Catastrophe Bonds[*]

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Abstract

Catastrophe bonds are one of the most significant innovations in the risk transfer landscape of the last three decades. This chapter is a comprehensive discussion of catastrophe bonds. We contextualize catastrophe bonds within the broader realms of alternative risk transfer and alternative capital, introduce the relevant terminology, explain the main structural and market characteristics, discuss the state of the art in catastrophe bond pricing, and provide an outlook for further developments in this area. Throughout the whole chapter, we highlight relevant academic research combined with current evidence from industry practice.

[*]This chapter succeeds the chapter "Innovations in Insurance Markets: Hybrid and Securitized Risk-Transfer Solutions" by J. David Cummins and Pauline Barrieu in the Handbook of Insurance, 2nd edition.

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Contents

1 Introduction

Catastrophe bonds (cat bonds) are a securitized form of reinsurance through which natural disaster risk can be transferred to the capital markets. They were developed in the mid-1990s in response to natural disasters that caused significant insured losses, most notably Hurricane Andrew in 1992 and the Northridge earthquake in 1994 (Polacek, 2018). Such events are characterised by a low frequency but high severity: they are rare but when they occur, they can cause significant damage, ranging from physical destruction of property to loss of life and economic disruption. From an insurance perspective, large-scale natural disasters are problematic because they give rise to stochastic dependence of claims on a regional level (Cummins, 2006). This hampers diversification and generates heavy-tailed aggregate loss distributions (Beer et al., 2019).

Accordingly, nondiversification traps and capitalization frictions are considered to be primary reasons for the failure of the private market for catastrophe insurance (see Jaffee and Russell, 1997; Froot, 2001; Zanjani, 2002; Harrington and Niehaus, 2003; Froot and O'Connell, 2008; Ibragimov et al., 2009).[1] Insurers underwriting disaster risk need to hold considerable amounts of capital to maintain their ability to settle losses even in extreme scenarios. They are reluctant to do so due to their high cost of equity capital.

Cat bonds are a possible remedy because most uninsurable catastrophe risks are still globally diversifiable through securities markets (Cummins, 2006). The objective of this chapter is to provide an overview and assessment of cat bonds as a dominant instrument in the area of alternative capital and insurance-linked securities. We explain the relevant terminology, introduce the reader to the mechanics of cat bonds and their various characteristics, showcase the evolution of the market, evaluate the risk-return profile, and discuss the state of the art in cat bond pricing. Throughout the whole chapter, we highlight relevant academic research combined with current evidence from industry practice. The chapter exhibits the following structure. In Section 2, we provide a high-level overview of alternative risk transfer and alternative capital, and discuss the prominence of cat bonds

[1] See Niehaus (2002) for an overview of the early literature on catastrophe risk allocation.

among other instruments in these sectors. In Section 3, we introduce the characteristics of cat bonds, including their general mechanics, the most important trigger types, the main perils, and the types of embedded reinsurance contracts. In Section 4, we describe the cat bond market and its evolution, the investor base, trading and liquidity, as well as the risk-return profile of the asset class. In Section 5, we review the different approaches for cat bond pricing. Finally, in Section 6, we conclude the chapter.

2 Categorization

2.1 Alternative Risk Transfer

Cat bonds are part of the wider realm of alternative risk transfer (ART). ART is a set of solutions for the transfer of risk that go beyond the traditional insurance and reinsurance sector (Cummins and Weiss, 2009).[2] Figure 1 contains an ART taxonomy. The categories differ from left to right by the degree to which they utilize the capital markets as a risk bearer. Self insurance means that a corporate sets aside funds to cover potential losses rather than purchasing coverage from an insurance company. This is often used for risks that are predictable and measurable. An institutionalised form of self insurance are captives, i.e., insurance companies that are wholly owned and controlled by the corporation that is looking to self insure. Self insurance does not involve the capital markets.

Furthermore, structured reinsurance solutions, also known as hybrid covers, are customized reinsurance contracts, designed to meet specific needs of the primary insurer that cannot be addressed by traditional reinsurance, such as multiple types of risk, multiple years, and multiple triggers. They are typically used to manage complex or large risks, provide capital relief, enhance capital efficiency, manage volatility, and improve the cedent's overall financial performance. Structured reinsurance solutions may incorporate features of both insurance and capital markets.

[2] A more detailed overview of ART is available in Cummins (2008) and Cummins and Weiss (2009). Note that we exclusively focus on the nonlife side of ART. More information on the much smaller market of ART instruments for life insurance risk can, e.g., be found in Barrieu et al. (2012).

The third distinct category within ART is alternative capital. The corresponding solutions are explicitly designed for a direct risk transfer from the cedent into the capital markets. Alternative capital comes into play in the presence of low-frequency high-severity risks that are hard to digest for insurers and reinsurers. Apart from cat bonds, alternative capital comprises industry loss warranties, collaterized reinsurance, and sidecars. In the following section, we briefly discuss the latter three instruments, before moving on to cat bonds in Section 3.

2.2 Alternative Capital

Figure 2 illustrates the evolution of alternative capital over the last two decades. With a volume of more than $90 bn, it amounts to between 15 and 20% of today's total reinsurance capital and is thus an important pillar in the risk transfer landscape. Figure 3 breaks the aggregate amount of alternative capital down into the individual instruments listed in Figure 1. Cat bonds and collaterized reinsurance represent the two largest segments, while sidecars and ILWs are of lesser importance in terms of overall volume.

ILWs are highly standardized reinsurance contracts whose payout depends on two variables: the total loss to the insurance industry from a catastrophe (known as an index trigger) and the individual losses incurred by the insurer purchasing the ILW cover (Beer et al., 2019). There is also a pure derivative version of the ILW, called a catastrophe swap, in which the payoff exclusively depends on industry losses (Braun, 2011). Catastrophe swaps can be used by non-insurance entities such as hedge funds to gain exposure to catastrophe risk. Benefits of ILWs include their simplicity and the speed at which claims can be settled. However, because ILW payoffs are primarily driven by the index trigger, they involve basis risk (Gatzert and Kellner, 2011). This means that the cedent may face uncovered losses when the aggregate industry loss is too low to trigger a payout.

Collateralized reinsurance allows capital market investors to sell reinsurance coverage and thus gain exposure to catastrophe risk. This is possible through an interposed transformer vehicle with a reinsurance license. In contrast to classical reinsurance, the full layer is collateralized (hence the name) by cash or highly rated assets. In contrast to ILWs, collateralized reinsurance contracts are bespoke instead of standardized and in contrast to cat bonds, they not securitized. Thus, there is no secondary market and investors need to hold on to their position until maturity. Another difference to cat bonds is that collateralized reinsurance transactions tend to cover lower layers of the loss tower and thus exhibit a more aggressive risk-return profile. Academic literature on collateralized reinsurance is scarce. An example of an exception is Bockius and Gatzert (2022) who analyse the impact of counterparty risk on the basis risk of industry loss warranties as well as collaterised reinsurance under different dependence structures.

Sidecars are financial structures that enable investors to take exposure to catastrophe risk alongside (as the name indicates) reinsurance companies. The reinsurer sponsoring the sidecar transfers the underlying risk to a special purpose vehicle through a quota share reinsurance contract Cummins and Weiss, 2009).[3] The special purpose vehicle, in turn, is owned by a holding company that raises capital for the sidecar by issuing equity and debt to investors. The returns on these investments depend on the premiums and claims that materialize on the underlying insurance portfolio. A tiered structure, akin to an asset-backed security, can be employed when issuing debt. This approach caters to lenders with varying levels of risk tolerance. To date, sidecars have been primarily established in Bermuda and employed for property-catastrophe risk (Ramella and Madeiros, 2007). However, Bugler et al. (2021) provide some first insights adapting the structure to the longevity sector.

[3]Quote share reinsurance is a form of proportional reinsurance under which two counterparties share claims and premiums according to a fixed percentage. As we will discuss below, the typical cat bond structure is similar to a sidecar, but contains excess of loss reinsurance instead of proportional reinsurance. Sidecars and cat bonds can therefore function in tandem as complementary tools, similar to how quota share and excess of loss reinsurance contracts complement each other in a conventional reinsurance program.

