Managing Physical Climate Risk: Leveraging Innovations in Catastrophe Risk Modelling

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The Geneva Association

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Foreword

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There was a time when catastrophe risk modelling was prepared on a spreadsheet—one per each peril, perhaps. The insurance industry has been instrumental in the evolution of this field. From its humble beginnings the so-called Cat modelling has evolved into a complex, rigorous, multi-layered discipline that has revolutionised the way insurance companies assess, price, underwrite and put in place efforts to mitigate catastrophe risk.

Cat modelling is more relevant than ever. By some estimates, total global economic losses from natural disasters and man-made catastrophes in 2017 were USD 337 billion, and global insured losses from disaster events in 2017 were USD 144 billion. Just to put it in perspective, hurricanes Harvey, Irma and Maria resulted in combined insured losses of USD 92 billion, equal to 0.5% of U.S. GDP.

The question is: are Cat models broad and detailed enough to assist insurers and policymakers fully grasp the costs and implications of catastrophe risk? In a world with natural phenomena so complicated and affected by climate patterns so erratic, what is the predictive power of the insurance industry's Cat modelling capabilities?

The conditions are ripe for the next generation of Cat models. The insurance industry, with is extensive experience in catastrophe risk modelling, can make a significant contribution. It is imperative to bring together different fields of science to ensure that Cat models widen their scope and address the unprecedented complexity of natural and man-made disasters and the interconnections between them.

The usefulness of Cat models to the insurance industry and wider society could be even further enhanced by integrating the latest climate science and a variety of technologies into the modelling framework. This requires an in-depth understanding of the fundamental assumptions, intended model usage, and model limitations. The incorporation of data from advanced hazard simulations or innovative engineering perspectives on physical damage, just to name two examples, would go a long way in reinforcing the value proposition of Cat models. A collective endeavour across insurers, the scientific community and model vendors is necessary, not only to benefit further from the current modelling framework but also to extend the Cat models' capabilities.

While Cat modelling is not the panacea to catastrophe risk, it is unlikely that extreme Natcat losses recorded in 2017 will be a one-off event. As the effects of climate change become more severe, the insurance industry must keep up with market demand and anticipate future changes through the advancement of risk analytics.

Few sectors of the economy play a role as intense in catastrophe recovery as insurance. Individuals, families, communities and governments rely on the sector's capacity to provide financial relief in the form of claims. What is at stake is not only the stability of the industry but also society's resilience to catastrophe risk.

Key messages

1) *For the past several decades, Cat models* have served the (re)insurance industry well, facilitating strong risk analysis and management culture as well as portfolio management practices of property risks throughout the industry value chain.

2) There is much *more that could be done* to extend the value of *Cat models* for the (re)insurance industry and wider society. This requires a collective endeavour across (re)insurers, brokers, model vendors and other key stakeholders to not only *further benefit from the current Cat model framework, but also extend the Cat models' capabilities*.

3) The usefulness of *Cat models* to the (re)insurance industry and wider society could be even further enhanced with new climate modelling and observational capabilities, as well as other emerging new technologies (e.g. supercomputers, cloud sourcing, deep learning, visualisation, engineering and materials science).

4) There is an opportunity to extend the Cat loss model *value proposition by addressing the Cat modelling reliance on historical data* through *integration of the latest climate science and modelling*. This could support *new climate insurance* products and service offerings as well as leveraging these forward-looking tools for *integration of physical climate risk*, *into core business* both now and for the future based on the recommendations of the Financial Stability Board's Task Force on Climate-related Financial Disclosures (TSB-TFCD).

5) In light of the large investment gap in infrastructure globally, *expansion of Cat risk modelling to the infrastructure project life cycle to assess risks of extreme weather/climate events* could provide a great opportunity to de-risk the projects, enhance climate resilience, offer risk transfer solutions and increase investment opportunities.

6) Development efforts by practitioners should consider connecting *Cat models to other systems-based models* for economics analysis, food, energy and water management, and the provision of critical infrastructure and health services. This will lead to a better *understanding and assessment of the impacts of feedback loops and cascading effects* that can further aggravate disaster impacts, prolonging recovery and increasing costs.

Executive summary

Over the past 30 years, Catastrophe Loss Modelling—arguably the first *InsurTech* offering in the form of innovative tools (Cat models)— has transformed the (re)insurance industry's capacity to assess, price and manage risk for property catastrophe business and has provided a shared common *language of risk* for risk transfer.

Today, Cat models are used across the world, addressing a growing suite of hazards for an increasing number of countries. Funded at hundreds of millions of U.S. dollars by the (re)insurance industry, specialist firms of model *vendors* have assembled an eclectic mix of technical disciplines[1] to supply these multi-disciplinary tools that have helped (re)insurance companies manage the downside risk from extreme events. The value of Cat models has also been recognised across many other sectors and users, leading to various derivatives of these models that are supported by development professionals, the financial sector and national to local governments, for making risk-based decisions (Geneva Association 2016a-c; The Geneva Association and IDF 2017).

The framing of *climate risk* under *physical, liability* and *transition* risk has made it possible to quantify it and incorporate it into core business (Carney 2015; FSB-TCFD 2017).[2] For companies, issues are increasingly around development of standard tools and methodologies, acquiring the expertise for analysing physical and transition risk, and conducting stress testing for different climate scenarios (e.g. 1.5°/2°/3°/4°C) to properly price the risk and appropriately allocate capital to manage it. Since the release of the FSB-TCFD recommendations in 2017, banks, asset managers and institutional investors are increasingly considering assessing risks of extreme weather (physical risk) in their investment portfolios. Indeed, Cat models could play an important role in capturing physical risk of climate change. However, they need to be conditioned on rapidly advancing earth observations and climate change models to better understand the sensitivity of this risk to *climate change* and the associated impacts that may result from changes in distributions of this risk for insurable assets. The resulting analysis can help companies from various sectors (e.g. (re)insurance, banking, asset managers, energy) to understand the extent of their physical risk in relation to their assets, operations, investments and risk management practices.

Recommendations for the way forward

Recommendation 1: ***Further leverage and enhance current Cat modelling methodologies and tools***

To some extent it can be said that *models make markets*. In turn, *markets are also needed to stimulate investment* in the current commercially driven catastrophe model paradigm. There is much more that could be done to extend the value of *Cat models* to the (re)insurance industry. We recommend a call for action to (re)insurers, brokers, model vendors, the development community and the public sector in the following areas:

(i) Drive for interoperability among Cat models;

(ii) All stakeholder groups should scale up ambition for global coverage of natural peril models for every country, across high-, middle- and low-income countries;

(iii) Extend existing models to address current limitations and gaps, particularly: business interruption (BI) and contingent business interruption (CBI) and supply chain modelling, economic demand surge, and loss adjustment expenses;

(iv) Set expectations of transparency and uncertainty quantification in model design and limitation, while remaining sensitive to commercial considerations around investment in intellectual property;

1 Geophysical scientists, various types of engineers, mathematicians, software engineers, actuaries and insurance professionals

2 Classification of climate risk (FSB-TCFD 2017):
- Physical risk: Climate- and weather-related events impact on property, infrastructure, supply chains and trade (e.g. floods, storms) - Increased severity and frequency of extremes or long-term shifts in climatic patterns
- Transition risk: Financial risks from transitioning towards a lower-carbon economy–Policy and legislative, technology and physical risks could prompt asset-value reassessment (stranded assets)
- Liability risk: Those who have suffered loss or damage from climate change seeking compensation from those they hold responsible - Potential to hit carbon extractors and emitters – and, if they have liability cover, their insurers – the hardest

(v) Improve risk communication of model outputs and related model uncertainty among users;

(vi) Agree on and develop a uniform international exposure data standard to enable transparency, comparability and acceptance of results and allow for efficient use of Cat models.

Recommendation 2: ***Embed latest climate science in Cat models and explore opportunities for improving modelling of physical climate risk with a forward-looking approach, taking into consideration the climate change scenarios.***

While a highly complex issue, integration of latest climate science, earth climate system simulations (synthetic data) and nested models within the Global Climate Models (GCMs) into Cat models could potentially be a game changer to develop Cat modelling towards a forward-looking approach.

Building on the international scientific cooperation in climate science and modelling, this offers the opportunity to extend the Cat loss model value proposition to also support new climate insurance product offerings, both now and for the future. Furthermore, such enhanced models linked to GCMs could be critical for integrating physical climate risk into core business, financial systems and investment applications (linking to FSB-TCFD recommendations). Integration of such climate change calibrated Cat risk models could potentially enable (re)insurers, other segments of the financial sectors, businesses, public sectors and other stakeholders to manage the physical risk of climate change now and for the future.

Cat models need conditioning to understand climate change sensitivity and the associated impacts that may result from changes in risk distribution for insurable assets. Perils that would clearly benefit from such enhancement include: wildfire, large-scale hail, agricultural crop yields, drought, coastal surge flooding (via sea level rise), and extreme precipitation like cloudburst and even snowmageddon type events. With advancements in the understanding of climatic regimes and interconnectivities in the weather patterns the inclusion of the correlations between 'independent' peril regions within existing Cat models may be considered.

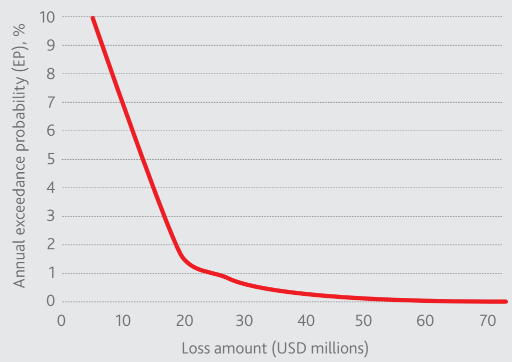
Recommendation 3: ***Consider 'models of models' and embrace a systems-based thinking for development of the next generations of Cat risk models***

The usefulness of Cat models to the (re)insurance industry and wider society could be even further advanced if connections are made to models in other domains and fields of study. The overarching benefit of coupling models would be to better understand feedback loops and cascading effects within and across sectors (e.g. water-energy-food nexus). Cat models, extended to reflect climate-conditioned future scenarios, could provide new insights and support policy, planning and decision-making.

Cat models have transformed (re)insurance industry's capacity to assess, price and manage risk for property catastrophe business

Hazard module	Exposure module	Vulnerability module	Financial module
Assesses the level of physical hazard across a region considering factors such as the topography, soil type, land use and built-in environment	Estimates of the location and event response characteristics of exposure.	Estimates the physical damage on the asset at risk, expressed in terms of a certain percentage loss of value to the exposure.	Monetises losses of the physical damages; estimates of insured losses are computed using insurance policy terms and contract structures.

Summary example results of an EP analysis



Expansion of Cat models by peril and geography has been 'demand-led'

Perils

- Hurricane
- Earthquake
- Extratropical cyclone
- Severe thunderstorm
- Coastal flooding
- Inland flood
- Agriculture and wildfire
- Severe hailstorm
- Man-made perils
- Liquefaction
- Tsunami
- Landslide
- Rainfall-induced flooding

Regions

- U.S.
- Europe
- Japan
- Canada
- Australia
- New Zealand
- South America
- The Caribbean
- Southeast Asia
- China
- India

Beyond (re)insurance, Cat models are used in a variety of applications with potential for further expansion to other sectors

- (Re)insurers in property/Cat business, development planning
- Public-sector disaster risk management
- Agricultural insurance
- Development planning
- Financial and capital markets
- Managing natural infrastructure

Seven key factors drive the Cat models

- Methodologies
- Data requirements, hazard, exposure and vulnerability
- Standards and interoperability
- Regulatory issues
- Open framework and open source versus restricted
- Model validation and uncertainty estimation
- Resource requirements

Source: The Geneva Association

Our recommendations

1 *Further leverage and enhance current Cat modelling methodologies and tools*

2 *Embed latest climate science in Cat models and explore opportunities for improving modelling of physical climate risk with a forward-looking approach taking into consideration climate change scenarios*

3 *Consider 'models of models' and embrace a systems-based thinking for development of the next generations of Cat models*

1. Context

Over the last three and a half decades, we have observed a trend of rising economic losses from extreme events globally. Between 1980 and 2017, Munich Re's NatCatSERVICE reported 17,320 disaster loss events. Of those, 91.2 per cent were caused by weather-related extremes (meteorological, hydrological and climatological events), accounting for 49.2 per cent of the total of 1,723,738 lives lost, 79.8 per cent of the total USD 4,615 billion in reported economic losses and 90.1 per cent of total insured losses of USD 1,269 bn.[3]

