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The Impact of the Financial Crisis and Natural Catastrophes on CAT Bonds

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Abstract

This article employs secondary market data to examine how natural catastrophes or financial crises affect CAT bond premiums. We find evidence that both the financial crisis and Hurricane Katrina significantly affected CAT bond premiums. The premium increase resulting from natural catastrophes can primarily be attributed to an increased coefficient of expected loss calculated by catastrophe modeling companies. Furthermore, our results indicate a positive relationship between corporate spreads and CAT bond premiums. Thus, CAT bonds should not be regarded as "zero-beta" securities. Moreover, our results indicate that deal complexity, ratings, and the reinsurance cycle are significant drivers of CAT bond premiums.

Introduction

In recent decades, severe natural catastrophes have led to a substantial increase in insured losses. This increase has caused the problem of insufficient traditional reinsurance due to a shortage of capacity. Several alternative instruments have been developed to remedy the capacity shortage in reinsurance markets (Cummins and Weiss, 2009), with CAT bonds being of particular importance. These bonds transfer the risk of catastrophe for a defined event, such as a certain natural catastrophe in a certain region, from a sponsor to investors. The sponsor pays a premium for this protection, while investors in CAT bonds receive coupons and the principal payment if no event falling under the trigger mechanism leads to the default of the bond.[1] In 2011, the total risk capital of CAT bonds was USD11.89 billion (Carpenter, 2012), and the CAT bond

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[1]For example, the structure of CAT bonds is described in detail in Cummins and Weiss (2009).

market is expected to continue to grow in the future (Cummins and Weiss, 2009). However, Barrieu and Loubergé (2009) find that the growth in CAT bond volume is limited by investors' aversion to downside risk and ambiguity resulting from the link between the financial markets and the CAT bond market. This link between the financial markets and the CAT bond market is often discussed in the literature. While the sponsor's motivation to issue a CAT bond is to obtain catastrophic risk insurance, it is often stated that it is advantageous for investors to buy CAT bonds due to the diversification effects that they provide. These effects result from low correlations to other securities that are traded on capital markets. However, the events of Hurricane Katrina and the recent financial crisis call this assumption into question.

It is widely accepted in the literature that if a huge natural catastrophe occurs, both the CAT bond market and the capital markets are affected and the correlation between these two markets increases (Cummins and Weiss, 2009). However, it is not clear how the CAT bond market reacts to huge natural catastrophes. For example, CAT bond premiums for all types of perils could increase due to a general increase in the risk aversion of market participants. There might also be an increase in premiums for bonds that insure against perils of the same type as the catastrophe that occurred because investors adjust their expectations for that type of peril. The relationship between financial crises and the CAT bond market is also unclear. The CAT bond market might remain independent of developments in the capital market even in the event of a financial crisis because the probability of a natural catastrophe is independent of economic developments. Alternatively, a financial crisis could affect not only the capital markets but also the CAT bond market, for example, due to a general increase in the risk aversion of market participants. Against this background, this article analyzes how natural catastrophes and financial crises influence CAT bond premiums.

We analyze this question using a broad data set of secondary market CAT bond premiums from 2002 to 2012. This is virtually the entire data set available for secondary market CAT bond premiums. We find a dependence between the CAT bond market and capital markets measured by means of the credit spreads of corporate bonds. This dependence increased significantly over the course of the recent financial crisis. Thus, we can conclude that the financial crisis has an important influence on CAT bond premiums. Moreover, we find that after the natural mega-catastrophe Hurricane Katrina, the premiums for hurricane perils increased significantly. This increase can mainly be attributed to a higher multiple of the expected loss calculated by catastrophe modeling companies. This finding suggests that market participants reacted to Hurricane Katrina with mistrust in the expected losses calculated for hurricanes.

In addition to the question of how CAT bond premiums react to natural catastrophes and financial crises, it is challenging to determine how to accurately price CAT bonds because CAT bonds are not standardized. The determination of accurate prices is an important condition for the successful trading of securities. Moreover, greater transparency in the mechanism of price discovery could facilitate the evolution of the CAT bond market. Various factors influence the risk premium required by investors. For instance, the trigger mechanism or peril is usually assumed to affect the CAT bond premium. However, the literature only contains a few empirical studies with relatively small data sets investigating which factors influence CAT bond premiums (Berge, 2005; Lane and Mahul, 2008; Dieckmann, 2011; Galeotti et al., 2013). The small sample sizes of these studies lead to some degree of uncertainty about their empirical findings and could be one reason for their conflicting results. For instance, Berge (2005) does not find any significant influence of the trigger mechanism on CAT bond premiums, whereas Dieckmann (2011) finds that CAT bonds using an indemnity trigger have higher risk premiums than nonindemnity-triggered CAT bonds. Only one study analyzes the pricing of CAT bonds on a larger data set (Braun, 2012). However, this study only considers primary market data. Thus, additional analyses of larger data sets, particularly regarding pricing by investors in secondary markets, can provide new insights on the factors that influence CAT bond premiums.

We study secondary market data and find no significant influence of the applied trigger mechanism on the premium. This is in contrast to the widespread expectation in the literature, but it could result from a special payment structure included in most indemnity-triggered CAT bonds (Cummins and Weiss, 2009), whereby the sponsor and investor share the risk above the trigger level proportionally. Addressing perils, we find that if the number of insured peril regions or peril types increases, then the premium increases due to the greater complexity of the deal. Furthermore, we find that even if several other influencing factors are already present in the model, the CAT bond premium increases if the rating declines. Thus, investors use ratings as an additional source of information for their investment decisions. Finally, we cannot find any empirical evidence for a liquidity premium measured by the maturity and issue volume of the CAT bond.

In summary, this study makes the following contributions. First, we show that financial crises significantly affect CAT bond premiums by demonstrating a high correlation between CAT bond premiums and corporate spreads. Second, we provide new insights into the reaction of investors to natural catastrophes. Our results suggest that investors react with distrust of the expected loss calculated by catastrophe modeling companies. Third, our results improve our understanding of which factors influence the secondary market premiums of CAT bonds.

The remainder of the article is structured as follows. The research hypotheses are derived in the second section, where we consider CAT bond-specific hypotheses as well as macroeconomic and event hypotheses. The third section describes the data set used for the empirical analysis. We present and discuss the results of our empirical analysis in the fourth section. Finally, the fifth section presents the conclusions of this work.

HYPOTHESES

Multiple studies in the literature have addressed the factors that determine CAT bond premiums. Against this background the following subsection relates to CAT-bond-specific factors that may affect CAT bond premiums. Subsequently, we discuss the possible influence of macroeconomic factors and catastrophic events. Over the course of this discussion, we derive several hypotheses on factors that determine premiums and on the reactions of CAT bond premiums to catastrophic events.

CAT-Bond-Specific Hypotheses

Typically, the default of a CAT bond is measured by a trigger mechanism. Trigger mechanisms can be separated into indemnity and nonindemnity triggers. Nonindemnity triggers can be further divided into parametric (index) triggers, industry index triggers, modeled loss triggers, and hybrid triggers.[2] Indemnity triggers depend on the actual losses of the sponsor, implying no basis risk for the sponsor, but exposing investors to possible information asymmetries in terms of moral hazard (Lee and Yu, 2002). This moral hazard can be reduced or eliminated by applying nonindemnity triggers, although this introduces basis risk for the sponsor (Cummins et al., 2004). The literature analyzing the trade-off between basis risk and moral hazard argues that CAT bonds with indemnity triggers have higher premiums and are traded less than CAT bonds with nonindemnity trigger mechanisms (Doherty, 2000; Dubinsky and Laster, 2003; Cummins and Weiss, 2009). On a relatively small data set, Dieckmann (2011) finds empirical evidence for the assumption that investors require an additional risk premium when exposed to indemnity-triggered CAT bonds. In contrast, Berge (2005) does not identify a significant influence of the applied trigger mechanism. In addition, Carpenter (2007) states that indemnity triggers result in several disadvantages for both sponsors and investors. The rating process takes longer than the rating process in the context of other trigger mechanisms and a more detailed risk analysis is required, resulting in a longer preparation phase than when a nonindemnity trigger is applied. However, market developments show that the indemnity trigger has regained importance in recent years. Cummins and Weiss (2009) assume that this development is a consequence of a special payment structure included in the CAT bond contract. In this structure, the sponsor and investor share the risk proportionally above the trigger level, an arrangement referred to as an incentive provision. However, Cummins (2008) notes that this structure does not eliminate the problem of moral hazard. In accordance with the literature, we assume that the *trigger hypothesis* is valid.

> *Trigger hypothesis (H1): Investors demand higher risk premiums for CAT bonds with indemnity triggers than for CAT bonds with nonindemnity triggers.*

The insured peril can be distinguished with regard to peril type and peril region. Moreover, a CAT bond can insure a single peril or multiple perils. Banks (2004) finds that the number of multiple peril bonds is increasing. Carpenter (2007) states that sponsors in particular prefer to insure as many peril types as possible in a single CAT bond in order to reduce transaction costs and to share limits for several risk regions. Investors tend to prefer single peril CAT bonds, as this enables them to buy the CAT bond that best fits their investment strategy. Berge (2005) finds empirical evidence that CAT bond premiums decline if only one risk type is insured. Based on these

[2]We refer to Cummins and Weiss (2009) and Galeotti et al. (2013) for further information on nonindemnity trigger mechanisms.

considerations, we propose the *complexity hypothesis*.

> *Complexity hypothesis (H2): Investors require higher risk premiums when exposed to multiple peril types or multiple peril regions within a single CAT bond.*

Specialized firms assess the risk of catastrophe involved in securitizing different perils. After the catastrophe risk has been determined, the rating process begins. Because CAT bonds are fully collateralized with highly rated securities, the rating is mainly performed by analyzing the probability that a triggering event will occur (Cummins, 2008). Therefore, the rating agencies basically rely on the catastrophe risk assessment as established by risk modeling firms because the rating agencies are not particularly specialized in catastrophe risk assessment. However, it is questionable whether a rating process is independent and reliable if it is based on models provided by the risk modeling firms (Anders, 2005). Krutov (2010) even states that investors in general do not rely on CAT bond ratings. Despite all these points of criticism, the rating agencies provide easily accessible information for investors that can support the investment decision process. If investors use these ratings to make investment decisions, then lower CAT bond ratings should result in higher risk premiums. Thus, we assume the *rating hypothesis*.

