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Catastrophe and Climate

Catastrophe Modeling Insights

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On a Collection of Essays on Catastrophe Modeling for Life & Health Insurance

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Introduction

The insurance industry is operating under a level of uncertainty that feels structurally different from the past. Climate change is reshaping the frequency, severity, and geography of extreme events: hurricanes are strengthening, wildfire seasons are lengthening, and flood behavior no longer matches the historical record on which many risk tools were built. At the same time, regulators and supervisors are asking tougher questions.

These converging drivers are expanding the role of catastrophe models far beyond traditional underwriting, pricing, and capital-adequacy analyses. Insurers now deploy these models not just to estimate probable losses, but also to support resilience planning, disaster management, and risk-recovery strategies. With richer data and improved computing, portfolios can be stress-tested against multiple climate scenarios, regulators can evaluate systemic exposures, and communities can use model outputs to plan evacuation, mitigation, and rebuilding efforts. So, the tools that once served only property-and-casualty (P&C) underwriting are becoming central to broader risk-management agendas - helping insurers, regulators, and public-sector actors navigate a world where weather no longer plays by yesterday's rules.

Concurrently, gains in computing power, a surge in climate and geospatial data, and the growth of open modelling ecosystems have started to change how catastrophe models are built and used. Tools that were once proprietary and opaque are gradually being supplemented by more transparent, open-source alternatives.

Components of a Catastrophe Model – and the Evolution from Three to Four Modules

Modern catastrophe ("Cat") models are essentially large simulation engines that connect a physical event to a loss outcome. They take rare, high-severity hazards - hurricanes, earthquakes, floods, wildfires - and run thousands of "what if" scenarios to estimate how much an insurer might lose.

In their classic form, Cat models were built from three modules - hazard, vulnerability, and financial loss. As portfolios became more granular and geocoded, a fourth module, exposure, was pulled out explicitly so that "what is at risk and where it sits" could be modeled in its own right.

HAZARD MODULE

The hazard module models the underlying physical peril by producing *a stochastic event set* comprising thousands of simulated events, each defined by its frequency and intensity parameters.

This module contains two critical subcomponents (Sousounis, 2025):

- **Event catalogs -** which simulate all physically possible future events rather than relying only on historical observations. These catalogs are often generated using physics-based and statistical models to represent events that have never yet occurred but remain scientifically plausible.

- **Intensity engines -** which calculate how strong each event would be at specific locations (e.g., wind speed, flood depth, ground shaking, flame length).

For example, a hurricane model estimates surface wind speeds at individual building locations, while a flood model calculates water depth and velocity. The industry's shift to this probabilistic, physics-informed approach was a direct response to the unprecedented losses like Hurricane Andrew and helped catalyze modern catastrophe modeling.

VULNERABILITY MODULE

The vulnerability module translates hazard intensity into damage, addressing - *given a certain hazard strength, how much damage should we expect?* This relationship is typically represented using damage functions or fragility curves - often S-shaped that map hazard intensity to expected loss.

While early vulnerability models focused on property damage, the concept has expanded to include human and system vulnerability, such as injury and fatality risk, or loss of functionality in critical infrastructure like hospitals and transport networks. In addition to deterministically calculating fractional damage for each property (mean damage ratio), uncertainty is explicitly modeled, allowing identical exposures subjected to the same hazard intensity to experience different outcomes due to random factors such as flying debris, secondary hazards, and construction quality, resulting in probabilistic damage distributions rather than a single deterministic value (Sousounis, 2025).

FINANCIAL (LOSS) MODULE

The financial module translates physical damage into monetary loss. It applies insurance policy terms - such as deductibles, limits, reinsurance layers, and attachment points - to determine the insured loss rather than just the physical or economic loss. Beyond property damage, this module can also factor in business interruption, additional living expenses, supply chain disruption, and liability claims, along with health impacts and mortality in more advanced life and health models (Sousounis, 2025).

This is where catastrophe models connect directly to actuarial practice, enabling users to derive metrics such as Average Annual Loss (AAL), Probable Maximum Loss (PML), and Exceedance Probability (EP) curves used in pricing, capital modeling, and solvency assessment.

EXPOSURE MODULE (THE FOURTH PILLAR)

The exposure module defines *what is at risk and where*, using detailed, geocoded information on location, construction characteristics, occupancy, age, code compliance, and insured values. This module became critical as insurers moved from coarse, region-level risk estimates to property-level modeling. Advances in satellite imagery, remote sensing, geospatial data, and digital property records have allowed exposure databases to become far more granular and dynamic than in the 1990s.

