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IAA Risk Book Catastrophe Risk

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Comment and feedback

Comment and feedback on Risk Book chapters is welcome.

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Introducing the IAA Risk Book

The actuarial profession has contributed significantly to the development of risk management tools and processes, in insurance, pensions and related industries. Actuarial skills are also increasingly being applied in new and developing areas of knowledge.

Actuarial practice continues to improve the understanding, measurement and communication of risk and risk events and their implications through the development of tools and increasingly processes to manage the future uncertainty of risks in a sustainable and transparent way. These tools and processes trace, manage and mitigate the acceptance and transmission of the uncertain outcomes of risks.

The Risk Book is intended to provide high-quality reference materials to support a better understanding of the risks and inherently uncertain future outcomes that need to be managed when delivering financial services products – whether they involve insurance, investments or retirement incomes, or more broadly. The Risk Book is written to be accessible to a wide range of readers, many of whom may not be actuaries or experts in the areas discussed but may be decision-makers in those areas. Consequently, the Risk Book should provide insight into the ideas and concepts behind actuarial topics and concepts. It is therefore focused on being descriptive rather than being formal and mathematically precise.

All the Risk Book chapters are publicly available on the IAA website and are periodically updated. See www.actuaries.org and follow the path to 'Knowledge / Publications / IAA Risk Book'. A discussion of their structure and relationships is provided in the chapter *Introduction – Using the Risk Book*.

The Risk Book is intended to be a dynamic and evolving resource, updated over time, reflecting new areas where actuarial expertise can add value, experience and advances, and topics of current interest and importance. It is electronically distributed to support ongoing updates. Risk Book chapters will be reviewed periodically at least every 5 years and more frequently if significant changes or developments occur.

The development and maintenance of the Risk Book is managed by the Risk Book Editorial Board of the IAA Insurance Regulation Committee.

Many people, mostly actuaries, have contributed to the Risk Book. Contributors are listed on the website.

To submit comments or questions about this Risk Book chapter, or to report any problems with the website, please email riskbookcomments@actuaries.org. To express interest in becoming involved with the Risk Book please go to the website and provide the requested information.



1. Overview

1.1 Introduction

“Catastrophes” refers to certain adverse events whose occurrence results in sudden and mass damage to or the destruction of property, lives, the environment and/or the economy. Catastrophes can be caused by natural (including biological) or human-made events.¹ An adverse event will not rise to the level of a catastrophe or disaster if it occurs in an area that does not have a vulnerable population or significant physical assets. Catastrophe risk is highest where significant potential for adverse events coincides with dense (large) populations and wealth including physical assets such as buildings. Some also label pandemics as natural catastrophes. This chapter focuses on catastrophes with a physical basis. It also acknowledges emerging concerns with future risks, such as solar flares, but does not attempt to address these hazards in detail.

According to statistics published by the United Nations, the magnitude of disasters has increased significantly since 2001². Increasing population density in urban areas and higher concentrations of property values in areas prone to disasters are leading to increased chances of mega-losses from natural and human-made catastrophes. The World Bank indicates that “today, some 56% of the world’s population – 4.4 billion inhabitants – live in cities. This trend is expected to continue, with the urban population more than doubling its current size by 2050, at which point nearly 7 of 10 people will live in cities.”³

The risk arising from catastrophes can severely impact an individual insurer’s solvency position (or even have market-wide implications) if not properly managed. Effective catastrophe risk management requires a comprehensive approach to identifying, assessing, transferring and mitigating the risk and large-loss potential.

1.2 Aims of This Chapter

Catastrophe risk has become an increasing focus for those involved in risk management, largely driven by the financial impacts of catastrophic events such as hurricanes, floods, wildfires, windstorms and earthquakes in developed and developing parts of the world. This chapter provides an overview of the types of catastrophes faced by the global insurance industry and discusses how companies estimate and manage catastrophe risk. This chapter is written at a particular point in time but recognizes that the understanding of catastrophes and the tools used to quantify and manage catastrophe risk continue to evolve.

After a brief introduction, this chapter discusses how the risk of such events is generally quantified, and the issues associated with that quantification.

¹ This paper focuses for the most part on natural catastrophes.

² <https://www.undrr.org/gar/gar2025#download>

³ <https://www.worldbank.org/en/topic/urbandevelopment/overview>

1.3 Relevance to Actuaries

Actuaries play a crucial role in assessing catastrophe risks, actively designing, implementing and using catastrophe models. Quantifying tail risks is pivotal in crafting risk-mitigating financial structures, pricing (re)insurance policies and determining adequate capital requirements. Actuaries are key users of catastrophe (cat) models both in pricing of and reserving for risks, and importantly also in assessing capital requirements and where the quantification of tail risks is particularly important.

1.4 Executive Summary

Key observations/findings from the chapter include:

1. Catastrophes result in sudden and mass damage to or the destruction of property, lives, the environment and/or the economy.
2. Catastrophes can result from natural hazards, such as storms or earthquakes, or be human-made, such as terrorism or cyber-attacks.
3. The frequency and severity of catastrophe losses have been increasing over the past several decades, primarily due to increasing concentrations of population and property in geographical areas prone to a range of disasters, including those that may be attributed to environmental changes (such as increasing temperatures or decreasing water supplies). These losses may be sudden or incremental.
4. Catastrophes impact society first and then insurers only to the extent of insured losses. The management of non-insured catastrophe losses is a matter of concern to other stakeholders, such as governments.
5. Their infrequent nature means analysis of past catastrophe losses cannot sufficiently measure future risk, so many insurers use catastrophe models to estimate potential losses.
6. Catastrophe models are based on four primary components – event catalogs, intensity formulas that quantify the hazard across the event footprint, damage functions and a financial module.
7. Model uncertainty is unavoidable. It is impacted by data issues (related to quality and availability), how the issues unfold in practice in situ and are addressed by insurers, and political issues reflecting how the issues are addressed by governments as they emerge in times of stress. Additionally, there is always the challenge of managing the uncertainty of outcomes that accompanies random events.
8. Model development and usage is evolving, including a trend towards open models (as opposed to closed proprietary models) and their use for scenario analysis.
9. Catastrophe modeling is part of the risk management process both in terms of pricing/underwriting and in terms of solvency/capital management.