> *Rating hypothesis (H3): Investors demand higher risk premiums for CAT bonds with lower ratings.*

According to Edwards et al. (2007), corporate bonds with larger issue volumes and bonds with a shorter time to maturity have lower transaction costs than other bonds. Lower transaction costs lead to higher liquidity and, consequently, to lower bond premiums. However, for the CAT bond market, neither Dieckmann (2011) nor Berge (2005) is able to identify any influence of time to maturity or issue volume on CAT bond premiums. Because these studies only analyze observations of the CAT market over a short period and because these empirical findings are not in agreement with the results of the corporate bond market, we consider the following *liquidity hypothesis*.

> *Liquidity hypothesis (H4): Investors demand a higher risk premium for CAT bonds with longer maturity periods and lower issue volumes.*

Macroeconomic and Event Hypotheses

CAT bonds usually have longer maturity periods than traditional reinsurance. While CAT bonds have an average maturity of about 3 years, reinsurance contracts last about 1 year. Therefore, the sponsor of a CAT bond is protected against the cyclical behavior of the reinsurance market (Cummins, 2008). Furthermore, traditional reinsurance markets are affected by capacity shortage after a catastrophe, which drives prices up (Froot, 2001). For instance, after Hurricane Katrina, the traditional reinsurance market tightened due to capacity shortage and prices increased. Although the CAT bond market is not affected by shortage of capital, it exhibited similar behavior. One reason for this development is that expertise is required to participate in the CAT bond market. Thus, if the demand for CAT bonds shifts after a catastrophe, new market participants need to build expertise before participating in the CAT bond market. Consequently, the premiums increase due to “shortage of expertise” instead of “shortage of capital” as in the traditional reinsurance market (Cummins and Weiss, 2009). In addition, CAT bonds can be regarded as an alternative to traditional reinsurance (Cummins and Trainar, 2009; Finken and Laux, 2009). This would imply that the premiums on both markets should behave in a similar way. Against this background, we formulate our *reinsurance hypothesis*.

> *Reinsurance hypothesis (H5): A positive correlation exists between traditional reinsurance premiums and CAT bond premiums.*

In the past, hurricanes in particular have resulted in severe losses to insurance companies. Hurricane Katrina in 2005 caused USD62.2 billion insured losses, the highest recorded single event loss for the insurance industry. The third and fourth largest catastrophes since 1980 were Hurricane Sandy in 2012 and Hurricane Ike in 2008, with USD30 billion and USD18.5 billion insured losses, respectively.[3] In addition, simulation studies predict that even more severe hurricanes might occur in the future due to climate change and related problems (Banks, 2004). Lane and Mahul (2008) find that investors demand higher risk premiums for wind perils in the United States, which include hurricanes, than for other perils. Cummins and Weiss (2009) state that premiums and expected losses rose significantly after Hurricane Katrina, which was driven to a considerable degree by an increase in the uncertainty about the accuracy of risk models after this huge natural catastrophe. However, it is not apparent whether premiums increased for the entire CAT bond market or only for CAT bonds insuring hurricane perils. Therefore, it is necessary to analyze the impact of huge catastrophes[4] on the risk premiums of different types of CAT bonds. We expect to find two reactions of risk premiums. First, the absolute level of risk premiums may increase after catastrophic events. Second, investors may react with mistrust to the expected loss calculated by catastrophe modeling companies. The latter effect should be particularly high if the CAT bond covers a peril of the type that occurred because in this case, the expected loss calculation is associated with this specific type of peril. The premiums in the primary reinsurance market seem to react in a similar way after a catastrophe. In addition to an increase in catastrophe reinsurance premiums after the occurrence of a catastrophe, premiums increased significantly for earthquake reinsurance contracts after the 1994 Northridge earthquake, whereas these premiums were largely unaffected after Hurricane Andrew in 1992 (Gron and Winton, 2001).[5] Thus,

[3]The second catastrophe with USD 40 billion insured losses resulted due the Tohoku earthquake in 2011. This information is provided by the NatCatSERVICE of Munich Re (2012).

[4]Because our data set does not contain sufficient data from the period after the devastating Tohoku earthquake in 2011, we do not analyze the market reaction to this event. However, reports indicate that the market is awaiting new results on earthquake risk modeling due to the Tohoku earthquake (Carpenter, 2012).

we propose the following *natural catastrophe hypotheses*.

> *Natural catastrophe hypothesis (H6a): CAT bond premiums increase after the occurrence of a huge natural catastrophe.*
>
> *Natural catastrophe hypothesis (H6b): The premium increase described in H6a is more pronounced for CAT bonds that refer to the type of peril that occurred than for other CAT bonds.*

The literature often states that CAT bonds are attractive for investors because they are weakly correlated with other asset classes if they are correlated at all. The reason for this low correlation is that natural catastrophes occur independently of market development. For instance, Litzenberger et al. (1996) find that catastrophes are weakly correlated with security market returns. Thus, instruments with a catastrophe-related payment structure are suitable for investor diversification. Galeotti et al. (2013) are not able to identify any correlation between financial markets and the CAT bond market on the basis of the S&P 500 Index. Barrieu and Loubergé (2009) state that natural catastrophes are historically not correlated with financial market returns. However, they argue that it is not clear whether this relationship will hold in the future. In contrast, Dieckmann (2011) computes correlation coefficients between 2002 and 2011 for several capital market variables and CAT bond returns. He finds a high correlation between different bond indexes and CAT bond returns. However, these results lead to the question of whether this high correlation results from the recent financial crisis triggered by the bankruptcy of Lehman Brothers.

Krutov (2010) supposes that high correlations existed between capital markets and the CAT bond market over the course of the financial crisis. Lane and Beckwith (2009) measure the correlation between the returns of insurance-linked securities and the S&P 500 Index. They find that the correlation was very low before mid 2008 and rose to over 30 percent by the end of 2008. In contrast, Cummins and Weiss (2009) find that CAT bonds performed better during the financial crisis than comparable corporate bonds and conclude that CAT bonds seem to be largely independent of other capital market securities. However, it seems plausible to assume that the flight to quality observed in financial crises due to an increased risk aversion (Caballero and Krishnamurthy, 2008) also affects the CAT bond market and leads to increased risk premiums. Because this market reaction affects both corporate bonds and CAT bonds, the correlation between corporate spreads and CAT bond premiums should be higher after the financial crisis. Based on this discussion, we formulate the *financial*

[5] According to Gron and Winton (2001), exposure from past business transactions can reduce an insurer's activity in related lines of business, particularly if new business exposure is highly correlated with existing exposure. Thus, premiums should exhibit stronger reactions if the correlation between the event and the new business is high.

crisis hypothesis.

> *Financial crisis hypothesis (H7a): Premiums of CAT bonds increase after the occurrence of a financial crisis.*

> *Financial crisis hypothesis (H7b): If a financial crisis occurs, then the positive correlation between corporate credit spreads and CAT bond premiums increases.*

Data

Sample Selection

The initial data set consists of 386 CAT bonds issued between December 1997 and March 2012 that insure against natural catastrophe perils. This data set represents virtually the whole universe of CAT bonds that are traded on secondary markets. The secondary market premiums were obtained from data provided by Lane Financial LLC. These data start in the second quarter of 2002 and are determined as the average yield spreads over the LIBOR on a quarterly basis. To determine the published yield spreads, bid and ask quotes are surveyed from several dealers. These values are averaged for each dealer, leading to a single yield spread per dealer. These spreads are averaged again across all dealers. The resulting averaged yield spreads correspond to the secondary market premiums that are used in our analyses. At the beginning of the period, the considered dealers were Aon, Cochran Caronia, Goldman Sachs, and Lehman (Lane and Beckwith, 2003). Over time, the dealers who provided secondary market spreads changed slightly (Lane and Beckwith, 2006, 2009, 2010). The information on the applied trigger mechanisms and perils has been collected from Aon Benfield Securities, Standard & Poor's, and the online portal ARTEMIS.

Several CAT bonds were eliminated from the original data set. First, we removed CAT bonds for which the expected loss, peril type or rating is missing because we assume that these factors are essential determinants of the CAT bond premium. Second, we eliminated CAT bonds that have been labeled *lehman* or *distressed* by Lane Financial LLC.[6] Four CAT bonds have been labeled *lehman*. These bonds defaulted following the bankruptcy of Lehman Brothers because Lehman Brothers Special Financing was the swap counterparty swapping the total returns on investments to a LIBOR-based rate. There are also 11 CAT bonds that have been labeled as *distressed*, as they were somehow affected by a triggering event such as Hurricane Katrina in 2005, Hurricane Ike in 2008, or the Tohoku earthquake in 2011.[7] Therefore, our results provide information

[6]The literature does not provide an exact definition of the term *distressed CAT bond*. A private conversation with Roger Beckwith (Vice President and Secretary of Lane Financial LLC) revealed that generally speaking, distressed CAT bonds are issues for which a possible triggering event has occurred. Prices for these bonds can be depressed just based on the possibility of loss. Once loss estimates are released that approach or exceed the trigger level, prices will begin to become firm at the estimated level of loss. Determining the real loss can be a lengthy process depending on the type of trigger.

[7]Among these distressed labeled bonds is the KAMP Re 2005 Ltd. deal ("trigger: indemnity" and "peril: U.S. hurricane, U.S. earthquake"), which was the first natural catastrophe bond that has been triggered and defaulted due to Hurricane Katrina. Bonds that have been labeled

about the premiums of nondistressed CAT bonds and do not seek to provide details regarding the price reaction if a CAT bond becomes distressed.[8] Third, concerning the type of peril, we exclude transactions that insure floods, hail, tornadoes, or industry losses because only a few transactions insure these perils. Fourth, we exclude CAT bonds if the data are implausible, for example, if the expected loss does not equal the product of the probability of the first loss and the conditional expected loss.

