

An Empirical Analysis of Recent Dynamics of Catastrophe Bonds

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Received : August 26, 2025 Revised : November 25, 2025 Accepted : December 16, 2025

Abstract

This study extends catastrophe bond pricing analysis to the post-2012 period, examining how structural innovations, market regime shifts, and cross-peril diversification influence primary market spreads. I analyze catastrophe bond tranches issued over the past decade and a half, incorporating extended structural variables including life/mortality risks, emerging risks, risk modeling disclosure, upsize options, and aggregate structures. Structural break tests identify economically meaningful regime shifts at 2020 (COVID-19 pandemic) and 2022 (hard reinsurance market peak). Quantile regression across the spread distribution reveals substantial pricing heterogeneity masked by conditional mean analysis. Cross-peril differentials constitute first-order pricing determinants: life bonds trade at material discounts while emerging risks command sizable premiums, magnitudes that dwarf structural feature effects. Post-2020 repricing exhibits steeper expected loss slopes, surging PEAK territory premiums, and activated emerging risk premiums, representing demand-side risk aversion distinct from 2022's supply-side capacity constraints. Expected loss pricing is strongly convex, rising dramatically from lower to upper quantiles, while capital market pass-through amplifies in distribution tails. These findings reveal pronounced cross-sectional and temporal heterogeneity in catastrophe bond pricing, with implications for sponsors' peril selection strategies, investors' portfolio positioning, and sovereigns' regional risk-pooling arrangements.

Keywords: Catastrophe bonds, Insurance-linked securities, Expected loss pricing, Quantile regression, Disaster risk financing

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Introduction

Catastrophe bonds transfer extreme tail risks from insurers and reinsurers to capital market investors through fully collateralized securities. Since 1997, the market has grown from \$1 billion to \$40-50 billion in annual issuance, offering (re)insurers contingent capacity uncorrelated to financial market cycles while providing investors decorrelated returns and eliminating counterparty risk through full collateralization (Cummins, 2008; Lane, 2012; Tomunen, 2025; Herrmann & Hibbeln, 2023). The transaction structure isolates the sponsor-related credit risk, which is held by the Special Purpose Vehicle (SPV) that issues the bond (Zhao et al., 2021; Ando et al., 2022).

Braun (2016) established the foundational framework for catastrophe bond pricing using primary market data from 1997-2012, demonstrating that expected loss, regional concentration, sponsor characteristics, and post-Katrina regime shifts significantly explain spread variation. Studies on CAT bond pricing often employ sophisticated models like compound Poisson processes and extreme value theory to estimate annual losses and prices, addressing the rarity and uncertainty of catastrophic events (Anggraeni et al., 2022; Mistry & Lombardi, 2023). However, the insurance-linked securities (ILS) market has evolved fundamentally since 2012, motivating the reexamination using 2011-2025 data across three dimensions.

First, the market has matured structurally. Annual issuance has tripled to \$40-50 billion with mainstream institutional investors entering previously specialized markets (Braun et al., 2019). Peril diversity expanded beyond traditional natural catastrophes to include mortality/longevity bonds and nascent cyber catastrophe bonds (Zhao, 2019; Schwarcz, 2021). Structural innovations - aggregate deductibles, upsize options, parametric triggers - became prevalent (Finken & Laux, 2009; Gürtler, 2016), while Solvency II regulatory frameworks now explicitly recognize ILS as eligible capital relief. Note that the non-indemnity nature of some bonds, such as industry loss index triggers, introduces basis risk the risk that the sponsor's losses and the bond's trigger event may not align (Braun & Kousky, 2021; Götze & Gürtler, 2022). Do newer peril classes command different risk premiums? Have structural innovations become standardized and priced differently?

Second, exogenous shocks reshaped risk perceptions. COVID-19 (2020-2021) updated investor beliefs about tail event probabilities while triggering parametric pandemic bonds (World Bank, 2018; Herrmann & Hibbeln, 2021; Schwarcz, 2021). The 2022-2023 hard reinsurance market - driven by Hurricane Ian, persistent severe convective storms, and inflation - created the steepest capacity constraints in modern ILS history. Climate change awareness intensified as 2024 marked Earth's hottest year with natural disaster losses following persistent 5-7% annual growth. Does post-COVID pricing exhibit fundamentally different risk-return trade-offs? Did the 2022 hard market shift pricing through supply-side capacity constraints distinct from demand-side risk aversion?

Third, methodological advances enable investigation of pricing heterogeneity. Catastrophe bonds exhibit substantial right-skewness, suggesting different investor clienteles may dominate different market segments. Quantile regression allows testing whether expected loss pricing is convex, whether capital market pass-through

amplifies in distribution tails, and whether emerging risk premiums vary across quantiles questions conditional mean analysis cannot address. Building on Braun (2016), I analyze 696 tranches issued January 2011-March 2025, extending the literature in four dimensions. First, I incorporate extended structural variables reflecting post-2012 evolution: risk modeling disclosure, extreme life risk (mortality/pandemic), extreme emerging risk, upsize options, and aggregate structures. Second, I conduct explicit structural break analysis at 2020 (COVID) and 2022 (hard market peak) using Chow tests and sub-sample comparisons. Third, I employ quantile regression at 25th, 50th, and 75th percentiles to reveal pricing mechanism heterogeneity.

This analysis yields three principal findings. First, life/mortality bonds trade at 1.5-1.92 percent discounts reflecting portfolio diversification from near-zero correlation with natural disasters, stable across quantiles. Emerging risks command 2.6-5.0 percent premiums reflecting model immaturity and systemic tail correlation. On \$100 million issuance, 2 percent differentials represent \$2 million annual cost differences, establishing peril selection as central to strategy. Second, economically meaningful regime shifts occurred around 2020 and 2022. Post-2020, expected loss slopes nearly doubled (from 0.50 to 0.99 percent), PEAK territory premiums surged (from 0.36 to 3.13 percent), and emerging risk premiums activated (from -0.9 to 4.64 percent), suggesting demand-side risk aversion increases. The 2022 break reflects supply-side capacity constraints with less pronounced coefficient changes. This distinction has forecasting implications: demand-side 2020 effects should persist while 2022 supply pressures mean-revert as capital rebuilds.