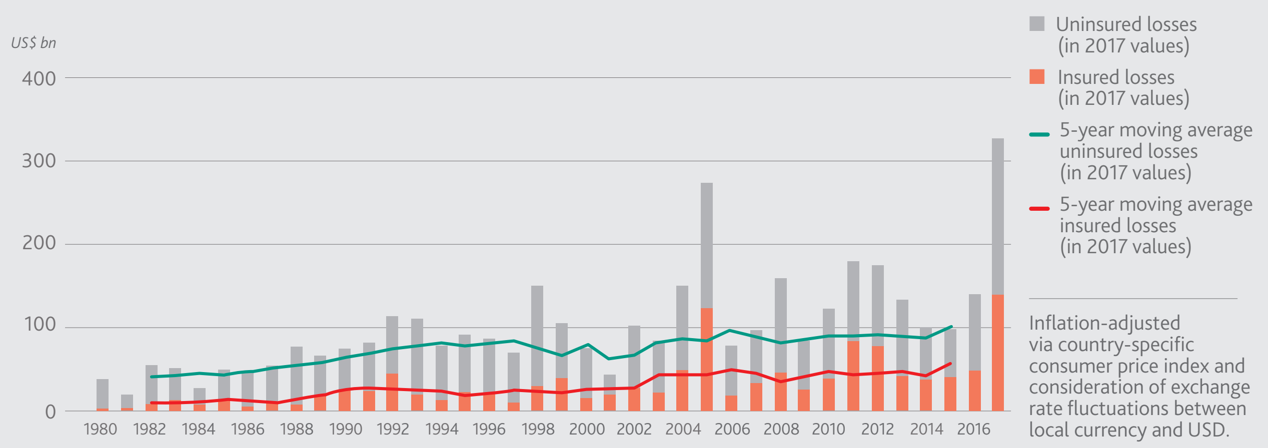
In 2017, weather-related extremes accounted for 97 per cent of total reported economic losses and 98.2 percent of total insured losses (Figure 1).[4] A significant portion of economic losses, particularly in the middle- and high-income countries, were caused by damages to infrastructure.

Climate variability and change, along with socio-economic factors such as population growth, construction practices, rising urbanisation and complex interconnected supply chains and trade patterns globally, further drive and exacerbate these impacts.

These point to the growing demand for risk information, risk modelling and stress testing tools, expertise and data for managing the impacts of weather-related extremes in both public and private sectors.[5] The adoption of the Sendai Framework for Disaster Risk Reduction (2015–2030), the 2030 Sustainable Development Summit and the COP21 Climate Change Paris Agreement have promoted the need for a comprehensive and integrated approach to managing risks and building socio-economic resilience to extreme events and climate change, involving different economic sectors and levels of government. As a result, a complex landscape of stakeholders has emerged to promote and support the governments with the development of risk-based proactive policies, regulatory measures and development strategies in the public sector (The Geneva Association 2016a-b, 2017, 2018).

However, the game changer for the financial markets and all publicly traded companies was the framing of economic impacts of climate change under physical risk, liability risk and transition risk (Carney 2015).[6]

Figure 1: Global weather-related loss events (1980–2017)



Source: Munich Re NatCatSERVICE

3 Both are inflation-adjusted.
4 Total economic losses associated with weather-related extremes reached USD 330 billion, with both reported insured and uninsured losses at a record high.
5 In fact, Sendai Framework's first priority for action is 'Understanding Disaster Risk'. Similarly, the Paris Agreement stresses the importance of risk-informed adaptation planning.
6 Mark Carney, Governor of the Bank of England and Chairman of the G20's Financial Stability Board, delivered his historical speech, 'Breaking the tragedy of the horizon—climate change and financial stability' at Lloyd's of London on 29 September 2015.

Subsequently, the industry-led FSB-TCFD has offered recommendations for publicly-traded companies for disclosing comparable and consistent information about the risks and opportunities presented by climate change. Pricing physical risk of climate change is an emerging category of risk for all sectors to support informed, efficient capital allocation decisions.

The global insurance industry has been leading the way in innovating and advancing Cat modelling since the late 1980s, prompted by unprecedented insurance losses and company insolvencies in the 1980s and 1990s, owing to major catastrophes in the U.S. and Europe. Over the last few years, the (re)insurance industry has been working closely with the international community to transfer these technologies for the public sector to areas such as disaster risk management, development planning and sovereign risk transfer in the middle-and low-income countries (The Geneva Association 2017). A few initiatives are underway to explore the value proposition of the insurers' expertise and Cat modelling tools for assessing physical risk exposure in other parts of the financial system (ClimateWise 2018).

In this report, we examine Cat modelling as a critical tool to help improve and even reshape the future of disaster and climate risk management. To this end, The Geneva Association has brought together leading international experts from the commercial Cat risk modelling firms, the (re)insurance industry, the scientific community (specifically, operational weather and climate modelling) and academia to explore this issue and offer collective insights for future consideration. This report has also been informed by the 2017 Geneva Association Forum on Extreme Events and Climate Risks on 'How Will Risk Modelling Shape the Future of Risk Transfer?' co-organised with the SCOR Foundation and hosted by SCOR SE in Paris.

Section 2 describes the evolution of Cat modelling since the 1980s. In Section 3 we highlight challenges of developing and utilising Cat models. Section 4 outlines a number of potential areas where expansion of Cat models could help with improving decision-making and risk management practices. In Section 5 we highlight some technological developments that could be leveraged for improving Cat modelling. Our recommendations for the way forward are provided in Section 6.

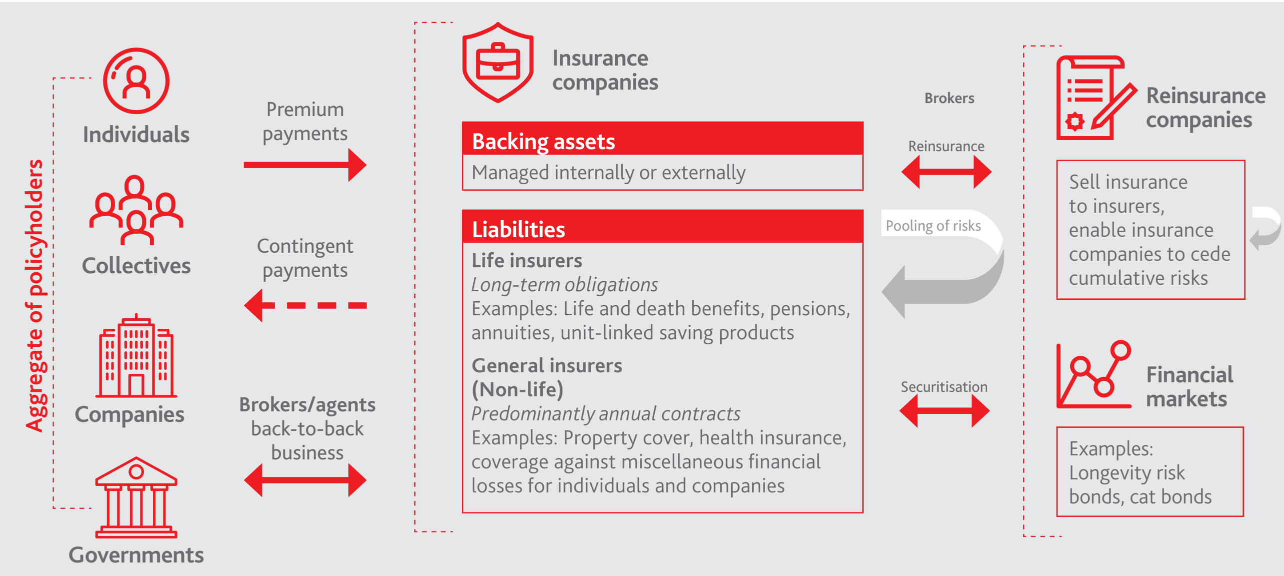
2. Evolution of Cat risk modelling since the 1980s

Commercial catastrophe risk modelling tools emerged as the first InsurTech offering to transform the assessing, pricing and managing of the property catastrophe business. This followed a series of insolvencies, linked to a number of major catastrophes in the U.S. and Europe in the 1980s. Over the past three and a half decades, Cat models have revolutionised approaches to pricing, underwriting and managing property and catastrophe portfolios across the insurance industry value chain.

The origins of catastrophe risk modelling are rooted in the fields of property insurance, structural engineering and scientific research of 'natural hazards' (Friedman 1975). Cat models have become ubiquitous tools for managing large and unpredictable losses associated with natural catastrophe risks across the insurance industry value chain (Figure 2). They are used to inform risk pricing and underwriting decisions, claims settlement processes, portfolio management, calculating solvency, and other regulatory, rating agency and economic capital requirements. Over the years, the (re)insurance industry's reliance on Cat models has increased to the point that in some jurisdictions the regulators require the Cat models to be officially certified for use in markets.

Widespread adoption of Cat models combined with an on-going feedback loop between users ((re)insurers) and providers (Cat model vendors) have contributed to model improvements and increasing expertise among the insurance industry users. Data and insights from past high-impact natural catastrophes have helped to develop the Hazard and Vulnerability modules (Boxes 1 and 2) and incorporate additional loss sources in subsequent model releases.[7] Real-world events have also revealed the limitations of Cat models as well as the importance of understanding the underlying assumptions and inherent uncertainty in model outputs. Cat model developers have in turn responded by educating the users about the sources of model uncertainty and the importance of sensitivity testing of model assumptions.

Figure 2: The insurance industry value chain



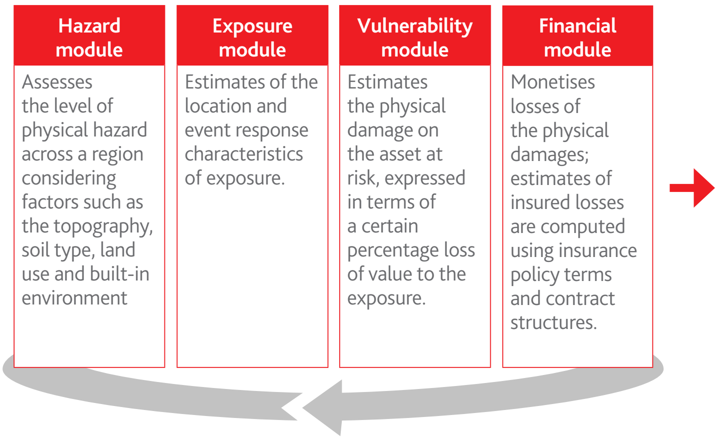
Source: The Geneva Association (2018)

7 Key high-impact catastrophes such as hurricane Andrew (1992), Northridge earthquake (1994), storms Lothar, Martin, and Anatol (1999), hurricane Katrina (2005), Tohoku earthquake (2011), Christchurch earthquake (2011), Bangkok floods (2011), and hurricane Sandy (2012) provided substantial data that was instrumental in improving the Cat models.

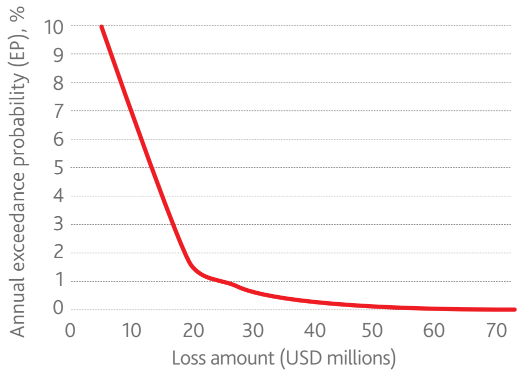
Box 1: Components of a Cat model designed for (re)insurance applications

Cat models are built on four key components:

- **Hazard module:** Assesses the level of physical hazard across a region, integrating factors such as the topography, soil type, land use and interaction with the built environment. *The stochastic event generation sub-module* creates a catalogue of hypothetical events by simulating thousands of event footprints for each specified region-peril combination, typically parameterised on historical hazard data.
- **Exposure module:** The proximity of properties or infrastructure to the hazard is what generates risk. Estimates the location and event response characteristics of exposure.
- **Vulnerability module:** Estimates the physical damage to the asset at risk (e.g. various types of structures and their contents).
- **Financial module:** Monetises losses associated with the physical damage and estimates financial losses.



Summary example results of an EP analysis



Stochastic event generation defines the hazard phenomena by simulating thousands of catastrophic events in time and space, based on historical hazard data.

