A Consumption-Based Evaluation of the Cat Bond Market

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This paper shows that catastrophe bond returns correlate significantly with economic fundamentals such as consumption. Hence, I build a consumption-based equilibrium model trying to reconcile investor preferences with several features of the cat bond market. The driving force behind the model is a habit process, in that catastrophes are rare economic shocks that could bring investors closer to their subsistence level. The calibration requires shocks with an impact between -1% and -3% to explain a reasonable level of cat bond spreads. Such investor preferences are not only able to generate realistic cat bond returns and price comovement among different perils, they may also explain why cat bonds offer higher rewards compared to equally-rated corporate bonds.

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JEL Classification: D51, D53, G12, G22.

1 Introduction

The catastrophe bond market has been active for 15 years and has attracted a large but specialized investor base, which is typically told that an investment is beneficial due to substantial diversification benefits. The textbook treatment of cat bonds still claims they carry no or very little systematic risk, and they should be treated as zero-beta securities. Simultaneously, the small academic literature that has emerged about cat bonds focuses on computing accurate expected losses, but pays no attention to incorporating risk premiums. To my knowledge, this strong assumption has never been proven. What has been tested is to which extent cat bonds might correlate with stock market variables, but such a comparison lacks rigor because the stock market itself is an endogenous entity.

Until recently, a quantitative evaluation of cat bonds was difficult because data, not so much about the primary market but about the secondary market, was not available. This has changed in that Swiss Re has launched several performance indices, named Swiss Re Cat Bond Indices, that make the secondary market activity more transparent to investors. For the maximal time period available starting in 2002, Table 1 shows correlations between the performance of the cat bond market and several other financial variables. It shows that cat bond returns covary positively with the stock market and the corporate bond market, high-yield as well as investment-grade. For example, the correlation between deflated quarterly excess returns of the broadest cat bond portfolio and the FINRA high-yield corporate bond portfolio is 41.4%. Measured in terms of monthly returns the correlation is 27.0%, but the degree of correlation is smaller among all financial variables while measured monthly. Diversifying a portfolio using cat bonds would of course lead to benefits given such correlations. However, they are clearly not uncorrelated with other asset classes.

To understand whether cat bonds (should) carry a risk premium we have to look into economic fundamentals, and the goal of this paper is to link the cat bond market to consumption expenditures. Before explaining the link, note that Table 1 also shows correlations between the performance of the cat bond market and consumption growth rates. For example, I find that quarterly growth of real non-durable consumption expenditures and the deflated excess return of the broadest cat bond portfolio correlate with 27.5%. In monthly terms this correlation is equal to 17.5%, which is the larger than the correlation between consumption and any other asset class. Most importantly, economic fundamentals and cat bond returns are clearly not uncorrelated – a key motivation for this paper.

The claim here is that cat bonds are subject to severe natural perils that might have an impact on consumption. Only one of the nine outstanding cat bonds covering the Gulf region triggered due to hurricane Katrina in 2005. As pointed out by Cummins (2006), Katrina is the most severe natural disaster in the U.S. in terms of economic impact up to date, with a total economic cost between 100 and 200 billion dollars, and we should consider the possibility that cat bonds are subject to some amount of systematic risk. If even the costliest catastrophe was not severe enough to trigger the cat bond market at large, then market participants perceive that those bonds securitize mega-catastrophes. I show that the model provided in this paper requires shocks with an impact between -1% and -3% only to explain a reasonable level of cat bond spreads. A data set of individual cat bonds also analyzed in this paper allows for further insight: Cat bonds cover a variety of natural perils such as windstorms and earthquakes. Bonds linked to windstorm risks securitize events expected to occur roughly once every 40 years, those linked to non-windstorm risks once every

100 years. Bond spreads equal between two and three times expected losses after controlling for bond-specific characteristics, which is similar in magnitude to the prices discussed in Cummins and Weiss (2009). But given such a generous reward for investors in terms of spreads and a relatively small impact on consumption, where does the amplification effect come from?

The proposed model assumes that preferences contain a habit process in that catastrophes are rare economic shocks that could bring investors closer to their subsistence level. Bantwal and Kunreuther (2000) were the first to point out the difficulties in reconciling cat bond prices with economic fundamentals based on standard CRRA preferences – the required economic shocks are simply too large. In contrast, preferences in which individuals do not measure their felicity with respect to the absolute level of consumption but with respect to a subsistence level, originally proposed by Campbell and Cochrane (1999), allow for an amplification effect due to increased effective risk aversion. Such time non-separable preferences have become a workhorse in financial economics and have been successful in explaining several features of capital markets. This includes the level of the equity premium at various horizons, the excess volatility of the stock market, reconciling predictability of returns and growth rates as in Menzly et al. (2004), and features of the riskless term structure as in Wachter (2006). Motivated by this, I find it relevant to explore to what extent such preferences can explain the cat bond market.

A convenient way of modeling catastrophes is to incorporate Poisson risk as it captures the highly skewed law of motion in natural hazards. Several papers have argued to incorporate rare events into traditional models in asset pricing, including Rietz (1988), Naik and Lee (1990), Longstaff and Piazzesi (2004), and more recently Du (2011) also in the context of habit preferences. In addition to Poisson risk, my model is also subject to normal economic risk represented by a Brownian motion. The calibration requires a relatively small amount of catastrophic risk compared to normal economic risk. Specifically, 25% of the total quadratic variation in fundamentals correspond to catastrophes, the remaining 75% correspond to normal economic shocks. In contrast, the calibrated model of Du (2011) requires more than 50% of risk in fundamentals stemming from rare events in order to explain the volatility smirk for index options. Although such percentages are far more reasonable than those required under standard preferences, the magnitude of the required shocks suggests that cat bond prices contain a 'Peso problem' in that an event triggering the market at large has indeed not yet occurred.

The model also highlights an important difference between the market price of normal economic risk and catastrophe risk. Chen et al. (2009) link the level of corporate bond spreads to consumption data based on habit preferences in the case of normal economic risk. The new question is, should investors expect a similar reward in the cat bond market? For a clear cut comparison I assume that corporate bonds are subject to normal economic risk, and first derive the spread of corporate bonds as in Chen et al. (2009). While holding expected losses constant across bonds, I find that cat bond spreads can be multiples of the equivalent corporate bond spread; the theoretical result is ambiguous, but for most states of the economy cat bonds should offer a larger reward for investors. After matching individual cat bonds with equally-rated corporate bonds, I show that this prediction is confirmed in the data.

1.1 The Cat Bond Market

The cat bond market enables the transfer of cat risk exposure from the seller to the buyer of the bond. The key feature of a cat bond is a provision causing interest and/or principal payments to be lost in the event a specified catastrophe. The bond's payoff is either linked to an indemnity trigger or to an index trigger. The indemnity trigger represents an actual loss value, whereas an index trigger links to an industry loss index or to a parametric index. Payoffs can take on a step structure depending on the severity of the loss. Consequently, a cat bond might have a probability attached to a first loss, average loss, full loss, or a more complex conditional loss distribution.

A cat bond origination typically involves a special purpose vehicle (SPV), and reinsurers are the dominant sponsors. A sponsor enters into a reinsurance contract with an SPV, and the SPV then hedges itself by issuing cat bonds to investors in the capital market. The proceeds from the sale of the securities are invested in high grade securities typically held in a collateral trust, minimizing credit risk in the transaction. An unusual event happened in September 2008 after the Lehman Brothers collapse: Losses occurred on four cat bonds which involved Lehman Brothers in the SPV construction, as some of the collateral was invested in securities which had lost substantial value. Such an SPV failure, however, only occurred once. Typically, bondholders receive full payment if the stipulated event does not occur. If the catastrophe does occur, however, the SPV makes a payment to the sponsoring company instead. To rule out that the SPV failure in September 2008 significantly affected the correlation structure among cat bonds, economic fundamentals, and other asset classes, I show the correlations excluding the respective quarter, see Panel B of Table 1. The degree of correlations is slightly lower relative to Panel A, but not only with respect to cat bond returns, also among other asset classes.

