is strictly positive. The increase in expected losses from the higher chance of outright default outweighs the premium that lenders save, so under risk-neutral pricing the net expected loss per dollar of face value, i.e. the spread, rises when the trigger is set tougher.

For the verification friction, if τ increases, the effective debt relief the sovereign receives during a disaster diminishes. This leaves the sovereign with a higher residual debt burden in the post-disaster state, keeping the threshold for default higher. Rational and risk-neutral lenders anticipate this elevated default probability and charge a higher ex-ante spread to compensate. The result is summarized in second part of proposition 1.

The third part of proposition 1 is similar to Phan and Schwartzman (2024) regarding $\frac{\partial s}{\partial \theta}$. When the share of CAT bond is smaller than the threshold ($\theta < \theta^*$), raising θ shifts the repayment threshold left, cuts the probability of outright default, and therefore reduces the spread. In contrast, when the share exceeds such threshold ($\theta > \theta^*$), a larger θ enlarges the insurance premium lenders must forfeit whenever the CAT bond is triggered, and that premium grows faster than the incremental fall in default risk, so the sovereign spread widens.

Proposition 1. The equilibrium spread schedule s_{it} for an indemnity-triggered CAT bond is strictly increasing with respect to both the trigger threshold $\bar{d}$ and the verification friction τ. Furthermore, there exists a threshold θ^* determining the relationship between the spread and the CAT bond share θ, such that $\frac{\partial s_{it}}{\partial \theta} < 0$ for $\theta < \theta^*$ and $\frac{\partial s_{it}}{\partial \theta} > 0$ for $\theta > \theta^*$

Proof: Appendix A.1

In sum, for indemnity-triggered CAT bonds, payouts are based on the actual damages incurred by the insured party. This ensures accuracy and alignment with realized damages, but it often requires a lengthy claims assessment process, which can delay the release of funds. In contrast, parametric triggers rely on predefined physical indicators such as rainfall exceeding a threshold, flood depth at a given location, or even flooded area to activate payouts. These triggers allow for faster disbursement and greater transparency but may result in a basis risk where payouts do not perfectly match the actual economic losses experienced. We then model parametric trigger CAT bond in the following section.

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

[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 $H(d') = \mathbb{P}(\omega > \bar{\omega}|d') = 1 - \Phi_\epsilon(\frac{\bar{\omega} - \chi d'}{\sigma_\epsilon}) = \Phi_\epsilon(\frac{\chi d' - \bar{\omega}}{\sigma_\epsilon})$ since the normal distribution is symmetric around mean 0.

spread, as derived in Equation 3.20.

$$s_{pt}\big(\bar{g},\theta,\bar{\omega}\big) = (1-p)\,\Phi_g(\bar{g}) + p\int_0^\infty \underbrace{\big[1-H(d')\big]}_{\text{Prob. of No Trigger}}\;\Phi_g\big(\bar{g}+\tfrac{\alpha}{1-\alpha+\psi}\,d'\big)\,f_{d'}(d')\,\mathrm{d}d'$$

$$+\;p(1-\theta)\int_0^\infty \underbrace{H(d')}_{\text{Prob. of Trigger}}\;\Phi_g\Big(\bar{g}+\tfrac{\alpha}{1-\alpha+\psi}\,d' + \underbrace{\tfrac{1}{1-\alpha+\psi}\ln\big(1-\theta\big)}_{\text{Maximized relief }(\tau=0)}\Big)\,f_{d'}(d')\,\mathrm{d}d'$$

$$+\;\underbrace{p\,\theta\int_0^\infty H(d')\,f_{d'}(d')\,\mathrm{d}d'}_{>0,\text{ Parametric CAT bond premium}}\;. \tag{3.20}$$

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 parametric 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 ($\sigma_\epsilon^2 \to 0$), 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 (s_{it}), the trigger mechanism is deterministic and perfectly correlated with actual damage, represented by the rigid integration bounds ranging from 0 to $\bar{d}$ (no payout) and $\bar{d}$ to ∞ (guaranteed payout). There is zero basis risk, meaning investors never suffer Type I errors and the sovereign never suffers Type II errors. However, this precision comes at the cost of the verification friction τ. In the third term of s_{it}, the effective relief is reduced to $\ln(1-\theta(1-\tau))$, keeping the sovereign's residual default risk higher compared to the maximized relief in s_{pt}. For the parametric bond to strictly dominate the indemnity bond ($s_{pt} < s_{it}$), the macroeconomic benefit of frictionless relief must outweigh the combined costs of Type I and Type II errors. We formalize this dominance by stating three necessary 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 Noise Distribution (Mean-Preserving Spread). The observation noise ϵ is drawn from a symmetric continuous distribution where an increase in variance σ_{ϵ} constitutes a mean-preserving spread.

*Assumption 3: Optimal Threshold Alignment (Single-Crossing Property).*The contract threshold ($\bar{\omega}$) is optimally aligned such that the incremental trigger cost satisfies the single-crossing property.

The theoretical dominance of the parametric CAT bond over its indemnity counterpart hinges on three foundational assumptions that ensure 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 achieve 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, meaning the basis risk acts purely as random noise around true economic damages without systematically biasing the trigger up or down. 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 contract's trigger threshold must be optimally aligned to satisfy a single-crossing property, ensuring the instrument functions as genuine disaster insurance rather than an inefficient, unconditional cash transfer. Specifically, the threshold must be calibrated so that the bond yields an expected net loss for the sovereign during minor nuisance events, where the ex-ante premium outweighs the marginal benefit of debt relief, and an expected net gain during severe catastrophes, where liquidity is critical to averting sovereign default. We formalize this parametric dominance and its eventual reversal in Proposition 2.

Proposition 2. Suppose the observation noise ϵ is drawn from a symmetric continuous distribution where an increase in variance σ_ϵ constitutes a mean-preserving spread (small-noise limit and symmetric noise spread). Further, assume the contract threshold ($\bar{\omega}$) is optimally aligned such that the incremental trigger cost satisfies the single-crossing property, meaning the bond yields an expected loss for minor events and an expected gain for severe disasters (optimal threshold alignment). Under these conditions:

(i) For sufficiently low basis risk, the parametric CAT bond strictly dominates the indemnity bond: $s_{pt}(0) < s_{it}(\tau)$.

(ii) The equilibrium spread of the parametric bond $s_{pt}(\sigma_\epsilon)$ is strictly increasing with respect to basis risk σ_ϵ.

(iii) Provided the asymptotic basis risk penalty is sufficiently large, there exists a unique basis risk threshold $\sigma_\epsilon^* > 0$ such that for all $\sigma_\epsilon > \sigma_\epsilon^*$, the indemnity bond becomes strictly preferred: $s_{pt}(\sigma_\epsilon) > s_{it}(\tau)$.

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 fundamentally alters the severity of extreme weather events. To capture this realistically, 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 sense of the Monotone Likelihood Ratio Property (MLRP). This shift moves probability mass away from minor, manageable shocks and creates a fatter right tail of catastrophic economic damages. Analyzing this distributional shift reveals a critical theoretical divergence in how risk-neutral lenders price the structural frictions of the two CAT bonds. The primary inefficiency of the indemnity bond (the verification friction: τ) acts as a proportional deduction from the sovereign's debt relief during severe states. Conversely, the primary inefficiency of the parametric bond (the expected cost of basis risk) is concentrated at the lower end of the damage distribution, where minor floods might mistakenly trigger the index

Because climate change shifts the probability mass toward the extreme right tail, it disproportionately penalizes the indemnity structure. Under the worsened distribution $\tilde{f}(d')$, the sovereign finds itself in severe disaster states much more often, meaning the deadweight losses associated with loss-adjustment and auditing expenses (τ) compound dramatically. Lenders anticipate this recurring drain on post-disaster liquidity and consequently demand a steeply higher ex-ante spread. Meanwhile, the parametric bond escapes this severe penalty because its relief remains entirely frictionless, regardless of the disaster's magnitude. This asymmetric vulnerability to extreme tail risks mathematically guarantees that a worsening climate strictly drives a wedge between the borrowing costs of the two instruments, as formalized in the following proposition 3

Proposition 3. Let climate change be defined as a shift in the disaster severity distribution from $f(d')$ to $\tilde{f}(d')$, such that $\tilde{f}$ dominates f via the Monotone Likelihood Ratio Property. Assuming the condition for parametric dominance holds (i.e., basis risk is sufficiently small) such that $s_{pt} < s_{it}$, this worsening of the damage distribution strictly widens the equilibrium spread differential between indemnity and parametric CAT bonds. The spread premium $\Delta s = s_{it} - s_{pt}$ strictly increases under $\tilde{f}$.

