LIBRARY OF CONGRESS
FEDERAL RESEARCH DIVISION

Catastrophic Events Impacting Transportation Infrastructure: Understanding Funding and Risk Management Approaches

A Report Prepared by the
Federal Research Division, Library of Congress
under an Interagency Agreement with the
Federal Highway Administration, Department of Transportation

August 2022

Researchers: Madelin O'Toole
Sema Hasan

**74 Years of
Fee-Based
Research
Services to
the Federal
Government
1948–2022**

Table of Contents

Table of Tables

1. KEY FINDINGS

Extreme weather and catastrophic events pose an increasing threat to infrastructure in the United States.[*] Given the impact such events are known to have on public infrastructure, the Department of Transportation's Federal Highway Administration (FHWA) contracted the Library of Congress' Federal Research Division (FRD) to conduct a comprehensive overview and detailed analysis of methods used to determine financial risk with respect to rare, catastrophic events.

For this report, researchers reviewed academic literature on insurance modeling and risk financing for natural disasters, publicly available data from FHWA and FEMA, and government reporting. In addition, researchers compiled case studies on domestic and international examples of risk-management approaches.

Based on research and analysis, FRD identified the following key findings:

- The two primary insurance models referenced in relation to disaster risk management are catastrophe bonds (or CAT bonds) and parametric insurance.
- Parametric insurance has three main advantages: faster payouts, flexibility, and the ability to provide coverage for losses that are difficult to model.
- CAT bonds offer governments a method of funding catastrophic-event recovery without building expansive reserve funds.
- CAT bonds are customizable to the sponsor's specific risk and cost.
- Mexico offers an example of a national government leveraging CAT bonds as a means to reduce risk.
- Japan offers an example of a successful public-private partnership in addressing and mitigating disaster risk.
- The number of billion-dollar weather events is increasing by five percent each year.
- Climate change limits insurance and reinsurance firms' capacity to predict catastrophic weather events and costs accurately.

Concluding with recommendations for further research and appendices with additional related proofs, this report is intended to be a broad overview of financial risk management strategies employed in a number of areas similar to, though not necessarily identical to, the work in which FHWA is engaged. Further study will be necessary to identify the best path forward for FHWA's specific requirements and circumstances.

---

[*] For this report, researchers define extreme weather events as hurricanes, tornados, floods, droughts, wildfires, blizzards, excessive heat, and excessive cold. Catastrophic events include all extreme weather events in addition to earthquakes, tsunamis, terror attacks, and major traffic accidents.

2. BACKGROUND

According to the National Oceanic and Atmospheric Administration (NOAA), since 1980 the United States has experienced 308 weather and climate disasters that have each caused or surpassed $1 billion in damage.[1] NOAA estimates that the total cost of these 308 events is over $2.085 trillion.[2] Severe weather and climate disasters (including earthquakes, hurricanes, tornadoes, and wildfires) have disruptive effects on transportation infrastructure systems, including roads, bridges, and highways, and are only expected to increase in frequency.[3] This represents a substantial and growing financial concern, given the challenges of allocating funding for relief in the event of unforeseen and difficult to predict catastrophic disasters.

2.1. FHWA Emergency Relief Program

The Department of Transportation's Federal Highway Administration (FHWA) provides federal assistance for disaster-related damage to transportation infrastructure through its Emergency Relief Program (ER). Transportation infrastructure includes over 617,000 public road bridges[4] and over 500 tunnels across the United States.[5] In the event of a natural disaster or catastrophic failure, the ER program provides funding to repair infrastructure to its pre-disaster state.[6]

The ER program is administered through the joint efforts of state departments of transportation and FHWA field offices. The program receives $100 million in permanent authorized funds from the Highway Trust Fund annually.[7] FHWA established the $100 million authorization in 1972 and has not adjusted the amount since that time.[8] Presently, FHWA would require an authorization in the range of $500 million to $600 million to match the purchasing power of $100 million in 1972.[9]

FHWA does not automatically disperse emergency funding. The decision to seek FHWA ER funding rests solely with state governments and federal land management agencies.[10] All ER funding requests require a declaration of disaster by the President or the state's governor.[11] Additionally, damage caused by a given event is expected to have caused a minimum of $700,000 in damage to the impacted infrastructure.[12]

Since FY2012, the FHWA ER program has received nearly $9 billion in total funding and averaged about $900 million in appropriated funds annually.[13] The FAST Act authorizes additional appropriated funds from Congress on a "such sums as necessary" basis.[14] In the past 10 years, permanent annual authorization accounted for roughly 10.4 percent of the total amount made available, and appropriations acts provided the other 89.6 percent.[15] For FY2022, FHWA allocated a total of $1,399,820,782.72 for Federal-aid highways and federally owned roads.[16]

FHWA offers two methods of funding disbursement: quick release and standard.[17] Quick release funds act as immediate relief for disaster-related damages, and provide intermediate relief until the completion of the standard application.[18] FHWA maintains a reserve at all times to ensure the availability of quick release funding.[19] FHWA typically uses standard disbursement for permanent repairs, which require onsite inspections and surveying.[20]

Standard funds disbursement occurs twice a year, and includes recent and backlogged projects.[21] FHWA cannot commit to funding obligations greater than the amount of funding provided via appropriation and authorization.[22] FHWA adds projects requiring funding greater than these amounts to unfunded project requests.[23] FHWA provides funding on a proportional basis when unallocated funds do not fully cover quick release and the biannual disbursement.[24]

2.2. U.S. Bridge and Tunnel Conditions and Vulnerabilities

FHWA evaluates Federal-aid highway bridge conditions on a yearly basis. In 2020, 45,031 (seven percent) of the 618,456 Federal-aid highway bridges were rated as poor.[25] FHWA also collects data on tunnel conditions, but does not provide aggregate ratings for the structures. Instead, individual tunnel elements receive ratings of 1 (good) through 4 (severe).[26] Bridge and tunnel conditions provide insight into structural integrity and safety. However, condition ratings do not assess how the structure will perform during an extreme weather event.[27]

Broadly, the literature characterizes vulnerabilities of transportation systems to extreme weather events in four ways:[28]

- **Direct physical** pathways of disruption: Impact on physical infrastructure, such as washout of a bridge due to flooding.
- **Non-direct physical** pathways of disruption: Impact on human behavior and decision making, such as traffic congestion due to extreme precipitation.
- **Indirect physical** pathways of disruption: Impact or disruption resulting from interconnected or co-located infrastructure.
- **Indirect non-physical** pathways of disruption: Disruption resulting from loss of informational, social, or financial resources. For example, an information and communication technologies (ICT) outage can disrupt traffic communications.

An examination of available literature indicates very little information or analysis on previous bridge or tunnel failures in the United States, particularly related to extreme weather events. Only a few notable cases are available, including the 1-10 Twin Span Bridge in Louisiana (2005) and the Kinzua Bridge in Pennsylvania (2003).

Originally built in 1963, the I-10 Twin Span Bridge covers 5.4 miles across Lake Pontchartrain, connecting New Orleans and Slidell, Louisiana. High winds from Hurricane Katrina resulted in significant damage to the bridges' structure.[29] Reports conducted in the aftermath by the Louisiana Department of Transportation and Development indicated that "38 spans from the eastbound bridge and 20 spans from the westbound bridge were dislodged and fell either directly or partially into the water."[30]

On July 1, 2003, a tornado vortex struck the Kinzua Bridge, with wind speeds over 90 miles per hour. As a result, 11 support towers were separated from their concrete bases at the center of the bridge and 23 of the bridge's 41 spans collapsed.[31]

As climate change intensifies and weather events become more severe, bridge and tunnel failures will likely increase. According to the 2022 Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, transportation infrastructure faces an increasing threat from slow onset and extreme events caused by climate change, particularly in urban areas. Damage caused by climate change and extreme weather events result in "economic losses, loss of services, and impacts to wellbeing."[32] Public resources are often the source of financing for infrastructure adaption; however, adverse impacts from climate change reduce available financing for repairs and resiliency improvements.[33] More information on climate change and infrastructure can be found in Section 6.

3. INSURANCE TYPES AND ACTUARIAL METHODS

3.1. Overview of Insurance

In order for a structure to be insurable, two conditions must be met. First, it must be possible to quantify the chances of an event occurring and to estimate its associated impact. Second is "the ability to set premiums for each potential customer [...] at prices that provide a competitive return at the assumed level of risk."[34] When considering natural disasters and associated risk, scholars and statisticians generally contend that risk can be defined as:

$$Risk = probability\ of\ occurrence * hazard\ impact \tag{1}$$

or

$$R = f(PxC) \tag{2}$$

where R is risk, P is the probability of occurrence of the natural hazard, and C is the impact of the natural hazard.[35] In this instance, "hazard" refers to an event that affects the probability of the risk occurring. Hazards can be described in terms of *negative hazards,* which make risk more likely, and *positive hazards,* which make risk less likely.[36] Based on this assessment, insurers decide whether to cover the risk. In determining whether to provide coverage, economist J.M. Stone's well-cited model assumes firms maximize profits when a constraint related to the survival of the firm is met.[37] The maximum number of policies insurance companies are willing to provide, n, is given by the following equation:

$$Probability\ [L^* > (n \cdot P + S)] < p_1 \tag{3}$$

where L^* is the probability of "experiencing total claim payments greater than some predetermined amount," P is the insurance premium, S is amount of dollars, and p_1 is a threshold probability.[38] Once insurers decide to offer coverage, they generally determine a premium rate that results in a profit. However, a central component in setting premiums is the ambiguity of risk due to limited information. Under ambiguous risk, insurers will set a premium,

$$z_i = p_i + k \tag{4}$$

where k is the "risk loading" term and p_i is a unique estimate.[39] Professors of Mathematics Sudradjat Supian and Sukono Kalfin of the University of Padjadaran, in collaboration with Professors Mustafa Mamat and Abdul Talib Bon of University Sultan Zainal Abidin and University Tun Hussein Onn Malaysia, developed a model for calculating the value of a natural disaster insurance premium. As detailed in Appendix II, the variables of their model include the number of recent natural disaster cases, standard deviation from natural disaster cases, risk-free interest rates, time, and benchmark value.[40] Similarly, in his study of disaster risk insurance in Australia, George Walker of insurance company Anon explains another common formula for expressing an insurance premium:

$$P = V_m P_p \tag{5}$$

where V_m is the volatility-multiplying factor, denoted as $V_m = (c_1 + c_2 C_v)$ where c_1, c_2 are the premium risk factors and C_v is the coefficient of variation of annual losses.[41] In this context, considerations that determine the premium risk factors include the "statistical characteristics of the risk, the reinsurance arrangements, the rate of return on investments, and the operational costs, including tax." Walker notes that the price of catastrophe insurance is determined by the cost of reinsurance, with each reinsurer carrying a different risk.[42]

While there is a lack of literature discussing the specific risk associated with highway infrastructure, a recent study by Professor Yong Ding of Ningbo University attempts to develop a simplified risk assessment method. Drawing on the "As Low as Reasonably Practicable" (ALAPR) logic, Ding et al. argue that the accident probability of highway structures in natural disasters can be determined by the following:

$$P = \sum_{i=1}^{m} Z_i q_i \tag{6}$$

where P is the value of the "accident probability of the structure in a natural disaster," while Z_i and q_i are the score and weight of a primary indicator, Y_i.[43]

Professor Gina Tonn of the Wharton School and her colleagues explain three general strategies for risk management: avoid, control, or transfer. They note that "the optimal risk management strategy often relies upon multiple layers of risk transfer."[44] Broadly, these layers are self-insurance or mitigation, insurance, reinsurance, and public sector aid or backstops.

Similarly, Professor Mustafa Erdik of Bogazici University explains that the following can denote a discrete calculation of risk for a given structure exposed to earthquake hazard:

$$ALLR_k = \sum_{IM} MDR_k(IM) \times \lambda(IM) \tag{7}$$

where $ALLR_k$ is the Expected Annual Damage Ratio or Average Annual Loss Ratio and $MDR_k(IM)$ is the Mean Damage Ratio.[45]

3.2. Parametric Insurance

Parametric insurance (also referred to as risk-based insurance) is an insurance method under which a payout is determined by a trigger, or an "objective measure of the causal event, instead of the damage sustained."[46] The literature identifies three main benefits to parametric insurance: faster payouts, flexibility, and the ability to provide coverage for losses that are difficult to model. In addition, parametric insurance triggers are not subject to moral hazard and adverse selection, which are typically inherent in regular insurance.[47]

One of the major drawbacks of parametric insurance as identified in the literature is "their susceptibility to basis risk."[48] Basis risk refers to an instance in which policyholders may not recover their true losses caused by a disaster. This can occur as either positive basis risk, where payouts are issued when no losses occur, or negative basis risk, where no payout is issued when loss occurs.[49] Generally, the following formulas are used to calculate basis risk for parametric insurance:[50]

$$Overpayment = median\left(\frac{Loss_{Index} - Loss_{Indemnity}}{Exhaustion - Attachment}, 0\%, 100\%\right) \tag{8}$$

$$Shortfall = median\left(\frac{Loss_{Indemnity} - Loss_{Index}}{Exhaustion - Attachment}, 0\%, 100\%\right) \tag{9}$$

In parametric insurance, the exhaustion point captures the severity of loss, at which point the maximum payment is triggered. The attachment point is defined as "the severity of the event that gives rise to a payment" and is measured by the probability of event occurrence in terms of years.[51]

As Professors Xiao Lin and W. Jean Kwon of St. John's University note, there are several factors that can affect basis risk for parametric insurance, including insufficient data and imperfect modeling.[52] Lin and Kwon further explain the three types of parametric insurance: aggregate loss index insurance, pure parametric insurance, and parametric index insurance.[53] Pure parametric insurance describes a contract under which a predetermined payment is issued after the event of a trigger. The literature identifies several case-specific examples of possible triggers, such as wind speed or rainfall, but contains few details on the decision process required to establish these benchmarks. Recognizing that triggers can take several forms, the Wharton Risk Center identifies a basic set of criteria, including that triggers be "independent, objectively measurable immediately after the disaster, and correlated with actual losses."[54] They further note that in some instances, more than one trigger must be met before payout occurs.

According to Lin and Kwon, under this type of parametric insurance, the insurer pays "regardless of the difference between the modeled loss and the actual loss of each of the insured."[55] In addition, parametric insurance payouts are typically based on an index, "which should be highly correlated with actual losses or damages" to ensure losses are adequately covered.[56]

3.3. Catastrophe Bonds

Catastrophe bonds (CAT bonds) originated following Hurricane Andrew in 1992, which caused $27 billion in damages.[57] The insurance industry covered roughly 60 percent of economic losses, paying out around $15.5 billion.[58] Noninsured losses, which included uninsured and underinsured assets, revealed a protection gap of $11.5 billion.[59] Between 1992 and 1993, eight insurance companies became insolvent and several others became technically insolvent after significantly underestimating their catastrophic risk exposure.[*][60] As a result of widespread defaults, insurance companies developed CAT bonds.[61]

A CAT bond is a type of insurance linked security (ILS) designed to insure against costly damages caused by the most catastrophic natural disasters.[62] Insurance companies originally utilized CAT bonds as a method of reinsurance that protected firms from risk of default. However, companies, municipalities, and federal governments soon began to issue CAT bonds to protect against loss.[63] Since the first CAT bond issuance, the market for the financial instrument has grown significantly. In 1997, the market's outstanding and issued bonds totaled $785.5 million.[64] In 2021, the market reached nearly $14 billion in new issuances and $35.89 billion in outstanding bonds.[65]

CAT bonds offer governments an alternative to traditional financial preparation methods like budget allocations or reserve catastrophe funds. Reserve building requires substantial time and money, and large reserve amounts are subject to reallocation, especially in times of low disaster frequency. With CAT bonds, governments can transfer the risk to a pool of investors. However, CAT bond structuring, design, issuance, and pricing require careful consideration of the risk an organization seeks to mitigate.

---

[*] Technically insolvent insurance companies received funds from parent companies to pay outstanding claims.

3.3.1. CAT Bond Structure

In its most basic form, a CAT bond consists of three participants: the sponsor, the special purpose vehicle, and investors.[66] CAT bond sponsors seek to transfer the risk of a catastrophic event to a large set of investors by issuing a CAT bond via a special purpose vehicle (SPV).[67] The SPV acts as an intermediary between the CAT bond sponsor and investors.[68] The SPV receives premium payments (ρ) from the sponsor in return for providing coverage via issued securities.[69] Investors pay principal (h) to the SPV in exchange for securities.[70] The SPV then holds the principal in a collateral trust that the SPV invests into highly rated and liquid collateral securities, such as U.S. Treasury Bills.[71]

Throughout the lifetime of the CAT bond, the SPV pays investors coupons (c), which consist of the interest earned (r), typically LIBOR, and the sponsor's premium payments (ρ).[*][72] If a qualifying event satisfies the bond's trigger, the SPV liquidates all or part of the collateral and transfers it to the bond sponsor.[73] If the bond reaches maturity without a qualified trigger event, investors receive the principal amount (h) and previous coupon payments consisting of the premium (ρ) and interest earned over the lifetime of the bond (r).[74] Table 1 summarizes the symbols utilized in CAT bond modeling.