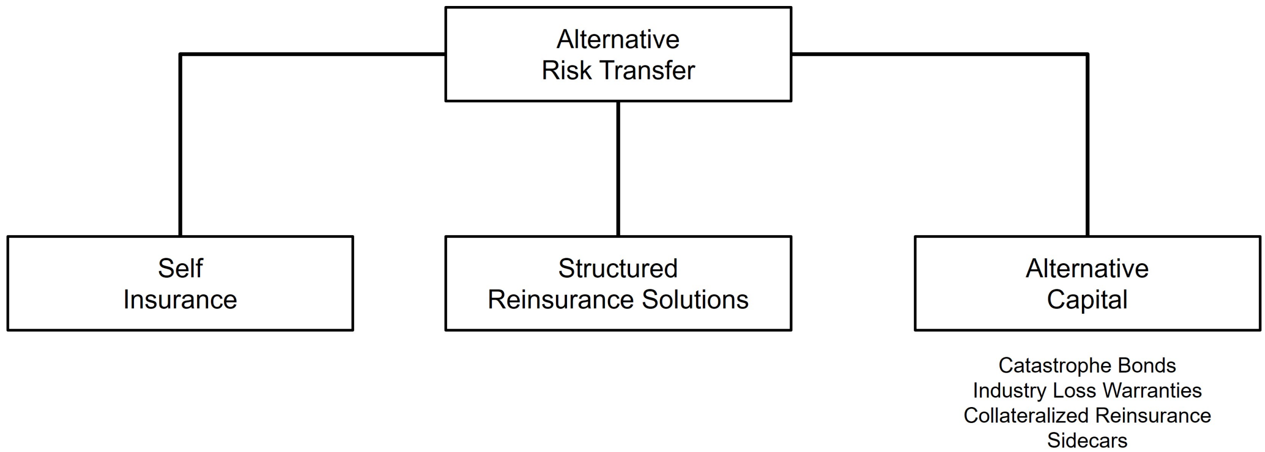

Figure 1: A Taxonomy of Alternative Risk Transfer

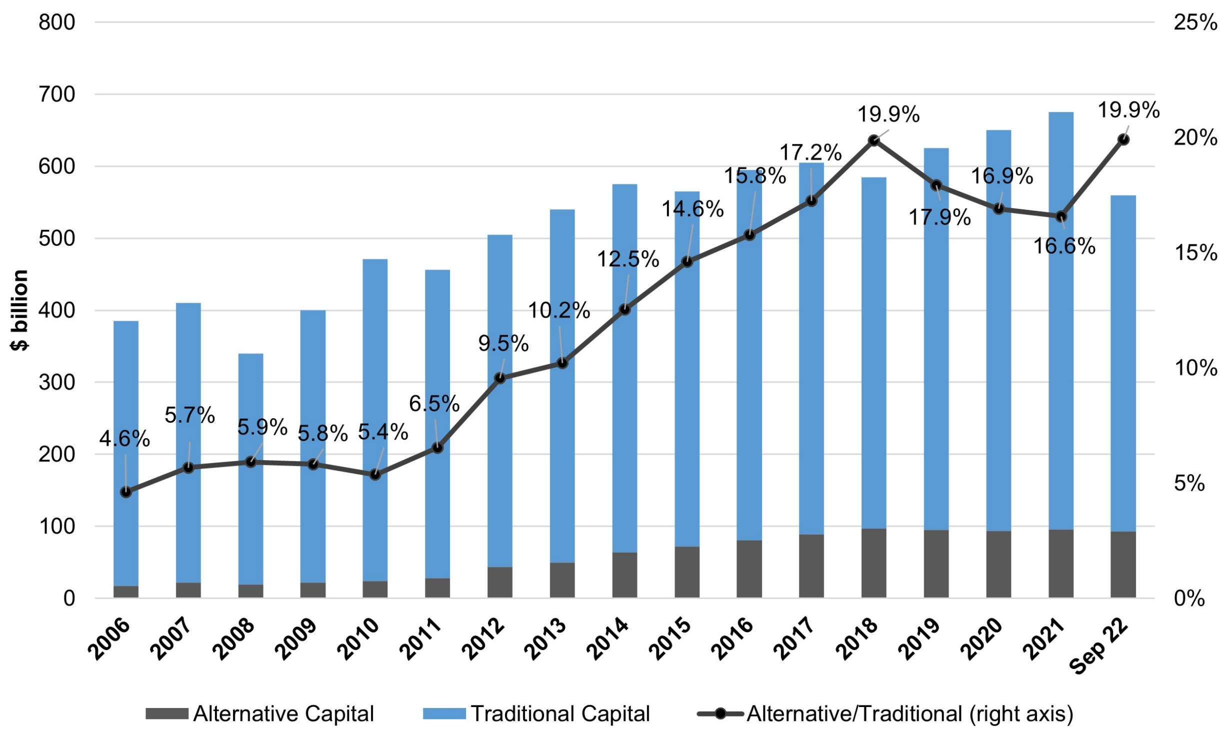

Figure 2: Global Reinsurance Capital. Source: AON, 2023.

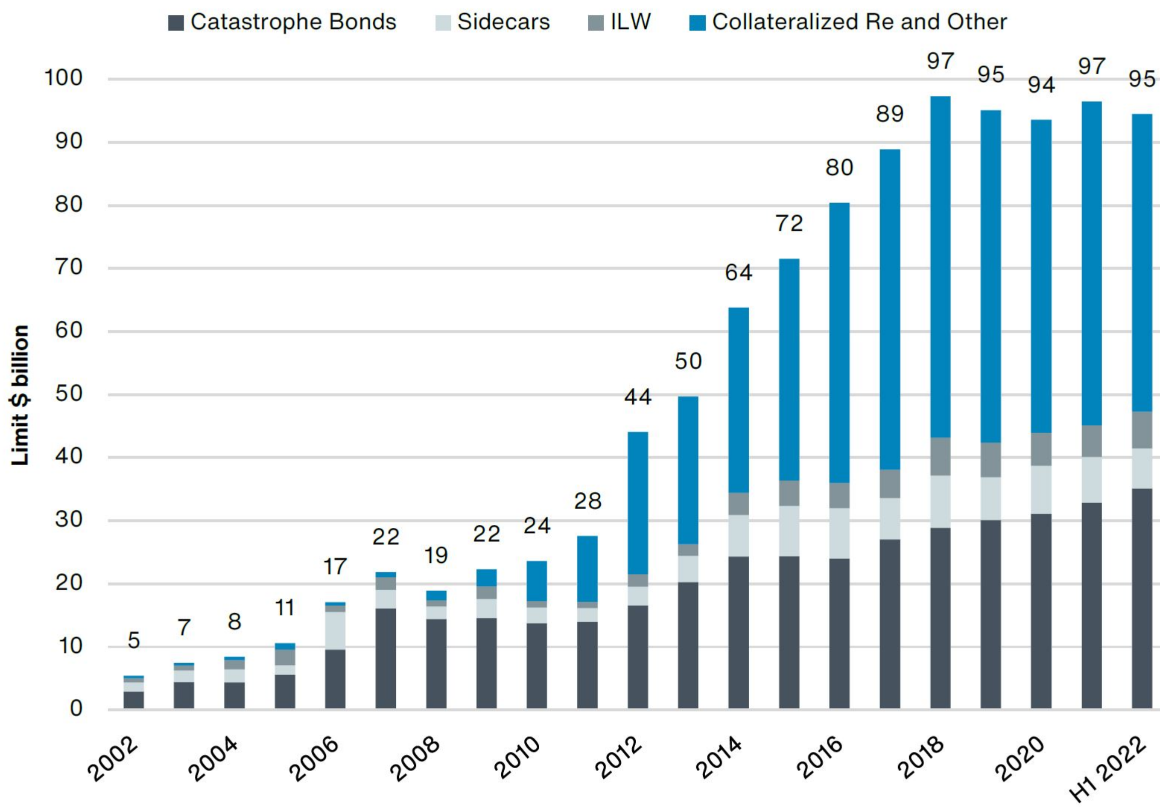

Figure 3: Breakdown of Alternative Capital. Source: AON (2022).

3 Structural Characteristics

3.1 General Mechanics

We now begin our in-depth discussion of cat bonds. Where not indicated otherwise, the content of Sections 3 and 4 is based on the recent cat bond primer by Braun and Kousky (2021). Cat bonds are insurance-linked securities (ILS), because their values are driven by insurance loss events. The standard structure of a cat bond is illustrated in Figure 4. The sponsor or cedent is the entity aiming to offload catastrophic risk from its balance sheet. Sponsors are typically insurers or reinsurers, but there have been instances where corporations (e.g., Disney), public institutions (e.g., the New York City Metropolitan Transportation Authority), and sovereign nations (e.g., the Republic of Chile) relied on cat bonds to manage their risk exposure. To issue a cat bond, the sponsor establishes a special purpose vehicle (SPV). The function of the SPV is to insulate both parties in the transaction from each other's counterparty default risk.[4] In securitization markets, this is called bankrupcty remoteness. After its creation, the SPV grants coverage to the sponsor under an excess of loss reinsurance contract. To capitalize itself, the SPV issues the cat bond to investors. It then uses the proceeds from the investors to purchase high-quality collateral, which it holds in a trust account. Typical collateral securities for cat bonds are U.S. Treasury Bills, accessed through treasury money market funds. They exhibit a low default probability, a high liquidity, and, due to their short terms, little interest rate risk. An alternative collateral that has increased in use since the mid 2010s are Structured Notes provided by the International Bank for Reconstruction and Development (IBRD) (Swiss Re, 2018).

The collateral produces a consistent flow of variable rate returns. Together with the rate on line or premium of the reinsurance contract, which is paid by the sponsor, these floating rate returns form the coupon received by the cat bond investors. In the cat bond context, the rate on line is called spread. Cat bond coupons thus comprise a term premium (the floating rate) and a risk premium (the spread). The latter compensates investors for shouldering the disaster risk. Due to their high-quality collateral, cat bonds themselves are floating rate notes with little interest rate and credit risk. In other words, cat bond investors benefit from an almost pure investment in property catastrophe risk (Braun et al., 2022). This has important implications for the risk-return and correlation profile of the asset class, which we discuss in Section 4.

If a predetermined trigger event occurs during the bond's term, the collateral is liquidated and all or part of the corresponding proceeds are transferred to the sponsor as an indemnification under the embedded reinsurance contract. Consequently, for investors, a trigger event implies a complete or partial loss of the principal. If, in contrast, the bond reaches maturity without the trigger event taking place, the principal is refunded to the

[4]If the bonds were issued directly by the sponsor instead of the SPV, investors would lose their principal in case the sponsor defaulted. Similarly, if the investors did not post the collateral upfront, their default would leave the sponsor without a its hedge against property catastrophe losses.

investors. Cat bonds have an average maturity of three years, with longer maturities of up to five years being less common (Braun, 2016).

There are two types of coverage, determined by the reinsurance contract embedded within the cat bond: per occurrence and annual aggregate. In the per-occurrence case, the cat bond features an excess-of-loss per event (XL/E) reinsurance contract, which means it will only trigger if losses resulting from a single catastrophe event surpass a specified threshold (attachment point). On the other hand, the annual aggregate case involves a stop-loss reinsurance contract, allowing for the accumulation of insured losses caused by all catastrophe events in a single year. At the time of writing, the outstanding market volume was nearly evenly divided between per-occurrence (51.3%) and annual-aggregate (48.7%) cat bonds (Artemis.bm, 2023).

Cat bonds can exhibit a proportional or a binary payoff. In a proportional payout scenario, the percentage loss of principal for investors increases as the underlying insurance losses surpass a preset threshold, called the attachment point. Investors suffer a full write-down once the underlying insurance losses reach a second, higher threshold, called the exhaustion point. On the other hand, a binary payout transfers a predetermined amount of principal (usually 100%) to the sponsor as soon as the underlying insurance losses hit the attachment point.

