Catastrophe and Climate

Risk Management and Climate Risk: A Collection of Essays

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SOA Research INSTITUTE

SOCIETAL PURPOSE

Risk Management and Climate Risk

A Collection of Essays

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INTRODUCTION

The Society of Actuaries Research Institute Catastrophe & Climate Strategic Research Program Steering Committee issued a call for essays to supply actuaries and others with ideas and methods for identifying, quantifying, reporting, and managing the financial impacts of climate-related risks, and invited essay submissions on how climate risks can be integrated into the risk management processes used by actuaries and other risk managers.

The thirteen essays that form this collection are included below. The top five essays chosen for creativity, originality, and the extent to which an idea might help promote further thought in this area, are noted here:

Award Winner	**Cross-Platform Climate Catastrophe Models: How LLM Translation Enables Actuarial Adoption** Robert Lieberthal, Ph.D.
Award Winner	**The Hidden Climate Exposure: How Operational Fragility Becomes a Systemic Risk for Insurers** Sathiya Livingston
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Thank you for your interest in this essay collection. We welcome your feedback via the survey banners embedded in this document.

THE CALL FOR ESSAYS

BACKGROUND AND PURPOSE

Climate-related risks, including those linked to climate change, can significantly impact the operational and financial performance of the institutions that actuaries serve. Looking ahead, these risks can lead to major effects on mortality, morbidity, property damage, liability, and asset values. Therefore, actuaries and other risk managers dealing with risks need to address these risks in a systematic and comprehensive manner.

Climate risk is complex, encompassing a wide range of damages and losses linked to climate and weather events, such as storms, wildfires, floods, heatwaves, and effects on food and water quality. Therefore, recognizing and integrating these risks into regular management practices can be challenging.

In addition, both expected and unanticipated effects may be considered when adapting existing processes, and mitigating (reducing greenhouse gas emissions) may be involved. Educating key stakeholders, including policyholders, staff, and those involved in corporate governance, may also be relevant.

Key steps in the risk management process include identifying and quantifying the costs involved. These can be performed either explicitly or implicitly in combination with other risks. The question of the extent of effort needed for estimating and projecting these risks can be significant.

This Call for Essays aims to supply actuaries and others with ideas and methods for identifying, quantifying, reporting, and managing the financial impacts of these risks. In addition, reporting requirements—whether for regulators or investors—can enhance understanding of the underlying conditions leading to these risks, which can assist in evaluating them, including a framework for decision-making and suggestions for future research.

TOPICS OF INTEREST

The SOA Research Institute (SOA) invites essay submissions on how climate risks can be integrated into the risk management processes used by actuaries and other risk managers. This call has been intentionally kept broad to encourage diverse perspectives and approaches. Contributors may choose to explore one or more of the sample topics listed below or propose alternative subjects that align with the overall theme and objectives of this Call. The examples provided are illustrative and neither comprehensive nor exhaustive.

Sample topics include:

- A typology describing the range of climate and weather-related risks that could be considered.
- A framework for evaluating actuarial and risk management of these risks.
- How these risks could be managed by a standard or specialized risk management process of an entity, such as an insurance company, pension program, or other risk-bearing organization?
- Case studies on implemented processes, programs, and initiatives.
- For insurance companies, how could these risks be incorporated into an actuary's ORSA (Own Risk and Solvency Assessment) process? Or for other reporting purpose?
- The application of AI in decision-making processes
- Discussions regarding quantitative techniques for evaluating these risks.
- Practical applications in actuarial work.

Although this Call for Essays is primarily focused on climate-related risks, it can also cover the management of risks from other catastrophes or disasters, such as earthquakes and pandemics.

Award Winner

Cross-Platform Climate Catastrophe Models: How LLM Translation Enables Actuarial Adoption

Robert D. Lieberthal, Ph.D.

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

INTRODUCTION

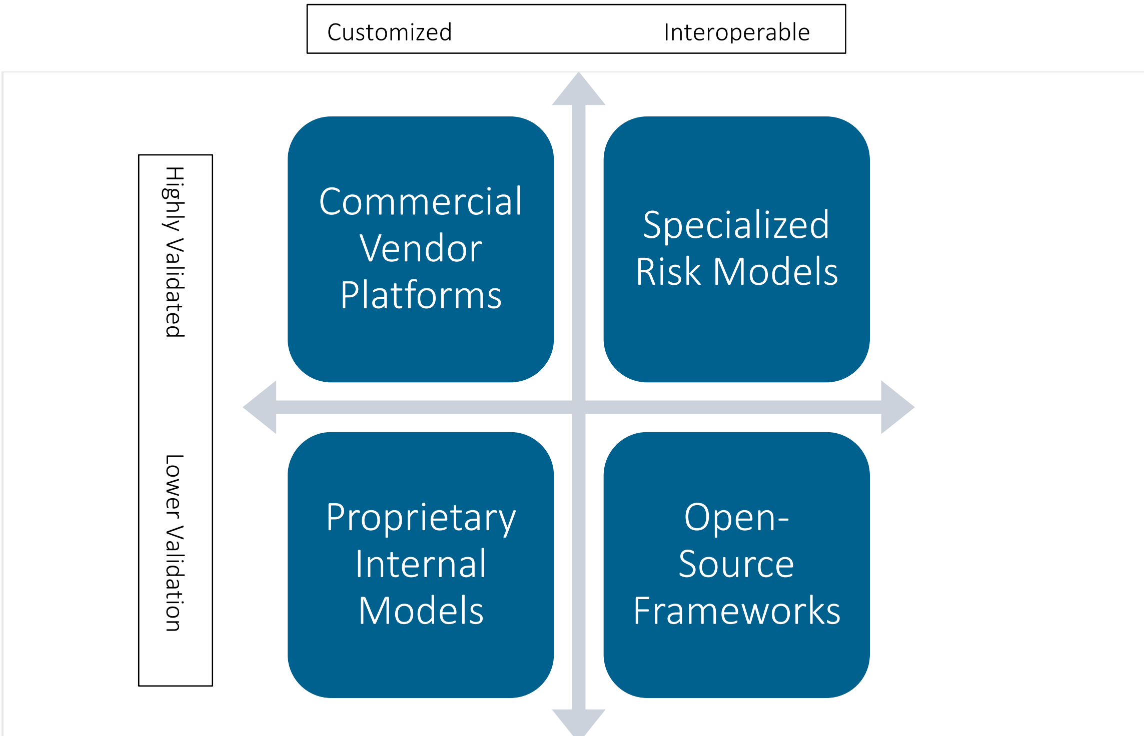
Climate change creates catastrophe scenarios that actuaries must continuously learn to model. When natural disasters strike, health system disruption follows a predictable pattern that generates correlated exposures across multiple insurance lines. Hurricane Maria's impact on Puerto Rico demonstrates this dynamic. The category four hurricane that struck in September 2017 produced cascading failures across healthcare, power, water, and transportation infrastructure that persisted for months (Cowan and Zavala, 2021). The initial impact involved immediate physical damage, but secondary effects proved equally consequential.

The global scale of climate-related health impacts extends far beyond individual catastrophic events. Non-optimal temperature exposure has been associated with 5 million deaths annually worldwide, with 9.43% of global deaths attributable to cold and hot temperatures (Zhao et al., 2021). Wildfire-related particulate matter presents another growing threat. Recent actuarial research quantifies how PM2.5 exposure during wildfire season affects prevalence of circulatory conditions, mental and behavioral disorders, neoplasms, and respiratory conditions (Yi et al., 2025). Complementary mortality analysis demonstrates that wildfire smoke impacts extend beyond immediate respiratory effects to include systemic inflammation and cardiovascular incidents (Titon et al., 2025). Cross-platform models, enabled by large language model (LLM) translation capabilities, preserve computational power while maintaining accessibility for broader actuarial adoption. This capability has value because climate risks require customization that varies by use case, line of business, and analytical need.

A TYPOLOGY OF CLIMATE CATASTROPHE MODELING

Climate catastrophe models can be categorized along two dimensions: validation maturity and customization flexibility. This framework helps actuaries select appropriate tools for different organizational contexts and risk questions.

Commercial vendor platforms occupy the high-validation, low-customization quadrant. These platforms provide extensively validated models for a wide range of hazards. They benefit from substantial development resources, industry acceptance, and refinement informed by user experience. Many vendors now offer climate-conditioned catalogs enabling scenario analysis under different warming pathways. The primary limitation involves customization constraints imposed by vendor development cycles and licensing frameworks. Organizations seeking to incorporate emerging climate science or test novel risk scenarios often find vendor timelines incompatible with rapid analytical iteration.



Specialized frameworks represent a different approach. Recent actuarial research has developed climate-adjusted models that incorporate pollution variables and temperature effects into stochastic mortality projections. For wildfire impacts specifically, these frameworks separate baseline mortality from climate-sensitive components, enabling projections under alternative pollution scenarios while preserving familiar actuarial structures (Titon et al., 2025). However, broader deployment may require translation into spreadsheet formats or other internal tools for stakeholder review, creating a barrier to adoption across organizational hierarchies.

Proprietary internal models occupy the low-validation, low-customization quadrant. Organizations may develop catastrophe estimates using internally maintained spreadsheets with limited external validation or peer review. These models offer familiarity and ease of inspection but lack computational scalability for complex climate scenarios involving correlated exposures, time-varying parameters, or high-dimensional uncertainty. The limited interoperability means insights remain locked within specific organizational workflows, making it difficult to incorporate external research or compare results across industry frameworks.

Open-source frameworks represent an emerging category in the high-customization, low-validation quadrant. Recent work demonstrates how modular, auditable methodologies can be implemented with cross-platform accessibility (e.g., Lieberthal et al., in progress). A useful design pattern develops both code implementation (for computation) and spreadsheet implementation (for transparency), intended to be mathematically equivalent. This dual-platform approach supports and facilitates internal model approval and aligns with expectations for clear documentation. These approaches enable rapid incorporation of emerging research and customization for organization-specific portfolios, though validation quality may vary by implementation and requires careful implementation.

LLM TRANSLATION AS AN INTEROPERABILITY LAYER

Large language models now make it feasible to translate actuarial calculations between platforms while preserving mathematical logic. From an economic perspective, this development addresses a market friction that has historically limited catastrophe modeling accessibility. The friction involves a coordination problem between technical and business stakeholders. Risk committees and boards may prefer examining explicit spreadsheet formulas, while actuarial and data science teams require computational efficiency for Monte Carlo simulation, reverse sensitivity analysis, or portfolio-level aggregation.

Actuaries developing loss allocation algorithms in R and Python can generate equivalent formulas via a combination of LLM translation and open-source packages (Gazoni and Clark, 2024; Barbone et al., 2026). The work then primarily involves verifying that both platforms produce equivalent results within numerical tolerances. This cross-platform translation effectively turns the LLM into an interoperability layer that bridges code-centric and spreadsheet-centric environments. The same underlying logic becomes both high-performance and highly inspectable, depending on the audience.

An open research question concerns which programming languages produce more accurate translations. R's statistical orientation and relatively standardized syntax for common actuarial operations may produce more consistent translations for advanced modeling constructs.[1] Python's broader adoption across industries may increase the volume and diversity of training data, potentially improving translation performance for general modeling patterns and data-handling workflows. Systematic evaluation of translation accuracy across languages represents an important research direction, particularly for complex operations like credibility weighting, mixture distributions, correlation structures, and time-varying hazard intensities that are central to climate catastrophe risk estimates.

VALIDATION AND GOVERNANCE AS RESEARCH FRONTIERS

Automated validation presents a critical frontier for cross-platform climate modeling. Current practice relies on manual verification that spreadsheet and code implementations produce identical results for test cases, supplemented by spot checks and peer review. While effective for smaller models, manual approaches become burdensome for large-scale, multi-peril climate scenarios with complex dependencies. The economic cost of manual validation creates a barrier to model iteration, slowing the incorporation of emerging climate science into actuarial practice.

A next step involves developing systematic pipelines that audit spreadsheet formulas against reference code implementation, identify discrepancies, and track resolution. Such pipelines could integrate with version control systems, enabling continuous verification as models evolve and new climate research is incorporated. When combined with LLM translation, this suggests a model lifecycle process where updates are made in code, translated to spreadsheets, automatically regression-tested across platforms, and documented for governance and regulatory review.

Credibility theory provides conceptual tools for thinking about these validation pipelines. In many catastrophe and climate-related applications, parameter uncertainty dominates process uncertainty because observational histories are short, nonstationary, or incomplete relative to the tail events of interest (Guin, 2018; Jensen and Traeger, 2024). Explicitly integrating parameter-uncertainty diagnostics into cross-platform validation could make climate models more robust by stress-testing parameter sets or applying credibility-style weighting to alternative specifications.

[1] The author thanks an anonymous discussion with a colleague that included this point.

PATH FORWARD: DEMOCRATIZING SOPHISTICATED CLIMATE RISK ANALYSIS

Climate catastrophe models benefit from flexibility because exposure patterns continually evolve as climate science advances. Actuarial organizations increasingly use multiple modeling approaches: vendor models for regulatory capital and well-established perils, specialized frameworks for mortality and morbidity projections, and open or exploratory tools for emerging exposures. The challenge involves ensuring that insights from these diverse tools are accessible, explainable, and auditable across the full range of stakeholders involved in risk management and governance.

Cross-platform capabilities enabled by LLM translation support this ecosystem by reducing barriers between computational environments and facilitating validation across technical backgrounds. For climate risks specifically, where parameter uncertainty, model risk, and deep uncertainty about future hazard pathways often outweigh the information in historical frequencies, this combination of analytical power and organizational accessibility is particularly valuable. Smaller insurers or pension funds without extensive data science teams can leverage shared frameworks and then translate results into formats suitable for boards, rating agencies, and regulators.

The emergence of LLM translation as an interoperability layer represents both opportunity and responsibility for the actuarial profession. Organizations previously constrained by tool limitations or expertise gaps can now access sophisticated modeling techniques while maintaining transparent validation processes. However, actuaries must help design standards, testing protocols and governance practices that ensure cross-platform models remain reliable as they are updated in response to new climate science and regulatory expectations.

In the context of climate risk, where impacts on mortality, morbidity, property, and assets are likely to intensify over the coming decades, the value of accessible and trustworthy models extends beyond technical sophistication. The documented health effects of temperature extremes, wildfire smoke, and compound disaster scenarios demonstrate the scale of risk that actuarial organizations must quantify and manage. Cross-platform climate catastrophe modeling, supported by LLM-enabled translation and robust validation, can help ensure that innovation in climate risk assessment reaches practitioners who need it, regardless of their preferred analytical environment. As climate scenarios continue evolving, this accessibility may prove as important as the analytical sophistication itself in supporting informed, forward-looking risk management decisions.

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Robert Lieberthal, Ph.D., is Founder and Senior Principal at Lieberthal & Associates, LLC. He can be reached at rob@lieberthalandassociates.com.

Award Winner

The Hidden Climate Exposure: How Operational Fragility Becomes a Systemic Risk for Insurers

Sathiya Livingston

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INTRODUCTION

Climate risk has become a defining preoccupation in actuarial practice, yet the profession's frameworks remain largely concentrated on external hazards—physical perils such as hurricanes, floods, wildfires, and heatwaves, or transitional pressures such as policy change and carbon pricing. What is often less explicitly examined is the climate-driven vulnerability of insurers' own operational architectures. As climate volatility grows, insurers face correlated disruptions to claims volumes and operational capacity. To address this blind spot, this essay introduces the **OFCR Framework (Operational Fragility in Climate Risk)**—a conceptual model for understanding how operational disruptions interact with claims, reserving, capital, and enterprise risk. Through two fictionalized yet realistic case studies, the essay illustrates how climate-linked operational failures distort development patterns, widen uncertainty, and challenge governance. The essay concludes by discussing how this perspective may broaden actuarial climate-risk thinking.

CLIMATE RISK HAS MOVED INSIDE THE INSURER

The actuarial profession has made enormous progress in understanding climate risk, but much of the attention has remained anchored in the physical world—storms that damage roofs, heatwaves that affect mortality, or wildfires that erase entire communities. These are critical concerns. Yet the industry often treats climate events as if they occur at arm's length from the insurer, as though the insurer is a passive observer holding a checkbook.

This assumption is breaking down.

Climate events have the potential to disrupt the systems insurers rely upon:

- Contact centers
- Claims intake platforms
- Document-processing hubs
- Offshore operational centers
- Cloud-region dependencies
- Actuarial modeling environments
- Third-party vendor networks

This convergence creates a new category of correlated risk: climate event **+** operational disruption **occurring simultaneously**.

When a climate-event triggers claims *and* impairs the insurer's capacity to respond, the result is not additive loss—it is a multiplier.

What was once treated as a hypothetical risk can be viewed as increasingly relevant in climate-risk discussions. Operational fragility may function as a climate-risk accelerant.

THE UNSEEN AMPLIFIER: HOW OPERATIONAL DISRUPTION MAGNIFIES LOSS

When actuaries model climate risk, they typically estimate:

- Frequency
- Severity
- Exposure distribution
- Vulnerability curves
- Loss development
- Capital needs

But these projections implicitly assume that the insurer's internal systems will continue to operate as expected.

The problem is that climate volatility does not respect this assumption.

When operational performance deteriorates during a climate event, the insurer's financial exposure is magnified through several mechanisms:

- **Delayed claims progression:** Disruptions to intake workflows, indexing, or initial triage slow claim setup. This delay affects inspection timing, loss mitigation, settlement pace, and ultimately severity.
- **Distorted reserving signals:** When case setup lags or documentation is incomplete, actuarial teams receive delayed or degraded data. This creates noise in triangles, complicates projections, and widens confidence intervals.
- **Extended loss tails:** Delays encourage disputes, re-openers, litigation, and worsening damage. These lengthen tail patterns and shift expected ultimate costs.
- **Elevated LAE:** Manual workarounds, overflow staffing, and inefficient routing increase loss adjustment expenses.
- **Liquidity strain:** Slower adjudication delays recoveries from reinsurers or subrogation, shifting liquidity timing.
- **Capital uncertainty:** Operational fragility introduces new volatility into emerging losses, affecting capital planning and risk appetite.

These distortions seldom appear in traditional models, yet they are increasingly fundamental to climate-driven performance.

CASE STUDY #1: THE HEATWAVE THAT SLOWED THE SYSTEM

Consider a fictionalized multi-line insurer headquartered in the United States. Its operations depend on three major hubs:

- A claims processing unit in Manila
- A document-scanning and ingestion team in Phoenix

- A cloud region based in Singapore

During an extreme heatwave, Manila experiences rolling blackouts. Backup generators prove insufficient for sustained heat, leading to fluctuating system uptime and reduced productivity.

Phoenix simultaneously experiences elevated auto, property, and health-related claims due to record temperatures.

Meanwhile, a power-demand spike in Singapore briefly disrupts the cloud region's performance.

The insurer is hit from three directions:

- Increased claims frequency
- Impaired claims-processing capacity
- Periodic data-system delays

The combined impact reshapes the financial pattern:

- Claims linger in queues, delaying review and settlement
- Initial reserves and development signals become less reliable
- LAE increases due to manual workarounds and reprocessing
- Loss-development patterns and capital projections become more volatile

The event is not catastrophic in the physical sense, yet the financial outcome resembles that of a mid-scale catastrophe—because operational fragility became a second hazard.

THE INTERDEPENDENCE PROBLEM: MODERN INSURANCE IS A NETWORK OF NETWORKS

The modern insurance enterprise is a distributed, digital, multi-site, multi-vendor ecosystem. This increases efficiency—but also introduces fragility.

Operational dependency structures have become deeply intertwined with climate-sensitive geographies:

- U.S. Gulf states (hurricanes) host major call centers
- India and the Philippines (heat, cyclones, monsoons) host processing hubs
- Western U.S. state (wildfires, heatwaves) house tech and cloud-engineering teams
- Europe (heatwaves, grid instability) contains data science centers

At the same time, these geographic concentrations intersect climate-sensitive digital infrastructure, vendor networks, and remote-work dependencies.

Climate change does not merely increase claims—it alters the functioning of the insurance machinery.

This is the interdependence problem: vulnerabilities in one part of the operational ecosystem propagate across the enterprise.

CLIMATE RISK AS A MULTI-LAYERED SYSTEMS PROBLEM

Conceptual insights from engineering, ecology, and systems theory describe modern organizations as 'tightly coupled systems'—networks in which stress in one node can propagate quickly across the entire structure. Insurance has quietly become one such system. What differentiates the current era from prior decades is the intensity and simultaneity of climate stressors.

From a systems and risk-theory perspective, climate volatility introduces the possibility of more geographically synchronized, prolonged, and layered stress events. Under such conditions, insurers may face scenarios in which operational vulnerabilities are triggered at the same time that claims obligations surge.

This creates **climate-induced systemic coupling**: claims intake, digital platforms, vendor networks, and actuarial pipelines cease to act independently. The insurer begins to behave like a single interconnected organism rather than a set of distributed capabilities.