More than 170 cat bonds have been issued during the last 15 years, the outstanding capital at risk was 13 billion USD as of December 2010, according to Swiss Re. This might appear small compared to the dimension of other financial innovations such as credit derivatives. However, the cat bond market is only a window allowing us to look into pricing of severe layers of risk, and it complements other insurance-linked securities, reinsurance programs, extreme weather derivatives and so forth, which should also carry the risk premiums studied here. Whether these risk premiums should be visible in the stock market is difficult to say since it is unclear to which extent corporations expose themselves to such extreme layers of risk. The model here has no direct implications for the size of the cat bond market as investors are assumed to be homogeneous. Further background information is provided by Bantwal and Kunreuther (2000), Cummins et al. (2004), Cummins and Weiss (2009), and Michel-Kerjan et al. (2011).

I utilize two data sets in the quantitative evaluation of the model. First, the indices provided by Swiss Re. They are a series of performance indices constructed to track the total rate of return of cat bond portfolios. The broadest index corresponds to a basked containing all outstanding USD denominated catastrophe bonds. Sub-indices, such as only BB-rated bonds are also available. After injecting consumption shocks to model, the resulting returns of a hypothetical cat bond appear realistic. They are realistic in the sense that the consumption-based return series and the Swiss Re return series correlate more than 30%, and the variations of returns are also similar.

The second data set contains price information about individual cat bonds. Prices are represented as a yield spread in basis points, in this case as a per annum spread relative to the interest rate swap market, a typical representation in the cat bond market. Descriptive statistics are shown in Table 3. Unfortunately, this individual cat bond data is not available for the entire time period. However, it does include the important event of hurricane Katrina, and a requirement for a bond to be included is that it exists at Katrina's landfall in August 2005. To keep the cross section of bonds constant I only consider bonds that are alive and prices are recorded within three quarters prior and post to that event. This leads to a total of 61 cat bonds, representing 90% of the cat bond volume outstanding during that time. Part of the evaluation of the model is to derive a prediction about how cat bonds reacted to Katrina. A commonly held view is that economic agents might revise their estimates about the likelihood or impact at the occurrence of a catastrophe, see Born and Viscusi (2006). While this could of course also matter in the context of Katrina, the purpose of this exercise is to illustrate what effects arise simply due to increased effective risk aversion. I find the model can explain up to 6.5% increase in the market price of windstorm risk, and even 10% increase in the market price of non-windstorm risk, which is about a third of the market reaction during that time. In Zanjani (2002), the cost of capital is an important argument in his model on pricing and allocations in catastrophe insurance. However, the goal of his paper is not to develop an equilibrium model where the cost of capital arises endogenously from economic primitives. Hence, my work complements Zanjani (2002) in illustrating the possible economic nature of such capital costs.

The cat bond market is also subject to features that the model does not capture. While I try to control for them to have a cleaner view of the risk premium component, it is insightful to also interpret the bond-specific characteristics shown in Table 4. First, I find that the presence of an indemnity trigger is priced in the cat bond market. It is likely that a trigger related to reported losses leads to a moral hazard issue possibly reflected in higher spreads, see Doherty and Richter (2002) or Froot (2001). The counterpart basis risk, of course, could be similarly reflected in cat bonds subject to non-indemnity triggers.[1] My finding is that cat bonds with indemnity triggers reward investors with more than 110 basis points additional premium.

Second, I control for variables capturing illiquid market conditions. Adapting hypotheses already tested in the corporate bond market, I follow the suggestions by Edwards et al. (2007) and measure liquidity by age and issue size. I expect that a bond's age (amount) is positively (negatively)

[1] Cummins et al. (2004) impose the question to what extent the use of index-linked cat loss securities leave the issuer exposed to basis risk. Based on 255 issuers active in the hurricane insurance market in Florida, their simulation exercise shows that index-linked cat loss securities have a high degree of hedging effectiveness for the largest insurers, though not a perfect hedge. In a related paper, Finken and Laux (2009) develop some positive theory for parametric (as opposed to indemnity-based) triggers in the cat bond market.

associated with cat bond spreads if investors require an additional reward for facing a potentially illiquid market. The finding is that neither the age nor amount add any consistent insight, possibly a reflection that the cat bond market is in the hands of a specialized investor base. Third, the results show a moderately upward-sloping cat bond term structure. Every month of remaining time to maturity increases the level of spreads between 1.45 and 1.88 basis points on average. In comparison, we also have evidence that the term structure of spreads is usually upward-sloping in the corporate bond market, see for example Helwege and Turner (1999). Although the model does have implications for the shape of the cat bond term structure, those effects are outside of the scope of the current paper.

2 The Model

2.1 Exogenous Risk and Economic Primitives

Suppose consumption is subject to multiple sources of uncertainty and follows the process

$$\frac{dC_t}{C_{t-}} = \mu_c dt + \sigma_c dB + \sum_{i=1}^{2} \kappa_{ci} dN(\lambda_i) \qquad t \in [0, \infty). \tag{1}$$

First, normal economic risk enters through a standard Brownian motion B with a volatility parameter $\sigma_c > 0$, as typical in the continuous-time formulation of an exchange economy. Second, the economy is subject to two separate sources of catastrophic risk, i.e. windstorm risk and earthquake risk, or more generally non-windstorm risk. Non-windstorm risk enters through a Poisson process with arrival intensity λ_1 and impact size κ_{c1}, non-windstorm risk enters through a Poisson process with arrival intensity λ_2 and impact size κ_{c2}. I assume no common occurrences among windstorm risk and non-windstorm risk, and impact sizes to be in the interval $(-1, 0)$ to ensure that consumption remains positive. The deterministic growth rate of the economy is given by μ_c. For simplicity, I assume all exogenous parameters to be constant values. For regular economic risk, this appears to be reasonable as time-variation of growth rates and volatility in economic fundamentals is difficult to detect. For natural perils, this assumption allows me to abstract from phenomena like seasonality in windstorm risk, or the evolution of faults and plates in case of earthquake risk. The surprise element of the occurrence of a catastrophe, however, is essential to the model.

The assumed process in equation (1) nests a case in which consumption is subject to only one type of catastrophic risk, but has a random impact size drawn from an independent two-point distribution. For example, suppose $\lambda = \lambda_1 + \lambda_2$ and $p = \lambda_1/\lambda$, then consumption follows the process given by

$$\frac{dC_t}{C_{t-}} = \mu_c dt + \sigma_c dB + \kappa_c dN(\lambda), \tag{2}$$

and is subject to three sources of uncertainty, i.e. normal economic risk, catastrophic risk with the arrival intensity λ, and a random impact size κ_c. The impact of a catastrophe can be large with size κ_{c1} and likelihood p, or small with size κ_{c2} and likelihood $1-p$. The main focus of this section will be the equilibrium characterization corresponding to the formulation in equation (1). However, I will also use the latter formulation to tie the model to a hypothetical cat bond that is subject to multiple perils.

The economy is populated by educated and informed investors with external habit formation preferences as in Campbell and Cochrane (1999). A representative investor maximizes expected utility given by

$$E\left[\int_0^\infty e^{-\rho t}\frac{(C_t - X_t)^{1-\gamma} - 1}{1-\gamma}dt\right], \tag{3}$$

where C_t is the investor's level of consumption, X_t measures the habit level, γ is the risk aversion coefficient, and ρ is the subjective discount factor. As usual, it is convenient to characterize this economy in terms of the surplus consumption ratio defined as

$$S_t = \frac{C_t - X_t}{C_t}, \text{ and } s_t = \ln(S_t).$$

The surplus consumption ratio has the assumed dynamics given by

$$ds_t = \phi(\bar{s} - s_t)dt + \theta\sigma_c dB + \sum_{i=1}^{2} \kappa_{si} dN(\lambda_i), \tag{4}$$

with a central tendency parameter given by $\bar{s}$ and a reverting rate of ϕ. While the process of s_t is standard with respect to normal economic risk as in Campbell and Cochrane (1999), catastrophic risk can also lead to changes in the investor's (habit and) surplus consumption level. Essential to the solution of this problem is therefore the proper identification of the sensitivity parameters, i.e. θ for the case of normal economic risk, as well as κ_{s1} and κ_{s2} for the case of catastrophic risks.