Finally, as fixed income securities, cat bonds are sometimes rated by credit rating agencies. For example, Moody's rating methodology for cat bonds is based on the expected loss to investors, which includes the likelihood that one or more catastrophe events will happen and the potential losses to investors arising from their occurrence (Artemis.bm, 2016). However, since the expected loss is provided by catastrophe risk modelling firms and not the rating agencies themselves (see Section 5), more and more new issuances do not have any credit rating attached to them. This increase in non-rated cat bonds in recent years reflects the maturation of the market (Makariou et al., 2021). That there are a lot of specialized investors that purely rely on the risk assessment of the catastrophe modelling firms and do not derive any value added from an additional credit rating.

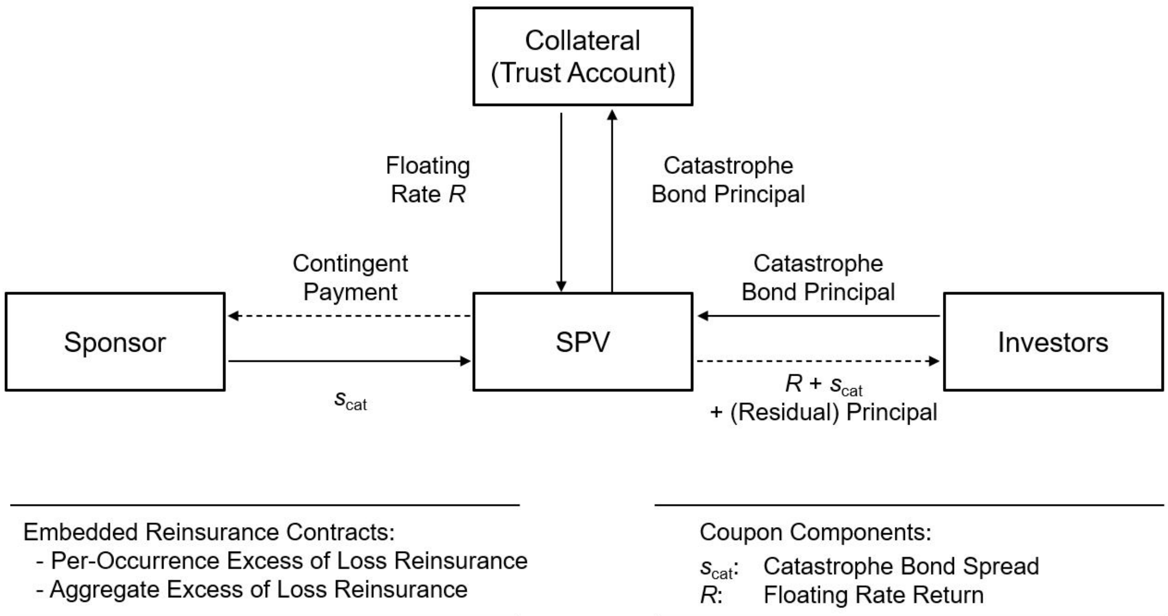

Figure 4: Typical Structure of a Cat Bond. Source: Braun (2016).

The sponsor transfers the property-catastrophe risk in its books to the SPV by means of an excess of loss reinsurance contract. To back the risk with capital, the SPV issues fixed income securities (the cat bonds) to investors. The principal paid by investors is held in safe collateral in a trust account. If a predetermined trigger event occurs during the bond's term, the collateral is liquidated and all or part of the corresponding proceeds are transferred to the sponsor as an indemnification under the embedded reinsurance contract. Consequently, for investors, a trigger event implies a complete or partial loss of the principal. If, in contrast, the bond reaches maturity without the trigger event taking place, the principal is refunded to the investors. For bearing the catastrophe risk, investors are compensated with regular coupons, consisting of a floating interest rate plus the cat bond spread.

3.2 Triggers

Basic Types

In order to determine whether a trigger event has occurred, cat bonds can use a variety of trigger types. The trigger type defines the conditions of the catastrophic event that would lead to the release of the principal to the sponsor (Braun, 2016). Figure 5 shows a breakdown of trigger types in the cat bond market at the time of writing.

The dominant mechanism today, accounting for a little more than 60% of the outstanding cat bond risk capital, is the indemnity trigger. A cat bond with an indemnity trigger works exactly like a standard reinsurance contract. It references the actual insured losses incurred by the sponsor and is thus a perfect hedge against disaster risk.

The second most common trigger type, the industry loss index trigger, represents 25% of the outstanding risk capital. Under this trigger, a payout to the sponsor is due if an index of aggregate insured losses incurred by all insurers in the covered territory surpasses a threshold value.[5] The index that determines the trigger event is compiled by an independent third party, the so-called calculation agent, from loss reports of the insurance industry. Typical calculation agents are Property Claims Services (PCS), subsidiary of Verisk, in the U.S. and PERILS AG in Europe.

The least common trigger type today is the parametric trigger, which constitutes a mere 5% of the outstanding risk capital. Under this mechanism, a trigger event occurs, if a quantifiable characteristic of the covered catastrophe, such as earthquake strength on the moment magnitude scale or hurricane peak wind speed in miles per hour, exceeds a threshold at a given range of measurement stations (Hagedorn et al., 2009). To obtain these measurements, cat bonds may rely on government agencies, such as the National Oceanic and Atmospheric Association (NOAA) for atmospheric data and the U.S. Geological Survey for seismological data (Braun (2023).

The vast majority of cat bonds today relies on one of these three trigger types. In the early years of the cat bond market, however, a fourth trigger type, the modelled loss trigger, was also prevalent. Under a modelled loss trigger, a catastrophe risk model is used to estimate the losses of the sponsor. These triggers have recently become rather rare. Finally, cat bonds may also employ multiple triggers at once. This is similar to double-trigger reinsurance contracts or ILWs, which comprise an industry index trigger and an indemnity trigger (Gatzert and Schmeiser, 2012).[6]

[5]Note that the industry loss trigger explicitly references industry-wide *insured* losses, i.e., the losses covered by insurance policies. Due to prevailing protection gaps, these are usually much lower than the overall *economic* losses caused by natural disasters.

[6]The indemnity trigger in these instruments is included to achieve regulatory acceptance as a reinsurance substitute and the industry loss index trigger mitigates moral hazard. We discuss the criteria for trigger choice in the next paragraph.

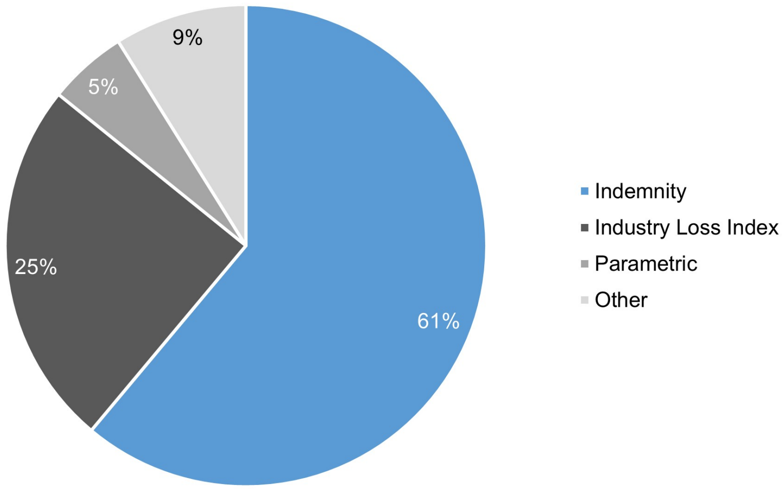

Figure 5: Cat Bond Capital Outstanding by Triggers. Source: Artemis.bm (2023).

Criteria for the Trigger Choice

Hagedorn et al. (2009) discusses the choice of triggers for cat bond transactions and highlights four key criteria: i) transparency, ii) basis risk, iii) settlement time, and iv) accounting and regulatory treatment. These criteria need to be traded off against each other, as sponsors and investors have different target functions and no single trigger type allows for the optimal outcome in all dimensions. This is most obvious for i) and ii): reducing basis risk leads to more intransparency and vice versa.

The concern with intransparency is a classical moral hazard problem. If the information asymmetry between sponsor and investor is large, the former may be inclined to take actions that increase the loss frequency or severity. Specific forms of moral hazard in the context of cat bonds are the relaxation of underwriting standards (pre event) or claims handling standards (post event) by the sponsor to the detriment of investors (Braun, 2016). Basis risk, on the other hand, describes the possibility that the payoff from the cat bond is less than perfectly correlated with the sponsor's loss (Doherty, 1997). In traditional reinsurance, there is no basis risk, since the payoff is determined by the actual losses in the sponsor's portfolio and hence perfectly matches his exposure.

Moral hazard, basis risk, and the trade-off of these two phenomena in the catastrophe risk transfer market have long been a subject of the academic literature (see Doherty, 1997; Harrington and Niehaus, 1999; Doherty and Richter, 2002; Cummins et al., 2004). In recent years, Zhang and Tsai (2018) developed a model to quantify the hedge effectiveness of cat bonds with industry loss index triggers and analysed its impact on pricing.

Further work has considered the issue of moral hazard from an empirical perspective. Götze and Gürtler (2020b) suggest an approach to measure moral hazard in the cat bond market. According to their analyses, sponsors of indemnity-trigger cat bonds are prone to ex-ante but not ex-post moral hazard. Braun (2016) finds no evidence for a spread markup on indemnity trigger cat bonds, but documents that long-standing sponsors with a strong track record achieve a tighter execution pricing. He concludes that the reputation of the sponsor seems to be more important to investors than moral hazard concerns associated with the trigger type. Braun et al. (2022) confirm the results of Braun (2016) for realized cat bond returns. If indemnity triggers have an effect at all, they correspond to lower rather than higher (excess) returns.

Evaluation of the Trigger Types

Indemnity triggers exhibit no basis risk for the sponsor but are intransparent for investors, since the latter do not have direct access to information about the sponsor's insurance portfolio. This raises the aforementioned moral hazard concern. If the sponsor is an insurer or reinsurer, it may loosen underwriting and claims handling standards once the cat bond coverage is in place. In addition to a potential moral hazard problem, indemnity triggers require a prolonged settlement process, i.e. loss reporting and verification for the sponsor's insurance portfolio must be completed before funds can be released. Since the indemnity trigger works just as classical reinsurance, it usually qualifies for reinsurance accounting[7] and the sponsor achieves full regulatory capital relief under modern risk-based capital standards, such as Solvency II (Braun and Weber, 2017).