Proof: Appendix A.3

A profound and somewhat counterintuitive implication of proposition 3 is its effect on the financial instrument's basis risk. While a fatter right tail of damages strictly magnifies the expected deadweight losses of indemnity verification, it theoretically suppresses the expected costs of parametric basis risk. Basis risk generates two inefficiencies: Type I errors (false positives) and Type II errors (false negatives). Because Type I errors are heavily localized at the lower end of the damage distribution, a rightward shift in probability mass renders these false alarm states statistically less frequent. Consequently, the ex-ante premium penalty that lenders charge for unwarranted payouts shrinks as a fraction of the total spread. Furthermore, as climate change pushes extreme damages further into the right tail, the argument of the trigger function $(\chi d' - \bar{\omega})$ becomes massive. The continuous trigger probability $H(d')$ therefore asymptotically approaches unity, effectively driving the probability of Type II errors (trigger failures during severe catastrophes) toward zero. Ultimately, a worsening climate distribution not only renders indemnity structures fiscally unsustainable, but dynamically improves the relative macroeconomic precision of parametric indices for tail-risk events. We examine its welfare implication in corollary 1.

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 $s_{pt} < s_{it}$ and the spread differential $\Delta s = s_{it} - s_{pt}$ strictly widens under the MLRP shift from f to $\tilde{f}$. The change in the ex-ante welfare differential under climate change, $\widetilde{\Delta W} - \Delta W$, can be exactly decomposed as:

$$\widetilde{\Delta W} - \Delta W = \underbrace{\left[SE(\tilde{f}) - SE(f)\right]}_{\text{Spread-Efficiency Gain}} + \underbrace{\left[TRS(\tilde{f}) - TRS(f)\right]}_{\text{Tail-Risk-Smoothing Penalty}}$$

where:

(i) **The spread-efficiency effect ($SE > 0$) strictly favors the parametric bond.** As the spread differential widens under climate change ($\widetilde{\Delta s} > \Delta s$), the parametric bond's lower unconditional borrowing cost raises mean consumption relative to the indemnity bond across all states of the world. Furthermore, the absence of verification frictions ($\tau = 0$) provides strictly larger effective debt relief whenever the parametric bond successfully triggers. Thus, the efficiency gain strictly widens: $SE(\tilde{f}) - SE(f) > 0$.

(ii) **The tail-risk-smoothing effect ($TRS < 0$) strictly favors the indemnity bond.** Under the worsened climate distribution, catastrophic damage states receive greater probability weight. In these extreme states, the indemnity contract provides certain debt relief, whereas the parametric index exposes the sovereign to a probabilistic lottery over payouts ($H(d') < 1$). For a risk-averse sovereign, the certainty-equivalent welfare penalty of this uninsured basis risk strictly increases as catastrophic tail-risks become more frequent, yielding a widening penalty: $TRS(\tilde{f}) - TRS(f) < 0$.

(iii) **The net welfare impact depends on the degree of risk aversion (γ).** Because the marginal utility cost of uninsured catastrophic states grows without bound as risk aversion increases, while the consumption benefits of spread efficiency remain bounded, there exists a unique threshold $\gamma^* > 1$ such that:

- For $\gamma < \gamma^*$: The spread-efficiency effect dominates ($\widetilde{\Delta W} - \Delta W > 0$), and the parametric welfare advantage strictly widens.
- For $\gamma > \gamma^*$: The tail-risk-smoothing effect dominates ($\widetilde{\Delta W} - \Delta W < 0$), and the parametric welfare advantage strictly narrows.

Proof: Appendix A.4

Corollary 1 reveals that the welfare comparison between parametric and indemnity CAT bonds under climate change is governed by two forces that pull in opposite directions. The first is a spread-efficiency effect that strictly favors the parametric design. This efficiency gain operates through two distinct channels: first, because parametric bonds carry a lower equilibrium spread (Proposition 2), the sovereign faces cheaper borrowing costs in every period, which raises the bond price q_{pt} and unconditionally expands the budget set. Second, because parametric triggers bypass the loss-adjustment process ($\tau = 0$), they deliver strictly larger effective debt relief whenever a payout does occur. Proposition 3 establishes that climate change amplifies both channels, so the parametric bond's combined financial and frictionless-payout advantages strictly grow as flood risk intensifies.

The second force is a tail-risk-smoothing effect that operates conditionally, only in disaster states where the two trigger mechanisms diverge. When a severe flood strikes, the indemnity bond triggers with certainty and delivers guaranteed debt relief, whereas the parametric bond triggers only probabilistically, leaving the sovereign fully exposed to the debt burden with probability $1 - H(d')$. Under Epstein-Zin preferences with $\gamma > 1$, the sovereign assigns disproportionate welfare weight to these uninsured catastrophic states, and the welfare cost of the parametric trigger lottery grows steeply in γ. Climate change amplifies this penalty by increasing the frequency of severe damage states where $H(d')$ remains bounded below unity. The corollary establishes that a threshold γ^* separates the two regimes: for moderately risk-averse sovereigns ($\gamma < \gamma^*$), the unconditional spread savings dominate and the parametric advantage widens under climate change; for highly risk-averse sovereigns ($\gamma > \gamma^*$), the welfare cost of uninsured tail events dominates and the parametric advantage narrows, with indemnity's guaranteed consumption smoothing becoming increasingly vital.[7]

[7] Our quantitative calibration at $\gamma = 4$ falls in the latter regime (shown in Table 2), underscoring the practical importance of layering both instruments in a stratified disaster risk financing framework.

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.

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[8]. We set the marginal damage for 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.

[8]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 $\chi = \frac{1}{\mu_{pt}}$. 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: $\sigma_\epsilon = 0.2\chi d'$, 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 $\bar{\omega} = \chi\bar{d} + \Phi^{-1}(0.7)\sigma_\epsilon$, 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 $\bar{d}$

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	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	90th percentile of ω	

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

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[9], 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 blue), (ii) an Indemnity CAT bond (dashed red), and (iii) a Parametric CAT bond (dotted green). 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[10]. 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 insurance payouts mitigate the immediate need for post-disaster borrowing, with the indem-

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

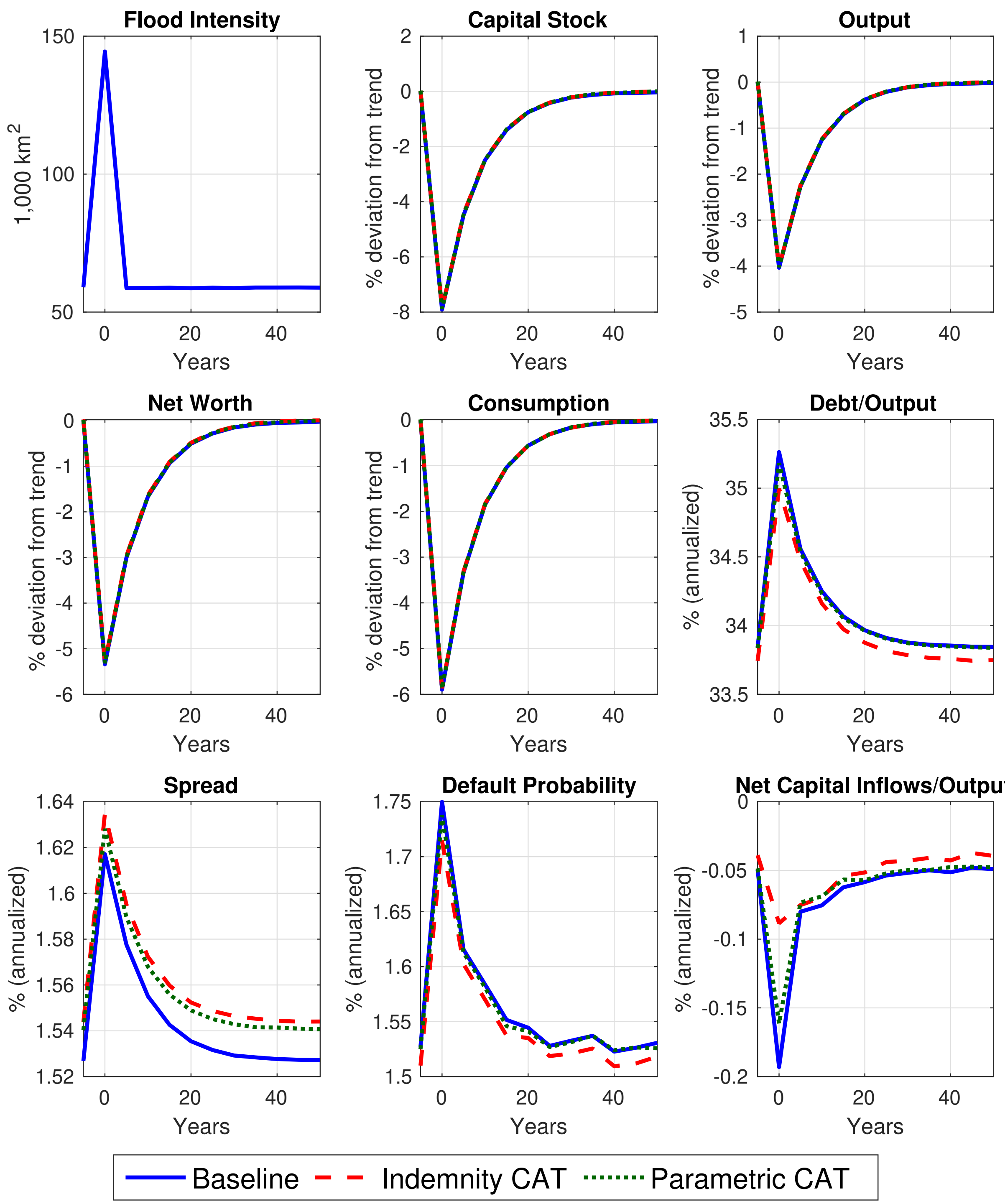
[10]While the level responses in Figure 3 appear nearly identical across regimes, Figure 6 isolates the marginal stabilization benefit of each instrument, revealing that the indemnity CAT bond improves capital retention around 0.02 percentage points relative to the uninsured baseline on impact, and provides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