The investor is assumed to face a complete market of financial claims. Suppose her state price density process is given by

$$\frac{d\xi_t}{\xi_{t-}} = -r dt + \sum_{i=1}^{2}(\lambda_i - \lambda_i^Q)dt - \eta dB + \sum_{i=1}^{2}\left(\frac{\lambda_i^Q}{\lambda_i} - 1\right) dN(\lambda_i), \tag{5}$$

where r is the riskless interest rate, η is the market price of (normal) economic risk, λ_1^Q and λ_2^Q are the risk-adjusted arrival intensities of catastrophic risks, respectively. As usual, the state price density can be found from the investor's optimality conditions, and the equilibrium will be uniquely determined by comparing the state price density process with the marginal utility process resulting from equation (3), given the solution to the sensitivity parameters.

2.2 Endogenous Risk Premia and Sensitivity Parameters

Straightforward algebra leads to the following equilibrium characterization. The market price of normal economic risk is given by

$$\eta = \gamma\sigma_c(\theta + 1), \tag{6}$$

which has the same functional form as in Campbell and Cochrane (1999). The addition of catastrophic risk leads to a market price of catastrophic risk given by

$$\lambda_i^Q = \lambda_i(\kappa_{ci} + 1)^{-\gamma} e^{-\gamma\kappa_{si}}, \tag{7}$$

for $i = 1, 2$. Intuitively, the term $e^{-\gamma\kappa_{si}}$ not only induces time-variation, it also generates an amplification effect in risk premiums comparable to θ for the case of normal economic risk. The case of standard CRRA preferences is nested in this formulation. Suppose $X(t) = 0$, then θ and κ_{si} are identically zero, and the standard CRRA risk premiums emerge as $\eta = \gamma\sigma_c$ and $\lambda_i^Q = \lambda_i(\kappa_{ci}+1)^{-\gamma}$. As will be verified later, these are indeed the boundary solutions as the surplus consumption ratio approaches the maximal value of its distribution.

The expected value of the surplus consumption ratio converges to a steady state as $t \to \infty$ because of it's mean-reverting nature, see Das (2002). Suppose $\widehat{\kappa}_{s1}$ and $\widehat{\kappa}_{s2}$ are the sensitivity parameters for catastrophic risk observed at the steady state, then $\widehat{s} = \overline{s} + \frac{\widehat{\kappa}_{s1}\lambda_1 + \widehat{\kappa}_{s2}\lambda_2}{\phi}$ corresponds to the steady-state level of the surplus consumption ratio. The equilibrium in Campbell and Cochrane (1999) is derived under three key assumptions, i.e. a constant riskless interest rate, as well as a predetermined habit level *at* and *near* the steady state. With only one source of uncertainty, this leads to three restrictions through which the equilibrium can be uniquely determined. However, adding two sources of uncertainty adds a layer of complexity as outlined below.

First, I adopt the assumption of a constant riskless interest rate as in Campbell and Cochrane (1999). The functional form is given by

$$r = \rho + \gamma(\mu_c - \frac{1}{2}\sigma_c^2) + \lambda_1 - \lambda_1(\kappa_{c1} + 1)^{-\gamma} + \lambda_2 - \lambda_2(\kappa_{c2} + 1)^{-\gamma} + \alpha + \beta_1 + \beta_2, \tag{8}$$

where the parameters α, β_1, and β_2 represent the degrees of freedom to obtain a constant value of r. Specifically, α will be associated with normal economic risk, β_1 and β_2 with catastrophic risk, respectively.

Second, an equilibrium in this economy can be found by expanding the process of the surplus consumption ratio to

$$ds_t = [(\nu_1 + \nu_2 - 1) + (1 - \nu_1) + (1 - \nu_2)]\phi(\overline{s} - s_t)dt + [...] \tag{9}$$

where ν_1 and ν_2 are constants to be determined endogenously. Intuitively, the three sources of uncertainty can contribute separately (and possibly to a different extent) to the mean-reverting nature of the surplus consumption ratio. The sensitivity value for normal economic risk can be found as in the benchmark case. After solving for the functional form of θ, the values for α and $\widehat{s}$ are determined by the restrictions

$$\theta(\widehat{s}) = e^{-\widehat{s}} - 1, \tag{10}$$

and

$$\theta'(\widehat{s}) = -e^{-\widehat{s}}. \tag{11}$$

The former restriction leads to a predetermined habit level *at* the steady state, and the latter to a predetermined habit *in close proximity* to the steady state; the solutions for α and $\widehat{s}$ depend on ν_1 and ν_2. The maximal value of the distribution of s can be determined where the habit model collapses to the benchmark case without a habit, $\theta(s^{\max}) = 0$, given by

$$s^{\max} = \frac{1}{2} - \frac{\gamma\sigma_c^2}{2(\nu_1 + \nu_2 - 1)\phi} + \ln\left(\frac{\sqrt{\gamma}\sigma_c}{\sqrt{\nu_1 + \nu_2 - 1}\sqrt{\phi}}\right). \tag{12}$$

What remains to be determined are the sensitivity parameters for catastrophic risks. The functional form of the sensitivity parameter follows from the interest rate restriction, such that κ_{si} solves

$$\beta_i - \lambda_i(\kappa_i + 1)^{-\gamma} = (1 - \nu_i)\phi\gamma(\overline{s} - s_t) - \lambda_i(\kappa_{ci} + 1)^{-\gamma}e^{-\gamma\kappa_{si}}, \tag{13}$$

for $i = 1, 2$. I adopt the same notion of predetermination, such that the occurrence of a catastrophe has no instantaneous effect on the habit level at $\widehat{s}$, leading to

$$e^{\kappa_{si}(\widehat{s})} = e^{-\widehat{s}} - \frac{e^{-\widehat{s}} - 1}{(\kappa_{ci} + 1)}. \tag{14}$$

However, I relax the assumption that the habit level is immune to the occurrence of a catastrophe in close proximity to the steady state. An important gain of this relaxation is that a well-defined distribution can be preserved, where $\kappa_{t,s}(\widehat{s})$ does not take on values larger than zero. Therefore, equivalent to equation (12), I assume the economy can be closed by solving for the remaining unknowns via

$$\kappa_{si}(s^{\max}) = 0. \tag{15}$$

It can be shown this leads to a monotone function of $\kappa_{si}(s)$ taking on negative values only. The calibration in the next section shows that this relaxation only leads to a small impact of a catastrophe on the habit level in close proximity to the steady state, and does not affect asset pricing implications to a large extent.

Lemma 1 *An equilibrium in this economy exists. The market prices of normal economic risk and catastrophic risks are given by equations (6) and (7), respectively, at the riskless interest rate determined by equation (8). The equilibrium restrictions in equations (10) to (15) lead to the identification of the sensitivity parameters θ and κ_{si}, as well as the parameter values for α, β_1, β_2, ν_1 and ν_2. They preserve a distribution of the surplus consumption ratio with a steady state $\widehat{s}$ and maximal value $s^{\max}$.*

Proof of Lemma 1. Since the habit is external, the investor's intertemporal rate of substitution equates to the state-price density in the form of

$$\xi_t = e^{-\rho t} e^{-\gamma s(t)} e^{-\gamma c(t)} e^{\gamma s(0)} e^{\gamma c(0)}. \tag{16}$$

Applying Ito's formula allowing for discontinuous innovations yields the process

$$\begin{aligned} d\xi_t &= -\rho \xi_t dt - \gamma \xi_t ds_t + .5\gamma^2 \xi_t \left(ds_t\right)^2 - \gamma \xi_t dc_t \\ &\quad + .5\gamma^2 \xi_t \left(dc_t\right)^2 + \gamma^2 \xi (ds_t dc_t) + \sum_{i=1}^{2} (\xi_t - \xi_{t-}) dN(\lambda_i), \end{aligned} \tag{17}$$

where ds_t corresponds to the continuous innovations of the log surplus consumption ratio, and dc_t to the continuous innovations of log consumption. After substitution, the state-price density process yields

$$\begin{aligned} d\xi_t &= -\rho \xi_t dt - \gamma \xi_t [\phi(\overline{s} - s_t) + \theta \sigma_c dB_t] + .5\gamma^2 \xi_t \theta^2 \sigma_c^2 dt \\ &\quad -\gamma \xi_t [(\mu_c - .5\sigma_c^2) dt + \sigma_c dB_t] + .5\gamma^2 \xi_t \sigma_c^2 dt + \gamma^2 \xi \theta_t \sigma_c^2 dt \\ &\quad + \sum_{i=1}^{2} [(\kappa_{ci} + 1)^{-\gamma} e^{-\gamma \kappa_{si}} - 1] \xi_{t-} dN(\lambda_i), \end{aligned} \tag{18}$$

through which the riskless interest rate, the market price of normal economic risk in equation (6), and the market prices of catastrophic risk in equation (7) can be identified. Based on the assumption of a constant interest rate, the functional form of θ can follow from

$$a = (\nu_1 + \nu_2 - 1)\gamma \phi(\overline{s} - s_t) - .5\gamma^2 \theta^2 \sigma_c^2 - .5\gamma^2 \sigma_c^2 - \gamma^2 \theta \sigma_c^2,$$

which, together with the restrictions (10) and (11) pin down a and $\overline{s}$. The implicit habit process can be found using the identity

$$X_t = C_t(1 - S_t).$$

In addition to Brownian motion risk, I need to examine the sensitivity of the habit with respect to Poisson risks, i.e.