2. Introduction

2.1 Types of Catastrophes

Broadly, catastrophes can be categorized into two types: natural and human-made.

A natural catastrophe is an event with a major adverse impact from either weather or geological events. Examples of weather-related events include tropical cyclones,⁴ floods, tornados, hailstorms, wildfires and blizzards. Geological events include earthquakes, tsunamis, volcanic eruptions, mudslides and avalanches. Natural catastrophes are relatively well understood by the scientific community but are difficult to predict and impossible to prevent.

The economic impact of catastrophe losses has increased over the past few decades, with inflation, demographic changes and climate change as the main causes. Catastrophe losses have grown and will likely continue to grow steadily over time, primarily due to increasing concentrations of people and property values in hazardous regions. That said, there is some evidence of climate change's impact on an increase in extreme precipitation trends in certain regions, and also a rise in sea levels. These trends should be appropriately considered in the assessment of catastrophe risk.

“human-made catastrophes” refers to events caused by accidental or deliberate human actions, such as aviation accidents, acts of terrorism, cyber-attacks, civil unrest, wars, nuclear power plant explosions and oil/chemical spills. These events can cause great damage to property and lives. Malicious human-made events often target large cities and high-profile landmarks, such as international airports and civilian or government facilities.

2.2 Risk Implications of Catastrophes

While there is wide variation from year to year, the trend of the growth in annual global catastrophe insured losses has been 5 to 7% in the past decades, according to Swiss Re.⁵ The economic impact of the natural disasters has also increased over the past 20 years, with the total for 2024 being estimated at USD327 billion, according to Munich Re; around 58% of these economic losses were uninsured⁶.

As an example, total economic losses from a catastrophic event will typically include damaged infrastructure, lost jobs, disruption to services and other costs not covered by insurance policies.

Additionally, insurance policies in many countries exclude or limit coverage for certain types of perils that are considered “uninsurable” due to their very infrequent but severe nature and consequently the inability to credibly price the risk – although there may be coverage through the reinsurance or Lloyd’s of London (Lloyd’s) markets, which are often willing and able to accept these risks. Nonetheless, insurers will still be impacted by the indirect costs of

⁴ This term is meant to include hurricanes, typhoons and cyclones – all the same phenomena but with different names based on where they occur.

⁵ <https://www.swissre.com/institute/research/sigma-research/sigma-2024-01/in-short.html>

⁶ <https://www.munichre.com/en/risks/natural-disasters.html>

uninsured risks resulting from infrastructure damage, disruptions to supply chains and so on.

There is wide variation between countries with respect to how catastrophe losses are funded. Governmental policies can influence how much of these losses are pre-funded through mechanisms such as insurance versus post-funded through taxation, borrowing and international disaster assistance.

Insurance can be provided by governments or the private market. For example, in New Zealand and in California (in the United States), earthquake insurance is provided through both the private market and government-sponsored entities. In New Zealand, earthquake insurance for households is quasi-compulsory,⁷ while in California it is not. Where coverage is voluntary, there is the concept of “take-up rates” that indicate the percentage of policyholders purchasing certain coverages. For example, the earthquake insurance take-up rates in California range between 10% and 30% depending on the length of time since the last major event. A 2022 study shows that only 13% of the residential policies cover earthquake.⁸ This may impact the unit cost of cover due to the anti-selective nature of voluntary “take-up”.

Private market insurance and risk-based pricing (where the prices reflect any changes in the assessment of the risks) are generally thought to be the most efficient ways to insure against catastrophe losses. Immediately after an event, insurers can begin to assess and settle claims so that policyholders can start rebuilding homes and businesses. It will typically take several months, and often years depending on the size or nature of the event, for all of the claims to be identified and paid by the insurance industry, leading to a relatively long payout pattern. Risk-based pricing also encourages mitigation activities that can help societies become more resilient to future events.

Both natural and human-made catastrophe losses continue to adversely affect the insurance industry. They have led to insolvencies of insurers of varying sizes, and significantly adversely impacted the profitability of (re)insurance companies, according to a 2021 report.⁹ While the reinsurance capital increased steadily in the past decade, the return on equity decreased from levels in excess of 10% to levels below 5%. For example, property and casualty (P&C) insurance companies in the US state of Florida reported declining profits with nine insurers having become insolvent since 2021.¹⁰

More generally, in the United States, since the start of 2021 18 US-based companies became financially impaired due to natural catastrophes; 14 were domiciled in Florida or Louisiana. Previously AM Best also reported that during the period from 1969 to 2012 two peaks of losses were experienced – one in 1992 following Hurricane Andrew and the other

⁷ Home insurance provided by the Earthquake Commission is compulsorily attached to home insurance offered by private insurers. While take-up rates are high, private insurance is voluntary.

⁸ <https://www.insurance.ca.gov/0400-news/0200-studies-reports/0300-earthquake-study/upload/EQEXP2022Summary.pdf>

⁹ <https://www.wtwco.com/-/media/wtw/insights/2021/04/willis-re-reinsurance-market-report-april-2021-results-for-full-year-2020.pdf>.

¹⁰ <https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/a-ray-of-sunshine-for-florida-s-troubled-residential-property-insurance-market-76572524>

in 2005 after Hurricane Katrina, with a total of 53 US-based P&C insurers becoming impaired as a result of catastrophe losses and 11 becoming insolvent from one event, Hurricane Andrew.

In Japan, the P&C insurance sector has also faced challenges due to natural disasters. The 2011 Tōhoku earthquake and tsunami resulted in significant losses for insurers, leading to increased premiums and stricter underwriting practices. In recent years, typhoons have become more frequent and intense, prompting several insurers to reassess their risk exposure. For example, Typhoon Hagibis in 2019 caused widespread flooding and damage, leading to substantial claims that pressured insurers' profitability.