In a systems context, climate risk becomes less about the frequency of a hazard and more about its ability to cause cascading failures. This reframing matters because cascading failures can produce nonlinear loss patterns, where modest operational slowdowns generate outsized financial distortions. Once delays compound and feedback loops emerge, outcomes can exceed the expectations of even sophisticated models.

In this sense, operational fragility is not simply an administrative concern—it is a systemic property of the insurance enterprise under climate stress.

CASE STUDY #2: THE ICE STORM THAT DISRUPTED MORTALITY CLAIMS

A fictionalized life insurer based in the Midwest experiences a severe ice storm that overburdens local hospitals and elevates mortality rates among elderly populations.

What proves more damaging is the sequence of operational effects: Mail intake, customer-service staffing, remote-access infrastructure, and offshore data-entry capacity are simultaneously disrupted across multiple locations.

The result: incoming death claims stack unprocessed.

Families wait, call queues grow, complaints rise, and regulators raise concerns about delays.

Reserving becomes unstable as case estimates lag, documentation issues drive reopeners, and capital teams struggle to adjust projections with incomplete data.

The financial impact flows as much from system degradation as from the storm itself.

INTRODUCING THE OFCR FRAMEWORK: A CONCEPTUAL MODEL FOR OPERATIONAL FRAGILITY IN CLIMATE RISK

The OFCR Framework provides a thought-leadership lens for incorporating operational-climate interdependence into climate-risk thinking. It contains five conceptual pillars.

1. **Exposure Mapping (where climate risk meets operational architecture).** This involves mapping climate-sensitive exposures across:

- Geographic nodes
- Digital infrastructure
- Staffing clusters
- Vendor locations

- Cloud regions
- Claims supply chains

The goal is to understand the climate vulnerability of the insurer's own ecosystem.

2. **Dependency Structures (where single points of failure reside).** Modern insurance relies on concentration:

- A single offshore center for a key workflow
- One cloud region for critical systems
- One vendor for indexing
- One region for customer support

Climate risk interacts with these dependencies and can turn them into systemic risk points.

3. **Propagation Channels (how operational disruption becomes financial loss).** This pillar conceptualizes how disruptions cascade into:

- Reserving uncertainty
- Tail-length extension
- LAE inflation
- Liquidity timing shifts
- Reinsurance friction
- Volatility in IBNR emergence

Propagation channels translate operational impact into actuarial terms.

4. **Resilience Levers (high-level concepts for stress absorption).** Within a thought-leadership context, resilience levers refer to conceptual categories of mitigation such as:

- Geographic diversification
- Automation of climate-sensitive workflows
- Multi-node operational designs
- Redundancy of digital infrastructure
- Climate-informed vendor governance

These are strategic concepts, not tactical corporate prescriptions.

5. **Governance Embedding (integrating operational fragility in risk thinking).** Climate-linked operational fragility can be conceptually embedded within:

- ERM frameworks
- Climate-risk taxonomies
- ORSA narratives
- Risk-appetite discussions
- Strategic risk reviews

The emphasis is on broad governance integration rather than process-level instructions.

QUANTIFICATION: CONCEPTUAL APPROACHES FOR ACTUARIES

Thought leadership on this topic includes high-level approaches actuaries may consider conceptually without specifying processes or corporate actions.

1. **Climate-linked scenario design, examples include:**

- Operational outage during a climate event
- Cloud-region stress coinciding with CAT surge
- Workforce impairment during extreme heat

These scenarios highlight interdependence between hazard and operational capacity.

Conceptual propagation modeling. Actuaries can think in terms of how operational delays shift:

- Reserve uncertainty
- Severity expectations
- Loss-adjustment patterns
- Tail distributions

This creates a more holistic view of risk.

2. **Stress-band widening:** Operational fragility conceptually widens the band of plausible development outcomes.

3. **Time-based sensitivity thinking.** Actuaries may consider how timing disruptions affect:

- IBNR emergence
- Settlement patterns
- Liquidity modeling

These conceptual tools help integrate operational fragility into climate-risk thinking without prescribing corporate processes.

CORRELATION STRUCTURES AND THE CHALLENGE OF CLIMATE-ERA VOLATILITY

One of the most difficult conceptual challenges in integrating operational fragility into climate-risk thinking is understanding correlation. Traditional actuarial models generally assume that operational performance is uncorrelated with hazard severity. This assumption has been implicitly embedded in decades of reserving, capital modeling, and catastrophe analysis.

But climate dynamics are creating new correlation structures.

Conceptually, extreme climate events create conditions under which operational throughput may move inversely to claims volume. In such scenarios, rising claim demands can coincide with declining operational efficiency, a dynamic that runs counter to traditional modeling assumptions. Framed this way, the interaction can be understood as a potential volatility multiplier, in which hazard stress and operational strain compound financial uncertainty.

From a thought-leadership perspective, actuaries may conceptualize this as a form of "correlation drift," in which the relationships among operational metrics and loss metrics shift during climate events. Drift does not necessarily occur gradually. It may emerge suddenly when certain thresholds—temperature, grid instability, flooding, or infrastructure stress—are crossed.

It raises practical modeling questions: what if claim-reporting lags lengthen nonlinearly at temperature thresholds? How do loss-development patterns behave when operational capacity is simultaneously impaired across multiple continents? Conceptualizing these interactions—rather than assuming historical independence—positions actuaries to develop more resilient risk perspectives.

LINKING OPERATIONAL FRAGILITY TO QUANTITATIVE RISK MEASURES

While the OFCR Framework is conceptual by design, its elements can be mapped to quantitative risk measures already familiar to actuarial practice. For example, operational fragility can be reflected in climate-linked stress testing by adjusting assumptions related to claim-reporting lags, loss-development variability, or loss-adjustment expense during extreme-event scenarios. In a reserving context, such adjustments may manifest as wider confidence intervals, altered tail factors, or increased uncertainty around IBNR emergence under stressed operational conditions.

From a capital and enterprise risk perspective, operational-climate interdependence can be incorporated through scenario-based modeling rather than point estimates. Climate scenarios that combine hazard severity with constrained operational capacity may be evaluated using existing tail-sensitive metrics, such as Value-at-Risk or Tail Value-at-Risk, to assess the sensitivity of capital requirements to correlated disruption. Importantly, the framework does not require the invention of new metrics; rather, it provides a structured way to interpret changes in familiar quantitative outputs when operational assumptions are stressed alongside climate hazards.

In this sense, the OFCR Framework functions as a bridge between qualitative risk identification and quantitative risk measurement, helping actuaries understand how climate-driven operational fragility may influence modeled outcomes without prescribing specific parameter values or modeling techniques.

WHY THIS RISK HAS BEEN OVERLOOKED

Much of the industry still operates on inherited mental models built for a world where operational capacity was largely stable, and climate events were episodic rather than systemic.

Legacy frameworks often treated climate risk as external to the insurer, implicitly assuming operational stability during climate events. Operational risk and actuarial modeling were therefore frequently considered separate domains. In addition, historic datasets were not designed to capture correlated operational-climate disruptions of this nature.

As climate events grow geographically wider, more frequent, and more synchronous, operational fragility may therefore be viewed as an increasingly important systemic exposure.

THE EXPANDING ROLE OF ACTUARIES

Actuaries are well positioned to contribute thought leadership on this topic due to their expertise in:

- Risk interdependence
- Capital structure
- Uncertainty quantification

- Long-tail modeling
- Scenario construction
- Enterprise risk perspectives

The profession has the analytical tools to contribute meaningfully to broadening the climate conversation beyond portfolio losses toward organizational resilience.

For actuaries engaged in ORSA, capital modeling, and climate scenario design, recognizing operational fragility as a correlated climate exposure may change how uncertainty is framed in these contexts. This perspective builds on established actuarial approaches rather than departing from them.

CONCLUSION: CLIMATE CHANGE WILL TEST THE INSURANCE ENTERPRISE FROM THE INSIDE OUT

Climate change is poised to challenge insurers in ways that extend far beyond underwriting. The next decade will expose how well insurance enterprises themselves can withstand disruption. Operational fragility may represent an increasingly important dimension of climate risk—a dimension that has, until now, been largely underexamined.

This essay argued that the structures enabling insurers to function—claims workflows, vendor networks, staffing models, cloud ecosystems, and digital architecture—are increasingly climate-sensitive. It introduced the OFCR Framework as a way to conceptualize this emerging class of risk and to integrate operational fragility into climate thinking at a governance and enterprise level.

The framework is intended to support interpretation of quantitative results under climate stress rather than to replace existing actuarial models or metrics. The insurance sector has long defined climate risk through the lens of the perils it insures. This analysis suggests the value of also understanding climate risk through the lens of the insurer itself. Climate change is not only reshaping the world insurers protect—it is reshaping the environment in which insurers must operate.

This analysis suggests the value of recognizing that climate risk is no longer solely a matter of external hazard, but a test of internal structure.

THE BROADER STRATEGIC HORIZON

As climate volatility continues to reshape global infrastructure, supply chains, and workforce stability, insurers will increasingly face the challenge of operating in an environment where external shocks and internal capabilities are interconnected. This new landscape places a premium on intellectual frameworks that acknowledge interdependence, recognize the limits of historical data, and adapt to emerging climate-era dynamics. For actuaries, expanding climate-risk thinking to include internal operational resilience is not merely an academic exercise—it is a prerequisite for building the insurance systems of the future.

Organizations that understand this shift early may help shape the next era of risk management.

THE FUTURE ARC OF OPERATIONAL–CLIMATE RISK

While climate-linked operational fragility is already visible today, its future trajectory suggests even deeper challenges—and opportunities—for insurers. Several global trends indicate that climate-era operational risk will not remain a peripheral concern but rather evolve into a central axis of enterprise resilience. Many climate-risk scenarios consider the possibility of more temporally clustered events, creating periods where multiple regions experience stress simultaneously. In such multi-hazard environments, dependencies once assumed to be independent—such as U.S. call centers, Asian processing hubs, and European data-science teams—may experience parallel disruptions. Cross-regional operational diversity, once viewed as a safeguard, could become a source of shared vulnerability.

The growing digitization of insurance introduces new climate-sensitive touchpoints. Data centers require stable electricity and cooling; transmission networks depend on grid stability; remote-first workforces rely on climate-resilient broadband infrastructure. As these dependencies expand, so does the network through which climate-induced operational stress can propagate.

Finally, some regulatory frameworks may place greater emphasis on operational resilience alongside capital adequacy. The evolution of ORSA and climate-stress frameworks suggests a future where insurers must demonstrate not only exposure modeling sophistication but also credible strategies for maintaining continuity during correlated operational and hazard shocks.

Understanding this arc is essential: the insurers that prepare for next-generation operational-climate risk will shape new standards of industry stability.

It is, at its core, a test of internal strength. Insurers have long measured the durability of the risks they underwrite; the coming decade will measure the durability of the insurers themselves. The institutions that recognize this shift early—and respond with imagination rather than inertia—will not simply withstand the climate era. They may help shape evolving perspectives on resilience in the climate era.

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Sathiya Livingston is a Business Development Manager – Insurance Services for Flatworld Solutions Pvt LTD. He can be reached at Sathiya.l@flatworldsolutions.com.

Award Winner

Incorporating Climate Risk Modeling into ORSA Reporting

Terry Narine, FSA, FCIA

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

INTRODUCTION

Imagine you are the CRO of XYZ Life Insurance company. XYZ is not domiciled or doing business in a state where the NAIC Climate Survey Disclosure is available. While sitting in your office one afternoon, you receive an email from the CEO. Her email mentions that the Board of Directors has just reviewed your most recent ORSA report. The Board is somewhat surprised that there are no references in the ORSA to climate risk. The CEO is questioning what your intentions are with regard to incorporating climate change risks in the next ORSA report. You panic on reading the email as your mind races to formulate a response. Climate change risk is something you have been aware of on the horizon of your work. However, because of your many job duties and more pressing needs, you have unfortunately not given it the attention it deserves.

Now all that is about to change as you have no choice in this regard. You respond to the CEO's email by letting her know that you and your team will be looking into the matter and will get back to her shortly. She emails with thanks. She also mentions that one of the board members had mentioned a situation where a competitor of XYZ had recently been sued by an activist shareholder for not doing enough to address climate risks. Your stress level just increased significantly. But have no fear. The pathway below will shine a light on one possible approach to modeling climate change in the ORSA report.

STANDARDS

Your first step is to ask a junior team member to pull together all the reporting standards they can find on climate change disclosures. Using their favorite AI tool, the junior member prepares a high-level summary of many standards around the globe:

- Task Force on Climate Change Disclosure (TCFD)
- IFRS S-1 – sustainability
- IFRS S-2 – climate disclosure
- NAIC Climate Disclosure Survey
- UK SS 5/25
- OSFI B-15 in Canada
- California (SB 253/261)
- EU Directive on ORSA scenario testing
- Australian requirements
- Recent pronouncements in Japan, South Korea, Singapore, and Colombia
- IAA ISAP-8
- IAA IAN 200

There's enough reading there to keep you up all night. Your next move is to assign one standard to each of your team members to summarize. You on the other hand decide to read the SOA Research Institute's well written publication on Implication for Actuaries from the ISSB and Global Climate-related Financial Disclosure Standards[1] in order to get an overview of the subject.

You then schedule a meeting with your team to discuss all of the standards. At the meeting, you discover that many of these global standards all seem to have similar corresponding frameworks. Typically, they are divided into sections like Governance, Strategy, Risk Management, and Metrics and Targets. Many also refer to Physical and Transition Risk. Physical risk can be defined as the risk from climate events such as floods, wildfires, storms, heatwaves, cold snaps, etc. Transition risks refer to the risk, and in some cases opportunities, as we transition to a lower greenhouse gas world. Opportunities in climate change may seem like a strange term in risk management. But for pension and annuity actuaries, mortality deterioration from climate change may reduce their liabilities minimally to the advantage of their clients. Not so in the life and health insurance space.

SCENARIOS

But how do you incorporate any of the standards into ORSA/Financial Condition Reporting? The brilliant genie that lives rent-free in your head suggests that you first start identifying scenarios to model.

You recall a webinar where someone mentioned the NGFS scenarios. NGFS stands for Network For Greening the Financial System.[2] It is a series of seven scenarios used by central banks and supervisors to "provide a window into plausible futures." The seven scenarios are long term in nature. They are:

- Net Zero 2050
- Below 2^0 Celsius
- Delayed Transition
- Nationally Determined Contributions
- Fragmented World
- Current Policies
- Low Demand

Recently, NGFS has also developed four short term scenarios. They are:

- Highway to Paris
- Sudden Wake-up Call
- Disasters and Policy Stagnation
- Diverging Realities

Since these scenarios focus on a five-year horizon, they may be more appropriate for ORSA/FCR due to their short-term nature. These scenarios place significant emphasis on physical and transition risks.

Underlying the NGFS scenarios are a plethora or maybe a mountain of statistical data. The IPCC (Intergovernmental Panel on Climate Change) has approximately 20,000 datasets. A few of these actually

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[1] Society of Actuaries. (2024, August). *Implications for actuaries from the ISSB and global climate-related financial disclosure standards*. https://www.soa.org/resources/research-reports/2024/issb-fin-disclosure-standards/

[2] Network for Greening the Financial System. (n.d.). *NGFS Scenarios Portal*. https://www.ngfs.net/ngfs-scenarios-portal/

have life and health data. But with your busy work schedule, you don't have enough time in the day to go through 20,000 datasets. The United Nations Environmental Program (UNEP) has approximately 100 tools on climate change. But none are suitable for your purposes.

You decide instead to use the seven NGFS scenarios as stress tests in your ORSA reporting. But how do you incorporate them into this process?

You start to look for research articles on relationships between climate change, mortality, and morbidity. The data is mostly sparse. There is some data from NOAA on weather related mortality. [Weather Related Fatality and Injury Statistics](). The latest study covers the 2024 calendar year.

A study by RGA Re in South Africa shows a less than 40 basis point change in deaths from physical risks.[3]

You begin to contemplate how to model the transition risk. One possible approach is to project out energy usage and the transition of CO^2 emissions under the seven NGFS scenarios. Then you could look at causal relationships between the CO^2 pathways and mortality and morbidity outcomes. One UK study suggests that 10% of all future lung cancers will be climate change related. A Chinese study suggests that there is an almost one-for-one relationship between the increases in CO^2 emissions and healthcare costs in Beijing.

Other research focusses on the health effects of climate change on mental health disorders, diabetes, and a host of other diseases. For instance, one study found that there is a 50% spike in mental health illness in the six months following a flood for those impacted. The challenge for you is that many of these research articles are not in jurisdictions where XYZ operates.

LLMS

You begin to wonder if maybe you could use Large Language Models ("LLMs") to do some of the stress testing and ORSA work. You reach out to a consultant who tells you that developing such models will cost between $1 million to $100 million to develop. Your company doesn't have the time or the budget to stand up a Large Language Model. You are hopeful that at some point the industry will develop an LLM model to be used by all practitioners. But that day is not today.

You have also heard recently about Graduated Linear Models ("GLMs"). GLMs are like the spaghetti models shown on weather forecasts. They combine a series of weak models to produce a more robust model. However, neither of the language model approaches seem feasible for your assignment at this point. You abandon those approaches.

STRESS TESTING

With the thin and disjointed level of data on climate mortality and morbidity out there, you decide to take a different approach. You decide to incorporate a climate mortality table into your scenario testing for your life business to get a better handle on the effects of climate change on your capital and balance sheet. You will also use the same table for your annuity and pension de-risking business. For your employee

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[3] Falkous, C. (2024). *The impact of climate change on future mortality in South Africa* (White paper). Reinsurance Group of America. https://www.rgare.com/docs/default-source/knowledge-center-articles/south-africa-climate-change-white-paper-final.pdf?sfvrsn=debd283a_1

benefits/worksite marketing health business, you will use a climate morbidity table for stress testing the NGFS scenarios. Now it's time to put some hard metrics together for your ORSA report.

Let's assume that XYZ insurance company has 10,000 policyholders on its' life insurance business. All are age 65 and female. Each has a life insurance policy with a death benefit of $100,000. An excerpt from the climate mortality tables for the Net Zero 2050 scenario looks as follows:

Table 1
CLIMATE MORTALITY TABLE FOR NET ZERO 2050 SCENARIO

Age	Female Climate Mortality
65	0.003%
70	0.0035%
75	0.005%
80	0.01%
85	0.03%

Reprinted with permission from the CliScen model created by the author.

The annual claims payout at age 65 are 10,000 * 100,000 * 0.00003

= $30,000

For simplicity at this point, discount rates, premiums, lapse rates, and expenses will not be discussed. The model used shows an uptick in GAAP reserve of $350,000 under the Net Zero 2050 scenario. Under the full seven NGFS scenarios, the range of results is $225,000 to $1,200,000. This becomes a liability stress that has to be funded by free capital on the ORSA. Resiliency can be demonstrated by showing there is enough free capital to cover this uptick in mortality from climate change.

ORSA

Now that the liability side of the balance sheet has been addressed, it's time to think about the asset side. One possible approach is to apply an algorithm to depress the market value of energy assets on the balance sheet. Correspondingly, the sustainable assets can have their market values increased with the algorithm. Let's delve into this concept a little further. XYZ owns an energy asset that's currently trading at 250 basis points over the 10-year treasury. However, the climate asset algorithm suggests that the asset should really be trading at 400 basis points above the 10-year treasury spread given the current climate (no pun intended) around energy assets with many investors. The climate asset algorithm would be based on established parameters. It reduces the market value of the asset based on what it perceives to be the "correct" spread in the market for an energy asset. On the flip side, renewable assets may have their market values increased.

Let's look at just a few of the assets XYZ owns in its portfolio, see Table 2.

Table 2
CURRENT SAMPLE ASSETS

Asset	Issuer	CUSIP	Book Val	Mrkt Val	Mk Yield
ABC	L Motors	111111	1000000	900000	5.0%
DEF	B Energy	222222	5000000	4500000	4.5%
GHI	R Renew	333333	3000000	2800000	7.0%
JKL	C Constr	444444	6000000	5700000	4.0%
MNO	T Food	555555	9000000	8600000	5.5%
Total			24000000	22500000	5.1%

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After running the assets through the climate risk algorithm, market values for the Net Zero 2050 scenario come back as follows:

Table 3
MARKET VALUES FOR NET ZERO 2050 SCENARIO

Asset	Issuer	CUSIP	Book Val	Mrkt Val	Mk Yield
ABC	L Motors	111111	1000000	900000	5.0%
DEF	B Energy	222222	5000000	3000000	8.5%
GHI	R Renew	333333	3000000	3500000	7.0%
JKL	C Constr	444444	6000000	5700000	4.0%
MNO	T Food	555555	9000000	8600000	5.5%
Total			24000000	21700000	5.7%

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The energy and renewable assets have had their market values adjusted under the Net Zero 2050 scenario by the climate risk algorithm. Under the Net Zero 2050 scenario, the market value of these five assets has been depressed by:

22,500,000 – 21,700,000 = 800,000

So, the total capital reduction under this scenario from both the liability and asset side of the balance sheet becomes:

Capital reduction is 350,000 + 800,000

= 1,150,000

The algorithm also provides for asset defaults and rating downgrades. But those two concepts will be ignored or brevity of this example.