$$\begin{aligned} dX_t &= (1-S_t)C_t(\mu_c dt + \sigma_c dB_t) - C_t S_t[(\phi(\overline{s}-s_t) + .5\theta^2\sigma_c^2)dt + \theta\sigma_c dB_t] \\ &\quad + \sum_{i=1}^{2}[C_{t-}(\kappa_{ci}+1)(1-S_{t-}e^{\kappa_{si}}) - C_{t-}(1-S_{t-})]dN(\lambda_i). \end{aligned} \tag{19}$$

If the habit level is immune to the occurrence of a catastrophe at the steady state, this requires

$$\frac{(\kappa_{ci}+1)(1-e^{s_t}e^{\kappa_{si}})}{(1-e^{s_t})} - 1 = 0 \tag{20}$$

for $i = 1, 2$ evaluated at $\overline{s}$. For completeness, the equivalent to determine sensitivity around the steady state is given by

$$\kappa'_{si} = \frac{-\kappa_{ci}e^{-s_t}}{\kappa_{ci}e^{-s_t}+1}. \tag{21}$$

The latter property, however, is neglected to preserve a distribution for which the process for the surplus-consumption ratio is well-defined at $s^{\max}$. Analytically,

$$\kappa_{si}(s^{\max}) = 0,$$

simplifies to

$$\left(\frac{\sigma_c + \frac{\sqrt{\nu_1+\nu_2-1}\sqrt{\phi}\kappa_{ci}}{\sqrt{\gamma}}}{\sigma_c + \sigma_c\kappa_{ci}}\right)^{-\gamma} - \frac{\gamma(\nu_i-1)(\gamma\sigma_c^2 - (\nu_1+\nu_2-1)\phi)(1+\kappa_{ci})^{\gamma}}{2(\nu_1+\nu_2-1)\lambda_i} = 1, \tag{22}$$

for $i = 1, 2$. Suppose that $\mu = \nu_1 + \nu_2 - 1$, then the solution for ν_i can be expressed in terms of μ as

$$\nu_i(\mu) = \frac{-2\mu(1+\kappa_{ci})^{-\gamma}\left(1 - \frac{\sigma_c + \frac{\sqrt{\mu}\sqrt{\phi}\kappa_{ci}}{\sqrt{\gamma}}}{\sigma_c+\sigma_c\kappa_{ci}} - \frac{\gamma(\mu\phi-\gamma\sigma_c^2)(1+\kappa_{ci})^{\gamma}}{2\lambda_i}\right)\lambda_i}{\gamma(\mu\phi-\gamma\sigma_c^2)}. \tag{23}$$

Upon substitution, an equilibrium follows from a fixed point as given by

$$\mu = \nu_1(\mu) + \nu_2(\mu) - 1, \tag{24}$$

which has a solution on the interval $\mu \in (\frac{\gamma\sigma_c^2}{\phi}, 1]$. For $\mu = \frac{\gamma\sigma_c^2}{\phi} + \epsilon$ the difference between the rhs μ and lhs $\nu_1(\mu) + \nu_2(\mu) - 1$ is strictly negative. It is continuous and increasing in μ with one root satisfying equation (24). At the solution for μ, it is verified that $1 - \nu_i(\mu)$, as given in equation (23), constitutes positive values smaller than one.

■

3 Quantitative Evaluation

3.1 Calibration

A calibration of the model requires the choice of 9 parameters. The growth rate and volatility of consumption, conditional on non-catastrophe times, are set to match the real U.S. consumption expenditure data. Based on the same time period for which cat bond data is available, the growth rate μ_c is 1.93% for total consumption expenditures, and 1.92% for non-durables only. The volatility of consumption σ_c is given by 0.99% and 1.32%, respectively. Hence, economic fundamentals are slightly smoother in the decade under observation as compared to the historical average of 1.5% used in Campbell and Cochrane (1999). Table 2 summarizes the calibration scenarios, in which scenario A corresponds to using total consumption expenditures, and scenarios B - D correspond to non-durable consumption expenditures. While both series are strongly positively correlated, the model is of course more accurately described by non-durable consumption measures, hence I display scenario A as a robustness check.

I choose the patience parameter ρ such that the interest rate r equals zero, allowing me to directly compute excess returns as used in the correlation exercise. This is mainly for simplicity, all predictions would hold if the calibration would target the average real riskless interest rate instead. I follow Campbell and Cochrane (1999) and Chen et al. (2009) in assigning the reverting rate ϕ to be 0.13, in order to match the serial correlation of historical price/output ratios.

The curvature parameter γ and the initial level of the state variable S are crucial in determining the size of risk premiums. As both are unobservable it is important to impose some discipline: I extract the starting level S^{start}, such that the average surplus consumption ratio between 2002 and 2011 equals the steady-state value. This leads to a starting value slightly below the steady state in all calibration scenarios. The corresponding maximal values are also shown in Table 2, and since the model is formulated in continuous time these are the true maximal values of the state variable distribution even after adding discontinuous shocks to the surplus consumption process. Scenario D follows Chen et al. (2009) in assigning a value 2.45 for γ, which is above the value of 2 suggested by Campbell and Cochrane (1999), and I also consider a scenario in which the investor is even more risk averse, with γ equal to 5. This leads to generous levels for the market price of normal economic risk η of .47 and above (at the steady state), confirming those studies' results. While such values are reasonable for long-term studies, they are above the realized Sharpe ratios during the time period of this study. Hence, I also assign a lower value for γ of 1.50, i.e. scenarios A and B, leading to a market price of risk of .31 which is more in line with recent data.

Finally, the remaining 4 parameters determine the degree of catastrophe risk in the economy. I choose the average first loss probabilities based on the data set of individual cat bonds, conditioning on the type of catastrophe as in Table 3, and assign the arrival intensity for non-windstorm risk λ_1 to be 1.08%, and λ_2 to be 2.79% for windstorm risk. Assuming independence among perils, this maps into the arrival of a catastrophe in consumption with a first loss probability of 3.87%, triggering a non-windstorm impact with probability 27.91% or a windstorm impact with 72.09%, respectively. The economic impact values, however, are not reported to investors. Hence, they are calibrated in order to match the observed spread levels at the steady-state level. Cat bond spreads equal between two and three times expected losses after controlling for several bond-specific characteristics of the individual cat bond data set, which is similar in magnitude to the spreads discussed in Cummins and Weiss (2009). Given the premium is larger for non-windstorm catastrophes, see specification 3 in Table 4, I assume λ_1^Q/λ_1 to be equal to 3, and λ_2^Q/λ_2 to be equal to 2.

The resulting impact values range between -1% and -3%. Given that the ratio λ_i^Q/λ_i is fixed I expect to observe less negative impact values for larger degrees of curvature. For γ equal to 5, for example, investors would anticipate an economic impact of windstorm (non-windstorm) catastrophes of -1.14% (-1.74%). The values for κ_{ci} are generally smaller for windstorm risk, as compared to non-windstorm risk, which appears plausible given experts' predictions about the potential impact of severe natural disasters. For example, the Mid-America Earthquake Center estimates that a possible earthquake in the Midwest U.S. reaching 7.7 on the Richter scale, due to New Madrid Seismic Zone, could result in economic losses of up to 400 billion USD. According to the U.S. Geological Survey, Southern California plans for a 7.8 earthquake, the San Andreas Fault, with an economic impact between 200 and 240 billion USD. Similarly, the Hayward Fault could affect Northern California with a 7.0 quake by up to 220 billion USD, according to Risk Management Solutions.[2] The anticipated magnitudes of windstorm impacts appear to be lower, with another category 4 hurricane like Katrina having a potential impact of up to 150 billion, and the projections of the even stronger 1926 Miami Hurricane to 2011 demographics show a similar magnitude.