Cross-sectional heterogeneity is substantial. Expected loss pricing exhibits dramatic convexity: insignificant at Q25 (0.131 percent), strongly positive at median (1.076 percent), steeper at Q75 (1.494 percent) revealing increasing absolute risk aversion. Emerging risk premiums concentrate at Q25 (4.95 percent) versus Q75 (2.57 percent, insignificant). Life discounts remain stable (-1.54 percent median, -1.50 percent Q75), confirming risk-level-independent diversification value. This findings provide actionable guidance for three stakeholder groups. Sponsors should reorient strategy from structural optimization to fundamental peril portfolio decisions: prioritize securitizing life and mortality exposures while deferring emerging perils until models mature, and avoid concentrating expected loss in single tranches to exploit convex pricing. Investors should align bond selection with portfolio objectives: concentrate in Q25-Q50 bonds for pure diversification from traditional assets, or target Q75 bonds for absolute returns while recognizing catastrophe-plus-credit exposure during systemic stress. Most significantly for sovereigns, multi-country regional pooling offers transformative cost savings: an ASEAN catastrophe bond covering Thailand's Chao Phraya floods, Philippine typhoons, Vietnam's Mekong Delta floods, and Malaysia's monsoon floods, with uncorrelated seasonal peaks and a 10% pandemic component, eliminates the PEAK concentration premium and exploits convex pricing to achieve cheaper spreads comparing with solo issuance, representing substantial cost savings while providing immediate post-disaster liquidity.

Section 2 reviews literature and market evolution. Section 3 develops hypotheses on extended determinants, regime shifts, and heterogeneity. Section 4 details data, variables, and methodology. Section 5 presents results across baseline regressions, structural breaks, and quantile analysis. Section 6 discusses mechanisms, compares to prior work, and derives policy implications including Southeast Asian applications. Section 7 concludes with contributions, limitations, and future research directions.

Literature Review

1. Catastrophe Bonds in Risk Transfer Markets

The development of catastrophe (cat) bonds has transformed the landscape of risk transfer, bridging capital markets and insurance. Since the 1990s, cat bonds have provided insurers and reinsurers with an alternative to traditional reinsurance by securitizing extreme event risks and transferring them to capital market investors (Cummins, 2008; Finken & Laux, 2009; Lane, 2012). Braun (2016) provides a comprehensive survey of the primary cat bond market through 2012, emphasizing that cat bonds address capacity shortages, high reinsurance pricing, and systemic exposure.

The market has evolved substantially since then. Subsequent research (Braun et al., 2019) highlights the growing role of insurance-linked securities (ILS) to include mortality and longevity bonds, while recent years have witnessed increasing ESG investor interest in catastrophe bonds as climate adaptation financing instruments. Institutional investors increasingly view cat bonds as aligned with environmental and social objectives while maintaining attractive risk-adjusted returns, creating new capital flows particularly relevant for sovereign issuers in climate-vulnerable regions (OECD, 2024). This influx of ESG-oriented capital has implications for pricing dynamics, market capacity, and the feasibility of regional pooling structures. This literature review synthesizes theoretical and empirical research on catastrophe bond pricing, extending Braun's (2016) foundational framework to incorporate structural innovations, ESG capital trends, and market dynamics that have emerged in the 2011-2025 period.

2. Foundational Pricing Determinants: The Braun Framework

2.1 Expected Loss and the Cat Risk Premium

The valuation of cat bonds follows actuarial, financial, and econometric approaches. A consistent finding is that cat bond spreads reflect modeled expected loss (EL) plus a “cat risk premium” above actuarially fair values, attributed to event risk and investor risk aversion (Braun, 2016; Lane, 2012). Finken & Laux (2009) employ intensity-based models to capture default dynamics, while Gürtler (2016) applies contingent claims analysis to highlight embedded options in cat bond structures. Gotze (2019) provides empirical evidence that cat bonds exhibit excess spreads compared to corporate bonds of equivalent rating, establishing EL as the anchor of primary market pricing.

2.2 Trigger Mechanisms and Basis Risk Trade-offs

The literature distinguishes among indemnity, industry loss, parametric, and modeled-loss triggers (Cummins et al., 2009). Indemnity-based structures align with insurers' actual losses but introduce moral hazard (Lane, 2012). Parametric triggers reduce moral hazard but introduce basis risk, whereby payouts may diverge from actual losses (Jarrow, 2010). Empirical assessments show parametric triggers are favored for speed of settlement, especially in sovereign bonds such as Mexico's multi-peril cat bonds (World Bank, 2018). More recent research explores hybrid structures designed to balance basis and moral hazard trade-offs (Gotze, 2019; Zhao, 2019).

3. Extended Structural Determinants Beyond Braun (2016)

3.1 Risk Modeling Disclosure and Information Asymmetry

Catastrophe risk modeling forms the backbone of bond structuring and primary market pricing. Catastrophe models simulate stochastic event frequencies and severities, generating exceedance probability curves for loss distributions (Cummins, 2008; Galeotti et al., 2013). Research shows that modeling accuracy critically determines investor demand and pricing efficiency (Gürtler, 2016; Lane, 2012). Third-party risk modeling disclosure (e.g., AIR, RMS, KCC) serves as a credibility signal that mitigates information asymmetry between sponsors and investors. The signaling literature in corporate finance suggests that voluntary disclosure of verifiable information reduces the cost of capital when it alleviates information frictions, establishing H1a: risk modeling disclosure should reduce spreads in the primary market.

3.2 Cross-Peril Diversification: Life/Mortality Cat Bonds

Institutional investors dominate the cat bond market (Lane, 2012; Braun et al., 2019). The key attraction lies in diversification, as cat bond returns exhibit low correlation with equity and fixed income markets (Braun, 2016). Gotze (2019) shows that adding cat bonds to institutional portfolios improves risk-adjusted returns. Life and mortality cat bonds (e.g., Swiss Re's Vita Capital series, pandemic bonds) offer unique diversification benefits because mortality risks are driven by epidemiological events and demographic shifts rather than natural disaster frequencies (Galeotti et al., 2013; World Bank, 2018). Portfolio theory predicts that assets with low correlation to existing risk factors command lower risk premiums, motivating H1b: life/mortality cat bonds should trade at discounts in the primary market.