When examining secondary market premiums for CAT bonds, the problem of seasonality arises for all considered peril types except for earthquakes. We outline this problem for hurricanes. During hurricane season, the probability of a triggering event is considerably higher than at other times. If a CAT bond that insures hurricanes matures after hurricane season, the CAT bond is almost risk-free in this final period, resulting in a low premium. Similarly, the premium of a CAT bond with a time to maturity of 6 quarters will be low if the period only contains one hurricane season, but high if this period contains two hurricane seasons. If the time to maturity is a multiple of a full year, then the (yearly) premium of a hurricane insuring CAT bond reflects the risk of the hurricane season regardless of whether the bond matures after or before a hurricane season. Thus, to avoid such seasonal fluctuations, we eliminate observations for perils other than earthquakes if the remaining time to maturity deviates from a multiple of a full year. The remaining data set consists of 272 CAT bonds with 1,119 observations of premiums.

Variables

CAT-Bond-Specific Variables. An essential component of the CAT bond premium is the *expected loss* (EL). The EL results from the risk analysis performed by specialized

distressed because of Hurricane Ike are the Nelson Re Ltd. transaction ("trigger: indemnity" and "peril: U.S. hurricane, U.S. earthquake, European windstorm") and the Blue Coast Ltd. bond ("trigger: industry index" and "peril: U.S. hurricane"). The bonds Mariah Re 2010-1 and 2010-2 (both "trigger: industry index" and "peril: U.S. severe thunderstorm") have been labeled distressed due to the severe U.S. tornado season in 2011. In the course of the Tohoku Earthquake in 2011 the following bonds have been labeled distressed: Valais Re Ltd. A and C ("trigger: indemnity" and "peril: U.S. hurricane, U.S. earthquake, European windstorm, Japan typhoon, Japan earthquake"), Montana Re Ltd. ("trigger: hybrid" and "peril: U.S. hurricane, U.S. earthquake, European windstorm, Japan typhoon, Japan earthquake"), Topiary Capital Ltd. ("trigger: industry index" and "peril: U.S. hurricane, European windstorm, U.S. earthquake, Japan earthquake"), and Successor X Ltd. (II-BY3) ("trigger: hybrid" and "peril: U.S. hurricane, European windstorm, Japan earthquake"). Finally, the Avalon Re Ltd. bond ("trigger: indemnity" and "peril: industrial losses") failed because of a complicated deal structure and loss calculation. See www.artemis.bm for more information on these CAT bonds.

[8]If these bonds were distressed because of different characteristics, then the elimination of these observations could lead to sample selection bias. However, these CAT bonds became distressed because of a natural catastrophe, which is a random event. This is in contrast to corporate bonds, for example, where distress mainly results from nonrandom characteristics or actions. Consequently, the sample of CAT bonds should not be biased by this elimination of observations.

firms such as Applied Insurance Research Worldwide (AIR), Risk Management Solutions Inc. (RMS), and Eqecat Inc. (EQECAT). The EL consists of the probability of first loss (PFL) and the conditional expected loss (CEL) of the CAT bond according to EL = PFL·CEL, and refers to the loss percentage of the nominal value within 1 year. In insurance economics, the EL of a nonnegative random loss variable can be interpreted as a lower bound for the premium to avoid the insolvency of the insurance company, making it an important parameter of the CAT bond premium. However, it is important to realize that the variable EL has some major limitations that have to be considered when interpreting the results. First, the EL is calculated at origination by risk modeling companies. Thus, the variable does not reflect any time-varying risk component. Therefore, the EL will likely substantially deviate from market expectations if new information arrives. Second, even at origination, the EL does not necessarily reflect market expectations, so investors might calculate a different value for the expected loss. To avoid confusion, "EL" will always refer to the value calculated at the time of issue by risk modeling companies.

To measure the influence of *trigger mechanisms* on the CAT bond premium, we build the dummy variable "Trigger Indemnity," which is defined as follows:

$$\text{Trigger Indemnity} = \begin{cases} 1, & \text{if an indemnity trigger is applied,} \\ 0, & \text{if a nonindemnity trigger is applied.} \end{cases} \tag{1}$$

The nonindemnity trigger observations consist of parametric triggers, with approximately 47 percent of observations; industry index triggers, with approximately 33 percent; hybrid triggers, with approximately 12 percent; and modeled loss triggers, with approximately 8 percent.

We generate several variables related to the *peril*. We measure the complexity of the deal using the variables "Number of Types" and "Number of Locations." The variables measure how many perils are securitized in how many regions within one CAT bond. Furthermore, we combine different peril types into reasonable groups and generate dummy variables. Here, "Hurricane (HU)" comprises typhoons, tropical cyclones, and hurricanes because these names refer to the same type of storm that occurs in different regions. The dummy variable "Wind" includes windstorm, winterstorm, and thunderstorm, while "Earthquake (EQ)" only refers to earthquakes. Furthermore, we generate peril regions. The region "North America (NA)" comprises all perils that have been securitized in Canada and the United States. The region "Europe (EU)" comprises all perils that have been securitized in Europe, while "Japan (JP)" refers to perils in Japan. All other regions are summarized in the variable "Other."[9]

The initial data set contains *rating* information from S&P, Fitch, and Moody's. These ratings are converted to a point scale where a one point increase reflects a rating that is one notch worse. If ratings differ, then the average rating is computed from the point

[9]For some CAT bonds, the location can be more precisely described. In North America, there are securitized perils in places such as California, North Carolina or Los Angeles. In Europe, perils have been securitized in France or the United Kingdom. Other perils have been securitized in Australia, Mexico, and Taiwan.

scales. Based on this average rating, we determine the rating letter (AAA, AA, ..., B) that is relevant for our empirical analysis.

As already mentioned in the context of the liquidity hypothesis, we measure liquidity by *maturity* and *volume* of the CAT bond. The variable "Maturity" is provided in the initial data set as total maturity at issue in terms of years. We also determine the variable "Time to Maturity (TTM)," which measures the maturity remaining at the time of observation. The volume of the CAT bond is measured in terms of the natural logarithm of the issue volume.[10]

Macroeconomic Variables. We use two approaches to analyze whether capital market developments influence CAT bond premiums. First, we apply the quarterly return of the S&P 500 Index in the variable "S&P 500." Second, we generate the variable "Corporate Credit Spread (Corp. Spread)" to analyze whether a significant correlation exists between corporate credit spreads and CAT bond premiums. Therefore, we consider the credit spreads of U.S. corporate bonds with maturities of 1–3 years for different rating classes provided by Merrill Lynch. These credit spreads are matched with the CAT bond premiums for identical rating classes. Thus, we are able to accurately measure whether a positive correlation exists between corporate credit spreads and CAT bond premiums.

To analyze whether the reinsurance cycle is associated with CAT bond premiums, we analyze the annual relative change of the "Guy Carpenter Global Property Catastrophe Rate on Line (RoL)[11] Index," generating a variable referred to as the "Reins. Index." This index is presented in Carpenter (2012) and is composed of the output from intensive annual surveys that Guy Carpenter & Company Ltd. undertake with its brokers at each data point. This index represents its best estimate of price changes on a like-for-like basis year on year. The index was set to 100 points in 1990.[12]

Event Variables. We analyze in detail two huge catastrophes that occurred within the period from 2002 to 2012, namely, Hurricane Katrina and the financial crisis. As mentioned above, the most expensive natural catastrophe for the insurance industry was Hurricane Katrina, which occurred in August 2005. To measure the effect of Hurricane Katrina, we build a dummy variable "Katrina" as follows:

$$\text{Katrina} = \begin{cases} 1, & \text{if quarter} \geq \text{quarter } 4/2005, \\ 0, & \text{if quarter} < \text{quarter } 4/2005. \end{cases} \tag{2}$$

[10]We use the logarithm to measure the magnitude instead of the absolute value of the volume.
[11]The rate on line is commonly defined as the premium divided by the insured limit.
[12]This information is from a private conversation with a managing director of Guy Carpenter & Company Ltd. This analysis is carried out through paper surveys and phone calls. The data are then reviewed by the managing director and by the catastrophe business practice leaders to obtain the final output.

TABLE 1
Summary Statistics: CAT-Bond-Specific Nominal Variables for 272 Deals

	Obs.	Percentage
Trigger		
Indemnity	59	21.69
Nonindemnity	213	78.31
Peril type		
Hurricane (HU)	147	54.04
Wind	98	36.03
Earthquake (EQ)	178	65.44
Peril region		
North America (NA)	205	75.37
Europe (EU)	73	26.84
Japan (JP)	51	18.75
Other	13	4.78
Rating		
AA	4	1.47
A	4	1.47
BBB	17	6.25
BB	166	61.03
B	81	29.78

Note: Because multiple peril types and peril regions can be assigned, the category percentages do not add up to 100 percent.

The second mega-event we analyze is the financial crisis triggered by the bankruptcy of Lehman Brothers in September 2008. To measure the effects of this event, we build the dummy variable "Lehman" as follows:

$$\text{Lehman} = \begin{cases} 1, & \text{if quarter} \geq \text{quarter } 4/2008, \\ 0, & \text{if quarter} < \text{quarter } 4/2008. \end{cases} \tag{3}$$

Hurricane Ike, the third largest natural catastrophe for the insurance industry since 1980, made landfall in the United States in September 2008. At this stage, we cannot determine with certainty whether the bankruptcy of Lehman or Hurricane Ike was responsible for the effects observed in the CAT bond markets at that time. This question will be analyzed subsequently.

Descriptive Statistics

Table 1 presents summary statistics for CAT-bond-specific dummy variables. This table indicates that there are a large number of earthquake-insuring CAT bonds, accounting for 65.44 percent of bonds, followed by hurricane-insuring CAT bonds, accounting for 54.04 percent.[13] Furthermore, most bonds insure against perils in North

[13]Because multiple peril types and peril regions can be assigned for a single CAT bond, the category percentages do not add up to 100 percent.