Such values are smaller than the impact figures that would arise from man-made catastrophes. Barro (2006), for example, considers mainly wars and great depressions having a much larger

[2]Sources: Impact of Earthquakes on the Central USA, Mid-America Earthquake Center at the University of Illinois at Champaign-Urbana, Report 2008; 1868 Hayward Earthquake: 140-Year Retrospective, RMS Special Report 2008.

impact between -15% and -64% on output while attempting to match the equity premium. Even Du (2010), assuming habit preferences and γ values equal to 1, requires a jump size of -15.8% in order to explain implied volatility surfaces. Such large contractions should not be expected for the type of disasters securitized in cat bonds, in particular for advanced economies. An exception is the massive 1923 Tokyo Earthquake through which at least 40% of Japan's output was destroyed, but I claim such numbers are less likely to occur in today's times. The aggregate impact of the Great East Japan Earthquake and Tsunami of March 11, 2011 can not be determined yet.

3.2 Cat Bond Returns

Given this calibration, I will now analyze predictions that arise from the model and tie them to the cat bond market. For the quantitative evaluation I will use scenario B, i.e. the case assuming a curvature parameter of γ equal to 1.5, as well as shocks to non-durable consumption expenditures. The results based on scenarios A, C, and D are qualitatively similar.

The first prediction relates to the return/consumption correlation. Namely, does the model imply a cat bond return series that is comparable in magnitude to the actual return series? For shocks to consumption I use the 37 observations to non-durable consumption expenditures (normalized), and inject these as the series dB to the model. To generate a model-impled return I need to value a synthetic cat bond. Formally, the value of a (zero-coupon) cat bond at time t with maturity in T and face value of one unit is given by

$$CB(t,T) = E_t\left[\frac{\xi_T}{\xi_t}[(1 - I_{(t,T)}) + \omega(T) I_{(t,T)}]\right], \tag{25}$$

where $I_{(t,T)}$ is an indicator function that equals one if the stipulated catastrophe has occurred between t and T, and zero otherwise. Contingent on a catastrophe, the bond pays a recovery rate of $\omega(T)$ percent at time T. In general, the conditional expectation in equation (25) can be evaluated through simulation under the physical probability measure. However, for this problem it serves to be convenient to evaluate the expression under the risk-adjusted probability measure while discounting at the riskfree interest rate. Hence, the problem reduces to finding the risk-adjusted likelihood of a catastrophe between t and T via numerical integration. In order to generate a bond that is more representative for the cat bond market as a whole, I am assuming the multi-peril mapping explained in the previous subsection. According to the values in Table 3, a representative recovery rate is assumed to be 21.5%, and the time to maturity is assumed to be 43 months. After evaluating $CB(t,T)$, the percentage changes it the price series directly reveal excess returns.

Figure 4 shows the results. The correlation between the model-implied series and the actual return series based on the Swiss Re cat bond portfolio is 30.9%. Since this is a one-factor model, the correlation between dB and the model-implied return series is expected to be high, in this case 95%. I find that the model generates sufficient variation in the surplus consumption ratio such that implied returns and actual returns correlate realistically, and only slightly stronger than the 27.5% correlation between actual returns and consumption shocks observed in the data, see Table 1. As can also be seen in Figure 4, the model appears to track the return series more accurately since 2005, i.e. in post-Katrina times - possibly a reflection of market participants realizing that cat bonds are indeed subject to the most severe layers of risk.

3.3 Market Price of Cat Risks

The model does not only predict realized returns due to consumption shocks, but also ex-ante risk premiums. Since the calibration ties the model to the ratio λ_i^Q/λ_i equal to 3 and 2, respectively, we might ask what realizations of risk premiums one should expect in better or worse economic states. Figure 4 shows the market prices of cat risk as a function of the surplus consumption ratio. For example, to insure catastrophic risks in an extreme recessional state, the model implies that cat bond spreads can be equal to 10 or even 20 times expected losses. Assuming the opposite extreme, the amplification effect of the habit process vanishes and market prices approach the level that would be implied by standard CRRA preferences.

The adjustment in market prices at the occurrence of Katrina was one of the largest price movements that have occurred in the cat bond market thus far. Measured in return space, aggregate prices dropped more than 2% during the third quarter of 2005, as can be seen in Figure 1, and spreads increased accordingly. The data set of individual cat bonds was chosen specifically to contain the Katrina event. To predict the change in spreads at the occurrence of Katrina I first need to assess the impact of the hurricane on economic fundamentals. Katrina formed on August 23, 2005, and its final landfall as a category 3 storm took place on August 29, 2005. Direct estimates of the total economic cost of Katrina range between 100 and 200 billion dollars. For example, Risk Management Solutions estimates the total economic cost to be 125 billion dollars, which is between 1% and 1.5% of U.S. consumption. One economic channel through which the widespread nature on the aggregate economy can be explained is the destruction of several production technologies in the metropolitan areas of the Northern Gulf Coast. The hurricane disrupted oil refining activity and destroyed 10% of its U.S. capacity, such that, according to the Energy Information Administration, the price per barrel of U.S. crude oil peaked in September 2005 with a 12% price increase relative to pre-Katrina levels. Obviously, the economic impact is smaller while measured on a more aggregated level, and not all of the Katrina effect should be assumed permanent. In order to be more conservative I will use a .5% drop in consumption while perturbing the equilibrium to generate a Katrina prediction.

The results are shown in the bottom figure of Figure 2. The model predicts an increase in the market price of catastrophic risk of 7.5% for windstorm risk and of 10% for non-windstorm risk at the steady state, respectively. Why is this increase so steep for a relatively small decrease consumption, and why does the market price for non-windstorm risk increase stronger than the equivalent for windstorm risk? An explanation can be found in the existence of the habit. A shock to fundamentals of -.5% brings the investor closer to the habit. Of course a future catastrophe would bring the investor even closer to ruin such that individuals are willing to pay a larger price for insurance as compared to the pre-Katrina state. However, since the habit level is the same for all perils, a future negative shock of 3.3% in case of non-windstorm risk would leave the investor with more dramatic consequences as compared to a negative shock of 2.3% in case of a windstorm impact. To show this formally, suppose the economy is evaluated at the steady state, then the ratio of risk-adjusted relative to physical probability changes incrementally by

$$\frac{\partial \frac{\lambda_i^Q}{\lambda_i}}{\partial s} = \frac{\gamma \kappa_{ci} (\kappa_{ci} + 1)^{-\gamma} \left(\frac{1 + e^{-\widehat{s}} \kappa_{ci}}{\kappa_{ci} + 1} \right)^{-\gamma}}{e^{\widehat{s}} + \kappa_{ci}} < 0. \tag{26}$$

However, this effect is weaker for a less negative impact size κ_{ci} since

$$\frac{\partial^2 \frac{\lambda_i^Q}{\lambda_i}}{\partial s \partial \kappa_{ci}} = \frac{\gamma (\kappa_{ci} + 1)^{-\gamma} \left(\frac{1 + e^{-\widehat{s}} \kappa_{ci}}{\kappa_{ci} + 1} \right)^{-\gamma} (e^{\widehat{s}} - \gamma \kappa_{ci})}{(e^{\widehat{s}} + \kappa_{ci})^2} > 0. \tag{27}$$

This result implies that at the occurrence of Katrina, cat bond prices should have reacted stronger for non-windstorm risk, as compared to windstorm risk, a prediction that can be tested in the data. I define an indicator variable ‘wind’ that equals 1 if the bond is subject to windstorm risk, and zero otherwise. In addition, ‘post kat’ is an indicator variable that equals 1 if the observation corresponds to post-Katrina, zero otherwise, and I interact these variables with ‘expected losses’ in the multiple regression analysis. The results shown in specifications 4 and 5 of Table 4 confirm the prediction. Cat bond spreads significantly increased from 2.37 to 2.79 times expected losses, and this increase was stronger for non-windstorm risk. Namely, windstorm risk increased from 2.29 to 2.78 times expected losses, while non-windstorm risk increased from 2.74 to 3.6 times expected losses.

