

# An Analysis of the Market Price of Cat Bonds

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## Abstract

**Motivation.** Existing models of the market price of cat bonds are often overly exotic or too simplistic. We intend to offer a model that is grounded in theory yet also tractable. We also intend for our analysis of cat bond pricing to shed light on broader issues relating to the theory of risk pricing.

**Method.** We analyze several years of cat bond prices “when issued.”

**Results.** We describe the market clearing issuance price of cat bonds as a linear function of expected loss, with parameters that vary by peril and zone.

**Conclusions.** The results provide a compact form of describing market prices of cat bonds and thus provide a framework for measuring differences in prices across various perils and zones; the results also allow us to measure changes in the price function over time. The results also suggest an overarching theory of risk pricing, in which price depends on two factors: the first factor is the required rate of return on downside risk capital in a portfolio context, and the second factor is the uncertainty of the estimate of the expected loss.

**Keywords.** Cat bonds; Insurance Linked Securities (ILS); market price of risk; reinsurance

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## 1. INTRODUCTION

Describing the market price of property catastrophe (cat) bonds is important on two planes: the practical and theoretical. On the practical plane, firms desire to know how prices have behaved in the past, how prices vary by type of risk, and, potentially, how prices will behave in the future. Moreover, a model that accurately describes prices can also assist in benchmarking an observed price relative to a predicted price. On the theoretical plane, describing the market price of cat bonds illuminates the more general question of risk pricing, which relates to reinsurance contracts and other risk bearing transactions.

### 1.1 Research Context

Cat bond pricing has been investigated in Lane [6]. More recently, Gatamel [2] has reviewed Lane’s model as well as other models of risk pricing.

### 1.2 Objective

Our objective is to propose a model that describes the market clearing price of cat bonds.<sup>1</sup> We propose a model that builds on theory, parsimoniously conforms to empirical data, and accentuates

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<sup>1</sup> We do not intend for our model to address the full spectrum of complex issues that affect the prices of cat bonds. Rather, our proposed model, like all models, serves only as an approximation to reality.

practicability.

## **2. BACKGROUND**

Insurance and reinsurance companies have used “cat bonds” to transfer, for a price, the risk of property catastrophe (cat) loss to investors.<sup>2</sup> Essentially, investors supply capital equal (usually) to the amount of the bond; the capital is then available to pay any covered losses from property catastrophe as defined in the bond. The insurance and reinsurance companies who sponsor the bonds thus hedge their exposure to cat risk, while investors earn return on capital via the coupon payments on the bonds.<sup>3</sup> If no cat event takes place, the investors receive all the coupon payments and return of principal, whereas if a cat loss does occur, the investors will typically lose out on some coupons and also sustain loss of principal.

The coupon rate received by the investors is usually split into two components. First, because the investors contribute money for one (or more) years, the investors receive interest payments for the time value of their money, which is usually based on the LIBOR rate.<sup>4</sup> In addition, the investors are subject to a potential cat loss, so they receive an additional coupon rate for taking on this risk; this additional coupon rate, quoted as a percentage of the amount of the bond, can be referred to as “risk premium,” “risk spread,” “spread over LIBOR,” and “spread.” In this paper, we will use the term “spread.” Thus, we can say that:

$$\text{Total coupon rate \% to investors} = \text{LIBOR \%} + \text{spread \%} \quad (2.1)$$

The LIBOR rate is intended to compensate investors primarily for the holding of their money but not for cat risk; thus the spread is the component of the coupon rate that relates to the event

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<sup>2</sup> This section serves as basic introduction and background for the purpose of discussing the market price of cat risk. It is not intended as a comprehensive text on the cat bond market. Therefore, we caution the reader that some statements that are generally true may have caveats and exceptions; we typically choose not to highlight these caveats and exceptions, because our concerns are materiality and brevity.

<sup>3</sup> We caution the reader that this section serves as a streamlined background and does not address all the various technicalities of cat bonds. One example of a technicality is that an insurance company typically uses a Special Purpose Vehicle (SPV) to “issue” the bond; the company only “sponsors” the bond. In this paper, we use the terms “sponsor” and “issue” interchangeably.

<sup>4</sup> Technically, the time value of money should be based on a risk-free rate. The LIBOR rate, which is slightly higher than the risk-free rate, incorporates a modest amount of credit risk as well. Thus the reach for higher yield has served as a Trojan horse to insinuate credit risk into the cat bond market; these issues are beyond the scope of this paper.

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risk of a cat loss. Therefore, we will generally use the spread to measure the “price” of risk transfer of cat risk:

$$\text{Price of risk transfer} = \text{spread \%} \quad (2.2)$$

While the spread represents the price of the bond, it does not measure the “net cost” to the sponsor of the bond. After all, the sponsor has a mathematical expectation of receiving some cat loss recoveries from the bond; the “annual average loss” (AAL) or “expected value” measures this quantity. In fact, as part of the bond issuance process, the sponsor will typically hire a third-party cat modeling firm to estimate the expected loss (which is then usually expressed as a percentage of the amount of the bond, a convention we follow in this paper). Usually, the spread should exceed the modeled expected loss, because the spread should be large enough to provide for the mathematically average loss and still provide some additional rate of return (above zero). Thus we can say:

$$\text{Spread \%} = \text{expected loss \%} + \text{additional rate of return \%} \quad (2.3)$$

$$\text{Spread \%} = \text{expected loss \%} + \text{margin \%} \quad (2.4a)$$

$$\text{Margin \%} = \text{spread \%} - \text{expected loss \%} \quad (2.4b)$$

Generally, these values are quoted as percentages of the amount of the bond; thus in this paper the terms “spread,” “expected loss,” and “margin” will typically be used in the context of “as a percentage of the bond amount.” We also note that the bond amount is analogous to the occurrence limit and the aggregate limit of a property cat reinsurance contract; we will therefore use the term “limit” interchangeably with “bond amount.”<sup>5</sup>

The question we investigate in this paper relates to the market pricing of cat bonds: how can we explain and predict the spreads of cat bonds? Do models of spread behavior conform to conceptual frameworks and also conform to empirical evidence? How does a theory of risk pricing inform our

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<sup>5</sup> Where “limit” is the “100% limit” reduced for “co-participation” or “coinsurance.”

choice of model? Simultaneously, how does our inspection of empirical data affect our theory of risk pricing? These are the themes we explore in this paper.

### **3. MODELS OF CAT BOND PRICES**

Each buyer and seller in the market uses his own risk preferences to evaluate price. Models of cat bond prices do not necessarily attempt to replicate the exact risk preferences and decisions of each market participant; rather, using a macro-level perspective, they describe the observed market clearing price, which is the outcome of all the risk preferences of all the individual buyers and sellers.

Before proceeding with our analysis, we discuss several pre-existing models of cat pricing and describe what motivates us to find an alternative model. Because the issue of pricing for cat risk arises in both the cat bond market as well as the traditional reinsurance market, we discuss models of cat risk pricing that derive from both sources.