In Europe, the impact of climate change has similarly affected the insurance market. In Germany, for instance, the catastrophic flooding in July 2021 resulted in billions of euros in insured losses, with many insurers reporting significant impairments. The event highlighted the vulnerability of the P&C insurance sector to extreme weather events, prompting regulators to call for more robust risk management practices. The UK's insurance market has also been under pressure, particularly in relation to flooding and storms, with some insurers reevaluating their coverage options in high-risk areas.

In Australia, the bushfire season of 2019–2020, known as the “Black Summer”, led to unprecedented losses for the P&C insurance industry. Insurers faced a wave of claims related to property damage, business interruption and vehicle losses, resulting in several companies reporting significant impairments. The Insurance Council of Australia declared the bushfires a catastrophe, and the event underscored the growing risks associated with climate change and its effects on the insurance landscape. Additionally, the increasing frequency of severe weather events, such as cyclones and floods, has prompted Australian insurers to reassess their underwriting criteria and pricing models.

The impairments experienced in the aftermath of Hurricane Andrew (1992), which struck in the Bahamas, Florida and Louisiana, were a turning point in the insurance industry's recognition of catastrophe risk as a serious solvency threat. This resulted in a widespread adoption of sophisticated catastrophe models in enterprise risk management (ERM) and in the determination of capital requirements. This has since resulted in increased insurance company resilience to recent catastrophes.

3. Estimating Losses from Catastrophes

Catastrophes are infrequent events in specific geographical regions, which means there is a paucity of data for loss estimation. Standard actuarial approaches using historical claims and loss data to project future losses are not appropriate for most types of catastrophes. Due to sparse historical data, any approach will be characterized by significant uncertainty, so it is prudent for insurance companies to use a variety of methods to identify the types of events that could result in large losses and estimate the magnitude of those losses.

One method that can be used even if there is no data on past events is to add up total insured values in specific regions exposed to severe events and apply factors representing the percentages of total values that could be lost in one event or an aggregation of events over some time period – usually one year. Total insured values would represent the upper bound of loss potential.

Scenario testing is another method used to estimate the losses from specific events. For example, Lloyd’s has developed a set of Realistic Disaster Scenarios (RDS) and requires syndicates to report on their loss estimates from these scenarios each year. Many companies employ scenarios as part of their ERM framework.

Catastrophe models provide a robust structured approach for estimating a wide range of possible future scenario losses along with their associated probabilities. The catastrophe models provide full probability distributions and therefore they are suitable for many types of actuarial analyses, provided they are appropriately parameterized. Loss estimates produced from catastrophe models can be deterministic for a specific event (e.g., a magnitude 8.0 earthquake affecting the San Francisco Bay area in the United States, or a tropical cyclone impacting Brisbane in Australia) or probabilistic from a catalog consisting of both historical and hypothetical events.

Catastrophe models, however, often face challenges due to the paucity of direct historical data in specific geographical regions, leading to significant uncertainty in loss estimation. To mitigate this, insurance companies could consider using proxy data from analogous regions or related phenomena to enhance their model predictions. Furthermore, employing advanced statistical techniques, such as Bayesian statistics, can help companies better handle sparse data and incorporate expert judgment into model parameters. Additionally, collaboration with international agencies, research institutions and other stakeholders is crucial for accessing a broader range of data, thereby improving the robustness of the models. These collaborative efforts and advanced methods are essential to more accurately identify and estimate the magnitude of potential losses from catastrophic events.

3.1 Key Components of Catastrophe Models

For all types of catastrophes and for all peril regions, catastrophe models generally have the same four primary components, as shown in Table 1:

Model Component	Description
Event catalog	Defines event parameters, including frequency and physical severity by geographical region
Intensity formulas	Estimates the hazard intensity (e.g., wind speed, shaking intensity) experienced at each location in the area affected by each event

Damage functions	Estimates the damages to buildings and contents, and time-element exposures (may also estimate casualties), without reference to insurance policy terms and conditions
Financial module	Applies insurance policy conditions and reinsurance terms to estimate insured losses

a) *Event Catalog*

The event catalog includes the important parameters defining the characteristics of each simulated event, such as location, severity and size. For tropical cyclones, the event catalog includes landfall point, peak wind speed and radius of maximum winds. For earthquakes it includes epicenter, depth and magnitude. For terrorist attacks, the event catalog could include the location, type and size of an explosive device.

For each event in the catalog, there is a rate of occurrence that is estimated using statistical analysis of historical information if there is enough data (tropical cyclones, other windstorms) or by scientific studies and expert opinion where there is less data (earthquakes, terrorist attacks). The catalogs typically include a large sample of events generated by Monte Carlo simulation or stratified sampling techniques.

The event catalog is extremely important because it defines the frequency and physical severity of events by geographic region. The reliability of the catalog varies considerably across peril regions depending on the quality and quantity of historical data and the scientific understanding of the hazard. For example, in California and Japan, there have been several significant earthquakes, and the nature of the faulting is generally understood by scientists (although there are many unknowns with respect to the magnitudes and locations of future events; e.g., the previously undocumented Northridge thrust fault, which triggered the 1994 Northridge earthquake).

In contrast, regions like Turkey and Indonesia also experience significant seismic activity, yet the understanding of their geological structures is still evolving. Turkey, located on the complex boundary between the Eurasian and Arabian tectonic plates, has a history of devastating earthquakes, such as the 1999 İzmit earthquake. The intricate fault systems in this region pose challenges for predicting future seismic events, as evidenced by the ongoing research into the North Anatolian Fault.

Similarly, Indonesia, situated on the Pacific Ring of Fire, is prone to both earthquakes and volcanic eruptions. The 2004 Sumatra earthquake and subsequent tsunami highlighted the region's vulnerability, but the understanding of the tectonic processes at play remains an area of active research. The diverse geological settings across Indonesia complicate the development of a comprehensive event catalog, as many islands have different seismic characteristics.