Table 1. CAT Bond Symbol Summary

Variable	Symbol	Definition
Premium	ρ	$\rho = EL + \Lambda$
Interest Rate	r	
Coupon Payment	c	$c = r + \rho$
Principal Amount	h	
Load of Margin and Expenses	Λ	
Expected Value Loss	EL	$EL = PFL \cdot CEL$
Risk or Maximum Insured Loss	X	Range [0,∞) Insured Risk Interval (0,X]
Attachment Point	a	
Exhaustion Point	$a + h$	
Conditional Expected Loss	CEL	
Probability of First Loss	PFL	

3.3.2. CAT Bond Design

CAT bonds feature three core design elements: the trigger, coverage, and payout type. All CAT bonds consist of a predetermined principal amount that begins paying out when the catastrophic

---

[*] LIBOR is the benchmark interest rate at which major global banks lend to one another.

event activates the trigger.[75] CAT bonds are 100 percent collateralized, which guarantees the bond's entire principal amount in the event of payout.[76] If a triggering event does not occur in the specified period, then the bonds achieve maturity.[77] Most CAT bonds mature within three to five years; however, nothing prevents a longer term.[78] Longer-term bonds spread out amortization, reducing upfront cost relative to time and providing better stability.[79]

Trigger Type

CAT bonds specify triggers, or elements of the covered peril (natural disaster) that initiate the payout of the principal to the sponsor. There are four types of triggers: indemnity, industry loss, parametric (index), and modeled loss. Sponsors can design CAT bonds with more than one trigger to better hedge against their specific risk.[80]

An indemnity trigger initiates payout based on the sponsor's actual monetary loss. A CAT bond with an indemnity trigger provides a "complete hedge against disaster risk," as the principal pays out once the total monetary loss reaches a previously specified threshold.[81] Indemnity triggers must assess and verify the losses prior to payout, which results in a longer time horizon.[82] CAT bonds using an indemnity trigger reduce the basis risk, but are less transparent to investors.[83] Sponsors typically receive payment two to three years after the event. Despite this wait, it remains one of the most used trigger types in the CAT bond market.[84]

The second most frequently utilized trigger, industry loss, requires the entire insurance industry to experience an aggregate loss exceeding a predetermined threshold, or attachment point.[*][85] A third party, like Property Claims Services, collects and aggregates loss reports into an industry loss index.[86] The third party determines if the losses meet the attachment point independently of bond sponsors.[87] Catastrophe modelers provide an initial loss estimate immediately following the event and update the estimate as new loss information becomes available.[88]

A parametric trigger provides a predetermined payout amount when a natural disaster reaches an established level (e.g., hurricane category or earthquake magnitude) in a specific geographic location.[89] A parametric trigger index is similar to a parametric trigger; however, instead of relying on a single measure, several data points are collected across a geographical area.[90] The data points are entered into a special formula, which defines a particular index.[91] The insured losses covered by a CAT bond do not perfectly correlate with the actual trigger parameters, leading to substantial basis risk; however, trigger parameters are more transparent to investors.[†][92] A

---

[*] The attachment point is the minimum monetary loss that releases at least a portion of the bond's principal.

[†] Basis risk is the difference between the loss and what can be claimed. Basis risk is equal to zero when the payment covers 100 percent of insured claims.

parametric trigger or parametric trigger index offers the fastest payout at about three months, as the SPV can verify the trigger and liquidate the collateral immediately following the natural disaster.[93]

The least common trigger type, modeled loss, relies on a third party risk modeler to estimate the sponsor's projected loss.[94] Unlike an indemnity trigger, a modeled loss trigger features a faster payout but experiences significant basis risk.[95]

Coverage

CAT bonds offer two forms of coverage: annual aggregate and per-occurrence.[96] Annual aggregate CAT bonds provide coverage for all catastrophic events experienced by a specified geographic region in one year.[97] This coverage type uses stop-loss reinsurance, which covers all losses once they exceed a predetermined claim threshold.[98] Per-occurrence coverage includes an excess of loss per event clause that only triggers if a single event's losses meet the threshold.[99]

Payout Type

CAT bonds most commonly feature either a binary or proportional payout design. Under a binary payout, sponsors receive a predetermined principal amount once the underlying losses reach the attachment point.[100] For proportional payout, the percentage of the principal paid out increases as underlying insured losses exceed the CAT bond attachment point.[101] Once the losses exceed the exhaustion point, the bond pays out the full principal amount.[*][102]

3.3.3. CAT Bond Issuance

In practice, CAT bond issuance involves multiple agents and a number of transaction costs. The bond's creation requires the input of a structuring agency, an independent modeling agency, legal counsel, and a rating agency. Table 2 details the costs associated with creating a CAT bond.

Table 2. CAT Bond Transaction Costs

Fee Type	Cost*	Special Considerations
Legal Fees	50 bps	
SPV Administrator Fees	3-4 bps	Dependent on bond size

---

[*] The exhaustion point is the maximum monetary loss that releases the bond's full principal amount.

Rating Agency Fees	6-7 bps

* The cost is presented in basis points of the principal of the bond (100bps=1 percent).
Source: Erwann Michel-Kerjan et al., *Catastrophe Financing for Governments: Learning from the 2009–2012 Multicat Program in Mexico* (OECD Working Papers on Finance, Insurance, and Private Pensions No. 91, OECD [Organisation for Economic Cooperation and Development] Publishing, May 2011), 17, https://doi.org/10.1787/5kgcjf7wkvhb-en.

The structuring agency, usually an investment bank or reinsurer, acts as an advisor and underwriter for the CAT bond.[103] The sponsor and structuring agent identify the triggering event (peril).[104] The modeling agency "employs catastrophe models to estimate the risk to which the sponsor is exposed" and calculates the expected loss (EL).[105]

The modeling agency evaluates the trigger across three dimensions: hazard, engineering, and financial.[106] The hazard dimension consists of event generation and intensity calculations for the selected peril.[107] The engineering component estimates damage with relevant exposure information.[108] The modeling agency then determines the financial component by calculating insured loss with context from potential policy implications.[109] After the modeling agency identifies the risk profile, the sponsor and structuring agent identify the appropriate level of risk protection.[110]

The modeling agency will often create an exhibition that provides investors and rating agencies with documentation detailing the bond's risk.[111] A rating agency acts as a third party verification agent and classifies the bond based on the risk of default.[112] The legal counsel ensures the bond's regulatory compliance prior to issuance.[113]

Once the bond design is finalized, the structuring agency conducts a road show for potential investors.[114] The road show introduces the bond to investors and allows them to ask questions regarding the bond and risk assessment.[115] When the road show concludes, the sponsor and structuring agent finalize the premium and sell the bond to qualified investors in the primary market.[116] Investors can then sell to investment banks in the secondary market.[117] The primary market spread often remains internal information known only to the sponsor and involved parties; however, the secondary market spread, or interest spread, represents the premium paid by the sponsor.[118]

3.3.4. CAT Bond Models

The structuring agent and the risk-modeling agency typically price CAT bonds. The specific models used in bond issuance are not publicly available due to the proprietary nature of models created by these agencies and bond sponsors' specific budgetary requirements. Generally, CAT models include the hazard, asset inventory, asset vulnerability, and loss.[119] Alternatively, there are several premium pricing models throughout academic literature that evaluate CAT bond pricing using data from primary and secondary bond markets.[*] University of Florence Professor Marcello Galeotti, University of Braunschweig Professor Marc Gürtler, and Christine Winkelvos of the University of Braunschweig find that linear models and the Wang transformation are the most accurate in evaluating premium price determining factors.[†] CAT bond pricing research and modeling continues to evolve as more CAT bond data becomes available.

In its most basic form, a CAT bond pricing model includes the premium (*ρ*), which "consists of the expected value loss (*EL*) plus a risk load for risk margin and expenses (*Λ*)," and monetary coverage up to a predefined limit (*h*).[120] Insurance pricing identifies risk as X, or the maximum insured loss.[121] The attachment point (*a*) and exhaustion point (*a+h*) represent the initiation of loss and the maximum loss, respectively. Galeotti et al. present the basic linear relationship for calculating the premium for the "last" layer (*a*, *a+h*):

$$\rho(x) = EL + \Lambda = PFL \cdot CEL + \Lambda \qquad (10)$$

where $\rho(X)$ is the premium, EL is the expected value loss, ∧ is the risk load, PFL is the probability of first loss, and CEL is the conditional expected loss rate.[‡][122] There are several alternative models that represent the relationship between $p(X)$ and EL, which is written as

$$\rho(X) = f(EL,\ y_1, \dots, y_N) \qquad (11)$$

where f is a real function and $y_1, \dots, y_N$ represent additional risk load parameters.[123] Several studies sought to determine additional factors influencing CAT bond premiums by adding to the model and testing with specific data. The Lane model evaluated risk load as the only determining factor of premium and utilized a dataset consisting of ILS securities issued in 1999; however, the approach was abandoned due to a lack of variety in *CEL*.[124]

$$\rho(X) = EL + \gamma \cdot (PFL)^{\alpha} \cdot (CEL)^{\beta} \qquad (12)$$

---

[*] Reference Appendix II for relevant proofs.

[†] Academic studies do not replace the estimated loss and premium payment calculations conducted by modeling and structuring agents, but these models offer insight on determining factors of premiums.

[‡] *CEL* is the expected loss given that the loss is greater than or equal to the portfolio's value at risk. Value at risk refers to a worst-case loss within a given time horizon and probability.

The Berge model introduced peril and trigger mechanism as price (premium) determining factors, using the following multivariate linear equation and CAT bond issue data from 1994 to 2004:

$$\rho(X) = \alpha + \beta \cdot EL + \gamma_1 \cdot y_{peril} + \sum_{i=2}^{N} \gamma_i \cdot y_i \tag{13}$$

where $\alpha, \beta, \gamma_1 \ldots \gamma_N$ are coefficients, y_{peril} refers to the peril, and $y_i, \ldots y_N$ are the further determining factors.[125]

In 2007, Lane Financial President Morton Lane, Vice President Roger Beckworth, and Jason Overbey suggested adding cyclical adjustments to explain risk load in multiple linear models.[126] The Lane and Mahul model expanded on this notion by testing a multiple linear regression that incorporated cyclical effects (y_{cycle}) using a dataset consisting of 247 tranches of CAT bonds from 1999 to 2008.[*][127]

$$\rho(X) = \alpha + \beta \cdot EL + \gamma \cdot y_{cycle} \tag{14}$$

Professor Marc Gürtler, Dr. Martin Hibbeln, and Christine Winkelvos of University of Braunschweig utilized multiple linear models, fixed effects, and random effects to evaluate premiums in the secondary CAT bond market from 2002 to 2012, which provides significantly more data points for analysis.[128] The equation for a CAT bond premium with fixed effects is

$$\rho_{it} = \alpha' X_i + \delta' X_t + u_{it} \tag{15}$$

where X_i represents the bond fixed effects, X_t represents time fixed effects (quarterly or yearly), and u_{it} represents the error term that varies over bond and time.[129] The equation for a CAT bond with random effects is

$$\rho_{it} = \alpha + \beta' X_i + \gamma' X_{it} + \delta' X_t + a_i + u_{it} \tag{16}$$

where i is 1,...n, CAT bonds, t is 1,...,T points in time, X_i represents CAT bond specific variables unrelated to time, X_{it} represents CAT bond variables that consider time, X_t represents CAT bond

---

[*] Cyclical effects refer to the pattern of behavior observed in the insurance market. The insurance market fluctuates between "hard" and "soft" markets. A soft market occurs at the beginning of an underwriting cycle when there are several insurers in the market and premiums are low. A hard market occurs after an increase in insurance claims that reduces the number of insurers in the market.

variables that depend on time only, a_i represents unobservable individual effect, and u_{it} represents the error term variable over time.[130]

Researchers found that premiums increase as the bond becomes more complex in terms of perils and geographic locations covered. The Major and Kreps model tested a log linear function and added geographic location and lead insurers as determining factors using an original dataset.[131] According to Major, the usage of the log linear function appeared to be motivated by the presence of heteroscedasticity in their log-log scatterplot.[132]

$$\ln\big(\rho(X)\big) = \alpha + \beta \cdot \ln(EL) + \gamma_1 \cdot y_{geocode} + \sum_{i=2}^{N} \gamma_i \cdot y_i \qquad (17)$$

The Wang model operated on the assumption that it was not possible to prove a direct relationship between *EL* and the premium due to linear models violating translation variance requirements illustrated by Université Louis Pasteur Professor Emeritus of Mathematics Philippe Artzner. Southern University of Science and Technology Professor Shaun S. Wang modeled a transformed version of *EL* and risk premium, which is represented by the following premium calculation model, using an original dataset.[133]

$$\rho(X) \cdot h = \int_{a}^{a+h} S_X^{+}(x)dx = EL^{+} \qquad (18)$$

According to Professor Galeotti, Professor Gürtler, and Christine Winkelvos, the linear premium principle and Wang transformation are the most accurate models that do not consider the 2008 financial crisis.

4. CASE STUDIES: A NATIONAL AND INTERNATIONAL PERSPECTIVE

Scholars contend there is great variation in how countries insure against catastrophes. Considerations include the level of income available for insurance costs or to save in disaster funds; the availability of affordable insurance coverage; awareness of possible disasters and their impact; implementation and enforcement of budget codes; access to global risk transfer markets; and the effectiveness of public-private risk transfer partnerships.[134]

As Professors Aglaia Petseti and Milton Nektarios of the University of Piraeus explain, several countries use tax revenue to create pre-funded disaster relief funds, including Mexico, Australia, Denmark, the Netherlands, Norway, and Poland. These countries provide compensation only when losses cannot be privately insured.[135] In contrast, the governments of France and Japan act as a reinsurer and set premiums. Similarly, Spain has a government insurance program that "collects all premiums and accepts all risk, while private insurers market the policies and handle the claims."[136]

4.1. Asia and the Pacific

Within Asia and the Pacific, New Zealand, Japan, and Australia provide examples of earthquake insurance, public-private partnerships, and illustrative applications of parametric insurance.

4.1.1. New Zealand

In 2014, New Zealand was considered the third-most vulnerable country to natural disasters. Economically, when measuring associated destruction of natural disasters as a percentage of GDP, New Zealand's is relatively higher than that experienced by other countries.[137] There are an estimated 15,000 earthquakes in the country every year,[138] and the country incurs an estimated annual average loss of US$832 million due to natural disasters.[139] In light of this, the country introduced the Earthquake Commission (EQC) in 1945, a government-owned crown entity, to provide public natural disaster insurance for residential property. The EQC assists property owners in addressing damage from "earthquakes, volcanic eruption, hydrothermal activity, landslip, tsunami, or fire."[140] Damage caused by storms or floods are excluded. In order to make EQC affordable, "a single rate of premium with maximum limit applies to all homeowners."[141] The maximum limit is US$100,000 for homes and US$20,000 for the home's contents. In addition, policyholders' costs are set at 15 cents per US$100,000.[142]

From 1980 to 2018, the EQC received over half a million claims.[143] The most dramatic test of New Zealand's EQC was in 2010, when the Canterbury region was struck with a 7.1 magnitude earthquake. The event resulted in extensive damage to infrastructure and buildings, but no deaths.

Within five months of this event, another earthquake struck the city of Christchurch, also in the Canterbury region, killing 185 people. The Canterbury Earthquakes are considered "the most costly disaster for insurance claims in New Zealand's history."[144] It is estimated that as many as 770,000 individual claims were received for residential buildings, land, and contents in the wake of the earthquakes. The country's reserve bank estimates that the total claim cost is approximately US$38 billion, and as of June 2020, more than US$36 billion had been paid.[145] More recent reports indicate that as of June 2021, 85 percent of outstanding claims were settled.[146]

According to New Zealand's Independent Ministerial Advisor to the EQC, the damage caused by these earthquakes was greater than the system could accommodate or anticipate.[147] Individuals whose home or belongings were damaged first had to file a claim with the EQC, which would "investigate and pay up to its cap [of US$100,000 for a house and US$20,000 for contents]."[148] Claims that exceeded these amounts were transferred to private insurers.[149]

Following additional earthquakes in 2016, the EQC established a partnership model with private insurers, which would investigate and pay out claims. The Insurance Council of New Zealand reported this method efficiently addresses claims from other earthquakes.[150]

4.1.2. Japan

Japan is recognized as being at a high risk for natural disasters, including earthquakes and tsunamis, due to the country's close proximity to oceanic plates. The country is also subject to additional hazards such as landslides, floods, and typhoons. The country's largest earthquake in recent years occurred in 2011. Known as the Great East Japan Earthquake of 2011, this event resulted in government spending equivalent to an estimated eight percent of its GDP and 21 percent of its general account budget, totaling US$210 billion.[151] When such disasters occur, the government acts as the reinsurer.

Japan's Earthquake Reinsurance (JER) Program was established in 1966. Initially, the program was mandatory for residential property owners and added to property insurance policies, but it was made optional in 1979. Like New Zealand's EQC, JER provides coverage on residential buildings and their contents. JER acts as an insurance pool, where a portion of the liability is retained and the rest is transferred to private insurers.[152] As of 2011, the total claims-paying capacity of the program was 5,500 billion yen (approximately US$38 billion).[153] In terms of responsibility, the distribution is such that the burden for the government of Japan, JER, and private insurers is 87 percent, ten percent, and three percent, respectively.[154] Currently, Japan does not have disaster risk insurance for government assets; however, infrastructure such as railroads, airports, and ports are typically covered by private insurance.[155] A more comprehensive overview of Japan's infrastructure insurance is displayed in Table 3 below.