#### **3.1 Some Existing Models**

One existing model of spreads is “multiple of expected loss.” Practitioners in the cat bond market often measure, report, and benchmark cat bond spreads as a “multiple of expected loss.” Implicitly, they espouse a model such that:

$$\text{Spread \%} = \text{expected loss \%} * \text{multiple} \quad (3.1)$$

In this model, the parameter “multiple” varies quite significantly: when expected loss is large, the multiple is small, and when expected loss is small, the multiple is large. As a result, the “multiple of expected loss” model is neither a complete nor an accurate description of spread. Thus one of our central motivations is to find an alternative model that better describes spread behavior, yet preserves both the parsimony and tractability of the “multiple of expected loss” model.

A different class of existing models focuses on some form of volatility metric or risk measure of the individual bond (or layer or “tranche”) in order to model the spread. Thus:

$$\text{Spread \%} = \text{expected loss \%} + \text{margin \% based on standalone risk} \quad (3.2)$$

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This family of models includes:

1. Margin % = function of standalone standard deviation.<sup>6</sup>
2. Margin % = function of conditional expected loss (i.e., conditional severity).<sup>7</sup>

One problem with using standard deviation is that for highly skewed distributions, which are prevalent in property cat reinsurance, standard deviation is not an accurate description of extreme downside risk; rather, the skewed downside risk must be measured using other metrics.<sup>8</sup> Thus we hypothesize that the following model, which focuses on the extreme downside of total amount of capital at risk, might be a suitable candidate:

$$\text{Spread \%} = \text{expected loss \%} + \frac{(\text{amount of capital at risk} * \text{required rate of return on capital \%})}{\text{amount of the bond}} \quad (3.3)$$

For typical cat bonds, a severe downside loss can wipe out the entire principal; so the amount of “capital at risk” equals the full amount of the bond. Returning to equation (3.3), if we replace the term “amount of capital at risk” with “amount of the bond” and cancel the term in the numerator and the denominator, we derive:

$$\text{Spread \%} = \text{expected loss \%} + \text{required rate of return on capital \%} \quad (3.4)$$

Another problem with the standalone standard deviation and conditional severity models is that they violate a key principle of risk pricing: that one ought to measure risk not on a standalone basis but rather in a portfolio context. Thus the standard deviation or conditional severity of a particular bond should be much less important in a portfolio context—what matters is the bond’s contribution to the total risk of the portfolio, which may differ from its standalone volatility.<sup>9</sup>

What attribute of a cat bond can approximately indicate its contribution to the risk of the overall

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<sup>6</sup> See Kreps [5]; this model enjoys widespread popularity in the traditional reinsurance market.

<sup>7</sup> See Lane [6].

<sup>8</sup> See Kozik [4].

<sup>9</sup> Indeed, Kreps [5] states quite explicitly that a price based on standalone standard deviation should be viewed only as an upper bound of the price, whereas the actual market price should be lower.

portfolio?<sup>10</sup> In the context of property catastrophe risk, it seems that different perils ought to behave independently of one another; thus, we would expect virtually no connection or correlation between losses on a bond covering Southeast USA Hurricane and losses on a bond covering California Earthquake. At the same time, two bonds that both cover California Earthquake would likely tend to be correlated—if there’s a loss on one bond, there will likely be a loss on the second bond as well. So a bond’s covered “peril and geographical zone” (often “peril” for short), such as Southeast USA Wind, California Earthquake, etc., ought to be important for understanding a bond’s contribution to the risk of the total portfolio.

### 3.2 Initial Hypothesis

As a result of the discussion above, our initial hypothesis is that cat bond pricing ought to conform to the following model:

$$\text{Spread \%} = \text{expected loss \%} + \text{peril specific required rate of return on capital \%} \quad (3.5)$$

$$\text{Spread \%} = \text{expected loss \%} + \text{peril specific margin \%} \quad (3.6)$$

Such a model states that a bond’s spread over LIBOR must be large enough to cover the expected loss and also provide an “additional rate of return on capital” to compensate for the bond’s contribution to total portfolio risk, which varies based upon the covered peril. One advantage of this type of model, in which the compensation for risk is expressed as an additional rate of return, is its similarity to other bond market models.<sup>11</sup> In addition, such a model would satisfy the intuition of practitioners that:

1. If a bond’s expected loss is small, then the spread’s “multiple of expected loss” is relatively high.

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<sup>10</sup> This “overall portfolio” could theoretically be as diverse as the portfolio of all investments opportunities, but we note that taking cat risk may require critical mass of time, money, and expertise, which implies an “overall portfolio” that is concentrated in cat bonds. At the same time, cat bond pricing can be influenced by pricing in the traditional reinsurance market. So the “overall portfolio” in which we evaluate the risk of a cat bond may range from the portfolio of all investment opportunities to the portfolio of all cat bonds to the portfolio of all reinsured exposures; or it may reflect a mixture of these various perspectives. This issue requires further research.

<sup>11</sup> Hull [3].

2. If a bond's expected loss is large, then the spread's "multiple of expected loss" is relatively low.

### 3.3 Revised Hypothesis

A cursory glance at cat bond market prices, however, shows that this model does not fully describe the data. Rather, as the expected loss increases, not only does the spread increase, but the margin itself (which equals spread minus expected loss) tends to increase as well. This surprising phenomenon occurs in the corporate bond market as well, where it is sometimes referred to as the "credit spread puzzle."<sup>12</sup>

We therefore revise our hypothesis and propose the following model:

1. Spread % = expected loss % + peril specific margin %
2. Peril specific margin % = increasing function of expected loss %

To describe margin as an increasing function of expected loss, we begin with a basic model, a linear relationship:

$$\text{Peril specific margin \%} = \text{peril specific flat margin \%} + \frac{\text{peril specific factor} *}{\text{expected loss \%}} \quad (3.7)$$

Combining all the pieces of equations (3.6) and (3.7), we obtain:

$$\text{Spread \%} = \text{expected loss \%} + \text{peril specific flat margin \%} + \frac{\text{peril specific factor} *}{\text{expected loss \%}} \quad (3.8)$$

Or, more concisely, we have a straightforward linear function to describe spread:

$$\text{Spread \%} = \text{peril specific flat margin \%} + \text{expected loss \%} * (1 + \text{peril specific factor}) \quad (3.9)$$

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<sup>12</sup> Hull [3].

Or, for each peril, we can say:

$$\text{Spread \%} = \text{constant \%} + \text{loss multiplier} * \text{expected loss \%} \quad (3.10)$$

Because the variables of “spread,” “constant,” and “expected loss” are defined as “% of bond amount,” we also wish to show the equation in dollar terms. Multiplying both sides of the equation by “bond amount,” we obtain:

$$\text{Spread \$} = \text{bond amount \$} * \text{constant \%} + \text{loss multiplier} * \text{expected loss \$} \quad (3.11)$$

This form of the model clarifies that the total dollar price of risk transfer in the cat bond market is a linear function of expected loss and bond amount.