3.3 Emerging Non-Natural Catastrophe Risks

Recent work extends catastrophe securitization beyond natural perils. Zhao (2019) discusses the feasibility of cyber cat bonds, though challenges in data scarcity and correlation risks remain. Pandemic bonds, introduced by the World Bank in 2017, illustrate both potential and controversy surrounding novel perils (World Bank, 2018; Herrmann & Hibbeln, 2021). Emerging risks face fundamental model uncertainty investors cannot confidently assess tail probabilities or systemic accumulation in the absence of actuarial track records. Behavioral finance and

ambiguity aversion theories suggest that investors require higher compensation when probability distributions are ill-defined, establishing H1c: emerging perils should command risk premiums at primary issuance.

3.4 Structural Features: Upsize Options and Aggregate Deductibles

Upsize options. In bookbuilding, an explicit right to increase deal size (an over-allotment/“greenshoe”-style mechanism) lets the arranger expand supply if demand proves strong. In primary markets, that can signal high demand, mitigating adverse-selection worries, and improve expected secondary liquidity via a larger float; both forces push required spreads down. At the same time, the same mechanism dilutes scarcity value and embeds supply-expansion risk for initial allocations, for which investors typically require compensation; these push spreads up. In CAT bonds specifically, the liquidity channel is weaker/ambiguous empirically relative to corporate credit (issue size/liquidity proxies have mixed results), so the dilution/supply-risk channel plausibly dominates in tight capacity regimes. Hence, our ex-ante prediction is that noting an upsize option in termsheets is associated with a higher primary-market spread, all else equal.

Annual aggregate deductibles. Per-occurrence layers attach only when a single event breaches the attachment; annual aggregate structures attach once cumulative losses across events exceed the deductible. For a given layer, aggregate structures therefore raise the probability of attachment (they “count” frequency clusters and loss creep), shift risk toward frequency-over-severity, and load more model uncertainty. Investors typically price that higher trigger probability / model risk with a spread premium over occurrence, *ceteris paribus*. Market practice echoes this: after active loss years, issuance has shifted away from aggregate toward occurrence, consistent with investors demanding more compensation for aggregate exposure. I therefore expect aggregate deductible deals to carry higher spreads than comparable per-occurrence notes. These structural choices warrant empirical examination in H1d and H1e.

4. Temporal Dynamics and Market Regime Shifts

4.1 Post-2020 Repricing: COVID-Era Shock

The COVID-19 pandemic triggered global risk repricing across asset classes, characterized by increased risk aversion and heightened tail-risk awareness. For cat bonds specifically, 2020 marked disrupted reinsurance renewals with capacity withdrawals and pandemic cat bond triggers that crystallized model uncertainty (Braun et al., 2019; Herrmann & Hibbeln, 2021). Asset pricing theory suggests that preference parameters and the market price of risk are time-varying, particularly following systemic shocks that update investors' probability beliefs. This motivates H2a: structural break tests at 2020 to assess whether the risk-price slope steepened and whether premia on PEAK exposures and emerging perils increased post-pandemic.

4.2 Post-2022 Hard Market: Supply-Side Capacity Shock

The 2022-2023 period represented the peak of the modern reinsurance hard market, driven by Hurricane Ian (2022's \$50B+ insured loss) and consecutive severe convective storm losses. The 1/1/2023 reinsurance renewal was characterized as the hardest market in decades, with significant capacity withdrawal and ROL increases exceeding 50% in catastrophe-exposed programs. Unlike the 2020 COVID shock (preference/risk aversion), the 2022 break represents a supply-side capacity shock, potentially manifesting through regime shifts in spread-ROL relationships and increased premiums for high-attachment PEAK risks. This establishes H2b: structural break tests at 2022.

5. Research Gap and Contribution

While Braun (2016) established foundational pricing relationships for the 1997-2012 primary market, the 2011-2025 period has witnessed rapid transformation: increasing issuance volumes, diversification across perils (life, emerging), greater sophistication in trigger mechanisms, and market regime shifts following COVID-19 and the 2022 hard market (Braun et al., 2019; Zhao, 2019). The investor base has broadened significantly, influencing pricing dynamics and risk transfer efficiency. This study extends Braun's framework by: (1) incorporating extended structural variables (risk modeling disclosure, extreme life risk, extreme emerging risk, upside options, aggregate structures) to test H1a-H1e; (2) conducting structural break analysis at 2020 and 2022 to capture regime shifts (H2a-H2b); and (3) employing quantile regression to reveal cross-sectional heterogeneity in pricing mechanisms. By examining these dynamics in the 2011-2025 primary market, this research contributes new empirical evidence on how catastrophe bond pricing has evolved in response to structural innovations, market shocks, and the maturation of the ILS market.

Research Methodology

1. Research Design and Scope

This study extends Braun's (2016) primary market pricing framework to analyze 696 catastrophe bond tranches issued January 2011–March 2025. I employ a three-stage empirical strategy: (1) baseline OLS regressions with year fixed effects, (2) Chow structural break tests at 2020 and 2022, and (3) quantile regressions at the 25th, 50th, and 75th percentiles.

Following Braun (2016), I examine catastrophe bonds exclusively at initial issuance in the primary market, using adjusted yield spreads and structural characteristics available at issuance. I do not incorporate secondary market trading data or post-issuance dynamics, ensuring analysis reflects the initial risk transfer negotiation between sponsors and investors without confounding effects from secondary market illiquidity or counterparty risk variations.

2. Data and Sample

Artemis Deal Directory, covering all primary market issuances January 1, 2011–March 31, 2025, and Bloomberg for Adjusted Yield information.

3. Variable Definitions and Hypotheses

Dependent Variable: Adjusted Yield Spread (percent) = bond coupon minus collateral reinvestment rate (3-month LIBOR/SOFR), representing pure catastrophe risk premium above risk-free rate.

Independent Variables: Braun's variables and a list of extended variable definitions, hypotheses, expected signs, and brief rationales are summarized in the table below.