Table 3. Japan's Infrastructure Insurance

Infrastructure Type	Company Type	Total Companies that Insure Against Typhoon and Flood	Total Companies that Insure Against Earthquake
Railroads	**Large Companies**	78%	22%
	Small-Medium Companies	56%	5%
	Quasi-Public Companies	100%	N/A
Airport		79%	13%
Port		63%	N/A

Source: Japan, "Disaster Risk Financing and Insurance Policies of Japan" (presentation, APEC Seminar on Disaster Risk Financing and Insurance Policies, Nha Trang, Vietnam, February 21, 2017), pg 6, http://mddb.apec.org/Documents/2017/FMP/SEM1/17_fmp_sem1_007.pdf.

According to a 2017 Asia-Pacific Economic Cooperation (APEC) presentation by Japan, the central government covers two-thirds of recovery costs for public assets, while the remaining third is the responsibility of local governments. If local governments face financial constraints, they may issue bonds to cover the loss.[156]

Beyond the JER program, Japan has coordinated with German company Munich Re to issue CAT bonds. Specifically, in 2008 Japan received a three-year Muteki CAT bond of US$300 million, which covered earthquake damage to the country's National Mutual Insurance Federation of Agricultural Cooperatives (JA).[157] The risk period for this bond extended from May 2008 through May 2011 and included a "dropdown trigger," meaning that if the event reached beyond the predetermined level of the parametric index, the contract would become "more risky for investors since the levels of attachment and exhaustion are lowered."[158] This contract featured an annual probability of adjustment of 4.4 percent and an annual probability of exhaustion of 0.6 percent. The annual expected loss was estimated at 0.79 percent before the dropdown trigger and 1.94 percent after the dropdown.[159]

Public-Private Partnerships

Japan's Ministry of Finance has additionally developed a public-private earthquake insurance program for residential properties, where risk is shared between JER and the private insurance sector. Under this system, claim payouts are "not proportional to damage," but rather rely on a four-step system of total, large, small, and proportional losses, which correspond to 100, 60, 30, and five percent payouts, respectively.[160] Table 4 below provides a concise overview of Japan's public and private sector responsibilities with JER.

Table 4. Japan's Public-Private Partnership

Indicators	Japan
Name, Year of Establishment	Japanese Earthquake Reinsurance Scheme (JER), 1996
Program Duration	Permanent
Compulsory Coverage	No
Official Trigger	No
Responsibility of Public Sector	Provide state guarantee, reinsurance, and risk management
Responsibility of Private Sector	Administer and sell insurance policies, provide direct coverage

Source*:* Youbaraj Paudel, "A Comparative Study of Public–Private Catastrophe Insurance Systems: Lessons from Current Practices," *Geneva Papers on Risk and Insurance* 37, no. 2 (2012): 260, http://www.jstor.org/stable/41953178.

4.1.3. Australia

Australia's Natural Disaster Relief and Recovery Arrangements (NDRRA) is a government-run program that allows for emergency relief, including infrastructure restoration for communities targeted by natural disasters prior to 2018. Similar to the United States' FEMA program, the NDRRA provides states with financial assistance following natural disaster. Under this arrangement, state governments determine which areas receive funding, and the Australian government may fund "up to 75 percent of the assistance available to individuals and communities."[161] Notably, assistance can be provided to restore transport or public infrastructure assets, including roads, bike lanes, bridges, tunnels, and culverts.[162] According to a 2020 report by the Menzies Research Centre, the Commonwealth of Australia "contributes from 50 to 75 percent of the cost of replacing essential public assets such as roads."[163] Assistance is only provided if an eligible event occurs, defined as one of the following: bushfire, earthquake, flood, storm, cyclone, storm surge, landslide, tsunami, meteorite strike, or tornado.[164]

In 2021, Lloyd's Disaster Facility launched a parametric cyclone insurance product in Northern Australia. Known as Redicova, the product provides payouts to policyholders "in relation to wind speeds from severe tropical cyclone[s]" characterized as Category Three or above.[165]

4.2. Latin America and the Caribbean

The Latin American and Caribbean section reviews disaster response and risk mitigation programs for Mexico, Jamaica, and the Caribbean. Mexico and Jamaica provide examples of national governments sponsoring, designing, and implementing CAT bonds to mitigate natural disaster risks. The Caribbean Catastrophe Risk Insurance Facility provides an example of multinational risk pooling via parametric insurance.

4.2.1. Mexico

Hurricanes, earthquakes, flooding, tsunamis, wildfires, landslides, and volcanic eruptions affect 31 percent of Mexico's population and 41 percent of its territory, annually.[166] Post-disaster recovery costs for low-income housing and public infrastructure average US$880 million per year.[167] Because of this exposure, the nation took a proactive approach in its disaster risk management programs to ensure expedited aid disbursement to citizens and repairs to damaged infrastructure.

Following Mexico City's destructive 8.0 magnitude earthquake in 1985, Mexico established the Sistema Nacional de Protección Civil (SINAPROC).[168] Since then, Mexico has continued to improve and expand its disaster risk management (DRM) through risk assessment, risk reduction, the promotion of a culture of prevention, and insurance.[169]

In 1996, Mexico established FONDEN "as an inter-institutional financial vehicle for natural disasters" that distributed budgeted funds as needed.[170] In 2006, the Mexican government incorporated additional risk transfer solutions and issued its first CAT bond.[171] Mexico pooled various risks across multiple geographic areas in 2009 with the creation of MultiCAT and subsequent bonds in 2012, 2017, 2018, and 2020, summarized in Table 5.

Table 5. Mexican CAT Bonds

Bond Name	Issuance Date	Size	Peril
CAT-MEX Ltd.	May 2006	US$160 million	Earthquake
MultiCat Mexico 2009 Ltd.	October 2009	US$290 million	Earthquake and Hurricane
MultiCat Mexico Ltd. (Series 2012-1)	October 2012	US$315 million	Earthquake and Hurricane
IBRD/FONDEN 2017	August 2017	US$360 million	Earthquake and Named Storms
IBRD CAR 118-119	February 2018	US$260 million	Earthquake
IBRD/FONDEN 2020	March 2020	US$485 million	Earthquake and Named Storms

Source: Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory," accessed August 30, 2022, https://www.artemis.bm/deal-directory/.

In October 2020, the Mexican government officially dissolved FONDEN and other government-funded public trusts.[172] Despite FONDEN's dissolution, the program can be examined as a model for other national governments with high-risk exposure seeking means to utilize risk transfer instruments as an alternative for funding relief in the wake of natural disasters.[173]

FONDEN

In 1996, Mexico established FONDEN as a special budget allocation managed by the Ministry of Finance and Public Credit (SHCP).[174] The FONDEN Program for Reconstruction financed emergency expenses after a natural disaster and provided aid to the affected population.[175] The program also transferred funds to Mexican agencies and states to recover and reconstruct infrastructure and low-income dwellings, if the damages overran state and agency budgets.[176] For example, FONDEN transferred funds to the Ministry of Transport for the reconstruction and repair of roads and bridges.[177]

In 1999, Mexico established the FONDEN Trust, a public trust that administered FONDEN Program for Reconstruction funds that were pre-approved for specific projects.[178] The FONDEN Trust acted as a lender of last resort and "as the contracting authority for insurance and other risk transfer instruments."[179] Mexican law dictated that FONDEN could not operate a deficit, but required that the government provide financial assistance from other federal financial sources if damages exceeded FONDEN's allocated funds.[180]

Starting in 2001, Mexico decreased the allocated funds for the FONDEN program.[181] Mexico reallocated budgeted funds to other areas of the federal government following low levels of disaster loss in 2001 and 2002.[182] After Mexico reallocated and decreased budgeted funds in 2001, subsequent years incurred higher rates of disaster loss.[183] In 2006, Mexico restructured FONDEN's budgeted allocation to provide a minimum reserve to cover a portion of damages from natural disasters and purchase risk transfer instruments, like insurance, to better hedge against earthquake risk.[184] Article 37 of Mexico's Federal Budget Law states that "the annual allocation together with the uncommitted funds from the previous fiscal year cannot be less than 0.4 percent of the total Federal budget."[185]

In 2006, Mexico voted to supplement FONDEN's allocated budget using market-based risk transfer instruments as a way to address budgetary shortfalls.[186] Mexico became the first national government to issue a CAT bond (CatMEX).[187] CatMEX provided US$160 million in earthquake coverage, which Mexico combined with a reinsurance scheme to provide US$450 million in coverage over a three-year maturity.[188] In 2009, Mexico pooled "multiple risks in multiple areas," including hurricane risk, and created MultiCAT with assistance from the World Bank Treasury.[189]

Mexico continued to work with the World Bank Treasury to create CAT bonds in 2012, 2017, 2018, and 2020. The 2012 MultiCAT provided US$315 million in coverage for hurricanes and earthquakes.[190] Hurricane Patricia in 2015 triggered a US$50 million payout of the bond's Class C tranche, resulting in a 50 percent loss of principal for investors.[191] The 2017 FONDEN CAT bond provided US$360 million in protection from earthquakes and hurricanes.[192] An 8.0 magnitude earthquake triggered the full payout, US$150 million, for the Class A earthquake note.[193]

In 2018, Mexico worked with Pacific Alliance members Peru, Chile, and Colombia to create the 2018 Pacific Alliance CAT bond.[194] The bond provided US$260 million in protection from earthquakes, but no seismic events triggered the bond's release.[195]

Most recently, Mexico issued its 2020 FONDEN CAT bond, which provides US$485 million in coverage for earthquakes and hurricanes.[196] The bond features four tranches of notes.[197] Class A notes provide US$145 million in coverage for low-risk exposure earthquakes.[198] Class B notes provide US$60 million in coverage for high-risk exposure earthquakes.[199] Class C notes provide US$125 million in coverage for named storms and hurricanes in the Atlantic.[200] Class D notes provide US$100 million in coverage for named storms and hurricanes in the Pacific.[201] In 2020, Mexican lawmakers voted to dismember FONDEN with hopes of diverting remaining funds to the nation's COVID-19 response. The 2020 FONDEN CAT will continue to provide coverage until maturity despite the termination of the FONDEN program.[202]

Building the 2009 MultiCAT Program

Mexico was the first national government to issue CAT bonds as a means to transfer natural disaster damage risk via a market-based instrument. The Mexican government selected the World Bank Treasury as the global coordinator and together created the 2009 MultiCAT program.[203]

The World Bank Treasury, AIR Worldwide, Goldman Sachs, and Swiss Re designed the bond's trigger mechanism.[204] The parties decided the MultiCAT bond would provide binary parametric coverage with a "cat in the box" trigger, meaning the event would have to take place in a certain geographic area in addition to non-geographic criteria to trigger payout. The parameters were earthquake magnitude, hurricane central pressure, and the declaration of disaster by the Mexican government within predefined zones.[205] The parties selected the United States Geological Survey and the U.S. National Hurricane Center as neutral parameter verification agencies.[206]

The bond totaled US$250million and featured four tranches of notes: three notes for hurricanes and named storms and one note for earthquakes in various geographic zones.[207] Class A provided US$140 million of coverage for earthquakes within three regions of Mexico.[208] Classes B, C, and

D provided US$50 million each to cover hurricane risk.[209] Standard and Poor's rated the A, B, and C notes as BB and note D as BB-.[210]

AIR Worldwide conducted the bond's risk modeling by updating the 2006 CatMEX bond earthquake model and expanding it to include hurricane risks for the 2009 MultiCAT.[*][211] Mexico had a fixed budget throughout the bond's creation.[†] As a result, AIR Worldwide ran the risk model multiple times for various scenarios within the covered area to determine if the resulting premium fit within the budgeted amount.

The bond's structure differed slightly from traditional CAT bonds. Due to Mexican law, the bond required FONDEN to first purchase insurance through a local insurance company. As a result, FONDEN, as the bond sponsor, purchased insurance from Agroasemex, which became the official cedent. Agroasemex then reinsured itself with Swiss Re to cover claims made by FONDEN. Swiss Re then entered into a derivative counterparty contract with the Cayman-based special purpose vehicle, MultiCAT Mexico 2009 Ltd.

When MultiCAT issued in October 2009, the bond was already "two-and-a-half times oversubscribed."[212] Due to high demand, the bond was upsized from US$250 million to US$290 million.[213] The MultiCAT program's series structure allowed Mexico to reuse the legal framework and reduce administrative fees for future bond issuance.[214] Future bond iterations only required pricing supplement documentation detailing the parameters of the new bond.[215]

4.2.2. The Caribbean

Caribbean nations primarily rely on a regional insurance pool, Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC).[216] Risk pooling systems like CCRIF SPC offer developing nations an opportunity to hedge against risk, particularly when the central government does not have the economic or bureaucratic capacity to respond quickly to catastrophic events.

The CCRIF SPC was established in 2007 with guidance from the World Bank, a grant from the Japanese government, and capital donations made to a multi-donor trust fund (MDTF) by several nations, including the United States. The World Bank estimated the original project costs at US$33.4 million but it ultimately cost US$74 million, due to project restructuring in 2007, 2010, and 2011.[217]

---

[*] The models utilized are not publicly available.

[†] The budgeted amount and premium payment remain internal to the Mexican Government.

CCRIF SPC is the world's first multinational fund leveraging parametric insurance to provide member nations low-cost insurance against hurricane, earthquake, and excess rainfall events.[218] The fund acts as a joint reserve mechanism fully backed through reinsurance markets.[219] A country's annual premium is calculated based on their own risk exposure and the level of coverage agreed upon by participating parties.[220] Currently, the organization provides multiple coverage types to 19 Caribbean and three Central American nations, detailed in Table 6 below.[221]

Table 6. CCRIF SPC Member Nations

Country	Tropical Cyclone (TC)	Earthquake (EQ)	Excess Rainfall (XSR)
Anguilla	✓	✓	✓
Antigua and Barbuda	✓	✓	✓
Barbados	✓	✓	✓
Belize	✓		✓
British Virgin Isles	✓	✓	✓
Cayman Islands	✓	✓	
Dominica	✓	✓	✓
Grenada	✓	✓	✓
Haiti	✓	✓	✓
Jamaica	✓		✓
Montserrat	✓	✓	✓
St. Kitts and Nevis	✓	✓	✓
Saint Maarten	✓	✓	✓
St. Vincent and Grenadines	✓	✓	✓
The Bahamas	3		4
Trinidad and Tobago	2	✓	2
Turks and Caicos Islands	✓		✓
Guatemala			✓
Nicaragua	✓	✓	✓
Panama			✓
Total Policies	22	15	23

Source: CCRIF, *2020–2021 Annual Report* (Grand Cayman, Cayman Islands: CCRIF, accessed August 30, 2022), 27, https://www.ccrif.org/sites/default/files/publications/annualreports/CCRIF_SPC_Annual_Report_2020_2021.pdf.

Since its conception, the fund has paid US$245 million in claims, 19 percent of which supported long-term infrastructure projects.[222] In 2020, CCRIF SPC paid US$44 million to five countries with qualified triggering events, summarized in Table 7 below.[223]

Table 7. CCRIF SPC 2020 Payouts

Country	Payout	Policy	Triggering Event	Date
Haiti	US$7.2 million	XSR	Hurricane Laura	August 2020
Trinidad and Tobago	US$176,146	XSR	Excess Rainfall Event	August 31 – September 2, 2020
Jamaica	US$3.5 million	XSR	Excess Rain from Tropical Cyclones Zeta and Eta	October 2020 November 2020
Panama	US$2.7 million	XSR	Excess Rain from Tropical Cyclone Eta	November 2020
Nicaragua	US$30.6 million*	TC and XSR	Hurricane Eta (TC and XSR) Hurricane Iota (TC)	November 2020

[*] Total of three separate payouts.
Source: CCRIF, *2020–2021 Annual Report*, 29.

In 2021, the 23 member nations increased protection 13 percent by renewing five parametric insurance products and ceded over US$1 billion in risk to CCRIF SPC.[224] Twenty-two countries purchased tropical cyclone coverage, 15 purchased earthquake coverage, and 23 purchased excess rainfall coverage.[225]

Catastrophe Bonds

In June 2014, the World Bank issued its first CAT bond to provide reinsurance protection for CCRIF.[226] The bond provided US$30 million in multi-year coverage against hurricanes and earthquakes, providing protection to 16 CCRIF SPC member nations over three years.[227] The World Bank and CCRIF SPC did not issue any additional CAT bonds after CCRIF 2014-1 matured. Table 8 details the CCRIF SPC CAT bond parameters.

Table 8. CCRIF SPC CAT Bond

Bond Dimension	Details
Issuer	World Bank CCRIF 2014-1
Cedent/Sponsor	Caribbean Catastrophe Risk Insurance Facility (CCRIF)
Structuring Agents	CG Securities Munich Re
Placement Agent	CG Securities
Risk Modeling Agents	Unknown
Risks/Perils Covered	Caribbean Hurricanes and Earthquakes
Size	US$30 million

Trigger Type	Parametric Modeled Loss
Date of Issue	June 2014
Time to Maturity	3 years

Source: Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: World Bank–CCRIF 2014-1," accessed August 30, 2022, https://www.artemis.bm/deal-directory/world-bank-ccrif-2014-1/.

Jamaica is the only Caribbean nation to independently leverage CAT bonds as a form of risk reduction.[228] In July 2021, the World Bank's International Bank for Reconstruction and Development (IRBD) and Jamaica issued Jamaica's first CAT bond, IBRD CAR 130, detailed in Table 9.[229] The bond provides US$185 million in multi-year coverage for named storms on a per occurrence basis.[230]

Table 9. Jamaican CAT Bond

Bond Dimension	Details
Issuer	World Bank IBRD CAR 130
Cedent/Sponsor	Government of Jamaica
Structuring Agents	Aon Securities Swiss RE Capital Market
Risk Modeling Agents	AIR Worldwide
Risks/Perils Covered	Named Storms
Size	US$185 million
Trigger Type	Parametric
Date of Issue	July 2021
Maturity Date	December 29, 2023

Source: Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130," accessed August 30, 2022, https://www.artemis.bm/deal-directory/ibrd-car-130-jamaica/.