Similarly, we note that we can rewrite equation (3.11) in the terminology of traditional reinsurance<sup>13</sup>:

$$\text{Premium \$} = \text{aggregate limit \$} * \text{constant \%} + \text{loss multiplier} * \text{expected loss \$} \quad (3.12)$$

This form of the model clarifies that the total dollar price of risk transfer in the reinsurance market is a linear function of expected loss and aggregate limit.

One favorable aspect of this type of model, as described in equations (3.10), (3.11), and (3.12), is that it satisfies the “no arbitrage principle of pricing” as described by Venter [9]. In contradistinction, a pricing model based on standalone standard deviation violates the principle of “no arbitrage.”

### **3.4 Conjecture on Revised Hypothesis**

Why does the original hypothesis, “spread % = constant % + expected loss %,” fail? Why do we

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<sup>13</sup> Here the “spread” is the “price” (or “premium”) and the “bond amount” is the aggregate limit. This analogy holds for reinsurance contracts that have no reinstatement premium and no reinstatement of limit. We require further research to determine how to adapt the cat bond pricing formula for a reinsurance contract with reinstatable limit and premium.



need the revised model, “spread % = constant % + loss multiplier \* expected loss %”? Why does the expected loss need to be multiplied by a factor to obtain a viable model for spread? What does the “loss multiplier” represent? On one hand, we do not strictly need to answer these questions; so long as one model does a superior job of approximating, describing, and predicting reality, we should generally choose the better model (all else equal). On the other hand, formulating a reasonable conjecture about why a promising initial model fails, and why a modified model works better, can provide insight and potentially assist us in our later analysis.

Our conjecture is that the “loss multiplier” parameter relates to uncertainty in the expected loss estimate. Recall that we do not actually know the true underlying value of expected loss; rather, cat modeling firms, using computer software, provide values that are merely estimates of the true expected loss.<sup>14</sup> Perhaps if we knew the precise value of expected loss, then we could say that a reasonable model is “spread % = constant % + expected loss %.” But given the uncertainty in the estimated expected loss, we must amend the model to say that “spread % = constant % + loss multiplier \* expected loss %.”<sup>15</sup>

## **4. ANALYSIS OF EMPIRICAL DATA**

In this section, we discuss the underlying data that we use in our analysis and investigate the results of fitting parameters of our proposed model to the empirical data.

### **4.1 Data and Limitations**

When investigating the price of risk in the cat bond market, we can analyze the spreads of bonds “when issued” (when they are first bought by investors in the “primary market”) and also later on when the bonds are resold and traded in the “secondary market.” Although trading in the secondary market has become more active, many initial investors prefer to buy and hold their bonds to maturity. Thus, we view the pricing of “when issued” bonds to be more informative and robust, whereas the secondary market, still in its formative stages, may not be sufficiently reliable (yet) for analyzing the price of risk. As a result, we use only the data points for cat bonds in the primary market, when they are originally issued.

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<sup>14</sup> A telling manifestation of this loss estimation uncertainty is the fact that various major modeling firms calculate values for expected loss that are sometimes quite different from each other.

<sup>15</sup> The uncertainty of the estimated expected loss may explain the “credit spread puzzle” as well. Several competing explanations for the “credit spread puzzle,” however, would not explain our observations in the cat bond market.

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The data for this study comprises various tranches of bonds, their expected loss, spreads, and the perils they cover, for the years 1998–2008. Before proceeding to analyze the data, we applied a number of filters to the data. First, because we describe cat bond spreads with peril-specific parameters, we could use only single peril bonds; we excluded from this analysis any bonds that covered more than one peril.<sup>16</sup> This initial filtering left us with approximately 150 useable data points. Next, some bonds can be issued for a longer duration than the time that they are exposed to property cat risk; thus, the published spread, which corresponds to the entire lifespan of the bond, does not correspond to the time that the bond is “on risk.” To avoid this problem, we excluded any bonds whose issuance date preceded the inception date by more than 30 days. A similar complication arises when the bond covers a seasonal risk such as Wind: because the risk of cat loss is not uniform throughout the year, there can be a difference between the lifespan of the bond and the amount of time it is “on risk.” To deal this problem, we excluded any bonds whose covered peril was Wind and whose duration exceeded a whole number of years by more than 30 days. After applying the various data filters, we began the analysis with 115 data points. We also mapped the data to “issuance year” based on a 12-month period ending June 30; thus the “2008 issuance year” comprises bonds issued between July 1, 2007 and June 30, 2008.<sup>17</sup>

### **4.2 Results**

In this section we use the empirical data to fit the parameters of our proposed model:

$$\text{Spread \%} = \text{constant \%} + \text{loss multiplier} * \text{expected loss \%} \quad (4.1)$$

#### **4.2.1 Wind: USA**

We begin by inspecting results for USA Wind.<sup>18</sup> Exhibit 1 shows the fitted parameters:

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<sup>16</sup> With sufficiently detailed information, one could include multi-peril bonds in the analysis; however, because we could not obtain reliable data quantifying how much the various perils contributed to the total expected loss of multi-peril bonds, we could not include these bonds in our analysis.

<sup>17</sup> This mapping is used in AON Capital Markets [1].

<sup>18</sup> The bonds in this category generally cover some combination of Florida, Southeast USA, and/or Northeast USA. We could not split this large category into more granular subcategories.

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Exhibit 1									
Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)		
							Lower Bound	Upper Bound	
Wind	USA	All years	Full cycle	Constant %	3.33%	0.45%	2.38%	4.27%	
Wind	USA	All years	Full cycle	Loss Multiplier	2.40	0.17	2.05	2.76	

The parameters in Exhibit 1 show that we can approximate the spread (when issued) of any cat bond that covers USA Wind as follows:

$$\text{Spread \%} = 3.33\% + 2.40 * \text{expected loss \%}$$

The model provides an approximation for describing spread; one can use expert judgment to refine the modeled spread by incorporating the many additional factors that influence the actual issuance spread (market conditions, trigger type, etc.).

As noted in Exhibit 1, the regression applies to USA Wind, using all years of data (1998-2008); the time horizon of the historical data covers market conditions ranging from the high prices of a “hard market” to the low prices of a “soft market.” We note that the model’s intercept (Constant %) and slope (Loss Multiplier) are significant variables.

One benefit of having a mathematical model of cat bond pricing is that it allows us to take the wide array of cat bond prices and summarize them in compact form (two variables). Such a model also enables us to compare and contrast price behavior for various different perils, zones, time periods, and market conditions.