We should not expect, however, that the model is able to explain the entire observed increase. At the state variable realization corresponding to Katrina the model-implied spreads increase 10% and 6.5%, while the observed increases are 31% and 21%, respectively. Hence, about a third of the market reaction can be linked to economic fundamentals. Of course there can be additional channels at work here that also deliver comovement across perils and that the models does not capture, such as learning patterns about catastrophes and emergency relief.

3.4 Cat Bonds versus Corporate Bonds

Cat bond returns and corporate bond returns also correlate significantly during the time period of our study, and they should. For example, the correlation between Swiss Re cat bond returns and the return of the FINRA high yield corporate bond portfolio is 41%, and with the Barclays Bond Index it is even 44%, see Table 1. And they might correlate not necessarily because corporate bonds are subject to catastrophe risk, but because they are part of the same universe of marketable assets. It is generally difficult to determine how much catastrophe risk is shared through the stock market and the corporate bond market, and to which extent corporations expose themselves to such layers of risk. But due to the existence of the habit process, cat bonds and corporate bonds would correlate even if corporations had zero exposure to cat risks.

A comparison between the two is often made in ex-ante terms. For simplicity I show the case in which corporate bonds are subject to normal economic risk, and cat bonds are subject to cat risk only. Corporate bonds are studied in Chen et al. (2009) in the context of the habit model based on normal economic risk. Following the constant default boundary case in their paper I first compute the price of a one-year hypothetical corporate bond with an annual expected loss of 3.87%. In addition, I compute the equivalent market price of catastrophe risk assuming the same annual expected loss. Figure 4 shows both cases expressed as the ratio of premium/expected loss as a function of the surplus consumption ratio.

The main message is that although both bonds are subject to the same expected loss figure we should not expect both bonds to trade at the same price. In very prosperous states the difference appears minimal, i.e. above .09 of the surplus consumption ratio. In recessional states, however, the difference can be very substantial and the ratio of premium/expected loss can be twice as large for cat bonds. Averaging over all states, this calibration predicts that cat bonds trade at significantly larger premium/expected loss ratios relative to comparable corporate bonds. Please note, depending on the state the difference between the two bonds is ambiguous as there is small region in which the corporate bond has a higher ratio, i.e. at a surplus consumption ratio between .09 and .10.

In order to take this prediction to the data I assume that the rating is a criterium allowing me to compare bonds with similar expected loss figures. Specifically, I express cat bond spreads relative to the spread derived from a representative corporate bond (issued by firms in the financial sector) with the same rating and the same time to maturity. The data source for corporate bond spreads is the Merrill Lynch fixed income database, containing 'rating-specific' constant-maturity yield curves, interpolated to match the time to maturity of the respective cat bond. Table 5 shows the results of a multiple regression analysis. The univariate result shows that cat bond spreads were 3.24 times the spread of comparable corporate bond. The impact of expected losses as a pricing determinant does not entirely vanish, as shown in specifications 2 to 4; while statistically significant, this effect does not appear to be economically significant. After controlling for the same bond-specific characteristics as in Table 4, I find that cat bonds offer a yield spread approximately twice the size of equally-rated corporate bonds, thereby conforming the prediction qualitatively.

3.5 Habit Sensitivity

To construct an equilibrium subject to normal economic risk as well as cat risks, I relaxed the assumption of a predetermined habit in close proximity to the steady state. As a result it could be possible that consumption and habit do not move in the same direction at the occurrence of a catastrophe. Hence, it is important to examine the characteristics of the implied habit process (dx/dc) to rule out implausible cases, see Figure 4. The sensitivity with respect to normal economic risk confirms equation (11) in that any positive shock dB will have a non-negative impact on the habit level. The lower figure shows the sensitivities with respect to cat risk, and I find that a small violation occurs for some values of the surplus consumption ratio in the case of non-windstorm risk. However, the violation is very small. A -3.27% drop in consumption leads to an increase in the habit level of less than .01% in the worst case, and I infer that relaxing the predetermined habit in close proximity to the steady state does not lead to implausible cases.

4 Conclusion

The first conclusion of this paper is that, contrary to the often held belief, returns of cat bonds do not appear uncorrelated with economic fundamentals. Hence, the natural follow-up question is to which extent cat bond prices can be explained via investor preferences. Adding rare events to an otherwise standard habit-based model allows for several insights. It implies a reasonable correlation structure between model-implied and actual cat bond returns, and even relatively small shocks in consumption amplify to the level of yield spreads observed in the data. The reward per unit of risk can be different for normal economic risk relative to catastrophe risk as seen in the comparison of corporate bonds versus cat bonds. Of course this consumption-based evaluation generates systematic risk only, all idiosyncratic components in cat bond market remain unexplained.

Quarterly	**37 obs**								
	CON all	CON nd	CAT bb	CAT all	SPX	VIX	CB hy	CB ig	BCB
CON all	1.000								
CON nd	0.807	1.000							
CAT bb	0.191	0.252	1.000						
CAT all	0.201	0.275	0.966	1.000					
SPX	0.396	0.452	0.366	0.426	1.000				
VIX	-0.153	-0.300	-0.213	-0.228	-0.689	1.000			
CB hy	0.305	0.436	0.455	0.414	0.634	-0.502	1.000		
CB ig	-0.036	0.002	0.263	0.218	0.108	-0.283	0.577	1.000	
BCB	0.497	0.472	0.452	0.441	0.288	-0.132	0.635	0.524	1.000

Quarterly	**36 obs**								
	CON all	CON nd	CAT bb	CAT all	SPX	VIX	CB hy	CB ig	BCB
CON all	1.000								
CON nd	0.751	1.000							
CAT bb	0.120	0.188	1.000						
CAT all	0.148	0.232	0.965	1.000					
SPX	0.358	0.423	0.345	0.410	1.000				
VIX	0.026	-0.147	-0.158	-0.186	-0.681	1.000			
CB hy	0.126	0.285	0.424	0.390	0.628	-0.406	1.000		
CB ig	-0.338	-0.302	0.201	0.166	0.025	-0.126	0.463	1.000	
BCB	0.283	0.232	0.447	0.459	0.229	0.166	0.510	0.312	1.000

Monthly	**112 obs**								
	CON all	CON nd	CAT bb	CAT all	SPX	VIX	CB hy	CB ig	BCB
CON all	1.000								
CON nd	0.521	1.000							
CAT bb	0.148	0.158	1.000						
CAT all	0.156	0.175	0.966	1.000					
SPX	0.119	-0.011	0.230	0.251	1.000				
VIX	-0.076	0.012	-0.198	-0.199	-0.690	1.000			
CB hy	0.028	-0.007	0.270	0.250	0.591	-0.478	1.000		
CB ig	0.004	0.032	0.300	0.268	0.217	-0.334	0.607	1.000	
BCB	0.107	0.099	0.407	0.384	0.278	-0.365	0.537	0.769	1.000

Table 1: **Correlations between 01/01/2002 and 4/29/2011.** The table shows pairwise correlations among the following variables: CON all and CON nd are the growth rates of real U.S. personal consumption expenditures, total and non-durables, respectively; CAT all and CAT bb are the excess returns of the Swiss Re cat bond portfolios, all bonds (SRCATTRR) and bb-rated bonds (SRBBTRR), respectively; SPX is the excess return of the S&P 500 index; VIX is the change in the VIX index; CB hy and CB ig are the excess returns of the FINRA corporate bond portfolios, high yield (NBBHTR) and investment grade (NBBITR), respectively; BCB is the excess return of the Barclays bond index (BNDUS), formerly the Lehman Bros corporate bond Index. The T-Bill return is assumed to compute excess returns, all return series are deflated. The source for financial data is Bloomberg, the source for consumption and cpi data is FRED. The top panel is based on 37 quarterly observations; middle Panel is based on 36 quarterly observations excluding the 3rd quarter of 2008, the bottom panel is based on 112 monthly observations.