You remember the comment from the board member about lawsuits for not addressing climate change appropriately. You decide to add an additional credit spread for lawsuits in the climate asset algorithm of 40 basis points. Your market value of assets moves a further $920,000.

XYZ holds $30 million of free capital. The Net Zero 2050 climate change scenario would represent a

Capital Reduction of ($1,150,000+$920,000)/$30,000,000

= 6.9% of free capital

This does not represent a significant impairment to XYZ's capital ratios. However, the above is all under the Net Zero 2050 scenario. Other scenarios may be more or less punitive.

You decide to stress test other operational climate risks that could impact your risk management profile. For instance, you look at a scenario where a large forest fire in the Western U.S. shuts down an important brokerage operation for six months. The brokerage provides significant sales and support to XYZ and its policyholders. You quantify the potential loss of premium revenue based on the last three years of sales as $1,500,000 for a six-month operational shutdown of the brokerage. You assign that loss as an operational risk from climate change.

CONCLUSIONS

This essay has taken a look at how climate change stress testing may be incorporated into ORSA and/or Financial Condition Reporting for life and health companies. While it's certainly not the only approach available, it provides one roadmap for practitioners struggling with how to incorporate climate risk modeling into their overall risk management framework.

It is believed at the time of this writing that approximately 15% of the Russel 1000 companies report on climate change impacts to their organizations. Given that the U.S. SEC has paused climate change reporting and the California legislation is also pending, this reveals how important climate change disclosure is for companies even when the requirements are voluntary in nature. Beyond the ORSA/FCR reporting, we need to also think about including climate change analysis in our pricing. At its core, we have to ask ourselves the question if we as an industry are charging the right price for the products we sell.

As more knowledge and best practices emerge under climate change risk modeling, it's expected that the approaches and standards of practice will become more streamlined.

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Terry Narine, FSA is a climate actuary and peer reviewer. He can be reached at terrynarine@actuwit.com.

Award Winner

Forecasting What Has Never Happened

Long (Mark) Nguyen, ASA, ACAS and Stefanos Orfanos, FSA, Ph.D.

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

This essay examines whether AI weather models can reliably forecast the high-impact extremes that drive catastrophe losses as climate change pushes conditions beyond the historical record. We present evidence from recent tropical cyclone experiments and European windstorm case studies showing that AI models often smooth peak hazard intensities—the very values that matter most for solvency. The limitation is not a bug to be fixed, but a consequence of how these models learn: they are empirical interpolators, not physical extrapolators. We propose FACT (Forecast with AI; Anchor to physics; Calibrate to exposure; Tie to governance) as a hybrid workflow that leverages AI's speed for scenario exploration while using physics-based models to adjust tail behavior.

INTRODUCTION: WHEN EXPERIENCE FALLS SHORT

Hurricane Ian in 2022 made landfall in Florida as a Category 4 storm, bringing catastrophic storm surge and up to 27 inches of rainfall, causing an estimated $113 billion in damage. That same year, monsoon rains and glacier melt left one-third of Pakistan underwater, affecting 33 million people and causing over $30 billion in total losses. In 2023, Canada saw its worst wildfire season on record, with more than 18 million hectares burned—about seven times the national 10-year average—driving prolonged smoke across parts of the United States.

These events share an uncomfortable theme: they sit outside what these communities have experienced before. For actuaries, they represent exactly the outcomes we need to anticipate and the ones we struggle with the most. Our traditional tools like credibility theory, experience rating, and statistical frequency analysis, are fundamentally backward-looking. They assume the future will resemble a weighted average of the past. Climate science tells us this assumption is breaking down.

At the same time, weather prediction is undergoing one of the fastest shifts in its history. Since around 2022, AI weather models such as Huawei's Pangu-Weather and Google DeepMind's GraphCast have demonstrated forecast skill comparable to or exceeding traditional physics-based numerical weather prediction (NWP) systems, producing accurate global predictions at a fraction of the computational cost.

But underneath the hype lies a crucial question: can AI reliably forecast rare, high-impact events? The answer, increasingly supported by research, is "not yet—at least not alone." And that limitation matters more as climate change pushes weather conditions into territory the historical record never prepared us for.

TWO WAYS OF KNOWING THE ATMOSPHERE

To understand why AI models struggle at the tails and why that issue is structural, we need to distinguish two fundamentally different approaches to forecasting. This is not just a technical detail; it is the conceptual foundation for everything that follows.

THE PHYSICIST'S WAY: EXTRAPOLATION FROM FIRST PRINCIPLES

Traditional NWP starts with physics. Air flows from high to low pressure. Water changes phases according to thermodynamics. Earth's rotation bends winds through the Coriolis effect. The atmosphere can be represented as a three-dimensional grid, and partial differential equations—conservation of mass, momentum, and energy—are solved forward in time.

Physics-based models have a critical advantage: they can extrapolate. They can simulate a Category 5 hurricane even if the historical record contains few storms at that strength. If the initial conditions support such a storm, the equations will produce it. Nothing in the mathematics forbids outcomes that have never been observed, like 200-knot winds or 60°C surface temperatures, if physics permits them. But this power comes at a cost: each forecast cycle can take hours on dedicated supercomputers, and running many scenarios at high resolution is often impractical when decisions are time-sensitive.

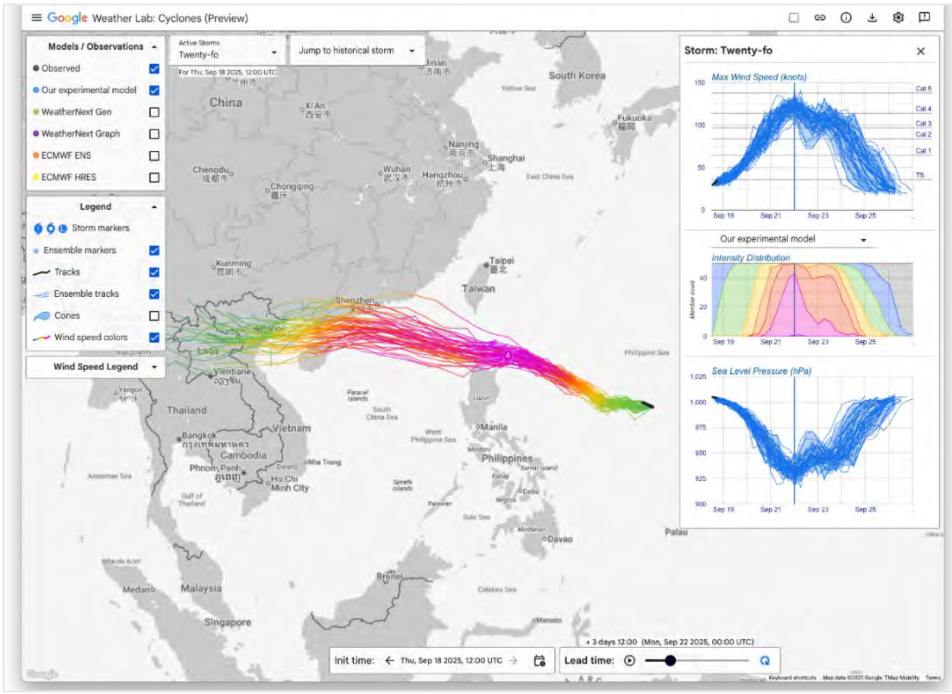
THE DATA SCIENTIST'S WAY: INTERPOLATION FROM PATTERNS

AI weather models take a different approach. Instead of solving equations, they learn from examples. Feed decades of global weather data (typically the European Centre for Medium-Range Weather Forecasts reanalysis v5 (ERA5), which reconstructs atmospheric states from 1979 to the present) to a neural network and ask it to learn what tomorrow tends to look like given today. The "intelligence" is pattern recognition at scale, identifying statistical regularities across four decades of weather.

These models interpolate. They encode correlations: when the atmosphere looked like this in the past, it subsequently looked like that. A model trained on data where maximum recorded winds reached 180 knots has no principled basis for predicting 200-knot winds. It may do so accidentally, but the prediction carries no theoretical warrant. More often, the model regresses toward familiar territory; confronted with inputs unlike anything it has seen, it produces outputs closer to the training mean.

Figure 1

EXAMPLE OF RAPID, ENSEMBLE-STYLE CYCLONE FORECASTING



This example is an AI-driven interface, showing many plausible tracks and intensity trajectories from a single initialization. Source: Google Weather Lab, Cyclones preview (https://developers.google.com/weathernext/guides/research). Licensed under CC BY 4.0. No changes made.

WHY THIS DISTINCTION MATTERS FOR CAPITAL

Actuaries will recognize this tension. Credibility theory is fundamentally interpolative: it weights recent experience against a broader mean, assuming the future looks like a weighted average of the past. Catastrophe modeling is fundamentally extrapolative: it uses physical principles (engineering, seismology, atmospheric dynamics) to simulate events that have never happened.

AI is the ultimate credibility engine: fast, data-driven, excellent at the middle of the distribution. Physics is the ultimate catastrophe engine: slower, more expensive, but capable of reaching into the tails. The question for actuaries is not which to choose, but how to allocate each to its comparative advantage.

Several independent studies now document the same pattern: machine learning weather models match or exceed physics-based forecasts for typical conditions but systematically underestimate rare extremes.

CONTROLLED EXPERIMENTS: REMOVING THE TAILS

Sun and collaborators (2025) ran controlled experiments with NVIDIA's FourCastNet, deliberately removing strong tropical cyclones from training data. When all Category 3–5 storms were excluded globally, the model failed to forecast Category 5 storms. When strong storms were removed only from the Atlantic but retained in the Pacific, Atlantic Category 5 performance recovered substantially because the model transferred patterns learned elsewhere.

The researchers call this distinction translocation vs. extrapolation. Machine learning models can recognize a pattern seen in one region when it appears in another—they can translocate. They struggle to predict intensities beyond anything in the global training set; hence they cannot truly extrapolate.

CASE STUDY: DUBAI 2024

Dubai's April 2024 rainfall illustrates the power of translocation. Some locations received over 250mm in 24 hours—roughly double anything in the regional historical record. This was a "gray swan" for the Arabian Peninsula: unprecedented locally, but dynamically similar to mesoscale convective systems the model had seen thousands of times in the tropics and the U.S. Midwest.

GraphCast predicted the event eight days in advance, demonstrating that AI can help identify risks in regions with poor local historical data, provided the hazard mechanism is not unique to that location. For actuaries, this is good news: AI can scan for "gray swans" that local experience would miss. But even here, the model underestimated peak intensity. Translocation worked; extrapolation did not.

CASE STUDY: STORM CIARÁN 2023

In November 2023, Storm Ciarán—a rapidly intensifying "bomb" cyclone—struck Western Europe. Charlton-Perez and colleagues compared four leading AI models (FourCastNet, FourCastNet-v2, Pangu-Weather, and GraphCast) with ECMWF's physics-based forecasts.

The AI systems captured the large-scale structure, timing, and rapid deepening of the cyclone. But all of them systematically underestimated the strongest near-surface winds. They got the storm at roughly the right time and shape but missed the peak gusts that drive losses.

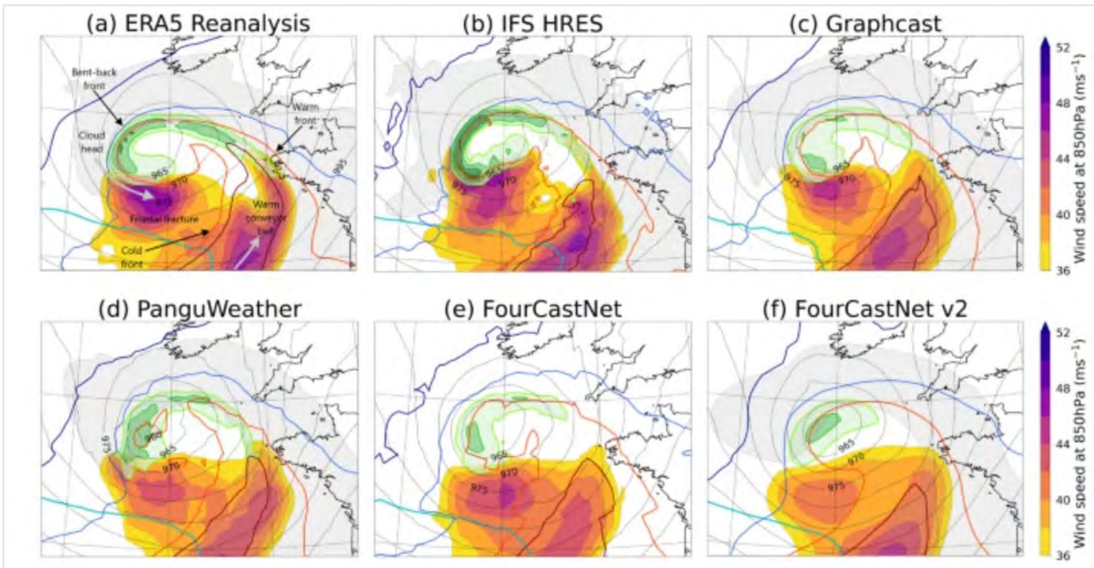
The underlying mechanism relies on mathematics. Most AI weather models minimize mean squared error (MSE), which penalizes large mistakes heavily. The loss-minimizing strategy is to produce "safe" predictions near the middle of the distribution—to smooth.

THE FINANCIAL TRANSLATION: SMALL ERRORS, LARGE LOSSES

Why should actuaries care about a 10% wind speed error? Because wind damage scales roughly with the cube of gust speed above a threshold. If the AI predicts 45 m/s gusts but the reality is 50 m/s (a 10% miss), the modeled energy and potential damage is understated by approximately 27%. A 15% wind underestimate can push loss error toward 50%.

Figure 2

DYNAMICAL STRUCTURE OF STORM CIARÁN AT 18 UTC ON 1 NOVEMBER 2023



The first two panels show 10-m wind and sea-level pressure from (a) reanalysis data and (b) NWP model, while panels (c)–(f) show the corresponding forecasts from four AI weather models. The AI forecasts exhibit noticeably smoother wind and pressure gradients than the analysis and NWP fields, with weaker peak values in the storm core.
Source: Charlton-Perez, C., et al. (2024). 'AI Weather Prediction Models and Extreme Events: A Storm Ciarán Case Study.' npj Climate and Atmospheric Science. https://doi.org/10.1038/s41612-024-00638-w. Licensed under CC BY 4.0. No changes made.

For a portfolio heavily exposed to European windstorms, relying solely on AI forecasts for capital setting (one-in-200-year return period) would lead to systematic under-capitalization. The "safe" mean prediction of the AI becomes a dangerous underestimation of capital need. Small errors in the meteorological tails become solvency-sized mistakes.

FACT: A HYBRID WORKFLOW

None of this means AI has failed. It means AI and physics need to work together, especially for high-stakes rare events. We propose FACT as a practical workflow for actuaries and risk managers who want to integrate weather forecasts into catastrophe modeling and capital adequacy.

F—FORECAST WITH AI

Define the peril and time horizon relevant to the decision: hurricane season in the Gulf, winter windstorm in Europe, monsoon flooding in South Asia. Rather than using machine learning, use generative AI like GenCast. These models utilize diffusion processes to generate ensembles that preserve variance and fine-scale structure.

Generate hundreds or thousands of plausible atmospheric trajectories by perturbing initial conditions or sampling from the generative model. This takes minutes on GPUs compared to hours for a 50-member NWP ensemble. Translate scenarios into preliminary hazard footprints and overlay on portfolio exposure to identify attention events: scenarios where hazard and exposure coincide in ways that could produce material losses.

This phase exploits AI's comparative advantage: speed. The output is a ranked shortlist, not a final loss estimate.

A—ANCHOR TO PHYSICS

For attention events identified in Phase F, apply physics-based methods to refine tail behavior. Run flagged scenarios through high-resolution NWP, regional dynamical downscaling, or vendor hazard modules calibrated on extreme events. The objective is to sharpen peak winds, resolve localized rainfall maxima, and capture storm surge and flood depths that depend on fine-scale topography.

Document adjustments explicitly: which hazard variables were refined, what methods were used, how upper quantiles changed. This transparency supports model validation and regulatory review. The AI tells you where to look; physics tells you how bad it could get.

C—CALIBRATE TO EXPOSURE

Risk is not just hazard; it is hazard × vulnerability × exposure. Pass the tail-adjusted hazard footprints through vulnerability functions and overlay on your portfolio's specific locations, construction types, and insured values. Look for "translocation hotspots"—areas where the AI predicts a hazard type (e.g., convective flood, rapid cyclone intensification) that local historical experience would miss.

Next, compute gross and net losses under current policy terms and reinsurance structures. Use the scenario set for stress testing: What is the one-in-100-year loss under current exposures? How does the answer change under climate-driven hazard intensification? For longer planning horizons, such as the Own Risk and Solvency Assessment (ORSA) and strategic capital planning, extend the analysis to alternate climate states (+1.5°C or +2°C warming).

T—TIE TO GOVERNANCE

The "black box" nature of AI creates model risk that must be managed through governance, not just mathematics. Connect analysis to action and accountability: use scenario-derived estimates to set risk appetites, adjust pricing, and identify accumulation hotspots requiring limits or exclusions.

Integrate FACT into the ORSA by explicitly documenting the hybrid nature of the assumptions: "Frequency and track derived from AI ensembles; intensity anchored by physics-based models." This satisfies requirements for understanding model components and demonstrates robustness against climate shifts. Make sure to back-test AI hazard estimates against observed events and monitor for drift as climate shifts distributions. Finally, report limitations transparently to boards and regulators: AI models are reliable for the body of the distribution, less so for the tails that drive solvency risk.

WHAT'S NEXT: AI WEATHER ON THE HORIZON

The current generation of ML weather models represents the first wave. Several developments suggest how the field may evolve:

Foundation models are emerging for weather and climate. Microsoft's Aurora, trained on over a million hours of diverse atmospheric and ocean data, aims to generalize across forecasting tasks rather than optimizing for a single prediction type. Early results suggest improved performance on some out-of-distribution events, though rigorous evaluation on true record-breakers remains limited.

Physics-informed architecture embeds conservation laws and dynamical constraints directly into network structure. NowcastNet, for precipitation nowcasting, incorporates advection physics into its design, producing sharper, more physically plausible rainfall predictions than pure pattern-matching approaches.

Generative models like GenCast already produce probabilistic forecasts by sampling from learned distributions. Future systems may better capture tail behavior through loss functions that explicitly weight rare events, or through training augmented with physics-generated synthetic extremes—scenarios simulated by NWP that push beyond the historical record.

None of these developments eliminates the fundamental constraint: empirical models learn from data, and data cannot contain what has not yet occurred. But they suggest a trajectory where AI weather systems become less brittle at distribution edges and better at translocation; more respectful of physical constraints and more honest about what they do not know.

CONCLUSION: THE ACTUARY'S ROLE

Weather forecasting has gained powerful new tools. Deep neural networks can match decades of physics-based development on standard metrics, producing global forecasts in minutes. For ordinary weather, these systems have earned a central role.

But the events that reshape balance sheets are not ordinary—the hurricanes that intensify beyond expectation, the heatwaves that exceed historical records, the floods that surpass engineering tolerances. For these, AI models show consistent weakness: they underestimate intensity, smooth peaks, and regress toward historical averages. The reasons are structural, rooted in training objectives that penalize boldness and data that cannot contain what has not yet occurred.

Physics-based models remain essential for the tails. They encode causal knowledge, such as conservation laws, thermodynamics, and fluid dynamics, which extend beyond any training set.

The path forward is integration. Use AI for fast, cheap exploration of scenario space, identifying where translocation reveals "gray swans" that local experience would miss. Use physics to anchor the extremes, ensuring that the tails of your loss distribution reflect thermodynamic possibility, not just statistical history. Build workflows, like FACT, which allocate each method to its comparative advantage. And develop a risk management framework that is both agile enough for the chaotic future and robust enough for the balance sheet.

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Long (Mark) Nguyen, ASA, ACAS, is a graduate student at Georgia State University. He can be reached at tuanlongnguyenha@gmail.com.

Stefanos Orfanos, FSA, Ph.D. is a Clinical Assistant Professor at Georgia State University. He can be reached at sorfanos@gsu.edu.

Award Winner

When Climate Risk Becomes Endogenous: Macro-Risk Feedback Loops in Insurance Pricing and Capital

Rajeshwarie VS

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INTRODUCTION

Climate change is often described as a series of isolated shocks—a flood here, a wildfire there, a storm that breaks one more record. But for insurers, the real challenge is not the individual event, it is the system of reactions that follows. These are not simple cause-and-effect relationships. They are macro-risk feedback loops—reinforcing cycles in which climate-driven losses interact with economic and financial conditions to amplify risk across multiple layers of the system. For example, a heavy loss pushes premiums up; higher premiums push people out of the market; uninsured losses weaken local economies; weaker economies reduce investment returns; lower investment income strains insurers' balance sheets; and round we go. By the time the next climate event arrives, the system is already on thinner ice.