nity 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

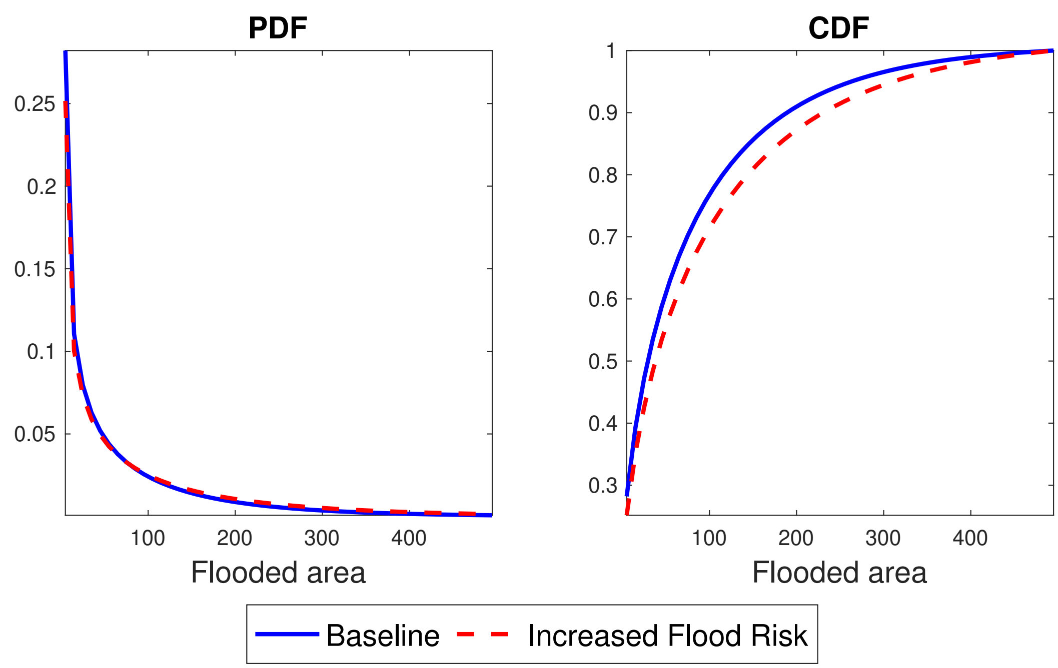


Note: Impulse responses are drawn from one-million simulated samples.

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.

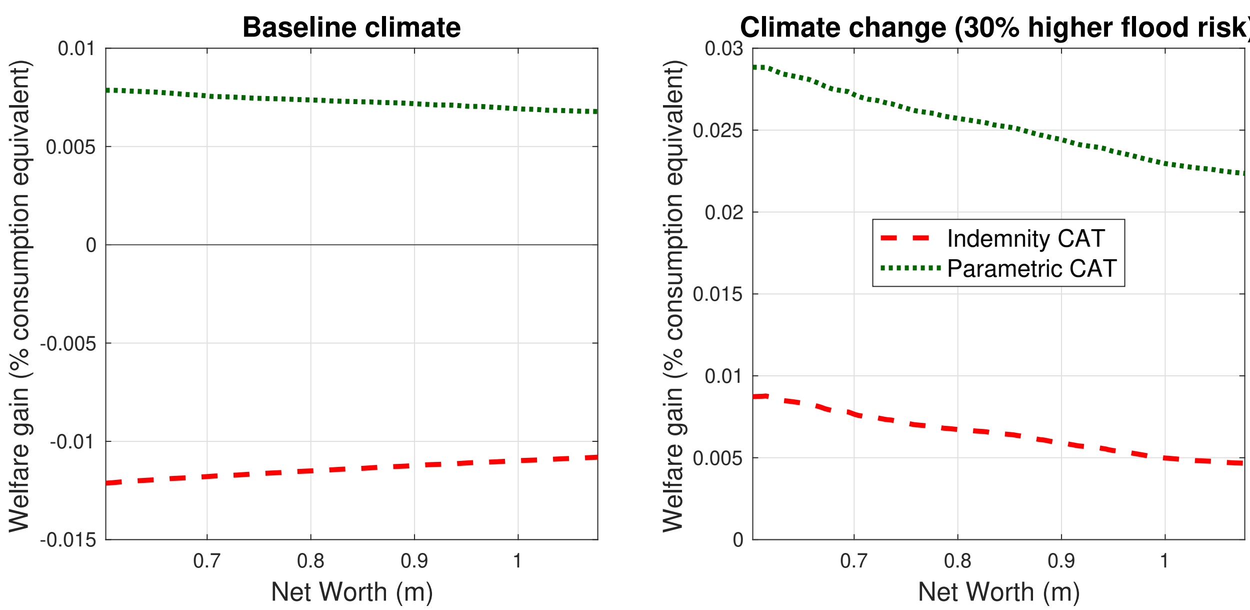
Figure 5 plots Δw_j against the distribution of government net worth under two climate regimes. Each panel measures the gain relative to the uninsured economy under the same climate regime, so the vertical gap between the two lines directly reveals the parametric bond's welfare advantage over the indemnity 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 evaluates how sovereign catastrophe (CAT) bonds can shield flood-prone emerging economies, exemplified by Thailand, from severe macroeconomic fallout. Using a calibrated dynamic small open economy model, we embed both indemnity- and parametric-trigger CAT bonds to trace their general-equilibrium effects on capital accumulation, government net worth, sovereign spreads, and capital inflows following exogenous flood shocks. By contrasting indemnity contracts (accurate but friction-laden payouts) with parametric triggers (immediate, frictionless relief subject to basis risk), our analysis quantifies how instrument design influences liquidity provision and the mitigation of macroeconomic volatility.

Our theoretical and quantitative findings reveal a nuanced trade-off between financial efficiency and macroeconomic welfare, which is highly sensitive to both the underlying climate regime and the sovereign's risk aversion. Theoretically, we establish that if the basis risk of a parametric index is sufficiently low, the absence of verification frictions allows the parametric bond to yield a strictly lower equilibrium spread than its indemnity counterpart (Proposition 2). Furthermore, as climate change worsens the disaster distribution, this spread premium strictly widens, making parametric bonds increasingly cheaper to finance relative to indemnity bonds (Proposition 3).

Nonetheless, Corollary 1 demonstrates that this widening financial advantage does not necessarily translate into a proportional divergence in welfare. The corollary decomposes the welfare effect of climate change into two competing forces: a spread-efficiency effect that unconditionally favors the parametric bond through cheaper borrowing in all states, and a tail-risk-smoothing effect that favors the indemnity bond by eliminating the welfare cost of uninsured catastrophic states where the parametric trigger fails to fire. The net sign depends on risk aversion below a critical threshold, the spread savings dominate and the parametric advantage widens under climate change; for higher level of risk aversion, the certainty-equivalent penalty from parametric Type II errors dominates and the advantage narrows. Under current baseline climate conditions, the parametric bond strictly dominates by providing cheap liquidity and generating positive welfare gains, while the indemnity bond imposes a slight welfare drag due to its costly verification frictions. Yet, under a severe climate change scenario, our quantitative calibration confirms that the tail-risk-smoothing effect dominates: while the parametric bond remains the most financially efficient instrument overall, the perfect, state-contingent consumption smoothing of the indemnity bond becomes increasingly vital for a highly risk-averse sovereign facing frequent catastrophic tail-risks. Consequently, the indemnity design transforms from a net welfare cost into a robust, welfare-enhancing instrument, significantly narrowing the performance gap and increasingly justifying its higher issuance spread as climate risks intensify.