[7] In the U.S., e.g., "credit for reinsurance can be claimed if the collateral for paying the reinsured claims is held in an U.S. trust" (Smack, 2016).

Trigger / Criterion	**Transparency**	**Basis Risk**	**Settlement**	**Statutory Acceptance**
Indemnity	low	low	slow	high
Industry Index	high	low	slow	moderate
Parametric	very high	very high	fast	low

Table 1: Evaluation of the Trigger Types (Hagedorn et al., 2009)

The moral hazard issue associated with indemnity triggers can be mitigated with an industry loss index trigger, because the sponsor can neither influence the losses of all other insurers nor the behaviour of the calculation agent. Yet, industry loss index triggers introduce basis risk, because the underlying index will not be perfectly correlated with the sponsor's own losses. As the reporting of claims for a whole range of insurance portfolios is time consuming, the industry loss index trigger, just as the indemnity trigger, requires an extended settlement time during which investor capital will be trapped in the cat bond's collateral.[8] Another disadvantage for the sponsor is that industry loss index triggers do not generally qualify for reinsurance accounting and regulatory capital relief (Smack, 2016; Braun and Weber, 2017).

Finally, the parametric trigger offers a high transparency and enables a rapid payout, as the necessary measurements come from independent third parties such as national weather services and are available immediately after the catastrophe has occurred. However, since the underlying physical parameters will exhibit a relatively low correlation with insurance losses, this trigger type presents a high basis risk for cedents and does not qualify for reinsurance accounting and regulatory relief. Table 1 summarizes these considerations for the three main trigger types.

3.3 Perils

Cat bonds are designed to offer coverage against the most expensive natural disasters globally. The underlying natural disaster risk is characterized by two dimensions: peril

[8] To reduce uncertainty surrounding the trigger probability, catastrophe risk modelling firms usually offer an initial estimate of aggregate insured losses immediately after the natural disaster. This estimate is then updated as new loss information becomes available.

and reference territory. The former refers to the type of hazard insured (e.g., windstorms or earthquakes), whereas the latter specifies the location where the hazard event must occur to be covered by the bond. Figure 6 shows the prevailing peril/territory combinations in terms of outstanding risk capital at the time of writing. The coverage of windstorm and earthquake risks in the U.S., Japan, and Europe is a reflection of the scale and significance of primary insurance markets worldwide. In recent years, however, the available range of peril/territory combinations has expanded through a growing number of cat bonds that cover natural catastrophe risks in emerging markets such as China (Panda Re 2015-1), Turkey (Bosphorus Re 2015-1), Chile (IBRD CAR 116), Colombia (IBRD CAR 117), Peru (IBRD CAR 120), Mexico (FONDEN 2020), and the Philippines (IBRD CAR 123-124).

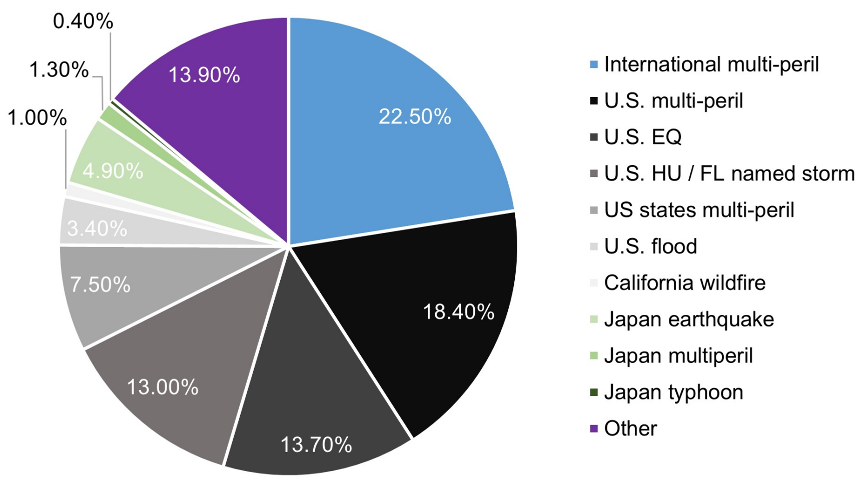

Figure 6: Cat Bond Capital Outstanding by Perils. Source: Artemis.bm (2023).

4 Market Characteristics

4.1 Evolution of the Cat Bond Market

Figure 7 shows both the new issuance volume and the outstanding risk capital in the cat bond market from 1997 to 2022. The first cat bond was issued by Hannover Re in 1994

(Cummins and Weiss, 2009). Since then, the market has consistently expanded. Issuance volumes grew from less than $1 billion in 1997 to more than $8 billion in 2007, followed by a sharp decline during the 2008 economic downturn. A correction of structural deficiencies[9] led to a rebound and prolonged upswing of the primary cat bond market, ending with a record issuance volume of $14 billion and a total outstanding capital of almost $36 billion in 2021. To put these numbers in perspective, we can draw on a comparison with Figure 2. In 2021, cat bonds accounted for 5 to 6% of the total global property reinsurance policy limits. Since cat bonds are mainly used as coverage against the most extreme insurance events, they represent even larger proportions of the total limits for high-layer property reinsurance.

A trend that has added to the strong development of the cat bond market is the advent of cat bond lite structures. The cat bond lite allows for a maximally smooth and low-cost issuance process (Artemis.bm, 2022b). In contrast to the regular 144A cat bond, it comes with a notably reduced documentation and does not provide a risk analysis by a catastrophe model vendor. It therefore primarily targets highly sophisticated ILS investors with own catastrophe risk modelling capabilities. Cat bond lite structures initially appeared in the early 2010s and surpassed $1 billion in issuance volume in 2020 for the first time (Artemis.bm, 2023). At first, the issuance size of individual cat bond lite transactions was very small, but meanwhile it amounts to between $30 million and $50 million on average, with some outliers reaching the $100 million mark.

Despite this remarkable evolution, there are no signs of slowing growth. In 2022, the cat bond market exhibited the largest overall size in history, with an outstanding volume of almost $38 billion, see Figure 7. Cat bonds have long become an important part of the strategic arsenal of risk-hedging tools regularly used by insurers and reinsurers. With

[9] Prior to late 2008, it was typical to use lower-grade collateral, such as structured finance securities, and safeguard it against interest rate risk and impairment using a total return swap (TRS). In exchange for fixed coupons and value gains from the assets in the trust account, the swap counterparty would offer a floating rate payment minus the TRS spread and cover any potential value losses (Towers Watson, 2010). However, the collapse of investment bank Lehman Brothers, which served as a swap counterparty in four transactions, exposed that the combination of TRS and insufficient collateral, in terms of both quality and maturity, carried a non-negligible degree of credit risk (Cummins and Weiss (2009); Braun (2016)

new perils and rapid technological innovation, the market's expansion can be expected to continue (Braun and Kousky, 2021).

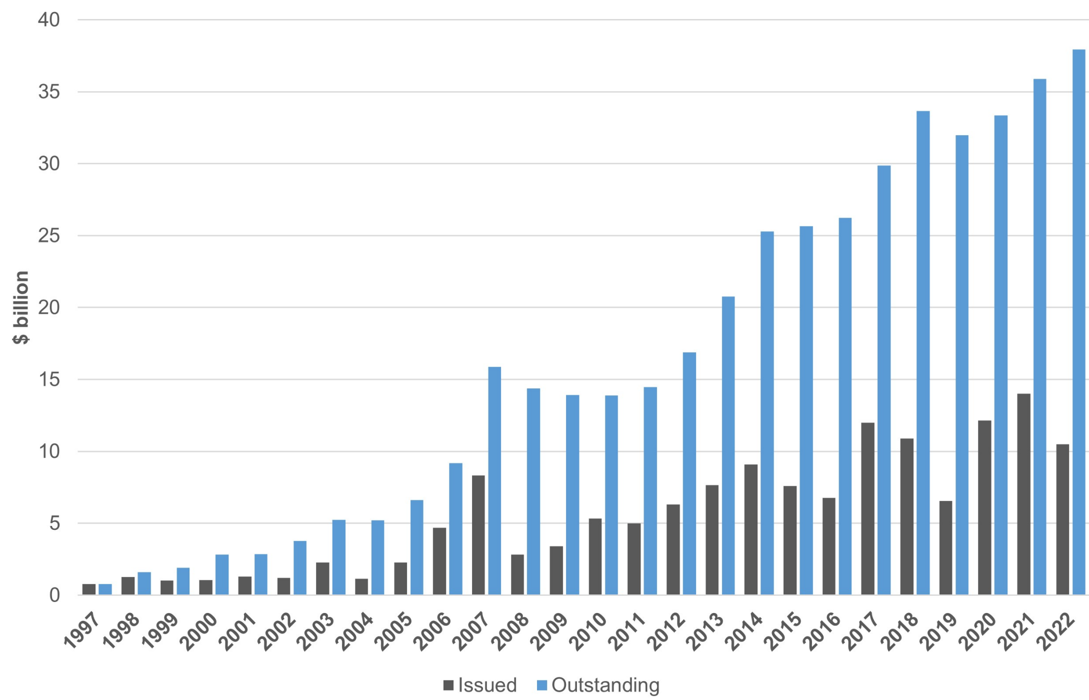

Figure 7: Cat Bond Issuance and Capital Outstanding. Source: Artemis.bm (2023).

4.2 Investor Base

Throughout the 2010s, investor demand for cat bonds as an alternative investment was particularly high, likely driven by the persistent low-interest rate environment. Direct investments in cat bonds demand considerable expertise and can thus be challenging for investors who are not familiar with extreme event risk. A cat bond portfolio may consistently grow in value over an extended period, displaying very low return volatility. Yet, in the event of a significant catastrophe loss year like 2017, the investment could suddenly face a substantial drawdown. Moreover, some cat bond structures can be quite complex, encompassing multiple perils, territories, and triggers.