TABLE 2
Summary Statistics: Continuous CAT Bond-Specific and Macroeconomic Variables

	Obs.	Mean	Std. Dev.	Min.	q25	q50	q75	Max.
CAT-bond-specific variables								
Premium (in %)	1,119	6.074	3.506	0.670	3.630	5.280	7.610	19.23
Expected Loss (EL) (in %)	272	1.767	1.390	0	0.825	1.290	2.165	6.130
No. of Locations	272	1.349	0.901	0	1	1	1	4
No. of Perils	272	1.603	0.849	1	1	1	2	4
log(Volume) (in USD million)	271	4.194	1.021	0.956	3.689	4.317	4.990	6.473
Maturity (in years)	272	2.891	0.958	1	2.625	3	3	5
TTM (in years)	1,119	1.981	1.098	0	1	2	3	5
Macroeconomic variables								
Reins. Index (yearly) (in %)	11	3.114	15.51	−10.19	−8.740	−6.000	9.500	36.59
S&P 500 (quarterly) (in %)	40	0.947	9.261	−22.56	−3.415	1.575	7.045	15.22
Corp. Spread (in %)	1,119	5.264	3.139	0.390	3.015	5.263	7.162	17.57

Note: The statistics for variables that are CAT bond specific and vary over time are reported on the observation level. For variables that are CAT bond specific and constant over time, we report the statistics on the issue level.

America. This is consistent with the observations of Cummins and Weiss (2009). In addition, most CAT bonds are rated "BB," followed by "B."

Table 2 presents summary statistics of continuous variables. We report the statistics on the observation level for variables that are CAT bond specific and vary over time such as the Premium, TTM, and Corp. Spread. For variables that are only CAT bond specific, namely the EL, Number of Locations, Number of Perils, log(Volume), and Maturity, we report the statistics on the issue level. The macroeconomic variables are reported yearly for the Reins. Index and quarterly for the S&P 500 because the premium observations are on a quarterly basis as well.

The mean of premiums is almost four times the mean of EL. The variables Number of Locations and Number of Perils indicate that a single CAT bond typically insures fewer distinct regions than peril types. In addition, the range of values of the variable log(Volume) varies between 0.956 and 6.473, measured in USD million. Thus, the issue volume varies between 2.6 ($\approx e^{0.956}$) and 647.6 ($\approx e^{6.473}$) USD million. Furthermore, the typical CAT bond has a maturity of 3 years, which indicates that the maturities of CAT bonds are significantly longer than the maturities of traditional reinsurance contracts.

Table 3 presents the correlations between the variables described above. The high correlation between the EL and the premium is a first indication that the EL is indeed an essential component of the CAT bond premium. Moreover, the number of locations and peril types as well as the reinsurance index are positively correlated with CAT bond premiums, as expected in the hypotheses. In contrast, the correlations of the variables Volume, Maturity, and TTM with Premium have the opposite signs to those predicted by the liquidity hypothesis. However, analyzing CAT bond premiums in

Table 3
Table of Correlations

	Prem.	EL	No. of Lc.	No. of Pe.	Vol.	Mat.	TTM	Rein.	S&P	Sp. Cp.
Premium	1.00									
EL	0.75	1.00								
No. of Loc.	0.28	0.29	1.00							
No. of Perils	0.28	0.07	0.39	1.00						
log(Volume)	0.10	−0.10	−0.05	0.19	1.00					
Maturity	−0.18	−0.22	−0.09	0.04	−0.01	1.00				
TTM	−0.01	−0.07	0.01	0.13	0.07	0.55	1.00			
Reins. Index	0.14	−0.02	0.02	−0.04	−0.02	−0.01	0.10	1.00		
S&P 500	−0.01	−0.01	−0.03	0.04	−0.05	0.07	0.07	0.14	1.00	
Corp. Spread	0.46	0.35	0.03	0.05	0.19	0.01	0.03	−0.36	−0.14	1.00

Note: This table presents the pairwise correlations of continuous CAT-bond-specific and macroeconomic variables.

a multivariate setting might lead to a different dependence, and this analysis will be carried out subsequently. Regarding the different independent variables we can observe the highest correlations between Maturity and TTM as well as between No. of Locations and No. of Perils. The first correlation is a consequence of how the variable TTM is calculated. The second correlation shows that CAT bonds that insure multiple peril types mostly insure multiple peril regions at the same time.[14]

Empirical Results

The following empirical analysis consists of several linear approaches in which the CAT bond premium is always the dependent variable.[15] First, we determine the maximal fraction of the variance that can be explained by time-invariant bond-specific or by time-dependent data. Second, we analyze the influence of the expected loss. Third, CAT-bond-specific factors are included in the model to test CAT-bond-specific hypotheses. Finally, we carry out an analysis of macroeconomic factors and relevant events.

[14]We believe that the negative correlation between the reinsurance index and corporate spreads should not be interpreted as a negative causal relationship. The observed correlation seems to be rather a consequence of the fact that reinsurance premiums substantially increased after hurricane Katrina whereas corporate spreads continued to decrease at that time. In the following years, the reinsurance index decreased almost to the pre-Katrina level whereas credit spreads increased substantially due to the subprime and the resulting financial crisis. Thus, there seems to be a positive causal relationship with CAT bond premiums for both variables Reins. Index and "Corp. Spread," but the negative correlation *between* these influencing factors seems to be coincidental.

[15]There are several modeling approaches to CAT bond premiums in the literature, namely, linear models, loglinear models, and the Wang transformation model (Wang, 2000; Major and Kreps, 2003; Lane and Mahul, 2008). Because evidence shows that the linear model is an appropriate approach to describe and predict CAT bond premiums (Galeotti et al., 2013), we implement linear models.

TABLE 4
Benchmark

	(I.1)	(I.2)	(I.3)
Bond fixed effects	Yes	Yes	Yes
Quarter fixed effects	No	Yes	No
Year fixed effects	No	No	Yes
Observations	1,119	1,119	1,119
R^2	0.871	0.950	0.923

Note: The CAT bond premium is the dependent variable in each model. R^2 has been determined based on pooled OLS estimates.

Benchmark

To analyze the maximal fraction of variance that can be explained by bond-specific or time-dependent variables, we explain the CAT bond premium by fixed effects using a least squares dummy variable (LSDV) estimation:

$$\text{premium}_{it} = \beta' X_i + \gamma' Y_t + u_{it}, \tag{4}$$

for $i = 1, \ldots, n$ CAT bonds and $t = 1, \ldots, T$ different points in time. X_i refers to bond fixed effects, meaning that dummy variables are included for every bond. Consequently, an intercept is generated for every bond. Y_t refers to time fixed effects, which can be quarterly or yearly. A dummy variable is included for every unit of time. Finally, u_{it} refers to the error term, which varies over bond and time. We estimate the coefficients of the model with OLS regressions. This implementation of the fixed effects model is also known as the LSDV regression.

Table 4 presents the results of the benchmark analysis based on Equation (4). The goodness of fit of the models is measured by R^2, which is determined based on pooled OLS estimates. It can be interpreted as the part of the variation in the dependent variable premium$_{it}$ that is explained by the explanatory variables. In model (I.1), we consider bond fixed effects only that is $Y_t = 0$. The R^2 of this analysis is 87.1 percent. Thus, a significant portion of premium variation can be explained by CAT-bond-specific information. Model (I.2) considers not only bond fixed effects X_i but also quarter fixed effects Y_t. The corresponding R^2 is 95 percent. When replacing quarter fixed effects with year fixed effects, the R^2 is only slightly lower, 92.3 percent. Consequently, time effects measured by quarter or year are less relevant than bond effects for the explanation of premium variance. The same is true for influencing factors that vary over both bond and time, as these can explain at most the remaining 5 percent of premium variation.

The results presented above have two implications for our subsequent analysis. First, we only consider year fixed effects instead of quarter fixed effects because the R^2 remains very high when quarter fixed effects are replaced by year fixed effects, but the number of variables can be substantially reduced. Second, because a large proportion of the variation in risk premiums is due to those bond-specific factors that are time invariant, we apply random effects models to reveal these influencing factors.

Concretely, we consider random effects models of the following form

$$\text{premium}_{it} = \beta' X_i + \gamma' Y_t + \delta' Z_{it} + a_i + u_{it}, \tag{5}$$

for $i = 1, \ldots, n$ CAT bonds and $t = 1, \ldots, T$ different points in time. X_i refers to CAT-bond-specific variables that are not affected by time, for example, the number of types of insured perils. Z_{it} refers to variables that vary by bond and time, similar to the variable TTM of a bond. Y_t contains variables that depend on time only, which is the case for the year fixed effects considered here. Note that the unobservable individual effect a_i and the error term u_{it} that vary over time are assumed to be random with a_i and u_{it} being independently and identically distributed. The mean and standard deviation of the individual effects a_i are μ_a and σ_a, respectively, whereas the error term u_{it} has a mean of zero and a standard deviation of σ_u. In addition, all explanatory variables are assumed to be independent of a_i and u_{it} for all i, t. Under these assumptions, the random effects estimator is consistent and asymptotically efficient (Baltagi, 2008; Wooldridge, 2013). However, it should be noted that the assumptions of the random effects model are quite strong, particularly because there could be omitted time-invariant variables that are correlated with the considered influencing factors, which would lead to biased estimates. As the assumption of independence between the explanatory variables and a_i as well as u_{it} cannot be tested, it is important to consider all economically relevant influencing factors that are likely to be correlated with the considered variables.

In addition to time-invariant variables, we are also interested in the effects of macroeconomic factors, the financial crisis, and natural catastrophes, which are not bond specific. To study these factors and events, we apply fixed effects models as follows:

$$\widehat{\text{premium}}_{it} = \gamma' \hat{Y}_t + \delta' \hat{Z}_{it} + \hat{u}_{it}, \tag{6}$$

where the fixed effects (within) transformation has been applied to the variables. This means that the variables with the hat notation are expressed as deviations from their means. The advantage of the fixed effects model compared to the random effects model is that the estimators are consistent even if the explanatory variables are correlated with the unobservable bond-specific effect a_i in Equation (5) (Baltagi, 2008; Wooldridge, 2013).

For every subsequent analysis of the random effects model, we performed the Breusch-Pagan test (BP test) to verify whether the assumption of a random effects model is appropriate or whether a pooled OLS model should be applied instead. The BP test examines the hypothesis that the variance of the individual intercept σ_a is zero, determining whether it can be assumed that there are no CAT-bond-specific differences within the units. This hypothesis is rejected for almost every subsequent model.[16] Thus, it is not appropriate to establish pooled OLS and a random effects model should be applied. In the following, all R^2 values reported for the random effects models represent overall R^2 values. We also report the adjusted R^2, which is based on the overall

[16]To be more precise, we use a modified version of the BP test for unbalanced panel data (Baltagi and Li, 1990). The resulting Lagrange multiplier (LM) statistics and the statistical significance of σ_a are reported in the tables for each random effects model.