For middle-income, disaster-exposed economies like Thailand, these results strongly advocate for a stratified and layered disaster risk financing strategy rather than reliance on a single instrument. The parametric bond's advantage lies in its unconditional borrowing cost savings, cheaper financing that benefits the sovereign in every period, not just when disasters strike. A parametric tranche should therefore be utilized to capitalize on its frictionless pricing advantage, delivering rapid liquidity when conventional debt markets are most stressed. However, our analysis reveals that this financial efficiency advantage tells only half the story. For a highly risk-averse sovereign, the welfare cost of being left uninsured during a catastrophic flood when the parametric index fails to trigger despite severe damage grows disproportionately as climate risks intensify. This rapid-response layer must therefore be complemented by exact-match indemnity buffers or domestic fiscal reserves designed to catch catastrophic tail events, precisely because their guaranteed payouts eliminate the worst-case consumption drops that matter most for welfare. The optimal balance between the two tranches is regime-dependent: economies facing moderate climate risk can lean more heavily on the cheaper parametric instrument, while those confronting severe and escalating tail-risks should progressively increase the indemnity share to ensure robust consumption smoothing. To contain coupon costs, governments should link issuance to credible adaptation investments, thereby lowering background default risk. Regulatory recognition of CAT-bond proceeds as counter-cyclical buffers, alongside partial donor-supported premium subsidies as pioneered by the Pacific CAT Facility, would further amplify their stabilization power.

This framework provides a rigorous foundation for deeper inquiry into sovereign climate finance. Future extensions could enhance the model's realism by incorporating endogenous adaptation investments, multi-period climate degradation trends, and household-level heterogeneity to track the distributional impacts of disaster shocks. Our finding that the welfare comparison between the two instruments hinges on a critical level of risk aversion also opens a natural avenue for calibration-based policy guidance: estimating where a given sovereign's revealed risk preferences sit relative to this threshold would provide concrete recommendations on the optimal parametric-to-indemnity mix under projected climate scenarios. Additionally, exploring the political-economy frictions that influence contract design and payout deployment would yield an even richer picture of CAT bond effectiveness. Empirically, the expanding track record of sovereign CAT transactions offers a valuable opportunity to fine-tune structural parameters regarding index quality and verification costs and to rigorously test the predicted interactions between disaster risk financing and global capital inflows.

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 $(\bar{g}, p, \alpha, \psi)$ and let $k \equiv \frac{\alpha}{1-\alpha+\psi} > 0, \lambda \equiv \frac{1}{1-\alpha+\psi} > 0$. Define the (verification-adjusted) relief shifter

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

and let F_d and f_d denote the CDF and PDF of damages, with $f_d(\bar{d}) > 0$. Write the indemnity-spread schedule (3.20) as

$$s_{it}(\bar{g}, \theta, \bar{d}; \tau) = (1-p)\,\Phi_g(\bar{g}) + p \int_0^{\bar{d}} \Phi_g(\bar{g} + kd')\, f_d(d')\,\mathrm{d}d' \\ + p(1-\theta) \int_{\bar{d}}^{\infty} \Phi_g\big(\bar{g} + kd' + C(\theta,\tau)\big)\, f_d(d')\,\mathrm{d}d' + p\,\theta\,\big(1 - F_d(\bar{d})\big).$$

For convenience define

$$J(\theta,\tau) \equiv \int_{\bar{d}}^{\infty} \Phi_g\big(\bar{g} + kd' + C(\theta,\tau)\big)\, f_d(d')\,\mathrm{d}d', \qquad \bar{F} \equiv F_d(\bar{d}),$$

so that $s_{it} = (\text{terms independent of } \theta) + p(1-\theta)\, J(\theta,\tau) + p\,\theta\,(1-\bar{F})$.

Step 1: Monotonicity in $\bar{d}$. Differentiate using Leibniz's rule:

$$\frac{\partial}{\partial \bar{d}} \int_0^{\bar{d}} \Phi_g(\bar{g} + kd')\, f_d(d')\,\mathrm{d}d' = \Phi_g(\bar{g} + k\bar{d})\, f_d(\bar{d}),$$
$$\frac{\partial}{\partial \bar{d}} \int_{\bar{d}}^{\infty} \Phi_g(\bar{g} + kd' + C)\, f_d(d')\,\mathrm{d}d' = -\Phi_g(\bar{g} + k\bar{d} + C)\, f_d(\bar{d}),$$

and $\frac{\partial}{\partial \bar{d}}(1-\bar{F}) = -f_d(\bar{d})$. Hence

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

Therefore, s_{it} is strictly increasing in $\bar{d}$ whenever the following dominance condition holds:

$$\Phi_g(\bar{g} + k\bar{d}) - (1-\theta)\,\Phi_g\big(\bar{g} + k\bar{d} + C(\theta,\tau)\big) > \theta. \tag{A.1}$$

Condition (A.1) states that the jump in default risk from removing relief at $d' = \bar{d}$ dominates the premium saved by reducing trigger probability. Together with $f_d(\bar{d}) > 0$, this implies $\frac{\partial s_{it}}{\partial \bar{d}} > 0$.

Step 2: Monotonicity in τ. Only $C(\theta,\tau)$ depends on τ. Since Φ_g is increasing and differentiable,

$$\frac{\partial J}{\partial \tau} = \int_{\bar{d}}^{\infty} \phi_g\big(\bar{g} + kd' + C(\theta,\tau)\big)\, \frac{\partial C(\theta,\tau)}{\partial \tau}\, f_d(d')\,\mathrm{d}d',$$

where $\phi_g = \Phi_g'$ and

$$\frac{\partial C(\theta,\tau)}{\partial \tau} = \lambda\, \frac{\theta}{1 - \theta(1-\tau)} > 0 \quad (\theta > 0).$$

Thus $\frac{\partial J}{\partial \tau} > 0$ and

$$\frac{\partial s_{it}}{\partial \tau} = p(1-\theta)\,\frac{\partial J}{\partial \tau} > 0 \quad \text{for } \theta \in (0,1).$$

If $\theta = 0$, there is no CAT bond, so τ is irrelevant and the derivative is 0.

Step 3: U-shape in θ and existence of θ^*.

$$\frac{\partial s_{it}}{\partial \theta} = p\Big[(1-\bar{F}) - J(\theta,\tau) + (1-\theta)\,J_\theta(\theta,\tau)\Big],$$

where

$$J_\theta(\theta,\tau) = \int_{\bar{d}}^{\infty} \phi_g\big(\bar{g} + kd' + C(\theta,\tau)\big)\,C_\theta(\theta,\tau)\,f_d(d')\,\mathrm{d}d',$$
$$C_\theta(\theta,\tau) = -\lambda\,\frac{1-\tau}{1-\theta(1-\tau)} < 0,$$

so $J_\theta(\theta,\tau) < 0$. Assume the marginal risk-reduction at $\theta = 0$ dominates the marginal premium cost:

$$\left.\frac{\partial s_{it}}{\partial \theta}\right|_{\theta=0} < 0. \tag{A.2}$$

At $\theta = 1$, we have $(1-\theta)J_\theta = 0$ and $J(1,\tau) \le \int_{\bar{d}}^{\infty} 1 \cdot f_d(d')\,\mathrm{d}d' = 1-\bar{F}$, with strict inequality if default is not certain in all $d' \ge \bar{d}$ states. Hence

$$\left.\frac{\partial s_{it}}{\partial \theta}\right|_{\theta=1} = p\big[(1-\bar{F}) - J(1,\tau)\big] > 0. \tag{A.3}$$

By continuity of $\frac{\partial s_{it}}{\partial \theta}$, (A.2) and (A.3) imply there exists $\theta^* \in (0,1)$ such that $\frac{\partial s_{it}}{\partial \theta} < 0$ for $\theta < \theta^*$ and $\frac{\partial s_{it}}{\partial \theta} > 0$ for $\theta > \theta^*$, provided the crossing is unique. A sufficient condition for uniqueness is strict convexity of s_{it} in θ:

$$\frac{\partial^2 s_{it}}{\partial \theta^2} = p\Big[-2\,J_\theta(\theta,\tau) + (1-\theta)\,J_{\theta\theta}(\theta,\tau)\Big] > 0 \quad \text{for all } \theta \in (0,1), \tag{A.4}$$

where

$$J_{\theta\theta}(\theta,\tau) = \int_{\bar{d}}^{\infty} \Big[\phi_g'(\cdot)\,\big(C_\theta(\theta,\tau)\big)^2 + \phi_g(\cdot)\,C_{\theta\theta}(\theta,\tau)\Big] f_d(d')\,\mathrm{d}d',$$
$$C_{\theta\theta}(\theta,\tau) = -\lambda\,\frac{(1-\tau)^2}{\big(1-\theta(1-\tau)\big)^2} < 0.$$