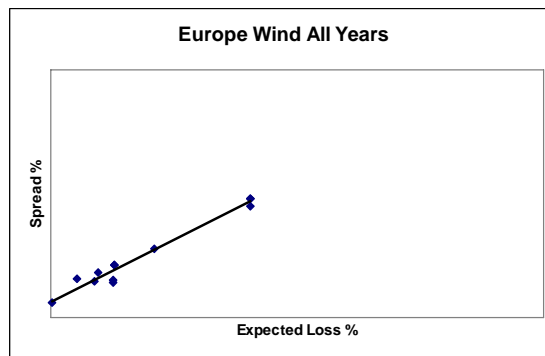
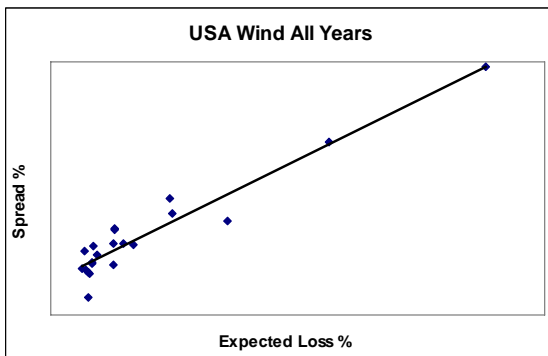
#### 4.2.2 USA Wind vs. Europe Wind

We now inspect the results for the peril Wind in two different geographical zones: USA and Europe.

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Exhibit 2

Peril	Zone	Years	Market Condition	# of Observations	R Square
Wind	USA	All years	Full cycle	21	91.6%
Wind	Europe	All years	Full cycle	12	96.8%



Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Wind	USA	All years	Full cycle	Constant %	3.33%	0.45%	2.38%	4.27%
Wind	USA	All years	Full cycle	Loss Multiplier	2.40	0.17	2.05	2.76
Wind	Europe	All years	Full cycle	Constant %	1.61%	0.33%	0.88%	2.33%
Wind	Europe	All years	Full cycle	Loss Multiplier	2.49	0.14	2.17	2.81

We note that the parameter “Constant %” for Wind is significantly higher for USA than for Europe. Given the very large accumulation of exposure in USA, it is reasonable that USA Wind contributes much more than Europe Wind to the total risk of an overall portfolio; thus the higher value of “Constant %” for USA is consistent with our hypothesis that this parameter relates to the “peril-specific required rate of return on capital.” We also note that the second parameter, “Loss Multiplier,” is significantly different than unity. Interestingly, the “Loss Multiplier” for Wind does not vary much between USA and Europe. This may suggest a similar magnitude of uncertainty for expected loss estimates for USA Wind and Europe Wind.

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**4.2.3 USA Wind All Years vs. USA Wind Hard Market**

Having inspected two different zones, we now turn to analyzing two different time periods.

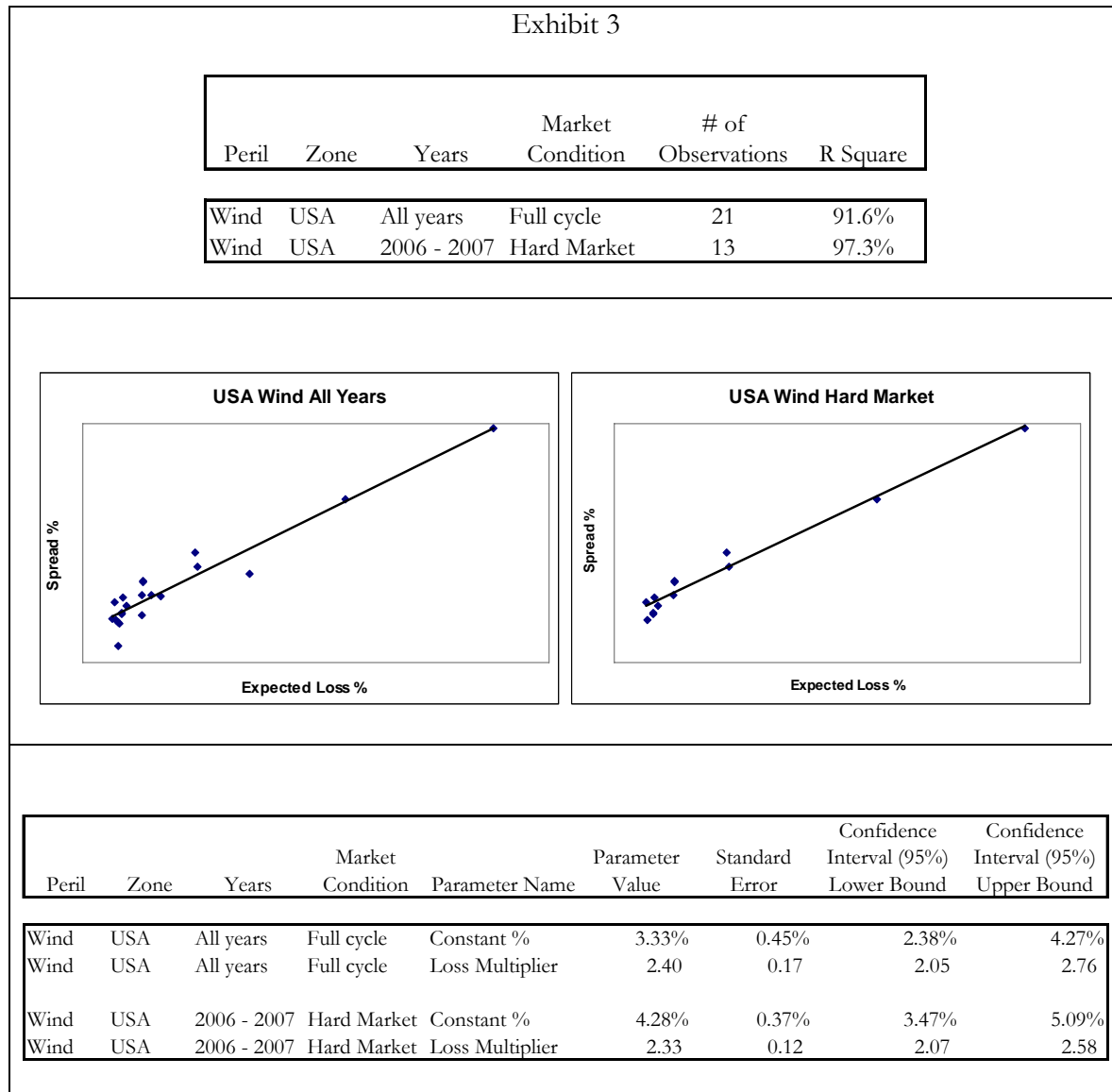


Exhibit 3 shows results for the peril Wind and the zone USA on two bases:

1. Using all years of data across a full cycle of market conditions.
2. Using the 2006 and 2007 years of data, which correspond to a “hard market,” a time