Table A: Variables, Hypothesis and Expected Signs

Variable	Definition	Hypothesis	Expected Sign	Rationale
Expected Loss (EL)	Modeled annualized loss (percent) from AIR/RMS		$\beta > 0$	Original Control Variable
PEAK Territory	Binary: US Gulf/Atlantic hurricanes, CA/Japan earthquakes, EU windstorms		$\beta > 0$	Original Control Variable
Swiss Re Sponsor	Binary: Swiss Re sponsored		$\beta < 0$	Original Control Variable
Investment Grade	Binary: BBB- or higher rating		$\beta < 0$	Original Control Variable
ROL Index	Guy Carpenter Property Cat Rate-on-Line (level)		$\beta < 0$	Original Control Variable
BB Spread	ICE BofA BB Corporate (percent)		$\beta > 0$	Original Control Variable
Risk Modeling	Binary: Third-party disclosed model (AIR/RMS)	H1a	$\beta < 0$	Reduces information asymmetry; credible third-party models signal quality
Extreme Life Risk	Binary: Life/mortality/pandemic Bond	H1b	$\beta < 0$	Portfolio diversification benefit; mortality uncorrelated with natural catastrophes
Extreme Emerging Risk	Binary: Non-natural cat (e.g. Cyber) Bond	H1c	$\beta > 0$	Model uncertainty and ambiguity aversion require higher compensation

Variable	Definition	Hypothesis	Expected Sign	Rationale
Upsize Option	Binary: Post-issuance size increase right	H1d	$\beta > 0$	Supply expansion risk and dilution outweigh liquidity benefits in tight market
Aggregate Structure	Binary: Cumulative loss vs. per-occurrence	H1e	$\beta > 0$	Higher trigger probability and frequency risk increase investor required returns

4. Econometric Specifications

I employ three complementary econometric strategies to test the hypotheses developed in Section 3

4.1 Hypothesis 1a-He: OLS Regression

Four OLS regression specifications are used to determine the spread:

$$Adj\ Spread_i = \alpha + \beta_1 EL_i + \beta_2 PEAK_i + \beta_3 SwissRe_i + \beta_4 ROL_t + \beta_5 InvGrade_i + \beta_6 BBSpread_i + \varepsilon_i \quad (1)$$

$$Adj\ Spread_i = \alpha + \beta_1 EL_i + \beta_2 PEAK_i + \beta_3 SwissRe_i + \beta_4 ROL_t + \beta_5 InvGrade_i + \beta_6 BBSpread_i + \sum_t \delta_t Year_t + \varepsilon_i \quad (2)$$

$$Adj\ Spread_i = \alpha + \beta_1 EL_i + \beta_2 PEAK_i + \beta_3 SwissRe_i + \beta_4 ROL_t + \beta_5 InvGrade_i + \beta_6 BBSpread_i + \gamma_1 RiskModeling_i + \gamma_2 ExtremeLife_i + \gamma_3 ExtremeEmerging_i + \gamma_4 Upsize_i + \gamma_5 Aggregate_i + \varepsilon_i \quad (3)$$

$$Adj\ Spread_i = \alpha + \beta_1 EL_i + \beta_2 PEAK_i + \beta_3 SwissRe_i + \beta_4 ROL_t + \beta_5 InvGrade_i + \beta_6 BBSpread_i + \gamma_1 RiskModeling_i + \gamma_2 ExtremeLife_i + \gamma_3 ExtremeEmerging_i + \gamma_4 Upsize_i + \gamma_5 Aggregate_i + \sum_t \delta_t Year_t + \varepsilon_i \quad (4)$$

Newey-West HAC standard errors (lag=4) is used to address autocorrelation from clustered issuance around renewal dates. Year fixed effects absorb common time shocks. Estimated coefficients from equations 3 and 4 shall determine the hypothesis testing results.

4.2 Hypothesis 2a and 2b: Structural Break Analysis¹

¹ I adopt sub-sample estimation rather than pooled interaction terms for three reasons: (1) Chow tests suggest parameter instability that sub-sample captures more flexibly; (2) Post-2020 and post-2022 regimes differ fundamentally in mechanism (demand-side risk aversion vs. supply-side capacity constraints), warranting separate estimation; (3) With extended variables, interaction specification would introduce 18 interaction terms causing multicollinearity

Structural break tests formally assess whether the pricing relationship changed at specific dates corresponding to major market events. This approach identifies shifts in both intercepts and slope coefficients that may signal changes in investor risk preferences or market supply conditions. I employ Chow Tests at two break dates:

- **Break 1:** December 31, 2019 (pre/post-2020: COVID shock, testing H2a)
- **Break 2:** December 31, 2021 (pre/post-2022: hard market, testing H2b)

Null hypothesis: $H_0: \beta_{pre} = \beta_{post}$ (parameter stability)

$$F = \frac{\frac{(SSR_{pooled} - SSR_{pre} - SSR_{post})}{k}}{\frac{(SSR_{pre} + SSR_{post})}{(n - 2k)}} \sim F(k, n - 2k)$$

4.3 Quantile Regression

Quantile regression estimates the conditional quantiles of the spread distribution rather than the conditional mean. This analysis offers how pricing determinants vary across low-spread, median-spread, and high-spread bonds using covariates from equation 4 (with fixed effect).

$$Q_{\tau}(Adjusted\ Spread|X_i) = \alpha_{\tau} + \beta_{\tau}^T X_i$$

Estimated at $\tau = \{0.25, 0.50, 0.75\}$ with bootstrap standard errors (500 replications).

5. Conceptual Model

The conceptual model proposed in the paper extends traditional catastrophe bond pricing analysis by incorporating structural innovations, market regime shifts, and the influence of cross-peril diversification on primary market spreads. It analyzes tranches issued over the last decade and a half, introducing extended structural variables like life/mortality risks, emerging risks, and aggregate structures. The model aims to capture the pronounced cross-sectional and temporal heterogeneity in catastrophe bond pricing that has become evident in the post-2012 market.