Another option for an investor to access cat bonds is through open-end funds. While these funds are occasionally categorized alongside mutual funds or hedge funds within the fixed-income domain, the returns generated by funds that hold cat bonds exhibit a rather distinct pattern (Braun et al., 2019). This unique behaviour is characterised by low volatilities and low correlations to the broader capital markets. Most cat bond funds pursue buy and hold strategies. In some cases, however, sophisticated trading strategies such as live and dead cat trading are attempted (Jaeger et al., 2010). The former implies speculating on the pricing movement of a cat bond while a natural disaster is evolving (e.g., a hurricane before landfall). The latter implies buying a cat bond at a major discount during the reporting process for the underlying claims and speculating on a price recovery if insured claims fall short of the attachment point.

Figure 8 and Figure 9 illustrate the investor base of the cat bond market at the time of writing. Dedicated ILS fund managers currently absorb nearly three-quarters of the newly issued volume. These experts possess extensive experience in reinsurance risk, making them well-prepared to create and manage diversified cat bond portfolios for other institutional investors like pension funds.[10] The latter appreciate the low correlation of cat bond returns with the rest of their asset portfolios and their liquidity advantage compared to other alternative capital instruments. Apart from specialized ILS funds, the cat bond investor base comprises institutional investors (16%), reinsurers (10%), and multi-strategy funds (4%). In terms of geography, the U.S. (46%) and Switzerland (23%) are the leading risk capital providers, followed by Bermuda (9%), France (8%), and the UK (8%). The "Other" category comprises countries such as Canada, Japan, Germany, and Sweden.

[10] 14 cat bond funds are UCITS-compliant and thus open to retail investors (Plenum Investments, 2022).

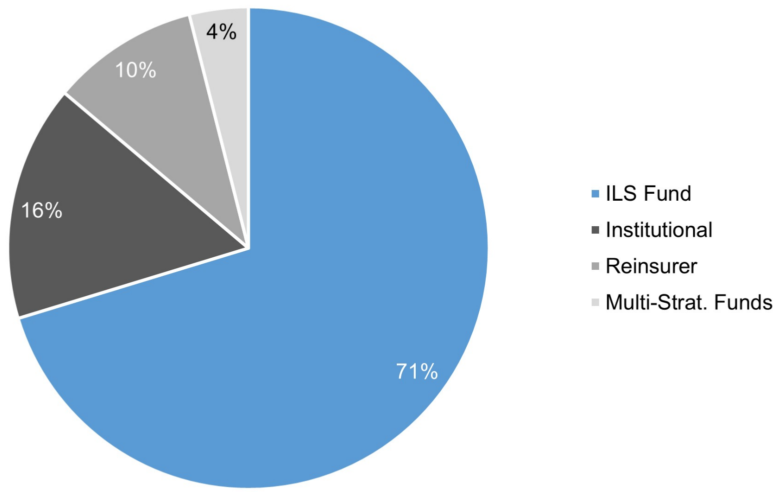

Figure 8: ILS Investor Base by Category (Source: AON, 2021a)

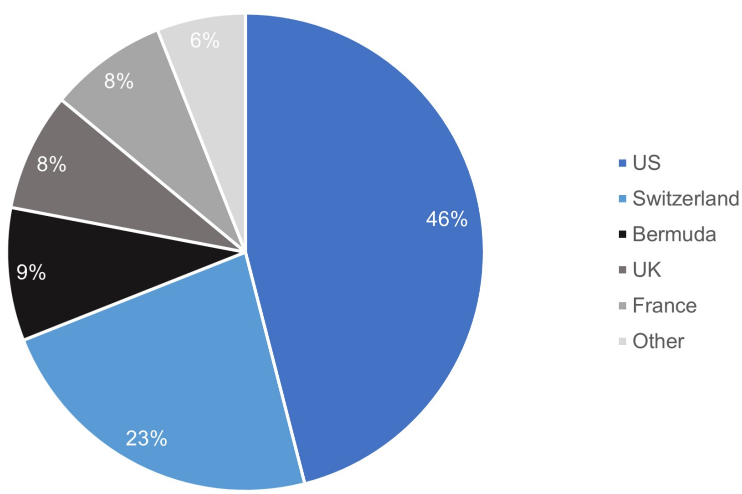

Figure 9: ILS Investor Base by Geography (Source: AON, 2021a)

4.3 Trading and Liquidity

A major advantage of cat bonds is the existence of an active secondary market. This means that investors can trade out of positions before maturity if necessary. The most impactful academic analysis of liquidity in the secondary cat bond market to date is Herrmann and Hibbeln (2023).[11] Figure 10, taken from their paper, shows the quarterly number of trades in the secondary market for cat bonds in the period from Q1/2015 to Q1/2019. Utilizing transaction data reported on TRACE (Trade Reporting and Compliance Engine), they observe that the seasonality of certain perils influences intrayear trading patterns. US wind cat bonds, for example, are less frequently traded during the hurricane season and are more commonly traded as they approach maturity. Moreover, according to Herrmann and Hibbeln (2023), the prevailing trading patterns suggest that the secondary market is primarily controlled by brokers who do not maintain a proprietary inventory. They also find that liquidity for individual bonds depends on the overall activity in the market and that cat bonds with a lower probability of first loss are more liquid than those with higher probabilities of first loss. Finally, using realized bid-ask spreads as a measure of liquidity, they estimate that 21% of the observable yield spread in the secondary market are a liquidity premium.

Building on Herrmann and Hibbeln (2023), Braun et al. (2022) investigate whether liquidity is a significant driver of realized returns of cat bonds. Their analysis also relies on TRACE data (from July 2014 to December 2020) and bid-ask spreads as a measure for liquidity. Sorting the whole cross section of cat bonds in a given month into quintile portfolios according to their liquidity and taking the difference between the return series of the least and the most liquid portfolio, Braun et al. (2022) create a liquidity factor. In doing so, they find that wider bid-ask spreads, which indicate less liquidity, are associated with higher expected excess returns. Their model, including the liquidity factor, can be applied to measure the liquidity premium in cat bond returns.

[11] While Zhao and Yu (2019) also measure the liquidity of cat bonds, they use liquidity proxies from the primary market and assess their impact on yield spreads.

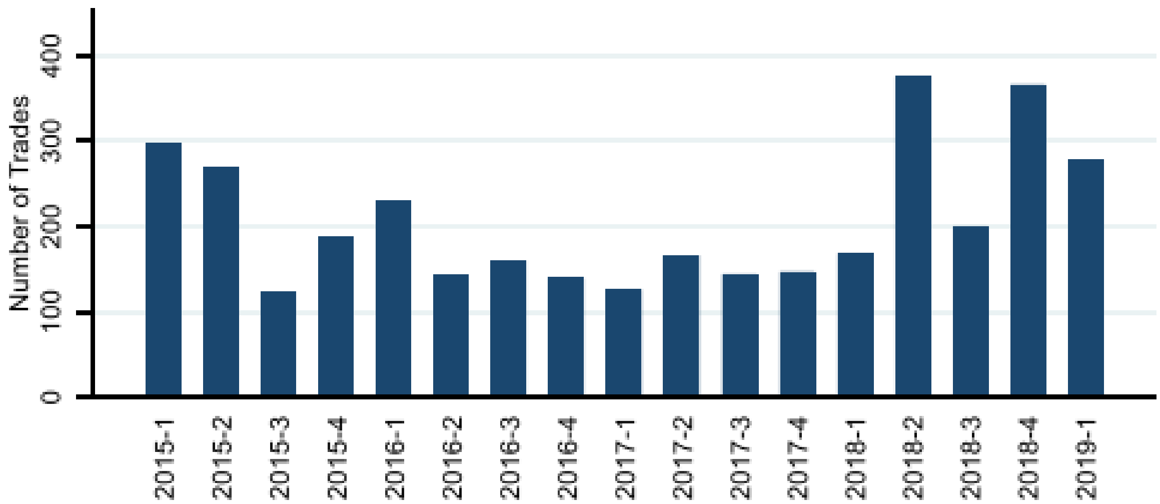

Figure 10: Number of Cat Bond Trades per Quarter (Q1/2015–Q1/2019)
(Source: Herrmann and Hibbeln, 2023)

4.4 Risk-Return and Correlation Profile

Owing to the existence of the secondary market for cat bonds, monthly return data is available and can be used for an empirical assessment of the asset class' risk-return profile.[12] Figure 11 shows the historical performance of cat bonds compared to the S&P 500 stock market index, the Barclays U.S. Treasury Index, and the Barclays U.S High Yield Corporate Bond Index. During the period under consideration, cat bonds delivered equity-like annual returns of between 6.8% p.a., paired with a low volatility (3.7%) and a negligible correlation of less than 0.2 to other asset classes.

Historical cat bond return time series have been analyzed by several empirical studies. Cummins and Weiss (2009) draw on the Swiss Re Cat Bond Index suite as well as the return time series of a small set of dedicated ILS funds to assess the risk-return profile of cat bonds. A similar effort is made by Kish (2016), using the Eurekahedge ILS Advisors Index.[13] Moreover, Mariani and Amoruso (2016) and Trottier et al. (2019) also use Swiss

[12]Since historical return data was not available in the early years of the market, first studies of the risk-return profile, such as Litzenberger et al. (1996), relied on hypothetical returns.

[13]The Eurekahedge ILS Advisors Index is an equally-weighted portfolio of 27 ILS funds that have at least 70% of their assets under management allocated to non-life insurance risks. For more information see the Eurekahedge website.

Re data. The latter go beyond a pure descriptive analysis and develop a regime-switching model for the returns of cat bonds. In addition to the risk-return profile, a number of studies has considered the correlation of cat bond returns with the broader capital markets (see Carayannopoulos and Perez, 2015; Sterge and van der Stichele, 2016; Mouelhi, 2021; Haffar and Le Fur, 2022) and the diversification effects of cat bonds in multi asset class portfolios (see Clark et al., 2016; Drobetz et al., 2020).

However, knowledge about the drivers of expected excess returns on cat bonds is still scarce. So far, the only empirical studies in this area are Braun et al. (2019) and Braun et al. (2022). The former develop novel factor models in the spirit of arbitrage pricing theory to explain the expected excess return of ILS funds based on the cat bond market and various additional factors. In doing so, they are able to show that most ILS funds do not generate alpha, but earn excess returns associated with hitherto unknown ILS-specific risk factors. Braun et al. (2022) analyze the drivers of realized returns on the bond level, using univariate sorting and multivariate Fama-MacBeth regressions. They then develop a factor model for the expected excess returns of cat bonds that includes a factor, reflecting a cat bond's time-varying probability of first loss as in Herrmann and Hibbeln (2021), and a liquidity factor based on Herrmann and Hibbeln (2023) (see description in Section 4.3). Finally, both Braun et al. (2019) and Braun et al. (2022) document a (weak) link between the cat bond market and the corporate bond market, which is attributed to the fact that the vast majority of rated cat bonds falls into the high yield category.