The bond utilizes a parametric trigger that includes a calculated central pressure figure within a series of predetermined parametric boxes.[231] Triggering events are validated using data from NHC's automated tropical cyclone forecasting system.[232] The bond's value represents about 1.3 percent of Jamaica's GDP and is the largest World Bank bond issued relative to beneficiary GDP.[233] In a news report by Artemis, Fitch Ratings noted that the bond significantly strengthens Jamaica's risk mitigation strategies and prevents the excessive debts typically incurred by rebuilding after catastrophic events.[234]

IBRD CAR 130 Risk Modeling

Unlike other government sponsored CAT bonds, an explanation of AIR's risk modeling methods is available for IRBD CAR 130. AIR Worldwide designed "an alternative loss estimation methodology based on statistical simulation techniques."[235] Unlike traditional actuarial practices, AIR Worldwide utilized computer programs to provide a mathematical representation of the physical characteristics of catastrophe events.[236] Results were expressed in a probability distribution, which provided "a distribution of potential losses and the relative likelihood of occurrence at various loss levels," given "specific insurance exposures under policies in force."[237]

AIR simulated 10,000 annual hurricane scenarios, which resulted in an assigned value for each modeled meteorological characteristic.[238] AIR then estimated potential property damages and modeled loss, which resulted in the following:[239]

- Modeled Annual Attachment Probability: 2.37 percent
- Modeled Annual Expected Loss: 1.52 percent
- Modeled Annual Exhaustion Probability: 0.76 percent

AIR also conducted correlational, historical, and sensitivity analyses to strengthen the probability distribution. The methodology emphasizes that the probability distribution is not a forecast of any weather event, but instead a model of potential losses.[240]

4.3. The United States

In the United States, California and Florida are susceptible to extreme catastrophic events, including wildfires, earthquakes, and hurricanes. Recognizing this, both states have either established public-private partnerships or bolstered insurance mechanisms for residential properties.

4.3.1. California

Subject to both wildfires and earthquakes, the state of California required insurers to offer earthquake insurance coverage to residents until the state established the California Earthquake Authority (CEA) in 1996. Under the CEA, premiums for private insurers must be based on "modelled estimates of expected losses."[241] Individuals can purchase CEA earthquake insurance from CEA-member residential insurers.[*] Coverage is available for homes, condominiums, mobile homes, and rented properties. Reportedly, the CEA has the capacity to absorb losses on par with some of the largest historical earthquakes, including the 1906 San Francisco Earthquake.[242] The largest earthquake the CEA can sustain is "two Northridge-size events, estimated at a 400y[ear] return period."[243] In California, the CEA writes approximately two-thirds of the residential policies,

---

[*] For a full list of CEA insurance members, see: California Earthquake Authority, "CEA Participating Earthquake Insurance Providers," 2021, https://www.earthquakeauthority.com/California-Earthquake-Insurance-Policies/Participating-Residential-Insurers-Earthquake

while private-sector companies cover the remaining third.[244] More details of specific dimensions of the CEA are illustrated in Table 10 below.

Table 10. CEA Risk Management

Dimension	California Earthquake Authority (CEA)
Coverage Provided	Residential earthquake only
Take up Rate and Mandates	10%; mandatory offer, no mandatory purchase
Financing	Premiums, reinsurance, insurer contributions and assessments, debt, accumulated capital
Claims Paying Ability (up to the Given Event)	1/250 year all perils occurrence exceedance probability (2014)
Incentives or Mandates for Risk Reduction	Premium discounts for seismic retrofits on older homes and mobile homes reinforced by earthquake-resistant bracing system
Affordability Addressed	No

Source: Carolyn Kousky and Howard Kunreuther, "Risk Management Roles of the Public and Private Sector," *Risk Management Insurance Review* 21, no. 1 (2018): 189, https://onlinelibrary.wiley.com/doi/abs/10.1111/rmir.12096.

The California Fair Access to Insurance Requirements (FAIR) Plan ensures basic earthquake insurance is available to individuals whose homes are in "high risk" areas. Additionally, in California, surplus line broker JumpStart sells parametric insurance coverage against earthquake risk for residents and property owners. In this instance, "the policy trigger is not based on the Richter Magnitude, but on the shaking intensity."[245]

When modeling wildfire risk, California's wildfire disaster fund relies on modeling from AIR Worldwide. The AIR model considers factors such as "ignition, fuel and fuel characteristics, terrain, wind, land use and land cover, wildland-urban interface, and building construction and materials."[246]

4.3.2. Florida

According to Florida Statutes, in 2021 the state legislature found there was a viable state interest in maintaining an "orderly private-sector market for property insurance."[247] The legislature declared that when the private sector is unable to maintain a market, the state would provide support to do so. In the aftermath of Hurricane Andrew, which is estimated to have caused $20 billion in damage, the legislature declared that residential insurance providers were "unable or unwilling to maintain reserves, surplus, and reinsurance sufficient to enable all insurers to pay all claims in full in the event of a catastrophe."[248] The Florida State Board of Administration (the Board), created in 1993, maintains contractual agreements with insurers, promising reimbursement for 45, 75, or 90 percent of losses from each covered event.[249] The Board maintains a claims payment capacity of $17 billion.

In 2021, the Board partnered with an independent consultant to create a formula "for determining the actuarially indicated premium to be paid to the [Hurricane Catastrophe] Fund."[250] The Florida Hurricane Catastrophe Fund (FHCF) is recognized as a successful example of a public-private partnership.[251] Established in 1993, the FHCF functions as a state trust fund "under the direction and control of the [Board]."[252] It is designed to maintain the state's insurance capacity by providing reimbursements to insurers for a fraction of their hurricane loss. The FHFC is meant to be self-sufficient "except in extraordinary circumstances."[253]

For each zip code, the FHCF formula determines the insurance premium "for each $1,000 of insured value."[254] The formula is expected to consider factors such as "deductibles, types of construction, type of coverage provided, [and] relative concentration of risks."[255] Additionally, the formula is expected to include a cash build-up factor and must be approved by the Board. Annually, the Board receives a Ratemaking Formula Report for the FHCF. The 2021 report states an estimated premium of $1.206 billion, signaling a negative rate change of 4.73 percent from 2020.[256] A more detailed breakdown of annual premiums can be found in Appendix III. Additionally, Table 11 provides an overview of the key differences between FHCF and the Florida Citizen's Property Insurance Corporation, a state-operated risk pool.

Table 11. Florida's Risk Management

Dimensions	Florida Citizen's Property Insurance Corporation	Florida Hurricane Catastrophe Fund
Coverage Provided	Residential policies or wind-only policies	Mandatory reinsurance to companies writing insurance
Take-up Rates and Mandates	Wind coverage required	Mandatory participation for authorized property insurance
Financing	Premiums, reinsurance, CAT bonds, Hurricane Catastrophe Fund, post-loss assessments on policyholders and non-policyholders	Premiums, reinsurance, investment income, revenue bonds
Claims Paying Ability (up to the Given Event)	1/100 year all perils occurrence exceeded probability (2013); no post-event assessment for 1/100 year event (2016)	N/A
Incentives or Mandates for Risk Reduction	Premium discounts for wind-resistant features	None
Affordability Addressed	No	No

Source: Kousky and Kunreuther, "Risk Management Roles of Public and Private Sector," 188.

Five models are used to calculate risk, all of which have been approved by the Florida Commission on Hurricane Loss Projection Methodology. They include AIR, CoreLogic EQECAT, RMS, Applied Research Associates (ARA), and the Florida Public Hurricane Model (FPHM).[257]

FPHM has three main components: meteorological (wind hazard), structure-engineering (vulnerability), and actuarial (insured loss cost).[258] The insurance loss model (ILM) calculates the expected loss during storms and is delineated into three classes: personal residential, commercial residential for low-risk policies, and commercial residential for high-risk policies. Input data includes wind speeds, "exposure and building characteristics of residential properties, and engineering vulnerability matrices."[259]

CoreLogic's Hurricane Model inputs the following variables[260]:

- **Landfall Location**: Characterized as ten nautical miles along the coastline of the Texas-Mexico border through Maine. According to CoreLogic, there are 310 distinct landfall segments used in creating a probabilistic hurricane dataset.
- **Track Distribution**: Generated using National Hurricane Center data from 1900-2020.
- **Maximum One-Minute Sustained Wind Speed**: Used to measure hurricane intensity. According to CoreLogic, it is "one of the most critical items when considering loss sensitivity." Ranges fall between 74 and 192 miles per hour.
- **Radius of Maximum Winds**: Measured as the distance between the geometric center of the storm "to the region of the highest winds."
- **Translational Speed**: The movement of the storm itself.
- **Inland Decay Rate**, or Filling Rate: Measured as the exponential decay of a hurricane's central pressure deficit, also known as the difference between "the background pressure and the storm central pressure."
- **Inflow Angle**: The angle between the circular motion and direction of airflow towards the center of the hurricane.

Additionally, CoreLogic computes the average amount of insured loss with the following expression:[261]

$$TIV \cdot [\int_{D}^{D+L} x - D \cdot f(x)\, dx + \int_{D+L}^{1} L \cdot f(x) dx] \tag{19}$$

where *TIV* refers to "total insurable value," *x* is amount of damage, *D* is the deductible, and *L* is the policy limit.

In Florida, Topa Insurance offers parametric insurance to protect individuals against hurricane risks through its StormPeace program.[262] StormPeace provides coverage of up to $100,000 in the event of “named hurricanes” identified by the National Hurricane Center.

5. Comparative Analysis: Hurricanes Sandy and Irene

To examine the financial and physical impact of extreme weather events on bridges and tunnels via comparative analysis, FRD researchers examined two distinct events: Hurricane Irene and Hurricane Sandy. Both events affected the northeastern part of the United States and had similar characteristics. However, as illustrated in Table 12 below, while Hurricane Irene resulted in an initially estimated $10 billion worth of property damage, Hurricane Sandy was more severe, with an estimated $20 billion worth of damage according to 2013 figures.

Table 12. Comparison of Hurricanes Irene and Sandy

	Irene	**Sandy**
Landfall Date	August 27, 2011	October 29, 2012
Strength at First U.S. Landfall	Category One Hurricane	Post-Tropical Cyclone
Landfall Location (Sustained Winds)	8/27 – Cape Lookout, NC (90 mph) 8/28 – Little Egg Inlet, NJ (80 mph) 8/28 – Coney Island, NY (75 mph)	10/29 – Atlantic City, NJ (80 mph)
Distance of Tropical Storm-Force Wind from Center	300 miles	500 miles
Peak Flooding	New York City – 9.5 feet Philadelphia – 9.9 feet	New York City – 14.1 feet Philadelphia – 10.6 feet
Initial Estimated Property Damage	$10 billion	$20+ billion
Deaths	45	131

Source: U.S Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*, April 2013, https://www.hsdl.org/?abstract&did=750499.

5.1. Geographic Area

As demonstrated in Table 13, both Hurricanes Sandy and Irene made landfall in similar geographic areas, moving upwards along the eastern part of the United States. In total, both events had overlapping impacts in 11 states.

Table 13. Number of Days Declared as Emergency and Major Disaster

State	**Irene**		**Sandy**	
	Emergency	**Major Disaster**	**Emergency**	**Major Disaster**
Connecticut	6	5	12	12
Delaware	–	6	12	12
District of Columbia	6	6	3	5
Maine	–	2	–	–
Maryland	10	12	13	9
Massachusetts	10	2	12	12
New Hampshire	–	10	5	13

State	Irene		Sandy	
	Emergency	Major Disaster	Emergency	Major Disaster
New Jersey	10	9	13	13
New York	11	7	12	12
North Carolina	7	7	–	–
Ohio	–	–	–	1
Pennsylvania	19	4	13	13
Puerto Rico	3	3	–	–
Rhode Island	3	2	13	5
Vermont	7	6	–	–
Virginia	9	2	6	13
West Virginia	–	–	10	10

Source: DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*.

5.1.1. Hurricane Irene

On August 15, 2011, Hurricane Irene began as a tropical wave off the coast of Africa, transitioning to a tropical storm on August 21 east of Dominica.[263] Irene struck the Bahamas as a Category Three hurricane before traveling north, making landfall in North Carolina. Upon impact, Irene produced flooding and wind damage in North Carolina, with additional reverberating effects in parts of New England. On August 28, Irene again made landfall and hit the coast of New England, "traversed through western Connecticut and Massachusetts and then along the New Hampshire/Vermont border," eventually exiting New England through northern Maine.[264] Only the North Carolina impact was considered a hurricane landfall, while additional landfalls in Puerto Rico, New Jersey, and New York were classified as tropical storms.[265] In the wake of Hurricane Irene, Major Disaster Declarations were issued in Delaware, the District of Columbia, Maryland, Maine, Virginia, Pennsylvania, New Hampshire, Rhode Island, Massachusetts, Connecticut, Vermont, North Carolina, New York, New Jersey, and Puerto Rico.[266]

5.1.2. Hurricane Sandy

Hurricane Sandy began as a tropical wave on the west coast of Africa on October 11, 2012. The storm developed into a hurricane in the Caribbean and made its first landfall on October 24 in Kingston, Jamaica. Sandy strengthened to a Category Two hurricane and struck Cuba the next day. The storm traveled north and hit Haiti, the Dominican Republic, Puerto Rico, Cuba, and the Bahamas. On October 29, Hurricane Sandy made landfall in Atlantic City, New Jersey as a post-tropical cyclone with winds that reached up to 80 mph. Hurricane Sandy ultimately affected 24 states with subsequent coastal flooding and heavy snowfall in Central and Southern Appalachia.[267]

5.2. Storm Characteristics

Hurricanes Sandy and Irene produced strong winds upon impact, resulting in severe rains and flooding. As illustrated in Table 14, both events produced comparable storm tides, with Hurricane Sandy being relatively more severe. While the U.S. Department of Energy notes that Hurricane Sandy was weaker than Irene at landfall, "Sandy brought tropical storm conditions to a larger area of the East Coast, and blizzard conditions as far west as the Central and Southern Appalachians."[268]

Table 14. Maximum Recorded Storm Tides (by Feet)

Location	Irene	Sandy
Wilmington, NC	5.24	5.91
Washington, DC	3.87	6.11
Baltimore, MD	2.98	4.66
Philadelphia, PA	9.93	10.62
Atlantic City, NJ	6.96	8.90
Bergen Point West Reach, NY	10.22	14.58
The Battery, NY	9.50	14.06
New Haven, CT	11.57	12.25
Providence, RI	8.25	9.37
Boston, MA	11.95	12.92
Portland, ME	11.96	11.90

Source: DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*.

5.2.1. Hurricane Irene

Upon making landfall in North Carolina, Hurricane Irene produced Category One hurricane-force winds. Tropical storm-force winds extended approximately 300 miles from its center, but Irene was categorized as a "slow moving storm, traveling at top speeds of 20 miles per hour, compared to speeds of 30-40 [miles per hour] for similarly sized storms."[269] By the time it hit Vermont, Irene had sustained winds of 80 km/h and deposited 4-8 inches of rain across the state.[270] At higher elevations, rainfalls resulted in flash flooding and "progressed to widespread flooding throughout Central and Southern Vermont."[271] According to Engineering Professor Ian Anderson of the University of Vermont and colleagues, rainfall in Vermont "caused record flows in nine streams [with] nine other streams [having] peak flows among the top four on record."[272] Overall, the flooding brought on by Irene is considered "one of the worst flood disasters ever recorded in the Northeast."[273]

5.2.2. Hurricane Sandy

When Hurricane Sandy made landfall in Atlantic City, New Jersey, it was categorized as a post-tropical cyclone with hurricane-speed winds reaching 80 mph.[274] While Sandy did not produce comparably high winds, the storm did produce tropical storm-force winds up to 500 miles from the storm's core.[275] Experts began referring to Hurricane Sandy as SuperStorm Sandy after it combined with a cold core low-pressure system, which caused flooding and snowstorms throughout the Mid-Atlantic and Northeast regions.[276]

5.3. Damage

The National Oceanic Atmospheric Administration (NOAA) ranks both Hurricane Irene and Hurricane Sandy as "among the costliest and deadliest weather events in U.S. history."[277] Shortly after each storm, Hurricane Irene was estimated to have caused damage totaling $10 billion, while Sandy-related damage was estimated at over $20 billion. However, costs for both storms were later determined to be higher, as detailed below.

Both storms are reported to have caused "extensive damage to electric transmission and distribution infrastructure in the Northeast and Mid-Atlantic." [278] Infrastructure, including substations, power lines, and utility poles, was subject to damage. In New York, the Long Island Power Authority (LIPA) experienced damage to an estimated "50 substations, 2,100 transformers, and 4,500 utility poles following Sandy, as compared to 22 substations, 1,000 transformers, and 900 utility poles following Irene."[279]

5.3.1. Hurricane Irene

In the state of Vermont, which is the most well-documented case in terms of damage related to Hurricane Irene, major damage to residential property and public infrastructure occurred.[280] Namely, the flooding and high stream flows from Irene are estimated to have damaged or contributed to the failure of 389 Vermont bridges.[281] Bridge damage was delineated along four categories: scour (erosion of soil), channel flanking, superstructure damage, and debris blockage. Bridge damage was further categorized into four levels:

- **Slight:** Includes channel erosion not impacting bridge foundation, superstructure and guardrail damage, and debris accumulation with scour present.
- **Moderate:** Includes scour affecting foundation short of a critical state, bank and approach erosion, superstructure damage short of a critical state, and heavy aggradation.
- **Extensive:** Includes critical scour, with some settlement to a single foundation but not collapse, and damage to understructure, making it structurally unsafe.