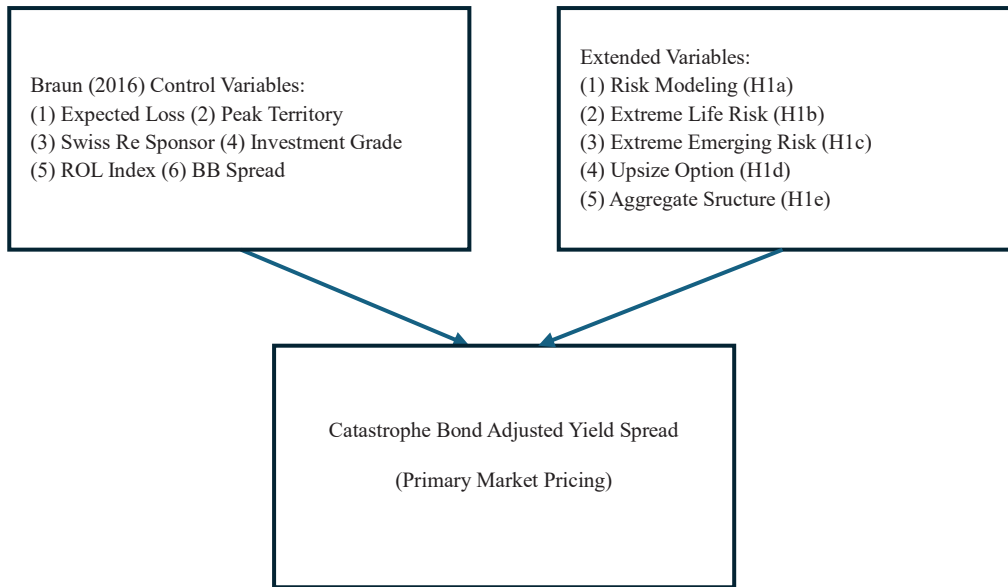


Figure 1: Conceptual Model of the Full Model Equation

Research Findings

This section presents empirical evidence on catastrophe bond pricing dynamics during 2011-2025. I organize results in three stages corresponding to methodological approach: descriptive analysis, baseline regression estimates, and tests for temporal and cross-sectional heterogeneity.

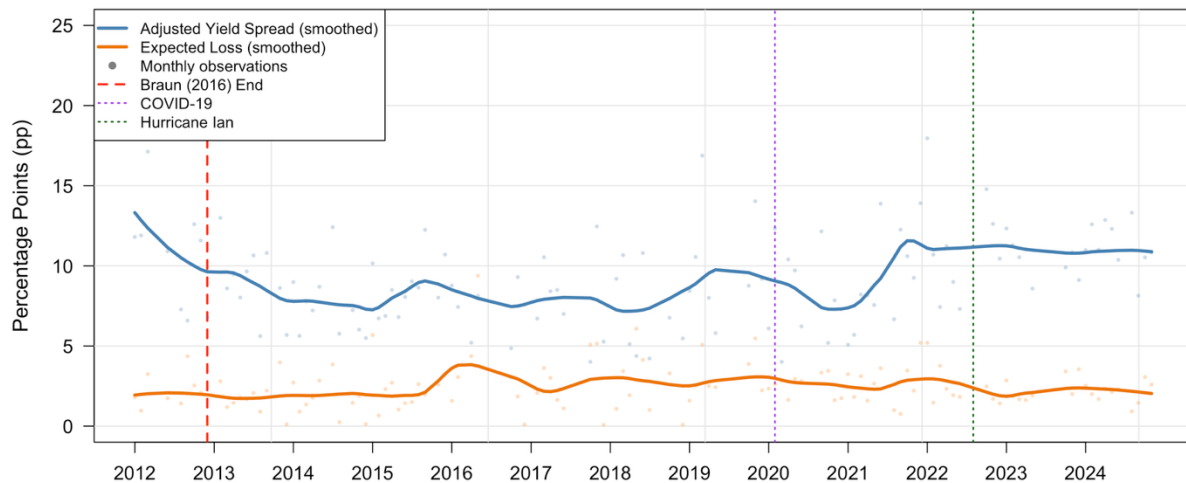


Figure 2. Evolution of catastrophe bond spreads and expected loss (2012 - March 2025).

Figure 2 plots monthly means of adjusted yield spreads and expected loss (EL) for catastrophe bonds, 2012 to early 2025. The dashed line marks December 2012 (end of Braun's 2016 sample), with vertical markers for COVID-19 (March 2020, purple) and Hurricane Ian (September 2022, green). Spreads remained stable at 6–8

percent through 2019, then rose progressively after COVID-19 and accelerated sharply post-Hurricane Ian, reaching 11–13 percent by 2023–2024. Expected loss remained relatively constant at 2–4 percent throughout. The widening spread-EL gap from approximately 4–5 percentage points pre-2020 to 8–10 percentage points post-2022 implies a substantially higher risk premium per unit of modeled loss, motivating the structural break tests and composition controls.

Table 1 : Descriptive Statistics (N = 696 Tranches)

Statistic	Mean	St. Dev.	Min	Pctl(25)	Median	Pctl(75)	Max
Adjusted Yield Spread (percent)	9.463	4.174	1.740	6.406	8.901	11.714	26.275
Expected Loss (percent)	2.367	2.038	0.010	1.000	1.760	3.090	14.060
PEAK Territory	0.888	0.316	0	1	1	1	1
Swiss Re Sponsor	0.036	0.187	0	0	0	0	1
ROL Index	195.0	52.9	135.2	149.9	178.7	276.9	280.0
Investment Grade	0.150	0.358	0	0	0	0	1
BB Spread (percent)	0.926	0.363	0.388	0.652	0.880	1.159	2.149
Risk Modeling	0.822	0.383	0	1	1	1	1
Extreme Life Risk	0.141	0.384	0	0	0	0	1
Extreme Emerging Risk	0.113	0.371	0	0	0	0	1
Upsize Option	0.451	0.498	0	0	0	1	1
Aggregate Structure	0.408	0.492	0	0	0	1	1

Table 2 : Correlation Matrix (Continuous Variables Only)

Variable	Yield Spread	Expected Loss	ROL Index	BB Spread
Yield Spread	1.000	0.329* * *	0.299* * *	0.081* *
Expected Loss	0.329* * *	1.000	-0.108* * *	-0.058
ROL Index	0.299* * *	-0.108* * *	1.000	-0.020
BB Spread	0.081* *	-0.058	-0.020	1.000

*** p<0.01, ** p<0.05, * p<0.10

Issuance-weighted adjusted yield spreads average 9.46 percent with wide dispersion (SD 4.17; min–max 1.74–26.28), while expected loss (EL) averages 2.37 percent (SD 2.04; 0.01–14.06), indicating substantial cross-sectional heterogeneity in pricing relative to modeled risk. The deal mix is skewed toward PEAK territories (88.8%), and risk-modeling disclosure is present in 82.2% of tranches. Investment-grade issuance is 15.0%; aggregate structures and upsize options appear in 40.8% and 45.1%, respectively. The ROL Index averages 195 (SD 52.9), and the contemporaneous BB corporate spread averages 0.93 percent (SD 0.36), capturing market conditions used as controls. Presence of life and emerging peril bonds are 14.1% and 11.3%, respectively. Bonds with risk model disclosure are at 82.2%. Yield Spread is positively associated with both Expected Loss (EL) ($\rho = 0.329$, $p < 0.01$) and the ROL Index ($\rho = 0.299$, $p < 0.01$), consistent with spreads rising with modeled risk and tightening (harder) reinsurance market conditions. All magnitudes are modest, implying low multicollinearity among key covariates supporting the joint inclusion of EL, ROL, and BB spread in the regressions that follow. No discrete variables are presented in the correlation matrix.