Regions that are located along tectonic plate boundaries, such as Japan, have a more documented history of seismic activity. The 2011 Tōhoku earthquake, which struck off the

northeastern coast of Japan, is one of the most powerful earthquakes ever recorded, with a magnitude of 9.0. This event not only caused widespread devastation and loss of life but also triggered a massive tsunami. The Tōhoku earthquake serves as a stark reminder of the potential for catastrophic seismic events in plate boundary regions, while highlighting the challenges faced by intra-plate regions in predicting and preparing for future earthquakes.

b) Intensity Formulas

For each event in the catalog, the models estimate the hazard intensity of a peril at each affected location using the event parameters discussed above, site information and scientific formulas developed by the wider scientific community. While scientists have collected and analyzed intensity data from past events to develop these formulas, the amount and quality of the intensity data varies significantly across perils and regions. The hazard intensity of each event footprint from the catalog is also expressed by a pre-defined time frame.

For example, tropical cyclone intensity is defined by wind speed, and scientists have developed well-established formulas for hurricane wind speeds over water. When a storm makes landfall, however, wind speeds start to dissipate because the hurricane loses its source of energy and due to frictional effects from the rougher terrain. As there are relatively few reliable over-land wind speed measurements for historical events, a degree of judgment goes into estimating hurricane intensity over land.

For earthquakes, intensity is defined by peak ground acceleration or ground motion and is estimated using attenuation equations developed by scientists around the world. There is limited observed ground-motion data for past historical events, and therefore earthquake intensity has also been inferred from the damage using the Modified Mercalli Intensity (MMI) scale.

A further complication with earthquakes is that the ground motion experienced at a location will be influenced by the nature of the rock and soil the energy waves pass through before getting to that location – these complexities cannot be reliably modeled. A simplifying approach of applying factors based on local soil conditions is typically used where detailed soil data is available. Secondary hazards, such as liquefaction and fire following earthquakes, might also be considered by the model.

While the likely frequency and severity of future human-made catastrophes is highly uncertain, there is a wealth of information on the impacts of terrorist attacks, particularly attacks using conventional types of weapons.

In the examples mentioned above, scientists aim to collect and calibrate data and parameters in order to accurately model the intensity of hazards. In instances of missing historical data, a synthetic set of events is generated using stochastic scenarios, incorporating the relevant parameters based on peril and area. In both cases, each event in the catalog is assigned a rate of occurrence, or frequency.

c) Damage Functions

The model damage functions estimate for different intensity levels the damages that will be

experienced by different types of exposures. For property exposures, the damage functions will consider the building construction type, occupancy, year constructed and other characteristics depending on the peril.

The damage functions are expressed as the ratio of the repair costs (as a result of the damage, i.e., modeled loss) to the building replacement value (it can be the exposure or sum insured). The nature of actual damage is not uniform, and therefore for any given wind speed and mean damage ratio, different properties will experience different levels of damage – potentially ranging from 0 to 100%. This uncertainty is typically called “secondary uncertainty” and includes the uncertainty in the intensity and damage calculations, given that an event has happened. In the catastrophe modeling terminology, “primary uncertainty” refers to uncertainty with the event-generation process (e.g., event frequency) and event parameter assumptions such as storm intensity, storm size and storm speed.

d) *Financial Module*

Once the damage function is determined, given the hazard intensity in relation to, for example, the structure of a building and its contents, the total losses (also named ground-up losses) can be calculated. At this stage, these losses do not consider any (re)insurance financial structures. Generally, losses are calculated with some degree of uncertainty, with the mean and standard deviation also provided. The distributions of the losses, including the secondary uncertainty distributions, are used to determine the insured losses, accounting for policy terms and conditions.

After the total building, contents and time-element (ground-up) losses are calculated, the secondary uncertainty distributions are used to estimate the insured losses, accounting for policy terms and conditions. Policy terms include loss triggers, deductibles by coverage, aggregate deductibles, total and sub limits, coinsurance, attachment points and applicable reinsurance terms. This model component is essentially the same across all peril regions (except for accounting for country- and peril-specific policy conditions). Health and life risks may need to be considered separately. In conclusion, to construct the first three model components for a specific peril region (e.g., US hurricane, Sydney hailstorm or Turkish earthquake), data and information are collected from external entities such as government bodies and scientific organizations. The models are, for the most part, based on the same information collected, published and maintained by the wider scientific community – model differences result from how the data is interpreted and analyzed to develop the many model assumptions.

3.2 Model Input

Exposure inventory is the key input in the catastrophe models. The most basic information is the replacement value for a building and contents, time-element coverages and the sums insured. Ideally, this information would be provided for each insured property by geo-coded location. In reality, the resolution¹¹ and quality of the exposure data varies by peril region.

¹¹ “Resolution” refers to the level of detail or granularity of the data.

Most companies can provide this level of detail for the models, along with other building characteristics, such as construction details, occupancy and year built. Note that this information could significantly vary year on year or even at the level of individual locations. The more detailed the information on the structure and contents, the more reliable the model loss estimates will be. In other regions, the data may be the total insured value (TIV), or 100% replacement value (RV), which could be different from the TIV where a policy sub-limit might be applied.¹² Such data can be aggregated by CRESTA (Catastrophe Risk Evaluation and Standardizing Target Accumulations) zone and line of business (residential, commercial, industrial). For example, in France, insurers typically collect data on the number of rooms rather than TIV, and the data is aggregated by CRESTA zone. Often, within the catastrophe modeling world, such data is captured in a database, better known as an industry exposure database.

Exposure data quality is an important issue in the quantification of catastrophe risk. As most types of catastrophes impact localized areas, detailed knowledge of where exposures are located and the replacement values of those exposures are critical for credible loss estimates. For example, for properties exposed to storm surge flooding, it is important to know how far the properties are from the coast, as well as elevation above ground. In seismic regions, the risk depends heavily on how close the exposed properties are to active faults.