R^2 but adjusts for the number of explanatory variables that are applied in the model. For the fixed effects models, we report the within-R^2, which can be interpreted as the percentage of variation in the dependent variable around the bond-specific means that can be explained by the explanatory variables.

Analysis of the Expected Loss

The expected loss is assumed to be highly important for the CAT bond premium (Galeotti et al., 2013). Therefore, we begin by analyzing the influence of the expected loss on the CAT bond premium in the models presented in Table 5. In model (II.1), we only consider the expected loss as a premium determining factor. We find that in addition to a constant value, the average CAT bond premium is about two times the expected loss. In model (II.2), we include year fixed effects to account for differences in absolute risk premiums over time, and find that the adjusted R^2 increases significantly to 64.07 percent. Moreover, we find that in comparison to 2002 the premium is significantly lower in 2004 and 2005 and increases significantly after 2008, which could be a result of the financial crisis and its impact on risk assessment of investors. We also include the interaction effect of EL and year in model (II.3) to account for differences in relative risk premiums over time. The R^2 increases slightly compared to the previous specification. However, the hypothesis that the interaction coefficients are equal to zero can be rejected at the 99.9 percent level. Thus, the variables of the interaction effect of EL and year are jointly significant. The negative coefficients of the interaction terms imply that in comparison to the high marginal effect of EL during the year 2002, the coefficient of EL is significantly lower in the subsequent years. This is most likely a consequence of an increasing transparency of the CAT bond market.

Having identified that the year fixed effects and the interaction effect of EL and year are relevant influencing factors, we use these variables in the following models in addition to the EL and other factors.

Analysis of CAT-Bond-Specific Variables

The objective of this section is to test CAT-bond-specific hypotheses. Based on the results of the previous section, we use year fixed effects and the interaction effect of EL and year as control variables in each model in Table 6. Model (III.1) is only reported for comparison, as it is identical to model (II.3) in Table 5. Next, we include CAT-bond-specific variables X_i that address trigger mechanisms and perils. The adjusted R^2 of 77.46 percent for model (III.2) is significantly higher than that for model (III.1). Finally, we include variables X_i regarding the rating, maturity, and volume of the CAT bond. Note that TTM is a CAT-bond-specific variable that varies over time, and thus is of type Z_{it}. The adjusted R^2 of model (III.3) is slightly higher than that of model (III.2).[17]

[17]It should be kept in mind that random effects estimates are only consistent under the assumptions discussed in the "Benchmark" section, including the assumption of independence of the considered variables and omitted time-invariant influencing factors. Though, an explained share of variance of about 80 percent in model (III.3) indicates that most economically relevant influencing factors have been considered in the model.

TABLE 5
Impact of the Expected Loss on Premiums

	(II.1)	(II.2)	(II.3)
EL	2.134***	2.098***	3.033***
	(0.100)	(0.102)	(0.201)
Year fixed effects			
2003		−0.488***	−0.230
		(0.146)	(0.207)
2004		−1.418***	−0.795***
		(0.161)	(0.192)
2005		−1.511***	−0.618**
		(0.176)	(0.220)
2006		0.056	0.186
		(0.258)	(0.340)
2007		−0.918***	0.136
		(0.240)	(0.306)
2008		−0.120	1.049**
		(0.281)	(0.388)
2009		2.451***	3.354***
		(0.331)	(0.518)
2010		0.236	1.664***
		(0.264)	(0.396)
2011		−0.001	1.662***
		(0.300)	(0.467)
2012		0.951*	2.181***
		(0.380)	(0.616)
EL × Year			
EL × 2003			−0.380*
			(0.173)
EL × 2004			−0.747***
			(0.181)
EL × 2005			−0.996***
			(0.202)
EL × 2006			−0.455+
			(0.242)
EL × 2007			−1.046***
			(0.232)
EL × 2008			−1.120***
			(0.237)
EL × 2009			−0.955***
			(0.286)
EL × 2010			−1.247***
			(0.245)
EL × 2011			−1.361***
			(0.281)
EL × 2012			−1.117**
			(0.358)

(*Continued*)

TABLE 5
Continued

	(II.1)	(II.2)	(II.3)
Observations	1,119	1,119	1,119
μ_a	3.517***	3.689***	2.815***
σ_a	1.8748***	1.7733***	1.7337***
LM statistic	836.25	1,137.47	1,026.01
σ_u	1.4462	1.1239	1.0990
R^2	0.5555	0.6442	0.6629
Adjusted R^2	0.5551	0.6407	0.6564

Note: This table reports random effects estimates of the expected loss and related variables on the CAT bond premium (in %). The base variable is the year 2002. Standard errors shown in parentheses are clustered by bonds and are robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

We cannot confirm the trigger hypothesis (H1). Neither model specification exhibits a significant influence of the dummy variable Trigger Indemnity. In addition, the coefficient is close to zero, indicating that the effect is economically insignificant. Thus, our results support the rejection of the trigger hypothesis. This implies that investors do not demand additional premium components due to problems arising from information asymmetries. Probably, the risk-sharing mechanism between sponsor and investor described above that is included in most indemnity CAT bonds sufficiently remedies the moral hazard problem. Furthermore, it seems to be important for sponsors to avoid basis risk by applying indemnity trigger mechanisms. Based on these findings, it is likely that the market share of indemnity-triggered CAT bonds will continue to increase as was already identified by Cummins and Weiss (2009).

Our results support the complexity hypothesis (H2). Both of the variables Number of Locations and Number of Types have a positive impact on premiums, which is statistically and economically significant. Increasing the Number of Locations and the Number of Types by one standard deviation leads to an increase in the CAT bond premium by 1.09 percentage point and 0.336 percentage point, respectively. Given the average premium of 6.1 percent, these values correspond to a change of 17.9 and 5.5 percent of the mean premium. Thus, investors tend to strongly prefer CAT bonds that securitize perils in the same region. In addition, they prefer CAT bonds with fewer different peril types.

Concerning the peril location, we find that insured perils in the European Union, Japan, or other regions have significantly lower premiums than CAT bonds securitizing events in North America. Furthermore, CAT bonds that insure hurricane events have significantly higher premiums than bonds insuring earthquakes. This could result from the above-mentioned fact that several of the most expensive catastrophes thus far have been hurricanes in North America. The latter supposition will be analyzed with respect to Hurricane Katrina and Hurricane Ike in the “Analyses of the Financial Crisis and Natural Catastrophic Events” section.

TABLE 6
Impact of CAT-Bond-Specific Variables on Premiums

	(III.1)	(III.2)	(III.3)
EL	3.033***	3.058***	2.688***
	(0.201)	(0.188)	(0.203)
Trigger Indemnity		0.175	0.153
		(0.254)	(0.246)
Peril			
Number of Locations		0.796***	1.074***
		(0.200)	(0.200)
Number of Types		0.384*	0.479**
		(0.181)	(0.178)
Region EU		−1.006*	−1.390**
		(0.495)	(0.473)
Region JP		−1.012**	−1.247***
		(0.336)	(0.314)
Region Others		−3.598***	−3.501***
		(0.563)	(0.526)
Region Missing		0.420	0.617
		(0.425)	(0.406)
Hurricane		1.245***	1.001***
		(0.248)	(0.255)
Wind		−0.314	−0.035
		(0.421)	(0.396)
Rating			
Rating AA			−3.486***
			(0.766)
Rating A			−2.085**
			(0.792)
Rating BBB			−1.811***
			(0.507)
Rating BB			−0.323
			(0.365)
Maturity			0.047
			(0.112)
TTM			−0.116
			(0.075)
log(Volume)			0.161*
			(0.081)
Year fixed effects	Yes	Yes	Yes
EL × year	Yes	Yes	Yes
Observations	1,119	1,119	1,118
μ_a	2.815***	1.347***	1.678+
σ_a	1.7337***	1.2290***	1.1342***
LM statistic	1,026.01	544.40	412.31
σ_u	1.0990	1.0990	1.0960
R^2	0.6629	0.7806	0.8032
Adjusted R^2	0.6564	0.7746	0.7965

Note: This table reports random effects estimates of CAT-bond-specific variables on premiums (in %). The base variables are B for rating, NA for peril region, and EQ for peril type. Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

Our results also support the rating hypothesis (H3). We find that investors demand significantly higher premiums for CAT bonds with lower ratings, even after controlling for several other influencing factors. Thus, despite all points of criticism concerning the rating of CAT bonds, investors use these ratings as additional information for their risk assessment.

Finally, as mentioned above, we measure liquidity by the variables Maturity, TTM, and log(Volume). Neither Maturity nor TTM have a significant influence on CAT bond premiums, which is in agreement with the results of other empirical analyses. Surprisingly, a higher volume leads to significantly higher premiums, which is in contrast to the liquidity hypothesis. In summary, we find no empirical evidence for the liquidity hypothesis (H4), which means that investors do not demand a liquidity premium for CAT bonds.

Robustness Checks for CAT-Bond-Specific Variables

We next present several robustness checks of the CAT-bond-specific effects. First, we analyze whether the results are stable for different periods of time. Second, we check whether the results are driven by a specific type of peril. Third, we split the data set into subsamples of CAT bonds that insure against multiple or single peril types. All of these robustness checks are based on model (III.3) from the previous section.