Under (A.4), $\frac{\partial s_{it}}{\partial \theta}$ is strictly increasing, so the root is unique and the spread is U-shaped in θ with a unique minimiser θ^*. □

A.2 Proof of Proposition 2

Fix $(\bar{g}, p, \alpha, \psi, \theta, \tau)$ and retain k, λ from Appendix A.1. Define the contract-specific relief shifters

$$C_{it}(\theta,\tau) \equiv \lambda \ln\bigl(1-\theta(1-\tau)\bigr),$$
$$C_{pt}(\theta) \equiv \lambda \ln(1-\theta).$$

Let ω denote the flood intensity with PDF f_ω on $[0,\infty)$. The observed index is $d' = \chi\omega + \varepsilon$, $\chi > 0$, $\varepsilon \sim \Phi_\varepsilon(\cdot\,;\sigma_\varepsilon)$, where $\Phi_\varepsilon(\cdot\,;\sigma_\varepsilon)$ is a continuous, symmetric CDF centred at 0 (e.g. $\varepsilon = \sigma_\varepsilon Z$ with Z standard normal). The parametric bond triggers when $d' \geq \bar{d}$, equivalently when $\varepsilon \geq \bar{d} - \chi\omega$. Hence the trigger probability conditional on ω is

$$H(\omega;\sigma_\varepsilon) \equiv \Pr(d' \geq \bar{d} \mid \omega) = 1 - \Phi_\varepsilon(\bar{d} - \chi\omega;\sigma_\varepsilon) = \Phi_\varepsilon(\chi\omega - \bar{d};\sigma_\varepsilon).$$

Define the effective cutoff in ω-space: $\bar{\omega} \equiv \bar{d}/\chi$.

Parametric spread representation. With frictionless relief ($\tau = 0$ when triggered), the equilibrium spread can be written as

$$s_{pt}(\sigma_\varepsilon) = (1-p)\,\Phi_g(\bar{g}) + p\int_0^\infty \Bigl[\bigl(1 - H(\omega;\sigma_\varepsilon)\bigr)\,\Phi_g(\bar{g}+k\omega) + H(\omega;\sigma_\varepsilon)\Bigl((1-\theta)\,\Phi_g\bigl(\bar{g}+k\omega+C_{pt}(\theta)\bigr)+\theta\Bigr)\Bigr] f_\omega(\omega)\,\mathrm{d}\omega.$$

Equivalently,

$$s_{pt}(\sigma_\varepsilon) = \text{const} + p\int_0^\infty m(\omega)\,H(\omega;\sigma_\varepsilon)\,f_\omega(\omega)\,\mathrm{d}\omega,$$

where the incremental trigger cost is

$$m(\omega) \equiv \Bigl((1-\theta)\,\Phi_g\bigl(\bar{g}+k\omega+C_{pt}(\theta)\bigr)+\theta\Bigr) - \Phi_g(\bar{g}+k\omega).$$

Assume:

(A) *Small-noise limit.* $\lim_{\sigma_\varepsilon\to 0} H(\omega;\sigma_\varepsilon) = \mathbf{1}\{\omega \geq \bar{\omega}\}$ for all $\omega \neq \bar{\omega}$.

(B) *Symmetric noise spread.* Because $\Phi_\varepsilon(\cdot)$ is symmetric around 0, an increase in σ_ε is a mean-preserving spread. Therefore $H(\omega;\sigma_\varepsilon)$ is strictly increasing in σ_ε for $\omega < \bar{\omega}$, and strictly decreasing in σ_ε for $\omega > \bar{\omega}$.

(C) *Optimal threshold alignment.* The threshold $\bar{\omega}$ satisfies the single-crossing property: $m(\omega) > 0$ for $\omega \in [0,\bar{\omega})$ and $m(\omega) < 0$ for $\omega \in (\bar{\omega},\infty)$.

Step 1: Small basis risk implies $s_{pt} < s_{it}(\tau)$. By (A) and dominated convergence,

$$\begin{aligned} s_{pt}(0) &\equiv \lim_{\sigma_\varepsilon \to 0} s_{pt}(\sigma_\varepsilon) \\ &= (1-p)\,\Phi_g(\bar{g}) + p \int_0^{\bar{\omega}} \Phi_g(\bar{g} + k\omega)\, f_\omega(\omega)\,\mathrm{d}\omega \\ &\quad + p \int_{\bar{\omega}}^{\infty} \Big((1-\theta)\,\Phi_g\big(\bar{g} + k\omega + C_{pt}(\theta)\big) + \theta \Big) f_\omega(\omega)\,\mathrm{d}\omega. \end{aligned}$$

This is exactly the indemnity-like spread evaluated with the same trigger set ($\omega \geq \bar{\omega}$) but with no verification friction in the relief term, i.e. $s_{pt}(0) = s_{it}(0)$ when the indemnity trigger is interpreted over ω. Since $\tau \in (0,1)$ implies $C_{it}(\theta,\tau) > C_{pt}(\theta)$ (less relief under indemnity), monotonicity of Φ_g gives $s_{it}(0) < s_{it}(\tau)$ for $\theta \in (0,1)$, hence

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

By continuity of s_{pt} in σ_ε, there exists $\underline{\sigma} > 0$ such that $s_{pt}(\sigma_\varepsilon) < s_{it}(\tau)$ for all $\sigma_\varepsilon \in [0, \underline{\sigma})$.

Step 2: $s_{pt}(\sigma_\varepsilon)$ is strictly increasing in σ_ε. Let $\sigma_2 > \sigma_1$. Split the integral at $\bar{\omega}$:

$$\begin{aligned} s_{pt}(\sigma_2) - s_{pt}(\sigma_1) &= p \int_0^{\infty} m(\omega)\,\big[H(\omega;\sigma_2) - H(\omega;\sigma_1)\big]\, f_\omega(\omega)\,\mathrm{d}\omega \\ &= p \int_0^{\bar{\omega}} \underbrace{m(\omega)}_{>0}\; \underbrace{\big[H(\omega;\sigma_2) - H(\omega;\sigma_1)\big]}_{>0}\; f_\omega(\omega)\,\mathrm{d}\omega \\ &\quad + p \int_{\bar{\omega}}^{\infty} \underbrace{m(\omega)}_{<0}\; \underbrace{\big[H(\omega;\sigma_2) - H(\omega;\sigma_1)\big]}_{<0}\; f_\omega(\omega)\,\mathrm{d}\omega. \end{aligned}$$

By Assumption (B), the fatter tails of σ_2 increase the probability of false positives ($H(\omega;\sigma_2) > H(\omega;\sigma_1)$ for $\omega < \bar{\omega}$) and false negatives ($H(\omega;\sigma_2) < H(\omega;\sigma_1)$ for $\omega > \bar{\omega}$). By Assumption (C), $m(\omega)$ is positive below $\bar{\omega}$ and negative above. Both integrands are therefore strictly positive, yielding

$$s_{pt}(\sigma_2) - s_{pt}(\sigma_1) > 0.$$

Step 3: Large basis risk implies eventual reversal. Under symmetry and continuity, $H(\omega;\sigma_\varepsilon) \to \frac{1}{2}$ pointwise as $\sigma_\varepsilon \to \infty$, so by dominated convergence

$$s_{pt}(\infty) \equiv \lim_{\sigma_\varepsilon \to \infty} s_{pt}(\sigma_\varepsilon) = \text{const} + \frac{p}{2} \int_0^{\infty} m(\omega)\, f_\omega(\omega)\,\mathrm{d}\omega = \text{const} + \frac{p}{2}\,\mathbb{E}[m(\omega)].$$

A sufficient condition for reversal is

$$s_{pt}(\infty) > s_{it}(\tau), \tag{A.5}$$

which holds if $\frac{p}{2}\,\mathbb{E}[m(\omega)]$ is large relative to the indemnity advantage from verification friction. When (A.5) holds, continuity implies there exists $\sigma_\varepsilon^* \in (0,\infty)$ such that $s_{pt}(\sigma_\varepsilon^*) = s_{it}(\tau)$.