5 Pricing

5.1 Preliminaries

As catastrophe bonds connect insurance and capital markets, they can be priced by means of i) actuarial methods, ii) contingent claims approaches, iii) utility-based approaches, and iv) statistical approaches. All methods have one thing in common, they derive the spread (or price) of a cat bond based on an estimate of the underlying distribu-

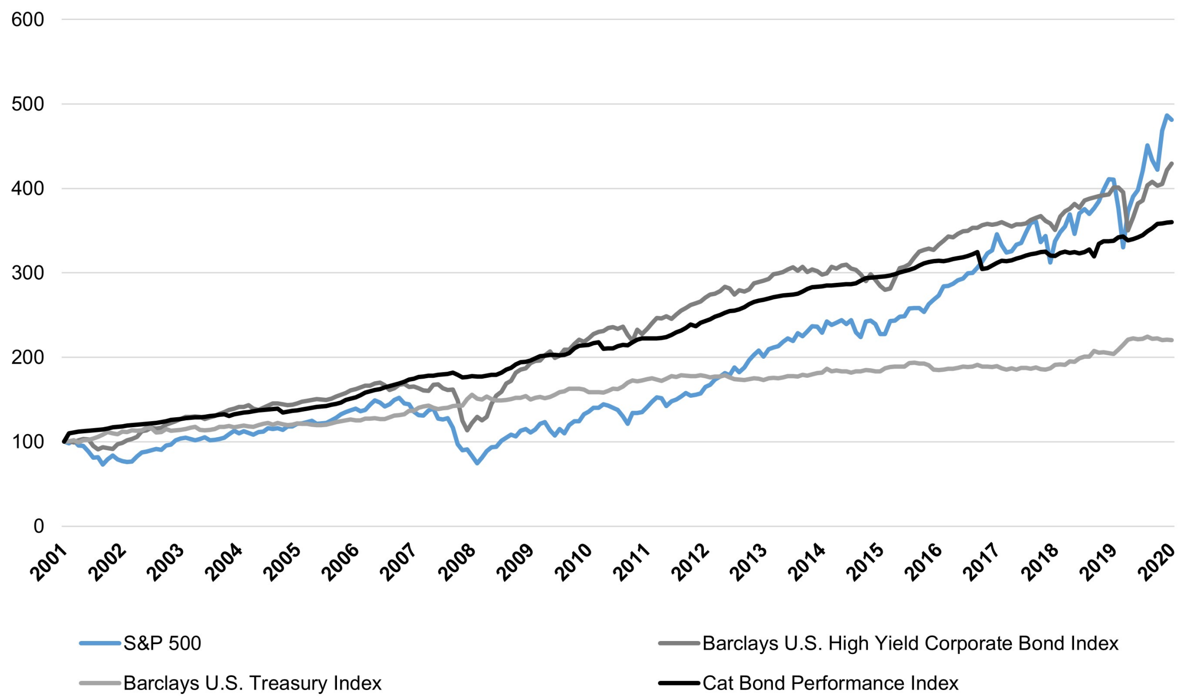

Figure 11: Historical Cat Bond Performance. Sources: Bloomberg and Braun et al. (2022).

tion of insured losses.[14]

Below, we illustrate how this underlying distribution of insurance losses relates to key metrics relevant for cat bond pricing. Let $\tilde{C}$ denote the stochastic claims in an insurance portfolio covered by the cat bond. The cat bond layer is defined by the attachment point A and the exhaustion point E. Based on these three variables, the stochastic percentage loss $\tilde{L}$ to investors on a cat bond with proportional payoff is defined as follows:[15]

$$\tilde{L}(\tilde{C}) = \begin{cases} 0, & \text{for } \tilde{C} \leq A \\ \frac{\tilde{C}-A}{E-A}, & \text{for } A < \tilde{C} \leq E \\ 1, & \text{for } E < \tilde{C}. \end{cases} \tag{1}$$

Intuitively, if the underlying insured claims $\tilde{C}$ remain below A, there is no trigger event on the cat bond. If the claims $\tilde{C}$ materialise between A and E, investors suffer a

[14]In case of a parametric trigger, the distribution of physical parameter values is used instead.

[15]If the cat bond exhibits a binary payoff, then this expression simplifies to two cases: i) 0 for $\tilde{C} < A$ and ii) a lump sum N for $A \leq \tilde{C}$. We use N for the lump sum, as the binary payoff is usually the full bond notional.

percentage write-down proportional to the amount by which A is exceeded. Finally, if the claims exceed E, the cat bond is a total loss to investors.

Given the payoff function of the cat bond in (1) and the probability density function (pdf) of the underlying insurance claims, $f_{\tilde{C}}(x)$, one can derive the standard cat bond risk metrics.[16] The probability of first loss (PFL) and the probability of exhaustion (POE) are formally defined as follows:

$$PFL = \Pr(A < \tilde{C}) = \int_A^\infty f_{\tilde{C}}(x)dx \qquad POE = \Pr(E < \tilde{C}) = \int_E^\infty f_{\tilde{C}}(x)dx. \tag{2}$$

Moreover, the conditional expected loss (CEL) is:[17]

$$\begin{aligned} CEL &= \mathbb{E}(\tilde{L}(\tilde{C}) \mid A < \tilde{C}) = \tfrac{\Pr(A<\tilde{C}\leq E)}{\Pr(A<\tilde{C})}\, \mathbb{E}(\tilde{L}(\tilde{C}) \mid A < \tilde{C} \leq E) + \tfrac{\Pr(E<\tilde{C})}{\Pr(A<\tilde{C})} \\ &= \textstyle\int_A^\infty f_{\tilde{C}}(x)\, \tilde{L}(x)\, dx, \end{aligned} \tag{3}$$

and the expected loss, $EL = PFL \cdot CEL$, equals:[18]

$$\begin{aligned} EL &= \mathbb{E}(\tilde{L}(\tilde{C})) = \Pr(A < \tilde{C})\, \mathbb{E}(\tilde{L}(\tilde{C}) \mid A < \tilde{C}) \\ &= \textstyle\int_0^\infty f_{\tilde{C}}(x)\, \tilde{L}(x)\, dx. \end{aligned} \tag{4}$$

Instead of the pdf, industry practitioners often use the exceedance probability curve $EP(x)$. The two concepts are linked through the cumulative distribution function (cdf) of the underlying insured claims, $F_{\tilde{C}}(x)$, as follows: $EP(x) = \Pr(x < \tilde{C}) = 1 - F_{\tilde{C}}(x)$,[19] with

$$F_{\tilde{C}}(x) = \Pr(\tilde{C} \leq x) = \int_0^x f_{\tilde{C}}(u)\, du. \tag{5}$$

[16] Due to the scarcity of historical data, $f_{\tilde{C}}(x)$ cannot be estimated empirically. Instead, it is the output of a catastrophe risk model. We will discuss the role of these model in the next section.

[17] The expression in the first line is already simplified, using the fact that $\mathbb{E}(\tilde{L}(\tilde{C}) \mid E \leq \tilde{C})$ is 1.

[18] Note from Equation (1) that $\Pr(\tilde{C} \leq A) \cdot \mathbb{E}(\tilde{L}(\tilde{C}) \mid \tilde{C} \leq A)$ is zero.

[19] It is straightforward to see that $EP(A) = PFL$ and $EP(E) = POE$.

5.2 Catastrophe Risk Models

Historical data on the most extreme natural disasters is too limited to estimate the extreme tail of the loss distribution (Poliquin and Lalonde, 2012). Hence, risk assessment for cat bonds critically depends on catastrophe risk models, maintained by specialized firms, such as AIR, RMS, and CoreLogic. These model vendors use the latest scientific insights to create a bottom-up estimate of the insured loss distribution $f_{\tilde{C}}(x)$. A typical catastrophe risk model comprises three modules: i) the hazard module, ii) the vulnerability module, and iii) the financial module (NAIC, 2023).

The hazard module generates stochastic event sets of hypothetical disaster scenarios, characterized by key physical parameters, such as wind speeds or earthquake magnitudes. Within the vulnerability module, these scenarios are then overlaid on extensive databases containing all properties exposed to the respective catastrophe risk. Along with information about each structure's vulnerability, determined by factors like construction materials, age, and size, it becomes possible to estimate the physical damage sustained by buildings and household possessions in every scenario. Finally, the financial module converts the physical damage into financial losses based on property values and active insurance policy terms, and aggregates them at the portfolio level.

In combination with the layer (attachment point A and exhaustion point E) and payoff profile (proportional vs. binary) of a risk transfer instrument, the resulting distribution of insured losses allows for a derivation of PFL, POE, CEL and EL as described in Section 5.1. EL in particular has become a central factor in the pricing of cat bonds (Braun, 2016). We will discuss this in further detail below.

A major question with regard to catastrophe risk models is their accuracy in estimating the risk metrics that serve as a basis for cat bond pricing. Lane (2022) provides a first empirical analysis in this regard, albeit on a relatively short time series of twenty years of data. He documents that actual losses on ILS were close to model-expected losses, if one adjusts for the fact that ILS cover the highest layers of the loss tower. This indicates that the major catastrophe models accurately represent the risks inherent in cat bonds.

5.3 Actuarial Pricing

Actuarial premium principles are the standard pricing method in insurance. They are used to derive the premium of a contract based on the expected loss plus a risk loading factor. There is a broad variety of premium principles. An overview can be found in Young (2014). For illustrative purposes, we briefly revisit the variance principle, which, in a cat bond context, formally looks as follows:

$$s_{cat} = \mathbb{E}(\tilde{L}) + \gamma \mathrm{Var}(\tilde{L}), \tag{6}$$

where s_{cat} is the spread on the cat bond, $\mathrm{Var}(\tilde{L})$ is the variance of the losses on the cat bond, and γ is a parameter that reflects the risk aversion of the investor.