Source: The Geneva Association

Box 2: First steps towards designing a Cat model

Design of a Cat model requires consideration of a variety of issues:

1) What questions would be addressed based on the risk model?
2) What perils are to be covered?
3) Who are the stakeholders (developers, users, data providers, etc.)?
4) Who will develop the risk model? What expertise is needed for the development of the model? What are the sources of data?
5) Who are the users of the risk model? What are their capacities with respect to running the models, interpreting the outcomes and utilising the information in their decision-making processes?

These issues can take time to resolve, especially within a resource-constrained environment. Interpretation of the results—especially for those without a deep understanding of probability and uncertainty—can be equally fraught.

Source: The Geneva Association and Insurance Development Forum (2017)

The expansion of Cat models for the (re)insurance industry has been 'demand-led'.

Since the 1980s, many Cat modelling providers have emerged, offering a variety of different Cat models, solutions, approaches and services. Figure 3 summarises major milestones in the expansion of Cat models by year. Figure 4 summarises overall developments in Cat models by peril, geography, application, and provider.

While the rising demand of the (re)insurance industry has been the primary driver, a number of other factors have also contributed, including (i) scientific progress on understanding of natural hazards and their characteristics (meteorological, hydrological, climatological and geological); (ii) engineering research and testing related to impacts of hazards on the built environment; (iii) progress with geographic information systems; and (iv) various government-based initiatives and an increasing number of industry-academic partnerships that have led to the availability of vast amounts of data and knowledge aligned with the needs of Cat model developers.

2.1 By peril and geography

The growing demand for insurance and reinsurance solutions in high-income countries with mature insurance markets has been the primary driver for steady expansion of Cat model coverage by peril and geography.

Focused initially on hurricane and earthquake modelling for the U.S., modelling of these perils has expanded to other countries with active and mature insurance markets as well as for a number of other natural perils, including extra-tropical cyclones, severe convective thunderstorms, e.g. tornado, hail, straight-line wind and coastal flooding. By the mid-2000s, Cat model vendors launched more complex perils, such as inland flood, agriculture and wildfires.

Figure 3: Evolution of Cat models since the 1980s

Catastrophe models have become an invaluable tool in managing large and unpredictable losses across the insurance industry—and beyond—since their introduction in the late 1980s to the point that today catastrophe model output has become a currency for understanding and quantifying risk in insurance and reinsurance transactions.

Source: The Geneva Association

1980	1990	2000	2010
Focused initially on hurricane and earthquake modelling for the U.S.	Within mature and well-developed markets, Cat model coverage expanded for a number of other natural perils, including, extratropical cyclones (winter storms); severe (convective) thunderstorms including tornado, hail, straight-line wind, and coastal flooding (storm surge).	Cat modelling of more complex perils such as inland flood, agriculture and wildfire risks was launched. Increasingly, latest observations are being used to expand the coverage of Cat models to more localised perils, such as a globally consistent severe hailstorm risk quantification model to price severe hail risk anywhere for (re)insurance purposes. Model coverage remained exclusively focused on natural perils until the terrorist attacks of 11 September 2001, after which man-made perils were added.	The last decade has also witnessed an increased focus on higher resolution modelling of sub-perils, such as liquefaction, tsunami, landslide for earthquakes, and rainfall-induced flooding for tropical cyclones.
Focused on the U.S., Europe, and Japan, which also had the largest amount of data and number of events to develop and update the models.	The next decade of development covered regions such as Canada, Australia, and New Zealand.	Other Cat-prone regions, including South America, the Caribbean and Southeast Asia, were covered. Geographic expansion into emerging markets, such as China and India.	Currently, the U.S., Canada, Japan, Europe, Australia have the most perils modelled; however, despite recent progress there are still gaps with respect to flood modelling.
The main application of Cat models was for portfolio management and pricing of Cat excess-of-loss reinsurance treaties.	In the mid-1990s the concept of Cat bonds (alternative risk transfer) emerged.	A number of initiatives got underway to use Cat modelling methodologies, combined with innovation in meteorological observations (e.g. use of radar data) to expand Cat models for agricultural insurance applications. Insurers also use real-time analytics from their Cat model providers, which can inform early estimates of the losses a company may experience and provide insights on where and how to deploy claims adjustment teams.	Insurers also use Cat models to supplement actuarial models for insurance pricing, portfolio optimisation, capital setting and solvency modelling, etc.
		2005: Hyogo Framework for Action (HFA) (2005-2015) **2010:** Cancun Adaptation Framework	**2015:** Sustainable Development Goals (SDGs) (2015-2030) **2015:** Paris Agreement **2015:** Sendai Framework For Disaster Risk Reduction (DRR) (2015-2030)

The last decade has also witnessed increased focus on higher resolution modelling of sub-perils, such as liquefaction, tsunami and landslide for earthquakes, rainfall-induced flooding for tropical-cyclones and major innovations in global elevation models.

Model coverage by peril and by region remained exclusively focused on natural perils until the terrorist attacks of 11 September 2001, after which man-made perils were added. With improvements in data and modelling techniques and growing recognition of their value as risk management tools, modellers and the (re)insurance industry are looking to other potential sources of catastrophic risk, such as pandemics and cyber-attacks.[8] Currently, more chronic or slow onset conditions such as solar storms, droughts and land degradation remain unmodelled.

2.2 By application

Cat models have also been used for quantifying risks for financial instruments that transfer risk directly to the capital market, such as Cat bonds and other insurance linked securities.

Since the mid-1990s the concept of Cat bonds (alternative risk transfer) emerged to address the prevailing capital shortages. The advent and acceptance of Cat models played a key role in the development of this market.

Today, some hedge funds specialising in trading these instruments also use Cat models. Cat models are also being considered by other stakeholders in the financial sector, who are increasingly hiring Cat modelling experts (e.g. central banks and rating agencies).[9,10]

Beyond their traditional use by (re)insurers in property/catastrophe business, Cat models are increasingly being applied to agricultural insurance, financial and capital markets, development planning and public sector disaster risk management applications.

By 2000, Cat models for agricultural insurance applications were developed, leveraging property-based Cat modelling methodologies with innovation in meteorological observations such as the use of radar data. The modelling of weather impacts on crop yields is advancing rapidly. Today, several probabilistic Cat models exist for the agriculture insurance sector. However, a number of issues have yet to be captured, for example, the seasonal variations of weather patterns, such as more frequent extreme variation particularly in the spring and fall, leading to earlier planting and later harvests. This has significant effects on agricultural production, trade and financial markets, potentially increasing the likelihood of multiple serious disruptions within a single annual cycle (Lloyd's 2013b, 2015). Furthermore, interactions that involve multiple major events, such as yield reduction of more than one major commodity crop within an annual cycle in relation to agricultural stocks, or the impact of long-term disruptions linked to damaged infrastructure (e.g. roads and bridges, water and electricity) from major earthquakes are not yet considered.

Cat models underpin the development of risk pools to protect government budgets, communities and individuals in a post-disaster situation.

Prominent examples of regional pools include the Caribbean Catastrophe Risk Insurance Facility (CCRIF), the Pacific Disaster Risk Financing and Insurance Program, which was built upon the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI), and the African Risk Capacity (ARC). Other national risk

8 Regarding pandemics, various pathogens have been modelled, and vendors are in the process of modelling cyberattacks both deterministically and probabilistically.

9 Cat bonds enable the transfer of catastrophe risk from traditional insurance/reinsurance markets to the capital markets. The Cat bond market has grown steadily since the launch of what many consider to be the first successful Cat bond, George Town Re in 1996. These securities are known for providing full collateralisation and multi-year coverage and are increasingly becoming a standard part of risk transfer strategies employed by insurers, reinsurers, corporate entities and public agencies as a primary or supplemental vehicle for insurance, reinsurance, or retrocession cover. The key function of Cat models is to provide an unbiased, transparent and objective way of estimating risk for all parties involved in the transaction.

10 For example, open source Cat models have been used to quantify the potential natural catastrophe impacts on country and company credit risk ratings (Standard & Poor's Ratings Direct, 2015a-b); recently, the central Bank of England hired leading experts to analyse impacts of extreme events on financial stability.

transfer programmes have also emerged (The Geneva Association 2017; The Geneva Association and Insurance Development Forum 2017).

Cat models are increasingly being used for assessing the role of nature-based (green) infrastructure in reducing disaster risk and conducting cost-benefit analysis.

Traditionally, the focus of Cat model vendors was to assess the risks associated with grey (built) infrastructure. More recently there has been considerable interest in their use to assess and understand the influence of natural infrastructure (such as reefs, marshes and wetlands) in risk reduction (Box 3).

Box 3: Cat models are used to demonstrate the financial benefits of investing in natural infrastructure

A recent study supported by the Lloyd's Tercentenary Research Foundation examined the role of wetlands in property damage in the northeast U.S. (Narayan et al. 2016). They estimated that during hurricane Sandy, temperate coastal wetlands saved more than USD 625 million in flood damages and hundreds of millions of U.S. dollars in New Jersey alone. Many wetlands have been lost in the northeast U.S., but where they remain, wetlands reduced damages by more than 10 per cent on average (Ferrario et al. 2014; Beck and Lange 2016).[12]

Another example is an online decision support system that evaluates the cost effectiveness of both nature-based (green) and built (grey) solutions to reduce coastal hazards risk and avert damages across the Gulf of Mexico (Beck et al. 2018; Reguero et al. 2014).

Cat models are also increasingly being used in disaster risk management and climate adaptation studies.

Cat models are increasing being used for development planning, informing policy and investing in risk reduction measures (e.g. land zoning), cost-benefit analysis of various preventive measures (e.g. retrofitting critical facilities and public assets, flood protections, investments in natural infrastructure) and emergency planning and response operations (Wieneke and Bresch 2016; Souvignet et al. 2016).[12]

2.3 By provider

A variety of stakeholders are engaged in Cat model development, including three prominent Cat modelling commercial vendors, large insurance and reinsurance companies, reinsurance brokers and, increasingly, small specialised enterprises.

The three Cat modelling companies, formed in the 1980s (AIR Worldwide, RMS and CoreLogic) remain the largest commercial providers of Cat modelling solutions, offering the most comprehensive coverage in terms of perils and geographies. Over time, these companies have expanded modelling capabilities across many insurance business lines such as property, casualty, workers' compensation, crop and agriculture, life and health, marine, onshore and offshore energy and cyber.

In addition to commercial models, large insurance and reinsurance companies have built their own models to develop more customised views of risk. Reinsurance brokers such as Aon Benfield, Guy Carpenter and Willis Towers Watson also develop models to facilitate risk transfer transactions, especially for regions that are not covered by Cat modelling firms, or to incorporate specifics of individual primary insurance companies that may be different from the industry average.

During the past ten years, smaller enterprises have emerged, specialising by either geography or peril, and increasingly leading the way in providing innovations in risk modelling in their speciality areas. Most prominent emerging companies include JBA, which now offers flood models globally and an increasing number of windstorm and cyclone models, and KatRisk with a similar breadth and focus on atmospheric perils.

11 In Ocean County, New Jersey, conserving wetlands reduces annual expected losses by 20 per cent on average and over 50 per cent for properties built just feet above sea level.

12 The use cases for an emergency manager are not the same, but the underlying analytics can help mitigate a crisis, especially in the case of mega-events, both before and after they occur.

Emergence of multi-lateral Cat modelling partnerships and platforms are providing new opportunities for coordinated engagement of scientists and risk modellers from the insurance industry, governments, academia and non-governmental organisations around the world.

The (re)insurance industry has expressed a high demand for open platforms to allow integration of internally developed custom models and to support plug and play of different vendor models on one platform.[13] Functionality to flexibly adjust models to reflect different views of risk would allow users to integrate their own expertise and support the knowledge exchange between model users, model developers and the scientific community. On the other hand, significant efforts are being made by the international organisations to expand and avail Cat risk modelling capacities to empower governments with evidence-based decision-making. Table 1 highlights some of the key developments.

Table 1: Examples of multi-lateral partnerships and platforms in Cat modelling

(Re)insurance industry-led multi-lateral Cat modelling partnerships and platforms

OASIS Loss Modelling Framework – The non-profit open-source loss modelling platform funded by the (re)insurance industry was launched in 2012 to address these challenges for the (re)insurance industry. OASIS aims to increase access to a larger pool of risk models and data from commercial and other private sector enterprises. OASIS is the first independent platform through which the users can access models from multiple providers using a consistent set of standards. The model outputs are available in a similarly consistent format. The plug and play engine of OASIS enables the Cat model developers to focus on hazard and/or vulnerability modelling without having to re-invent a financial modelling engine. The proliferation of open source risk modelling tools is increasingly providing ready-made software delivery options. This platform has facilitated access to new models being developed by a number of emerging smaller enterprises (www.oasislmf.org).