- **Complete:** Includes cases where the bridge was washed away, collapsed, or has significant foundation damage requiring replacement.[282]

Of the 389 bridges, 30 percent were deemed as having slight damage, 39 percent as having moderate damage, 14.5 percent as having extensive damage, and 16.5 percent as having complete damage.[283]

More broadly, Hurricane Irene had severe impacts on transportation between "the heavily populated corridor from Washington, DC to Boston."[284] Moreover, according to a 2012 report by the U.S. Department of Commerce, Irene was "the first natural disaster to close the NYC subway system. [A]ll service was suspended late Sunday, August 27, and did not fully resume until Monday, August 29."[285] The same report states that AMTRAK services were reduced "across much of the Mid-Atlantic and Northeast," with all train services in the DC-to-Boston corridor canceled. In Vermont, "much of the state's highway and town infrastructure was severely crippled with communities isolated for days."[286] In North Carolina, more than an estimated 270 roads and 21 bridges were closed "due to flooding, debris, and damage."[287]

5.3.2. Hurricane Sandy

Hurricane Sandy is the fourth most costly hurricane in U.S. history, with NOAA estimating total damages at $74 billion (CPI adjusted) in 2022, over $50 billion more than initially estimated by the Department of Energy.[288] This estimate includes damage to residential, commercial, and government buildings, as well as their "material assets," cost of business interruption, "offshore energy platforms, public infrastructure, and agricultural assets."[289] Using lessons learned from Hurricane Irene, state and local agencies took preventative actions to reduce damages. New York City shutdown all public transport and closed bridges and tunnels on a case-by-case basis 24 hours before Sandy made landfall.[290] Even with preparation, traffic and subway tunnels experienced significant flooding, but were able to reopen quickly. Only Hugh L. Carey Brooklyn-Battery and Queens Midtown Tunnels experienced flooding that slowed a return to operation.[291]

As indicated in Table 15, following Hurricane Sandy, the state of New York received several forms of assistance from both FEMA and the Army Corps of Engineers. Specifically, New York received the largest amount of assistance from FEMA's Public Assistance Program for both recovery from Sandy and preparation for future events. Beyond these amounts, New York received an additional $518 million to "provide upgrades and retrofit 105 bridges [...] vulnerable to erosion of foundation materials during flooding."[292]

Table 15. NY Hurricane Sandy Recovery and Mitigation Project Amounts, in Millions of Dollars

FEMA Hazard Mitigation Grant Program		FEMA Public Assistance		U.S. Army Corps of Engineers	
Total Estimated Project Amount	**Total Federal Amount Obligated**	**Total Project Amount**	**Total Mitigation Amount**	**Total Project Amount**	**Total Federal Amount**
$1,060.3	$867.6	$12,935.0	$11,641.6	$3,545.8	$3,320.4

Source: U.S. Government Accountability Office, "Natural Disasters: Economic Effects of Hurricanes Katrina, Sandy, Harvey, and Irma," GAO-20-633R, September 10, 2020, 2, https://www.gao.gov/assets/gao-20-633r.pdf.

5.4. Insurance

As stated in Section 5.3, Hurricanes Sandy and Irene are considered two of the costliest weather events in the past decade. The following sections provide further detail regarding insured and uninsured losses.

5.4.1. Hurricane Irene

In the aftermath of Hurricane Irene, the United States' Insurance Services Office and the National Hurricane Center (NHC) reported estimated damage totaling $4.3 billion in losses.[293] To account for uninsured losses, the $4.3 billion estimate was doubled, to $8.6 billion. Additionally, the NHC estimates that Irene caused $7.2 billion in losses "from inland flooding and storm surge,"[294] accounting for 45.5 percent of the total loss estimate.[295] Since NHC assumes economics losses are twice the insured loss, the total damage estimate for Hurricane Irene was $15.8 billion.[296] This estimate is slightly higher than the $10 billion figure presented by a 2013 U.S Department of Energy report, which considered only property damage.

FRD researchers were unable to locate more specific breakdowns of the above estimates. However, a 2012 analysis of wind speeds and hurricane loss by R. J. Murnane of the Bermuda Institute of Ocean Sciences and Professor J. B. Elsner of Florida State University developed a model confirming the above economic losses from Hurricane Irene. Using quantile regression, Murnane and Elsner modeled the log of normalized loss as a function of wind speed. Their model predicts an economic loss of $490 million for a corresponding wind speed of 39 $m\,s^{-1}$ and $140 million for a wind speed of28 $m\,s^{-1}$. According to their model, "the 90th centile loss for the landfall with 39 $m\,s^{-1}$ winds is $11 [billion] with a 90 [percent] confidence interval of $5 to $24 [billion]."[297] Similarly, the predicted "90th centile loss for the landfall with 28 $m\,s^{-1}$ winds is $7.5 [billion] with a 90 [percent] confidence interval of $2 to $28 [billion]."[298]

5.4.2. Hurricane Sandy

As of mid-April 2013, insurers had settled 93 percent of all Hurricane Sandy insurance claims, including wind and flood related damages. Out of the 1.5 million total claims, about 750 million claims originated from New York and New Jersey. Homeowners accounted for 1.1 million claims, vehicle owners accounted for 250,000 claims, and businesses made about 200,000 claims. While businesses only made 13 percent of claims, the Insurance Information Institute estimated in 2013 that these claims would ultimately account for 48 percent of the total Hurricane Sandy payout. The organization further estimated that insurance companies would pay a total of $18.8 billion to settle Hurricane Sandy related claims.[299]

The previous figures do not account for flood claims made under the National Flood Insurance Program (NFIP). In the case of New York, the NFIP had received 16,264 claim as of February 2013. Of those, 19 percent remained open at that time. The average closed claim was estimated at $54,000. Table 16 below provides further detail on the number and types of claims by structure.[300]

Table 16. NFIP Payments in New York Following Hurricane Sandy

Claim Type	Number of Closed Claims	Number of Claims at Policy Limit	Percent of Closed Claims Paid to Policy Limit
Residential			
One-to-four family dwelling	10,875	383	4
Condominium	116	9	8
Multifamily Dwelling	213	35	16
Mixed-Use Property	157	29	18
Commercial			
Commercial and Industrial	144	44	31
Transportation and Utility	52	7	13
Condominium	6	4	67
Other	225	24	11
Missing	365	44	12
Total	**12,153**	**579**	**5**

Source: Lloyd Dixon et al., "Insurance Payments After Hurricane Sandy and Hurricane Sandy's Impact on Insurance Markets," in *Flood Insurance in New York City Following Hurricane Sandy* (Santa Monica, CA: RAND Corporation, 2013), 21–32, https://www.rand.org/pubs/research_reports/RR328.html.

In addition to the NFIP, FEMA's Disaster Relief Fund (DRF) provided about $22 billion in cumulative obligations through FY2021, with New York and New Jersey accounting for about $21.7 billion of the total obligations. FEMA estimates that DRF funding associated with Hurricane Sandy will total $22.3 billion by the end of FY2022.[301]

6. CLIMATE CHANGE AND SEVERE WEATHER

In the past forty years, the United States has experienced an increase in the frequency and intensity of severe weather events. Billion-dollar disaster frequency is increasing by about five percent per year.[302] A billion-dollar weather event is one which causes damage costing at least one billion dollars. In 1980, three billion-dollar weather events resulted in $40.4 billion in damages.* In 2021, damage from 20 billion-dollar events totaled $145 billion.[303] NOAA suggests that increased exposure, vulnerability, and climate change are key reasons for the increase in events and costs.[304]

The National Centers for Environmental Information (NCEI) is the nation's leading authority for tracking and evaluating severe climate events in the United States and abroad.[305] In 2012, NCEI reviewed its methodology for predicting billion-dollar weather events, as the models produced decreasingly accurate results.[306] NCEI methods utilize a factor approach to convert insured losses to total direct losses.[307] Researchers found an underestimation of loss due to net effect of biases in the model, with the factor approach underestimating average loss by 10-15 percent.[308] Methodological recommendations include adding spatial and temporal variations in insurance participation to predict losses more accurately.[309]

In states like California, wildfires have become more damaging in recent years, encroaching on territory "once thought to be safe."[310] Prior to 2007, wildfires mostly affected forests, open grasslands, and the edges of wildland-urban interference.[311] The impact on insurance has been considered unprecedented, as shown in Table 17 below.

Table 17. California Wildfire Impact on Insurance

Year Range	Insurance Cost
1964-1990	Less than $100 million per year
1990-2010	$600 million per year
2011-2018	$4 billion per year

Source: Leslie Kaufman and Eric Roston, "Wildfires are Close to Torching the Insurance Industry in California," *Bloomberg,* November 10, 2020, https://www.bloomberg.com/news/features/2020-11-10/wildfires-are-torching-california-s-insurance-industry-amid-climate-change.

Insurance companies in the state have filed rate increase requests with the California Department of Insurance (CDI) based on their long-term expectations of catastrophe-related loss.[312]

In the United States, the federal government provides emergency disaster funding through agencies like FEMA and DOT; however, in some instances, such as FHWA's ER program, the budgeted funding can fall short.[313] For example, DOT FHWA's ER program allocated

---

* Dollar amounts are CPI adjusted.

$1,399,820,782.72 for the first half of FY2022, significantly exceeding the annual authorized amount of $100 million.[314] A GAO report recognized the increasing impact of climate change and recommended expanding ER funding to support climate resilience improvements.[315]

According to a report by the National Cooperative Highway Research Program, climate change will have a direct impact on bridges, tunnels, and highways.[316] Changes in temperature are expected to result in premature deterioration of bridges, including extra stresses through thermal expansion.[317] Damage to roads from buckling is an additional anticipated impact.[318] For example, hotter summers in Alaska resulted in "increased glacial melting and longer periods of stream flows," which caused increased sediment in rivers and scouring of bridge-supporting piers.[319] Greater changes in precipitation levels are expected to result in increased risk of landslides and floods, which may cause road washouts and closures.[320] This increased precipitation is anticipated to lead to high soil moisture levels, which may compromise the structural integrity of roads, bridges, and tunnels.[321] Stronger hurricanes with more precipitation, higher wind speed, and more significant storm surge are expected to increase.[322]

6.1. Climate Change and Insurance

The increase in catastrophic events due to climate change also increases volatility for insurance firms.[323] Swiss Re reported US$190 billion in global economic losses from natural catastrophes in 2020. Insurance covered US$89 billion of total losses, US$81 billion of which covered natural catastrophes. The United States faced the highest economic loss due to East Coast hurricanes, Midwest convective storms, and West Coast wildfires. Swiss Re explains that in 2020, Hurricanes Sally and Laura imposed the largest single-event economic losses, but most economic losses were due to several small- and medium-sized secondary peril events.[*] [324]

Berkeley Professor of City and Regional Planning Stephen Collier and his colleagues explain that insurers attribute the increasing losses to climate change and anticipate that this trend will continue.[325] Several industry leaders, multinational organizations, and regulators warn that increasing catastrophic events (storms, floods, wildfires, etc.) will render some risks uninsurable.[326] Conversely, some insurers view climate change as an opportunity to expand their role by developing climate-change sensitive actuarial pricing methods and insuring the increasing risk.[327]

Insurance and risk models are evolving to better predict catastrophic weather events and the associated cost of damages. Outdated risk models rely on historical weather data to forecast weather events and are ill equipped to predict frequent catastrophic weather events.[328] For

---

[*] Secondary peril events refer to small to mid-size events that follow a primary event. For example, flooding from a hurricane is considered a secondary event.

example, historic models failed to predict the severity of Hurricane Andrew in 1992. Of the $27 billion in damages caused by the storm, $11.5 billion were not covered by insurance and several insurance companies defaulted as a result.[329]

In the case of severe weather events, CAT models are considered an alternative to the historical data and experience typically used to determine plausible futures. Industry leaders like AIR Worldwide and RMS offer sophisticated catastrophe risk modeling that incorporates climate change elements to forecast risk and potential losses.[330] The four main areas of CAT modeling include:

- **Hazard**: The risk of the hazard phenomenon.
- **Inventory**: The assets at risk.
- **Vulnerability**: The assets' susceptibility to damage.
- **Loss**: The direct or indirect monetary losses of assets.[331]

Given previous industry-wide defaults, insurance firms often buy reinsurance policies as a way to transfer financial risk of default off their balance sheet.[332] In the event an insurance firm faces claims that exceed a predetermined point, reinsurance activates to provide liquidity for excessive claims.[333] Reinsurance firms often specialize in catastrophic events due to the associated high damage costs. Several reinsurers suggest their catastrophe pricing and risk models enable them to "pool, mitigate, and distribute risks associated with climate change" most effectively.[334] However, reinsurance markets are not immune to the influence of climate change. Global reinsurance prices doubled following Hurricane Andrew and did not decrease until 1995.[335] Severe catastrophic events lead to higher rates of payout, which reduces insurers' and reinsurers' capital reserves and leads to higher prices.[336]

Reinsurers like Swiss Re and Munich Re also play a significant role in the CAT bond market. As previously explained, CAT bonds offer organizations and national governments an alternative to traditional insurance. Since the 1990s, "the return per unit of risk or multiple on [CAT] bonds has steadily declined."[337] University of Milano-Bicocca Professor Claudio Morana and NEOMA Professor Giacomo Sbrana find evidence suggesting this decline is caused in part by significant undervaluation of climate change risk in the CAT bond market.[338] Given this significant undervaluation, there is an increasing likelihood that catastrophic events will cause more damage than originally anticipated, and thus insurance will not cover the full cost of the event.[339] Climate change poses an increasing risk to governments, the reinsurance industry, and insurance companies, limiting their capacity to accurately anticipate the actual disaster funding requirements for catastrophic events.

7. CONCLUSION

Catastrophic events and the cost of mitigating damages continue to increase yearly. Climate change contributes significantly to the frequency and intensity of these events, as well as the growing loss of assets. Several organizations utilize risk transfer tools like insurance, reinsurance, and bonds to alleviate the financial risk of catastrophic events.

Several case studies illustrate the implementation of various risk transfer tools. Specifically, the cases of Japan, California, and Florida—all of which are highly vulnerable to natural disaster—underscore the utility of public-private partnerships to distribute burden sharing and the role insurance plays as a tool for disaster financing.

The CAT bond market continues to grow, and more national governments are leveraging these bonds as a method of disaster-risk management. CAT bonds allow sponsors to design a bond that fits within their budgetary constraints, while still providing peril- and geographic-specific coverage. While the risk and premium calculation methods utilized by modelling and structuring agencies are not publicly available, academic literature explains which factors most influence bond premiums. Agencies offer catastrophic modeling software, like AIR Worldwide's Touchstone Re, to determine potential losses for a variety of risk scenarios. Risk modeling organizations create proprietary catastrophe models that continue to evolve as climate, policy, and financial conditions change, which may be of use to FHWA but are not available to researchers at this time.

This report provides an overview of the current insurance and financial instruments governments and private entities utilize when mitigating catastrophic risk. For future research, FRD recommends FHWA determine which practices would best serve FHWA needs and conduct more detailed research as appropriate. Catastrophic risk modeling and mitigation continues to evolve as severe weather and seismic events pose an increasing threat to U.S. transit infrastructure. FRD recommends FHWA continue to remain current on improvements and new discoveries within the field as more data points on catastrophic events become available.

Lastly, recognizing that this report serves as a broad overview, FRD recommends further examination of the case studies mentioned in this report. While available literature may be limited, FRD recommends that FHWA consider the following case studies for further research: California, Florida, Japan, and Australia. As demonstrated in this report, each of these cases represent different methods for insuring against natural disasters, including public-private partnerships, and further analysis could be beneficial.

8. APPENDIX I. METHODOLOGY

To build a comprehensive understanding of natural disaster risk, financing, insurance types, and actuarial methods, FRD researchers gathered and reviewed academic journals, U.S. government documentation, intergovernmental reports, and reports from relevant insurance agencies. Researchers used key search terms such as "natural disaster risk," "earthquake insurance," "climate change," "risk modeling," and "insurance." Where possible, researchers also reviewed reports and publicly available data from FHWA and FEMA.

Researchers selected cities, states, and regions for case studies based on their relevance and prevalence in cited literature. Included case studies serve as examples of how specific insurance methods are applied, both on a national and international scale. Researchers selected examples that represent a wide array of extreme events that have occurred over the past two decades, including earthquakes, wildfires, hurricanes, and tsunamis. With respect to national case studies, researchers reviewed and considered states most susceptible to extreme weather, as well those with a significant amount of available research.

9. APPENDIX II. MATHEMATICAL PROOFS

Appendix II includes the relevant proofs used to derive the basic CAT bond premium equation (eq. 10) and the Wang transformed premium equation (eq. 18). The proofs for each equation directly reference Galeotti et al.'s explanations of the derivations.[340]

9.1 Catastrophe Bond Model Proofs

Equation 10: CAT Bond Premium

Layered Loss [341]

$$X(a, a+h)\begin{cases} 0, & if\ X \le a \\ X-a, & if\ a < X \le a+h \\ h, & if\ X > a+h \end{cases} \qquad (10.1)$$

Where X is a non-negative random loss variable.