Actuarial pricing approaches for cat bonds have been particularly suggested in the earlier years of the market (see, e.g., Major and Kreps, 2002; Lane, 2004). More recently, Stupfler and Yang (2018) suggest a new financial loss premium principle for cat bonds, which links risk aversion to current developments in the financial market.

5.4 Contingent Claims Pricing

Contingent claims pricing models for cat bonds are rooted in option pricing theory as constituted by Black and Scholes (1973) and Merton (1974). They rely on stochastic processes that describe the occurrence of insurance claims from natural disasters in a probability space $(\Omega, \mathcal{F}, \mathbb{Q})$. This implies a change of measure, from the real-world or physical pricing measure $\mathbb{P}$ to a risk-neutral (or equivalent martingale) measure $\mathbb{Q}$. The cat bond price then equals the expected discounted future cash flows (coupon and principal payments), where the expectation $\mathbb{E}^{\mathbb{Q}}$ is computed under the risk-neutral measure $\mathbb{Q}$ and discounting relies on the risk-free interest rate. For an equivalent martingale measure $\mathbb{Q}$ to exist, markets need to be arbitrage-free. For it to be unique, markets need to be complete, meaning that the payoff of any contingent claim can be replicated using traded securities (Cochrane, 2009). Particularly the second condition causes problems in the context of cat bonds. The market for catastrophe risk instruments is generally incomplete, because their underlying are non-traded insurance losses, physical parameters or industry indices (Cox and Pedersen, 2000).

The contingent claims cat bond pricing literature has circumvented this problem in a variety of ways. Some authors simply derive a closed-form solution of their model under $\mathbb{Q}$ and assume the parameters to be identical as under $\mathbb{P}$ or do not further discuss the change of measure (see, e.g., Baryshnikov et al., 2001, Burnecki and Kukla, 2003, Pérez-Fructuoso, 2008, Wu and Chung, 2010, Jarrow, 2010, Burnecki et al., 2011, and Hainaut, 2012). Others suggest that cat bond payoffs can be spanned with existing catastrophe risk instruments such as reinsurance or ILWs (see, e.g., Balbás et al., 1999, and Gatzert et al., 2019). Yet others tackle the non-uniqueness of the state price system by selecting a particular measure through a distortion operator or transform (see, e.g., Wang, 2000, Wang, 2004, Godin et al., 2019, and Tang and Yuan, 2019).

Most studies, however, follow Merton (1976), who argued that jump risk is unsystematic and therefore fully diversifiable (see, e.g., Lee and Yu, 2002, Vaugirard, 2003a,b, 2004, Lee and Yu, 2007, Ma and Ma, 2013, Shao et al., 2017, and Chang et al., 2022). This is supported by the fact that cat bonds have repeatedly been classified as zero-beta assets (Litzenberger et al., 1996; Canter et al., 1997) and empirical work found only minimal correlations of cat bond returns with other asset classes (see Section 4.4). However, according to capital market theory, zero-beta assets should return no more than the risk-free rate, a prediction that is irreconcilable with the large realised excess returns of cat bonds over the last two decades (Braun et al., 2019, 2022).[20]

Against the background of the arbitrariness and the disadvantages associated with some of the above solutions to the problem of incomplete catastrophe risk markets, a promising direction is to follow Breeden and Litzenberger (1978) and isolate the pricing kernel used by the market. In this vein, some authors derive risk-neutral probabilities

[20] Whether or not these high excess returns are risk premiums remains an unresolved cat bond pricing puzzle. They may, in fact, represent frictions, unless the natural catastrophe risks are large enough to directly affect marginal consumption of the representative investor (Bauer et al., 2013).

from the prices of reinsurance contracts (see Geman, 1999; Muermann, 2008; Härdle and López Cabrera, 2010). Once the market for cat bonds became more mature and liquid, however, the logic turned around. Haslip and Kaishev (2010) develop a framework that relies on the observed prices of cat bonds to price reinsurance in a market consistent way.[21] Beer and Braun (2022) follow a similar logic. They utilize a closed form solution of the reduced form model by Jarrow (2010) under the forward pricing measure to extract implied Poisson intensities under $\mathbb{Q}$ from secondary market cat bond quotes. They then estimate implied parameter surfaces for peak perils along the time to maturity and the modeled PFL. These surfaces enable a market-consistent valuation of instruments on the same underlying catastrophe risk, for which no prices are observed.

5.5 Utility-Based Pricing

In an incomplete market framework, where perfect replication is not possible, one pricing method is based on individual preferences. The highest price an agent is willing to pay for a given risky asset is the one that makes them indifferent between entering into the transaction and not buying the asset, from their individual risk preferences' point of view (see, e.g., Hodges and Neuberger, 1989). It is therefore referred to as indifference buyer's price. To illustrate this approach in a simple setting, let's consider an uncertain universe characterised by a probability space $(\Omega, \mathcal{F}, \mathbb{P})$ and an agent, with a utility function u_B describing their preferences. This agent, with a random wealth W_0^B has an opportunity to buy a given risky asset with random payout F. In a simple static framework, ignoring the impact of interest rates for the sake of simplicity and setting them equal to 0 without any loss of generality, the buyer's indifference price P^B for the asset F is determined by the following equation:

$$\mathbb{E}^{\mathbb{P}}\left[(u_B(W_0^B + F - P^B)\right] = \mathbb{E}^{\mathbb{P}}\left[u_B(W_0^B)\right]. \tag{7}$$

[21] At the time of writing of their paper, the secondary market for cat bonds was still much less developed than today. However, they correctly anticipated that the liquidity and the variety of regions and perils would further develop.

Intuitively, the agent's expected utility after buying the asset must equal his initial expected utility (without the asset). An important point to note is that the indifference buyer's price is not necessarily the price at which the transaction will take place, but an upper bound to the price the agent is ready to pay to buy the asset. Similarly, the indifference price of the seller is determined by his utility function u_S and initial wealth W_0^S:

$$\mathbb{E}^{\mathbb{P}}\left[u_S(W_0^S - F + P^S)\right] = \mathbb{E}^{\mathbb{P}}\left[u_S(W_0^S)\right]. \tag{8}$$

The indifference pricing rules in (7) and (8) are typically non-linear and depend on the existing portfolio of buyer and seller.[22] Note that a transaction can only take place when $P^B \geq P^S$. The interval $[P^S; P^B]$ provide an acceptable price range for the transaction price rather than a single transaction price, leaving room for negotiation. The indifference pricing approach can used in a dynamic setting, incorporating hedging strategies etc., as it is extremely flexible. Obtaining closed form formulae for the indifference prices can be challenging depending on the class of utility functions, or risk measures used to characterise the preferences of the individuals.

The cat bond pricing literature is rich in works which acknowledge that the market is inherently incomplete and resort to utility-based pricing. Key articles in this strand include Cox and Pedersen (2000), Young (2004), Barrieu and El Karoui (2005), Zimbidis et al. (2007), Egami and Young (2008), Zhu (2011), Zheng (2015), Zhu (2017) Trottier et al. (2018), and Dieckmann (2019).

[22]The dependency of the price on the original portfolio is a valuable feature for the application to cat bonds, because it offers a theoretical explanation for spread discount on nonpeak observed in empirical work (see, e.g., Braun, 2016). Specifically, cat bond investors are prepared to accept a lower spread on an otherwise identical cat bond if it covers a non-US peril and thus offers diversification benefits in an ILS-only portfolio (further details follow in the next section).

5.6 Statistical approaches

We distinguish between two types of statistical approaches used in the catastrophe bond literature for pricing purposes. The first one is based on econometrics and the second one on machine learning. Details on how both methodologies are applied in the cat bond pricing context follow.

Econometric Pricing Econometric pricing can be viewed as an extension of actuarial pricing, which seeks to explain the markup above the expected loss by means of characteristics of the transaction and the prevailing market environment. Due to the availability of primary market data through Lane Financial LLC and the Artemis.bm Deal Directory, most published studies focus on the explanation of the cat bond spread at issuance (see, e.g., Lei et al., 2008; Bodoff and Gan, 2009; Papachristou, 2011; Galeotti et al., 2013; Ciumaş and Coca, 2015; Braun, 2016; Mariani et al., 2018). As a typical representative of the class of econometric cat bond pricing models, we briefly revisit the approach by Braun (2016), which has become a benchmark and basis for subsequent work in this area (see, e.g., Makariou et al., 2021; Carayannopoulos et al., 2022).

Using a battery of cross-sectional OLS regressions on all cat bond tranches issued between 1997 and 2012, Braun (2016) shows that the following specification outperforms earlier econometric models in terms of in-sample and out-of-sample pricing accuracy:

$$s_{cat,i} = \beta_{EL} EL_i + \beta_{PEAK} PEAK_i + \beta_{SR} SR_i + \beta_{ROLX} ROLX_i + \beta_{IG} IG_i + \beta_{BBSPR} BBSPR_i + \epsilon. \quad (9)$$

This regression model[23] with error term ϵ predicts the spread $s_{cat,i}$ of cat bond i based on its expected loss EL_i, the current state of pricing in the reinsurance market as reflected by a rate on line index $ROLX_i$, and the spread on comparably-rated corporate bonds $BBSPR_i$. Both $ROLX_i$ and $BBSPR_i$ are measured at the time issuance of cat bond i. Furthermore, the model contains three dummy variables, reflecting the identity of the

[23]Note that the model does not contain an intercept. Braun (2016) argues that the spread should be zero if all of the factors are zero.

sponsor (SR_i), investment grade versus high yield ratings (IG_i), and the distinction between peak and off-peak territories ($PEAK_i$). The dummy SR_i reveals the spread discount achieved by well-respected sponsors that serve the market repeatedly.[24] Moreover, the dummy $PEAK_i$ captures a markup in the spreads for cat bonds involving U.S. disaster risk (peak perils) relative to those covering risks from other parts of the world. The reason is the extremely U.S.-centred distribution of perils in the cat bond market, see Figure 6, which makes nonpeak perils a sought-after diversifier for ILS-only investors.