To analyze different time periods, we split the sample into observations before Hurricane Katrina, observations after Katrina and before the bankruptcy of Lehman, and observations after the Lehman event. As seen in Table 7, all subsamples have similar numbers of observations, ranging from 334 to 422. Looking at the EL, the coefficient is significantly higher for the pre-Katrina period (based on a significance level of $p < 1$ percent), with a difference in coefficients between the first and second periods of 1.249, and similarly, a difference of 1.263 if we compare the first and third periods ($p < 5$ percent). However, this effect has already been considered in the setting for the full sample, where we observed a decrease in the interaction term EL $\times$ year during the initial years. We find that most effects are similar between the time periods analyzed here. For example, the coefficients of the number of peril types and peril locations are positive for all periods and are highly significant in most cases. Furthermore, the effect of maturity on risk premiums is similar for the different subsamples, with an impact of at most 0.16 percentage points on the premium, which corresponds to 2.6 percent of the mean value, if the maturity changes by one standard deviation. Moreover, the rating is relevant for all periods. However, we can also observe some differences between periods. First, the effect of the indemnity trigger is significantly positive in the second period, which is in line with the trigger hypothesis (H1), but the coefficient is not significant in the pre-Katrina and the post-Lehman period. However, the difference between the second and third periods is not statistically different ($p = 15$ percent), so that it is unclear whether there are relevant differences between the periods. Second, the positive influence of volume can mainly be observed in the second period. Thus, the unexpected result from the previous section seems to be mainly driven by observations from that period. Third, the additional risk premium for hurricanes seems to be relevant only in the second and third periods. A compari-

TABLE 7
Robustness Check: Time Periods

	Pre-Katrina (IIIa.1)	Katrina-Lehman (IIIa.2)	Post-Lehman (IIIa.3)
EL	2.765***	1.516***	1.502***
	(0.268)	(0.207)	(0.397)
Trigger Indemnity	−0.223	1.275***	0.451
	(0.188)	(0.378)	(0.407)
Peril			
Number of Locations	0.587***	1.477***	0.600
	(0.126)	(0.283)	(0.549)
Number of Types	0.920***	0.315	0.697**
	(0.199)	(0.244)	(0.250)
Region EU	−1.274**	−1.242*	−0.432
	(0.454)	(0.564)	(0.838)
Region JP	−1.010***	−1.465***	0.059
	(0.137)	(0.377)	(0.944)
Region Others		−3.116***	−2.342**
		(0.517)	(0.895)
Region Missing	0.687***	0.774	
	(0.197)	(0.604)	
Hurricane	−0.283	0.773*	1.990***
	(0.179)	(0.333)	(0.524)
Wind	0.373	0.097	−0.771
	(0.413)	(0.532)	(0.580)
Rating			
Rating A	−2.388*	−2.132*	−1.386
	(1.022)	(0.939)	(0.901)
Rating BBB	−1.605+	−2.832***	−2.224+
	(0.968)	(0.709)	(1.178)
Rating BB	−0.189	−0.795+	−0.430
	(0.731)	(0.471)	(0.488)
Maturity	−0.168*	0.014	−0.141
	(0.086)	(0.125)	(0.320)
TTM	0.047	−0.329**	−0.098
	(0.098)	(0.104)	(0.116)
log(Volume)	0.117*	0.490***	−0.365
	(0.055)	(0.121)	(0.251)
Year fixed effects	Yes	Yes	Yes
EL × Year	Yes	Yes	Yes
Observations	362	422	334
μ_a	1.834	0.683	5.340*
σ_a	0.3695	1.1820***	1.6020***
LM statistic	0.03	559.71	34.45
σ_u	0.5434	0.7960	0.9885
R^2	0.9431	0.8309	0.7126
Adjusted R^2	0.9396	0.8207	0.6903

Note: This table reports random effects estimates of CAT-bond-specific variables on premiums (in %). The base variables are B for rating, NA for peril region, and EQ for peril type. Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

son of coefficients confirms that the premium for hurricanes in the second and third periods is also statistically significantly higher than in the pre-Katrina period ($p < 5$ percent and $p < 0.1$ percent, respectively). This indicates that the additional premium for hurricanes could be attributed to Hurricane Katrina. We will analyze this effect in the "Analyses of the Financial Crisis and Natural Catastrophic Events" section.

When analyzing different peril types in Table 8, we separately consider observations that include hurricanes, earthquakes, and windstorms. Comparing models (IIIb.1), (IIIb.3), and (IIIb.5), we find that most effects are similar for different peril types. The most obvious difference is that the EL-multiple is considerably lower for hurricanes than for earthquakes and windstorms. However, this difference is not statistically significant, which is a consequence of the high standard error of the EL-multiple for hurricanes. Furthermore, we observe that none of the interaction terms between year and EL are significant for hurricanes, which, on one hand, could result from the presence of a high number of variables in the subsample in relation to the number of observations. On the other hand, this result implies that the EL coefficient for hurricanes does not decrease over time. A reason could be that hurricanes were already well understood at the outset, at least relative to windstorms and earthquakes. A hypothesis test of the interaction terms confirms that these terms are jointly not significant. Thus, we repeat the estimation without these terms. For a better comparison of the results, we also implement this specification for earthquakes and hurricanes, leading to models (IIIb.2), (IIIb.4), and (IIIb.6). While the R^2 is slightly reduced by definition, the adjusted R^2 remains rather stable or is even higher in the case of hurricanes. Comparing the EL estimate of model (IIIb.2) and model (IIIb.1), we find that the standard error is now materially lower, and the coefficient is highly statistically significant. Moreover, the EL coefficients are similar for all peril types when comparing the models without the interaction terms between year and EL, in terms of economical and statistical significance. The other coefficients are almost not affected by the omission of the interaction term. We conclude that the results from the "Analysis of CAT-Bond-Specific Variables" section are not driven by a specific peril type.

Finally, we analyze whether the influence of the bond-specific factors differs between CAT bonds that insure against multiple peril types and those that insure against a single peril type. As can be seen from Table 9, the number of locations seems to have a higher effect for single-peril bonds than for multiperil bonds, but the difference is not statistically significant. Furthermore, the additional risk premium for hurricanes identified in the "Analysis of CAT-Bond-Specific Variables" section is materially higher for single-peril bonds than for multiperil bonds. This effect could be expected because for multiperil observations, the variable hurricane only means that hurricanes are one of several peril types. Thus, for multiperil observations, the hurricane effect is diluted by the influence of other peril types, which is not the case for single-peril observations. To sum up, the results for single-peril CAT bonds highlight the impact of hurricanes, thus confirming results from Tables 6 and 7. As the other coefficients are similar for both samples, we conclude that the observed effects are not driven by single- or multiperil observations.

TABLE 8
Robustness Check: Peril Types

	Hurricane		Earthquake		Wind	
	(IIIb.1)	(IIIb.2)	(IIIb.3)	(IIIb.4)	(IIIb.5)	(IIIb.6)
EL	1.257	1.742***	2.709***	1.907***	2.628***	1.894***
	(2.046)	(0.194)	(0.235)	(0.174)	(0.261)	(0.182)
Trigger Indemnity	0.168	0.095	−0.004	0.071	−0.247	−0.280
	(0.307)	(0.295)	(0.330)	(0.336)	(0.434)	(0.447)
Peril						
Number of Locations	0.896	0.866	1.167***	1.196***	0.955***	0.952***
	(0.556)	(0.555)	(0.352)	(0.349)	(0.215)	(0.240)
Number of Types	0.381*	0.394*	0.825***	0.820***	0.536**	0.589**
	(0.168)	(0.164)	(0.173)	(0.171)	(0.164)	(0.206)
Region EU	−1.125	−1.177	−1.758*	−1.745*	−1.674**	−1.553*
	(0.937)	(0.961)	(0.845)	(0.852)	(0.613)	(0.685)
Region JP	−1.339+	−1.272+	−1.515***	−1.400***	−0.856*	−0.588
	(0.777)	(0.736)	(0.299)	(0.291)	(0.385)	(0.461)
Region Others	−4.739***	−4.918***	−3.393***	−3.608***		
	(0.702)	(0.689)	(0.554)	(0.540)		
Region Missing	1.028+	0.906	0.108	0.181	0.428	0.736
	(0.602)	(0.575)	(0.733)	(0.683)	(0.723)	(0.816)
Rating						
Rating AA	−5.872***	−5.793***	−4.238***	−4.233***	−3.529***	−3.404***
	(0.803)	(0.806)	(0.882)	(0.874)	(0.767)	(0.787)
Rating BBB	−2.657***	−2.553***	−2.116**	−2.290**	−2.095**	−2.308**
	(0.641)	(0.651)	(0.705)	(0.699)	(0.715)	(0.749)
Rating BB	−0.832*	−0.711+	−0.406	−0.403	−0.450	−0.471
	(0.424)	(0.426)	(0.538)	(0.541)	(0.476)	(0.471)
Maturity	−0.002	−0.064	0.250+	0.214	0.184	0.149
	(0.246)	(0.237)	(0.148)	(0.143)	(0.201)	(0.209)
TTM	−0.068	−0.101	−0.136	−0.128	0.018	−0.002
	(0.109)	(0.105)	(0.097)	(0.099)	(0.117)	(0.119)
log(Volume)	0.094	0.027	0.222*	0.187*	−0.118	−0.162
	(0.171)	(0.165)	(0.097)	(0.094)	(0.102)	(0.119)
Year fixed effects	Yes	Yes	Yes	yes	yes	yes
EL × Year	Yes	No	Yes	no	yes	no
Observations	353	353	894	894	235	235
μ_a	4.364	4.470**	0.913	1.762+	2.654*	3.495*
σ_a	1.2797***	1.33724***	1.1222***	1.1698***	0.9231***	1.0614***
LM statistic	83.20	77.93	317.18	306.56	16.70	15.95
σ_u	1.0937	1.1130	1.1344	1.1643	0.9578	1.0072
R^2	0.7713	0.7674	0.8054	0.7996	0.9237	0.9102
Adjusted R^2	0.7468	0.7504	0.7975	0.7938	0.9103	0.8995

Note: This table reports random effects estimates of CAT-bond-specific variables on premiums (in %). The base variables are B for rating and NA for peril region. Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

Analysis of Macroeconomic Factors

We analyze the effects of macroeconomic factors on the CAT bond premium on the basis of a fixed effects model. The bond-specific variables cannot be analyzed in this model because they are included in the fixed effects. Thus, among the variables that