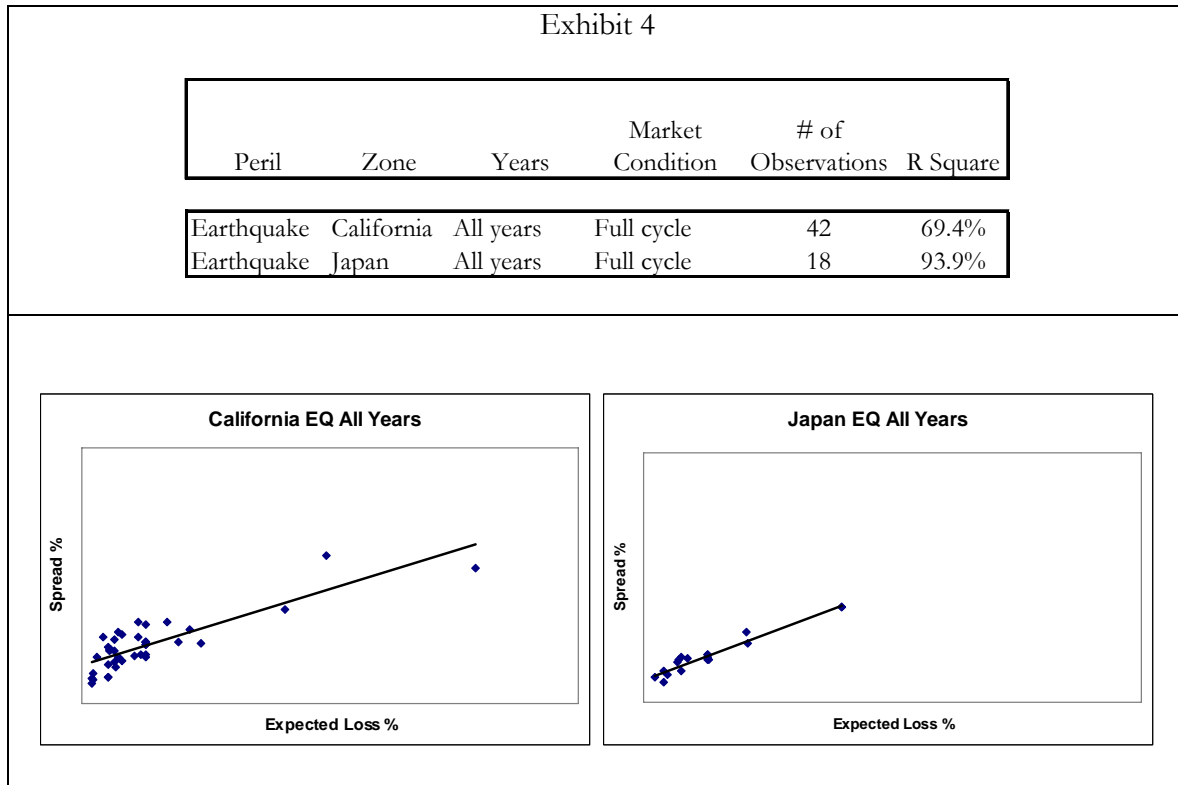
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period of increased risk aversion and higher prices.

We note that the “Constant %” tends to be significantly higher during the hard market than the all years average, which conforms to our expectations that the required rate of return on capital increases during a hard market. In contrast, the fitted value for “Loss Multiplier” does not vary much for USA Wind between the hard market and the all years average.

**4.2.4 Earthquake: California vs. Japan**

We now turn to the other major catastrophic peril, Earthquake (EQ). The exhibit below shows a comparison between California EQ and Japan EQ:



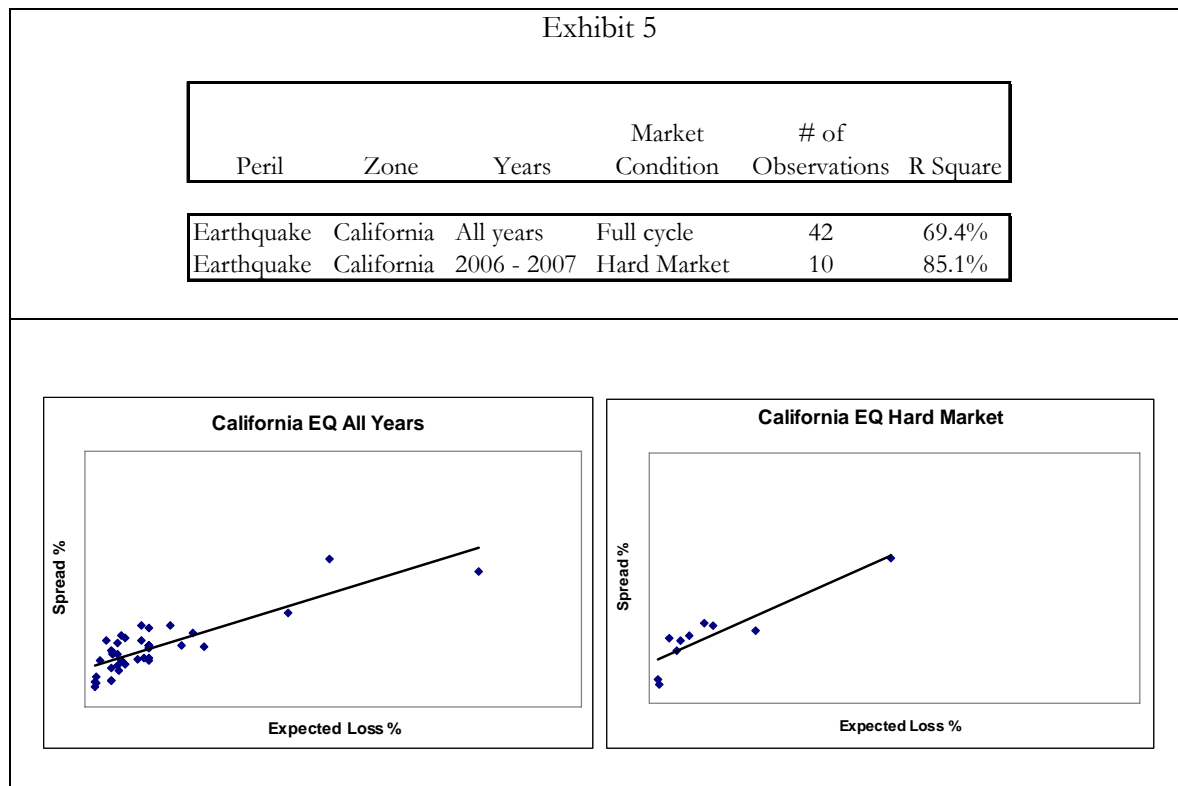
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Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Earthquake	California	All years	Full cycle	Constant %	3.78%	0.29%	3.19%	4.36%
Earthquake	California	All years	Full cycle	Loss Multiplier	1.48	0.16	1.16	1.79
Earthquake	Japan	All years	Full cycle	Constant %	2.28%	0.20%	1.85%	2.70%
Earthquake	Japan	All years	Full cycle	Loss Multiplier	1.85	0.12	1.60	2.10

California, with its peak level of exposure accumulation, has a significantly higher “Constant %” than Japan. The value of the parameter “Loss Multiplier” does vary between USA and Japan, although the difference is not as significant as the difference in the “Constant %” parameter.