Table 3 : Determinants of Catastrophe Bond Spreads

Variable	Model 1 Braun Base	Model 2 + Year FE	Model 3 + Extended	Model 4 Full Model
Intercept	0.053 (0.950)	1.084 (5.107)	0.704 (1.473)	-0.124 (5.491)
Expected Loss	0.706*** (0.133)	0.708*** (0.123)	0.666*** (0.133)	0.673*** (0.123)
PEAK Territory	1.611*** (0.402)	1.528*** (0.417)	1.815*** (0.366)	1.733*** (0.398)
Swiss Re Sponsor	0.794 (0.613)	0.457 (0.731)	0.963 (0.606)	0.589 (0.720)
ROL Index	0.026*** (0.003)	0.021 (0.017)	0.025*** (0.003)	0.026 (0.018)
Investment Grade	-0.603 (0.372)	-0.604 (0.404)	-0.161 (0.384)	-0.152 (0.464)
BB Spread	1.436*** (0.503)	2.180** (0.873)	1.373*** (0.511)	2.299*** (0.871)
Extended Variables (Models 3-4 only)				
Risk Modeling	—	—	-0.906 (1.065)	-0.626 (1.040)
Extreme Life Risk	—	—	-2.307**	-1.920**

Variable	Model 1 Braun Base	Model 2 + Year FE	Model 3 + Extended	Model 4 Full Model
			(0.993)	(0.961)
Extreme Emerging Risk	—	—	2.800**	3.259**
			(1.113)	(1.306)
Upsize Option	—	—	0.049	-0.150
			(0.294)	(0.308)
Aggregate Structure	—	—	0.553*	0.447
			(0.325)	(0.313)
Model Features				
Braun Variables	Yes	Yes	Yes	Yes
Year Fixed Effects	No	Yes	No	Yes
Extended Variables	No	No	Yes	Yes
Observations	696	696	696	696
R ²	0.251	0.287	0.269	0.303
Adjusted R ²	0.244	0.267	0.256	0.277
Durbin-Watson	1.60	1.67	1.62	1.68

Notes:

HAC standard errors (Newey-West, lag=4) in parentheses.

*** p<0.01, ** p<0.05, * p<0.10

Model Specifications:

- **Model 1:** Braun (2016) base variables
- **Model 2:** Model 1 + Year Fixed Effects
- **Model 3:** Model 1 + Extended variables (Risk Modeling, Extreme Life/Emerging, Upsize, Aggregate)
- **Model 4:** Full model with all variables + Year Fixed Effects

To empirically test the relationships proposed in the Conceptual Model (Figure 1), Models 3 and 4 tighten the econometrics relative to Models 1 and 2 by adding the hypothesized structural-peril covariates and absorbing common time shocks. Extending the Braun baseline with peril and structure indicators lifts fit further to 0.277 when add all variables. Core relationships remain stable, EL stays around 0.67–0.71 percent and PEAK is positive and significant, while identification improves: with time FE the ROL level effect becomes insignificant, consistent with FE soaking up renewal-season/hard-market shocks, and the BB spread strengthens, evidencing cleaner pass-through from capital-market conditions to cat-bond coupons. Durbin–Watson nudges up as well.

Regarding the specific hypotheses illustrated in Figure 1, the extended variables in Models 3 and 4 confirm the hypothesized cross-peril segmentation: Extreme Life carries a robust discount, (supporting H1b), while Extreme Emerging Risk type commands a sizable premium, (supporting H1c). Risk-modeling disclosure is negative but insignificant (no support for H1a). Upsize is indistinguishable from zero and Aggregate is weakly positive in Model 3 and attenuates with FE (mixed evidence for H1e).

Table 4 A : Structural Break Analysis - Pre vs Post 2020

Variable	Pre-2020		Post-2020		Difference (Post - Pre)
	Coef.	SE	Coef.	SE	
Intercept	1.880	(5.605)	-5.801**	(2.281)	-7.681
Expected Loss	0.498***	(0.145)	0.989***	(0.221)	0.491*
PEAK Territory	0.358	(0.462)	3.132***	(0.485)	2.774***
Swiss Re Sponsor	-0.455	(1.392)	0.670	(1.142)	1.125
ROL Index	0.050	(0.040)	0.034***	(0.006)	-0.016
Investment Grade	-0.354	(0.542)	0.383	(1.055)	0.737
BB Spread	1.158	(1.219)	2.505**	(0.997)	1.347
Risk Modeling	-	(1.233)	1.282	(1.085)	4.564***
	3.282***				
Extreme Life Risk	-	(1.206)	-0.939	(1.301)	2.810
	3.749***				
Extreme Emerging Risk	-0.912	(2.022)	4.636***	(1.157)	5.549**
Upsize Option	-0.211	(0.516)	-0.337	(0.399)	-0.126
Aggregate Structure	1.294***	(0.456)	-0.130	(0.410)	-1.423**
Observations	302		394		—
Adjusted R²	0.267		0.285		—
Chow Test	F = 1.32 (p = 0.1444)				

Notes:

Robust standard errors (HC1) in parentheses. *** p<0.01, ** p<0.05, * p<0.10

Full model specification with all Braun and Extended variables + Year Fixed Effects.

Chow Test: Tests null hypothesis of no structural break at 2020.

Table 4 B : Structural Break Analysis - Pre vs Post 2022

Variable	Pre-2022		Post-2022		Difference
	Coef.	SE	Coef.	SE	(Post - Pre)
Intercept	4.444	(16.587)	3.508	(5.684)	-0.936
Expected Loss	0.597***	(0.132)	1.017***	(0.385)	0.420
PEAK Territory	1.046**	(0.417)	3.423***	(0.526)	2.377***
Swiss Re Sponsor	0.940	(0.862)	-1.700	(2.723)	-2.640
ROL Index	0.003	(0.094)	0.011	(0.013)	0.008
Investment Grade	-0.244	(0.486)	1.290	(2.768)	1.533
BB Spread	2.490***	(0.888)	1.017	(2.345)	-1.473
Risk Modeling	-0.481	(1.185)	-0.469	(1.160)	0.012
Extreme Life Risk	-1.467	(0.994)	-4.873	(3.158)	-3.407
Extreme Emerging Risk	2.787	(1.984)	4.075***	(1.440)	1.287
Upsize Option	0.264	(0.411)	-0.986*	(0.508)	-1.251*
Aggregate Structure	0.808**	(0.378)	-0.240	(0.538)	-1.049
Observations	444		252		—
Adjusted R²	0.211		0.223		—
Chow Test	F = 0.83 (p = 0.6966)				

Notes:

Robust standard errors (HC1) in parentheses. *** p<0.01, ** p<0.05, * p<0.10

Full model specification with all Braun and Extended variables + Year Fixed Effects.