CLIMADA – This open source and open-access global probabilistic risk modelling platform has been used since 2010 in more than twenty case studies across the globe, ranging from Barisal, Bangladesh to San Salvador (Wieneke and Bresch 2016) and for integrative risk management involving various stakeholders (Souvignet et al. 2016) (https://github.com/davidnbresch/climada).

Global multi-lateral risk modelling partnerships – The Global Earthquake Model (GEM) and Global Volcano Model (GVM) are among the most prominent initiatives, bringing the insurance industry together with leading scientists around the world to establish local communities of practice that could assist governments and other stakeholders with the development of risk models for decision-making. GEM will start distributing their global earthquake models as Cat models to the (re)insurance sector via the OASIS and AIR platforms later in 2018.

Risk modelling initiatives of international organisations inspired by or leveraging (re)insurers' Cat modelling

Centre for Global Disaster Protection & InsuResilience Program Alliance – The *Program Alliance* brings together the DfID funded *Centre for Global Disaster Protection* and the KfW-World Bank supported *InsuResilience* initiative to support capacity building and new risk transfer facilities for the poorest and most vulnerable societies in the world. Together they support a Technical Assistance Facility providing research, data and knowledge transfer to help developing country governments manage disaster and climate risks. In addition, challenge funds are made available to stimulate innovation in InsurTech and big data solutions as well as commissioning new Cat models to support risk transfer in underinsured countries (https://www.insuresilience.org/).

World Bank's Global facility for Disaster Risk Reduction and Recovery (GFDRR) and its Innovation and Risk Lab – Building on cutting-edge science and technology, GFDRR has aimed to provide high-quality risk information that is available faster and at lower costs to development practitioners and governments (World Bank Group 2014a). Focus is on developing new tools that allow decision makers and communities to collect, share and understand risk information, remaining responsive to their questions and needs, and to support development of the full range of disaster risk management interventions—from preparedness to risk reduction and disaster risk financing and risk transfer solutions. GFDRR supported the development of programmes such as Central American Probabilistic Risk Assessment (CAPRA). In 2010, GFDRR also established the Understanding Risk Forum to bring together a global community of practice to share expertise, tools and experiences.
For more information see:

- www.gfdrr.org/innovation-lab
- http://thinkhazard.org
- https://understandrisk.org
- http://www.ecapra.org

13 Applied Insurance Research (AIR) started to support plug and play of models in their reinsurance platform CATRADER in 2013 and will allow the efficient integration of models (from other vendors or developed by scientists or by clients/users) in their new platforms Touchstone and Touchstone Re from 2018 onwards.

For more information see:

- www.globalquakemodel.org
- http://gfp.jrc.ec.europa.eu/
- http://globalvolcanomodel.org/
- globaltsunamimodel.org

The Insurance Development Forum (IDF) Risk Modelling and Mapping Group (RMMG) Initiatives – IDF is a joint effort engaging the insurance industry, World Bank Group, and the United Nations. The goal is to avail Cat modelling and risk transfer expertise to the most vulnerable and lowest-income countries, initially focusing on the Vulnerable Twenty Group (V20). The IDF RMMG was established, bringing together experts and practitioners from the insurance industry, the risk modelling and scientific communities to improve global quantification and understanding of disaster risk. IDF and its RMMG is supporting critical initiatives such as InsuResilience.

ClimateWise Physical Risk Project – A new project commissioned by the ClimateWise Council, the *Physical Risk Project* is bringing together researchers from a number of institutes to explore how Cat risk modelling and other risk analytics tools can be applied to financial systems applications. Researchers involved in this project have secured access to almost GBP 750 billion of real estate and lending data for this analysis (http://www.climatewise.org.uk).

The United Nations Global Risk Model Group – The UN Strategy for Disaster Risk Reduction (UNISDR) established this group to enhance the world's understanding of disaster risks and innovating risk communication for the public. This group coordinated the development of the Global Assessment Reports of the United Nations Strategy on Disaster Risk Reduction (GAR). Building on the concepts of insurance-driven Cat risk modelling methodologies, the UNISDR has facilitated a global consortium of scientific and technical organisations to develop the Global Risk Model (GRM). This will be further extended through the development of the Global Risk Assessment Framework (GRAF), which is currently being designed. GRAF aims to support decision makers with actionable insights by increasing the multi-science foundation of risk assessments in an inclusive, open collaborative environment, building on existing processes and data to the greatest possible extent, also advocating system-based thinking (www.risknexusinitiative.org).

Source: The Geneva Association

Figure 4: Evolution of Cat models by peril, geography, application and provider since 1980s

By region and peril: The growing demand for insurance and reinsurance solutions in high-income countries with mature insurance markets has been the primary driver for steady expansion of Cat model coverage by peril and geography.

Perils

- Hurricane
- Earthquake
- Extratropical cyclone
- Severe thunderstorm
- Coastal flooding
- Inland flood
- Agriculture and wildfire
- Severe hailstorm
- Man-made perils
- Liquefaction
- Tsunami
- Landslide
- Rainfall-induced flooding

Regions

- U.S.
- Europe
- Japan
- Canada
- Australia
- New Zealand
- South America
- The Caribbean
- Southeast Asia
- China
- India

By application: Beyond (re)insurance, Cat models are used in a variety of applications with potential for further expansion to other sectors.

- (Re)insurers in property/ Cat business, development planning
- Public-sector disaster risk management
- Agricultural insurance
- Development planning
- Financial and capital markets
- Managing natural infrastructure

By provider: A variety of stakeholders are engaged in Cat model development, including three prominent Cat modelling commercial vendors, large insurance and reinsurance companies, reinsurance brokers and increasingly small specialised enterprises.

By multi-lateral Cat modelling partnerships and platforms: Emergence of industry-led and other international partnerships and platforms is providing new opportunities for coordinated engagement of scientists, risk modellers from the insurance industry, governments, academia and non-governmental organisations around the world. These include:

- (Re)insurance industry-led multi-lateral partnerships and platforms.
- Risk modelling initiatives of international organisations inspired by or leveraging Cat modelling.

Source: The Geneva Association

3. Considerations for development and utilisation of Cat models

Effective development and utilisation of Cat models requires an in-depth understanding of the underpinning assumptions, intended usage and model limitations.

Key considerations for the development and utilisation of Cat models include: (i) methodology and underpinning assumptions; (ii) data-related issues; (iii) standards and interoperability; (iv) open source versus restricted approaches; (v) model verification and uncertainty estimation; (vi) resource requirements; and (vii) regulatory aspects (Figure 5).

3.1 Methodologies

Traditionally, the stochastic event generation and hazard modules have relied on statistical techniques using empirical (observed) historical data of physical events.[14] Increasingly, Cat model vendors are using weather and climate modelling to represent phenomenon like rainfall or extra-tropical cyclones, and to improve on the parametric approaches.

The topic of non-stationarity in the peril is a key challenge for risk assessment. Specifically, this refers to changes in the characteristics of hazards (e.g. frequency, severity and location) caused by natural climate variability or climate change within the time horizons of concern to the insurance industry.

Over the past decades, advancements in publicly funded research, global earth observing systems, computational capacities, data management systems, simulation and numerical technique capacities have led to modelling of meteorological, hydrological and climatic perils on different timescales. This is achieved by running physical climate models—developed from physical principles that mathematically replicate the complexities of the earth's climate system (i.e., land, ocean, atmosphere and their interactions) under varying climatic conditions. Increasingly, radar data, fine-resolution satellite images and analysis of Numerical Weather Prediction models (NWP) have become available quickly after events to outline event footprints. NWP and climate models are increasingly being used for the development of track models and event hazard footprints.

Understanding natural climate variability and related physical drivers that determine why some events are clustered in space and time is still at the forefront of scientific research, yet Cat model vendors must account for resulting shifts in the volatility of spatial and temporal characteristics in their simulations today.[15] Cat model vendors have taken some steps to produce different versions of their models calibrated to different periods of history to reflect natural climate variabilities, such as the multi-decadal oscillation in hurricane frequency or a probabilistic forecast of future hurricane activity over the next five years. However, the reliability of these approaches for (re)insurance placement and risk transfer is hotly debated within the industry, given the large uncertainties associated with the climate change scenarios, limited data and enhanced scientific understanding.[16]

Vulnerability curves are based on statistically derived relationships between hazard and damage ratios using historical loss data or engineering-based approaches.[17] A hybrid approach may be used consisting of curves created using a component engineering-based approach calibrated to empirical historical observations, such as claims data.[18]

14 Statistical methods are used to extrapolate beyond observations which are typically limited to observations of recent history, and bind the maximum severities to within observed physical limits.

15 One example was the conveyor of damaging European winter storms in December 1999: winter storm Anatole hit Denmark, followed by Lothar and Martin in Paris and central France within a three-day window. Another example, retrospectively, pertains to two extremely active seasons of U.S. Atlantic hurricane activity (2004, 2005) that gave impetus to developing views of risk that account for anomalously high sea surface temperatures since 1995.

16 Evaluation of climate forecasts (at seasonal and annual timeframes) for underwriting and capital management also remains in the research and development phase.

17 An engineering-based approach starts from first principles of building design and response to different hazards, taking into account the different vulnerability of each of the multiple components of a building.

18 The financial module uses a variety of approaches ranging from early computer-efficient methods such as applying the Beta-distribution to more recent full mathematical simulation models, which provide more accuracy for complex types of (re)insurance policies.

3.2 Data requirements

In general, limited availability of historical data for development and calibration of Cat models remains a key challenge. Quality of hazard and exposure data that are fed into the models determine the quality of model output, the uncertainty of model results and the reliability of results to a very high degree.

Hazard data

Despite the availability of a massive amount of records, a number of issues for various perils pose challenges, including length of records and event catalogues, location of observations and quality of the estimates.

Since the 1980s, Cat model vendors and the weather-climate scientific community have worked in concert to compile as complete historical weather-event records as possible from multiple sources. The data is usually a mix of hard-copy and digitized forms from public and private enterprises as well as scientific and academic institutions. Availability, quality and accessibility of observed hazard data and event catalogues (defining location and magnitude of events) are typically limited to relatively recent history (40–50 years) and highly varied around the world.[19]

Location of the observing stations could lead to more uncertainties in Cat modelling.

Short distances can make a large difference in modelling exposures. For example, severity of flooding and wind speeds from hurricanes significantly changes as they make landfall and immediately start to decay.

The choice for the location of weather stations has been primarily driven by the scientific research and public (and/or sectoral) safety (e.g. airport and airline safety, preparation of alerts and early warnings). Therefore, records of meteorological hazards, such as wind speed, are away from the built environment, which is what is actually required for Cat models for (re)insurance applications.

Advancements in observational methods, calibration, quality assurance, and data archiving techniques continue to improve the quality of estimates of severity and location of events. In addition, historical hand-recorded data and paleo-seismology studies are also providing more information on extreme events' frequency and severity further back in time.[20] Finally, investment in observational networks—e.g. installation of anemometers on buildings and critical infrastructures—could further improve the risk models in the future. Managing and interpreting this data requires significant expertise, which has been acquired in the Cat modelling teams.

Investing in digitized national hazard data platforms that are regularly updated, has multiple benefits, including Cat model development.

National government agencies, academic and other research centres collect and manage various databases using a wide range of observing platforms (land, air, ocean, space) and networks. Collection, quality assurance, cleaning and calibration of data could be difficult and resource-intensive but critical for modelling risks to enhance societal resilience to natural hazards.

Availability of and accessibility to hazard observations and reanalysis data have enabled the expansion of Cat models to new perils (e.g. the first global hailstorm Cat model).[21] Efforts to improve and expand climate reanalysis data could further improve the understanding of extreme event occurrences in the past.

In many middle- and low-income countries, much of historical hazard recording remains paper-based and has not yet been digitized; thus, it is at risk of being lost due to degradation, lack of adequate storage, disasters, conflicts and war.

19 By peril, earthquake catalogues are often longer than meteorological catalogues.

20 One of the challenges for a model developer is to ensure the models are not over-calibrated to the limited available data to avoid extrapolation to unrealistic extreme events.

21 A reanalysis is a climate data assimilation project that aims to assimilate historical meteorological observational data spanning an extended period, using a single consistent assimilation (or 'analysis') scheme throughout. Through a variety of methods, observations from various instruments are added together onto a regularly spaced grid of data. Placing all instrument observations onto a regularly spaced grid makes comparing the actual observations with other gridded data sets easier (Source: National Oceanic and Atmospheric Administration and the European Centre for Medium-Range Weather Forecasting).