Cumulative distribution function of the loss variable X

$$F_X(x) = P(X \le x) \qquad (10.2)$$

The decumulative distribution function

$$S_X(x) = 1 - F_X(x) = P(X > x) \qquad (10.3)$$

Assuming the existence of the density function

$$f_X(x) \qquad (10.4)$$

Thus

$$s_X(x) = S'_X(x) = -f_X(x) \qquad (10.5)$$

Decumulative distribution function of the layered loss[342]

$$S_{X(a,a+h)}(y) = \begin{cases} S_X(a+y) = P(X > a+y) & if\ 0 \le y < h \\ 0, & if\ y \ge h \end{cases} \qquad (10.6)$$

Expected arbitrary loss for X (minimum value 0)

$$E(X) = \int_0^\infty S_X(x)dx \qquad (10.7)$$

Expected value of absolute loss layer $X_{(a,a+h]}$ results from

$$E\left(X_{(a,a+h]}\right) = \int_0^{\infty} S_{X_{(a,a+h]}}(y)dy = \int_0^{h} S_X(a+y)dy = \int_a^{a+h} S_X(x)dx \tag{10.8}$$

Characterize the expected layered loss, EL, by the probability of first loss

$$PFL = S_X(a) = P(X > a) \tag{10.9}$$

The conditional expected loss rate

$$CEL = \frac{E\left(X_{(a,a+h]}\middle|X > a\right)}{h} \tag{10.10}$$

Because

$$EL = \frac{E\left(X_{(a,a+h]}\right)}{h} = P(X > a) \cdot \frac{E\left(X_{(a,a+h]}\middle|X > a\right)}{h} = PFL \cdot CEL \tag{10.11}$$

Introduce the probability of last loss

$$PLL = S_X(a+h) = P(X \geq a+h) \tag{10.12}$$

Premium for layer (a, a+h)

$$\rho(x) = EL + \Lambda = PFL \cdot CEL + \Lambda \tag{10}$$

General relationship

$$\rho(X) = f(EL, y_1 \dots y_N) \tag{11}$$

Equation 18: Wang Transformation

Premium calculation model

$$\rho(X) \cdot h = \int_a^{a+h} g\left(S_X(x)\right)dx \tag{18.1}$$

Distortion Operator

$$g_{k,\lambda}(u) = Q_k(\Phi^{-1}(u) + \lambda) \tag{18.2}$$

Q= student's t-distribution to account for parameter uncertainties with catastrophic events
k = degrees of freedom

Premium calculation considering the Wang 2 transformation

$$\rho(X) \cdot h = \int_{a}^{a+h} S_X^{+}(x)dx = EL^{+} \tag{17}$$

9.2. Parametric Insurance Model Proofs

Equation 1: Kaflin et al. (2020)

The value of natural disaster premiums can be calculated by first finding the cumulative distribution value of d_2,

$$d_2 = \frac{\ln\left(\frac{R_0}{R_T}\right) + (r - \frac{\sigma^2}{2})\, t}{\sigma\sqrt{t}} \tag{1}$$

where the variables are defined as:

$R_0 = \text{ value of the number of recent natural disaster cases}$
$R_T = \text{ benchmark value}$
$\sigma = \text{ standard deviation of natural disaster cases}$
$r = \text{ risk free interest rates}$
$t = \text{ time, in years}$

The value of natural disaster risk insurance premium can be calculated with the following equation:

$$Premi \;=\; Ke^{-rt}N(-d_2) \tag{2}$$

10. APPENDIX III. FLORIDA HURRICANE CATASTROPHE FUND

Florida's Annual Hurricane Catastrophe Fund details the following breakdown of premium changes since 2020:

Table 18. Florida Hurricane Catastrophe Fund Changes

FHCF Coverage	2021 Contract Year Modeled	2020 Contract Year Actual	2020 Contract Year Modeled
Industry Retention	$8.075 Billion	$7.832 Billion	$7.740 Billion
Limit	$17 Billion	$17 Billion	$17 Billion
Average Coverage	86.157%	85.941%	86.193%
FHCF Layer	$19.731 Billion	$19.781 Billion	$19.723 Billion
FHCF Premium	$1.206 Billion	$1.203 Billion	$1.193 Billion
Rate Change	-4.73%	-8.61%	-8.55%
Coverage Selection Change	0.25%	5.05%	5.36%
Exposure Change	4.92%	5.08%	3.79%
Premium Change	0.21%	0.88%	-0.01%
Overall Average Rate Change	-4.49%	-4.00%	-3.65%
Projected Payout Multiple	14.0980	14.0737	14.2531
90% Retention Multiple	6.4106	6.2149	6.2149
Exposure Bases	$2.613 Trillion	$2.490 Trillion	$2.45 Trillion
Overall FHCF Rate/$1,000 Exp.	0.4615	0.4832	0.4867

Source: Paragon Strategic Solutions, "Florida Hurricane Catastrophe Fund: 2021 Ratemaking Annual Report," March 16, 2021, 3, https://www.sbafla.com/fhcf/Portals/FHCF/Content/AdvisoryCouncil/2021/20210311_RatemakingReportFinal.pdf?ver=2021-03-16-165938-953.

11. References

[1] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters: Overview," 2022, https://www.ncdc.noaa.gov/billions/.

[2] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters."

[3] U.S. Senate, *Hearing on Rethinking Disaster Recovery and Resiliency, Part I: Protecting Our Nation's Transportation Systems, Before the Comm. on Appropriations, Subcomm. on Transportation, Housing and Urban Development, and Related Agencies*, 117th Cong., 1st sess. (May 13, 2021), "Prepared Statement of Elizabeth Repko, Acting Director, Physical Infrastructure, U.S. Government Accountability Office," 2, https://www.gao.gov/assets/gao-21-561t.pdf.

[4] Robert S. Kirk and William J. Mallett, *Highway Bridge Conditions: Issues for Congress*, CRS Report for Congress R44459 (Washington, DC: Library of Congress, Congressional Research Service [CRS], updated August 31, 2020), 14, https://crsreports.congress.gov/product/pdf/R/R44459.

[5] U.S. Department of Transportation (DOT), Federal Highway Administration (FHWA), "Bridges & Structures," updated May 11, 2022, https://www.fhwa.dot.gov/bridge/.

[6] DOT, FHWA, Office of Infrastructure and Office of Program Administration, *Emergency Relief Manual (Federal-Aid Highways*, updated May 31, 2013, 2, https://www.fhwa.dot.gov/reports/erm/er.pdf.

[7] Robert S. Kirk and William J. Mallett, *Emergency Relief for Disaster-Damaged Roads and Public Transportation Systems*, CRS Report for Congress R45298 (Washington, DC: Library of Congress, CRS, updated October 9, 2020), 3, https://crsreports.congress.gov/product/pdf/R/R45298.

[8] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 3.

[9] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 3.

[10] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, summary.

[11] DOT, FHWA, Office of Infrastructure and Office of Program Administration, *Emergency Relief Manual*, 30.

[12] DOT, FHWA, Office of Infrastructure and Office of Program Administration, *Emergency Relief Manual*, 2.

[13] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, summary.

[14] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 3.

[15] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 3.

[16] DOT, FHWA, "Special Federal-Aid Funding: Attachment; Allocation of Emergency Relief (ER) for Federal-Aid Highways (ERFA) Funds, Fiscal Year (FY) 2022—ERFA," December 21, 2021, updated January 10, 2022, https://www.fhwa.dot.gov/specialfunding/er/211221erfafunds.cfm; DOT, FHWA, "Special Federal-Aid Funding: Attachment; Allotment of Emergency Relief (ER) for Federally Owned Roads (ERFO) Funds, Fiscal Year (FY) 2022—ERFO," December 21, 2021, updated January 10, 2022, https://www.fhwa.dot.gov/specialfunding/er/211221erfofunds.cfm.

[17] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 6.

[18] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 7; DOT, FHWA, Office of Infrastructure and Office of Program Administration, *Emergency Relief Manual*, 33.FHWA, *Emergency Relief Manual* (May 13, 2013), 33.

[19] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 7.

[20] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 7; DOT, FHWA, Office of Infrastructure and Office of Program Administration, *Emergency Relief Manual*, 33.

[21] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 7.

[22] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 8.

[23] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 8.

[24] Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 8.

[25] DOT, FHWA, "Bridges & Structures: Safety Inspection; Bridge Inspection: Download NBI ASCII Files 2020," updated March 10, 2021, https://www.fhwa.dot.gov/bridge/nbi/ascii2020.cfm.

[26] DOT, FHWA, "Section 3: Elements; Introduction," in *Specifications for the National Tunnel Inventory*, Publication No. FHWA-HIF-15-006 (Washington, DC: DOT, FHWA, July 2015), 3-3, https://www.fhwa.dot.gov/bridge/inspection/tunnel/snti/hif15006.pdf.

[27] Gina Filosa et al., *Vulnerability Assessment and Adaptation Framework*, 3rd ed., Publication No. FHWA-HEP-18-020 (Washington, DC: DOT, FHWA, Office of Planning, Environment, and Realty, December 2017), 1, https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/.

[28] Samuel A. Markolf et al., "Transportation Resilience to Climate Change and Extreme Weather Events—Beyond Risk and Robustness," *Transport Policy* 74 (February 2019): 175, https://doi.org/10.1016/j.tranpol.2018.11.003.

[29] M. Z. Naser, "Can Past Failures Help Identify Vulnerable Bridges to Extreme Events? A Biomimetical Machine Learning

---

Approach," *Engineering with Computers* 37 (April 2021): 1101, https://doi.org/10.1007/s00366-019-00874-2.

[30] Genda Chen et al., "Analysis of the Interstate 10 Twin Bridge's Collapse during Hurricane Katrina," in *Science and the Storms: The USGS Response to the Hurricanes of 2005* (Washington, DC: U.S. Department of the Interior, U.S. Geological Survey [USGS], 2007), 37, https://pubs.usgs.gov/circ/1306/pdf/c1306_ch3_d.pdf.

[31] Laura Jeffrey, "Fall of the Eighth Wonder: The Kinzua Bridge," Pennsylvania State University Library, Center for the Book, Fall 2009, https://pabook.libraries.psu.edu/literary-cultural-heritage-map-pa/feature-articles/fall-eighth-wonder-kinzua-bridge.

[32] David Dodman et al., "Cities, Settlements, and Key Infrastructure," in *Climate Change 2022: Impacts, Adaptation, and Vulnerability*, Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, eds. Hans-Otto Pörtner et al. (Cambridge, UK: Cambridge University Press, 2022), SPM 11, https://www.ipcc.ch/report/ar6/wg2/.

[33] Dodman et al., "Cities, Settlements, and Key Infrastructure," SPM 27.

[34] Howard C. Kunreuther et al., "Private Insurers' Decision Making for Supplying Coverage," in *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes* (Cambridge, MA: MIT [Massachusetts Institute of Technology] Press: 2009), 130, https://doi.org/10.7551/mitpress/9780262012829.001.0001.

[35] Plamena Zlateva and Dimiter Vlavev, "A Method for Risk Assessment from Natural Disasters Using an Actuarial Model," *Journal of Economics, Business, and Development* 4, no. 5 (May 2016): 396, http://dx.doi.org/10.18178/joebm.2016.4.5.424.

[36] Rob Thoyts, "Insurance as a Risk Transfer Mechanism," in *Insurance Theory and Practice* (London: Routledge, 2010), 5, https://doi.org/10.4324/9780203850596.

[37] James M. Stone, "A Theory of Capacity and the Insurance of Catastrophic Risk (Part II)," *Journal of Risk and Insurance* 40, no. 3 (1973), https://www.jstor.org/stable/252223.

[38] Kunreuther et al., "Private Insurers' Decision Making for Supplying Coverage," 131.

[39] Howard C. Kunreuther and Mark Pauly, "Neglecting Disaster: Why Don't People Insure against Large Losses," *Journal of Risk and Uncertainty* 28, no. 1 (2004): 12, https://doi.org/10.1023/B:RISK.0000009433.25126.87.

[40] Kalfin et al., "Model for Determining Natural Disaster Insurance Premiums in Indonesia Using the Black Scholes Method" (Proceedings of the International Conference on Industrial Engineering and Operations Management, Detroit, MI, August 10–14, 2020), 2379, http://www.ieomsociety.org/detroit2020/papers/487.pdf.

[41] G.R. Walker, "Earthquake Insurance: An Australian Perspective," *Australian Journal of Structural Engineering* 8, no. 1 (2008): 43, https://doi.org/10.1080/13287982.2008.11464985.

[42] Walker, "Earthquake Insurance," 43.

[43] Yong Ding et al., "Risk Assessment of Highway Structures in Natural Disaster for the Property Insurance," *Natural Hazards* 104 (September 2020): 2669, https://doi.org/10.1007/s11069-020-04291-3.

[44] Gina L. Tonn, Jeffrey R. Czajkowski, and Howard C. Kunreuther, "Improving U.S. Transportation Infrastructure Resilience through Insurance and Incentives" (Working Paper No. 2018-01, University of Pennsylvania, Wharton School, Risk Management and Decision Processes Center, March 2018), 6, https://web-oup.s3-us-gov-west-1.amazonaws.com/showc/assets/File/CIRI_Tonn_Improving%20US%20Transportation%20Infrastructure%20Resilience%20through%20Insurance%20and%20Incentives.pdf.

[45] Mustafa Erdik, "Earthquake Risk Assessment from an Insurance Perspective," in *Advances in Assessment and Modeling of Earthquake Loss*, eds. Sinan Akkar et al. (Cham, Switzerland: Springer Tracts in Civil Engineering, 2021), 114, https://doi.org/10.1007/978-3-030-68813-4.

[46] Rohini Sengupta and Carolyn Kousky, *Parametric Insurance for Disasters*, University of Pennsylvania, Wharton School, Risk Management and Decision Process Center, September 2020, 2, https://riskcenter.wharton.upenn.edu/wp-content/uploads/2020/09/Parametric-Insurance-for-Disasters_Sep-2020.pdf.

[47] Rui Figueiredo et al., "A Probabilistic Paradigm for the Parametric Insurance of Natural Hazards," *Risk Analysis* 38, no. 11 (2018): 2401, https://doi.org/10.1111/risa.13122.

[48] Figueiredo et al., "A Probabilistic Paradigm," 2401.

[49] Figueiredo et al., "A Probabilistic Paradigm," 2401.

[50] Conor Meenan, "Unpacking Basis Risk," *Risk Management Solutions*, August 14, 2017, https://www.rms.com/blog/2017/08/14/unpacking-basis-risk.

[51] Morten Broberg, "Parametric Loss and Damage Insurance Schemes as a Means to Enhance Climate Change Resiliance in Developing Countries," *Climate Policy* 20, no. 6 (2020): 698, https://doi.org/10.1080/14693062.2019.1641461.

[52] Xiao Lin and W. Jean Kwon, "Application of Parametric Insurance in Principle-Compliant and Innovative Ways," *Risk Management and Insurance Review* 23, no. 2 (2020): 132, https://doi.org/10.1111/rmir.12146.

---

[53] Lin and Kwon, "Application of Parametric Insurance," 126.
[54] Sengupta and Kousky, *Parametric Insurance for Disasters*, 2.
[55] Lin and Kwon, "Application of Parametric Insurance," 9.
[56] Shubhalaxmi Sircar, "Role of Insurance in Building Resilience for Coastal Zones: Market Versus the State," in *Development in Coastal Zones and Disaster Management*, Disaster Research and Management Series on the Global South, eds. Amita Singh, R. Lalitha S. Fernando, and Nivedita P. Haran (Singapore: Palgrave Macmillan, 2020), 229, https://doi.org/10.1007/978-981-15-4294-7.
[57] Marla Schwartz, Megan Linkin, and Swiss Re, *Hurricane Andrew: The 20 Miles That Saved Miami* (Armonk, NY: Swiss Reinsurance Company, 2017), 1, https://www.swissre.com/Library/hurricane-andrew-the-20-miles-that-saved-miami0.html.
[58] Schwartz, Linkin, and Swiss Re, *Hurricane Andrew: The 20 Miles That Saved Miami*, 1.
[59] Schwartz, Linkin, and Swiss Re, *Hurricane Andrew: The 20 Miles That Saved Miami*, 1.
[60] Lynne McChristian, *Hurricane Andrew and Insurance: The Enduring Impact of a Historic Storm* (Tampa: Insurance Information Institute, August 2012), 5, https://www.iii.org/sites/default/files/paper_HurricaneAndrew_final.pdf.
[61] Alexander Braun and Carolyn Kousky, *Catastrophe Bonds*, University of Pennsylvania, Wharton School, Risk Management and Decision Process Center, July 2021, 1, https://riskcenter.wharton.upenn.edu/wp-content/uploads/2021/07/Cat-Bond-Primer-July-2021.pdf.
[62] Andy Polacek, "Catastrophe Bonds: A Primer and Retrospective," *Chicago Fed Letter* 405 (2018): 1–3, https://doi.org/10.21033/cfl-2018-405.
[63] Braun and Kousky, *Catastrophe Bonds*, 2.
[64] Artemis, "Catastrophe Bonds & ILS Issued and Outstanding by Year," accessed August 26, 2022, https://www.artemis.bm/dashboard/catastrophe-bonds-ils-issued-and-outstanding-by-year/.
[65] Artemis, "Catastrophe Bonds & ILS Issued and Outstanding by Year."
[66] Braun and Kousky, *Catastrophe Bonds*, 2.
[67] Braun and Kousky, *Catastrophe Bonds*, 2.
[68] Polacek, "Catastrophe Bonds," 2.
[69] Artemis, "What is a Catastrophe Bond (or Cat Bond)?," accessed August 26, 2022, https://www.artemis.bm/library/what-is-a-catastrophe-bond/; Polacek, "Catastrophe Bonds," 3.
[70] Braun and Kousky, *Catastrophe Bonds*, 2.
[71] Braun and Kousky, *Catastrophe Bonds*, 2.
[72] Braun and Kousky, *Catastrophe Bonds*, 2; Artemis, "What is a Catastrophe Bond (or Cat Bond)?"; Gilles Stupfler and Fan Yang, "Analyzing and Predicting Cat Bond Premiums: A Financial Loss Premium Principle and Extreme Value Modeling," *ASTIN Bulletin* 48, no. 1 (January 2018): 375–411, https://doi.org/10.1017/asb.2017.32.
[73] Braun and Kousky, *Catastrophe Bonds*, 2; Artemis, "What is a Catastrophe Bond (or Cat Bond)?"
[74] Braun and Kousky, *Catastrophe Bonds*, 2; Artemis, "What is a Catastrophe Bond (or Cat Bond)?"
[75] Braun and Kousky, *Catastrophe Bonds*, 1.
[76] Polacek, "Catastrophe Bonds," 3.
[77] Braun and Kousky, *Catastrophe Bonds*, 5.
[78] Erwann Michel-Kerjan et al., *Catastrophe Financing for Governments: Learning from the 2009–2012 Multicat Program in Mexico* (OECD Working Papers on Finance, Insurance, and Private Pensions No. 91, OECD [Organisation for Economic Cooperation and Development] Publishing, May 2011), 13, https://doi.org/10.1787/5kgcjf7wkvhb-en.
[79] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 13.
[80] Braun and Kousky, *Catastrophe Bonds*, 5.
[81] Braun and Kousky, *Catastrophe Bonds*, 3.
[82] Polacek, "Catastrophe Bonds," 5.
[83] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 12.
[84] Polacek, "Catastrophe Bonds," 5.
[85] Polacek, "Catastrophe Bonds," 5.
[86] Braun and Kousky, *Catastrophe Bonds*, 4.
[87] Polacek, "Catastrophe Bonds," 5.
[88] Braun and Kousky, *Catastrophe Bonds*, 4.
[89] Braun and Kousky, *Catastrophe Bonds*, 4.
[90] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 12.
[91] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 12.