Regulators should inquire about the geographical resolution of the exposure data and its level of granularity; for example, whether it is based on exact latitude-longitude coordinates, postal code centroids or aggregates by CRESTA zones. They should also know how building, contents and time-element values are being determined. The nature and extent of other building characteristics contained in the exposure data files would be an indication of the emphasis placed on exposure data quality.

Besides the characteristics of the building, business interruption also plays an important role when determining the value of the exposure. If personal lines exposure is considered, then additional living expenses will be used instead of business interruption costs. Further uncertainty about the modeling of property values may result from inflation relating to the cost of rebuilding. Whereas commercial third-party property valuation services exist for personal lines, providing a reliable measure of rebuild costs, these tend to be unreliable for commercial lines, for which often no suitable valuation services exist.

3.3 Model Output

The primary cat model output is the exceedance probability (EP) curve that shows the probabilities of a portfolio of exposures exceeding losses of different amounts (see Figure 1). The catastrophe models typically generate two types of EP curves: the annual occurrence distribution (OEP) and the annual aggregate distribution (AEP). The OEP gives the probabilities of losses from the maximum occurrence in a year, and the AEP the probabilities

¹² Or even when the exposure values are unreliable and/or not updated regularly. Aggregate data allows for unquestioning modeling of values that can be much less than RV, and as a result can generate much lower ground-up losses than would otherwise be the case.

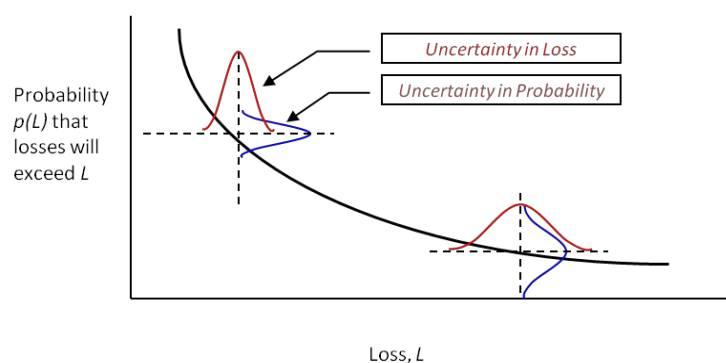
of total annual losses from multiple events in a year.

For very-low-frequency, high-severity events, such as earthquakes, the curves will be very similar and typically converge in the upper tail. For more frequent events, such as tornados and windstorms, the AEP losses can be significantly higher than the OEP losses at all probability levels. The AEP losses will also be higher than the OEP losses for geographically diversified portfolios versus more concentrated books of business.

There are different techniques for estimating the AEP distribution, depending on how the underlying stochastic event loss data is developed. If the data is developed in a year, event loss format is a simple aggregation exercise. Otherwise, it might involve convolution of frequency and severity distributions. Generally, it is more challenging to estimate and less robust than the OEP distribution. Theoretically, average annual losses (AAL) should be calculated from the AEP.

However, aggregate catastrophe covers that span multiple perils make it nearly impossible to determine AEP values from a single-peril cat model. One approach that can be taken is to use OEP curves from the various single-peril cat models and combine them in a separate model that incorporates the aggregate multi-peril catastrophe cover.

Figure 1. Illustrative Exceedance Probability Curve



Insurers and regulators have been relying on point estimates from this curve for risk management purposes. As such, the information from these curves is used to determine the level of reinsurance cover purchased by insurance companies, whether it is related to capital requirements or simply used to balance their underwriting and financial results. For example, in the United States, insurers use the points on the curve where the estimated probabilities of loss exceedance are 0.01 and 0.004, popularly known as the 1-in-100 and 1-in-250 year losses, respectively. These points are also referred to as the 100- and 250-year return periods or Probable Maximum Losses (PMLs). In Europe, the 0.005-point estimate, corresponding to the 200-year PML, is used more frequently.

Cat models can generate EP curves and the expected losses or AAL at any level of resolution. An EP curve is a complete probability distribution and therefore it is useful for

many types of actuarial analyses, including pricing and capital modeling.

3.4 Model Uncertainty

As Figure 1 illustrates, there is significant uncertainty surrounding the EP curves. The EP curves are better thought of as “fuzzy areas” versus lines. Apart from the model uncertainty, there is uncertainty in the exposure data input with respect to the claims-handling practices of individual insurers and due to other factors external to the model, such as political pressures on insurers after major events.

In large catastrophe loss events, there can also be material and labor supply shortages, if local resources are overwhelmed, causing the costs of repair to be higher than the replacement values of properties pre-event. This is typically referred to as “demand surge” or “loss amplification”. Such demand surge can be a result of various reasons, such as an individual large-loss event in either a heavily populated region or a region with poor infrastructure, or it could result from a consecutive series of moderate events impacting neighboring regions that depend on the same pool of contractor/adjustor/supplier resources.

These scenarios played themselves out in 2017, when the hurricanes Harvey, Irma and Maria all made landfall in different parts of the US coastline in a very short time span. The situation was amplified by the fact that Puerto Rico (impacted by Hurricane Maria) had very poor water and power infrastructure that was severely damaged.

Similarly, demand surge was observable following the 2022 South East Queensland and New South Wales floods in Australia. In addition, the 2011 earthquake and tsunami in Japan led to significant demand surge in the affected regions. The destruction of infrastructure and the overwhelming need for rebuilding efforts strained local resources, resulting in increased costs for materials and labor as contractors and suppliers were stretched thin.

In Europe, the 2020 flooding in Germany and Belgium also highlighted the issue of demand surge. The catastrophic flooding caused extensive damage to homes and infrastructure, and the local construction industry was quickly overwhelmed. As a result, the costs of repairs escalated due to shortages of materials and labor, exacerbated by the ongoing impacts of the COVID-19 pandemic on supply chains.