Finally, data policies for publicly funded hazard data remain highly varied from country to country, ranging from open data to partially or fully restricted and with minimum cost (fee-for-extraction service) to fully commercial fee structures.

Exposure and vulnerability data

The development of a unified international exposure data standard would significantly reduce the burden of applying Cat models to different risk assessments, increase transparency and reduce uncertainties of results and increase acceptance for all existing and new stakeholders.

In general, (re)insurance companies use their own exposure data for utilisation and verification of Cat models. Reinsurance markets bearing the major portion of material catastrophe losses are heavily dependent on exposure data provided by their clients (primary insurers, governments, multinationals.) Different model vendors have established their own proprietary exposure data formats in the markets. Exposure data are therefore provided in multiple formats and granularities. The burden on exposure data handling, interpretation and augmentation requires specialist expertise and limits the qualified usage of models to experts.

In instances where the available data is not at the right level, and/or is insufficient or low quality, most models use default methods either to disaggregate location-level information or use default occupancy for building data for the analysis.[22]

The completeness and accuracy of exposure data significantly impact model results and their reliability.

Missing or erroneous information on asset types (e.g. buildings) and characteristics (e.g. age, construction material) also lead to decreased accuracy in model results. In fact, many models include a default vulnerability based on average property characteristics for a given peril/geographic area as an approximation. Default assumptions are always a concern and provide reasons for discussions on reliability of results.

There are gaps with Cat modelling in countries with low penetration of market-based insurance. This is compounded by the fact that many of the essential data sets for model development are not available or accessible.

Development of Cat models in countries where there is low market-based insurance penetration has been limited by a number of factors such as less demand by the industry and lack of reliable data. However, publicly funded initiatives are beginning to provide the required investment to develop industry-grade probabilistic Cat models, leveraging the OASIS platform.[23]

3.3 Standards and interoperability

Lack of model standards and interoperability significantly burden the model users. The (re)insurance industry is putting pressure on the Cat risk modelling community for standards and greater interoperability across models.

Historically, each commercial Cat modelling firm has developed their own software platform, models and applications as an integrated package. Therefore, in order to use a model, the users also need the equivalent software platform.[24] Pressure from the (re)insurance industry to create more efficiency through greater interoperability is increasing, and major model providers are responding positively to assisting with this goal. Lack of interoperability of models across modelling platforms is a key challenge for extending these models to public sector use and for expansion of risk

22 There are many ways in which different models represent event footprint intensity and associated damage:
- Some only provide mean values (simple mean damage models);
- Others provide full probability distributions for both intensity and vulnerability.
- Many use point values for intensity and damage (vulnerability) distributions.
- Most use parametric distributions for damage while others, specifically flood models, use uniform distributions for flood intensity and truncated normal for damage; earthquake models popularly use truncated lognormal for intensity and beta for damage. A very few allow full histogram distributions, especially for vulnerability.
- Parameterised distributions are typically smooth and unimodal so do not reflect variations in damage outcomes due to substructures or incomplete classifications (e.g. occupancy might involve many construction types; 'unknown' would almost certainly mean a complex multi-modal distribution) (Taylor, 2012).

23 For example, the major H2020 Insurance project is funding the development of models to better improve risk understanding and insurance innovation (https://h2020insurance.oasishub.co/) across many aspects of risk, including a Danube river basin catastrophe model.

24 Exposure data has to be formatted differently for each different system, although the brokers have created translators over time, and some common formats are accepted by each platform.

transfer solutions, particularly in middle- and low-income countries. To this end, public–private partnerships could be instrumental in furthering the understanding and usage of such techniques. Increased interoperability may also assist with cost reduction in the insurance industry's usage of models generally. The promotion of interoperability, in part through the development of more consistent model and data standards, should be a key goal for the industry, governments and the international development community. In 2018, the Insurance Development Forum's Risk Modelling and Mapping Group is launching a new industry collaboration project on interoperability.

3.4 Open framework and open source versus restricted

As challenges related to open framework, open source versus restricted data and methodologies persist within and outside of the risk transfer industry value chain. The (re)insurance industry is putting pressures on the Cat risk modelling community to develop more open source options.

Among key drivers for outsourcing the development of Cat risk models are (i) demand for financial modelling of insurance and reinsurance structures; (ii) need for access to multiple sources of Cat models; and (iii) high operational costs and technical expertise associated with in-house model development, upgrades and verification.[25] Many industry-grade Cat models are owned by privately owned companies and licensed under commercial terms by insurers, reinsurers, brokers, and other financial and commercial organisations.[26]

Outside of the (re)insurance industry, however, many publicly available data sets, risk models and risk tools are available for different applications.

Increasingly, the public sector is promoting the importance of open data, risk models and risk information to ensure that all potential users are able to access risk information and make risk-informed decisions. GFDRR (2014) provides a review of available open-access risk modelling tools and data, highlighting models that do not require proprietary software. There is a place for both commercial, proprietary tools and models but also a place for open framework and interoperable models and frameworks. Finding a way of furthering the usage of Cat modelling tools by bringing together the important contribution of both proprietary and open framework providers is a critical issue.

3.5 Model validation and uncertainty estimation

Model validation is a critical and resource-intensive activity, undertaken by both Cat model developers and model users.

Model validation and exploring the sources of model uncertainty within and across model components require various tests.[27] If one component is uncertain or incorrect, the overall result will be uncertain or incorrect. The weakest component of the model determines the quality of the risk estimate. In addition, the reliability of a model depends on the quantity and quality of calibration data. A number of studies have attempted to classify the sources of uncertainty (AIR Worldwide 2010; Taylor 2012).[28] Guy Carpenter (2011) and AIR Worldwide (2015) have tried to capture systematically some of the uncertainty associated with Cat models; however, most other studies tend to focus on individual sources of uncertainty.[29] However, model uncertainty continues to remain largely unquantified within the Cat risk modelling world. With increasing computing power, Cat model developers will increasingly direct their focus on running multiple ensemble versions of a model,

25 For example, the development of the highest resolution and most advanced catastrophe models, such as a basin-wide U.S. hurricane or European flood model can total several million U.S. dollars in development cost. This is repeated every few years as the models are rebuilt and/or substantially upgraded to reflect new modelling methodologies and data.

26 There are very few publicly available complete catastrophe models (as per the definition used within the (re)insurance industry). The Public Hurricane Loss Projection Model for Florida was funded by the FL Office of Insurance Regulation at a cost of USD 2.7 million as an alternative to the commercially available catastrophe models for the purpose of the homeowner's insurance rate setting in the state of Florida.

27 In the industry, the term 'model validation' is used; however, the academic and scientific community use the term 'model verification'.

28 For example, uncertainties arising from the assumptions that were used in building the model and the decision made based on the probabilistic outputs that are generated.

29 There are multiple viable approaches as to how to handle model uncertainty, including model adjustments and model blending, and the choice of which path to follow is the responsibility of the model user. Further guidance is outlined in the ABI (2011) Guide to Good Practice for Catastrophe Modelling. The question of non-modelled risk should also be considered within the topic of model uncertainty. The ABI (2014) report on non-modelled risk is also a helpful guide to this topic.

using different assumptions, to produce a suite of possible outputs, similar to the way in which weather and climate forecasts are produced today. However, despite these improvements, the users of Cat models need to utilise uncertainty information in their decision-making.

3.6 Resource requirements

Development and utilisation of Cat models is a multi-disciplinary and resource-intensive process.

Resource requirements for the development and utilisation of a Cat model are dependent on the application and the specific risk management issue under consideration. For example, development of a large, high-resolution end-to-end Cat model used for insurance underwriting and reinsurance placement in a peak-peril region is a highly resource-intensive process.[30]

With set-up costs in the order of millions of U.S. dollars, many primary insurance companies choose not to license models and rely instead on third-party consultancies. Larger primary insurers tend to license all the commercial models and operationalise them in their business workflow.

Interpretation and communication of probabilistic Cat model output is also a challenging subject, requiring expertise.

Beyond operational applications, C-level executives and company boards require some understanding of Cat risk models, assumptions, uncertainties, and the implications of those uncertainties for their companies' risk profiles.

3.7 Regulatory issues

Cat models and/or their users are subject to regulatory control in a handful of jurisdictions around the world. This has led to additional resource requirements for developers and users of these tools.

In some jurisdictions (e.g. some states in the U.S.) Cat models are regulated in order to ensure that they are underpinned by sound scientific basis and are peer-reviewed.[31] Other countries (e.g. Peru, Mexico) have also introduced model approval processes. In Europe, the regulatory regime Solvency II requires in-depth validation and stress testing of models to prove that the individual model used by a (re)insurer properly reflects a company's individual risk profile. Standard vendor models are calibrated to meet the average market view of risk.[32] Furthermore, it is the use of Cat models by (re)insurers, which is under regulatory scrutiny rather than the models themselves. EU-based (re)insurers must comply with Solvency II, which requires that they demonstrate sufficient understanding of the Cat models they use for capital requirements, including at the board level (ABI 2014, 2011).[33] Other country legislators around the world are adopting Solvency II style regulations for (re)insurers, for example China.

30 Development of a Cat model for (re)insurance application requires (i) a team of 10-20 leading experts from a variety of disciplines (specialists with PhD degrees across disciplines such as seismology, meteorology, hydrology, engineering and mathematics, actuarial and computer science) to work together for over two to three years to produce the model, and then update and enhance the model regularly every 5–10 years; (ii) collection of critical data (e.g., hazard, exposure and vulnerability, and claims settlement data); and (iii) a reliable computing infrastructure. Finally, technology and regulatory issues impose additional costs.

31 The most prominent is the Florida Commission for Hurricane Loss Projection Methodology, which certifies Cat models for use in setting homeowner's windstorm insurance rates. (https://www.sbafla.com/method/). Hawaii, Louisiana, and South Carolina have similar legislature, and the State of Maryland examines other perils besides hurricanes.

32 Therefore, nearly all users have to recalibrate and adjust model parameters and results to reflect the individual companies' risk profiles.

33 The application of Cat models has to be embedded in capital modelling processes; results are used for portfolio management and to support the limit and threshold systems.

Figure 5: Seven key factors for Cat models

Methodologies

Traditionally, have relied on statistical techniques using empirical (observed) historical data of physical events

Data requirements, hazard, exposure and vulnerability

- Limited availability of historical data is a key challenge
- Quality of hazard and exposure data fed to models determine the quality of model output

Standards and interoperability

Lack of model standards and interoperability significantly burdens model users

Regulatory issues

Cat models and/or their users are subject to regulatory control in a handful of jurisdictions around the world

Open framework and open source versus restricted

Challenges related to open framework, open source versus restricted data and methodologies persist

Model validation and uncertainty estimation

Model validation is critical and resource-intensive for Cat model developers and model users

Resource requirements

Development and utilisation of Cat models is a multi-disciplinary and resource-intensive process

Source: The Geneva Association

4. Opportunities for expanding Cat models for shaping the future of disaster and climate risk management

The current generation of Cat models, while being instrumental for the (re)insurance industry and a number of other applications, represent a relatively simplified abstraction of the effects of natural catastrophes on the built environment.[34] However, current modelling methodologies do not fully capture classes of problems that require a more holistic systems-based approach to accounting for real-world complexities. In fact, many natural and man-made systems are profoundly interconnected and complex. There are a number of improvements in Cat modelling that could not only benefit existing (re)insurance users, but also further extend the value of these tools to a wider group of stakeholders (Figure 6).

4.1 (Re)insurance applications

Business interruption insurance (BI)

Typically, current Cat models generate losses linked to business interruption (BI) coverage largely as a function of the material damage loss calculation. BI vulnerability functions typically do not differentiate between 'loss of profit' and 'loss of revenue' coverage and do not adequately capture factors driving the expected duration of interruptions, which may depend on the recovery capacities of the affected region and its economy.[35] More sophisticated modelling of BI losses following disasters is possible but may require fundamentally new techniques and some dependency on the disclosure around business continuity planning.

Contingent business interruption (CBI)

Challenges with modelling BI related risks are compounded further when trying to account for contingent business interruption (CBI), which protects insureds against losses sustained due to damage at key suppliers or the principal distribution channels to customers. The principal challenge around modelling CBI arises from commercial sensitivity of major manufacturers to disclose details of their supply chains, contingency plans and inventory warehouse (Box 4). A first-order quantification of supply-chain risks from a global set of natural perils is possible today; however, it requires specification of the network of dependencies. For example, AIR Worldwide (2016) provides estimates of indirect losses in the Kumamoto earthquake in Japan; however, more research is needed.