**4.2.5 California EQ All Years vs. California EQ Hard Market**

We now analyze EQ pricing during different time periods.



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Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Earthquake	California	All years	Full cycle	Constant %	3.78%	0.29%	3.19%	4.36%
Earthquake	California	All years	Full cycle	Loss Multiplier	1.48	0.16	1.16	1.79
Earthquake	California	2006 - 2007	Hard Market	Constant %	4.40%	0.55%	3.12%	5.67%
Earthquake	California	2006 - 2007	Hard Market	Loss Multiplier	2.04	0.30	1.34	2.73

Exhibit 5 shows that for California Earthquake, the “Constant %” and the “Loss Multiplier” both increased significantly during the hard market of 2006–2007 relative to the all years average.

**4.2.6 Wind and EQ, USA and Europe, California and Japan**

We now examine our results for Wind and EQ in one combined context:

Exhibit 6a

Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Wind	USA	All Years	Full Cycle	Constant %	3.33%	0.45%	2.38%	4.27%
Wind	USA	All Years	Full Cycle	Loss Multiplier	2.40	0.17	2.05	2.76
Wind	Europe	All Years	Full Cycle	Constant %	1.61%	0.33%	0.88%	2.33%
Wind	Europe	All Years	Full Cycle	Loss Multiplier	2.49	0.14	2.17	2.81
Earthquake	California	All Years	Full Cycle	Constant %	3.78%	0.29%	3.19%	4.36%
Earthquake	California	All Years	Full Cycle	Loss Multiplier	1.48	0.16	1.16	1.79
Earthquake	Japan	All Years	Full Cycle	Constant %	2.28%	0.20%	1.85%	2.70%
Earthquake	Japan	All Years	Full Cycle	Loss Multiplier	1.85	0.12	1.60	2.10

Exhibit 6a displays the critical parameters that summarize the behavior of four major peril/zone combinations: USA Wind, Europe Wind, California EQ, and Japan EQ. Each unique combination of peril and zone contributes in a different way to the risk of the total portfolio; thus each peril/zone requires its own linear model with different parameters. Despite the differences in the models, however, there appear to be some similarities. We begin by focusing on the “Constant %”



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parameter of the linear models:

Exhibit 6b								
Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Wind	USA	All Years	Full Cycle	Constant %	3.33%	0.45%	2.38%	4.27%
Earthquake	California	All Years	Full Cycle	Constant %	3.78%	0.29%	3.19%	4.36%
Wind	Europe	All Years	Full Cycle	Constant %	1.61%	0.33%	0.88%	2.33%
Earthquake	Japan	All Years	Full Cycle	Constant %	2.28%	0.20%	1.85%	2.70%

Exhibit 6b shows that for the parameter “Constant %,” which is the intercept of the linear models, the values for the “peak” perils/zones of USA Wind and California EQ are quite similar. Additionally, the values for the significant yet “non-peak” perils of Europe Wind and Japan EQ are simultaneously similar to each other and also dissimilar to the values for the two peak perils.<sup>19</sup> This phenomenon is consistent with our hypothesis that the “Constant %” relates to the “required rate of return on capital”: peak zones with the largest accumulation of exposure tend to contribute the most to the total portfolio risk and thus ought to have the highest “required rate of return on capital”; non-peak zones, which have less acute accumulation of exposure, tend to correlate less directly with the overall portfolio, will receive some credit for their diversification effect, and will have lower “required rate of return on capital.”

We now turn to the second parameter of the model, “Loss Multiplier.”

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<sup>19</sup> See MMC Securities [8], which categorizes perils/zones into three major buckets:

1. “Peak” (USA Wind and USA EQ)
2. “Non-Peak” (Europe Wind and Japan EQ)
3. “Pure Diversifying Perils” (other perils such as Australia EQ, Mexico EQ, and Japan Wind)

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Exhibit 6c								
Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
Wind	USA	All Years	Full Cycle	Loss Multiplier	2.40	0.17	2.05	2.76
Wind	Europe	All Years	Full Cycle	Loss Multiplier	2.49	0.14	2.17	2.81
Earthquake	California	All Years	Full Cycle	Loss Multiplier	1.48	0.16	1.16	1.79
Earthquake	Japan	All Years	Full Cycle	Loss Multiplier	1.85	0.12	1.60	2.10

In exhibit 6c, parameter values are similar not based on “peak” and “non-peak” but rather they are similar based on geophysical peril. The value for Loss Multiplier for the peril Wind hardly varies, whether in the USA zone or in the Europe zone. In addition, the value for Loss Multiplier for the peril Earthquake for the California zone is somewhat similar to its value for the Japan zone; moreover, these values for Earthquake are dissimilar to the values for Wind. Returning once again to our conjecture: if the Loss Multiplier is greater than 1.0 because of the uncertainty in the cat model’s estimated expected loss, then this uncertainty would likely be similar within a common peril (Wind) and likely dissimilar across different perils (Wind vs. EQ).

Until now we have advocated the use of an individual linear model for each unique combination of major peril and zone, as described in Exhibit 6a; using two parameters to describe each major peril/zone combination, we have a total of eight parameters to describe cat bond pricing for these major perils. However, our discussion of the partial similarities of the linear models (the intercept is similar by zone, the slope is similar by peril) suggests the possibility of combining the various peril/zone combinations into one single linear model. We’ve seen that the Loss Multiplier varies by peril (Wind versus EQ) and that the Constant % varies by zone (peak USA Wind and California EQ, versus non-peak Europe Wind and Japan EQ). So a single linear model combining all the individual linear models ought to be:

$$\begin{aligned}
 \text{Spread \%} = & \text{Constant}_{\text{All}} \% \\
 & + \text{Additional Constant}_{\text{Peak}} \% * \text{Peak Peril Indicator} \\
 & + \text{Loss Multiplier}_{\text{EQ}} * \text{Expected Loss}_{\text{EQ}} \% \\
 & + \text{Loss Multiplier}_{\text{Wind}} * \text{Expected Loss}_{\text{Wind}} \%
 \end{aligned}
 \tag{4.2}$$

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For this model, we assign each data point's expected loss to either EQ or Wind. We also use an indicator variable to classify the data point as peak or non-peak (1 or 0). Now we can include all data points from single peril bonds covering USA Wind, California EQ, Europe Wind, and Japan EQ in one model and fit the parameters:

Exhibit 7a									
Peril	Zone	Years	Market Condition	# of Observations	R Square	Adjusted R Square			
Multiple	Multiple	All years	Full cycle	93	87.3%	86.9%			

Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%) Lower Bound	Confidence Interval (95%) Upper Bound
Multiple	Multiple	All Years	Full Cycle	Constant <sub>All</sub> %	2.31%	0.26%	1.79%	2.83%
Multiple	Multiple	All Years	Full Cycle	Additional Constant <sub>Peak</sub> %	1.24%	0.28%	0.70%	1.79%
Multiple	Multiple	All Years	Full Cycle	Loss Multiplier <sub>EQ</sub>	1.63	0.11	1.41	1.85
Multiple	Multiple	All Years	Full Cycle	Loss Multiplier <sub>Wind</sub>	2.32	0.10	2.12	2.52

Exhibit 7a shows how the spread varies based upon expected loss, peril (Wind vs. EQ), and zone (Peak vs. Non-Peak). The intercept of the line for a non-peak zone is Constant<sub>All</sub> %, whereas the intercept for a peak zone is the sum of Constant<sub>All</sub> % and Additional Constant<sub>Peak</sub> %; thus peak zones have a larger intercept value. The slope of the line depends upon the Loss Multiplier, which varies by peril; thus the slope of the line is steeper for Wind than for Earthquake.