Model uncertainty stems from a lack of high-quality data in sufficient quantities to credibly estimate all the model assumptions. For peril regions where events are infrequent, there will be less reliable data and higher uncertainty. Even in geographical areas with more recent events, there is typically not a comprehensive network of highly calibrated instrumentation required to collect high-resolution data.

The source and relative reliability of the data underlying the scientific and engineering model components are illustrated in Table 2 below. Green shading indicates a relative abundance of data and red indicates the least – yellow is in between. Note that even for the green shaded area there is generally significant uncertainty given the difficulty of obtaining useful data for extreme return periods, such as 1-in-250 years, especially if the climate or other factors are changing over time.

Table 2. Data Supporting the Catastrophe Model Components

	Event catalogs	Intensity formulas	Damage functions
Tropical cyclones	<p>In most regions of the world, these are based on historical data collected and maintained by government organizations, such as the National Hurricane Center and the Japan Meteorological Agency.</p> <p>The modeling companies rely on these databases and apply some expert judgment for assumptions on the characteristics of future events in regions where the historical data is sparse.</p>	<p>These are based on established meteorological formulas developed over the past several decades by government organizations and the wider research community. Formulas are well documented in the scientific literature. Expert judgment is applied for some aspects of hurricane intensity such as varying terrain impacts on overland winds. Land use data is maintained by and available through government agencies.</p>	<p>For a few regions, such as Florida and the Gulf states in the United States, historical loss and claims data have been made available to the modelers by insurance companies, and this data can be used to fine-tune the damage functions. However, because there are thousands of damage functions reflecting different occupancies, construction details and building characteristics, most of the functions are based on expert judgment.</p>

	Event catalogs	Intensity formulas	Damage functions
Earthquakes	<p>Historical data on earthquakes is collected and maintained by government organizations such as the US Geological Survey and European-Mediterranean Seismological Centre.</p> <p>These organizations also sponsor research such as paleoseismicity studies to supplement the historical record. Catastrophe modelers use this data and other information, such as hazard maps and scientific reports, as the bases for the earthquake event catalogs.</p>	<p>Next generation attenuation (NGA) equations have been developed by a global consortium of earthquake experts using data on significant earthquakes around the world, and these form the bases of the ground-motion formulas in the catastrophe models.</p> <p>Generally, soil data is inferred from geological data except in major urban areas where more detailed studies have been conducted.</p>	<p>There is limited claims data available to the modelers for construction of the earthquake damage functions. The global earthquake community compiles information and periodically publishes studies of building and contents vulnerability to ground motion. Limited, full-scale, shake table tests and sophisticated engineering analyses are available, but this model component is still heavily reliant on expert judgment.</p>

Terrorist Attacks	<p>There are many types of terrorist attacks and tens of thousands of potential targets for which there is little or no data for estimating the likelihood of future events. Given that terrorists want to intimidate by surprise, past data may not be a reliable guide for future events. The models rely heavily on the judgment of counterterrorism experts such as specialists from government bodies.</p>	<p>The shock waves and pressure impacts of various types of bomb blasts are well studied and understood even though the density and complexity of an urban setting can distort the resulting intensity pattern. The intensity footprints of chemical, biological, radiological and nuclear (CBRN) attacks are much larger and more difficult to project reliably, but these impacts have been studied and tools have been developed to estimate the effects.</p>	<p>As attacks using conventional weapons such as bomb blasts and aviation incidents are localized events, and the damage is often complete, the model damage functions are straightforward. Much more judgment goes into the construction of damage functions for CBRN incidents.</p>
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The paucity of data underlying the model components for many peril regions results in model assumptions relying in large part on expert opinion and judgment. Model variability and volatility frequently arise from differing scientific opinions and perspectives. In most countries there have simply not been any events that have affected the insurance peak zones in recent decades – this makes model calibration especially challenging, particularly in the lower tail. This applies to all earthquake models globally, to tsunami models, to fire-following models, to certain inland flood models, to wildfire models and to peripheral areas of the tropical cyclone models that have not seen major events for decades (e.g., a Northeast US hurricane and European windstorm).

The complexity and the infrequent nature of the natural hazards being represented by catastrophe models imply that the models will always contain a significant amount of uncertainty. This uncertainty is both aleatory (inherent process uncertainty related to the randomness in large events) and epistemic (introduced by the incomplete knowledge of the process parameters and/or the proper model structure¹³ due to limited historical records). In theory, aleatory uncertainty is impossible to reduce due to the stochastic nature of the process, and in a well-designed model it is suitably represented by the probabilistic distribution of loss from a single model. Estimation of epistemic uncertainty requires use of multiple models built using different parameterizations of the natural hazard process.

¹³ For example, studies of some past hurricanes and floods have identified the level of soil saturation from previous rains as a factor in the extent of the hazard intensity or damage. This generally is not modeled currently (perhaps due to practical difficulties in doing so).

Another important source of such uncertainty is in the parameterization of the vulnerability curves, which is typically hampered by the insurer's access to credible claims data. Even though a costly option, a few insurance companies might move towards the use of multiple catastrophe models (or multiple representations of the same catastrophe model enabled by newer, open loss models) to better manage the model risk arising from epistemic uncertainty. Various approaches have been devised to combine (blend) the output from these models or to adjust properly one of the selected models for any biases to derive a more robust view of risk.

The models do not anticipate all sources of loss from an event, and parameter risk cannot be accurately quantified. Typically, they do not produce confidence bands around the EP curves.

To mitigate these uncertainties, users can:

- Combine model outputs: Use outputs from multiple models to get a broader perspective on potential risks.
- Incorporate external data: Enhance model predictions by incorporating recent data and studies.
- Adopt conservative assumptions: When in doubt, adopt more conservative assumptions in their risk assessments to buffer against unforeseen losses.