Box 4: 2011 - The poster child for CBI losses

The year 2011 serves as the poster child for manifesting CBI losses with automotive industry disruptions following the Tohoku earthquake in March, displacing some component manufacturing to industrial parks in Thailand that subsequently flooded later that year, further disrupting computer hard drives and automotive manufacturing supply chains (SCOR 2013). A major nanotechnology pigments supplier of pearlescent pigments to all the principal auto manufacturers lay within the initial evacuation zone around the three reactor meltdowns at the Fukushima Daichi power plants. The challenge with modelling these situations resides both in the lack of data on the supply chains and the deep complexity of contingency (as in the manufacture shifting to Thailand followed by flooding in the same year).

34 This is due to the fact that the mechanics for damage and loss generation are broadly understood.

35 The range of insurance coverage that could be covered under the BI headline also includes denial of access and red zoning (as in Christchurch after the 2011 earthquake), loss of attraction (as in mid-town Manhattan hotels post 9/11) and the loss of services following almost every event.

Inclusion of other non-physical damage-related loss factors

Other issues are linked to more holistic systems-based risk analysis to quantify interlinkages and impacts. The full treatment of all the sources of post-loss amplification highlights the range of supplementary factors that can affect the ultimate losses in a catastrophe (Boissonnade et al. 2007). For example,

1) Economic demand surge - Whereby costs are inflated by factors such as the economics of high demand and limited supply of labour and materials to repair and reconstruct post-event loss;

2) Increasing vulnerability - Where losses could be exacerbated when not attended to in a timely fashion (e.g. a small hole in a roof or unattended flood leads to a property becoming ruined by mould);

3) Claims inflation - When insurers are unable to police low-level claims, encouraging potential fraud;

4) Coverage expansion - When insurers respond to political pressure and end up paying beyond the terms of their policy;

5) Super-Cat effects - When communities are evacuated due to failure of infrastructure leading to a lack of water, sewerage, electricity and supplies;

6) Demand surge – Meaning that the state of the economy at the time of loss will be a factor in determining the ultimate losses;

7) Post-disaster responsiveness to return to normality – Meaning the ability of the communities, local, provincial and national governments to expedite responding to and recovering from catastrophes.

These can vary according to the nature of the event and the level of technical expertise required for adjusting the claims. Currently, loss adjustment expense (LAE) does not have a standard model output; this will have to be added by the model user. Counter-intuitively, more extreme events could result in proportionally lower LAE costs as an increasing number of insured assets are deemed to be constructive total losses. Pressure from customers and regulators to settle quickly can also play a part in influencing the level of detail with which claims are scrutinised before settlement (as identified in models of claims inflation and coverage expansion).

Cascading effects and interdependencies of hazards (secondary perils)

Another opportunity for enhancing Cat risk modelling relates to impacts of secondary perils (cascading effects) when the impact may be highly dependent on the antecedent conditions. Today, many Cat models may not explicitly reference all the relevant antecedent conditions that lead to different outcomes. To this end, more research and cooperation of the Cat modelling community with the scientific community is needed to enhance understanding of the interactions and dependencies among the hazards.[36]

Cascading impacts of interacting natural and technological hazards

Consequences of catastrophes may be modified and/ or compounded by technological failures. The natural hazard technology interface events also represent a complex set of modelling challenges. Modelling these interactions requires a detailed understanding of the hazard technology interface. Examples of such events include (i) the Fukushima Daiichi nuclear power plant accident that occurred as a consequence of the Japan earthquake-tsunami-nuclear accident in March 2011, which demonstrated common features of cascading disasters (World Nuclear Association 2016); (ii) the eruption of Eyjafjallajökull volcano in Iceland in 2010, which affected an estimated 10 million travellers, albeit with low insurance impacts (Smits 2015; UCL Institute for Risk and Disaster Reduction 2010); and (iii) solar coronal mass ejection events that could generate geomagnetic storms that could induce strong currents in high latitude high voltage transmission lines (Lloyd's 2013a).

36 For example, increase in the number, severity and scale of earthquake-triggered landslides after high levels of precipitation, or the spread of fires after an earthquake, depending on wind speed and direction. Such interdependencies may only be reflected in a limited fashion in the Cat models today, although fully probabilistic assessments of fire following earthquake have also been achieved (e.g. Mortgat et al. 2004).

Critical infrastructure failures

Modelling weather-related risks of infrastructure projects is fundamental to building resilience and enabling insurability.

Destruction, disruption, interruption in critical infrastructure could lead to cascading effects across sectors and sometimes across borders, causing significant harm to populations' well-being and hindering socio-economic growth. Over the last three and a half decades, a significant portion of economic losses were related to impacts of weather-related extremes such as inland and coastal floods, windstorms, hurricanes, droughts and heat waves on critical infrastructure.[37]

The vulnerability of critical infrastructure to shock events such as natural catastrophes, cyberattacks and terrorism has become an increasing concern to many governments.

A significant portion of economic losses associated with natural catastrophes, particularly in the high- and middle-income countries have been caused by damage to infrastructure caused by extreme weather events. The 2005 hurricane Katrina in New Orleans, 2011 Thailand floods, 2012 super storm Sandy in the eastern U.S. and New York City, 2018 hurricane Maria in Puerto Rico, 2018 cyclone Gita, and the 2007 U.K. flood are just a few recent examples.

Rising frequency and severity of weather-related extremes and slow-changing trends (e.g. sea level rise, water scarcity) associated with climate change, rising concentration of people and assets in high-risk regions (e.g. coastlines), development patterns and construction practices are further exacerbating these impacts in all countries (OECD 2017; Forzieria et al. 2018; IISD 2013; European Commission Infrastructure website).

According to the World Bank Group (2014b, 2017), following a natural disaster a significant portion of direct and indirect economic impacts for governments are related: (i) post-disaster government spending to fix damages and/or rebuild uninsured or partially insured public infrastructure, government buildings and low-income dwellings; (ii) decreased tax revenues associated with business interruption due to infrastructure damages (e.g. electricity, transportation and water); and (iii) opportunity cost of diverting public funds from development plans to infrastructure reconstruction and recovery efforts (World Bank Group 2014b, 2017). On the other hand, infrastructure failures not only significantly compromise emergency relief and response operations and relocation of the at-risk population, but also the community's livelihood and their ability to return back to normality.

Insurers consider critical infrastructure as fundamental to scaling up socio-economic resilience to extreme events (The Geneva Association 2018). The insurance industry is already underwriting critical infrastructure, and there is willingness to expand coverage, but a number of challenges remain. Among these is the need for access to high-quality data to assess extreme event risks associated with the infrastructure projects' entire life cycle, including design, construction, operation and maintenance phases.

Furthermore, modelling of extreme event impacts on critical infrastructure and how infrastructure damage and failure could lead to secondary catastrophic consequences provides opportunities for taking preventive measures. Some examples include: the overtopping and failure of levees in New Orleans during hurricane Katrina; potential failure of major dams such as the Herbert Hoover dam around Lake Okeechobee in Florida in a repeat of the 1928 hurricane, with catastrophic flooding impacts for the communities to the north of the greater Miami area (Lloyd's, 2007); or the failure of dams and aqueducts in California following a major earthquake.

Solving the insurance protection gap in highly vulnerable low-income nations

Publicly available and open Cat models are needed to help solve the insurance protection gap in highly vulnerable low-income nations.

37 'Infrastructure' is generally defined as the systems, assets, facilities and networks that provide essential services and are necessary for the national security, economic security, prosperity, and health and safety of their respective nations (Critical Five, 2014). 'Critical' refers to the infrastructure that provides essential support for economic and social well-being, for public safety and the functioning of key government responsibilities (OECD, 2008). Definitions of 'critical infrastructure' in OECD countries are provided. Different countries consider different sectors under their critical sectors; however, for most of them energy, information and communication, transportation, dams and flood defense, water and sewage, health, finance and banking, and the chemical industry fall under top ten critical sectors (OECD, 2017).

Whilst models make markets there is a 'catch 22' around the availability of investment required to develop catastrophe models to underpin the development of disaster risk financing schemes, particularly in low-income countries. The funding and development of open source Cat models through public science is emerging as a way to support public–private partnerships such as the IDF and to address the insurance coverage gap for people and assets at risk in poor and vulnerable developing countries, such as the InsuResilience Climate Risk Insurance Initiative. However, these models need to be robust enough to be trusted by the (re)insurance industry and co-developed with the governments and countries to create a mutually accepted view of risk upon which transactions could be based. There is also an opportunity for these models to be leveraged for broader disaster risk management decisions by these countries if they have long-term ownership.

4.2 New opportunities to address impacts of physical climate risk in core business and investing

FSB-TCFD (2017) has provided guidelines for linking climate risk (physical risk, liability risk and transition risk) to governance, strategy, risk management, metrics and targets for companies in various sectors. Expansion of Cat models and leveraging insurers' expertise in this area could be considered.

Issues are increasingly evolving around three key areas: (i) the role of corporate policy and practice in measuring and managing these risks; (ii) acquiring expertise and standard risk analysis and stress testing tools for different climate change scenarios (e.g. 1.5°/2°/3°/4°C); and (iii) data needs.

For implementation of FSB-TCFD's recommendations more attention needs to be dedicated to quantification of changing characteristics of physical risks of climate (e.g. severity, frequency and location of extreme weather-related events such as tropical cyclones, severe precipitation, floods, etc.) in the strategy, risk management and financial strategies and investment portfolios under different climate change scenarios.[38]

Beyond (non-life) insurers, increasingly banks, asset managers and companies from various economic sectors are also considering integration of physical risks into their core business. This will require higher resolution data and models as well as the integration of forward-looking views of extreme weather risks to capture the impacts of climate change today and in the future. More attention needs to be given to exploring and expanding Cat models and leveraging insurers' expertise in the area (ClimateWise 2018).

4.3 Development planning and other public sector applications

For many applications, simplified and low-resolution Cat models which can be produced with fewer resources may be more relevant.

For example, risk maps can help with planning of emergency preparedness and response operations. This prompts an increasing need for innovative approaches to risk communication and greater investment in education and training for different users of risk information. To this end, an increasing number of niche risk modelling companies have been focusing on different applications. Artificial intelligence and deep learning technologies are also being increasingly utilised.

4.4 Redefining risk with a systems-based thinking

Global social-natural-economic systems have moved on from being formally 'complicated', and hence ultimately describable, to formally 'complex'.

This term describes systems that are highly dynamic where actions within the system change the system through time, and where the behaviour of the system may not simply be modelled by the behaviour of the system's components. Meanwhile, new mathematical approaches to modelling complexity, coupled with automated approaches to model use and curation are providing a new foundation for exploration of the dynamics of risk, its characterisation and management.

38 Leading centres include Massachusetts Institute of Technology, ETH Zurich, Cambridge Institute for Sustainability Leadership, IIASA and 2° Investing Initiative.

Catastrophe models that incorporate a systems-based approach could assist a broader range of stakeholders such as governments, humanitarian and development agencies, and civil society actors tasked with addressing complex disaster risk management issues.

One area of particular interest and concern relates to agricultural planning, food security and food system stability/fragility issues that confront the developed world in the event of a major global supply chain shock linked to large-scale droughts. The global food supply system is profoundly interconnected. A long-lasting drought in one or more major growing region, especially if coupled with a heat wave at a sensitive point in the crop's life cycle, could affect crop yield and/or spikes in global agricultural commodity prices. This indeed happened following the Russian drought in 2010, which led to Russia banning exports of wheat, barley and other grains.[39] The resulting food shortages and price increases are also believed to have contributed to the civil unrest throughout the Middle East in 2010–2011 (Lloyd's 2013b and 2015). Increasingly, governments are recognising the importance of systems thinking for managing defence policies and operational plans for addressing the national security implications of global food system vulnerabilities.[40]

39 As barley is used as an animal feed, and had knock-off on impacts on the livestock industry globally.

40 From the National Defense Authorization Act for Fiscal Year 2018. https://www.congress.gov/amendment/115th-congress/senate-amendment/784/text.

5. Harnessing latest scientific and technological developments to innovate Cat modelling

Advancement in climate research and modelling, rapidly expanding computational capabilities, explosive expansion of big data combined with other engineering and technological innovations are providing unprecedented opportunities to innovate and develop the next generation of Cat risk models.