---

[92] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 12.
[93] Artemis, "What is a Catastrophe Bond (or Cat Bond)?"
[94] Braun and Kousky, *Catastrophe Bonds*, 4.
[95] Braun and Kousky, *Catastrophe Bonds*, 4.
[96] Braun and Kousky, *Catastrophe Bonds*, 5.
[97] Braun and Kousky, *Catastrophe Bonds*, 6.
[98] Braun and Kousky, *Catastrophe Bonds*, 6.
[99] Braun and Kousky, *Catastrophe Bonds*, 5.
[100] Braun and Kousky, *Catastrophe Bonds*, 6.
[101] Braun and Kousky, *Catastrophe Bonds*, 6.
[102] Braun and Kousky, *Catastrophe Bonds*, 6.
[103] Harry White, "Modeling Fundamentals: So You Want to Issue a Cat Bond," Verisk, June 22, 2020, https://www.air-worldwide.com/publications/air-currents/2020/modeling-fundamentals-so-you-want-to-issue-a-cat-bond/.
[104] White, "Modeling Fundamentals."
[105] White, "Modeling Fundamentals"; Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32; Marc Gürtler, Martin Hibbeln, and Christine Winkelvos, "The Impact of the Financial Crisis and Natural Catastrophes on CAT Bonds," *Journal of Risk and Insurance* 83, no. 3 (2016): 591, https://doi.org/10.1111/jori.12057.
[106] Jeff Boyd, "Introduction to Catastrophe Bond Issuance," Air Worldwide, 2016, 13. https://www.air-worldwide.com/Site Assets/Publications/Presentations/attachments/Introduction-to-Catastrophe-Bond-Issuance.
[107] Boyd, "Introduction to Catastrophe Bond Issuance," 13.
[108] Boyd, "Introduction to Catastrophe Bond Issuance," 13.
[109] Boyd, "Introduction to Catastrophe Bond Issuance," 13.
[110] White, "Modeling Fundamentals."
[111] White, "Modeling Fundamentals."
[112] White, "Modeling Fundamentals."
[113] White, "Modeling Fundamentals."
[114] White, "Modeling Fundamentals"; Michel-Kerjan et al., *Catastrophe Financing for Governments*, 34.
[115] White, "Modeling Fundamentals"; Michel-Kerjan et al., *Catastrophe Financing for Governments*, 34.
[116] White, "Modeling Fundamentals"; Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[117] White, "Modeling Fundamentals"; Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[118] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[119] Howard C. Kunreuther and Erwann Michel-Kerjan, "Climate Change, Insurability of Large Scale Disasters, and the Emerging Liability Challenge" (NBER Working Paper 12821, National Bureau of Economic Research [NBER], Cambridge, MA, January 2007), 18, https://www.nber.org/system/files/working_papers/w12821/w12821.pdf.
[120] Marcello Galeotti, Marc Gürtler, and Christine Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds—An Empirical Analysis," *Journal of Risk and Insurance* 80, no. 2 (2013): 403, http://www.jstor.org/stable/24548156.
[121] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 405.
[122] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 405.
[123] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 405.
[124] Morton N. Lane, "Pricing Risk Transfer Transactions," *ASTIN Bulletin* 30, no. 2 (November 2000): 271, https://doi.org/10.2143/AST.30.2.504635; Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 406.
[125] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 405; Gürtler, Hibbeln, and Winkelvos, "The Impact of the Financial Crisis," 581.
[126] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 406.
[127] Morton N. Lane and Olivier Mahul, "Catastrophe Risk Pricing: An Empirical Analysis" (Policy Research Working Paper 4765, World Bank, Washington, DC, November 2008), 9, https://openknowledge.worldbank.org/bitstream/handle/10986/6900/WPS4765.pdf; Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 406.
[128] Gürtler, Hibbeln, and Winkelvos, "The Impact of the Financial Crisis," 590.
[129] Gürtler, Hibbeln, and Winkelvos, "The Impact of the Financial Crisis," 590.
[130] Gürtler, Hibbeln, and Winkelvos, "The Impact of the Financial Crisis," 590.
[131] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 406.
[132] John A. Major, "On Modeling Insurance Risk Pricing" (September 12, 2017), 3, http://dx.doi.org/10.2139/ssrn.30362

36; later published as "Methodological Considerations in the Statistical Modeling of Catastrophe Bond Prices," *Risk Management and Insurance Review* 22, no. 1 (Spring 2019): 39–56, https://doi.org/10.1111/rmir.12114.

[133] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 408.

[134] Aglaia Petseti and Milton Nektarios, "Proposal for a National Earthquake Insurance Programme for Greece," *Geneva Papers on Risk and Insurance* 37 (2012): 382, https://link.springer.com/content/pdf/10.1057/gpp.2012.12.pdf.

[135] Petseti and Nektarios, "Proposal," 382.

[136] Petseti and Nektarios, "Proposal," 382.

[137] Insurance Council of New Zealand (ICNZ), *Protecting New Zealand from Natural Hazards* (Wellington: ICNZ, 2014), 5, https://www.waikatoregion.govt.nz/assets/PageFiles/26012/protecting-new-zealand-from-natural-hazards.pdf.

[138] Cuong Nguyen and Ilan Noy, "Insuring Earthquakes: How Would the Californian and Japanese Insurance Programs Have Fared Down Under (After the 2011 New Zealand Earthquake)?," (SEF Working Paper 14/2017, Victoria University of Wellington, Victoria Business School, School of Economics and Finance [SEF], Victoria, New Zealand, June 2017), 3, http://hdl.handle.net/10063/6416.

[139] OECD, "New Zealand: Prevalence of Natural Hazards," OECD iLibrary, accessed August 29, 2022, https://www.oecd-ilibrary.org/sites/545226d1-en/index.html?itemId=/content/component/545226d1-en.

[140] Belinda Storey et al., "Insurance, Housing, and Climate Adaptation: Current Knowledge and Future Research," Motu Note 27, Motu Economic and Public Policy Research, accessed August 29, 2022, https://www.motu.nz/assets/Documents/our-work/environment-and-agriculture/climate-change-impacts/Insurance-Housing-and-Climate-Adaptation.pdf.

[141] Wei-Chun Cheng, "Comparative Studies on the Similarities and Diversities of the Legislations Regarding Earthquake Insurance in Asia: Examples of Japan, New Zealand and Taiwan," *US-China Law Review,* Vol. 17 No. 6 (June 2020,) 232, https://www.davidpublisher.com/Public/uploads/Contribute/5fc5c11e42845.pdf

[142] John McAneney et al., "Government-Sponsored Natural Disaster Risk Insurance Pools: A View from Down Under," *International Journal of Disaster Risk Reduction* 15 (March 2016): 3, https://doi.org/10.1016/j.ijdrr.2015.11.004.

[143] David A. Fleming et al., "Public Insurance and Climate Change (Part One): Past Trends in Weather-Related Insurance in New Zealand" (Motu Working Paper 18-09, Motu Economic and Public Policy Research, Wellington, NZ, July 2018), 8, https://docs.niwa.co.nz/library/public/MotuWP18-09.pdf.

[144] Robert Cole, *Funding and Reserving Canterbury Earthquake Insurance Claims*, Analytical Notes AN2021/2 (Wellington, NZ: Reserve Bank of New Zealand, February 2021), 2, https://www.rbnz.govt.nz/-/media/reservebank/files/publications/analytical%20notes/2021/an2021-2.pdf.

[145] Cole, *Funding and Reserving*, 2.

[146] Earthquake Commission, *Annual Report 2020–2021* (Wellington, NZ: Earthquake Commission, October 2021), 4, https://www.eqc.govt.nz/assets/Documents/AR2021_v18_web.pdf.

[147] Christine Stevenson, *Report of the Independent Ministerial Advisor to the Minister Responsible for the Earthquake Commission*, April 26, 2018, https://apo.org.au/sites/default/files/resource-files/2018-06/apo-nid175321.pdf.

[148] ICNZ, "Canterbury Earthquakes," accessed August 29, 2022, https://www.icnz.org.nz/natural-disasters/canterbury-earthquakes.

[149] ICNZ, "Canterbury Earthquakes."

[150] ICNZ, "Canterbury Earthquakes."

[151] OECD, "Japan: Prevalence of Natural Hazards," OECD iLibrary, accessed August 29, 2022, https://www.oecd-ilibrary.org/sites/001342f9-en/index.html?itemId=/content/component/001342f9-en.

[152] Olivier Mahul and Emily White, *Earthquake Risk Insurance*, Knowledge Note 6-2 (Washington, DC: World Bank, accessed August 29, 2022), 6, https://documents1.worldbank.org/curated/en/247551468272962819/pdf/800740drm0kn6020Box0377295B00PUBLIC0.pdf.

[153] Mahul and White, *Earthquake Risk Insurance*, 6.

[154] Mahul and White, *Earthquake Risk Insurance*, 6.

[155] OECD, "Japan: Prevalence of Natural Hazards."

[156] Japan, "Disaster Risk Financing and Insurance Policies of Japan" (presentation, APEC [Asia-Pacific Economic Cooperation] Seminar on Disaster Risk Financing and Insurance Policies, Nha Trang, Vietnam, February 21, 2017), 7 (slide 13), http://mddb.apec.org/Documents/2017/FMP/SEM1/17_fmp_sem1_007.pdf.

[157] Mahul and White, *Earthquake Risk Insurance*, 6.

[158] Fredrik Giertz Jonsson, "Analysis and Optimization of a Portfolio of Catastrophe Bonds" (master's thesis, Royal Institute of Technology, Stockholm, Sweden, 2014), 19, https://www.diva-portal.org/smash/get/diva2:723184/FULLTEXT01.pdf.

[159] Jonsson, "Analysis and Optimization," 19.

---

[160] World Bank, "Boosting Financial Resilience to Disaster Shocks: Good Practices and New Frontiers" (paper, G20 Finance Ministers and Central Bank Governors Meeting, Fukuoka, Japan, June 9, 2019), 20, https://www.mof.go.jp/english/policy/international_policy/convention/g20/annex7.pdf.

[161] Australia, Department of Home Affairs, "Natural Disaster Relief and Recovery Arrangements," last updated April 24, 2020, https://www.disasterassist.gov.au/disaster-arrangements/natural-disaster-relief-and-recovery-arrangements.

[162] Australia, Attorney-General's Department, "Natural Disaster Relief and Recovery Arrangements: Guideline 1," July 25, 2017, https://www.disasterassist.gov.au/Documents/Natural-Disaster-Relief-and-Recovery-Arrangements/Guideline-1-EPA-Restoration-2017.pdf.

[163] Menzies Research Centre, *Strengthening Resilience: Managing National Disasters After the 2019–20 Bushfire Season* (Barton, Australian Capital Territory: Menzies Research Centre, April 2020), 12, https://www.iag.com.au/sites/default/files/Documents/Announcements/Strengthening-resilience-managing-natural-disasters-report.pdf.

[164] Resilience NSW (New South Wales), *NSW Disaster Assistance Guidelines 2021*, 7, accessed August 30, 2022, https://media.opengov.nsw.gov.au/pairtree_root/29/05/f1/8b/96/24/48/2a/81/59/2a/72/9c/13/3e/c4/obj/NSW_Disaster_Assistance_Guidelines_2021.pdf.

[165] Lloyd's, "Lloyd's Disaster Risk Facility Launches a Parametric Cyclone Insurance Product in Northern Australia," November 22, 2021, https://www.lloyds.com/about-lloyds/media-centre/press-releases/lloyds-disaster-risk-facility-launches-a-parametric-cyclone-insurance-product-in-northern-australia.

[166] Miguel Navarro-Martin and Michael S. Bennett, "Insuring Mexico Against Natural Disasters," World Bank, 1, accessed August 30, 2022, https://thedocs.worldbank.org/en/doc/737151585254940284-0340022020/original/FONDENMexicoCatBondCaseStudy3.4.2020final.pdf; Miguel Navarro-Martin, "Insuring Against Natural Disaster Risk in Mexico," World Bank, 1, accessed August 30, 2022, https://documents1.worldbank.org/curated/en/170311468056076924/pdf/81172-REVISED-Mexico-MultiCatBond-2015.pdf; Rubem Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund—A Review* (Washington, DC: World Bank, International Bank for Reconstruction and Development [IBRD], May 2012), 2, https://documents1.worldbank.org/curated/en/408711468286527149/pdf/753220WP0P130800Box374323B00PUBLIC0.pdf.

[167] Navarro-Martin and Bennett, "Insuring Mexico Against Natural Disasters," 1.

[168] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 4.

[169] Navarro-Martin, "Insuring Against Natural Disaster Risk in Mexico," 1.

[170] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 5.

[171] Navarro-Martin, "Insuring Against Natural Disaster Risk in Mexico," 1.

[172] Steve Evans, "Mexico's Cat Bond Program Set for Shake-up or Cancellation, as FONDEN to Close," Artemis, October 22, 2020, https://www.artemis.bm/news/mexicos-cat-bond-program-set-for-shake-up-or-cancellation-as-fonden-to-close/.

[173] Navarro-Martin, "Insuring Against Natural Disaster Risk in Mexico," 1.

[174] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 23.

[175] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 23.

[176] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 23.

[177] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 23.

[178] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24; Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 11.

[179] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24; Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 11.

[180] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24.

[181] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24.

[182] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24.

[183] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 24.

[184] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 25.

[185] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 5.

[186] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 25.

[187] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 7.

[188] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 7.

[189] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 25.

[190] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 1.

[191] Artemis, "MultiCat Mexico 2012 Class C Cat Bond Notes Officially a 50% Loss," February 9, 2016, https://www.artemis.bm/news/multicat-mexico-2012-class-c-cat-bond-notes-officially-a-50-loss/.