We can also examine such a model for a restricted time period, when market conditions are more homogeneous:

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Exhibit 7b									
Peril	Zone	Years	Market Condition	# of Observations	R Square	Adjusted R Square			
Multiple	Multiple	2006 - 2007	Hard Market	32	95.7%	95.3%			

Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%) Lower Bound	Confidence Interval (95%) Upper Bound
Multiple	Multiple	2006 - 2007	Hard Market	Constant <sub>All</sub> %	2.07%	0.41%	1.23%	2.91%
Multiple	Multiple	2006 - 2007	Hard Market	Additional Constant <sub>Peak</sub> %	2.30%	0.38%	1.51%	3.09%
Multiple	Multiple	2006 - 2007	Hard Market	Loss Multiplier <sub>EQ</sub>	1.94	0.14	1.65	2.24
Multiple	Multiple	2006 - 2007	Hard Market	Loss Multiplier <sub>Wind</sub>	2.34	0.09	2.15	2.53

Exhibit 7b, together with Exhibit 7a, shows that when using the data of the hard market years of 2006–2007, the parameters of the linear model change in various ways. The parameter “Additional Constant<sub>Peak</sub> %,” which reflects the incremental additional price for peak zones, roughly doubles, from a 1.17% all years average to a hard market value of 2.30%; meanwhile, the parameter “Constant<sub>All</sub> %”, which serves as the intercept for “non-peak” zones, hardly changes. The parameter “Loss Multiplier<sub>Wind</sub>,” which already has a high value for the all years data, does not change when fitted to the hard market data; “Loss Multiplier<sub>EQ</sub>” which has a lower prevailing value for the all years data, increases significantly when fitted to hard market data.

#### 4.2.7 All Perils

When we describe bond spreads using individual linear models, there are certain peril/zone combinations that will not have sufficient data to support reliable parameters. For example, Australia EQ, Mexico EQ, Mediterranean EQ, and Japan Wind are some of the perils for which we do not have enough data points to support standalone linear price functions. However, one of the advantages of a “combined” model such as equation (4.2) is the ability to include many of these ancillary perils in one overall linear function. In order to do so, we first note that these ancillary perils are likely less correlated with the overall portfolio than “peak” and “non-peak” perils; as a result, they ought to have a lower required rate of return on capital and thus a materially different

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value for “Constant %.” We thus expand our categories of perils to three buckets<sup>20</sup>:

1. Peak (USA Wind, California EQ)
2. Non-peak (Europe Wind, Japan EQ)
3. Diversifying (Japan Wind, Australia EQ, Mexico EQ, Mediterranean EQ, Central USA EQ, and Pacific Northwest USA EQ)

We now can augment equation (4.2) to apply to all peril/zone combinations, as follows:

$$\begin{aligned} \text{Spread \%} = & \text{Constant}_{\text{All}} \% \\ & + \text{Additional Constant}_{\text{Peak}} \% * \text{Peak Peril Indicator} \\ & + \text{Additional Constant}_{\text{Diversifying}} \% * \text{Diversifying Peril Indicator} \quad (4.3) \\ & + \text{Loss Multiplier}_{\text{EQ}} * \text{Expected Loss}_{\text{EQ}} \% \\ & + \text{Loss Multiplier}_{\text{Wind}} * \text{Expected Loss}_{\text{Wind}} \% \end{aligned}$$

In equation (4.3), the slope of the linear price function depends on whether the covered peril is EQ or Wind; the intercept depends upon the peril/zone being peak, non-peak, or diversifying.

For a diversifying peril, the intercept is the sum of “Constant<sub>All</sub> %” and “Additional Constant<sub>Diversifying</sub> %.” We expect that the parameter value for “Additional Constant<sub>Diversifying</sub> %” should be negative, because a diversifying peril should have a lower required rate of return on capital and thus a lower intercept than other perils.

Exhibit 8a below shows the results of fitting parameters to the model in equation (4.3), using data from bonds covering all perils/zones:

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<sup>20</sup> See MMC Securities [8].

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Exhibit 8a								
Peril	Zone	Years	Market Condition	# of Observations	R Square	Adjusted R Square		
All	All	All years	Full cycle	115	87.4%	87.0%		

Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%) Lower Bound	Confidence Interval (95%) Upper Bound
All	All	All Years	Full Cycle	Constant <sub>All</sub> %	2.35%	0.25%	1.85%	2.85%
All	All	All Years	Full Cycle	Additional Constant <sub>Peak</sub> %	1.28%	0.27%	0.76%	1.81%
All	All	All Years	Full Cycle	Additional Constant <sub>Diversifying</sub> %	-1.09%	0.35%	-1.79%	-0.39%
All	All	All Years	Full Cycle	Loss Multiplier <sub>EQ</sub>	1.60	0.10	1.40	1.81
All	All	All Years	Full Cycle	Loss Multiplier <sub>Wind</sub>	2.29	0.10	2.10	2.48

The parameters displayed in Exhibit 8a describe the spreads of property cat bonds covering all perils and zones. They tell us that one can approximate the spread of any “single peril” cat bond by taking the product of the expected loss and a “Loss Multiplier” (which depends on whether the peril is Wind or EQ) and then adding a “Constant %” (which depends upon the whether the covered peril/zone is “peak,” “non-peak,” or “diversifying”).<sup>21</sup> Exhibit 8a also confirms our expectations that the linear function for a diversifying peril has a significant additional negative parameter (Additional Constant<sub>Diversifying</sub> %) and thus a lower intercept than other perils.

We now inspect the results of fitting parameters to the same model but using the more homogenous market conditions prevalent during the hard market years of 2006–2007:

<sup>21</sup> The equation should be easily extendable to apply to multi-peril bonds as well.