Each cycle reinforces the next reshaping, the foundations of pricing, reserving, and capital modeling. Understanding these feedback loops is essential for insurers, regulators, and policymakers in order to prevent localized climate shocks from evolving into systemic financial stress. In this essay we explore how these loops form, examine their implications for pricing and capital, and explore an actuarial framework capable of assessing where we are in these self-reinforcing cycles.

The proposed approach extends existing climate stress testing by transforming climate risk from an exogenous shock into a dynamic, state-dependent process. The central argument of this essay is insurer responses—pricing, capital allocation, and coverage decisions—are endogenous drivers of climate vulnerability. This mechanism can be modeled through Climate Vulnerability Rating (CVR) migration and a Feedback Stress Index (FSI) that measures the strength of reinforcing risk dynamics over time.

While subject to data and calibration challenges, the framework offers insurers and regulators a structured way to identify emerging systemic stress, smooth procyclical responses, and align financial decision-making with long-term resilience. The framework is intended as a decision-support tool rather than a precise forecasting model.

WHY THIS MATTERS?

Climate-risk analytics have made huge strides in the last decade, but the tools we use today still describe pieces of the problem rather than the systemic loop it creates. We treat climate change as a long-term headwind, not a short-term trigger of systemic feedback. The challenge with climate risk is not the absence of data, but the absence of structure. We have loss estimates, hazard projections, resilience indices, and stress tests, yet they remain loosely connected.

Useful but broad Indices exist—like the Climate Vulnerability Index (CVI), ND-GAIN, and municipal resilience scorings that measure infrastructure readiness, hazard exposure, and socio-economic resilience. Rating agencies increasingly acknowledge that climate risk may influence sovereign and municipal credit ratings. But climate-driven downgrades remain rare; the methodology is cautious and not designed for insurance decision-making. While informative, these methods are not actuarial tools built for pricing to decide how to load premiums or simulate balance-sheets.

The current insurance practices of risk management—ORSA, ALMs and capital adequacy regimes—look at a short term, typically single year, time horizon. Supervisors such as Australian Prudential Regulation Authority, the Bank of England, Monetary Authority of Singapore, and the European Central Bank have begun running climate vulnerability assessments. They stress-test insurers and banks under different hazards and map affordability, capital strain, and expected losses. These exercises capture exposure and sensitivity, but they are still snapshots—not continuous rating systems.

A climate event starts a loop by hitting multiple parts of the system simultaneously through interconnected stresses landing at once. Apart from the physical losses, it disrupts local economy, makes insurance and reinsurance costlier, and in the extreme case capacity disappears. This prices local communities out and gradually eats away resilience. What is missing is a framework that translates climate shocks into decision-relevant actuarial signals, while explicitly capturing how those signals **interact and reinforce one another over time**.

CONSTRUCTING A CLIMATE-RISK FEEDBACK LOOP

Most currently available climate-risk tools are static by design looking at vulnerability and exposure at a point in time. Stress tests explore hypothetical futures while resilience indices rank preparedness. These approaches are valuable, but they do not answer a practical actuarial question, which is, how today's climate event changes tomorrow's pricing, capital needs, and risk profile, and how does that change feed back into future outcomes? One possible way to answer this is by borrowing selected elements from credit-risk methodologies—rating migration and state-dependent transitions—and from established catastrophe modeling practices such as earthquake zoning, to develop a framework that treats climate risk as observable, comparable, and dynamically evolving rather than a sequence of isolated events.

CLIMATE VULNERABILITY RATINGS (CVR)

We first begin by constructing a Climate Vulnerability Rating (CVR), a state variable that evolves over time and that can be assigned to a defined geography or portfolio segment. The rating aggregates physical risk, economic resilience, and insurance-specific factors into a single measure that reflects not only hazard exposure, but also the system's ability to absorb and recover from shocks. Inputs may include hazard frequency and severity trends, current and projected exposure concentration, insurance penetration, protection gaps, mitigation investments, public-sector capacity, and historical claims volatility.

RATING MIGRATION AS THE ENGINE OF THE FEEDBACK LOOP

CVRs are dynamic by design, changing to reflect changed local realities. They can be downgraded following severe events, deterioration in economic resilience, or high loss volatility. They can be upgraded when mitigation measures, infrastructure investment, or improved risk governance materially reduce vulnerability. They can provide a common language across pricing, underwriting, capital management, and reinsurance, much as credit ratings do across financial markets.

Once the CVR exists, the feedback loop is modeled by CVR migration over time according to transition probabilities calibrated from historical loss experience, scenario analysis, and stress testing. A severe flood may move a region from A to BBB; repeated events may push it further down the scale. Recovery is possible but not guaranteed.

Following each downgrade, we can anticipate higher technical premiums and capital charges, tighter underwriting limits/conditions, and reduced reinsurance availability. While these are rational responses for firms, the resulting economic strain feeds back into vulnerability, increasing the likelihood of further downgrades. The loop now appears embedded in the rating migration process itself.

MEASURING THE LOOP: A FEEDBACK STRESS INDEX

It is not sufficient to determine just the rating factor for each location. Different regions may be susceptible to varying climatic phenomena. High frequency of events can mean shorter feedback loops, faster worsening of conditions and reduced available time for mitigation. Socio-economic factors can determine how fast and strong the feedback mechanism is. Well-to-do neighborhoods are usually better placed to absorb shocks and recover sooner from any kind of disaster. They are also not likely to lose out drastically on insurance coverage due to reducing affordability. In terms of the CVR, these are the locales that are likely to see smaller fluctuations, and possible upgrades.

To complement CVR, we therefore need a Feedback Stress Index (FSI), an indicator designed to measure how tightly the feedback loop is wound. This can be measured by studying over time premium elasticity, coverage attrition, claims ratio volatility, reinsurance capacity shifts, downgrade frequency, investment income reduction, and protection gap growth.

A rising FSI value signals that responses to climate risk are beginning to amplify rather than absorb shocks. For insurers, this provides early warning of emerging systemic stress. For regulators, it offers a macroprudential lens on climate-driven instability. This allows insurers to move beyond isolated stress tests for specific events towards multi-period simulations of feedback dynamics, determining how today's pricing and capital decisions influence tomorrow's vulnerability.

PRACTICAL USE CASES OF A CLIMATE FEEDBACK FRAMEWORK

A framework that captures climate-driven feedback loops is valuable only if it improves insurance decision making. The CVR and FSI are not intended as abstract metrics, but as tools that can be deployed across the insurance value chain.

- Pricing—Insurers already reprice after climate events. The problem is not re-pricing itself, but how abruptly and locally it occurs. By anchoring pricing adjustments to CVR migration rather than single-event losses, insurers can distinguish between transient shocks in otherwise resilient regions, and structural deterioration in vulnerability. This allows for smoother premium paths, clearer communication with policyholders, and reduced volatility in affordability. In effect, CVR acts as a stabilizer, preventing pricing decisions from overreacting to noise while still responding to genuine risk signals.
- Capital Allocation and Solvency—CVRs provide a structured way to reflect climate risk in capital assessments by combining fat tails with gradual deterioration in infrastructure, affordability, and therefore resilience. Regions or portfolios with persistent downgrades attract higher capital buffers, not because of a single extreme loss, but because of elevated uncertainty and feedback risk. Conversely, improvements in resilience can justify capital relief over time. This creates incentives that align financial strength with long-term risk reduction, rather than rewarding short-term premium growth in increasingly fragile markets.

- Portfolio Steering and Exposure Management—One of the least discussed climate risks is concentration risk disguised as diversification. Multiple regions may appear geographically distinct while sharing similar vulnerability dynamics. Using CVRs, insurers can manage exposure limits by rating bands, steer new business toward higher-resilience areas, and identify clusters of correlated downgrade risk.
- Reinsurance Strategy and Market Signaling—Reinsurance markets already act as an early-warning system for climate stress, but signals are often fragmented and reactive. CVRs could become a shared reference point and increase predictability at market level for cedants and reinsurers, reducing the risk of sudden capacity withdrawals driven by asymmetric information. With a clearer view of risk and accumulation, cedants and reinsurers can align expectations on adjustments to structures, attachment points, limits, and pricing systematically with vulnerability migration.
- Regulatory Oversight and Macroprudential Monitoring—From a regulatory perspective, the greatest risk is not insurer failure in isolation, but collective responses that amplify economic stress. This is especially true of climate-change-fueled weather phenomena that affect large areas and populations. The FSI provides a macroprudential view by highlighting when pricing capital tightening and coverage withdrawal begin reinforcing one another. Regulators can use this to target supervisory attention, calibrate countercyclical capital measures, or coordinate with public-sector risk mitigation efforts. In this sense, the framework helps connect micro-prudential solvency assessments and system-wide stability.
- Incentivizing Risk Reduction and Adaptation—Perhaps, the most important use case lies outside insurance balance sheets. Because CVRs are upgradeable, they create a measurable reward for investment in mitigation, infrastructure, and disaster management. Municipalities, developers, and policymakers can see how resilience investments translate into improved insurability and lower long-term costs. Unlike blunt restrictions or post-event subsidies, this mechanism rewards ex ante risk reduction—rewarding prevention rather than cure.
- Avoiding the “Uninsurability” Cliff—Left unmanaged, climate risk narratives tend toward a single endpoint: uninsurable regions. CVRs allow insurers and regulators to identify stress early and adjust gradually. The goal is not to deny coverage, but to prevent the system’s response from becoming more damaging than the original event.

LIMITATIONS AND IMPLEMENTATION CHALLENGES

While the proposed framework offers a structured way to model climate-driven feedback loops, it also introduces practical and conceptual challenges. Recognizing these limitations is essential, not as a weakness of the approach, but as a guide to responsible implementation and identifying future refinement opportunities.

- Data Gaps and Measurement Uncertainty—Climate risk data remains uneven in quality and granularity. Loss histories are short relative to climate time horizons, and resilience indicators are often qualitative or inconsistently reported. CVRs would need combining heterogeneous data sources into a single signal. This aggregation involves judgment, introduces model risk, and the potential for false precision.
- Calibration and Procyclicality Risk—A framework built around rating migration risks becoming procyclical if not designed carefully. Downgrades following major events may reinforce already tightening market conditions, accelerating coverage withdrawal, and affordability stress. To avoid this, calibration must distinguish between short-term volatility and structural vulnerability. Transition probabilities should incorporate recovery dynamics and mitigation effects, rather than relying solely on loss experience. This is easier said than done—other than loss history, other inputs can be qualitative and hard to quantify.

- Model Complexity and Transparency—Capturing feedback loops necessarily increases model complexity. Linking climate scenarios, rating migration, pricing responses, and capital impacts introduces layers of interaction that can be difficult to capture, explain to boards, regulators, and stakeholders. If a framework becomes opaque, it risks losing trust—particularly in regulatory or public-facing contexts. Clear documentation, explainability, and governance are therefore as important as technical accuracy.
- Behavioral and Political Constraints—Insurance responses do not occur in a vacuum. Political pressure, regulatory intervention, and social expectations can delay or distort actuarial signals. Premium increases may be capped, withdrawals may be restricted, capital relief may be granted for policy reasons. These interventions can dampen or redirect feedback loops in ways that are difficult to model. While the framework can highlight emerging stress, it cannot fully predict how non-market forces will alter outcomes.
- Coordination Challenges Across Stakeholders—The effectiveness of CVRs increases with shared adoption. However, insurers, reinsurers, regulators, and public bodies operate under different incentives and time horizons. Without coordination, fragmented implementation may weaken signals or create inconsistent responses. A rating downgrade that influences pricing but not public investment, or vice versa, limits the framework's ability to break feedback loops.
- Ethical and Distributional Considerations—Assigning vulnerability ratings to regions raises ethical questions. Poorer areas may face downgrades driven by limited resources rather than poor risk management, potentially worsening inequality. Importantly, CVRs and FSIs should function as indicators, not forecasts. They are designed to inform decisions, and target mitigation and support, rather than replacing judgement and simply justifying exclusion. There is a risk that ratings become treated as definitive assessments of future insurability or lack thereof, rather than as signals of evolving vulnerability. Used carelessly, the framework could reinforce exactly the rigidity it seeks to avoid.

CONCLUSION

Climate risk is often described as "nonlinear" and framed as a modeling problem rather than a modeling, governance, and coordination problem. Its nonlinearity does not come from the climate alone, but from the system's reaction to it. By borrowing the discipline of credit ratings and embedding it within actuarial modeling, this approach makes feedback loops visible, measurable, and importantly, manageable. It does not eliminate climate risk, but it allows insurers and policymakers to identify when rational responses begin to create collective instability. The value of this framework lies not in eliminating uncertainty, but in organizing it—making feedback loops visible before they become unavoidable. Its success depends as much on cautious interpretation and institutional discipline as on actuarial technique. In a climate-stressed world, the question is no longer whether losses will occur. It is whether actuarial frameworks can identify and moderate the feedback mechanisms that can prevent their own responses from becoming the next source of risk.

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Rajeshwarie VS is a P&C actuary based in India. She can be reached at r.eshwari.894@gmail.com.

Becoming Evolvers Rather than Forecasters Alone: Climate Risk and the Future of Actuarial Risk Management

Syed Danish Ali, CSPA

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WHEN FORECASTING BECOMES A LIABILITY

Actuarial risk management has long been built around forecasting. We estimate frequencies, severities, correlations, and trends, then translate those estimates into pricing, capital, and governance decisions. This approach works when the future behaves broadly like the past. Climate change disrupts that bargain. The problem is not that forecasts are wrong. The problem is that the conditions under which forecasting remains useful are quietly eroding.

Climate risk introduces non-stationarity in its most practical form. Hazard distributions shift. Exposure migrates. Vulnerability evolves as households, firms, and governments respond unevenly. When actuaries rely on historical calibration as the primary anchor, they assume that the system generating losses is stable enough for extrapolation. Under climate change, that assumption fails gradually rather than dramatically. The danger is not model collapse, but misplaced confidence delivered with precise-looking outputs.

Climate change also occupies an uncomfortable time horizon. It is not distant enough to dismiss with the argument that long-run uncertainty makes action futile. Nor is it so immediate that it forces a crisis-driven response. It unfolds in a Goldilocks risk zone: slow, compounding, and accelerating just fast enough to matter within institutional planning cycles. This is precisely the terrain actuaries are trained to manage. Insurance liabilities, pension promises, and asset strategies already operate on horizons where small misalignments accumulate into material outcomes.

Yet many risk frameworks still treat climate as an incremental adjustment rather than a structural shift. A new scenario is appended. A sensitivity is run. The core architecture of forecasting remains unchanged. What results is the appearance of diligence without corresponding adaptability. Forecasting precision is preserved even as the underlying system evolves between observation points.

This tendency is reinforced by institutional incentives. Narrow ranges feel professional. Clean estimates feel controllable. In a climate context, however, precision can become a liability. Highly refined forecasts built on fragile assumptions crowd out alternative views and delay escalation. When the world moves faster than the data, the most statistically elegant estimate is often the least useful input for decision-making.

Climate risk behaves less like a shock to be measured and more like a process that unfolds. Drought alters land use. Land use reshapes flood severity. Flood losses trigger insurer withdrawal. Withdrawal changes behavior, asset values, and political responses. By the time these dynamics appear in loss data or balance sheets, the window for proactive adjustment has narrowed. Forecasts lag not because actuaries are slow, but because the system itself is evolving between forecasts.

Forecasting remains necessary. It is no longer sufficient. Under climate change, the dominant failure mode of risk management is not miscalculation. It is delayed adaptation. Institutions optimize prediction quality when they should be optimizing for learning speed. Becoming evolvers rather than forecasters alone starts by recognizing when the distribution itself is becoming unstable and acting before statistical certainty arrives.

CLIMATE RISK AS A LIVING SYSTEM, NOT A SHOCK

Traditional actuarial frameworks tend to treat risk as additive. A peril is identified, modeled, priced, and capitalized. Climate risk resists this structure because it is rarely isolated. It interacts across underwriting risk, reserving risk, asset risk, operational risk, and governance risk. More importantly, these interactions are not linear. They feed back into one another.

Consider flood risk. The hazard may increase gradually, but exposure can grow rapidly as development follows perceived protection. Flood defenses reduce frequent losses, encouraging higher density and higher asset values in vulnerable areas. When defenses fail, severity explodes. The loss is not merely the sum of water damage. It includes disrupted supply chains, insurer retreat, litigation, and long-term depreciation of local assets. What appears as a single peril is, in reality, a system of reinforcing effects.

This pattern repeats elsewhere. In wildfire-prone regions, climate conditions increase ignition and spread. Losses rise, but the more destabilizing effect is insurer withdrawal. As coverage becomes unavailable or unaffordable, property values decline, mortgage risk increases, and public entities face pressure to act as insurers of last resort. Climate risk migrates from underwriting portfolios into credit risk, municipal finance, and social stability. Treating wildfire purely as a catastrophe modeling problem misses the broader transformation underway.

Pension systems face similar dynamics, albeit less visibly. Heatwaves affect mortality and morbidity unevenly across populations. Urban heat islands, occupational exposure, and income disparities create divergence within cohorts traditionally modeled as homogeneous. At the same time, asset portfolios are exposed to physical risk, transition risk, and policy responses that evolve faster than actuarial assumptions. The result is not a single shock, but persistent erosion of the assumptions underpinning funding adequacy.

These dynamics are characteristic of complex adaptive systems. Small changes accumulate. Feedback loops dominate outcomes. Interventions produce second-order effects that often outweigh the initial impact. Interactions matter. Complexity science, network theory, and agent-based thinking offer useful lenses, not to replace actuarial models, but to contextualize them. Climate risk is less about estimating an expected loss and more about understanding how behavior, incentives, and constraints reshape loss pathways over time.

Short illustrations make this clear. Agricultural insurance pricing may lag shifting rainfall patterns, encouraging planting decisions that amplify future losses. Energy transition policies may strand assets unevenly, creating correlated shocks across sectors previously treated as diversified. Flood events such as the Texas Hill Country 2025 floods show how drought, land use, and extreme rainfall interact to overwhelm assumptions embedded in static maps and return periods. In each case, the hazard matters, but the system response matters more.

Recognizing climate risk as a living system changes the role of actuarial risk management. The objective shifts from measuring isolated shocks to monitoring evolving patterns. Divergence between models becomes informative rather than inconvenient. Qualitative signals, governance strain, and behavioral responses become early indicators rather than afterthoughts.

WHAT ORSA, CAPITAL, AND GOVERNANCE SWEEP UNDER THE RUG

Most ORSA frameworks were built for risks that behave politely. They assume identifiable drivers, stable relationships, and management actions that can be planned and executed within familiar timeframes. Climate risk breaks those assumptions quietly. It does not arrive as a new risk category. It seeps into existing ones and changes how they behave.

In many insurers, climate risk appears in ORSA as a scenario exercise. A severe flood. A major wildfire season. A heatwave stress. These exercises are useful, but they are often treated as peripheral. The core capital assessment remains anchored to business-as-usual projections with modest overlays. This creates a structural mismatch. ORSA describes resilience while the balance sheet remains optimized for a different world.

The deeper challenge is that ORSA is still framed around forecast confidence rather than adaptation capacity. Climate risk demands the opposite. The question is no longer whether a specific scenario will occur, but whether the institution can recognize when its assumptions are breaking and respond before losses compound. That is a governance problem as much as a modeling one.

Capital adequacy under climate risk cannot be reduced to a single number. Climate-driven losses are often path-dependent. Early decisions change later outcomes. An insurer that exits a market too late absorbs concentrated losses. One that exits too early may create reputational and regulatory risk that damages franchise value. Capital planning therefore needs to incorporate decision timing, not just loss magnitude.

This is where ORSA can evolve from compliance artifact to living framework. Instead of asking whether capital is sufficient under predefined scenarios, ORSA should ask how quickly management can change course when conditions deviate from expectations. How fast can underwriting guidelines be revised? How quickly can pricing assumptions adjust without destabilizing the portfolio? How rapidly can asset allocations respond when climate correlations spike?

From a technical standpoint, this argues for a layered approach. Traditional stochastic and deterministic models remain essential, but they should be complemented by qualitative profiling and model pluralism. Divergence across models should not be averaged away. It should be tracked. When different methods begin failing differently, that divergence is often an early warning that the system is changing faster than the data.

Capital buffers should reflect this asymmetry. Climate risk is not symmetric around the mean. Upside surprises are limited. Downside surprises are not. This supports a bias toward resilience capital rather than efficiency capital and challenges the instinct to calibrate capital purely to historical volatility when the structure of volatility itself is evolving.