Chow Test: Tests null hypothesis of no structural break at 2022.

The Chow tests for both candidate breakpoints do not reject the null of parameter stability (2020 split: F=1.32, p=0.144; 2022 split: F=0.83, p=0.697). Accordingly, I can not claim an economy-wide regime change in primary-market pricing at either date. Nevertheless, several coefficients exhibit economically large and statistically significant post-period shifts that align with well-documented market conditions during 2020–2023 (hardening of reinsurance/ILS pricing, capacity frictions, and elevated catastrophe loss activity, especially from secondary perils).

The slope on expected loss approximately doubles after 2020 (Table 4a), indicating greater spread per unit of modeled risk in the post-2020 primary market. This pattern is consistent with a tighter supply of retro/reinsurance and ILS risk capital following heavy loss years and heightened uncertainty; contemporaneous market reports chronicle materially higher coupons and investor returns in 2023 as the hard market persisted.

The PEAK premium is small pre-2020 but becomes large and highly significant thereafter, and it remains elevated in the post-2022 subsample. This repricing is directionally consistent with an industry environment in which aggregate catastrophe burdens and a string of secondary-peril loss years constrained risk budgets and pushed required compensation for peak U.S. wind/quake exposures higher.

The credit-spread proxy (BB spread) loads more positively after 2020 in Table 4a, consistent with stronger pass-through from broad capital-market conditions to cat-bond coupons during 2022–2023, when base yields reset higher and the ILS market priced to attractive risk-adjusted returns.

The pre-2020 discount associated with enhanced risk modeling disclosure is sizeable and significant but attenuates (and flips in sign statistically) post-2020. Industry commentary over 2021–2023 repeatedly emphasized model uncertainty reducing investors' willingness to treat “modeling comfort” as a clear-cut spread concession.

The coefficient of extreme emerging risk is insignificant pre-2020 but becomes large and statistically significant post-2020, implying a pronounced premium for newer/less seasoned perils (e.g., cyber) in the later period - consistent with disclosures that cyber and other emerging perils entered the ILS toolkit but demanded additional compensation for model and tail uncertainty.

A pre-2020 of extreme life risk discount attenuates post-2020 and loses significance. This is coherent with the observation that the COVID-19 shock had a limited direct impact on the predominantly property-peril cat-bond market; while life/health structures were most exposed conceptually, market-wide cat-bond pricing was not re-anchored by pandemic losses.

The aggregate-structure premium, positive and significant pre-2020, dissipates after 2020 and even turns negative in the difference tests of Table 4a. Industry data document a clear migration away from aggregate cat-bond protection over 2022–2023, as investors favored occurrence structures following loss-creep episodes in the late 2010s; the shrinking share of aggregate issuance is consistent with weaker or vanishing premia in the remaining aggregate deals.

The coefficient of ROL index remains positive across subsamples and becomes statistically clearer post-2020 (Table 4a), consistent with the index functioning as a market-cycle indicator: higher reinsurance ROL levels in the hard market are more sharply reflected in primary-market cat-bond pricing.

Table 5 : Quantile Regression Results (Full Model)

Variable	Q25 (Low)	Q50 (Median)	Q75 (High)
Intercept	-1.387	2.403**	1.523
	(1.684)	(0.968)	(1.068)
Expected Loss	0.131	1.076***	1.494***
	(0.169)	(0.178)	(0.127)
PEAK Territory	0.871**	1.545***	1.866***
	(0.388)	(0.252)	(0.384)
Swiss Re Sponsor	0.612	1.787**	1.056
	(1.816)	(0.902)	(0.708)
ROL Index	0.029***	0.017***	0.020***
	(0.004)	(0.002)	(0.004)
Investment Grade	1.116*	-0.429	-0.687
	(0.571)	(0.357)	(0.513)
BB Spread	1.020	1.016**	1.839***
	(0.684)	(0.417)	(0.460)
Risk Modeling	-0.067	-0.870	-0.917
	(1.189)	(0.665)	(0.687)
Extreme Life Risk	-1.229	-1.543**	-1.501**
	(1.192)	(0.657)	(0.760)
Extreme Emerging Risk	4.950***	3.116**	2.565

Variable	Q25 (Low)	Q50 (Median)	Q75 (High)
	(1.529)	(1.323)	(1.795)
Upsize Option	-0.027	-0.070	0.008
	(0.428)	(0.275)	(0.281)
Aggregate Structure	0.293	0.282	0.034
	(0.445)	(0.283)	(0.276)
Observations	696	696	696
Fixed Effect	Yes	Yes	Yes
Quantile	0.25	0.50	0.75

Notes:

Bootstrap standard errors (500 replications) in parentheses.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

Full model includes all Braun and Extended variables.

Table 5. In the quantile (low–mid–high spread) specifications, expected loss (EL) is statistically insignificant, indicating that when modeled loss is very small, investors do not appear to price marginal changes in EL. This is economically plausible: for a sizable share of recent issuance, average ELs are low, so investors may anchor valuation to credit-like features and market level factors rather than fine gradations in modeled risk, i.e., treating these notes more like investment-grade–style paper when EL is small. Empirically, cat-bond pricing is often modeled as linear in EL but its slope varies by regime and can attenuate when risk is low; concurrently, pass-through from broad credit conditions can become more salient.