3.5 Model Usage

While the models are useful tools to quantify the nature and uncertainty of catastrophe risk, it is important to recognize that they are often constrained in their ability to fully capture all the varied aspects of the hazard and its consequences – they reflect the model developer's inherent assumptions and scientific judgment. The onus is on the model user to determine if the model is fit for purpose, use only credible models and adapt them to their specific business with appropriate settings.

If the model representation is reasonable but with certain gaps, then, to the extent possible, the model user may apply appropriate adjustments to the model output. If model adjustments are not possible due to the nature of the gap or the lack of transparency/flexibility in the model, the model gaps may need to be documented and accounted for separately. Addressing the material non-modeled gaps may necessitate a significant amount of model development.

For example, in certain regions, tsunami losses are not explicitly included in earthquake models, nor are losses from inland floods triggered by tropical cyclones. Likewise, the model may not represent certain exposures, such as outbuildings in residential exposures, contingent business insurance in commercial exposure or potential loss to infrastructure assets.

There may also be residual market pools or other societal mechanisms to provide insurance policies to otherwise uninsured risks. To the extent these mechanisms are funded by assessments on the insurance industry, they may lead to otherwise non-modeled

exposures.¹⁴ Such gaps are model-dependent, and models continue to evolve to address some of these gaps. The model user may use underwriting insight, industry and internal claims experience, where available, to calibrate and supplement the models.

The closed proprietary nature of the traditional catastrophe models may complicate the assessment of whether the portfolio risk is driven by the hazard (frequency, physical severity and intensity of the events) or vulnerability component of the model. Often, decision makers are interested in such underlying detail to devise optimal risk management strategies. There are various other risk measures that allow risk managers to assess the risk in more intuitive ways.

One such approach is to track the portfolio risk for certain events, such as the RDS developed by Lloyd's, as discussed earlier. Many companies might complement probabilistic risk measures derived from the model EP curves with the development of their own internal catalog of disaster scenarios to monitor accumulations and manage risk appetite. The uncertainty surrounding catastrophe risk, and its low-frequency, high-severity nature, necessitate multiple approaches to estimating losses to help inform decision makers.

3.6 The Future Evolution of Catastrophe Models

Catastrophe models have made significant strides since the late 1980s. They will continue to evolve as actual events occur, scientific discoveries are incorporated, technology advances and new data is analyzed, and when there is expansion to cover more perils and exposed regions. However, the models will never be complete or accurate, so the onus will remain on the model user to fully understand, validate and refine the model assumptions as appropriate. Some current shortcomings include the lack of model calibration in peril regions with few or no events; lack of a probabilistic fire-following-earthquake framework, aftershock-triggered event modeling in most earthquake-prone regions; and lack of fully probabilistic tsunami modeling.

Catastrophe model development requires scientific, engineering and computer programming expertise not usually found within insurance companies. Therefore, most insurers have been licensing catastrophe models from third-party vendors. Recently, regulators and rating agencies have emphasized the importance of (re)insurance firms demonstrating a deep understanding of the risk models. This pressure has led to several firms embarking on improving internal model validation and an increasing model transparency. That said, the proprietary nature of the third-party models makes it difficult for insurers to ascertain which assumptions are driving the model loss estimates. Model updates also add to the volatility of loss estimates, and it is very challenging and time-consuming for insurers to determine what is causing the changes.

3.6.1 Open Models

Future evolution is expected to include an increasing number of open-source models that

¹⁴ For example, the Earthquake Commission in New Zealand also covers non-modeled volcanic and flood perils.

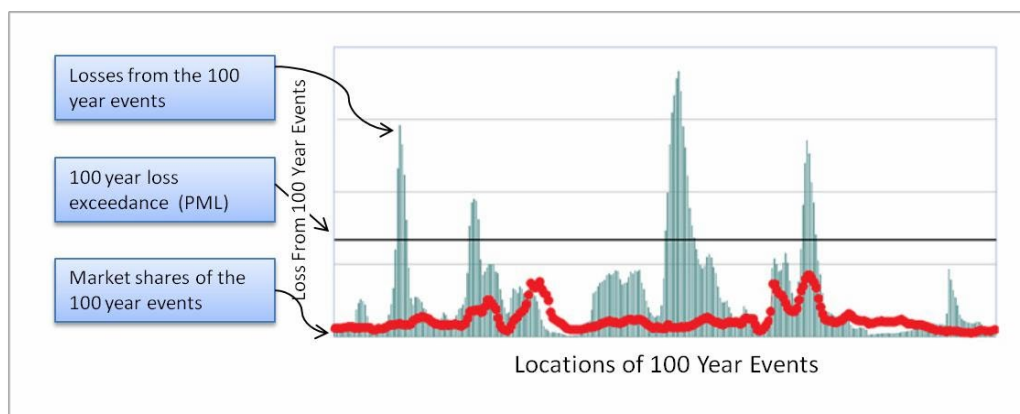
allow for a greater ownership of risk as well as better appreciation of the inherent uncertainty in catastrophe risk. Open models are transparent, enabling insurers to more fully understand the model assumptions and how different scientific opinions impact their losses. Open models enable users to test their portfolio losses against different sets of assumptions to clearly evaluate model sensitivities and key drivers of their loss estimates.

3.6.2 New Risk Metrics

New and intuitive risk metrics will give decision makers more insight into their large-loss potential. While the EP curve metrics are informative, they do not provide decision makers with all of the risk information they need, and they can be misleading. For example, the 100-year PML can be misinterpreted as the 100-year “event” loss, which can give a false sense of security. The largest losses incurred from the 100-year events will likely be much greater than the 100-year PML from the model-generated EP curve.

The new Characteristic Event (CE) approach in which the probabilities are based on the hazard as distinct to the loss provides additional and more intuitive information for risk management purposes. It gives decision makers their losses from the 100-year (and other return period) events – information many may have thought they already had. Figure 2 shows the loss estimates for the 100-year event at different locations for a hypothetical company. The 100-year PML is the point on the EP curve that represents a 1% chance the company will have a greater loss; the 100-year CEs show how much greater and where the larger losses are likely to be.