---

[192] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 1.
[193] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2017," accessed August 30, 2022, https://www.artemis.bm/deal-directory/ibrd-fonden-2017/.
[194] Artemis, "Pacific Alliance Targets 2018 Catastrophe Bond Issue," September 22, 2017, https://www.artemis.bm/news/pacific-alliance-targets-2018-catastrophe-bond-issue/.
[195] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 1.
[196] Hofliger et al., *FONDEN: Mexico's Natural Disaster Fund*, 1.
[197] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2020," accessed August 30, 2022, "https://www.artemis.bm/deal-directory/ibrd-fonden-2020/.
[198] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2020," accessed August 30, 2022, "https://www.artemis.bm/deal-directory/ibrd-fonden-2020/.
[199] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2020," accessed August 30, 2022, "https://www.artemis.bm/deal-directory/ibrd-fonden-2020/.
[200] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2020," accessed August 30, 2022, "https://www.artemis.bm/deal-directory/ibrd-fonden-2020/.
[201] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD/FONDEN 2020," accessed August 30, 2022, "https://www.artemis.bm/deal-directory/ibrd-fonden-2020/.
[202] Steve Evans, "Mexico's Cat Bond Coverage Continues, Despite Shuttering of FONDEN," Artemis, January 27, 2021, https://www.artemis.bm/news/mexicos-cat-bond-coverage-continues-despite-shuttering-of-fonden/.
[203] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 27.
[204] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 31.
[205] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 28.
[206] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 31.
[207] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: MultiCat Mexico 2009 Ltd.," accessed August 30, 2022, https://www.artemis.bm/deal-directory/multicat-mexico-2009-ltd/.
[208] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[209] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[210] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 32.
[211] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 27.
[212] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 34.
[213] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: MultiCat Mexico 2009 Ltd."
[214] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 16.
[215] Michel-Kerjan et al., *Catastrophe Financing for Governments*, 33.
[216] Caribbean Catastrophe Risk Insurance Facility (CCRIF), "Who We Are," accessed August 30, 2022, https://www.ccrif.org/.
[217] World Bank, "IEG ICR Review," March 14, 2013, 1, https://documents1.worldbank.org/ curated/en/901861475092273503/pdf/000020051-20140626080209.pdf.
[218] CCRIF SPC, "Who We Are."
[219] World Bank, "Caribbean Catastrophe Risk Insurance Facility," October 2015, 1.
[220] World Bank, "Caribbean Catastrophe Risk Insurance Facility," 1.
[221] CCRIF SPC, "Who We Are."
[222] CCRIF SPC, "Who We Are."
[223] CCRIF, *2020–2021 Annual Report* (Grand Cayman, Cayman Islands: CCRIF, accessed August 30, 2022), 29, https://www.ccrif.org/sites/default/files/publications/annualreports/CCRIF_SPC_Annual_Report_2020_2021.pdf.
[224] CCRIF, *2020–2021 Annual Report*, 26; Steve Evans, "CCRIF Members Renew over $1bn of Parametric Coverage," Artemis, June 15, 2021, https://www.artemis.bm/news/ccrif-members-renew-over-1bn-of-parametric-coverage/.
[225] CCRIF, *2020–2021 Annual Report*, 26.
[226] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: World Bank–CCRIF 2014-1," accessed August 30, 2022, https://www.artemis.bm/deal-directory/world-bank-ccrif-2014-1/.
[227] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: World Bank–CCRIF 2014-1."
[228] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130," accessed August 30, 2022, https://www.artemis.bm/deal-directory/ibrd-car-130-jamaica/; World Bank, "World Bank Catastrophe Bond Provides Jamaica $185 Million in Storm Protection," July 19, 2021, https://www.worldbank.org/en/news/press-release/2021/07/19/world-bank-catastrophe-bond-provides-jamaica-185-million-in-storm-protection.

---

[229] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130"; World Bank, "World Bank Catastrophe Bond."
[230] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130."
[231] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130."
[232] Artemis, "Catastrophe Bond & Insurance-Linked Securities Deal Directory: IBRD CAR 130."
[233] Steve Evans, "Jamaica Cat Bond is Largest World Bank Issue Relative to Beneficiary GDP," Artemis, September 15, 2021, https://www.artemis.bm/news/jamaica-cat-bond-largest-world-bank-relative-gdp/.
[234] Evans, "Jamaica Cat Bond."
[235] World Bank, IBRD, "Prospectus Supplement: US$185,000,000 Floating Rate Catastrophe-Linked Capital at Risk Notes Due December 29, 2023," July 19, 2021, 77.
[236] World Bank, IBRD, "Prospectus Supplement," 77.
[237] World Bank, IBRD, "Prospectus Supplement," 77.
[238] World Bank, IBRD, "Prospectus Supplement," 87.
[239] World Bank, IBRD, "Prospectus Supplement," 90.
[240] World Bank, IBRD, "Prospectus Supplement," 102.
[241] McAneney et al., "Government-Sponsored Natural Disaster Risk Insurance Pools," 5.
[242] Adrien Pothon, "Seismic Loss Modeling in Insurance Industry: Towards a New Model for Better Claims Management" [in French] (PhD diss., Université Grenoble Alpes, May 25, 2016), 26, https://tel.archives-ouvertes.fr/tel-02862122/document.
[243] Pothon, "Seismic Loss Modeling in Insurance Industry," 26.
[244] California Earthquake Authority (CEA), "CEA Background Paper," November 2021, https://www.earthquakeauthority.com/EQA2/media/PDF/CEA-Background-Paper-Nov-2021.pdf.
[245] Lin and Kwon, "Application of Parametric Insurance," 17.
[246] CEA, Wildlife Fund Administrator, *2021 Annual Report on the California Wildfire Fund's Operations* (Sacramento: CEA, Wildlife Fund Administrator, July 22, 2021), 8, https://afd51720-c676-4b03-89aa-fe73624dd23f.filesusr.com/ugd/754529_ddbb26842ddc44ca9250bfe6caac5c73.pdf.
[247] Fla. Stat. § 215.555 (2022).
[248] Fla. Stat. § 215.555.
[249] Fla. Stat. § 215.555.
[250] Fla. Stat. § 215.555.
[251] Sadie Frank, Eric Gesick, and David G. Victor, *Inviting Disaster: How Federal Disaster, Insurance, and Infrastructure Policies are Magnifying the Harm of Climate Change* (Washington, DC: Brookings Institution, March 2021), 24, https://www.brookings.edu/wp-content/uploads/2021/03/Inviting_Danger_FINAL.pdf.
[252] Florida, State Board of Administration, Florida Hurricane Catastrophe Fund (FHCF), "Florida Hurricane Catastrophe Fund: 2021/2022 Member Handbook," June 2021, 1, http://fhcf.paragon.aonbenfield.com/member-handbook/2021/.
[253] Florida, State Board of Admsinistration, FHCF, "Florida Hurricane Catastrophe Fund," 1.
[254] Fla. Stat. § 215.555.
[255] Fla. Stat. § 215.555.
[256] Paragon Strategic Solutions, "Florida Hurricane Catastrophe Fund: 2021 Ratemaking Annual Report," March 16, 2021, 3, https://www.sbafla.com/fhcf/Portals/FHCF/Content/AdvisoryCouncil/2021/20210311_RatemakingReportFinal.pdf?ver=2021-03-16-165938-953.
[257] Federal Association for Insurance Reform, "The Florida Hurricane Catastrophe Fund Demystified: Legislative Relief for Florida's Homeowners," June 3, 2021, 20, https://www.federalinsurancereform.org/wp-content/uploads/2021/07/FHCF-Demsytified-Signed-6.4.21.pdf.
[258] Yimin Yang et al., "Integrated Execution Framework for Catastrophe Modeling" (paper, Ninth IEEE International Conference on Semantic Computing, Anaheim, CA, February 7–9, 2015), 2, http://users.cis.fiu.edu/~chens/PDF/ICSC15_FPHLM.pdf.
[259] Yang et al. "Integrated Execution Framework," 5.
[260] CoreLogic, "Florida Commission on Hurricane Loss Projection Methodology: November 2020 Submission," April 30, 2021, 54–56, https://www.sbafla.com/methodology/Portals/Methodology/ModelSubmissions/2021/FCHLPM_CoreLogic2019_30April2021.pdf?ver=2021-06-17-104306-733.
[261] CoreLogic, "Florida Commission," 54–56.
[262] Lin and Kwon, "Application of Parametric Insurance," 138.

---

[263] A. Addison Alford et al., "Transition of the Hurricane Boundary Layer during the Landfall of Hurricane Irene (2011)," *Journal of the Atmospheric Sciences* 77, no. 10 (2020): 3511, https://doi.org/10.1175/JAS-D-19-0290.1.

[264] New England Water Science Center, "Remembering Tropical Storm Irene in New England," USGS, August 9, 2021, https://www.usgs.gov/centers/new-england-water-science-center/science/remembering-tropical-storm-irene-new-england.

[265] NOAA, National Weather Service, *Service Assessment: Hurricane Irene, August 21–30, 2011*, September 2012, 5, https://www.weather.gov/media/publications/assessments/Irene2012.pdf.

[266] U.S. Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), "Declared Disasters," accessed August 30, 2022, https://www.fema.gov/disaster/declarations.

[267] Eric S. Blake et al., "Tropical Cyclone Report: Hurricane Sandy (AL182012); 22–29 October 2012," National Hurricane Center, February 12, 2013, 14, https://biotech.law.lsu.edu/blog/AL182012_Sandy.pdf.

[268] U.S. Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*, April 2013, 1, https://www.hsdl.org/?abstract&did=750499.

[269] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, 1.

[270] Ian Anderson et al., "Analysis of Bridge and Stream Conditions of over 300 Bridges Damaged in Tropical Storm Irene," *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design, and Performance* 13, no. 11 (2017): 1437, https://doi.org/10.1080/15732479.2017.1285329.

[271] Anderson et al., "Analysis of Bridge and Stream Conditions," 1437.

[272] Anderson et al., "Analysis of Bridge and Stream Conditions," 1437.

[273] Anderson et al., "Analysis of Bridge and Stream Conditions," 1437.

[274] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, 1.

[275] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, 1.

[276] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, 2.

[277] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, v.

[278] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, iv.

[279] DOE, Office of Electricity Delivery and Energy Reliability, *Comparing the Impacts of Northeast Hurricanes*, 8.

[280] Anderson et al., "Analysis of Bridge and Stream Conditions," 1437.

[281] Anderson et al., "Analysis of Bridge and Stream Conditions," 1437.

[282] Anderson et al., "Analysis of Bridge and Stream Conditions," 1445.

[283] Anderson et al., "Analysis of Bridge and Stream Conditions," 1445.

[284] NOAA, National Weather Service, *Service Assessment: Hurricane Irene*, 13.

[285] NOAA, National Weather Service, *Service Assessment: Hurricane Irene*, 14.

[286] NOAA, National Weather Service, *Service Assessment: Hurricane Irene*, 14.

[287] NOAA, National Weather Service, *Service Assessment: Hurricane Irene*, 14.

[288] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters."

[289] U.S. Government Accountability Office (GAO), "Natural Disasters: Economic Effects of Hurricanes Katrina, Sandy, Harvey, and Irma," GAO-20-633R, September 10, 2020, 2, https://www.gao.gov/assets/gao-20-633r.pdf

[290] Sarah Kaufman, "Hurricane Sandy: Apple's Bobbing," *Roads & Bridges*, March 6, 2013, https://www.roadsbridges.com/home/article/10644826/hurricane-sandy-apples-bobbing.

[291] Sarah Kaufman et al., *Transportation During and After Hurricane Sandy* (New York, NY: New York University, Wagner Graduate School of Public Service, Rudin Center for Transportation, November 2012), 16, https://wagner.nyu.edu/files/faculty/publications/sandytransportation.pdf.

[292] GAO, "Natural Disasters," 9.

[293] R. J. Murane and J. B. Elsner, "Maximum Wind Speeds and U.S. Hurricane Losses," *Geophysical Research Letters* 39, no. 16 (2012): 2, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012GL052740.

[294] Murane and Elsner, "Maximum Wind Speeds and U.S. Hurricane Losses," 2.

[295] Maofeng Liu and James A. Smith, "Extreme Rainfall from Landfalling Tropical Cyclones in the Eastern United States: Hurricane Irene (2011)," *Journal of Hydrometerology* 17, no. 11 (2016): 2884, https://www.jstor.org/stable/10.2307/26152539.

[296] Lixion A. Avila and John Cangialosi, "Tropical Cycle Report: Hurricane Irene (AL092011); 21–29 August 2011," National Hurricane Center, February 28 2012, 2, https://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf.

[297] Murane and Elsner, "Maximum Wind Speeds and U.S. Hurricane Losses," 2.

[298] Murane and Elsner, "Maximum Wind Speeds and U.S. Hurricane Losses," 2.

---

[299] Insurance Information Institute, "Over 90 Percent of the New Jersey and New York Sandy Insurance Claims Have Been Settled; Likely to Be Third Largest Storm Ever for U.S. Insurers," April 19, 2013, https://www.iii.org/press-release/over-90-percent-of-the-new-jersey-and-new-york-sandy-insurance-claims-have-been-settled-likely-to-be-third-largest-storm-ever-for-us-insurers-041913.

[300] Lloyd Dixon et al., "Insurance Payments After Hurricane Sandy and Hurricane Sandy's Impact on Insurance Markets," in *Flood Insurance in New York City Following Hurricane Sandy* (Santa Monica, CA: RAND Corporation, 2013), 21–32, https://www.rand.org/pubs/research_reports/RR328.html.

[301] U.S. Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), "June 2022 Disaster Relief Fund Report," July 13, 2022, 10, https://www.fema.gov/sites/default/files/documents/fema_diaster-relief-fund-report_062022.pdf.

[302] Adam B. Smith and Richard W. Katz, "U.S. Billion-Dollar Weather and Climate Disasters: Data Sources, Trends, Accuracy, and Biases," *Natural Hazards* 67 (2013): 387–410, https://doi.org/10.1007/s11069-013-0566-5.

[303] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters."

[304] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters."

[305] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters."

[306] NOAA, National Centers for Environmental Information, "U.S. Billion-Dollar Weather and Climate Disasters".

[307] Smith and Katz, "U.S. Billion-Dollar Weather and Climate Disasters," 2.

[308] Smith and Katz, "U.S. Billion-Dollar Weather and Climate Disasters," 2.

[309] Smith and Katz, "U.S. Billion-Dollar Weather and Climate Disasters," 2.

[310] Leslie Kaufman and Eric Roston, "Wildfires are Close to Torching the Insurance Industry in California," *Bloomberg,* November 10, 2020, https://www.bloomberg.com/news/features/2020-11-10/wildfires-are-torching-california-s-insurance-industry-amid-climate-change.

[311] Kaufman and Roston, "Wildfires are Close to Torching the Insurance Industry in California."

[312] Eric J. Xu, Cody Webb, and David D. Evans, "Wildfire Catastrophe Models Could Spark the Changes California Needs" (Milliman White Paper, Milliman, Seattle, WA October 2019), 2, https://assets.milliman.com/ektron/Wildfire_catastrophe_models_could_spark_the_changes_California_needs.pdf.

[313] William L. Painter, *The Disaster Relief Fund: Overview and Issues*, CRS Report for Congress R45484 (Washington, DC: Library of Congress, CRS, updated January 20, 2022), 1, https://crsreports.congress.gov/product/pdf/R/R45484; Kirk and Mallett, *Emergency Relief for Disaster-Damaged Roads*, 1.

[314] DOT, FHWA, "Special Federal-Aid Funding: Attachment; Allocation of Emergency Relief"; DOT, FHWA, "Special Federal-Aid Funding: Attachment; Allotment of Emergency Relief."

[315] GAO, *Climate Resilience: Options to Enhance the Resilience of Federally Funded Roads and Reduce Fiscal Exposure,* GAO-21-436 (Washington, DC: GAO, September 2021), 42–43, https://www.gao.gov/assets/gao-21-436.pdf.

[316] Michael Meyer et al., "Climate Change, Extreme Weather Events, and the Highway System: A Practitioner's Guide," National Cooperative Highway Research Program, 2010, 65-67, https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP 20-83(05)_AdaptationGuidanceDoc.pdf.

[317] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 47.

[318] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 84.

[319] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 65.

[320] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 50.

[321] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 51.

[322] Meyer et al., "Climate Change, Extreme Weather Events and the Highway System," 54.

[323] Stephen J. Collier, Rebecca Elliott, and Turo-Kimmo Lehtonen, "Climate Change and Insurance," *Economy and Society* 50, no. 2 (2021): 161, https://doi.org/10.1080/03085147.2021.1903771.

[324] Lucia Bevere and Andreas Weigel, "Natural Catastrophes in 2020," Swiss Re, March 30, 2021, 1, https://www.swissre.com/institute/research/sigma-research/sigma-2021-01.html.

[325] Collier, Elliott, and Lehtonen, "Climate Change and Insurance," 161.

[326] Collier, Elliott, and Lehtonen, "Climate Change and Insurance," 162.

[327] Collier, Elliott, and Lehtonen, "Climate Change and Insurance," 162.

[328] Xu, Webb, and Evans, "Wildfire Catastrophe Models," 2.

[329] Braun and Kousky, *Catastrophe Bonds*, 1.

[330] Xu, Webb, and Evans, "Wildfire Catastrophe Models," 2; RMS, "Climate Change Models"; Jayanta Guin, "Climate Change: A Reckoning and a New Approach to Modeling Risk," Air Worldwide, June 22, 2020, https://www.air-

---

worldwide.com/publications/air-currents/2020/climate-change-a-reckoning-and-a-new-approach-to-modeling-risk/.

[331] Kunreuther and Michel-Kerjan, "Climate Change, Insurability of Large Scale Disasters," 18.

[332] J. David Cummins et al., "The Costs and Benefits of Reinsurance," *Geneva Papers on Risk and Insurance* 46 (2021): 178, https://doi.org/10.1057/s41288-021-00216-8.

[333] Cummins et al., "The Costs and Benefits of Reinsurance," 178.

[334] Collier, Elliott, and Lehtonen, "Climate Change and Insurance," 162.

[335] Tony Coleman, "The Impact of Climate Change on Insurance against Catastrophes" (paper, Institute of Actuaries of Australia Biennial Convention, Queensland, Australia, May 18–21, 2003), 9, https://actuaries.asn.au/Library/Events/Conventions/2003/1050%20coleman7a.pdf.

[336] Coleman, "The Impact of Climate Change on Insurance against Catastrophes," 9.

[337] Claudio Morana and Giacomo Sbrana, "Some Financial Implications of Global Warming: An Empirical Assessment" (FEEM Working Paper No. 01.2018, Fondazione Eni Enrico Mattei [FEEM], Milan, IT, March 20, 2018), http://dx.doi.org/10.2139/ssrn.3143429.

[338] Morana and Sbrana, "Some Financial Implications of Global Warming," 18.

[339] Morana and Sbrana, "Some Financial Implications of Global Warming," 18.

[340] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 404-408.

[341] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 404.

[342] Galeotti, Gürtler, and Winkelvos, "Accuracy of Premium Calculation Models for CAT Bonds," 404.