For pensions and asset-intensive institutions, the same logic applies. Longevity assumptions interact with heat stress, air quality, and healthcare capacity in nonlinear ways. Asset valuations embed climate exposure through supply chains, regulation, and consumer behavior long before defaults appear in financial statements. Risk management that waits for quantitative confirmation will consistently act late.

FROM BETTER MODELS TO BETTER EVOLVERS

Climate risk exposes a quiet weakness in how risk management has been practiced for decades. Most actuarial systems are designed to improve forecast accuracy within a stable structure. Climate change breaks the structure itself. When the underlying system is shifting, better calibration of yesterday's relationships does not produce better decisions tomorrow.

This is where becoming evolvers rather than forecasters matters. Forecasting assumes that the future is a variation of the past. Evolving assumes that the rules may change and prepares the institution to recognize and respond when they do.

Quantitative models remain essential, but no single model or class of models can claim authority under climate uncertainty. Frequency severity models, catastrophe simulations, climate-adjusted GLMs, machine learning approaches, and scenario analyses all capture different fragments of reality. The danger lies not in using imperfect models, but in mistaking any one of them for the system itself.

Model pluralism should therefore be deliberate. Different methods should be run in parallel, not to be averaged into a single answer, but to observe where and how they disagree. When multiple models begin to diverge in their implications, that divergence is information. It often signals regime change, emerging feedback loops, or shifts in exposure that are not yet fully visible in the data.

This is where qualitative methods stop being optional. Complexity science teaches that large system changes often emerge from small, localized interactions. Climate risk operates through these mechanisms. A drought alters migration patterns. Migration strains urban infrastructure. Infrastructure stress amplifies mortality and morbidity. Insurance losses appear last, not first. Quantitative data usually arrives after the causal chain is already underway.

This tension is especially visible in reserving. Traditional reserving practice often rewards stability of point estimates, which can quietly convert specific uncertainty into hidden systematic risk. We can frame this as a simple but uncomfortable question: are we reducing volatility in normal periods only to manufacture fat tails in stress? Bayesian machine learning offers a practical alternative. By treating reserve estimates as evolving probability distributions rather than fixed numbers, Bayesian approaches force uncertainty onto the surface instead of sweeping it under the rug. In a climate-stressed world, where reporting lags, development patterns, and tail behavior shift together, reserving needs to adapt in the same way as pricing and capital models: by explicitly modeling uncertainty, not minimizing its appearance.

Qualitative profiling helps actuaries map these chains early. This includes structured expert judgment, behavioral analysis, governance review, and sociological insight into how policyholders, regulators, and markets respond under stress. These inputs do not replace models. They guide where models should be stressed, where assumptions should be loosened, and where blind spots may exist.

Agent based modeling and network theory provide bridges between the quantitative and qualitative worlds. They allow actuaries to explore how individual behaviors aggregate into systemic outcomes without assuming equilibrium. In climate risk, equilibrium is often the wrong assumption. Feedback dominates. Delays matter. Nonlinear thresholds exist.

Game theory also has a role. Climate adaptation decisions are rarely taken in isolation. Insurers respond to competitors. Governments respond to voters. Policyholders respond to incentives. Modeling climate risk without considering strategic interaction risks producing technically elegant but operationally irrelevant results.

A practical example appears in underwriting cycles. Climate losses tighten markets. Tight markets alter behavior. Altered behavior reshapes risk pools. These dynamics cannot be captured by static capital models alone. They require iterative thinking that blends numbers with narrative.

The goal of this broader approach is not precision. It is preparedness. Institutions that evolve well are not those that predict losses most accurately, but those that detect when their assumptions no longer hold and adjust before losses compound. Climate risk management rewards humility, curiosity, and adaptability more than confidence in any single technique.

RISK MANAGEMENT WHERE THE SYSTEM IS ALREADY MOVING

Climate risk does not arrive through one channel. It enters balance sheets through many doors at once. Insurance claims, pension liabilities, asset impairments, operational strain, and reputational risk often appear disconnected on paper but are tightly linked in reality.

In insurance, climate change challenges the separation between underwriting, reserving, and capital risk. A flood is not just property damage. It is delayed reporting, litigation, asset volatility, and reinsurance uncertainty. ORSA processes that treat these independently miss the compounding effect.

Short illustrations make this tangible. A heatwave increases health claims while straining power grids insurers rely on for operations. A wildfire season worsens loss ratios and forces asset sales at depressed prices. A flood damages insured property and erodes municipal tax bases, weakening the credit quality of bonds held by the same insurer. These are interacting stressors, not isolated tails.

For pensions, climate risk hides behind long horizons. Longevity assumptions, contribution adequacy, and asset returns are all exposed. Climate migration reshapes labor markets. Heat stress affects mortality unevenly. A pension fund that models climate impacts only through asset stress tests manages half the problem.

Asset owners face a related challenge. Traditional diversification assumes correlations rise temporarily and then revert. Climate risk questions that assumption. Physical risks cluster geographically. Transition risks cluster by sector. Policy responses create sudden repricing. Risk management must focus less on optimization and more on fragility.

Across domains, the lesson repeats. Climate risk is not a parameter to be adjusted. It is a condition under which the system operates.

Actuaries are trained to work in the Goldilocks zone of time, long enough for compounding to matter, short enough for intervention to still work. Climate change sits squarely in that zone. It is already affecting results, but its full shape is still forming.

The most effective climate risk management frameworks will not be those with the most sophisticated models. They will be those that notice early when reality diverges from expectation and adjust course without waiting for perfect data. They will favor adaptability over optimization, resilience over precision, and learning over control.

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Syed Danish Ali, CSPA is an actuarial professional with 15 years of consulting experience in multiple countries across the world. He is Certified Specialist in Predictive Analytics from Institute of CAS and a graduate of University of London. He can be reached at sd.ali90@ymail.com.

A Minimum Viable Climate Integration Roadmap for Insurers

Carlos Arocha, FSA

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INTRODUCTION

Sometime in 2019, *The Economist*, a newspaper, featured on its cover a timeline from 1850 to the present day with a background of vertical stripes, each representing the global average temperature of each year. These stripes were colored in different hues of blue up to about the late 1990s. Then the stripes became pale pink, pale orange, red, and finally, dark red.[1] This illustration spurred me to start paying attention to climate risk, and most intriguingly, that I have found in my professional practice that many insurers have yet to fully adapt their loss models to account for climate risk.

To make climate risk actionable it should be treated with discipline within the insurer's ERM framework. It should be governed, measured, and linked to decisions, rather than be considered as a standalone risk. Supervisory and disclosure frameworks are typically aligned on expectations such as board oversight, integration into enterprise risk management, forward-looking scenario analysis, and metrics.

This article proposes a minimum viable climate integration roadmap across five organizational levers: people, process, data, models, and reporting. Early outputs should be visible and decision-relevant, while building the foundations for deeper processes such as catastrophe (CAT) model integration, internal vulnerability curves, and climate-adjusted experience analysis, in three phases over a two-year period: days 1–90, days 91–365, and days 366–730.

WHY IT WORKS FOR ACTUARIES?

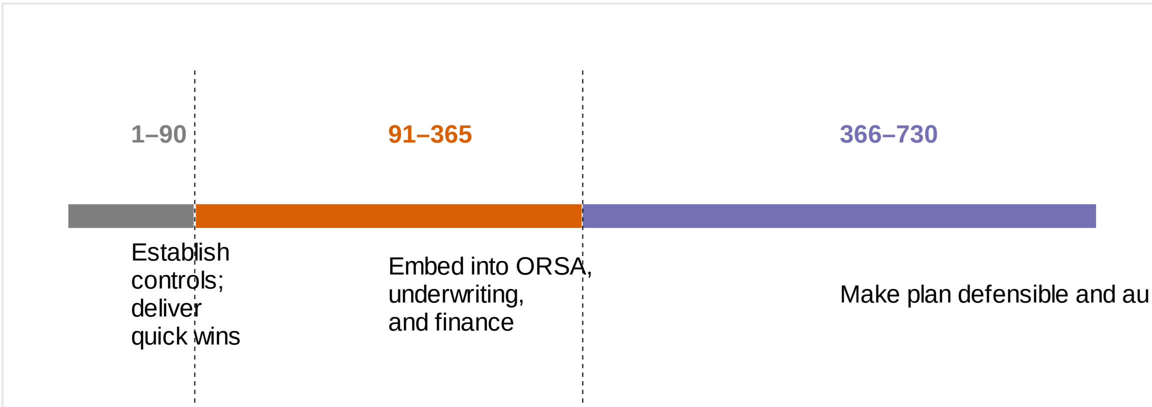
The proposed roadmap works for actuaries because it translates climate risk into the same disciplined workflow actuaries already use to manage uncertainty: define the risk, measure it with fit-for-purpose data and models, govern the assumptions, and link outputs to decisions and controls. The roadmap is essentially an actuarial "control cycle" applied to climate—identify and scope, quantify and monitor, then embed into pricing/reserving/capital and iterate—so it aligns naturally with established actuarial governance and ERM practice.

The roadmap also matches how actuarial work is operationalized in insurers: short decision cycles (pricing/underwriting) sit alongside longer balance-sheet cycles (reserving and capital) and disclosure cycles. By sequencing quick wins (exposure inventory, geocoding, heatmaps, risk metrics) ahead of deeper builds (vendor CAT integration, vulnerability curves, climate-adjusted experience studies), the roadmap

[1] *The Economist* published "The climate issue" piece (Sept 19, 2019) with the line "The world is about 1ºC hotter than when this newspaper was young," and the cover stripes are described as years 1850–2018.

respects actuarial materiality and proportionality by improving decisions immediately while building evidence over time for assumption changes and model enhancements.

THE ROADMAP



Phase 1 (Days 1–90) focuses on establishing basic controls and delivering visible "quick wins" that create momentum and credibility. The insurer appoints clear ownership (executive sponsor, cross-functional squad, committee oversight), runs an initial materiality assessment to prioritize a small number of use cases, and rapidly improves the exposure inventory, often starting with portfolio geocoding and a data-quality scorecard. In parallel, it produces a baseline view using existing vendor CAT models where available (and simple sensitivities where not), documents limitations, and launches a first metrics dashboard with owners and escalation thresholds. By day 90, tangible outputs include exposure heatmaps, an initial scenario set with an assumptions log, and basic change control for climate data and modeling overlays.

Phase 2 (Days 91–365) embeds climate risk into the annual management cycle—especially ERM, risk appetite, and ORSA (EIOPA, 2022)—so the work becomes "business as usual" rather than an initiative. Responsibilities are formalized in policies and committee terms of reference, and a training plan ensures underwriting, reserving, investments, and risk teams share a consistent vocabulary. Data capability is strengthened through automated geocoding refresh, standardized location schemas, and durable linkages to hazard layers and claims, with the same discipline applied to investment exposures where transition risk is material so concentrations can be monitored and stress-tested under scenarios. The deeper model build is initiated by integrating catastrophe vendor outputs into underwriting guidelines, reinsurance decisions, and accumulation controls, while starting internal vulnerability work in high-value segments (resilience attributes and quantified impacts). Reporting also matures from prototypes to consistent internal reporting and disclosure controls (International Sustainability Standards Board, 2023) aligned to a stable disclosure backbone (Task Force on Climate-related Financial Disclosures, 2017.)

Phase 3 (Days 366–730) is about making the plan defensible and auditable—turning climate insights into governed assumption changes and repeatable decisions. Climate capability is extended into underwriting authorities, actuarial assumption-setting, and investment mandates, with defined roles for model risk management and internal audit to review data controls and model overlays. Data moves from "where are we exposed?" to "why are we vulnerable?" through curated datasets that join exposure, hazard intensity measures, claims outcomes, and mitigation attributes, enabling credible experience analysis. The insurer completes climate-adjusted experience studies where signal is strong (for example, severity inflation, seasonality shifts, heat-related patterns) and expands internal vulnerability curves or adjustments so resilience features are reflected consistently with catastrophe-model vulnerability relationships. Reporting becomes decision-grade, with stable metrics over time (Task Force on Climate-related Financial

Disclosures, 2017), scenario results explicitly linked to risk appetite and management actions, and traceability back to governed data and models—supported by staged governance checkpoints at day 90, day 365, and day 730.

SUCCESS CRITERIA AND GOVERNANCE CHECKPOINTS

It is crucial to define success criteria as observable outcomes: improved exposure data quality, key metrics with owners and escalation thresholds, repeatable scenario analysis embedded in ORSA, and governed use of vendor CAT models with documentation, sensitivity testing, and disclosures that conform with your risk appetite.

Stage governance checkpoints

- By Day 90: approve ownership, scope, data standards, initial scenarios, and the metrics dashboard.
- By Day 365: approve the scenario set/cadence, risk appetite metrics and limits, and catastrophe model governance.
- By Day 730: approve climate-adjusted assumption changes in pricing/reserving/capital and confirm auditability of reporting and management actions.

CONCLUSION

In practice, a “minimum viable” climate risk integration roadmap succeeds when it turns climate risk from a narrative into a governed operating capability: one that is measurable, repeatable, and linked to concrete decisions in underwriting, pricing, reserving, capital, and investment management.

By sequencing quick wins in exposure intelligence and metrics with deeper builds in catastrophe model training, vulnerability analytics, and climate-adjusted experience work, insurers can improve near-term decision quality while building an auditable foundation for ORSA and external disclosure expectations.

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Carolos Arocha, FSA, is Founder and Managing Partner of Arocha & Associates GmbH and a member of the Swiss Association of Actuaries. He can be reached at ca@ArochaAndAssociates.ch.

Preparing for Climate Futures We Cannot Predict: An Actuarial Perspective

Nii Amoo Decardi-Nelson

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

INTRODUCTION

Climate change challenges a foundational assumption in financial risk management: that the future will resemble the past closely enough for historical experience to remain a reliable guide. For actuaries, whose work has long relied on carefully adjusted past data and prudently stressed models, climate risk represents a fundamental shift. Physical impacts, policy responses, technological change, and evolving societal expectations introduce uncertainty that is systemic, long-horizon, and difficult to quantify with traditional methods.

The purpose of this paper is to provide a concise starting point for actuaries engaging with climate risk. Drawing on guidance developed by the International Actuarial Association (IAA), this paper reflects on three themes: what decision-makers should understand about climate risk, why traditional actuarial models struggle in this context, and how tools such as scenario analysis and artificial intelligence can support, but not replace, professional judgment. The core argument is that preparing for climate futures we cannot predict requires humility, clarity, and a renewed focus on the actuarial role as a steward of uncertainty.

CLIMATE RISK: WHAT DECISION-MAKERS NEED TO UNDERSTAND

Climate risk is often discussed as an environmental concern, but for financial institutions it is also a financial risk. Climate-related risks affect mortality and morbidity, property damage, asset values, supply chains, and the long-term viability of business models. They also interact with existing financial risks in ways that can amplify losses or undermine diversification.

Actuarial literature commonly distinguishes between three broad categories of climate risk.

- Physical risks arise from acute events such as floods, storms, and heatwaves, as well as chronic changes such as sea-level rise and sustained increases in temperature.
- Transition risks emerge from the economic, technological, and policy responses to climate change, including carbon pricing, shifts in energy systems, and changes in consumer behavior.
- Legal and reputational risks reflect evolving societal expectations, regulatory scrutiny, and litigation related to climate impacts and disclosures.

These risks do not operate independently. Policy actions taken to reduce long-term physical risk may accelerate transition risk in the short to medium term. Legal and reputational risks may arise suddenly, triggered by changes in public sentiment rather than gradual trends. For insurers, pension funds, banks, and other risk-bearing institutions, climate risk therefore reshapes how traditional underwriting, investment, and capital decisions interact over time.

Importantly, climate risk is not confined to distant time horizons. While many physical impacts unfold gradually, their financial consequences may be felt much sooner as markets reprice risk, insurance coverage becomes constrained, or regulatory expectations change. Recognizing climate risk as a present and evolving financial issue is thus the first step toward managing it responsibly.

WHEN THE PAST IS NO LONGER A RELIABLE GUIDE

Actuarial practice has long been grounded in the careful use of historical experience. Mortality tables, catastrophe models, loss development methods, and asset return assumptions all reflect the same underlying principle: while the future is uncertain, the past provides a meaningful starting point. Climate change challenges this principle at a foundational level.

Climate-related risks evolve over time in ways that are neither stationary nor linear. Physical risks are changing in frequency and severity, but not smoothly or uniformly across regions. Transition risks may emerge abruptly, often triggered by political decisions, technological breakthroughs, or social tipping points. Legal and reputational risks can materialize even more suddenly, driven by shifting expectations of corporate responsibility.

In this context, reliance on historical data alone can be misleading. Past experience may understate future tail risk, obscure emerging correlations, or suggest a degree of precision that no longer exists. Importantly, the challenge is not simply a lack of data. Climate change introduces structural uncertainty, where the underlying processes generating risk are themselves changing.

IAA guidance emphasizes that climate risk should be viewed as a long-horizon, system-wide challenge. Its effects extend beyond individual lines of business or asset classes, influencing entire balance sheets and strategic choices. For actuaries, this requires a shift in mindset. The task is no longer to refine estimates within stable distributions, but to navigate uncertainty where the distribution itself is uncertain.

This does not imply abandoning quantitative analysis. Models remain essential tools for organizing information and testing assumptions. However, they must be interpreted with appropriate caution. In the context of climate risk, the appearance of precision should never be confused with reliability.

SCENARIO ANALYSIS AS A WAY OF THINKING

In response to deep uncertainty, scenario analysis has become a central tool for assessing climate-related risk. Yet scenarios are often misunderstood. They are sometimes treated as alternative forecasts or evaluated based on their perceived likelihood. This approach misses their primary value.

The IAA's work on climate-related scenarios emphasizes that scenarios are not predictions. Rather, they are structured explorations of plausible futures, designed to expose vulnerabilities, highlight trade-offs, and resilience under different conditions. Their purpose is not to answer the question "What will happen?" but to explore "What could happen, how would it affect us, and how should we respond?"

This distinction is particularly important for climate risk. Climate outcomes unfold over decades, while many financial decisions are made over much shorter horizons. Scenario analysis helps bridge this gap by allowing institutions to test decisions against long-term forces that are already in motion, even if their timing and magnitude remain uncertain.

Furthermore, effective climate scenarios combine quantitative analysis with narrative context. Numerical outputs alone can obscure critical assumptions about policy choices, technological adoption, or behavioral change. Narrative elements help decision-makers understand why outcomes differ across scenarios and how risks interact. In this sense, scenario analysis is as much a communication tool as it is a modeling technique.

For actuaries, scenario analysis aligns naturally with professional judgment. It encourages consideration of multiple futures, avoids over-reliance on point estimates, and supports governance processes that prioritize robustness over optimization. The actuarial contribution lies not in selecting the “right” scenario, but in ensuring that decisions remain defensible across a range of credible futures.

AI AND ADVANCED ANALYTICS

Advances in artificial intelligence and data analytics are reshaping how climate risk is measured and analyzed. High-resolution climate models, machine learning algorithms, and large geospatial datasets offer new insights into hazards, exposures, and vulnerabilities. Used appropriately, these tools can significantly enhance actuarial work.

AI is particularly effective at identifying patterns in large and complex datasets. It can improve hazard mapping, refine exposure assessments, and process unstructured data such as satellite imagery or climate simulations. In areas such as flood risk, wildfire exposure, or health impacts of extreme heat, advanced analytics provide valuable support for risk identification and monitoring.

However, AI systems are essentially constrained by the data on which they are trained. They perform best when future conditions resemble the past. Climate change undermines this assumption. Regime shifts, feedback loops, and tipping points are precisely the situations where historical data provides the least guidance. In such contexts, AI may generate outputs that appear precise while masking deep uncertainty.

There is also a risk that increasingly sophisticated models create a false sense of confidence. Highly granular results can give the impression that uncertainty has been resolved when it has merely been transformed. For decision-makers, this can be more dangerous than openly acknowledged uncertainty.

The actuarial role in an AI-enabled environment is therefore not diminished but strengthened. Actuaries are trained to question assumptions, assess model risk, and communicate uncertainty clearly. AI should be viewed as a supporting instrument, not a substitute for professional judgment. Governance, transparency, and interpretability remain essential, particularly when climate-related decisions have long-term and potentially irreversible consequences.

THE ACTUARY’S ROLE IN AN UNCERTAIN CLIMATE FUTURE

Climate change elevates the importance of actuarial judgment, communication, and governance. As institutions grapple with uncertain futures, actuaries serve as interpreters between climate science, advanced analytics, and decision-makers. This role extends beyond model construction to include explaining limitations, challenging overconfidence, and ensuring that uncertainty is neither ignored nor overstated.

Embedding climate risk into enterprise risk management, ORSA (Own Risk and Solvency Assessment) processes, and investment governance requires more than technical capability. It requires a willingness to engage with uncomfortable uncertainty and to support decisions that remain robust even when outcomes diverge from expectations. In this sense, actuarial professionalism is as important as actuarial technique.