TABLE 9
Robustness Check: Multiperil Versus Single Peril

	Multiperil (IIIc.1)	Single peril (IIIc.2)
EL	2.689***	2.584***
	(0.222)	(0.349)
Trigger Indemnity	0.405	0.098
	(0.355)	(0.395)
Peril		
Number of Locations	0.608	2.506*
	(0.510)	(1.218)
Number of Types	0.103	
	(0.417)	
Region EU	−0.752	−1.244*
	(1.214)	(0.538)
Region JP	−0.724	−1.734***
	(0.512)	(0.328)
Region Others	−4.648***	−2.613***
	(0.788)	(0.576)
Region Missing	0.592	1.957
	(0.638)	(1.231)
Hurricane	0.321	1.293***
	(0.575)	(0.320)
Wind	−0.384	0.107
	(0.891)	(0.496)
Rating		
Rating AA	−4.001***	
	(0.789)	
Rating A	−2.627***	−1.500+
	(0.751)	(0.794)
Rating BBB	−2.448***	−1.683**
	(0.729)	(0.640)
Rating BB	−0.705	0.076
	(0.493)	(0.490)
Maturity	0.335	0.038
	(0.334)	(0.119)
TTM	0.012	−0.210*
	(0.133)	(0.096)
log(Volume)	−0.053	0.206*
	(0.213)	(0.101)
Year fixed effects	Yes	Yes
EL × Year	Yes	Yes
Observations	275	843
μ_a	3.300	0.765
σ_a	0.9585***	1.1185***
LM statistic	25.18	195.63
σ_u	1.1404	1.0428
R^2	0.8875	0.7634
Adjusted R^2	0.8699	0.7531

Note: This table reports random effects estimates of CAT-bond-specific variables on premiums (in %). The base variables are B for rating, NA for peril region, and EQ for peril type. Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

Table 10
Impact of Macroeconomic Factors on Premiums

	(IV.1)	(IV.2)
TTM	−0.158*	−0.116*
	(0.077)	(0.053)
Reins. Index	0.041***	0.037***
	(0.004)	(0.004)
S&P 500	−0.018*	0.026***
	(0.009)	(0.005)
Corp. Spread		0.348***
		(0.032)
Constant	6.355***	4.396***
	(0.158)	(0.179)
Observations	1,119	1,119
Within-R^2	0.185	0.447
Adjusted within-R^2	0.183	0.445

Note: This table reports fixed effects estimates of macroeconomic factors on premiums (in %). Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

were analyzed in the previous section, we only consider TTM, which is time varying. Moreover, we do not consider time fixed effects because we attempt to *explain* the variation over time by macroeconomic factors. The results are presented in Table 10.

We include the macroeconomic variables S&P 500 and Reins. Index in model (IV.1). A significantly positive correlation is observed between the yearly relative change of the reinsurance index and the premium and a significantly negative correlation results between the quarterly return of the S&P 500 and the premium. The significantly positive effect of the variable Reins. Index remains stable for the following analyses. Thus, we find evidence for our reinsurance hypothesis (H5), which implies that the development of reinsurance premiums is positively related to the development of CAT bond premiums.

The coefficient of the variable S&P 500 is slightly negative. However, if the capital market variable Corp. Spread is included in model (IV.2), then the coefficient of S&P 500 becomes positive. This can be explained by the negative correlation of the two variables and the higher correlation between premium and Corp. Spread in comparison to the correlation between premium and S&P 500 (see Table 3). The coefficient of the variable Corp. Spread is positive and highly significant. Moreover, we observe that the adjusted within-R^2 increases substantially from 18.3 to 44.5 percent. Consequently, in model (IV.2), a major part of the related capital market development is represented by corporate credit spreads. In summary, we find evidence for a highly relevant correlation between capital markets and CAT bond premiums. In the next section, we analyze whether this effect remains valid over time or whether there are differences in the case of the recent financial crisis.

Analyses of the Financial Crisis and Natural Catastrophic Events

Next, we analyze the impact of natural catastrophes and the financial crisis on risk premiums. As already mentioned in connection with H6a and H6b, the absolute level of risk premiums may increase after huge catastrophes, or investors may react with mistrust in the expected loss calculated by catastrophe modeling companies. Whereas the first effect should result in a significantly increased intercept after the event, the second effect should lead to a higher coefficient of the EL after the event. For example, if the absolute level of risk premiums increases after Hurricane Katrina, then the coefficient of the dummy variable "Katrina" should be positive. Mistrust in the calculated EL would lead to a positive coefficient of an interaction term between EL and Katrina. Similarly, as stated in the financial crisis hypothesis (H7a), we expect that the risk premium increased after the bankruptcy of Lehman Brothers, as measured by the dummy variable "Lehman." We also consider an interaction term between EL and Lehman. However, the argument for an increased EL multiple due to mistrust in reported ELs does not hold for the bankruptcy of Lehman Brothers, so we do not expect the coefficient to be different from zero. Furthermore, it is important to note that the third largest hurricane since 1980, Hurricane Ike, occurred at the same time as the Lehman event. Thus, if the interaction term is significant, it is likely that the identified effect has to be attributed to Hurricane Ike instead of the Lehman event.

Some initial results about the effects of catastrophic events on risk premiums can be obtained from the fixed effects model in Table 11. In the first column, we find that year fixed effects can explain approximately 40 percent of the variation over time around the bond-specific means. In column 2, we additionally consider the interaction terms EL $\times$ Year, which we find to be jointly significant. Next, we want to replace the year dummies with event variables so that the model contains event variables and the interaction terms EL $\times$ Event instead of the battery of variables for year and EL $\times$ Year. For this purpose, we analyze which events might be the most important for the pricing of CAT bonds. Therefore, we implement the methodology of the panel threshold regression of Hansen (1999). In this model, it is considered that there might be different slopes for values below and above a threshold, and the optimal threshold value is determined that minimizes the sum of squared errors.[18] In our setting, this threshold value corresponds to the time variable Quarter. Consequently, in order to apply the within transformation of Hansen (1999) we have to differentiate between the quarters before and after the "threshold quarter." Having applied the regression for every possible threshold quarter, we are searching for the quarter that leads to the minimum sum of squared errors. Basically, if the threshold quarter is given, the estimation coincides with the setting of Allison (2009), who also implements the fixed effects model including interaction terms of time-invariant variables and time. However, in the panel threshold regression of Hansen this threshold is determined endogenously.

[18]To be more specific, Hansen (1999) considers a balanced panel $\{y_{it}, q_{it}, x_{it} : 1 \leq i \leq n, 1 \leq t \leq T\}$ and analyzes the equation $y_{it} = \mu_i + \beta_1 x_{it} I(q_{it} \leq \gamma) + \beta_2 x_{it} I(q_{it} > \gamma) + e_{it}$, where I is the indicator function. In a first step, Hansen determines the OLS slope coefficients $\beta(\gamma)$ depending on γ. In a second step, he minimizes the sum of squared errors with respect to γ to determine the "optimal" threshold γ^* and the corresponding slope parameters $\beta(\gamma^*)$.

TABLE 11
Impact of Catastrophic Events on Premiums: Preliminary Analysis

	(V.1)	(V.2)	(V.3)	(V.4)
TTM	-0.357^{+}	-0.372^{+}	0.686***	0.674***
	(0.211)	(0.210)	(0.063)	(0.062)
Event dummies				
Katrina			1.997***	1.157***
			(0.248)	(0.308)
Lehman			4.032***	3.895***
			(0.282)	(0.457)
Interaction effects				
Katrina × EL				0.762**
				(0.283)
Lehman × EL				0.076
				(0.163)
Constant	8.529***	7.939***	2.156***	1.876***
	(1.263)	(1.329)	(0.272)	(0.297)
Year fixed effects	Yes	Yes	No	No
EL × Year	No	Yes	No	No
Observations	1,119	1,119	1,119	1,119
Within-R^2	0.407	0.440	0.440	0.457
Adjusted within-R^2	0.401	0.429	0.438	0.454

Note: This table reports fixed effects estimates of catastrophic events on premiums (in %). Standard errors shown in parentheses are clustered by bonds and robust to heteroscedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

We find that the point in time that solves for the minimization procedure is the quarter 4/2008, which corresponds to our Lehman variable. Thus, it seems appropriate to allow for different CAT bond premiums before and after the bankruptcy of Lehman Brothers in the regression model. Next, we implement the procedure again to find a second event that had a strong effect on the premiums of CAT bonds. We find that in addition to 4/2008, the quarters 1/2006 and 4/2005 solve for the minimization. These points in time are likely to be attributed to Hurricane Katrina. Because the results are not significantly different for both threshold values and as Hurricane Katrina made landfall in August 2005, we subsequently consider potential differences in CAT bond premiums before and after the fourth quarter of 2005, which is our "Katrina" variable. The corresponding results for the specifications with and without interaction effects can be found in Table 11 in columns 3 and 4. Interestingly, the within-R^2 of these specifications remain constant and the adjusted R^2 is even higher than the adjusted R^2 of the previous specifications with year dummies. Consequently, the event variables are indeed important factors influencing the risk premiums. We find that both event variables are significantly positive. Furthermore, the interaction term EL × Katrina is significantly positive. Therefore, this provides initial evidence that investors mistrusted calculated ELs after Hurricane Katrina. In contrast, the interaction term EL × Lehman is insignificant. These results suggest that Hurricane Katrina caused investors to demand a higher risk premium by increasing the EL-multiple, whereas the bankruptcy of Lehman Brothers led to an absolute increase in risk premiums. These results are consistent with H6a and H7a. A decrease in reliance on calculated ELs can also be observed if we calculate the fraction of variance that can be explained by the EL before and after these events. Whereas the EL explains approximately 79 percent of variance before Hurricane Katrina made landfall, this fraction is reduced to 57 percent between Katrina and Lehman and to 37 percent after the bankruptcy of Lehman Brothers.

In Table 12, we analyze the influence of these events in more detail.[19] Based on the results of Table 11, we begin with a simple fixed effects model that includes the significant terms of model (V.4). In model (VI.2), we also include the macroeconomic variables from Table 10. Then, we examine the effects of Hurricane Katrina in model (VI.3) before we analyze the effects of the Lehman and/or Ike events in models (VI.4) and (VI.5).