5.1 Leveraging advancements in climate science and modelling

Scientific advancements in weather and climate research, facilitated through international research programmes such as the World Climate Research Programme (WCRP), World Weather Research Programme (WWRP), Global Climate Observing System (GCOS) and the World Meteorological Organization (WMO) have led to increasing understanding of the general circulation of the atmosphere and oceans, the greenhouse effect, the water cycle, the dynamics of weather systems and weather-related extremes.[41] These programmes have brought together thousands of scientists from around the world to coordinate, collaborate and leverage resources to advance the understanding of the earth's climate system, explore the limits of predictability and develop tools and models that could be linked to decision-making tools such as the Cat models.[42] While the Cat modelling community over the last 35 years has thrived to utilise latest scientific developments in meteorology and climate modelling, there is an unprecedented opportunity to establish multi-disciplinary global partnerships to innovate and expand Cat modelling methodologies with a forward-looking approach (The Geneva Association 2016a-b, 2017).

Figure 6: Opportunities for expanding Cat models for shaping the future of disaster and climate risk management

Expanding (re) insurance applications

- Business interruption
- Contingent business interruption
- Inclusion of other non-physical damage-related loss factors
- Cascading effects and interdependencies of hazards (secondary perils)
- Cascading impacts of interacting natural and technological hazards
- Critical infrastructure failures
- Solving the protection gap in vulnerable low-income countries

Public sector applications

- Emergency, preparedness and response operations
- Cost-benefit analysis of preventive and risk reduction measures
- Improving risk understanding and communication
- Development planning

Integration of physical climate risks into core business, investing strategies and financial systems

- Financial sector (banks, asset managers, rating agencies, etc)
- At the company level, compliance and reporting of climate risk for different sectors

Redefining risk with a systems-based thinking to reshape risk management

- 'Models of models', e.g. global social-natural-economic systems such as water-energy-food nexus, agricultural planning and food security, urban systems

Source: The Geneva Association

41 WCRP: https://www.wcrp-climate.org/; WWRP: https://www.wmo.int/pages/prog/arep/wwrp/new/wwrp_new_en.html; GCOS: https://public.wmo.int/en/programmes/global-climate-observing-system

42 Through these programmes, thousands of scientists in academia, public- and private-sector funded centres of excellence and research labs as well as national operational services (national meteorological, hydrological and climate services, space agencies) are working together in a coordinated way.

Major opportunities include:

Leveraging observations of the earth's climate system

Every day, massive amounts of data are collected from various platforms (space, ocean and land), archived and catalogued by many agencies and institutions around the world, using global standards established by the WMO. Access to these databases could help the Cat modelling community enhance the quality of these models.[43]

Understanding climatic regimes and interconnectivities in the global weather patterns

Predicting the drivers and characteristics of extreme weather patterns has been at the centre of climate research. Earth observations have been critical to increasing the understanding of the natural variations in the earth's climate system. The field of statistical climatology is the foundation for exploring the limits of predictability with respect to extreme event characteristics on different time and spatial scales. This area of research has led to a much deeper understanding of the drivers of earth's climate system, particularly in relation to natural climate variability. The following are particularly noteworthy:

1) Understanding that weather patterns in one part of the world could influence other parts of the world (referred to as *Teleconnections*);

2) Discovery of recurrent patterns within the earth's climate system such as El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Madden Julian Oscillation (MJO) (these are referred to as *modes of climate variability*);

3) Understanding the linkages of modes of climate variability and other factors with recurrent patterns of weather extremes in some regions around the world;

4) Understanding how climate change alters the modes of climate variability;

5) Exploration of how the underpinning factors in the earth's oceans, land and atmosphere drive characteristics of extreme events (e.g. severity, location and frequency) and their variations on different time scales.[44]

Advancements in seamless forecasting from minutes to decades

The scientific community is increasingly poised for simulating and predicting the evolution of the natural environment and assessing critical issues such as how climate change will affect the modes of climate variability and ultimately the characteristics of extreme events. Over the past decades, the scientific community has been developing computer models to mathematically replicate the physics of the earth's climate system, to advance weather forecasting and climate prediction. These models effectively simulate global weather patterns and ocean circulations with very few basic constraints.[45] With further advances in supercomputing power and better

43 However, in many regions, countries are faced with many challenges including: (i) maintaining these comprehensive observation networks that have taken many decades to build; (ii) developing these networks by introducing emerging and new technologies to enhance precision, accuracy and fidelity of the observations, without compromising their retrospective compatibility and prospective continuity; and (iii) enabling greater integration of observations to understand, model and predict the earth system's modes of variability that are key to the success of the rapidly emerging and promising field of 'seamless prediction' across time and space scales. Despite massive coordinated efforts, facilitated by the United Nations World Meteorological Organization over the past 60 years, there are still some regions of the earth that are not adequately observed and understood due to: (i) lack of observing system infrastructure and investments; (ii) difficulty to cover via conventional observing systems (i.e. surface and airborne); and (iii) limited availability, access and sharing of data.

44 Over the last decades, there has also been significant progress with the scientific understanding of the impacts of snow cover, sea ice, soil moisture, stratosphere-troposphere interactions, tropics-extra-tropics 'Teleconnections' on the earth's climate system. Proper inclusion of these factors in the computational models is leading to enhanced sub-seasonal and seasonal forecast skill in mid-latitudes.

45 Weather modelling: Numerical Weather Prediction (NWP), which began in the 1960s, is the bedrock of all weather forecasting from a few hours to over a week ahead (referred to as short-term weather forecasting) and up to two weeks ahead (referred to as medium-range weather forecasting). Weather forecasting skill has improved systematically such that, today, a global forecast for 5 days ahead is as skillful as or better than a forecast 40 years ago for 1 day ahead; in other words there has been a gain of 1 day/decade in predictive skill.
Climate modelling: Progress in climate prediction has been substantial over the past decades owing to a deeper understanding of modes of climate variability (ENSO, PDO, NAO, etc.) and their association with recurrent weather patterns. Building on the fundamentals of atmospheric simulation for weather forecasting, climate modelling began in earnest in the 1960s, although progress was limited by computing power. The need to run long simulations and to add other components of the climate system (e.g. the ocean) meant that climate modelling tended to develop along different paths and usually in different organisations from those in weather forecasting.

understanding of interactions in the climate system, increasingly weather and climate prediction are being considered as a continuum in forecasting across different timescales from minutes to several decades (Figure 7).

Earth system simulations, known as 'synthetic data'

Building on the pioneering work of Emanuel et al. (2006 and 2008)[46], over the last few years the concept of using weather and climate simulations to provide a much richer set of events is now a possibility. The latest generation of weather and climate models, coupled with enhanced supercomputing capability, has unlocked the potential for simulation to provide a new generation of event sets down to the regional and local scales. These can enable the quantification of risk from plausible but unprecedented extremes— 'black swans' or 'known unknowns' for today's environment. In other words, with these synthetic event sets the tail of the distribution of extremes could be filled more confidently for about 1 per cent or even less annual probabilities (Thompson et al. 2017). This is a potential game changer for improving the hazard module of Cat models.

Nested models within Global Climate Models

With progress in supercomputing, the scientific community has been able to use the full chain of models from Global Climate Models (GCMs) and Regional Climate Models (RCMs) to probabilistic high-resolution models in order to asses risk associated with extreme events, such as the European storms under different climate scenarios with high resolutions (Schwierz et al. 2010; Gettelman et al. 2017). This is particularly relevant to scenario analysis and stress testing methodologies for assessing impacts of weather-related extremes under different climate scenarios aligned with the FSB-TCFD recommendations. These downscaling techniques could also be applied to the output of GCMs to yield estimates of changes in tropical cyclone activity tied to natural and anthropogenic climate change. For example, the well-known modulation of Atlantic tropical cyclones by El Niño and other natural climate fluctuations has been replicated, and projections have been made for global changes in tropical cyclone destructive potential (Emanuel 2013), storm surges at particular locations such as New York City (Lin et al. 2012), and rainfall (Emanuel 2017). Such projections of future tropical cyclone activity have been used to estimate future losses, e.g. changes in sea level and future tropical cyclone activity (Hsiang et al. 2014).

5.2 Other technological advancements

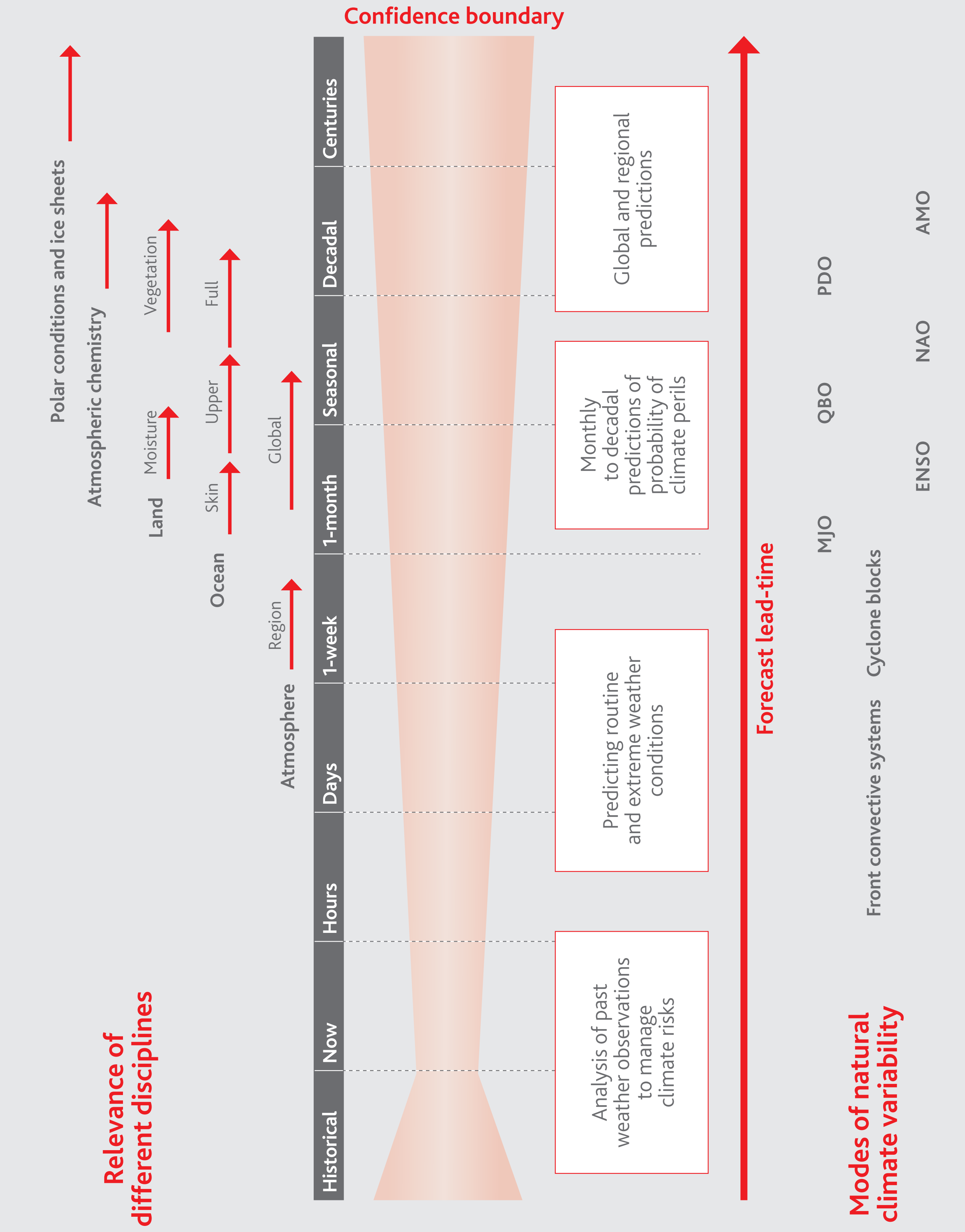
Accessibility to high-quality exposure and vulnerability data remains a major challenge in many parts of the world. New developments with industrialising the supply chain for construction, control systems for monitoring thresholds, and other engineering advancements offer new opportunities for enhancing vulnerability and exposure functions.

Availability of and accessibility to big data and improving IT capabilities are enabling continued improvements of model accuracy and resolution. Since the early 2000s, a number of Cat model developers have been working to incorporate more data to enhance the quality of output. For example, detailed digital terrain models are replacing coarser surface models, improving the calculation of hazard on a fine scale. For some cities, 3-D representations of the building stock now exist, and efforts are underway to expand aerial surveillance missions to further expand them. Overall, the understanding of the built environment is improving at a rapid pace, helping to constrain model assumptions and reduce uncertainties. Finally, improvements in remote sensing resolution and frequency of data collection are critical for continuous model improvements.