CONCLUSION

Climate change confronts financial institutions with futures that cannot be addressed through familiar modeling techniques alone. In this environment, the value of actuarial expertise lies not in forecasting a single outcome, but in helping organizations navigate uncertainty responsibly.

The IAA's work on climate risk highlights that scenario analysis is most effective when used as a framework for thinking rather than a tool for prediction. Advanced analytics and AI can enhance insight, but they do not eliminate uncertainty, nor do they replace professional judgment. If anything, their growing influence increases the importance of governance, interpretation, and clear communication.

Preparing for climate futures we cannot predict is ultimately about decision-making. The most enduring contribution actuaries can offer is not certainty, but perspective. As such, the central question should not be whether projections will be accurate (they won't), but whether decisions made today remain sound across a range of plausible futures.

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Nii Amoo Decardi-Nelson is a graduate student at the University of Wisconsin-Milwaukee. He can be reached at niiamoo@uwm.edu.

Risk Management and Climate Risk

Sam Gutterman, FSA, MAAA, CERA, FCAS, FCA, HonFIA

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INTRODUCTION

According to Europe's Copernicus Climate Change Service, if recent atmospheric warming rates continue, the world's goal, as set in the 2015 Paris Agreement, of limiting warming to 1.5°C above pre-industrial levels will be breached in 2030, a decade earlier than expected in 2015. In fact, over the three years from 2023 to 2025, the average temperature has exceeded the oft-cited 1.5°C benchmark. The next El Niño will likely push temperatures even higher.

This warming trend has already led to a wide range of property and health-related losses and damage, which may impose additional costs on many. A panoply of hazards, including floods, droughts, wildfires, extreme temperatures, and storms, drives these losses and damage. Compounding and cascading factors further exacerbate these losses and damage. Even excluding hurricanes, U.S. disaster costs in 2025 exceeded $100 billion. It is also upending and reshaping people's lives, insurance and reinsurance markets, bank lending, and numerous economic sectors.

To reduce losses and damage from climate-related risks, an effective multi-layered risk management system or set of processes will be needed. A necessary component of such a system is to recognize and understand the primary lines of defense against these losses and damage. Risk management can be assessed and practiced from both societal and individual perspectives. Society can often be assessed by governments on a global, national, local, or individual basis, as applicable. The relative roles and responsibilities of the public and private sectors can differ widely, depending on factors such as costs and affordability, benefits, and types of risk.

This essay will, in broad terms, explore these risk defenses in the context of risk management processes.

LINES OF DEFENSE AGAINST RISK

There are three lines of defense that can help manage risk. They are:

4. Mitigation.[1] Eliminate or reduce the frequency or severity of the underlying causes.
5. Ex-ante adaptation. Change the exposure or vulnerability to the hazard.
6. Ex-post adaptation. If the hazard and resulting damage occur despite the use of the first two lines of defense, actions taken during or after the hazard can reduce the resulting loss.

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[1] Mitigation in some contexts refers to overall loss reduction. In climate-related discussions, it is usually used solely to describe efforts to reduce the underlying causes of climate-related hazards.

When implementing these defenses (risk management tools), the relative roles and responsibilities of the private and public sectors can differ across the three lines of defense, with both contributing in different ways. The public sector can contribute in several ways, including providing objective information, financial support, and incentives to encourage constructive action.

The two types of adaptation can be distinguished by timing. Ex-ante actions occur before the hazard, while ex-post actions, also called damage control, occur during or after the hazard. When analyzing the value of these second and third lines of defense, vulnerability to specific losses and damage can be assessed using two key factors: exposure and sensitivity.

The general risk management process often follows the flow shown in Figure 1 and incorporates multiple feedback loops, with steps sometimes conducted in a different order.

Figure 1
THE RISK MANAGEMENT PROCESS

A brief description of these steps follows:

- *Identifying objectives and risks* that may threaten health, income, or other resources is usually addressed through a planning process. Particularly vulnerable areas and stakeholders, as well as potential opportunities, are also identified.
- *Assessing* risk probabilities and their expected severity and timing.
- *Controlling* through mitigation or adaptation to eliminate or reduce the probability and severity of losses or damages, as well as taking advantage of co-benefits and reducing co-costs.
- *Measuring* involves estimating the risks, costs, and benefits involved, as well as their timing, on an analytically sound quantitative basis, supported, as applicable, by qualitative analysis. In doing so, transparency regarding the assumptions used should be established and documented, where applicable, to enable independent review in both governmental and business applications. Developing a range that is not overly wide or otherwise communicating the uncertainty involved may be helpful.
- *Financing or transferring/sharing* the risks and expected or actual costs, including those related to mitigation and adaptation, on an ex-ante or ex-post basis.
- *Monitoring to identify new risks and opportunities, reflecting risk appetites dynamically, while recognizing and reporting on the effectiveness of the process, measures in place, and actual costs.*

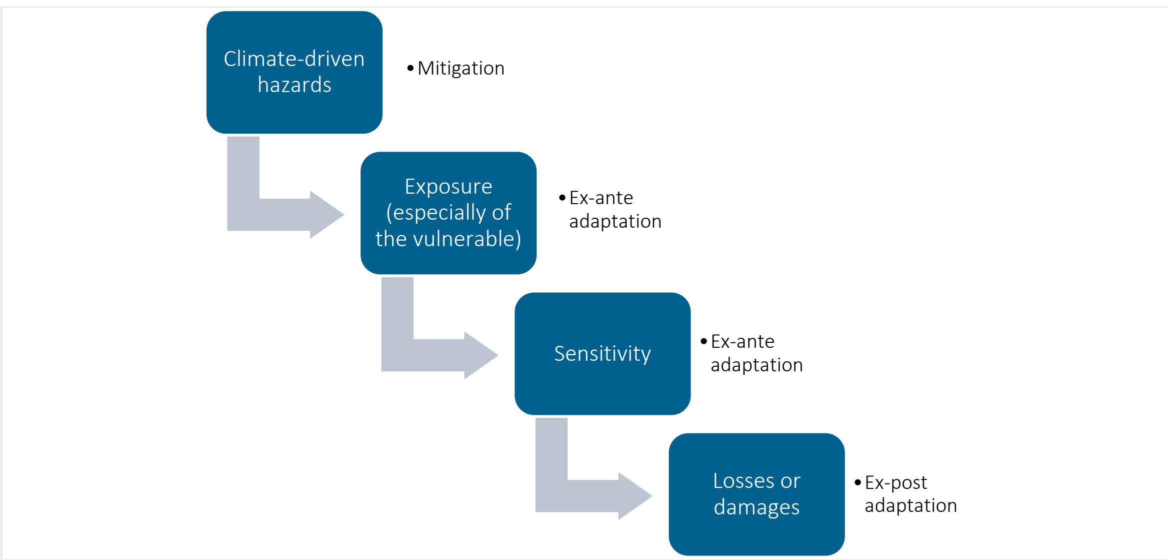
An actuary can be involved in each of these steps in a formal process, from identifying and evaluating potential risks to developing and assessing mitigation and adaptation measures, establishing and measuring progress toward objectives, managing the risk (e.g., through avoidance, financing through self-retention or (re)insurance, and transferring), and monitoring the results. One example of actuarial involvement is conducting cost-benefit analyses to evaluate possible approaches to implementing investments in mitigation or adaptation. This process can also be applied in a less formal way, particularly when applied to an individual or household.

RISK MANAGEMENT OF CLIMATE RISK

In this essay, I focus on applying the risk management process to climate-related risks. Note that a similar approach can be applied to other external causes of losses or damage.

In Figure 2, the corresponding lines of defense are listed to the right of each central element in the risk management process.

Figure 2
CLIMATE RISK LINES OF DEFENSE



Whether a risk assessment is conducted from the perspective of an individual, a business, or the public sector, the first step is to identify the entity or area of concern, the risks involved, the key sources/drivers of these risks, and the timeframe for the assessment. In addressing climate and climate-related risks, several climatic factors (e.g., temperature, precipitation, humidity, and wind) are influenced by a range of underlying factors. Some are natural, such as solar radiation and clouds, while others are directly or indirectly influenced by human activities, such as greenhouse gas emissions from energy production and use and transportation.

Although climate change will increasingly exacerbate losses and damage from climate-related perils, my focus here is on the total climate-related losses and damage associated with these considerable perils. This holistic focus is partly due to the complexity and controversy surrounding the extent to which these perils are generated by or result from human behavior, which underlies and justifies much of the mitigation investment. As our climate changes, these losses and damages will inevitably increase over time, making this an even more important issue. But bottom line, I am concerned here with preventing or reducing the resultant losses and damage, regardless of their attribution.

The following addresses both direct and indirect drivers of these losses and damage. To illustrate the importance of indirect losses, second or third-order consequences of climate-related hazards include reduced housing values in flood-prone or nearby locations, declines in asset values due to anticipated adverse effects of climate change, death or ill health from poor air quality caused by fossil fuel combustion and wildfire smoke, and vector-borne diseases due to the expansion of mosquito or tick ranges.

Given the potential severity of these hazards, a range of mitigation and adaptation actions (both ex ante and ex post) should be considered key components of a risk management process. The effectiveness of these efforts will determine the extent of losses and damage we will experience.

Mitigation and adaptation approaches constitute the lines of defense against climate-related damage. An elaboration of each line of defense follows.

- *Mitigation*, the first line of defense, reduces the effects of certain underlying causes of climate risk, primarily by lowering greenhouse gas emissions, thereby reducing their buildup in the atmosphere and the oceans. This can be done, for example, by reducing emissions, capturing and storing emissions through natural or man-made means, such as increasing the use of renewable energy, reducing emissions from transportation, expanding carbon sinks, or enhancing technological innovations and their implementation.

  Although greenhouse gas emissions are significant contributors to the hazards discussed here, they aren't the only ones. Other human behaviors and activities can also be important drivers, for example, inadequately maintained power lines, careless use of fire in dry forests, and failure to undertake traditional flood control methods. Some of these may be difficult to eliminate.

  Prospects for significant global mitigation efforts, at least in the short term, are less favorable than a decade ago, as evidenced by current results, including record-setting 2025 emissions (hopefully at peak levels) and record-high ocean temperatures. Even if emissions begin to decline, greenhouse gas concentrations will persist in the atmosphere for decades or even centuries. Mitigation efforts will have to continue for a long time—almost every climate projection assumes that at some point we will begin to reduce atmospheric concentrations (below net-zero), which may be optimistic.

  In any case, technological improvements and scale will help, such as inexpensive solar panels and enhanced battery storage. Although the contributions of individual decarbonization efforts may seem minuscule compared with global goals, they will help if these efforts are sufficiently widespread.
- *Adaptation (ex-ante).* The second line of defense is modifying existing resources or developing new ones, whether in location or form, to eliminate or reduce potential climate-related damage to properties or individual lives, thereby reducing losses. Until relatively recently, adaptation has been given less priority than mitigation, both globally and, at times, at regional, national, local, or individual levels. However, this relative emphasis appears to be evolving as these losses increase and receive more media attention. Some action is taken at multiple levels (e.g., local regulation can set a minimum adaptation level, individuals can adopt a more stringent level, governments can establish tax or other incentives, and insurance companies can provide their own premium or coverage incentives).

  - Ex-ante adaptation can modify the social environment (e.g., public services such as flood protection and emergency health care infrastructure), individual property (e.g., fire extinguishers, air conditioners, and zoning outside of flood zones), or individual behavior (e.g., maintaining good health, keeping air conditioners on during a heat wave, and following evacuation procedures). These measures can vary by hazard, though some remain the same (e.g., vaccines, bug spray, or bed nets against infectious diseases, whose use can increase as temperatures warm).
  - Limits on construction in unsafe urban areas (e.g., in a fire or flood zone) or on the use of hazardous building materials. In some cases, insurance regulators force insurance companies to hold down insurance rates in unsafe areas, thereby subsidizing immigration into those areas, while home values are discounted at the same time due to these risks. The pressure to hold down house prices can lead to skimping on safety features, which may, in turn, increase losses and damage.
  - Establishing an effective early warning system for potential heat, storms, or floods can be especially effective in reducing exposure to damage. Of course, this assumes that people pay proper attention to these warnings.
  - Some adaptations can serve multiple purposes. For example, improvements to public health infrastructure and emergency transportation can both reduce losses from climate risk, as well as from other causes. For instance, during a 2003 heatwave, Parisians experienced tens of thousands of avoidable deaths due to inadequate public health emergency infrastructure; subsequent improvements significantly reduced the number of such fatalities during a similar heatwave in 2013.
- *Adaptation (ex-post).* To the extent not eliminated or diminished by mitigation or ex-ante adaptation, the third line of defense, sometimes referred to as ex-post adaptation or loss prevention, involves managing losses or damage during or after an extreme weather event. This defense can help minimize the ultimate losses from climate-induced damage. Financial recovery may come from insurance, which can offset a portion of the economic cost of these damages. At the same time, public, community, or charitable assistance can be a significant factor in alleviating some of the remaining adverse effects.
  - In most cases, it is preferable to rely on ex-ante rather than ex-post adaptation. However, it is common to think that "such an event will never happen to me." Insurance and public help can sometimes serve as a backstop.
  - A key element of the recovery process is learning lessons from previously incurred losses or damage, especially by planning for enhanced future adaptation, ranging from improving building structures to relocating from high-risk areas.

Each of these defenses can target either climate-specific or broader risks. An example of the latter is enhanced public health services and infrastructure that can reduce both climate-related and general healthcare risks. Insurance can provide incentives for actions, such as premium discounts for adaptive building features or preventive healthcare, thereby reducing individuals' vulnerability by promoting good health.

When deciding how much to invest in these three lines of defense, trade-offs are inevitable, as in other risk management processes. Limited budgets can constrain action, even when the investments are financially justifiable. The default option is ex-post adaptation, to the extent available and effective, which people are stuck with in any case. These decisions apply not only at the national level, where financial resources must be allocated to other priority areas such as education, national defense, social welfare, and healthcare, but also at the state, community, and individual levels.

PROJECTIONS AND ESTIMATES OF LOSSES AND DAMAGES

An actuary may be called upon to develop projections and estimates of losses and damage from climate-related perils as part of a risk management system, typically through a cost-benefit analysis. In some cases, these are formal, e.g., through a firm's risk management committee, as described in a report with documented assumptions. If conducted by an individual for their household, they are usually developed informally, possibly relying solely on common sense. In any case, qualitative and quantitative analyses are typically used.

When analyzing options, financial and human losses and damages, including premature deaths and healthcare impacts, should be considered, with the method depending on the situation and type of analysis. Assessing the value of the lines of defense can be difficult because it often requires combining these costs, for example, property losses and morbidity. There are several ways to do this.[2] For costs and benefits involving an extended period, the choice of a discount rate is usually an important element.

Complicating such an analysis are the time lags between, for example, an extreme weather event and the ultimate losses and damage. For example, exposure to climate-related hazards such as wildfire smoke (particulate matter) or a heatwave can lead to or exacerbate cardiovascular, pulmonary, and communicable diseases weeks or even years after initial exposure. This contrasts with the usual distribution of causes of death or ill health from such an event, which typically includes only those reported in the few days after exposure. Because of these lags, the cost of climate-related risks is often underestimated.

To estimate expected losses and damage, a dynamic assessment is needed because both the climate and the underlying conditions change over time. Although I earlier indicated that overall climate risk is more important to consider in this estimation process, climate change projections can be significant for projecting future losses and damage, as the impacts of future warming scenarios are likely to worsen relative to current experience. Note that, depending on the effectiveness of the available and utilized lines of defense, the expected losses and damage may even be reduced.

Concentration risk for an insurer or a business can be significant. If a catastrophic event occurs, it is likely to affect many insured exposures. For instance, a storm, wildfire, or flood can severely damage the finances of a local government, business, or household, as well as an insurer without adequate capital or reinsurance. In addition, an existing health condition can be exacerbated by excessive heat. In any case, such an event can be catastrophic for a household.

Despite the challenges of developing a cost-benefit analysis of climate risk, these risks should be considered. During the risk management process, identifying, projecting, and reporting climate-related risks can be valuable. As part of this analysis, mitigation and adaptation options should be identified and their value evaluated.

CONCLUSION

Climate risk should be considered in many risk management analyses and projects. A risk manager should follow traditional risk management practice: identify and analyze possible climate risk scenarios, including the expected effects of both the risk manager's and society's mitigation and adaptation actions. It is easy to conclude that climate risk is not significant to the entity being assessed. However, due to several factors

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[2] Discussed in Gutterman, S. (2020). Social Discounting, Application to the Risk Management of Climate Change. *Society of Actuaries*. https://www.soa.org/globalassets/assets/files/resources/research-report/2020/social-discounting-climate-change.pdf

discussed in this essay, including concentration risk and climate change, a risk manager should also consider whether investments in adaptation are warranted.

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Sam Gutterman, FSA, CERA, FCAS, MAAA, FCA, HonFIA is a consulting actuary. He can be reached at sam.gutterman1@gmail.com.

From Emerging Risk to Business-as-Usual: Integrating Climate Risk Management and Scenario Analysis into ERM

Brian Hinkle, FSA, MAAA

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INTRODUCTION

Climate risk has often lingered in the shadow of risk management. It rarely has clean spreadsheets or a tidy model output. Typically, it shows up as a question that doesn't quite fit anywhere yet. How were we impacted by that severe weather event that garnered national attention? I'm hearing that insurance costs are moving faster than expected, how does that impact us? I just received a new survey from a regulator, who should handle this?

Early on, it was tempting to treat these as edge cases. Interesting, important, but not quite ready for the core risk framework. I've seen climate risk evolve from an actuarial student in ERM filling out an annual survey, to regularly showing up in emerging risk reports, to client inquiries and regulatory requests. As this progression unfolded, climate risk went from "worth watching" to "we need someone to own this, now."

From an actuarial and risk management perspective, that's uncomfortable territory. When we pause to think, we realize we have the tools to manage this: ERM frameworks, governance groups, risk tolerances, scenario analysis. The challenge with climate risk is not that it is unmanageable, it's that it's very uncertain and far-reaching. It's complex and requires significant judgment in the absence of solid models or data.

However, I believe climate risk becomes manageable when we stop treating it as something fundamentally different and start treating it as business-as-usual risk management work.

WHY CLIMATE RISK BELONGS IN ERM

Climate risk doesn't respect organizational boundaries. Physical risks can disrupt operations, third-party vendors, and investment portfolios. Transition risks can affect asset values, regulatory compliance, reputation, and long-term strategy. None of these live neatly in a single department.

That's why ERM is the right home for climate risk. ERM exists to do three things well:

- Bring people together across silos.
- Apply consistent structure to messy problems.
- Elevate the right information to decision-makers.

Climate risk management needs all three.

I've found it helpful to think of climate risk not as a new risk category, but as a risk amplifier. It intensifies risks we already manage: market risk, operational risk, underwriting risk, and strategic risk. Framing it this way lowers the barrier to integration. We don't need a new philosophy of risk management. We need to apply the one we already have to a new context.

MOVING PAST "EMERGING RISK"

Most organizations start in the same place. Climate risk shows up on a watch list and is then elevated to a high priority due to regulatory requirements, executive concern, or simply prudent risk management. A group of associates form a task force, perform initial analysis, maybe a qualitative assessment, and report to leadership. This is good work, necessary work, but it's not the end goal.

The shift happens when climate risk moves from that initial assessment and scoping to an embedded process. When different aspects of climate risk are mapped into existing risk categories and become a part of the ongoing governance of those risks. When the team monitoring mortality risk owns monitoring the impacts from climate risk on acute and chronic mortality. When climate considerations are embedded in your asset underwriting. And when third-party risk teams bring in geographic location and concentration into their risk assessment.

There are increasing external expectations around managing climate risk and governance matters. Cross-functional groups or committees, led by ERM, can help aggregate and coordinate risk and impact monitoring across the enterprise. They can own reporting and oversight of the management structure. Having a dedicated group also sends a signal this isn't a side project; it's part of how we manage risk.

SCENARIO ANALYSIS: WHAT IT IS AND WHAT IT ISN'T

Scenario analysis is often described as the cornerstone of climate risk management. That's true, but only if we're honest about what it can and can't do. Climate scenarios are not forecasts, they're not probability-weighted expectations of the future, and they are not precise predictions. Treating them that way sets everyone up for frustration, but it also doesn't mean they are useless.

What scenarios are good at is something actuaries already value deeply, stress-testing our assumptions. They help us ask, "If the world moves in this direction, how exposed are we, and how prepared are we to respond?" That's familiar risk management territory. We do this with interest rates, mortality improvement, and market shocks all the time. Climate scenarios are unique in that they extend that thinking further out in time and across more dimensions.

CHOOSING SCENARIOS AND TIME HORIZONS

It is now standard practice to use externally developed climate scenarios. Network for Greening the Financial System (NGFS) and Intergovernmental Panel on Climate Change (IPCC) scenarios are widely referenced, because they are independently created, explore a variety of pathways, and most importantly, not designed to tell a convenient story.