Step 4: Existence and uniqueness of the threshold. Define $\Delta(\sigma_\varepsilon) \equiv s_{pt}(\sigma_\varepsilon) - s_{it}(\tau)$. From Steps 1 and 3, $\Delta(0) < 0$ and $\lim_{\sigma_\varepsilon\to\infty} \Delta(\sigma_\varepsilon) > 0$ under (A.5), so by the intermediate value theorem there exists σ_ε^* with $\Delta(\sigma_\varepsilon^*) = 0$. From Step 2, Δ is strictly increasing, so the crossing is unique:

$$\begin{aligned}
\sigma_\varepsilon < \sigma_\varepsilon^* &\implies s_{pt}(\sigma_\varepsilon) < s_{it}(\tau),\\
\sigma_\varepsilon > \sigma_\varepsilon^* &\implies s_{pt}(\sigma_\varepsilon) > s_{it}(\tau).
\end{aligned}$$

□

A.3 Proof of Proposition 3

Let d' denote the realised damage state with baseline density $f(d')$ and climate-change density $\tilde{f}(d')$. Climate change is defined as an MLRP shift:

$$\frac{\tilde{f}(d')}{f(d')} \text{ is strictly increasing in } d'. \tag{A.6}$$

Let the indemnity trigger threshold be $\bar{d}$ and the parametric index be $d'' = \chi\omega' + \varepsilon$, $\chi > 0$, where the latent intensity ω is increasing in realised damages d' (so $\omega = \omega(d')$ with $\omega'(\cdot) > 0$), and ε has a continuous CDF $\Phi_\varepsilon(\cdot)$. Then the parametric trigger probability can be written as

$$H(d') \equiv \Pr(d'' \geq \bar{d} \mid d') = 1 - \Phi_\varepsilon\big(\bar{d} - \chi\omega(d')\big) \implies H'(d') > 0. \tag{A.7}$$

Retain k, λ, $C_{it}(\theta;\tau)$, $C_{pt}(\theta)$ from Appendix A.2, with $C_{pt} < C_{it} < 0$ for $\theta \in (0,1)$ and $\tau \in (0,1)$.

The state-contingent lender loss functions are

$$L_{it}(d') = \begin{cases} \Phi_g(\bar{g} + kd'), & d' \le \bar{d}, \\ (1-\theta)\,\Phi_g(\bar{g} + kd' + C_{it}) + \theta, & d' > \bar{d}, \end{cases} \tag{A.8}$$

$$L_{pt}(d') = \big(1 - H(d')\big)\,\Phi_g(\bar{g} + kd') + H(d')\,\Big[(1-\theta)\,\Phi_g(\bar{g} + kd' + C_{pt}) + \theta\Big]. \tag{A.9}$$

Let $\Delta L(d') \equiv L_{it}(d') - L_{pt}(d')$ and $\Delta s \equiv s_{it} - s_{pt} = p\int_0^\infty \Delta L(d')\, f(d')\,\mathrm{d}d'$.

Step 1: Sign structure of ΔL. Define the primitives:

$$\begin{aligned} A(d') &\equiv \Phi_g(\bar{g} + kd'), \\ B(d') &\equiv (1-\theta)\,\Phi_g(\bar{g} + kd' + C_{pt}) + \theta, \\ D(d') &\equiv (1-\theta)\,\Phi_g(\bar{g} + kd' + C_{it}) + \theta. \end{aligned}$$

Then $L_{pt}(d') = A(d') + H(d')\big(B(d') - A(d')\big)$ and

$$\Delta L(d') = \begin{cases} -\,H(d')\,U(d'), & d' \le \bar{d}, \\ V(d') - H(d')\,U(d'), & d' > \bar{d}, \end{cases} \tag{A.10}$$

$$\begin{aligned} U(d') &\equiv B(d') - A(d'), \\ V(d') &\equiv D(d') - A(d'). \end{aligned}$$

Lower domain. For $d' \le \bar{d}$, $\Delta L(d') = -H(d')\,U(d')$. A sufficient condition for $\Delta L(d') < 0$ on $[0, \bar{d}]$ is

$$U(d') = B(d') - A(d') > 0 \quad \forall\, d' \in [0, \bar{d}], \tag{A.11}$$

i.e. premature triggering (Type I error) increases expected lender loss. A sufficient restriction is $\sup_{d' \in [0,\bar{d}]} A(d') \le \theta$, since $B(d') \ge \theta$ and $\Phi_g \ge 0$.

Upper tail. As $d' \to \infty$, $H(d') \to 1$ by (A.7), so

$$\lim_{d' \to \infty} \Delta L(d') = \lim_{d' \to \infty} \big(D(d') - B(d')\big) = (1-\theta) \lim_{d' \to \infty} \Big[\Phi_g(\bar{g} + kd' + C_{it}) - \Phi_g(\bar{g} + kd' + C_{pt})\Big] > 0, \tag{A.12}$$

since $C_{it} > C_{pt}$ and Φ_g is strictly increasing. Thus $\Delta L(d') > 0$ for all sufficiently large d'.

Step 2: Single-crossing via a monotonicity condition. To rule out multiple sign changes, impose:

$$\Delta L'(d') > 0 \quad \text{for all } d' \ne \bar{d}. \tag{A.13}$$

Using (A.10) and differentiability of A, B, D, H:

$$\Delta L'(d') = \begin{cases} -H'(d')\,U(d') - H(d')\,U'(d'), & d' < \bar{d}, \\ V'(d') - H'(d')\,U(d') - H(d')\,U'(d'), & d' > \bar{d}. \end{cases} \tag{A.14}$$

Condition (A.13) holds if $H'(d') > 0$ (by (A.7)) and:

$$\begin{aligned} &\text{(i)} \quad -U'(d') \geq \frac{H'(d')}{H(d')}\,U(d'), && \forall\, d' \in (0, \bar{d}), \\ &\text{(ii)} \quad V'(d') \geq H'(d')\,U(d') + H(d')\,U'(d'), && \forall\, d' > \bar{d}. \end{aligned} \tag{A.15}$$

Furthermore, because $L_{it}(d')$ is piecewise, we verify that ΔL does not jump downward at $\bar{d}$. The jump size is

$$\Delta L(\bar{d}^{+}) - \Delta L(\bar{d}^{-}) = \left[V(\bar{d}) - H(\bar{d})\,U(\bar{d})\right] - \left[-H(\bar{d})\,U(\bar{d})\right] = V(\bar{d}).$$

Since $\tau \in (0,1)$ implies $C_{it} > C_{pt}$, we have $D(d') > B(d')$ and thus $V(d') > U(d')$ globally. By (A.11), $U(\bar{d}) > 0$, which ensures $V(\bar{d}) > 0$. The function jumps strictly upward at the discontinuity.

Therefore, under (A.11), (A.12), and (A.13), $\Delta L(d')$ is a globally strictly increasing function that changes sign exactly once from below at some $d^* \in (0, \infty)$:

$$\begin{aligned} \Delta L(d') < 0 \quad \text{for } d' < d^*, \\ \Delta L(d') > 0 \quad \text{for } d' > d^*. \end{aligned}$$

Step 3: MLRP raises the expectation of an increasing function. The MLRP condition (A.6) implies $\tilde{f}$ dominates f in the likelihood-ratio order, hence also in the usual stochastic order. Therefore, for any strictly increasing function φ:

$$\int \varphi(d')\,\tilde{f}(d')\,\mathrm{d}d' > \int \varphi(d')\,f(d')\,\mathrm{d}d'.$$

Applying this with $\varphi = \Delta L$ (strictly increasing by (A.13)) yields

$$\int_0^\infty \Delta L(d')\,\tilde{f}(d')\,\mathrm{d}d' \;>\; \int_0^\infty \Delta L(d')\,f(d')\,\mathrm{d}d'. \tag{A.16}$$

Step 4: Spread wedge widens. Multiplying (A.16) by $p > 0$ gives

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

so climate change strictly widens the equilibrium spread differential. □

A.4 Proof of Corollary 1

Retain all notation from Appendices A.2 and A.3. In particular, k, λ, $C_{it}(\theta, \tau)$, $C_{pt}(\theta)$ are as defined above, with $C_{pt} < C_{it} < 0$ for $\tau \in (0, 1)$. Let $H(d') = \Phi_\varepsilon\big(\frac{\chi d' - \bar{\omega}}{\sigma_\varepsilon}\big)$ denote the parametric trigger probability, with $H'(d') > 0$ and $H(d') \to 1$ as $d' \to \infty$.

Under contract $j \in \{it,\ pt\}$, the sovereign's value function satisfies the Epstein–Zin recursion

$$\nu_j(m)^{1-\iota} = \max_{k_n,\, b_n} \Big[c_j^{1-\iota} + \beta \cdot CE_j^{\,1-\iota} \Big], \tag{A.17}$$

where the certainty equivalent is

$$CE_j = \Big(\mathbb{E}\big[\nu_j(m_j')^{1-\gamma}\, e^{(1-\gamma) g'} \big] \Big)^{\frac{1}{1-\gamma}}. \tag{A.18}$$

Step 1: Hybrid counterfactual bond and exact decomposition. Define a fictitious bond h that combines the pricing advantage of the parametric design with the trigger certainty of the indemnity design:

- *Pricing.* Bond h carries the parametric spread: $q_h = q_{pt} = (1 - s_{pt})/(1 + r)$.
- *Trigger mechanics.* Bond h triggers deterministically, exactly as the indemnity bond: $T_h' = x'\, \mathbf{1}_{d' > \bar{d}}\, \mathbf{1}_{b_n \geq 0}$.
- *Debt relief.* Because h bypasses verification ($\tau = 0$), the effective per-trigger relief is $C_{pt}(\theta) = \lambda \ln(1 - \theta)$, strictly larger than the indemnity relief $C_{it}(\theta, \tau) = \lambda \ln\big(1 - \theta(1 - \tau)\big)$.