Regulators increasingly scrutinize exposure data quality when evaluating insurers' catastrophe risk management. The evolution from three modules to four reflects a critical shift: catastrophe losses are driven not by hazard alone, but by its interaction with vulnerability and highly detailed exposure.

Insights from the SOA Call for Essays

Catastrophe models have fundamentally redefined how insurers understand and price extreme events, replacing retrospective heuristics with probabilistic frameworks grounded in science and data. Originally developed for property and casualty risks, these models have expanded to encompass man-made and systemic perils such as terrorism and pandemics, revealing their power to quantify complex, interconnected losses. Now, as climate change accelerates the frequency and intensity of wildfires, heatwaves, and floods, new vulnerabilities in population health are emerging that traditional life and health actuarial models - built on assumptions of stability - can no longer capture. Across this Society of Actuaries (SOA) Research Institute call for essays, an emerging theme is the life and health insurance sector evolving to meet this new era of "catastrophic complexity." The 2025 Los Angeles wildfires underscore this turning point, showing that long-term solvency now depends on integrating risk reduction before disasters and resilience after they occur. This transition requires insurers to move beyond being purely payors toward becoming proactive partners in climate adaptation and societal stability.

CLIMATE CHALLENGE BEYOND PHYSICAL DAMAGE

Climate change poses a unique threat to life and health insurers because human health outcomes are nonlinear and often delayed. Unlike P&C risks, where damage is usually immediate and visible, climate events like wildfires initiate a "cascade" of health impacts.

- Nuanced Mortality and Morbidity: While mortality spikes may occur within days due to respiratory failure, other consequences such as heart disease complications, asthma, or reduced lung capacity in children may emerge over years. Research linked wildfire smoke exposure to a 42% increase in sudden cardiac arrests in affected areas (Ali, Syed Danish, CSPA, 2025), (Livingston, Sathiya, 2025).

- Behavioral Health Burdens: Catastrophes trigger long-term psychological trauma, including PTSD, anxiety, and depression, which rival the physical damage in terms of societal cost (Livingston, Sathiya, 2025).

- Systemic Infrastructure Stress: Catastrophes disrupt the very systems meant to provide care. Hospital evacuations, power outages, and pharmacy shortages lead to "indirect" mortality caused by gaps in medication adherence and overwhelmed emergency services (Ali, Syed Danish, CSPA, 2025), (Livingston, Sathiya, 2025).

WHY TRADITIONAL MODELS ARE FAILING

Traditional actuarial models could increasingly be viewed as "broken" because they rely on assumptions of stability that no longer exist.

- Static vs. Dynamic Risk: Historical models assume that environmental conditions stay relatively stable. However, climate change has altered the underlying risk profile of entire populations, making historical data a poor predictor of future events.

- Failure of Diversification: Traditional insurance operates by diversifying away accidents via risk pooling. Climate change is not an accident; it is a systemic shift that affects massive populations simultaneously, making it impossible to "diversify away" (Lee, Lauren, SOA Candidate, 2025).

- "Coordinates" Problem: Property models use static coordinates to determine risk. In contrast, humans are mobile; their distance from a hazard changes constantly, making it impossible for traditional "box" models to predict injury or exposure with certainty (Rajeshwari Vs, FIA, 2025).

MODELING LIMITATIONS AND DATA CHALLENGES

Developing robust L&H catastrophe models is hindered by structural and data-related hurdles that require a "shift in mindset."

- Attribution and Boundaries: It is extremely difficult to define the geographic and temporal boundaries for health claims. Unlike a fire-damaged house, symptoms from inhaling particulate matter can appear months later, making it hard for insurers to treat all claims as originating from a single event (Rajeshwari Vs, FIA, 2025).
- Data Silos: Health records, environmental satellite data, and insurance claims often live in separate systems, preventing a comprehensive view of risk (Livingston, Sathiya, 2025).
- Lack of Longitudinal Data: There is a significant shortage of long-term data connecting specific catastrophes to downstream consequences decades later (Lee, Lauren, SOA Candidate, 2025).
- Working Out the Challenges: Actuaries are beginning to bridge these gaps through interdisciplinary collaboration. By integrating climate science, epidemiology, and data science, insurers can adopt public health measures such as the Value of Statistical Life (VSL), Years of Life Lost (YLL), and Cost of Illness (COI) to better quantify the economic costs of health impacts (Ali, Syed Danish, CSPA, 2025), (Rajeshwari Vs, FIA, 2025) .

A FUNDAMENTAL SHIFT IN EXPOSURE AND VULNERABILITY

Catastrophe modeling is shifting from a tool for capital adequacy to an operational decision-support system.