	Scenario A	Scenario B	Scenario C	Scenario D
μ_c	0.0193	0.0192	0.0192	0.0192
σ_c	0.0099	0.0132	0.0132	0.0132
ρ	0.0396	0.0406	0.2032	0.0847
ϕ	0.13	0.13	0.13	0.13
λ_1	0.0108	0.0108	0.0108	0.0108
κ_{c1}	-0.0246	-0.0327	-0.0174	-0.0247
λ_2	0.0279	0.0279	0.0279	0.0279
κ_{c2}	-0.0176	-0.0233	-0.0114	-0.0169
γ	1.50	1.50	5.00	2.45
S^{start}	0.0306	0.0407	0.0707	0.0488
$\widehat{S}$	0.0474	0.0629	0.0884	0.0684
S^{max}	0.0781	0.1036	0.1452	0.1126
$\eta(\widehat{S})$	0.3130	0.3142	0.7454	0.4720
r	0.00	0.00	0.00	0.00
$\lambda_1^Q/\lambda_1(\widehat{S})$	3.00	3.00	3.00	3.00
$\lambda_2^Q/\lambda_2(\widehat{S})$	2.00	2.00	2.00	2.00

Table 2: **Calibration and Parameter Values.** The table shows 4 calibration scenarios. Scenario A corresponds to quarterly consumption data, total personal expenditures; Scenarios B - D correspond to quarterly consumption data, non-durables only. The consumption data covers 37 quarters between 01/01/2002 and 4/29/2011. In addition to the parameters explained in the main text, S^{start} is the start value, $\widehat{S}$ is the steady-state value, and S^{max} is the maximal value of the surplus consumption ratio, respectively.

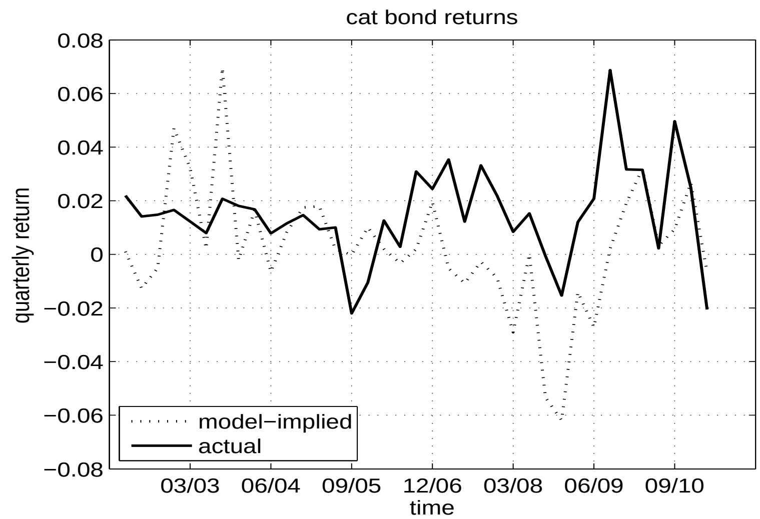

Figure 1: **Cat Bond Returns.** The figure shows the time series of actual and model-implied cat bond returns. The actual return series corresponds to deflated quarterly excess returns of the Swiss Re cat bond portfolio (SRCATTRR) between 01/01/2002 and 4/29/2011. The model-implied return series corresponds to the calibration scenario B based on shocks to non-durable consumption expenditures. It is assumed that the hypothetical catastrophe bond is subject to an annual cat likelihood of 3.87%, triggering an earthquake catastrophe with probability 27.91% or a windstorm catastrophe with 72.09%, respectively. In either case, the recovery rate is assumed to be 21.5%. The time to maturity is assumed to be 43 months.

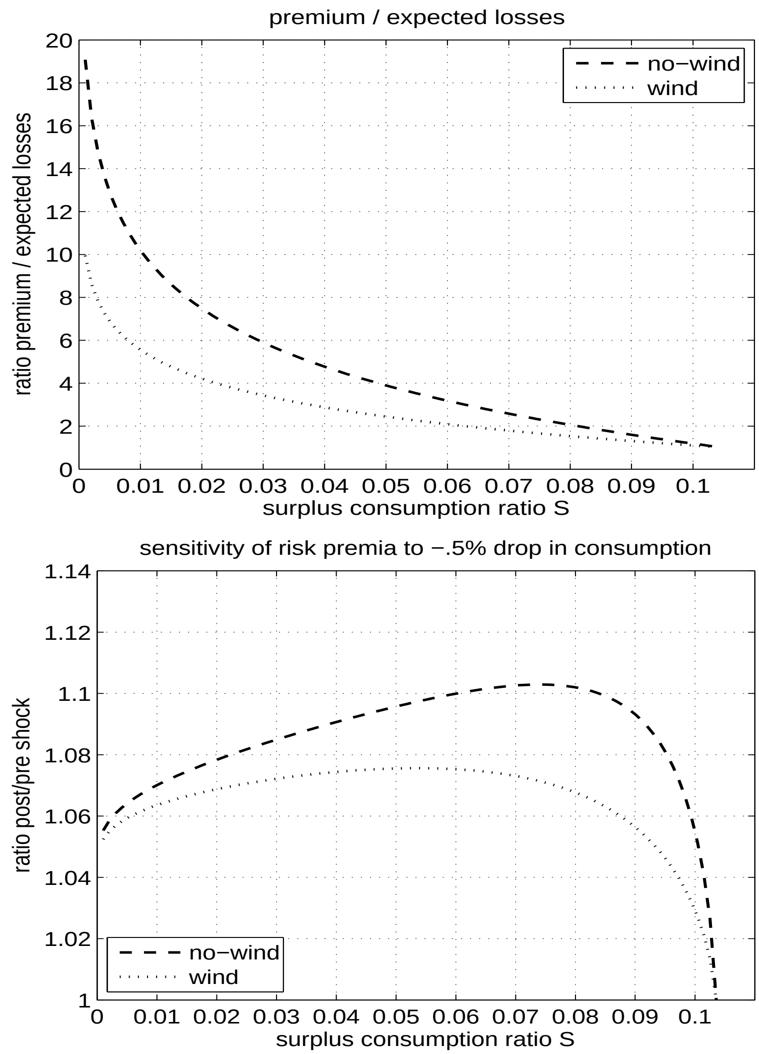

Figure 2: **Market Price of Catastrophic Risks.** The top figure displays the market price of catastrophic risks, expressed as the ratio of λ_i^Q/λ_i as a function of the surplus consumption ratio. The parameter values correspond to calibration scenario B, the arrival likelihood of non-windstorm catastrophes is given by $\lambda_1 = 1.08\%$, and the arrival likelihood of windstorm catastrophes by $\lambda_2 = 2.79\%$. The bottom figure displays the sensitivity of λ_i^Q with respect to a .5% drop in consumption, expressed at the ratio post/pre perturbation.

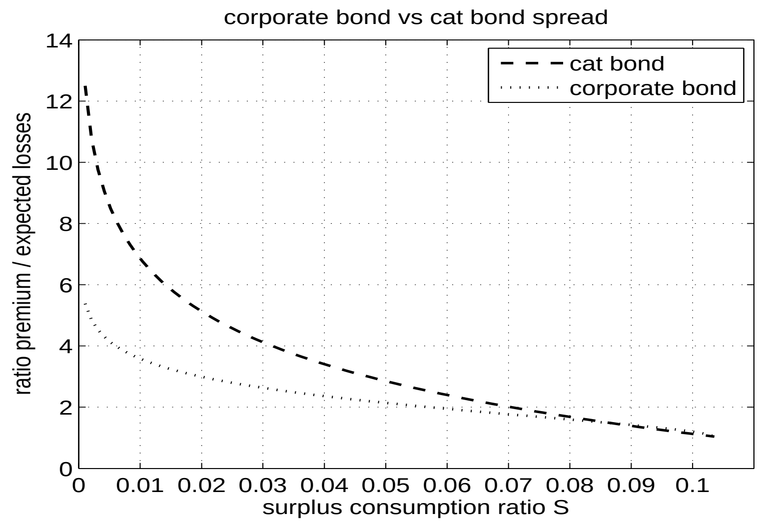

Figure 3: **Cat Bond Spreads versus Corporate Bond Spreads.** The figure displays the market prices of risk expressed as the ratio of premium/expected loss, as a function of the surplus consumption ratio. The parameter values correspond to calibration scenario B. It is assumed that both bonds are subject to an annual expected loss figure of 3.87%. The corporate bond is subject to normal economic risk, the catastrophe bond is subject to cat risk only – triggering an earthquake catastrophe with probability 27.91% or a windstorm catastrophe with 72.09%, respectively. For either bond, the recovery rate is assumed to be 0%. The time to maturity is 12 months.