Bond h does not exist in equilibrium; it serves purely as a proof device that separates the two transmission channels. Because h and it share identical trigger mechanics but differ in both pricing and per-trigger relief, both consequences of the verification friction τ, the gap $W_h - W_{it}$ isolates every welfare effect of removing τ. Because h and pt share identical pricing *and* identical per-trigger relief but differ only in trigger certainty versus trigger probability, the gap $W_{pt} - W_h$ isolates every welfare effect of basis risk.

Denote by $W_j(f) \equiv \mathbb{E}_f[\nu_j(m)]$ the ex-ante lifetime welfare under bond j and damage distribution f. The decomposition

$$\Delta W \;\equiv\; W_{pt} - W_{it} \;=\; \underbrace{(W_h - W_{it})}_{SE\;:\;\text{spread-efficiency effect}} \;+\; \underbrace{(W_{pt} - W_h)}_{TRS\;:\;\text{tail-risk-smoothing effect}} \tag{A.19}$$

is an *exact identity* for any damage distribution f.

Step 2: Conditional certainty equivalents. Define the conditional certainty equivalent at damage level d':

$$\Psi_j(d') \;\equiv\; \Big(\mathbb{E}_{g',T_j'|d'}\big[\nu(m_j')^{1-\gamma}\, e^{(1-\gamma)g'}\big]\Big)^{\frac{1}{1-\gamma}},$$

so that $CE_j^{1-\gamma} = \mathbb{E}_{d'}\big[\Psi_j(d')^{1-\gamma}\big]$.

To distinguish the inner conditional expectations from the ex-ante welfare objects W_j in (A.19), and from the lender-loss primitives A, B, D in Appendix A.3, we use Ω for the state-contingent continuation-value terms. Define:

$$\Omega_0(d') \equiv \mathbb{E}_{g'}\big[\nu(m'_{\text{fail}})^{1-\gamma}\, e^{(1-\gamma)g'}\big], \qquad \text{(no relief: full debt } b_n/e^{g'}\text{)} \tag{A.20}$$

$$\Omega_{it}(d') \equiv \mathbb{E}_{g'}\big[\nu(m'_{R,it})^{1-\gamma}\, e^{(1-\gamma)g'}\big], \qquad \text{(indemnity relief: factor } 1-\theta(1-\tau)\text{)} \tag{A.21}$$

$$\Omega_{pt}(d') \equiv \mathbb{E}_{g'}\big[\nu(m'_{\text{trig}})^{1-\gamma}\, e^{(1-\gamma)g'}\big]. \qquad \text{(full relief: factor } 1-\theta\text{)} \tag{A.22}$$

Since $C_{pt} < C_{it} < 0$, parametric relief exceeds indemnity relief per trigger event, so $m'_{\text{trig}} > m'_{R,it} > m'_{\text{fail}}$ for any g'. Because $\iota \in (0,1)$ implies $\nu > 0$, and the mapping $x \mapsto x^{1-\gamma}$ is *strictly decreasing* for $\gamma > 1$ on the positive reals, higher net worth produces a *lower* value of $\nu^{1-\gamma}$. Consequently, the Ω ordering is reversed relative to the net-worth ordering:

$$\Omega_0(d') > \Omega_{it}(d') > \Omega_{pt}(d') \qquad \forall\, d' > 0,\ \gamma > 1. \tag{A.23}$$

Intuitively, the *worst* economic state (no relief, lowest m') produces the *highest* value of $\nu^{1-\gamma}$ because the negative exponent magnifies low-wealth outcomes.

For $d' > \bar{d}$, the three bonds generate the following conditional certainty equivalents:

$$\Psi_{it}(d')^{1-\gamma} = \Omega_{it}(d'), \tag{A.24}$$

$$\Psi_h(d')^{1-\gamma} = \Omega_{pt}(d'), \tag{A.25}$$

$$\Psi_{pt}(d')^{1-\gamma} = H(d')\,\Omega_{pt}(d') + \big(1 - H(d')\big)\,\Omega_0(d'). \tag{A.26}$$

Equation (A.24) reflects that the indemnity bond triggers with certainty and delivers friction-reduced relief. Equation (A.25) reflects that the hybrid bond h triggers with certainty and delivers *full* relief ($\tau = 0$), so the sovereign attains the same continuation value as a parametric trigger that fires. Equation (A.26) reflects that the parametric bond triggers with probability $H(d')$ and fails with probability $1 - H(d')$.

Step 3: Spread-efficiency effect. Bonds h and it share identical, deterministic trigger mechanics. They differ in two manifestations of the verification friction τ:

(i) *Current-period budget constraint.* The parametric-priced bond commands a higher price: $q_h = q_{pt} > q_{it}$. Through the budget constraint $c = m - k_n + q\, b_n$, this raises consumption in *every* state—disaster or calm, trigger or no trigger.

(ii) *Continuation value in triggered states.* For $d' > \bar{d}$, bond h delivers the full θ write-down ($\tau = 0$), while indemnity delivers only $\theta(1 - \tau)$. The hybrid sovereign therefore has higher net worth in triggered states, which yields a higher certainty equivalent $\Psi_h(d') > \Psi_{it}(d')$. Equivalently, from (A.23) and equations (A.24)–(A.25),

$$\Psi_h(d')^{1-\gamma} - \Psi_{it}(d')^{1-\gamma} = \Omega_{pt}(d') - \Omega_{it}(d') < 0,$$

where the negative sign reflects the reversed Ω ordering under $\gamma > 1$. Since $x \mapsto x^{1/(1-\gamma)}$ is strictly decreasing, the lower value of $\Psi_h^{1-\gamma}$ corresponds to a *higher* certainty equivalent: $\Psi_h(d') > \Psi_{it}(d')$.

Both channels arise from eliminating the verification friction.

Define the spread-efficiency effect over distribution f as their joint contribution:

$$SE(f) \;\equiv\; W_h(f) - W_{it}(f) \;=\; \mathbb{E}_f\Big[\frac{\nu_h(m)^{1-\iota} - \nu_{it}(m)^{1-\iota}}{1-\iota}\Big] \;>\; 0. \tag{A.27}$$

The sign is unambiguous: higher consumption in all states (channel (i)) plus higher continuation value in triggered disaster states (channel (ii)) jointly raise lifetime utility ν and hence the period-utility metric $\nu^{1-\iota}/(1-\iota)$, since $\iota \in (0, 1)$ ensures $\nu^{1-\iota}$ is increasing in ν.

Climate change amplifies SE. Channel (i) grows because Proposition 3 establishes $\widetilde{\Delta s} > \Delta s$, so $\tilde{q}_h - \tilde{q}_{it} > q_h - q_{it}$. Channel (ii) also grows: the MLRP shift places more probability mass on severe damage states $d' > \bar{d}$ where the per-trigger relief gap is activated. Therefore,

$$SE(\tilde{f}) > SE(f) > 0. \tag{A.28}$$

This establishes effect (i) of the Corollary. $\square_{(i)}$

Step 4: Tail-risk-smoothing effect. Bonds pt and h share identical pricing (q_{pt}) and identical per-trigger debt relief (C_{pt}, since both have $\tau = 0$). They differ *only* in trigger certainty: h triggers deterministically when $d' > \bar{d}$, while pt triggers with probability $H(d') \in (0, 1)$.