Further utilisation of big data, cloud sourcing, satellites and remote sensing, wearable devices, computational advancement, artificial intelligence and neutral networking techniques along with predictive analytics are all among tools that, as they mature, will undoubtedly be co-opted into the new generation of advanced risk models which will be developed over the next few years (The Geneva Association 2016c).

46 Kerry Emanuel of MIT pioneered a method to produce tropical cyclone event sets by exploiting the dependence of tropical cyclones on the large-scale environment, which is better constrained statistically from observations of the tropical cyclone records, which are event-limited'. This means that a multitude of physically plausible large-scale environments can be produced statistically from observations, and then tropical cyclones generated deterministically based on their fundamental physics. This method works well for tropical cyclones, which are primarily slaves to the large-scale environment. Until global weather and climate model simulations can be performed that resolve the fine scale structure of tropical cyclones—probably close to the kilometre scale—this statistical-deterministic approach remains the most promising for estimating current and future extremes for this class of hazard.

Figure 7: Seamless forecasting system



Source: UK Met Office

6. Recommendations for the way forward

Against this backdrop, we offer three overarching recommendations:

Recommendation 1: Further leverage and enhancement of current Cat modelling methodologies

To some extent it can be said that *models make markets*. In turn, markets are also needed to stimulate investment in the current commercially driven catastrophe model paradigm. There is much more that could be done to extend the value of *Cat models* to the (re)insurance industry, and we recommend a call for action to (re)insurers, brokers, model vendors, the development community and the public sector in the following areas:

(i) **Drive for interoperability.** There is an urgent need to support deepening the pool of talent to address the technical challenges. Common data standards and model protocols are essential to engage academia, centres of excellence and government scientists. More specifically, data standards relating to exposure data input and model result outputs are key for accessing the efficiency gains from greater digitalization in the placing of insurance and reinsurance contracts. The global insurance industry is encouraged to actively support initiatives in this area. Model vendors can support *interoperability* by publishing proprietary data schema and maintaining data mapping support for open standards.

(ii) **All stakeholder groups should scale up ambition for global coverage of natural peril models for each country across high-, middle- and low-income countries.** This is fundamental to risk communication and raising risk awareness, risk-based planning and risk management measures, and development of risk transfer solutions in underinsured regions and economies. Such ambition is fully aligned with multi-stakeholder initiatives such as InsuResilience and the Insurance Development Forum.

(iii) **Extend existing models to address current limitations and gaps, particularly BI/CBI and supply chain modelling, economic demand surge, and loss adjustment expenses.** The incorporation of additional risk factors and outputs such as casualties and displacements— while improving the sophistication of assessing damage to infrastructure—will extend applicability and value for new stakeholder groups, e.g. public sector, country risk officers, and city mayors.

(iv) **Set expectations of transparency and uncertainty quantification in model design and limitation, while remaining sensitive to commercial considerations around investment in intellectual property.** Greater transparency is essential to enable buy-in, review and challenge by other interested parties, and perceptions of 'black box' models must be actively countered by increased disclosure to allow academics, government scientists, politicians and other key stakeholders to recognise risk, assess cost benefits of different measures and have the confidence to inform policy decisions and recommendations to prevent and reduce these risks. Drawing on fields of geophysical (e.g. weather and climate) modelling, ensembles of model runs could be more widely used to reveal uncertainty, and inter-comparison projects (as undertaken with climate models) would drive innovation in model development by highlighting areas for improvement.

(v) **Improve risk communication among users of the model outputs and related model uncertainty.** Risk metrics are not necessarily intuitive and can be badly presented, creating scope for misunderstanding and the potential for poor decision-making. To build a common understanding of Cat model results and make the insights generated more accessible there is a need to develop a broader programme of educational tools for non-practitioners. As the use of Cat models extends to new stakeholders, it is important to translate industry jargon into terminology that supports better public awareness of risk.

(vi) **Agree on and develop a uniform international exposure data standard to enable transparency, comparability and acceptance of results and allow for efficient use of Cat models.**

Recommendation 2: ***Embed latest climate science in Cat models and explore opportunities for improving modelling of physical climate risk with a forward-looking approach, taking into consideration climate change scenarios.***

Although it is a highly complex issue, integration of latest climate science, earth system simulations (synthetic data) and nested models within the GCMs into Cat models could potentially be a game changer to evolve Cat modelling towards a forward-looking approach.

This offers the opportunity to extend the Cat loss model value proposition to also support new climate insurance product offerings, both now and for the future. Furthermore, such enhanced models linked to GCMs could be critical for integrating physical climate risk into core business, financial systems and investment applications (linking to FSB-TCFD recommendations). Integration of such climate change calibrated Cat risk models could potentially enable (re)insurers, other segments of the financial sectors, businesses, public sectors and other stakeholders to manage the physical risk of climate (change) now and for the future.

Cat models need conditioning to understand climate change sensitivity and the associated impacts that may result from changes in risk distribution for insurable assets. Perils that would clearly benefit from such enhancement include: wildfire, large-scale hail, agricultural crop yields, drought, coastal surge flooding (via sea level rise), and extreme precipitation like cloudburst and even snowmageddon type events. With advancements in the understanding of climatic regimes and interconnectivities in the weather patterns the inclusion of the correlations between 'independent' peril regions within existing Cat models may be considered.

Building on the international scientific cooperation through the World Climate Research Programme (WCRP), World Weather Research Programme (WWRP), Global Climate Observing Systems (GCOS), World Meteorological Organization (WMO) and Global Framework for Climate Services (GFCS), there is an unprecedented opportunity for the (re)insurance industry and Cat modelling community to work more and more closely with the climate science community to enhance Cat models with a forward-looking approach.

We call on (re)insurers, risk modelling vendors, Cat modelling experts, development partners, the global climate science community and other relevant stakeholders to work together to:

(i) **Extend the model time horizon.** Current Cat model frameworks are designed to support risk assessment for 12 months contracts, typically calibrated using historical data. *Forward-looking* models are needed to support the short-, medium- *and* long-term horizons necessary for strategic planning for all stakeholder groups including (re)insurers. Such innovation is essential to facilitate Environmental Sustainability and Governance[47] assessments and disclosures, and longer-term investment studies (see below) and decision-making based on RCPs.

(ii) **Analyse model dependencies among region-peril models with consideration for implications of large-scale climate regimes.** This is a precursor to embedding forward-looking climate science into model frameworks. This is necessary for (re)insurers operating at a global scale to ensure that correlations between weather and climate risks in different markets are captured.

(iii) **Enable incorporating physical climate risks into financial modelling and investment risk analysis** to allow for analysing explicit dependencies between asset and liability risk for capital modelling/ management by (re)insurers, other segments of the financial sectors, businesses, public sectors and other stakeholders to manage the physical risk of climate (change) now and for the future. This could also allow for risk transfer product design and incentives (derived from the conclusions of these models) to create a stimulus for all stakeholders to use preventative measures that would bring down costs of consequences of climate for society as a whole.

47 ESG also stands for economic scenario generator in (re)insurance capital modelling terminology.

(iv) **Extend model conceptual frameworks from hardwired annual simulations to support multi-year contracts,** allowing for memory[48] in the systems. Again, there is a link to longer term investments and understanding infrastructure risk over the full project life-cycle.

Recommendation 3: ***Consider 'models of models' and embrace a systems-based thinking for development of the next generations of Cat models.***

The usefulness of Cat models to the (re)insurance industry and wider society could be even further advanced if connections were made to models in other domains and fields of study. The overarching benefit of coupling models would be to better understand feedback loops and cascading effects within and across sectors (e.g. water-energy-food nexus). Cat models, extended to reflect climate-conditioned future scenarios, could provide new insights and support policy, planning and decision-making in areas such as:

(i) **Critical infrastructure.** Destruction, disruption, interruption in critical infrastructure could lead to cascading effects across sectors and sometimes across borders, causing significant harm to populations' well-being and hindering socio-economic growth. Over the last three and a half decades, a significant portion of economic losses have been related to impacts of weather-related extremes such as inland and coastal floods, windstorms, hurricanes, droughts and heat waves on critical infrastructure. Electricity generation, transmission and distribution, water management, transport networks, and telecommunication services are all critical components of life. Failures in key infrastructure create ripple effects that aggravate damage, casualties and financial loss and hinder emergency management effort and rapid post-disaster recovery.

(ii) **Economic modelling with consideration for changing climate.** Linking models of economic activity to Cat models, which have been enhanced with latest climate analysis tools would bring benefits to a wide range of levels and sectors:

- ***National:*** Highlights the benefits of ameliorating contractions of GDP growth post-disaster. Informs regulators on the benefits of (cross-border) (re)insurance.
- ***Regional/municipal:*** Supports devolved responsibility and autonomous planning and policymaking in the post-austerity era.
- ***Insurance:*** Increased sophistication of economic demand surge, business interruption, contingent business interruption and supply chain, economic scenario generator modules in internal capital models by reflecting post-disaster movements in currency exchange rates, interest rates, and energy/commodity prices.
- ***Supranational:*** Organisations such as World Trade Organization, World Food Programme, international aid agencies, remittance flows, NGOs all stand to benefit.
- ***Company-level across many sectors:*** Integration of physical risks in governance, strategy, risk management, metrics and alignment of annual reporting with investors' needs.
- ***Financial system level:*** Increasingly, governments, the financial sector and other segments of the economy are considering the impacts of physical climate risks.
- ***Linking national security in areas such as global food security:*** Increasingly, legislative actions are underway requiring systems-based modelling linking various shocks (e.g. weather-related extremes such as floods and droughts) to support national security decisions in the energy/water/food domain.

48 For example, if conditions are conducive to extratropical storms in Europe in December, then models should be able to reflect this consistently for the following January.

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Glossary

Average annual loss (AAL)	The AAL is the mean value of a loss exceedance probability (EP) distribution. It is the expected loss per year, averaged over many years. The one-year return period loss is expected to be equalled or exceeded every year. Its exceedance probability is 100%.
Atlantic Multi-decadal Oscillation (AMO)	The AMO is a climate cycle that affects the sea surface temperature (SST) of the North Atlantic Ocean based on different modes of multi-decadal timescales.
Cat excess-of-loss treaty	A common reinsurance contract that provides protection to a primary insurer protection in excess of certain loss amount that the primary insurer might suffer from a catastrophe.
El Niño–Southern Oscillation (ENSO)	ENSO is an irregularly periodic variation in winds and sea surface temperatures over the tropical Eastern Pacific Ocean, affecting climate of much of the tropics and subtropics. The warming phase of the sea temperature is known as El Niño and the cooling phase as La Niña.
Exceedance probability (EP) curve	EP curves are displayed graphically, but also summarised by key return period loss levels. For example, a 0.4% annual probability exceedance corresponds to a 250-year return period loss.
Loss adjustment expenses (LAE)	The expenses associated with investigating and settling insurance claims. Loss-adjusted expenses that are allocated to a specific claim are called allocated loss adjustment expenses, while expenses not allocated to a specific claim are called unallocated loss adjustment expenses.
Loss of profit	Loss of profit is the loss of what is left over at the very end after the company has paid for the cost of goods sold, plus all of its expenses.
Loss of revenue	Loss of revenue is the loss of the total of all money that a company receives from people paying for its products or services.
Madden Julian Oscillation (MJO)	The MJO is the dominant intra-seasonal mode of organised convective activity in the tropics, and has considerable impact on the middle and high latitudes as well; it is considered to be a major source of global predictability on the sub-seasonal time scale.
North Atlantic Oscillation (NAO)	The NAO index is based on the surface sea level pressure difference between the Subtropical (Azores) High and the Subpolar Low. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the Eastern United States and Western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport, which in turn results in changes in temperature and precipitation patterns often extending from eastern North America to Western and Central Europe.
Pacific Decadal Oscillation (PDO)	PDO is often described as a long-lived El Niño-like pattern of Pacific climate variability. As seen with the better-known El Niño–Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in the Pacific Basin and the North American climate. In parallel with the ENSO phenomenon, the extreme phases of the PDO have been classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. When SSTs are anomalously cool in the interior North Pacific and warm along the Pacific Coast, and when sea level pressures are below average over the North Pacific, the PDO has a positive value. When the climate anomaly patterns are reversed, with warm SST anomalies in the interior and cool SST anomalies along the North American coast, or above average sea level pressures over the North Pacific, the PDO has a negative value.

As the effects of climate change become more severe, catastrophe risk modelling is more relevant than ever. Few sectors of the economy play a role as intense in catastrophe recovery as insurance; therefore, the industry should strive to continually strengthen the predictive power of its catastrophe modelling capabilities.

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