Figure 2. Example Characteristic Event Chart



The CEs help a company identify potential solvency-impairing exposure concentrations – information not provided by the EP curve metrics. The CEs are operational metrics that can be used to monitor and manage risk over time. Some limitations of the CEs include, for example, the difficulty in specifying what a “100-year event” is, as in reality the intensity will vary widely by location – for instance, a 100-year flood in one location does not necessarily correspond to that in another location. CEs are focused on specific sources (e.g., certain earthquake fault zones), which might exclude other ways to generate a loss of a certain size.

4. Catastrophe Risk Management

The first step in effective catastrophe risk management is to recognize the uncertainty inherent in estimating catastrophe losses and to utilize multiple approaches and risk metrics to gain as much insight as possible into large-loss potential. Then insurers can determine if they are overly exposed to specific events and decide how to underwrite and price the risk and how much to transfer to the reinsurance and financial markets.

4.1 Underwriting and Pricing

For many insurance coverages, underwriting rules and rates (prices) are based on the AAL of an insurance policy. AAL is the expected loss per year, averaged over many years. A proportion of the standard deviation around the expected losses can also be applied.

For example, actuaries often use model-generated AALs by postal code or a more granular geographic resolution, such as census block or custom grid level, to develop hurricane catastrophe loads for homeowners rating territories. In the United States, the California Earthquake Authority uses model-generated AALs to determine earthquake rates by territory. Some companies use AALs by location and policy to underwrite and price individual accounts. At this high resolution, however, and for specific types of risks, the traditional model output has the least credibility and is highly volatile.

The nature of catastrophes and the skewed, thick-tailed loss distributions may lead to moving from using expected losses and standard deviation metrics to catastrophe pricing approaches that factor in the capital consumed by different peril regions and even specific contracts. This is typically called “marginal impact” pricing because it is based on the additional capital required to write the new policy, line of business and so on. The capital amount, which can be a combination of internal capital (held on the company’s balance sheet) or external capital (such as reinsurance), is typically allocated to the policy or line of business based on specific risk measures. Rather than using the PML, a “value-at-risk” (VaR) measure, some insurers are moving to metrics capturing more of the EP curve, such as “tail-value-at risk” (TVaR), for their marginal impact decisions.

Apart from pricing considerations, it is also common for underwriters to manage the catastrophe risk in high-hazard and accumulation zones by offering restrictive policy terms and conditions, such as sub-limits, exclusions and higher deductibles, or by focusing on those building types/locations that are less susceptible to catastrophe losses.¹⁵ Risk metrics, such as CEs, enable companies to see where they have exposure concentrations that need to be reduced.

4.2 Enterprise Risk Management and Transfer

For solvency and risk transfer purposes, insurance companies, rating agencies and regulators in the United States have come to rely most heavily on the 0.01 and 0.004 loss

¹⁵ For example, analyses of recent hurricanes and floods have shown that it is possible in some cases to prevent or minimize susceptibility to damage through the use of certain building practices.

exceedance probabilities – the so called 100- and 250-year PMLs – respectively. For Europe, as previously mentioned, the 0.005-point estimate, corresponding to the 200-year PML, is used.

In such circumstances, this point estimate, considered by the Solvency II prudential regime, is also referred to as the 99.5% VaR measure. These numbers are used to set capital requirements and determine how much reinsurance to buy, and for formal risk tolerance statements, but there is a growing awareness of the danger in relying on point estimates from the EP curves.

To reduce the over-reliance on one point of an EP curve, insurers are leveraging other more robust tail risk measures, such as the TVaR or an Excess Annual Average Loss (XSAAL). The TVaR represents the expected loss amount conditional on the loss exceeding a certain threshold (at a certain exceedance probability). XSAAL represents the (unconditional) average value of loss exceeding a certain threshold (at a certain exceedance probability). Unlike the PML, both of these measures take into account the thickness of the tail, are not overly dependent on one point on the distribution and have attractive coherent properties (such as diversification). It makes them attractive to risk aggregators and portfolio managers. (As a caution, however, note that such values are based on the most uncertain and hence least reliably estimable sections of the loss exceedance curve.)

Portfolio management of catastrophe risk and timely monitoring is a key priority for most insurers. In addition to tail risk measures, such as the 100- and 250-year TVaRs, that impact capital, insurers may also be concerned about earnings volatility that may be introduced by high-frequency, low-severity catastrophe events. To manage earnings volatility, insurers might set budgets, risk appetites and guidelines around AAL and lower return-period losses (such as the 10- or 20-year PML). In addition, insurers might be interested in avoiding a loss scenario that is outsized compared to their market share of premium. The major third-party catastrophe risk models are typically equipped with industry loss curves, which lend themselves to such analysis. The appetite for a certain market share of loss is a valuable input into portfolio strategy. Once the portfolio objectives or appetites are determined, insurers might use various strategies, such as risk transfer and portfolio optimization, to meet these objectives in the most economic and efficient manner.

Risk transfer is a key exposure accumulation management strategy for insurers in their quest to limit net aggregate risk to their balance sheet or earnings. Some insurers may also use risk transfer to mitigate inherent model risk. The underwriting and pricing of risk transfer options fully leverages catastrophe model outputs, which are used to assess the expected loss in the contract, the marginal capital impact and the relative cost of that capital, in addition to corporate risk appetite considerations.

Due to the high demand and supplier interest, over the years, many different risk transfer approaches have evolved. Risks can be transferred at various levels: at the level of a single location or account, or at a business unit or a corporate aggregate portfolio level. The risk



can be assumed by reinsurers,¹⁶ retrocessionaires, institutional investors and insurance-linked securities (e.g., catastrophe bonds). The modes of risk transfer might include indemnity-based cessions, parametric/index-based cessions or a hybrid of both.

¹⁶ See the Risk Book chapter on reinsurance for more details.



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