For $d' > \bar{d}$, compare the conditional certainty equivalents using equations (A.25) and (A.26):

$$\Psi_h(d')^{1-\gamma} = \Omega_{pt}(d'), \qquad \text{(certain relief)}$$

$$\Psi_{pt}(d')^{1-\gamma} = H(d')\,\Omega_{pt}(d') + \big(1 - H(d')\big)\,\Omega_0(d'). \qquad \text{(lottery over relief)}$$

By the corrected ordering (A.23), $\Omega_0(d') > \Omega_{pt}(d')$ for $\gamma > 1$. The parametric lottery mixes the "certain-relief" value $\Omega_{pt}(d')$ with the strictly larger "no-relief" value $\Omega_0(d')$. Since $H(d') \in (0, 1)$, the convex combination is strictly interior:

$$\Psi_{pt}(d')^{1-\gamma} = H(d')\,\Omega_{pt}(d') + \big(1 - H(d')\big)\,\Omega_0(d') \;>\; \Omega_{pt}(d') = \Psi_h(d')^{1-\gamma}. \tag{A.29}$$

Now apply the transformation $x \mapsto x^{1/(1-\gamma)}$, which is *strictly decreasing* on the positive reals because $1/(1 - \gamma) < 0$ for $\gamma > 1$. The inequality in (A.29) therefore reverses:

$$\Psi_{pt}(d') \;<\; \Psi_h(d') \qquad \text{whenever } H(d') < 1. \tag{A.30}$$

The parametric certainty equivalent is strictly below the hybrid certainty equivalent in every disaster state where the trigger is uncertain. This is a pure monotonicity result: the parametric lottery mixes in the adverse no-relief outcome (which has a higher Ω value under $\gamma > 1$), raising $\Psi^{1-\gamma}$ and thereby lowering the certainty equivalent through the decreasing power transformation.

Integrating over all damage states, the tail-risk-smoothing effect is

$$TRS(f) \;\equiv\; W_{pt}(f) - W_h(f) \;<\; 0 \qquad \text{for } \gamma > 1. \tag{A.31}$$

The sign is strictly negative because $\Psi_{pt}(d') < \Psi_h(d')$ in every state where $H(d') \in (0, 1)$, so the parametric bond delivers strictly lower lifetime utility than the hybrid.

Climate change amplifies TRS. The MLRP shift increases the probability weight on severe damage states. In these states, $H(d')$ remains bounded below unity (especially near $\bar{d}$, where the parametric signal is most ambiguous), so the inequality (A.30) is activated more frequently. Therefore,

$$\big|TRS(\tilde{f})\big| > \big|TRS(f)\big| \qquad \text{for } \gamma > 1.$$

This establishes effect (ii) of the Corollary. $\square_{(ii)}$

Step 5: Risk aversion amplifies the smoothing penalty. Under Epstein–Zin preferences, the stochastic discount factor weights state d' by

$$\mathcal{M}(d') \;\propto\; \nu\big(m'(d')\big)^{1-\gamma}, \tag{A.32}$$

which is *increasing* in states with lower m' for $\gamma > 1$ (the negative exponent amplifies low-wealth outcomes). In states where the parametric trigger fails ($T'_{pt} = 0$), the sovereign retains the full debt burden, so m'_{fail} is minimal and the SDF weight is maximal.
Define the SDF-weighted smoothing penalty as

$$TS^{\gamma}(f) \;\equiv\; \int_0^{\infty} \big(1 - H(d')\big)\big[\Omega_0(d') - \Omega_{pt}(d')\big]\,\mathcal{M}(d')\,f(d')\,\mathrm{d}d' \;>\; 0, \tag{A.33}$$

where the integrand is strictly positive: $1 - H(d') > 0$ for d' near $\bar{d}$, and $\Omega_0(d') - \Omega_{pt}(d') > 0$ by (A.23). The quantity TS^{γ} measures the welfare cost of the parametric trigger lottery, weighted by the sovereign's marginal valuation of consumption in bad states.
Since value functions in this class of models scale approximately linearly with detrended net worth, the SDF weight on the worst states scales as $(m'_{\text{fail}})^{1-\gamma}$, growing without bound as $\gamma \to \infty$ because $m'_{\text{fail}} < 1$ in the detrended economy. As γ increases, $\mathcal{M}(d')$ concentrates mass on low-m' states, and the integrand $[\Omega_0 - \Omega_{pt}]$ is bounded away from zero near $\bar{d}$. Therefore,

$$\lim_{\gamma\to\infty} \frac{TS^{\gamma}(f)}{SE(f)} = \infty, \tag{A.34}$$

because TS^{γ} grows as $(m'_{\text{fail}})^{1-\gamma}$ while SE is bounded in γ, as we verify below.

Step 6: Existence of γ^*. Using the exact identity (A.19), the net welfare change from climate change is

$$\widetilde{\Delta W} - \Delta W \;=\; \underbrace{\big[SE(\tilde{f}) - SE(f)\big]}_{>0,\text{ by (A.28)}} \;+\; \underbrace{\big[TRS(\tilde{f}) - TRS(f)\big]}_{\text{sign depends on }\gamma}. \tag{A.35}$$

The exact welfare penalty $TRS < 0$ is driven by the SDF-weighted lottery cost $TS^{\gamma} > 0$ defined in (A.33): a larger TS^{γ} corresponds to a more negative TRS, so the divergence of TS^{γ} as $\gamma \to \infty$ forces the second bracket in (A.35) to become an arbitrarily large negative quantity that eventually dominates the bounded first bracket.

Case $\gamma \to 1^+$ (log-utility boundary). At $\gamma = 1$ the certainty equivalent reduces to the geometric mean $\text{CE} = \exp\big(\mathbb{E}[\ln V]\big)$, which is strictly concave in V but represents the *weakest* degree of risk aversion within the Epstein–Zin class for $\gamma \geq 1$. The SDF $\mathcal{M}(d')$ still tilts toward low-wealth states, but the tilt is minimal: the welfare penalty from the parametric trigger lottery in (A.26) is at its smallest positive value. Consequently, $TS^{\gamma}(\tilde{f}) - TS^{\gamma}(f)$ remains bounded and the corresponding change in TRS is dominated by the spread-efficiency gain, giving

$$\widetilde{\Delta W} - \Delta W\Big|_{\gamma \to 1^+} > 0.$$

The parametric welfare advantage strictly widens.

Case $\gamma \to \infty$ (extreme risk aversion). From (A.34), TS^{γ} grows without bound relative to SE. Under the MLRP shift, the increased probability of states near $\bar{d}$ where $H(d') < 1$ ensures $TS^{\gamma}(\tilde{f}) > TS^{\gamma}(f)$ for large γ, which implies that $TRS(\tilde{f})$ is strictly more negative than $TRS(f)$. Therefore, for sufficiently large γ:

$$\left| TRS(\tilde{f}) - TRS(f) \right| > SE(\tilde{f}) - SE(f),$$

giving $\widetilde{\Delta W} - \Delta W < 0$. The parametric welfare advantage narrows.

By continuity of $\widetilde{\Delta W} - \Delta W$ in γ, the intermediate value theorem guarantees the existence of $\gamma^* > 1$ such that

$$\widetilde{\Delta W} - \Delta W \begin{cases} > 0 & \text{if } \gamma < \gamma^* \ \text{(parametric advantage widens)}, \\ = 0 & \text{if } \gamma = \gamma^*, \\ < 0 & \text{if } \gamma > \gamma^* \ \text{(parametric advantage narrows)}. \end{cases} \tag{A.36}$$

Uniqueness. A sufficient condition for the crossing to be unique is that $\widetilde{\Delta W} - \Delta W$ is strictly decreasing in γ, which requires

$$\frac{\partial\, TS^{\gamma}}{\partial \gamma} > \frac{\partial\, SE}{\partial \gamma} \qquad \text{for all } \gamma > 1. \tag{A.37}$$

The spread-efficiency term $SE(f)$ defined in (A.27) is evaluated using the period utility $c^{1-\iota}$, whose curvature is governed by the IES parameter ι, not by risk aversion γ. The only channel through which γ affects SE is indirect: higher γ alters the sovereign's optimal savings policy, shifting the consumption function $c^*(m)$. This indirect effect is bounded because the policy function is Lipschitz in γ and the period utility is bounded on compact subsets of the state space. In contrast, TS^{γ} depends on the SDF-weighted mass of uninsured catastrophic states, scaling as $(m'_{\text{fail}})^{1-\gamma}$—a term that diverges as $\gamma \to \infty$ since $m'_{\text{fail}} < 1$ in the detrended economy. Therefore TS^{γ} eventually dominates SE, and condition (A.37) holds for all sufficiently large γ. Combined with the sign results at the two boundary cases, this ensures the crossing is unique. □

Note that in the quantitative exercise (Table 2), we have: $\gamma = 4$. The parametric welfare advantage narrows from 0.021 percentage points under the baseline calibration to 0.006 percentage points under climate change, confirming $\gamma = 4 > \gamma^*$. This is consistent with the high risk aversion typically required to match emerging-market spreads in the Aguiar-Gopinath framework. While parametric bonds remain the most financially efficient instrument (Proposition 3), the narrowing welfare gap underscores that indemnity bonds become increasingly vital for a risk-averse sovereign as climate risks intensify, precisely because their guaranteed payouts eliminate the worst-case consumption drops in catastrophic states.

A.5 Quantitative Results over Baseline

Figure 6: Improvement of indemnity and parametric trigger CAT bond over baseline