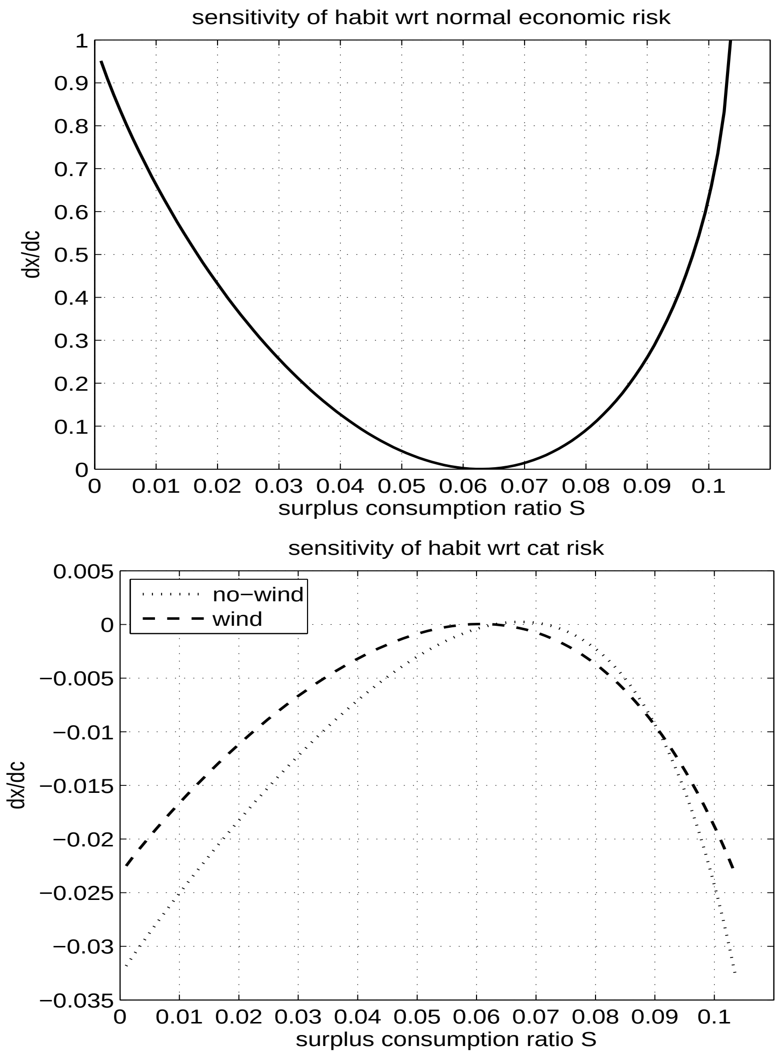

Figure 4: **Sensitivity of the Habit Level.** The top figure displays the sensitivity of the habit level with respect to regular economic risk, and the bottom figure displays the sensitivity of the habit level with respect to catastrophe risk. The parameter values correspond to calibration scenario B.

	mean	median	min	max	std dev	wind	no wind	indem	no indem
prem	539.6	429.9	90.2	1870.6	397.7	692.9	344.8	544.6	538.5
expl	158.9	128.0	15.0	486.0	147.1	219.0	82.5	115.7	168.6
prem / expl	4.3	3.8	1.4	20.2	2.3	3.8	5.0	6.3	3.9
p loss	205.4	159.0	23.4	597.0	189.2	279.0	107.8	174.3	210.2
loss gc	0.785	0.805	0.439	0.917	0.088	0.785	0.785	0.731	0.797
amount	58.1	25.0	1.8	300.0	60.9	54.1	63.3	127.3	42.6
age	24.9	25.7	2.7	92.6	13.9	22.3	28.3	12.0	27.8
ttm	17.5	12.3	3.3	52.3	11.5	18.3	16.6	22.6	16.4
no bonds	61	61	61	61	61	33	28	13	48

Table 3: **Descriptive Statistics.** The table shows descriptive statistics of the individual cat bond data set along the variables: prem (annualized premium in basis points), expl (annualized expected loss in basis points), the ratio of prem/expl, p loss (annualized probability of a catastrophe leading to a loss to bondholders), loss gc (expected loss to bondholder given the occurrence of a catastrophe), amount (notional in millions), age (in months), ttm (time to maturity in months), indem (bond is subject to an indemnity trigger), wind (bond is subject to windstorm risk). The data includes 61 cat bonds observed between 3/31/2005 and 03/31/2006. It is compiled from three sources: The main source are publications and trade notes by Lane Financial L.L.C. Those publications contain data of individual secondary market prices obtained from several different vendors, including Goldman Sachs, Lehman Brothers, Aon, and Cochran Caronia. The same data source contains several bond specific characteristics. Those are merged with cat bond data available in publications by Guy Carpenter and Company L.L.C., and the online deal directory available through Artemis, www.artemis.bm. While merging all three sources I did not find inconsistencies. Spreads are reported end-of-quarter, mid-market, averaged over vendors, and are converted to a 365 days per year convention to make them comparable to an annual measure of expected losses. Observations with a ratio of spread over expected losses larger than 20 are excluded, I consider them as outliers. This affects 5 bonds, and could be due to erroneous recording of prices and/or expected losses. The only cat bond that triggered due to the occurrence of Katrina, Kamp Re 2005, is excluded.

	(1)	(2)	(3)	(4)	(5)
intercept	86.14	42.02	59.80	38.08	114.73
	6.92	1.46	1.89	1.67	1.44
expl	2.54	2.58	2.53	2.37	2.29
	64.11	51.90	49.49	59.11	41.84
expl * (1-wind)			0.88		0.45
			1.57		1.65
expl * post kat				0.42	0.49
				7.06	6.11
expl * (1-wind) * post kat					0.86
					1.76
indem		124.47	111.46	124.47	111.46
		3.45	3.61	3.58	3.82
amount		-0.09	0.04	-0.09	0.04
		-0.68	0.24	-0.73	0.26
age		-0.83	-1.17	-0.83	-1.17
		-2.29	-2.37	-2.61	-2.58
ttm		1.88	1.45	1.88	1.45
		2.09	1.76	2.15	1.84
1-wind			-71.97		-71.97
			-1.79		-2.00
R - squared	0.89	0.90	0.91	0.92	0.93

Table 4: **Cat Bond Spreads - Multiple Regressions.** The table shows coefficient estimates of a multiple regression with t-statistics below the point estimate, using 'prem' as a dependent variable. In addition to the variables displayed in Table 3, 'indem' is an indicator variable that equals one if the bond has an indemnity trigger, 'wind' is an indicator variable that equals one if the bond is subject to windstorm risk, 'post kat' is an indicator variable that equals one if the observation corresponds to post-Katrina. All specifications include time fixed effects.

	(1)	(2)	(3)	(4)
intercept	3.24	2.61	2.00	2.81
	17.25	8.89	8.73	3.67
expl		0.01	0.01	0.01
		3.44	4.20	3.16
indem			2.25	1.75
			3.99	3.17
amount				0.00
				1.03
age				-0.02
				-1.25
ttm				-0.02
				-1.06
R - squared	0.00	0.09	0.27	0.29

Table 5: **Cat Bond Spreads versus Corporate Bond Spreads - Multiple Regressions.** Cat bond spreads are expressed relative to an equivalent corporate bond (issued by the firms in the financial sector) with same rating and same time to maturity. The table shows coefficient estimates of a multiple regression with t-statistics below the point estimate, using cat prem / corp prem (relative to swap yield) as a dependent variable. The data source for corporate bond spreads is the Merrill Lynch fixed income database, containing 'rating-specific' constant-maturity yield curves, interpolated to match the ttm of the respective cat bond.

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