Typically, a company will want to look at a minimum of two scenarios. One where the transition to a lower-carbon economy happens in an orderly way, and one where the world does not respond to climate change and global temperature rise. It is increasingly common to include a disorderly transition scenario, where the world waits to act and then enacts significant change very quickly. None of these scenarios are "right," but they can all be useful.

Time horizons matter quite a bit in climate scenarios and are typically longer than most stress testing done by insurance companies. Some climate risks show up quickly, such as insurance availability, operational disruptions, and regulatory change. Others unfold over decades, such as long-term mortality or morbidity trends. These long time horizons force us to confront an uncomfortable truth: the risks that matter most long-term are often the hardest to quantify today; the data simply doesn't exist.

LIVING WITH UNCERTAINTY

If you're waiting for perfect data on climate risk, you're going to be waiting a long time. Mortality impacts, migration patterns, and asset repricing all depend on pathways we can't assign probabilities to with confidence.

I've seen organizations respond to this in two unhelpful ways. One is paralysis, "We don't know enough yet, so we won't act." The other is overconfidence in complex models that produce very specific numbers without much transparency.

Actuarial judgment lives in the space between those extremes. Actuaries have always worked with imperfect information. Contrary to what many of our friends and families think, the actuarial profession hasn't persisted for almost 200 years because we're good at math, it's because we've developed sound judgement amid uncertainty.

QUALITATIVE FIRST, QUANTITATIVE WHERE IT COUNTS

A practical way forward is to implement a staged approach. Start with qualitative scenario analysis focusing on the key risks of your organization. Focus on the scenario narratives, not the numbers. Assess how and when your key risks may be impacted in these scenarios. Assess not just the impact and likelihood, but also your organization's response capability. Ask hard questions about where existing processes are strong and where they aren't.

This qualitative analysis will give you a roadmap for targeted quantification. Focus on the areas you rated highest in the qualitative assessment and determine how you can stress test that risk. You could look at acute impacts from severe weather on your liabilities. You could measure the impact of insurance cost increases on your investment portfolio. Or you could model the impact of a ratings migration in carbon-intensive assets. This targeted approach will give you insights you, and your leaders, can trust and understand. Trying to quantify everything at once isn't ambitious, it's inefficient.

BRINGING CLIMATE RISK INTO RISK REPORTING

Scenario insights should feed directly into ERM processes and reports. If any climate-related risks are deemed material, they should impact your risk appetite, capital planning, risk mitigation decisions, and strategic discussions. Integrating climate risk into your ERM framework leads to clear and consistent reporting as well. If climate risk is integrated into ERM, it fits naturally in a company's Own Risk and Solvency Assessment (ORSA). Leveraging your established ERM framework also makes Taskforce for Climate related Financial Disclosures (TCFD) aligned reports, such as the NAIC Climate Survey, straightforward and clear.

Risk reporting doesn't require false precision, but a thoughtful discussion of risk and management response. Qualitative climate scenarios fit well here when presented honestly with clear articulation of the implications and next steps.

Senior executives, boards, and regulators don't need complex climate science (nor are most actuaries qualified to provide it), they need clarity. What assumptions are we making, where are we exposed, how does this affect our strategy, what are we doing now, and what might we need to do later?

WHAT THIS HAS TAUGHT ME

Climate risk doesn't require us to reinvent ERM, it requires us to trust and leverage it. Scenario analysis doesn't require us to predict the future; it requires us to take it seriously. Most importantly, integrating climate risk is not about getting the answer right. It's about making sure the risk is seen, discussed, owned, and managed before it forces its way into the room on its own terms. Our understanding of climate risk and its impacts will continue to evolve and change as global warming unfolds. ERM frameworks are built to evolve and change with it.

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Brian Hinkle, FSA, MAAA is a senior actuarial consultant at Securian Financial Group. He can be reached at brianc.hinkle@gmail.com.

Adopting SASB Metrics for Climate Risk Management in Life Insurance Companies

King Yin Pang, FSA, CERA, FRM

Any views and ideas expressed in the essays are the author's alone and may not reflect the views and ideas of the Society of Actuaries, the Society of Actuaries Research Institute, Society of Actuaries members, nor the author's employer.

INTRODUCTION

The idea of sustainability reporting borrows the concept from more traditional financial reporting that higher transparency would promote the proper behavior of the company by allowing stakeholders to monitor and challenge the actions of management. Risk management is normally built on the observable metrics in financial reporting or factors directly affecting them, with the rationale that those are considered critical to the financial performance of the company and quantifiable for risk monitoring. It is therefore reasonable to hold similar expectations to manage climate risk based on sustainability reporting metrics.

In order for such mechanisms to work effectively, the items disclosed should be able to capture the sustainability factors which have/may have a material impact on the financial performance of the company. This may not be necessarily the case when those parameters are selected with the intention of covering all industries, or the purpose of the disclosure serves a broader range of stakeholders than people with financial interests in the company.

The primary goal of SASB standards is "to require an entity to disclose information about its sustainability-related risks and opportunities that is useful to *primary users of general purpose financial reports* in making decisions relating to providing resources to the entity" (IFRS S1, italics in the original text). The emphasis of "providing resources" and hence financial perspective of the company in its sustainability performance matches the consideration of risk management. This paper aims to examine how the parameters offered by the SASB Insurance Standard can supplement the climate risk management process and identify any gaps which may exist. The scope is limited to life insurance companies selling protection and savings products to allow for a more in-depth analysis useful for practical applications.

CATEGORIZATION OF CLIMATE RISK

Climate risk is often categorized into two items, physical risk, and transition risk. From the perspective of risk management of a life insurance company, these two categories are too board and shall be broken down into finer items. As an example, Bermuda Monetary Authority issued a guidance note in 2022 to identify the following risk factors which may arise from climate risk:

A) Insurance risk
B) Investment/market risk
C) Credit/counterparty risk
D) Operational risk
E) Reputational risk
F) Strategic risk
G) Legal/litigation risk (BMA, 2022)

In general, physical risk is more related to insurance risk and operational risk, while transition risk is more related to reputational, strategic, and legal/litigation risk, while asset risk (including both investment and credit risk) may arise from both physical and transition risk.

The above typology would allow us to analyze the parameters used in sustainability reporting to see if they have been sufficiently represented.

SUSTAINABILITY REPORTING STANDARDS

The full list of metrics used in the SASB Insurance Standard can be found at SASB website: https://navigator.sasb.ifrs.org/sector/FN/industry/FN-IN.

The focus of this paper is the relationship between disclosed metrics and risk management. Therefore, only sustainability reporting standards with specific metrics are considered. Standards such as the Task Force on Climate-related Financial Disclosures ("TCFD") and the European Sustainability Reporting Standards ("ESRS") provide general principles hence are not the subject of this paper. Among the standards offering list of quantitative and qualitative metrics, SASB and the Global Reporting Initiative ("GRI") are the most commonly adopted. While GRI announced in 2021 a plan to develop sector-specific standards, the one for financial services is still pending to be released. Without sector specific standards, the metrics offered by GRI remain relatively general and broad for the use of risk management within a company and instead are more useful for a high level understanding of the performance of the company toward sustainability goals only.

MATCHING DISCLOSURE METRICS TO RISK APPETITE

This section will examine the seven categories of risks induced by climate change to check whether the metrics listed in the SASB Insurance Standard can provide good measures of the risk.

A) Insurance Risk

For a long-term life insurer, this mostly refers to mortality and morbidity risk. Life and medical insurance coverage mean that any one-time shock in mortality and morbidity rate from physical risk such as tsunami or forest fire is important. **FN-IN-450a.1: Probable maximum loss from natural catastrophe** provides information regarding potential loss under extreme climate events as an indicator on the desired level of capital. Likelihoods from one-in-50 to one-in-250 are adopted to show the volatility of climate risk. This disclosure metric also requires the reporting of both gross and net loss. This is important given the long-term nature of the policy, during which changes in reinsurance arrangements— e.g., rate increases or even reinsurer —are possible. Another dimension of the metric is geographical location, which is a critical factor in management of climate risk due to varying degrees of impact (sometimes even in opposite directions) among different latitudes, altitudes, closeness to sea or river, etc. Monitoring this metric shall then give a sense to the potential financial impact arising from insurance risk.

For the above measure to give a reliable monitoring metric, the modeling capacity of natural disaster is critical. Hence SASB offers another metric, **FN-IN-450a.2: Losses split into modeled and non-modeled natural catastrophe.** This provides monitoring of the scope of modeling to understand whether the in-house model covers all natural disasters that have material financial impact on the entity. Events such as droughts and snowstorms may have had relatively limited impact in the past in some geographic locations, and therefore they are not explicitly modeled. An increasing portion of non-modeled losses may indicate an increased severity and frequency of such events due to climate change, and an enhancement of model capacity to cover a wider variety of natural disasters should be considered.

B) Investment/Market Risk & Credit/Counterparty Risk

These two risks rest on the asset side of an insurance company's balance sheet. Long-term life insurers normally have a huge balance sheet due to the timing difference between premium receipt and benefit payment of whole life or long-term policies. Climate risk may mean asset depreciation due to physical risks directly damaging the current value of assets, or transition risk affecting the on-going profitability of entities in the portfolio. Therefore, climate risk consideration should be factored into the overall investment management process. In performing pre-acquisition assessments or regular portfolio reviews, the physical risk and transition risk exposure should be covered to better understand how the performance of the investee may fluctuate due to climate change.

FN-IN-410c.2: Gross exposure for each industry by asset class is a useful starting point of the above. Fossil fuel industries like thermal coal and oil extraction will likely have declining profitability as the world transitions to more eco-friendly energy sources. The performance of the agriculture industry will also be subject to much higher volatility, depending on factors such as geographic location, frequency and severity of flooding and drought, global food supply, individual companies' capacity to cope with the changing environment, etc. The industry allocation of the portfolio can serve as a quick indicator of an insurer's exposure to climate risk.

FN-IN-410c.1: Absolute gross financed emissions by Scope 1, Scope 2, and Scope 3 supplements the investment and risk management decision by looking at the emission performance of individual assets. While **FN-IN-410c.2** identifies industries that are ostensibly impacted by climate change, **FN-IN-410c.1** distinguishes the future prospects of individual companies by examining their emissions levels. This allows companies within the same industry (e.g., automotive), but pursuing different strategies (e.g., electric vehicles vs. gasoline vehicles), to be differentiated and analyzed.

C) Reputational Risk & Legal/Litigation Risk

Reputational risk is often broadly defined as the risk that customers' and the general public's perceptions of a company's business activities negatively affect its performance.. For climate risk, it may mean that an insurer is offering insurance coverage which may sustain the continuous use of fossil fuel or energy intensive behavior, or the entity is not paying attention to its impact (e.g., investment) on climate change. The former is captured by **FN-IN-410b.1: Net premiums written related to energy efficiency**, but it is not very useful to life insurers, who are providing coverage to the life and health of an individual which is not linked to energy usage. The topic is better captured by the same metric **FN-IN-410c.1** on financed emissions as in the investment risk above, . It is expected that a company with financed emissions staying at a high level without any signs or roadmap of reduction will create an impression of irresponsible corporate behavior due to its lack of contribution to the net-zero target. The absence of any behavioral change also poses legal/litigation risk to the company.

D) Strategic Risk

Strategic risk is the key item determining the survival of an entity, and this is exactly why there is no single factor which can determine the level of strategic risk. It makes more sense to identify and analyze strategic risk using qualitative rather than quantitative approaches. SASB standards offer a number of discussion items on top of quantitative metrics, and items relevant to strategic risk include **FN-IN-410b.2: Products that incentivize environmentally responsible actions** and **FN-IN-450a.3: Approach to incorporate environmental risks into underwriting/risk management/capital process**. In essence, if the insurer could reflect climate risk considerations in its daily insurance operation process (i.e., product development/underwriting/risk management/capital management), the strategic risk can be mitigated if not reduced.

E) Operational Risk

Unfortunately, there is no metric in the SASB Insurance Standard which is related to operational risk. Alternative measures will be introduced in the next section.

LIMITATIONS AND ALTERNATIVE TOOLS FOR RISK MANAGEMENT

In spite of the intention of SASB standards, it is unreasonable to expect that the metrics proposed for public disclosure could provide a comprehensive assessment and monitoring of climate risk. The metrics only consider the most critical items to the insurance industry and do not distinguish between casualty vs. life insurance. Internal risk management within a long-term life insurer is expected to cover a more comprehensive list of risk factors and also more related to the business of life insurance. Some limitations and alternative risk management tools are discussed below:

A) Insurance Risk

FN-IN-450a.1: Probable maximum loss from natural catastrophe looks at the loss arising from climate risk, but only on a short-term basis. For long-term life insurers, it is often the longer-term trend on the increase of mortality and morbidity rate which is more difficult to predict and manage. With concrete records of medical technology advancement over the last two hundred years, it is common for actuarial assumption to embed an annual factor for mortality improvement (though less frequent for morbidity reduction). While it may remain a valid assumption to project further medical breakthroughs which could extend the life of human beings, it is uncertain how much of these technological benefits will be offset by the environmental factors, in particular if the average temperature increases by more than 2°C. Scenario testing is an important tool of risk assessment, with IPCC scenarios being the most widely used reference. However, IPCC scenarios often lack the level of granularity to perform a sufficiently detailed analysis for a company's use. Enhanced scenarios such as those prepared by NGFS should be considered.

Apart from scenario setting, the underlying assumptions on severity and frequency of natural disasters is critical. Companies should regularly monitor the quality of modeling to understand whether the underlying assumptions and distribution model are able to capture the volatility of climate risk. Very often we have sophisticated models on insurance liability, and this may lead to complacency over the level of risk control. This complacency could threaten the survival of an entity in particular when the projection runs far into the future and the reality could turn out to deviate significantly from expectations. Climate risk and long-term life policy are a combination which may run wild over multiple years, even decades. The analysis of variance over modeled values should be an early indicator of the necessity of assumption and/or model review.

B) Investment/Market Risk & Credit/Counterparty Risk

In comparison to other risk factors, investment/counterparty risks are quite well covered by **FN-IN-410c.1** and **FN-IN-410c.2** when both exposure by industry and the corresponding emission level are measured. These should be sufficient as a general measure in regular risk appetite monitoring, while investment management should drill down to the sustainability performance of individual assets to determine the level of physical and transition risks embedded in the investment.

C) Reputational Risk & Legal/Litigation Risk

As discussed above, financed emission is an important measure on reputational risk and legal/litigation risk given its level is directly linked to the impact to climate change and the achievement of the net-zero target. However, other potential incidents affecting reputation and inducing litigation may arise from time to time when opinion and expectation of the public changes, which may not be easily identified in advance. Keeping track of scandals and litigations related to climate risk for peer life insurers and other financial institutions could be a potential option for risk monitoring.

D) Strategic Risk

Maybe the most effective way of managing strategic risk arising from climate change is to ensure that such risk is well recognized and discussed at C-suite and Board levels. Only when climate risk is embedded into the derivation of the strategic plan can such risk be managed. On this area, instead of SASB, GRI 102: Climate Change may provide a good reference point on items such as transition plan and adaptation plan.

E) Operational Risk

While the SASB Insurance Standard may consider operational risk less material in the scope of sustainability reporting of insurance companies, there are items in other industry standards which may be useful. For example, the SASB Real Estate Standard requires disclosure of **IF-RE-450a.1: Area of properties located in 100-year flood zones**. Risk management for long-term life insurers could modify this to report the office/backup centers located in 100-year flood zones to assess the climate risk on operational disruption.

CONCLUSION

For companies starting the process of climate risk management, sustainability reporting metrics could provide a good starting point. This addresses the items considered to be most material from the investor perspective as they are closely related to financial performance of the company. Preparing and monitoring such metrics for risk management purposes also supports the external reporting which may be required in the near future due to local regulations or rules imposed by the stock exchange. However, this should only be a transitional step to a more comprehensive and sophisticated management of climate risk. In particular, scenario testing is a very critical tool in managing such long-term risk for a long-term portfolio. Getting familiar with IPCC and NGFS scenarios will be necessary for actuaries working for long-term insurers in climate risk management to support the derivation of a transition/adaptation plan.

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King Yin Pang, FSA, CERA, FRM, is a life actuary with more than 20 years of experience in financial reporting and capital management. His recent field of study is climate risk and sustainability reporting. He can be reached at kingyin.pang@gmail.com.

Stability of Actuarial Assumptions: Impact of Climate Change

Max Rudolph, FSA, CFA, CERA

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INTRODUCTION

The earth has enjoyed 10,000 years of climatic stability since the most recent Ice Age. Human actions since 1750, tied mainly to fossil fuels, have increased carbon dioxide and other greenhouse gases in the atmosphere and oceans, increasing temperatures and ocean acidification. Many impacts to climate have been recorded, from expanding drought, increased strength of hurricanes, and increased damage from convective thunderstorms.

The most recent ten years have been the warmest in the global historical record, with carbon dioxide levels their highest in at least 800,000 years. According to climate modelers, the earth's ecosystem is nearing temperature tipping points. Reaching three degrees Centigrade above pre-industrial temperatures globally could stimulate an additional three degrees of temperature increase. Some have hypothesized that these triggers could be due to war-time greenhouse gas release, changes in cloud formation, permafrost melt, or a slowing ocean current. *This Time is Different!* And not in a good way. Global warming acts as a threat multiplier to nearly every other risk we encounter and impacts nearly every actuarial assumption in some way.

Assumptions for extreme weather events are unknown knowns, where we have historical data but it is not predictive for future events. Many actuarial assumptions are constant or rely on a mean reversion relationship. Meanwhile, many of today's trends are changing in nonlinear ways. For those who have mispriced these risks the tide is going out, and we may soon discover who has been swimming naked. Modelers have some tools to reflect potential trends, but uncertainty is higher and interactions with other risks are complex and can have surprising outcomes. Of interest to individuals, businesses, insurers, and other financial institutions are direct linear and indirect impacts, but also higher order impacts on assumptions from a changing climate. How will this drive changes in assumptions used by actuaries? Let's break it down by broad category, using some examples of the drivers and the impacted assumptions.

FINANCIAL

Extreme weather events damage infrastructure. This costs money and repeated events can leave a regional economy uncertain of its future path. Residents often want to stay but property insurance costs reflecting sustainable practices may become too high for those in the working class.

Goals may also include being proactive and protecting areas susceptible to damage from extreme weather, but this can be very expensive. Historically in the U.S. there has been federal funding available, but it becomes untenable as events become more frequent and widespread. By default, each event becomes a local problem, with little national coordination to improve process efficiency.

IMPACT ON ACTUARIAL ASSUMPTIONS

Climate change leads to uncertainty and financial markets need to be compensated. When the 10-year Treasury rate permanently increases, so do rates used for other loans, everything from home mortgages to commercial loans to expand a business. From a recent rate of under 5%, even an increase of 100 basis points makes a big difference to decision makers. Investors raise their hurdle discount rates by a similar amount, accepting fewer investments and projects. All asset classes are impacted in such a scenario.

Property insurance requires stability to be sustainable. If claims become more volatile, or inflation spikes, some insurers may need to exit some markets. Excess litigation and fly-by-night insurers reduce the stability of the marketplace. A region without a viable insurance market may become uninvestable.

DEMOGRAPHICS

Western economies are slowing growth or contracting their population. Developing country fertility rates remain above long-term sustainability levels of 2.1 but are slowing. There are concerns about antimicrobial resistance, microplastics, pollution (potentially tied to lower semen counts), and science skepticism. About 1900, prior to improved sanitation, maternity methods, and vaccination schedules, the total fertility rate (TFR) necessary to maintain a population was about four. Losing maternal health improvements and vaccines would increase the TFR needed to three, meaning females would need to average three children to assure that enough would live to adulthood to maintain the population size.

Increased longevity is another trend that is changing in discontinuous spurts. Life expectancy has doubled globally over the last 100 years, and research is near breakthroughs for personalized treatments based on genes and vaccines targeting specific cancers, with artificial intelligence (AI) tools progressing quickly to develop solutions.

Climate change creates uncertainty but, when combined with government debt-to-GDP levels and demographic trends, acts as a threat multiplier. High levels of government debt mean it will be hard to find the money to repair or anticipate damage from a changing climate, and a smaller and aging population means fewer taxes are collected and fewer workers are available to cultivate crops and perform needed services like aides in nursing homes.

IMPACT ON ACTUARIAL ASSUMPTIONS

One could argue that demographics move slowly and impact all actuarial assumptions, but some vary by product. An older population drives interest rates higher as retirees decumulate their assets, decreasing values of assets and liabilities. Fewer children reduce the incentive to fund research on their behalf, increasing the price of health insurance for families. Payout annuities, especially those that are single premium focused and competitively priced, are susceptible to longevity increases and mismatched assets and liabilities. Scenarios should be developed to determine how additional improvement in retiree lifespans and ALM mismatches impact profitability and solvency.