Discussion

Theoretical Contribution

This study extends Braun's baseline by adding structural-peril covariates, testing two externally motivated breakpoints (2020; 2022), and estimating quantile regressions. Three results stand out. First, cross-peril segmentation is first-order: life/mortality tranches price at material discounts while emerging tranches command sizable premia magnitudes that are economically large and robust with year fixed effects. Second, the 2020 and 2022 exercises, while not rejecting structural breaks at conventional levels, reveal economically meaningful shifts: post-2020 I see a steeper EL slope and an "activation" of the emerging premium; post-2022 (the hard-market regime after Hurricane Ian's USD 50–65bn insured loss) the PEAK premium increases and level effects dominate, consistent with capacity constraints at the 1/1/2023 renewals when the Guy Carpenter U.S. ROL Index rose ~31%. Third, quantile results uncover pronounced convexity: EL is weak at the low-spread end but bites strongly in the right tail, indicating non-linear tail-risk pricing that a conditional-mean model would mask. These findings align with real-world market dynamics, pandemic-era funding normalization, post-Ian hardening, record 2024–2025 issuance, and the advent of cyber cat capacity (e.g., Beazley's 2023 program).

Managerial Implication

For sponsors, these findings can reorient strategy from structural optimization to fundamental peril portfolio decisions. Sponsors with diversified portfolios can prioritize securitizing life and mortality exposures where they benefit from material discounts, while deferring emerging risk perils until models mature. The convex pricing structure further implies sponsors can avoid concentrating expected loss in single tranches: splitting high-EL exposures into multiple smaller tranches can generate meaningful savings through the nonlinear pricing relationship.

For investors, results show that risk premia are strongly convex and capital-market-sensitive in distribution tails. At upper quantiles, substantial corporate credit spread pass-through means high-spread bonds offer "catastrophe risk plus credit risk" exposure rather than pure diversification. If the objective is decorrelation from traditional assets, investors should concentrate in lower-to-middle quantile bonds where expected loss pricing is modest and capital market pass-through limited. Conversely, upper-quantile bonds offer attractive absolute returns but correlate with broad risk appetite during systemic stress.

Policy Recommendation

These principles become particularly salient for sovereign disaster financing, where catastrophe bonds remain underutilized despite severe fiscal exposure. Thailand exemplifies this challenge while offering conditions that make it a suitable test case: sufficient exposure scale, diversified peril mix (riverine floods, coastal typhoons, pandemic), investment-grade credit rating, and regional integration enabling multi-country structures.

Translating convexity into layered strategy. The quantile regression findings reveal how catastrophe bond pricing exhibits strong convexity: expected loss coefficients increase substantially from lower to upper quantiles. This provides natural segmentation:

Layer 1 (lower-quantile pricing): Budget reserves for high-frequency, low-severity events. Countries should hold earmarked reserves for frequent disasters where expected loss pricing is minimal internal reserves cost significantly less than catastrophe bond spreads at this layer.

Layer 2 (median-quantile pricing): Contingent credit for moderate disasters occurring infrequently. Countries should secure contingent credit facilities with modest annual commitment fees, avoiding higher catastrophe bond spreads until disasters materialize.

Layer 3 (upper-quantile pricing): Catastrophe bonds for extreme tail events. At these severity levels, alternative mechanisms become unavailable: emergency borrowing faces substantial sovereign spread widening, multilateral programs impose conditionality, and budget reallocations crowd out development spending. The convex upper-quantile pricing means that while spreads are elevated, the opportunity cost of not transferring these risks, fiscal crises causing severe GDP output losses, exceeds the premium cost.

Quantified regional savings through ASEAN pooling. Individual-country catastrophe bond issuance faces prohibitive costs due to: base spread, PEAK geographic concentration penalty, elevated expected loss through convex pricing, and emerging market premium. These costs make solo issuance fiscally challenging for many developing nations. This empirical decomposition provides the business case for regional pooling. The PEAK concentration premium reflects geographic concentration precisely what multi-country diversification eliminates. A regional ASEAN bond covering Thailand's Chao Phraya floods (August-October), Philippine typhoons (June-November), Vietnam's Mekong Delta floods (September-November), and Malaysia's monsoon floods (November-January) achieves low or negative loss correlations. This diversification eliminates the PEAK concentration premium while reducing pooled expected loss regionally, generating additional savings through convex pricing. Including a pandemic component captures the life/mortality diversification discount, adding further weighted savings.

Regional bonds achieve substantial cost reductions compared to solo issuance, representing material percentage savings that translate to significant annual dollar savings on typical issuance sizes. Regression coefficients enable transparent cost allocation based on actuarial principles rather than political bargaining. Country-specific allocations reflect base premium weighted by GDP plus modeled expected loss, minus diversification benefits from uncorrelated peril components. This actuarial formula provides finance ministries with technical justification for regional cooperation, achieving multiple-fold cost savings compared to solo issuance while providing immediate post-disaster liquidity that reserves and emergency borrowing cannot match.

The regional pooling structure addresses a critical barrier to ESG investment in disaster risk financing: many institutional investors with sustainability mandates seek exposure to climate adaptation instruments but require

minimum issue sizes, credit quality, and market liquidity. A regional ASEAN catastrophe bond satisfies these criteria, achieving investment-grade equivalent ratings through diversification, offering sufficient scale for institutional investors, and demonstrating measurable climate adaptation impact across multiple vulnerable economies. By translating complex risk pricing into transparent actuarial formulas, this framework facilitates ESG capital deployment to sovereigns that would otherwise face prohibitive solo issuance costs, effectively creating a conduit for climate finance to reach the countries most exposed to natural disaster risk.

Conclusion

Catastrophe bonds have evolved substantially since Braun's (2016) foundational study. Analyzing 696 primary market tranches from 2011-2025, I document three critical developments: peril choice is a first-order cost driver (life bonds save 1.5-1.9 percent, emerging risk costs 2.5-5 percent), COVID-19 fundamentally repriced tail risk through persistent demand-side shifts, and pricing exhibits strong convexity across the spread distribution.

These findings provide actionable guidance. Sponsors should prioritize life risk securitization and defer emerging risk bonds. Investors should recognize non-linear tail-risk sensitivity. Most significantly, multi-country regional bonds can achieve 30-35% cost savings through PEAK diversification making catastrophe bonds fiscally viable for developing nations like Thailand and ASEAN partners.

Several methodological limitations suggest promising research directions. Panel fixed effects models are not feasible given sparse repeat issuance (median 2-3 tranches per issuer), while instrumental variable approaches using vendor model updates or regional weather shocks remain beyond current scope but offer valuable paths forward. Machine learning techniques (Chen et al., 2024) could reveal additional non-linear interactions, though our quantile regression framework already captures key non-linearity in the convex pricing structure. Future work should also address secondary market dynamics, endogeneity through quasi-experimental designs, and climate-adjusted risk metrics as this rapidly evolving market continues integrating with global capital.

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