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Exhibit 8b								
Peril	Zone	Years	Market Condition	# of Observations	R Square	Adjusted R Square		
All	All	2006 - 2007	Hard Market	43	95.5%	95.1%		

Peril	Zone	Years	Market Condition	Parameter Name	Parameter Value	Standard Error	Confidence Interval (95%)	
							Lower Bound	Upper Bound
All	All	2006 - 2007	Hard Market	Constant <sub>All</sub> %	2.20%	0.40%	1.38%	3.02%
All	All	2006 - 2007	Hard Market	Additional Constant <sub>Peak</sub> %	2.31%	0.38%	1.54%	3.08%
All	All	2006 - 2007	Hard Market	Additional Constant <sub>Diversifying</sub> %	-1.66%	0.45%	-2.56%	-0.76%
All	All	2006 - 2007	Hard Market	Loss Multiplier <sub>EQ</sub>	1.87	0.13	1.60	2.14
All	All	2006 - 2007	Hard Market	Loss Multiplier <sub>Wind</sub>	2.31	0.09	2.12	2.50

Exhibit 8b, together with Exhibit 8a, shows that when using the data of the hard market years of 2006–2007, the parameters of the model change in various ways. The parameter “Additional Constant<sub>Peak</sub> %,” which reflects the incremental additional price for peak zones, increases sharply. The parameter “Constant<sub>All</sub> %,” which serves as the intercept for non-peak zones, hardly changes. Finally, the parameter “Additional Constant<sub>Diversifying</sub> %” becomes even more negative when using hard market data, implying that the price of a “diversifying peril” is lower when the additional cost of peak perils is higher; stated differently, the “benefit” of a diversifying peril is larger when the incremental cost of peak perils is larger. However, the large standard error for this negative parameter indicates that this change may not be significant, so this issue requires further investigation. Finally, we note that the parameter “Loss Multiplier<sub>EQ</sub>” increases when fitted to hard market data, while the parameter “Loss Multiplier<sub>Wind</sub>” does not change. While the future seldom duplicates the past, these results may provide some hints about how key pricing parameters may behave during future hard markets.

## 5. AREAS FOR FURTHER RESEARCH

Some areas for further research are as follows:

1. Our analysis uses simple regression, which weights all squared errors equally. Future

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research may consider a linear model that allows for varying weights on the squared error terms when fitting parameters.

2. Because of data limitations, we included only single peril bonds in our analysis. For multi-peril bonds, one requires information about the amount of expected loss that various perils and zones contribute to the total expected loss. With such data, one can include price information from multi-peril bonds when selecting models and fitting parameters. One could also then quantify to what extent (if any) a multi-peril bond suffers a price penalty relative to what the price “should have been” based on its expected loss and covered perils. Such a model could help quantify the tradeoff of sponsoring several bonds that each cover a single peril (e.g., better price but higher transactional costs) versus the advantages of sponsoring one bond covering multiple perils (e.g., worse price but lower transactional costs).
3. The parameters of the proposed linear model tend to vary based on market conditions, which are constantly changing. With sufficient data, one may be able to fit parameters to many incremental time periods and produce a time series of fitted parameters; such a data set would allow one to analyze how the parameters drift over time. If one could identify the catalysts that drive the changes in the parameters over time, one could develop a forward-looking model that predicts the likely values of the key parameters of the price function for the next time period.
4. Our focus thus far has been on the price of transferring cat risk via the cat bond market. What about the price of transferring cat risk in the traditional reinsurance market? We note that reinsurance contracts, which typically have reinstatable limit and premium, have different contractual features than cat bonds. Still, would some form of linear model adequately capture the market price of reinsurance contracts? Would such a model for the price of reinsurance contracts be similar or dissimilar to the model for cat bond prices? What would the similarity or dissimilarity of these models tell us? What would these models tell us about which types of cat risk are best handled via balance sheet equity capital, reinsurance capital, and cat bond capital? For example, our analysis suggests that two forces affect the price of cat risk in the cat bond market: the first factor is required rate of return on capital, and the second factor is uncertainty in the estimate of expected loss. Now, the broad asset portfolios that hold cat bonds may provide excellent diversification, which may lower the required rate of return on capital and reduce the



price of risk transfer for cat bonds. But the uncertainty in the estimated expected loss raises the price of risk transfer for cat bonds. So cat bonds may be relatively attractive in situations in which price is dominated by the “required rate of return” factor, but not in situations in which price is dominated by the “uncertainty in the expected loss” factor. This suggests that cat bonds will likely continue to be relevant mainly for cat layers that have low expected loss and/or cover peak perils, whereas other forms of capital may be preferable in other situations. The implication is that insurers may be able to enhance their capital structure by mixing together equity capital, reinsurance capital, and cat bond capital in an optimal combination.

## **6. CONCLUSIONS**

In this paper, we describe the market clearing price of cat bonds by modeling cat bond spreads as a linear function of the bonds’ expected loss. This relationship between spread and expected loss, however, differs by cat peril and geographic zone; each unique combination of peril and zone sports its own “price line” with a different intercept and slope. We also present an approach that combines these individual models into one unified model. Whether using individual models or a combined model, the parameters change over time as market conditions change. We hypothesize that the key parameters in the linear models relate to two main drivers of price: required rate of return on capital and uncertainty of the expected loss. These two factors provide a roadmap for indentifying situations that are most suitable for reinsurance versus cat bonds and vice versa. We also note that the factor relating to uncertainty of the expected loss may help explain the broader issue of the “credit spread puzzle,” which appears in the corporate bond market.

Using the proposed linear models, we can compare the market clearing price functions for cat bonds for various perils and zones, how they compare and contrast to each other, and how they change over time. Such models help us understand the drivers of the price of cat risk and help us describe how prices have behaved in the past and, potentially, how they may behave in the future.

### **Acknowledgment**

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## **7. REFERENCES**

- [1] AON Capital Markets, “Insurance Linked Securities 2008,”

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- <http://www.aon.com/attachments/capitalmarketsreport.pdf>.
- [2] Gatamel, M., and D. Guégan, "Towards an Understanding Approach of the Insurance Linked Securities Market," Presented at the 2008 ASTIN Colloquium, July 13-18, 2008, Manchester, United Kingdom.
  - [3] Hull, J., M. Predescu, and A. White, "Bond Prices, Default Probabilities and Risk Premiums," *Journal of Credit Risk* 1:2, 2005, pp. 53-60.
  - [4] Kozik, T., and A. Larson, "The N-Moment Insurance CAPM," *Proceedings of the Casualty Actuarial Society* LXXXVIII, 2001, pp. 39-63.
  - [5] Kreps, R., "Investment-Equivalent Reinsurance Pricing," Chapter 6 in *Actuarial Considerations Regarding Risk and Return In Property-Casualty Insurance Pricing*, (Arlington, Va.: Casualty Actuarial Society, 1999) pp. 77-104.
  - [6] Lane, M., "Pricing Risk Transfer Transactions," *ASTIN Bulletin* 30:2, 2000, pp. 259-293.
  - [7] Lane, M., and O. Mahul, "Catastrophe Risk Pricing: An Empirical Analysis," (November 1, 2008) World Bank Policy Research Working Paper Series, <http://ssrn.com/abstract=1297804>.
  - [8] MMC Securities, "The Catastrophe Bond Market at Year-End 2006: Ripples into Waves," March 2007.
  - [9] Venter, G., "Premium Calculation Implications of Reinsurance Without Arbitrage," *ASTIN Bulletin* 21:2, 1991, pp. 223-230.

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