- Reconceptualizing Vulnerability: Vulnerability is no longer just about building codes; it is about social determinants of health. Factors like age, pre-existing conditions, income, and housing quality create asymmetric claims impacts that would be modeled to protect the most at-risk populations.
- Continuity of Care: Modeling now supports "resilience tactics" during crises. During the 2025 LA wildfires, insurers were required to ensure uninterrupted access by allowing 90-day prescription refills, waiving delivery charges, and expanding telehealth access (Whittaker, Gregory, FSA, FASSA, 2025).
- Proactive Triage: Predictive models can now flag high-risk clients to trigger health alerts or evacuation advice before conditions worsen, potentially reducing the severity of claims (Livingston, Sathiya, 2025).

THE POWER OF ADVANCED TECHNOLOGIES

Advanced technologies are the primary enablers of this transition from reactive to proactive management.

- Artificial Intelligence and Machine Learning: AI can process massive amounts of electronic health records to identify trends and predict peaks in health impacts. Natural Language Processing (NLP) detects underreported effects, like chronic stress, by analyzing clinical notes and claims data (Livingston, Sathiya, 2025).
- Remote Sensing and GIS: Satellite imagery and geographic mapping provide real-time views of fire spread overlaid with demographic data, pinpointing vulnerable populations in the path of smoke plumes (Livingston, Sathiya, 2025).
- Quantum Computing: For systems with “highly interdependent" variables such as population displacement and air pollutant exposure, quantum algorithms like quantum annealing offer the ability to model the

complexity that traditional machines find intractable. Quantum Amplitude Estimation (QAE) can be used for sensitivity analysis to identify specific parameters that trigger mortality risks (Ali, Syed Danish, CSPA, 2025).

INSURERS AS ACTIVE PARTICIPANTS IN PUBLIC-HEALTH RESILIENCE

Insurers are evolving into "resilience partners" by actively intervening to minimize loss of life.

- Risk Reduction via Preventative Care: Just as P&C insurers require flame-resistant materials, L&H insurers are focusing on health screenings for wildfire pollutants. Early detection of complications from lead or particulate matter leads to better outcomes and lower long-term costs (Lee, Lauren, SOA Candidate, 2025).

- Remote Monitoring and Early Intervention: During the COVID-19 pandemic, equipping high-risk customers with pulse oximeters for at-home monitoring led to a 38% lower fatality rate through early intervention (Whittaker, Gregory, FSA, FASSA, 2025).

- Virtual Health Expansion: By covering 24/7 telehealth and nurse hotlines, insurers ensure that displaced populations can receive care even when physical medical infrastructure is destroyed or inaccessible (Whittaker, Gregory, FSA, FASSA, 2025).

- Social Cohesion and Community Building: Innovative programs like South Africa's "Hollard Change Maker" allow policyholders to earn premium rebates by volunteering, fostering social stability after mass riots. Similarly, agricultural training programs for unemployed youth help build long-term food security and community resilience (Whittaker, Gregory, FSA, FASSA, 2025).

Conclusion

Catastrophe modeling has evolved from a specialized actuarial tool into a core framework for managing climate-driven uncertainty in a world where historical data no longer reliably predicts future risk. The transition from three to four modeling modules reflects a broader recognition that losses are shaped by the interaction of hazard, exposure, vulnerability, and interconnected systems. As climate change intensifies extreme events, these interactions grow more complex and increasingly affect life and health insurers, whose risks are dynamic, delayed, and population-wide. Traditional actuarial assumptions—stability, diversification, and clearly bounded events—are proving inadequate in the face of systemic climate risk. Health impacts from catastrophes often unfold over months or years, shaped by behavioral responses, infrastructure disruptions, and social determinants of health. As a result, exposure and vulnerability could be redefined around people, mobility, and continuity of care rather than fixed locations or assets.

Advances in data availability, computing power, and modeling techniques now enable this shift. Artificial intelligence, geospatial analytics, and emerging computational approaches are transforming catastrophe models into forward-looking decision-support systems rather than purely retrospective loss estimators. When integrated with climate science and public-health metrics, these models can support early intervention, targeted risk reduction, and resilience planning that materially reduce both human and financial losses. This evolution positions insurers not just as post-event payors, but as proactive partners in disaster preparedness and recovery. By embedding catastrophe modeling into prevention, response, and long-term adaptation strategies, insurers can help stabilize communities while protecting their own solvency. In an era of structural climate uncertainty, the true value of catastrophe modeling lies not only in quantifying loss, but in shaping outcomes.

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