In contrast to the analyses of cat bond issuance prices, econometric studies of yield spreads are rather limited. This is due to the challenges involved in securing secondary market data. Lane and Mahul (2008) were among the first to run a regression analysis on secondary market yield spreads. All subsequent insights are concentrated among the three major studies Gürtler et al. (2016), Herrmann and Hibbeln (2021), and Herrmann and Hibbeln (2023). The latter two are particularly innovative in that they are the first to provide empirical evidence of seasonality and liquidity effects in cat bond yields.

Machine learning Most recently a new area emerged in the cat bond pricing literature emerged, which employs machine learning models for spread prediction both in the primary market and in the secondary market. Makariou et al. (2021) introduce the random forest method to generate accurate spread predictions for new cat bond issues on both temporal and non-temporal bases and compared their results to highly competitive benchmark models. In absence of causal theory, they assess how spread predictors rank in terms of importance using two different methods, namely, permutation importance and minimal depth (see Ishwaran et al., 2010). The latter is random forest specific and has been applied by Makariou et al. (2021) in a financial context for the first time. The authors find their random forest prediction accuracy to be stable subject to multiple iterations of random subsampling and relatively robust to simultaneous missingness of more

[24]The sponsor variable first appeared in Braun (2016). Subsequent studies have either included it as a pricing factor (see, e.g., Chang et al., 2020b) or investigated the sponsor effect in more detail (see Götze and Gürtler, 2020a; Chatoro et al., 2023).

than one predictor. They also show how random forest can speed up decisions in the catastrophe bond industry both for would-be issuers and investors.

Götze et al. (2020) compare different machine learning methods for cat bond pricing at issuance, providing evidence that the random forest approach outperforms neural networks and linear regression, which they combine with variable selection via Lasso and Ridge penalizations. Götze et al. (2023) extend their earlier work using secondary market data. Given the current fast-paced developments in machine learning further research in this area will likely appear.

5.7 Historical Price Trends

Figure 12 shows the evolution of average issuance spreads and expected losses in the cat bond market between 1997 and 2022. The graph also includes the corresponding multiple, defined as spread divided by expected loss. The numbers underline that cat bonds are used to cover rare events with expected losses from one to three percent. Turning to the coupon spreads, two spikes stand out. One in 2006, following the extreme 2005 hurricane season with Katrina, Rita and Wilma, and another one in 2009, right in the middle of the financial crisis. This indicates a link of cat bond spreads to reinsurance premiums and corporate bond spreads, which has been empirically documented based on primary and secondary market data (see Braun, 2016; Gürtler et al., 2016). This illustrates why the reinsurance underwriting cycle with its hard and soft market periods has become a key factor in econometric cat bond pricing models (see Section 5.6).

The high multiples around the turn of the millennium may have been attributable to a novelty premium or behavioural aspects (Bantwal and Kunreuther, 2000).[25] Subsequently, multiples have declined for almost two decades, potentially reflecting a learning process among investors associated with the maturation of the market (Braun and We-

[25] Froot (2001) provides eight theoretical arguments for high multiples in catastrophe risk markets and deems capital market imperfections to be the most convincing one. Froot and Posner (2002) conclude that parameter uncertainty is unlikely to be the reason for the high multiples in the cat bond market.

ber, 2017).[26] Following an extended period of benign natural disaster losses, multiples reached their lows around 2017. In the subsequent years, they began to rise again, driven by a high catastrophe activity and severe wildfire, hurricane and severe weather losses (AON, 2021b). For the better part of the last two decades, cat bond multiples hovered in the range of three to five, which is in line with reports about reinsurance pricing for higher layers of coverage (see, e.g., Froot and O'Connell, 2008).

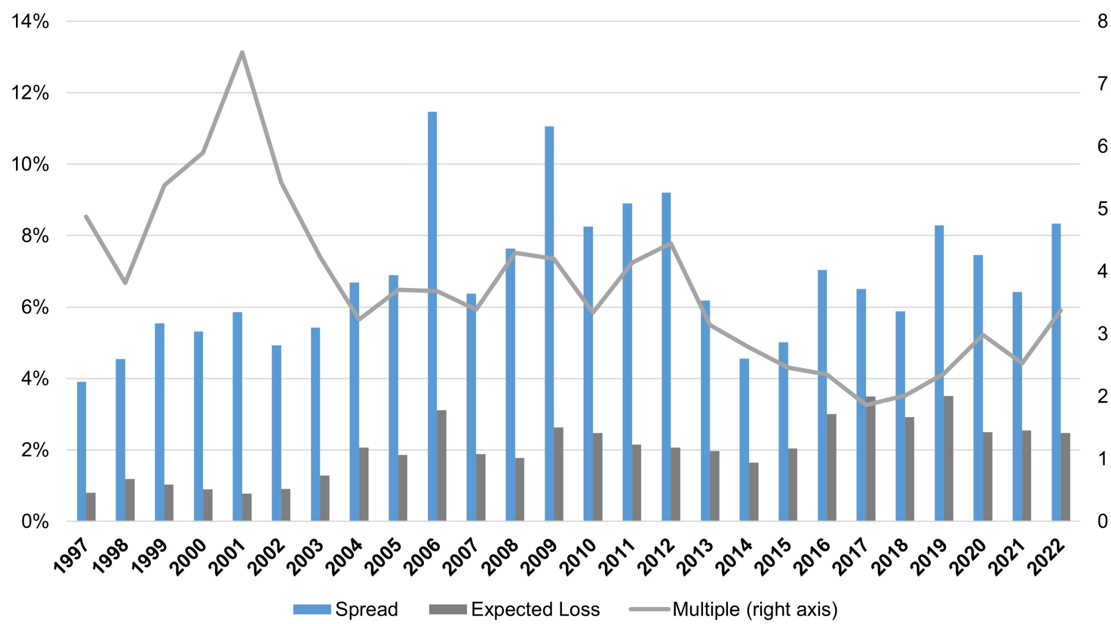

Figure 12: Evolution of Pricing in the Cat Bond Market. Source: Artemis.bm (2023).

6 Concluding Remarks and Outlook

Today, cat bonds are an established instrument in the risk management toolkit of insurance and reinsurance companies where they coexist with traditional reinsurance contracts.[27] A key question going forward is, in which directions the market for cat bonds

[26]Empirical evidence for this logical argument is scarce. Some results are provided by Braun et al. (2013), who, based on a survey of European insurance firms, document that experience and expertise is a driver of investor demand for cat bonds.

[27]Determinants of the mix between traditional reinsurance and cat bonds brought forward by the theoretical literature are regulation, basis risk, information asymmetries, the covered risk layer, and the default risk of reinsurers (Nell and Richter, 2000, 2004; Mutenga and Staikouras, 2007; Cummins and Trainar, 2009; Finken and Laux, 2009; Klein and Wang, 2009; Lakdawalla and Zanjani, 2012; Gibson et al., 2014; Braun and Weber, 2017; Trottier and Lai, 2017; Subramanian and Wang, 2018; Faias and Guedes, 2020;

and ILS in general will continue to evolve. Three focus areas in this regard are: i) new perils such as pandemic risk and cyber risk, ii) sovereign risk transfer, and iii) sustainability and climate change.

According to Swiss Re, pandemic risk could be an important driver of further ILS market growth (Artemis.bm, 2021). The World Bank took an initial step in this regard by issuing the first pandemic bond for developing countries in 2017, which covered various infectious diseases (World Bank, 2017). Whilst some aspects of this transaction, especially the long time until the trigger treshold was reached, have been criticized (see, e.g., Zheng and Mamon, 2023; Erikson and Johnson, 2020), it ultimately paid out approximately $195 million after the onset of COVID-19 (World Bank, 2020).

Another ILS market prospect is cyber risk. The recent growth in the cyber insurance market creates an urgent need for the transfer of tail risks. The academic literature has begun to cover the topic of cyber risk securitization (see, e.g., Xu and Zhang, 2021; Liu et al., 2022; Braun et al., 2023). Braun et al., 2023, in particular, assess the viability of transferring cyber risk via ILS. Their findings suggest that cyber ILS can be beneficial for both cedents and investors, provided the cyber risk is adequately comprehended. Therefore, hurdles associated with cyber risk modeling must be addressed before a substantial cyber ILS market can develop. In practice, the speciality insurer Beazley sponsored the first cyber cat bond in January 2023. This bond will pay out if aggregate claims from a cyber attack on its customers exceed $300 million (Beazley, 2023).

Promising perspectives for cat bonds also persist in the area of sovereign risk transfer. Particularly emerging market governments can increase the resilience of their public finances against natural catastrophes. To date, only a small proportion of cat bonds have been sponsored by governments, but more and more countries come forward to use this form of ex-ante risk financing (Maran, 2023). One example is Mexico, which to date, has recovered about $200 million of disaster losses from cat bonds of its sovereign risk pool FONDEN (Guy Carpenter, 2023). Another example are the Philippines which have

Chang et al., 2020a). Götze and Gürtler (2022) provide empirical evidence on the relationship between cat bonds and traditional reinsurance.

sponsored the first sovereign cat bond in Southeast Asia, comprising coverage against earthquake and tropical cyclone risk (World Bank, 2019). Due to the forceful effects of climate change, know-how from the cat bond market is already diffusing into the general sovereign bond markets. Specifically, the government of Barbados has issued government bonds with parametric natural catastrophe clauses (Artemis.bm, 2022a).

Finally, climate change and sustainability considerations impact the cat bond market in at least three ways. First, cat bonds are an important solution when it comes to the reduction of global disaster risk protection gaps, particularly in emerging markets (see previous paragraph). They are thus an inherently sustainable asset class. Second, global warming impacts the atmospheric perils (hurricanes, floods, wilfires etc.) that are being securitized in many cat bonds. It will therefore have a profound impact on the viability and pricing of the respective transactions (Michel-Kerjan and Morlaye, 2008; Morana and Sbrana, 2019). Third, cat bonds can support the transition to a low-carbon economy by investing exclusively in green collateral. The Italian insurer Generali has recently created the first ever green cat bond called Lion Re III. According to a 2021 press release The latter comprises EUR 200 million worth of reinsurance coverage against European windstorms and Italian earthquakes over four years. The collateral of Lion Re III has been invested into green bonds of the European Bank for Reconstruction and Development (EBRD).

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