Consistent with our natural catastrophe hypothesis (H6a), we find that CAT bond premiums significantly increased after Hurricane Katrina. In model (VI.1), the coefficients of the dummy variable "Katrina" and the interaction term EL $\times$ Katrina are significantly positive. However, if we consider the macroeconomic variables in model (VI.2), only the interaction term remains significant. This indicates that after Hurricane Katrina, there is mistrust in calculated ELs rather than an absolute increase in the perception of risk in the CAT bond market. However, corresponding with H6b, it is reasonable to assume that investors mainly adjusted their expectations for hurricanes after the occurrence of Hurricane Katrina, with smaller adjustments for other peril types. We test this in model (VI.3) by including the interaction effects Katrina $\times$ Hurricane and Katrina $\times$ Wind as well as Katrina $\times$ EL $\times$ Hurricane and Katrina $\times$ EL $\times$ Wind. We observe that the term Katrina $\times$ EL remains weakly significant, but the interaction effect Katrina $\times$ EL $\times$ Hurricane is significantly positive as well. The other interaction terms are not significant. First, these results provide evidence that Hurricane Katrina did not lead to higher premiums in absolute terms, but the increasing risk premiums can mainly be attributed to higher EL-multiples. Second, this effect can mainly be observed for hurricane perils. Consequently, we can conclude that Hurricane Katrina increased perceived risk, leading investors to demand a higher EL-multiple, which can also be interpreted as an adjustment of the EL that had been calculated by catastrophe modeling companies. This is in agreement with our natural catastrophe hypotheses (H6a) and (H6b).

Consistent with the financial crisis hypothesis (H7a), we find a significantly positive coefficient of Lehman, meaning that CAT bond premiums increased significantly after the bankruptcy of Lehman Brothers. Moreover, to identify whether the dependence of CAT bond premiums on corporate credit spreads increased after the financial crisis, we include the interaction effect of Lehman and corporate credit spreads in model (VI.4). The coefficient of the interaction effect is significantly positive. Simultaneously, the

[19] The results for the corresponding random effects and between effects estimates are available upon request.

TABLE 12
Impact of Catastrophic Events on Premiums: Main Analysis

	(VI.1)	(VI.2)	(VI.3)	(VI.4)	(VI.5)
TTM	0.675***	0.349***	0.360***	0.306***	0.291***
	(0.063)	(0.063)	(0.061)	(0.058)	(0.059)
Macroeconomic variables					
Reins. Index		0.020***	0.020***	0.021***	0.021***
		(0.004)	(0.004)	(0.004)	(0.004)
S&P 500		0.014**	0.014**	0.016***	0.015***
		(0.005)	(0.005)	(0.004)	(0.004)
Corp. Spread		0.219***	0.218***	0.155***	0.137***
		(0.028)	(0.028)	(0.028)	(0.028)
Event dummies					
Katrina	1.158***	0.401	0.199	0.112	0.088
	(0.308)	(0.301)	(0.328)	(0.333)	(0.335)
Lehman	4.015***	2.368***	2.389***	1.143**	0.838
	(0.283)	(0.270)	(0.269)	(0.415)	(0.833)
Interaction effects with Katrina					
Katrina × EL	0.762**	0.751**	0.711*	0.628+	0.605+
	(0.283)	(0.287)	(0.360)	(0.359)	(0.360)
Katrina × Hurricane			−0.304	−0.358	−0.373
			(1.062)	(1.049)	(1.048)
Katrina × Wind			0.777	0.705	0.682
			(0.546)	(0.545)	(0.546)
Katrina × EL × Hurricane			1.230*	1.299*	1.318*
			(0.572)	(0.561)	(0.560)
Katrina × EL × Wind			−0.327	−0.250	−0.228
			(0.445)	(0.445)	(0.446)
Interaction effects with Lehman/Ike					
Lehman × Corp. Spread				0.142***	0.192***
				(0.041)	(0.046)
Lehman/Ike × EL					−0.251
					(0.318)
Lehman/Ike × Hurricane					−0.267
					(0.730)
Lehman/Ike × Wind					0.697
					(0.688)
Lehman/Ike × EL × Hurricane					0.567*
					(0.242)
Lehman/Ike × EL × Wind					−0.411
					(0.274)
Constant	1.878***	2.348***	1.935***	2.525***	2.644***
	(0.297)	(0.360)	(0.343)	(0.324)	(0.313)
Observations	1,119	1,119	1,119	1,119	1,119
Within-R^2	0.456	0.545	0.562	0.573	0.582
Adjusted within-R^2	0.454	0.543	0.557	0.568	0.575

Note: This table reports fixed effects estimates of catastrophic events on premiums (in %). Standard errors shown in parentheses are clustered by bonds and robust to heteroskedasticity. The symbols +, *, **, and *** indicate statistical significance at the 10%, 5%, 1%, and 0.1% levels, respectively.

coefficients of the variables Corp. Spread and Lehman decline but remain significant. These findings can be interpreted as follows. Whereas the dependence of CAT bond premiums on corporate spreads was rather low before the bankruptcy of Lehman

Brothers, the dependence strengthened after the financial turmoil in the aftermath of the Lehman event, consistent with our financial crisis hypothesis (H7b). This result reveals that the general risk perception increased for both CAT bonds and other financial market securities. Consequently, the "flight to quality" can be observed not only in the corporate bond market but also in the CAT bond market. The reason for the declining coefficient of Lehman in model (VI.4) is that the effect of increasing CAT bond premiums is mainly contained in the dependence on corporate spreads. Because corporate spreads increased significantly after the bankruptcy of Lehman, and because we observe a high correlation between CAT bond premiums and corporate spreads after the Lehman event, the resulting effect on CAT bonds is a strong increase in premiums. Thus, our findings according to which CAT bond premiums significantly increased after the Lehman event are not affected, even if the coefficient of Lehman is reduced in model (VI.4). Finally, it is worth noting that the influences of the macroeconomic variables remain highly significant in all model specifications considered here, which confirms our findings from the previous section.

Our results from the preliminary analysis in Table 11 suggest that the effects identified here can be attributed to the Lehman event and not to Hurricane Ike, which occurred at the same time. However, in model (VI.5), we perform an additional analysis to test whether there is a smaller effect due to Hurricane Ike as well. If such an effect is present, we would expect the risk perception for the affected hazard to increase after the event as was observed in the case of Hurricane Katrina. Therefore, we include the interaction effect of "Ike" (which is defined identically to the variable Lehman) with "Hurricane" and "Wind," as well as the interaction effects of Ike $\times$ EL $\times$ Hurricane and Ike $\times$ EL $\times$ Wind. We find that the interaction effect of Ike $\times$ EL $\times$ Hurricane is significantly positive, which is consistent with H6b. The premiums of other peril types seem to be largely unaffected. This means that after the third quarter in 2008, two effects occurred at the same time. First, the CAT bond premiums increased as a result of the flight to quality after the bankruptcy of Lehman Brothers, which can be observed in terms of a high correlation between CAT bond premiums and corporate spreads. Second, the premiums increased due to Hurricane Ike, which can be observed by the higher multiple of the calculated EL for hurricanes after this event.

Conclusions

In this article, we examine whether and how natural catastrophes and financial crises affect CAT bond premiums. In addition, we analyze which bond-specific and macroeconomic factors influence CAT bond premiums. We find evidence that the financial crisis significantly affected CAT bond premiums. Concerning natural catastrophes, we find that the perceived risk of CAT bonds increased after huge natural catastrophes. The results for the hypotheses analyzed in this work are summarized in Table 13.

The analysis of the impact of CAT-bond-specific variables on premiums reveals that premiums increase with deal complexity in terms of the number of insured peril types or regions. Our results also support the hypothesis that investors use ratings information for their investment decisions and demand additional premium components for lower rated bonds. Our results do not confirm the expectation in the literature that investors require an additional premium for CAT bonds using the indemnity trigger.

TABLE 13
Summary of Results

Hypothesis	Variable	Expected Sign	Result
H1: Trigger hypothesis	Indemnity Trigger	+	✗
H2: Complexity hypothesis	No. of Locations/No. of Perils	+/+	✓
H3: Rating hypothesis	Rating Grade	−	✓
H4: Liquidity hypothesis	Volume/Maturity/TTM	−/+/+	✗
H5: Reinsurance hypothesis	Reinsurance Index	+	✓
H6a: Natural catastrophe hypothesis	Katrina × EL	+	✓
H6b: Natural catastrophe hypothesis	Katrina × EL × Hurricane	+	✓
H7a: Financial crisis hypothesis	Lehman	+	✓
H7b: Financial crisis hypothesis	Lehman × Corporate Spread	+	✓

Note: This table summarizes the hypotheses and results regarding the positive or negative dependence of CAT bond premiums.

This could result from incentive provisions that are included in most indemnity trigger CAT bonds to reduce problems resulting from asymmetric information. Moreover, we find no empirical evidence for a liquidity premium.

Regarding macroeconomic effects, we find a positive dependence between the reinsurance cycle and CAT bond premiums. Thus, CAT bond premiums do exhibit cyclical behavior similar to that of the reinsurance cycle. Furthermore, we find evidence that CAT bond premiums depend on capital market developments measured by corporate spreads. This positive dependence significantly strengthened after the bankruptcy of Lehman Brothers that triggered the financial crisis.

Concerning the impact of natural catastrophes, we first analyze the effects of Hurricane Katrina. We find that risk premiums increased significantly after this event. However, this increased risk premium can mainly be attributed to a higher multiple of the expected loss for CAT bonds insuring hurricanes. This finding suggests that investors adjusted their expectations about the likelihood of large hurricanes after Hurricane Katrina and consequently calculated a higher expected loss than that determined by catastrophe modeling companies. Therefore, we can conclude that after Hurricane Katrina, investors demanded additional premium components for CAT bonds with hurricane perils, most likely due to an increase in the perceived risk of hurricanes.

We also analyze the impact of Hurricane Ike, which occurred at the same time as the bankruptcy of Lehman Brothers. In this study, we observe that investors increased the multiple of the expected loss for hurricane perils again, which was the same effect as was observed after Hurricane Katrina but with a considerably smaller magnitude. Thus, it seems that investors slightly adjusted their assessment of the risk of hurricanes after Hurricane Ike.

An important implication of our results is that not only future natural crises but also future financial crises might affect CAT bond premiums. Our results reveal a positive dependence between corporate spreads and CAT bond premiums. Therefore, CAT bonds should not be regarded as "zero-beta" securities. This dependence strengthened following the recent financial crisis. Thus, investors should be aware that correlations exist between CAT bonds and other securities and that these correlations could become even stronger when diversification effects would be most valuable that is in extreme market conditions.

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