FEEDBACK LOOPS

Global warming drives ice caps, permafrost, and glaciers to melt. Reduced sea ice slows the ocean currents, impacting keystone species like krill that feed on plankton that use the nutrients pulled to the surface by the normal uplift function of the current. Permafrost melting is another feedback loop, releasing long frozen carbon along with diseases today's species have no immunity against. Glaciers provide fresh water to several billion people. As this water source becomes sporadic, the remaining resources will be fought over in regional conflicts. The loss of ice cover expands the albedo effect as sunlight that had been reflected back into space is now absorbed by the darker land and water that was underneath.

Extreme weather continues to interact in ways that make some areas less sustainable. Repeated cycles of drought and heavy rain due to atmospheric rivers have led to landslides and wildfires on the U.S. west coast, also leaving the areas impacted more susceptible to earthquakes. In the south and plains states convective storms with tornados and hail have become more prevalent.

Global tensions are high today, challenging the rules-based international order put in place after World War II, and a large war would release fossil fuels with a rebuild using carbon generating cement processes. Melting ice makes it easier to access fossil fuels and rare earth minerals in locations like Greenland and Alaska, creating another feedback loop.

IMPACT ON ACTUARIAL ASSUMPTIONS

Property insurance is becoming more expensive in many parts of the U.S. Repeated hail damage in the plains doubled homeowner premiums and limited the number of carriers willing to offer coverage. Some states have added government run insurers with taxpayer backing, but they often are subsidized and do not help create a sustainable marketplace or economy. Higher volatility of extreme weather could lead to a change in the way private insurers operate. They could require roofs to be fire resistant or expect community-based fire repressant strategies to be implemented. Property insurance could become an unsustainable product and life insurance susceptible to bouts of deflation and hyperinflation as temperatures rise, impacting the value of both assets and liabilities.

FOOD

Populations are naturally controlled through war, disease, and famine. Ben Franklin and Thomas Malthus expressed concerns 300 years ago about the ability of agriculture to increase yields quickly enough to meet a growing population’s needs. They asserted that yields grow arithmetically and populations exponentially. So far fertilizer pivots and aquifer depletion have kept this from happening, but concerns have arisen about soil nitrates and monoculture concentration risks. Pollution and microplastics are present in the soil and enter the food supply, eaten directly by humans and indirectly by animals in the food chain.

Temperature changes that are too rapid for natural evolution to keep pace with have led to research about phenology, where alignment of cyclic and seasonal natural phenomena are studied. Many crops now require traveling bee populations for pollination. Climate change has made the farmer’s job even harder, with stability already under pressure due to prices, market volatility and uncertainty, politics, bugs, diseases, and regulations. They are market takers and deal with incredible mental stress continuously. Stress may be the greatest cause of instability for the general population as we worry about our impact on climate change in addition to family, food, money, and relationships.

IMPACT ON ACTUARIAL ASSUMPTIONS

Healthy and plentiful food is a prerequisite for a population to succeed. Contaminants in our food supply and pollution lead to a reduced ability to learn at an optimal level, creating mortality and morbidity rates that vary by socioeconomic class. It becomes harder to access the American dream and comes to resemble the caste system found in other cultures. If small farms become impossible to maintain profitably the economy across these regions will suffer, leading to slowed growth.

TECHNOLOGY

The rapid rollout of artificial intelligence and the race for intelligent and autonomous agents have led to a construction bonanza for data centers. Backlogs of natural gas generators will slow this process, but reliance on fossil fuels is likely to add to the feedback loops already under way. This surge in electricity demand is inflationary in the short-term and risky as new technology could increase efficiency and leave additional electrical generation unnecessary. Electrification using renewables will be challenged to keep up with demand, but the short-term impact is being felt by consumers.

IMPACT ON ACTUARIAL ASSUMPTIONS

Technology tends to be deflationary to economic assumptions, making it cheaper to accomplish specific tasks. The interaction with climate change is a mixed bag as AI will present solutions while releasing greenhouse gases. It probably depends on how close we are to various tipping points, and that is uncertain at best due to complexity and lack of historical data sets.

Actuarial assumptions should always be reviewed by those qualified to provide oversight. Artificial intelligence today provides a black-box solution that must be justified to meet the transparency expectations established by actuarial standards. Processes need to be developed that work with AI tools and self-document the result.

TIME HORIZON

Climate change due to global warming occurs slowly, imperceptibly at first until some people start to notice surprising results. Perhaps the Galveston hurricane in 1900 was such an event, a Category 4 storm that killed up to 12,000 people and encouraged development to move to Houston, deemed to be a safer location. Now hurricane Harvey, among other storms, struck Houston. If we project out another 100 years will Austin or San Antonio be at risk?

Historically liability assumptions were conservative, but often by luck. Smoking became less prevalent as the life insurance market grew, so fewer people died than expected. Interest rates fell during the era of whole life and universal life coverages. Property insurance could reprice frequently enough to remain profitable, absent a spike in inflation, increase in convective storms, and higher wildfire risk. Some states did not allow insurers to price using anything except historical data, driving some out of those markets. Many products require reinsurance to be sustainable, but counterparties are not guaranteed forever, and many forms of reinsurance can be pulled.

Asset assumptions face similar uncertainty. A mortgage written in south Florida is likely to face tidal flooding as faraway ice melts and sea level rises. The region’s porous limestone allows sea water to infiltrate neighborhoods from below. A wall is ineffective and saltwater intrusion contaminates the freshwater supply.

A short time horizon mindset assumes that the economic pie is fixed in size. Infrastructure spending is delayed because circumstances don’t change quickly enough to make it worthwhile.

A long time horizon mindset seeks to grow the economic pie in total, recognizing that a new location may be more sustainable in the long run than a current one susceptible to sea level rise, subsidence, storm surge, aquifer depletion, and ocean currents (examples include Norfolk and New Orleans).

IMPACT ON ACTUARIAL ASSUMPTIONS

Property insurance that is allowed to frequently reprice and does not guarantee coverage for longer than a couple of years should be sustainable. These insurers should collaborate on updating building codes and a regulatory environment that takes into account local needs.

It is important that actuarial assumptions consider longer time horizons for products where liabilities are being written with option adjusted durations (OADs) longer than available asset OADs and uncertain cash flows that could extend to the end of the current century and beyond. Products like structured settlements and pension risk transfers should be priced in ways that reflect this. These are single premium products that have no ability to adjust outgoing cash flows in the future. Regulators have expressed concern that some owners and asset managers of insurers have increased the risk of their firms by being aggressive with assumptions and strategies. Actuarial assumptions can be strategically tested using AI tools accompanied by a risk manager to find concerns and risks over longer time horizons. Emerging risks are inevitable and they will not always have a positive influence on results.

STABILITY IN A COMPLEX SYSTEM

Financial institutions, including insurers and asset managers, along with pension plans, operate best in a simple and certain world. Today's environment is a complex adaptive system. Climate change, the global financial systems, geopolitics, and demographics all face growing uncertainty.

One way the insurance industry is unique is a reliance on state guaranty associations to protect policyholders from insolvency of the carrier. Historically the industry has been run conservatively with insolvencies due mostly to concentrated positions, either liabilities sold in one location that were mispriced or suffered from a weather or seismic event, or concentrated asset positions that went bad. But now regulators around the world are concerned with the entrance of private equity to the insurance industry as owners, asset managers, or both. These investors aim to optimize results.

Stability requires oversight that considers the higher order impact of interactions between various risks. Optimization techniques make the system more uncertain, increasing fragility. At the same time as extreme weather events are increasing, the need for stability to have a sustainable insurance marketplace also increases. The financial and risk management focus needs to be on solvency. Insurance serves its customers when it is available to pay a claim. Regulations should focus on principles and push back on rules that weaken the industry.

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Max Rudoph, FSA, CFA, CERA, is an adjunct professor at Creighton University and the University of Nebraska. He can be reached at max.rudolph@rudolph-financial.com.

Impact of Climate Risks on Automobile Insurance Market: An Approach Based on the Risk Management of Nonlinear Systems

Jorge Skotiuk and Julio Skotiuk

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ABSTRACT

Climate risk introduces nonlinear dynamics, temporal dependence, and abrupt regime shifts that challenge traditional actuarial approaches based on historical averages and assumptions of stability. This essay reviews the main methods used to quantify climate risk—scenario analysis, exposure metrics, and capital models—and proposes Chaos Theory as a complementary framework to capture the complexity of the phenomenon. Through an application to loss experience from extreme precipitation in automobile insurance, the analysis shows how the identification of regime shifts and the use of observational indicators can strengthen pricing, reserving, and climate risk management.

INTRODUCTION

Climate change is substantially altering the behavior of multiple risks that are relevant to actuarial practice. Beyond a gradual increase in the frequency or severity of certain events, patterns are emerging that are characterized by extreme episodes, temporal concentration of losses, and abrupt transitions between seemingly stable states.

These behaviors challenge the traditional assumptions underlying many actuarial models, particularly those based on temporal dependence, parameter stability, and the extrapolation of historical averages. In this context, climate risk poses a challenge that is not only quantitative, but also conceptual.

This essay explores the value of Chaos Theory as a complementary framework for interpreting these dynamics, with the aim of enriching actuarial analysis of climate risk without replacing its classical tools. From this perspective, practical implications are discussed for pricing, reserving, and risk management in environments characterized by nonlinearity and structural uncertainty.

TRADITIONAL QUANTITATIVE APPROACHES TO CLIMATE RISK MEASUREMENT

The measurement of climate risk relies on three approaches that are widely used in financial and actuarial practice: scenario analysis, exposure metrics, and capital shortfall models. Each serves a different purpose, although all can be aligned under regulatory frameworks such as the Task Force on Climate-related Financial Disclosures (TCFD), which acts as a backbone to ensure coherence between disclosure and risk management.

CLIMATE SCENARIOS: ANTICIPATING POSSIBLE FUTURE STATES

Scenarios developed by institutions such as the Network for Greening the Financial System (NGFS) and the Intergovernmental Panel on Climate Change (IPCC) allow the exploration of physical and socio-economic pathways. These include physical risks (temperature increases, heat waves, floods) and transition risks (decarbonization policies, carbon pricing, technological change).

Their purpose is to raise awareness of potential impacts and to inform strategic decision-making. However, they present several challenges, including high uncertainty over long horizons and difficulties in capturing nonlinear effects.

EXPOSURE METRICS: QUANTIFYING VULNERABILITY

Indicators such as WACI (Weighted Average Carbon Intensity) and Climate Value-at-Risk (Climate VaR) allow the measurement of carbon intensity in portfolios and the estimation of potential losses under climate scenarios.

These metrics are useful for disclosure purposes and for comparisons across portfolios, but they depend on company-reported data and do not reflect complex dynamics such as clustering or abrupt changes.

CAPITAL MODELS: TRANSLATING RISK INTO SOLVENCY

Tools such as CRISK (Climate Risk, an extension of the SRISK methodology) estimate capital shortfalls under climate stress scenarios, incorporating parameters such as Long-Run Marginal Expected Shortfall (LRMES) and climate betas. Their objective is to assess financial resilience under severe scenarios. This approach is particularly relevant for institutions required to demonstrate capital adequacy in the face of emerging risks.

These limitations justify the incorporation of a complementary approach based on Chaos Theory and Fractal Geometry, which contributes three critical elements:

7. Dynamic diagnosis of sensitivity and regime shifts.
8. Estimation of realistic predictability horizons to avoid over-extrapolation.
9. Measures of complexity and nonlinearity that strengthen risk governance.

SOME TOOLS FROM CHAOS THEORY–LYAPUNOV EXPONENTS AND FRACTAL GEOMETRY

The Lyapunov exponent measures the rate at which two initially close trajectories diverge in a dynamical system. If the value of the maximum Lyapunov exponent is positive, the system is chaotic, as divergence grows exponentially. If it is zero or negative, the system is stable or periodic.

This indicator not only confirms the presence of chaos but also allows the calculation of the predictability horizon: the higher the exponent, the shorter the period over which projections retain informational value. In practice, this helps define how far a projection can be trusted (for example, weeks rather than months)

TCFD AS AN ARTICULATING FRAMEWORK

Although these methods are not designed to be technically integrated with one another, the TCFD requires coherence across governance, strategy, risk management, and metrics. This makes the TCFD the axis that allows scenarios, metrics, and capital models to be presented as parts of a consistent narrative for regulators and investors.

CHAOS THEORY APPLIED TO CLIMATE RISK MODELING

Traditional approaches to climate risk measurement—scenarios, exposure metrics, and capital models—are essential, but they exhibit limitations that may reduce their ability to capture the true complexity of climate risk. Among these limitations are:

- Dependence on average relationships and linear assumptions that fail to reflect the nonlinear nature of climate dynamics and abrupt regime changes.
- The need to project over very long horizons (20–30 years), which increases uncertainty and reduces operational usefulness for short-term decision-making.
- Reliance on historical data that do not adequately represent future extremes, such as more intense heat waves or prolonged wildfire seasons.

Climate phenomena and actuarial loss rates do not follow linear patterns or normal distributions; instead, they exhibit fat tails, clustering, and temporal dependence. Multifractal analysis allows the identification of periods of high persistence (for example, consecutive weeks of extreme temperatures) and regime shifts. This information is valuable for adjusting severe loss models, defining activation thresholds, and reinforcing reserves during critical windows.

In this sense, Chaos Theory and Fractal Geometry complement traditional techniques along three dimensions:

- Predictability horizon: the Lyapunov exponent helps define how far projections remain reliable, avoiding excessive extrapolation and guiding strategy toward realistic temporal windows, particularly for phenomena such as heat waves or prolonged droughts.
- Regime shift detection: multifractal analysis and recurrence plots identify abrupt transitions between regimes, that is, shifts from one stable pattern to a fundamentally different one, which are common in climate phenomena and loss series.
- Nonlinear sensitivity: tools such as nonlinear causality may reveal hidden links between climate variables and loss experience, improving the calibration of actuarial models.

Incorporating Chaos Theory and Fractal Geometry does not replace traditional approaches but rather enhances them by providing quantitative criteria to define horizons, detect regime shifts, and manage uncertainty.

APPLICATIONS IN ACTUARIAL PRACTICE

CLIMATE RISK AND LOSS RATE FROM EXTREME PRECIPITATION

In automobile insurance, a relevant share of loss rates are associated with extreme weather events, particularly intense precipitation, and urban flooding, which constitute a growing risk in many regions. These events not only increase claim frequency, but also alter temporal patterns, generating abrupt concentrations of claims over very short periods and increasing average severity.

From an actuarial perspective, this behavior is particularly relevant, as it challenges the traditional assumptions of independence and parameter stability embedded in many pricing and reserving models.

TRADITIONAL ACTUARIAL APPROACH

Let Nt denote the number of flood-related claims during period t (for example, a day or a week). A classical actuarial model assumes that the random variable Nt follows a Poisson distribution, i.e., Nt ~ Poisson(λ), with independent severities Xi having mean μ.

This approach is appropriate under “normal” climatic conditions; however, it presents significant limitations when extreme events begin to dominate the behavior of the system.

EMPIRICAL EVIDENCE: CLUSTERING AND TEMPORAL DEPENDENCE

Recent experience shows that claims associated with intense rainfall are not uniformly distributed over time. On the contrary:

- Most days exhibit no material claims activity.
- A limited number of days concentrate an extraordinary volume of claims.
- These days tend to cluster during persistent meteorological episodes.

This phenomenon, commonly referred to as clustering, implies that the occurrence of one event increases the likelihood of additional events over a short time horizon, thereby violating the independence assumption implicit in homogeneous Poisson models.

REGIME SHIFTS AND RISK NONLINEARITY

Under normal climatic conditions, claim occurrence can be reasonably modeled through a counting process with stable parameters. However, once certain critical thresholds are exceeded—such as cumulative precipitation levels surpassing urban drainage capacity—the system transitions into a different regime, characterized by simultaneous increases in claim frequency and severity.

This behavior is consistent with the principles of Chaos Theory, particularly the existence of abrupt regime shifts and sensitivity to initial conditions. Meteorological events with apparently similar characteristics may lead to markedly different outcomes in terms of the magnitude of insured losses.

ILLUSTRATIVE NUMERICAL EXAMPLE

Consider an automobile insurance portfolio exposed to urban flood risk. Two operating regimes are identified:

Normal regime:

Expected frequency of relevant events:

λN = 2 events per year

Average severity per event:

μN = $5,000

Extreme regime:

Expected frequency of relevant events:

λE = 10 events per year

Average severity per event:

μE = $12,000

If the annual probability of entering an extreme regime is assumed to be 20%, while the system operates under normal conditions during the remaining 80% of the time, the expected annual loss can be approximated as:

$E[S] \approx 0.8 (\lambda N \cdot \mu N) + 0.2 (\lambda E \cdot \mu E)$

Substituting values:

E[S] = $32,000

This expected value, however, completely masks the underlying risk dynamics. In particular, extreme years account for a disproportionately large share of total losses, implying a level of volatility significantly higher than that suggested by the average.

At this point, it is worth referring to the Actuarial Climate Index (ACI), which measures changes in selected climate extremes relative to a baseline period, disaggregated by region, without aiming to establish causality or make predictions. Since the probability of entering an extreme regime can be conceptually linked to observed indicators of the climatic environment, the extreme precipitation sub-indices of the ACI provide an objective reference for identifying periods in which the climate system departs from its historical regime.

From an actuarial perspective, these indicators do not directly determine expected losses ratios, but they are useful to justify stress scenarios and regime shifts in frequency and severity parameters. In this sense, the following modeling framework may be adopted:

- When the ACI is close to zero, parameters λN and μN are used.
- When the ACI is persistently above zero, parameters λE and μE are adopted.

SUMMARY OF ACTUARIAL IMPLICATIONS

- Pricing: Premiums based solely on historical averages may underestimate climate-related risk.
- Technical reserves: Temporal aggregation of claims during extreme events requires margins beyond traditional premium, claims, and IBNR reserves.
- Reinsurance: Event-based or excess-of-loss structures are justified.
- Risk management: Monitoring climate indicators may help anticipate regime shifts.

FINAL CONSIDERATIONS

The breakdown of temporal independence is evidenced by the tendency of extreme climatic events to cluster within specific periods. This aggregation is not random but rather associated with persistent climatic conditions that signal a departure from the historical regime.

Observational indicators such as the extreme precipitation sub-indices of the Actuarial Climate Index help identify contexts of elevated climatic stress without establishing direct causal relationships with claims experience. From an actuarial standpoint, their value lies in contextualizing the risk environment and highlighting periods in which the probability of extreme events ceases to be temporally independent. A limitation, however, is that the ACI currently covers only the United States of America and Canada.

Chaos Theory provides a conceptual framework for interpreting these patterns as abrupt regime transitions. Persistent elevated values in observational climate indicators may be interpreted as evidence that the system has temporarily exited its historical regime, simultaneously increasing claim frequency and severity from an insurance perspective.

Actuarially, such regime shifts can be represented by adopting different parameter sets for claim frequency and severity. During periods characterized by indicators close to their baseline, parameters associated with a normal regime are applied. When indicators display persistent deviations, parameters corresponding to a stress regime become appropriate.

In an environment characterized by nonlinearity, clustering, and regime shifts, uncertainty is structural rather than purely parametric. Under such conditions, the use of robust actuarial tools—such as scenario analysis, sensitivity testing, and conservative risk bounds that do not rely on strict distributional assumptions—is particularly appropriate.

CONCLUSIONS

Climate change poses a substantial challenge to actuarial science, not only due to the quantitative increase in uncertainty associated with certain risks, but also because of the qualitative transformation of their dynamics. Phenomena such as extreme precipitation, heat waves, and compound climate events introduce nonlinear behaviors that expose the limitations of approaches based exclusively on historical averages and stability assumptions.

Throughout this paper, it has been argued that Chaos Theory provides a useful conceptual framework for understanding these dynamics, by highlighting the existence of critical thresholds, sensitivity to initial conditions, and abrupt regime shifts. These elements help explain why risks that appear moderate under traditional metrics may materialize as highly concentrated and disproportionate losses.

The practical application presented in the context of automobile insurance illustrates how these concepts can be incorporated into actuarial work in a straightforward manner. The numerical example shows that even with moderate probabilities of extreme regimes, a significant share of aggregate risk is concentrated in a small number of episodes, with direct implications for pricing, reserving, and reinsurance design.

From this perspective, climate risk should not be viewed merely as a gradual shift in parameters, but rather as a phenomenon capable of inducing structural changes in risky behavior. For actuaries, this implies the need to complement traditional models with approaches based on scenarios, sensitivities, and regime analysis, capable of capturing the nonlinear nature of the problem without sacrificing technical rigor.

In this context, tools developed by the profession itself—such as the Actuarial Climate Index—illustrate how observational indicators can be used to contextualize the climate risk environment. Without seeking to establish direct causal relationships or make predictions, such indices are useful for identifying persistent deviations from historical regimes and for justifying stress scenarios and regime shifts in actuarial analysis.

Ultimately, the integration of concepts derived from Chaos Theory does not replace classical actuarial tools, but rather enriches them, providing a more realistic framework for climate risk management. In an environment characterized by increasing volatility and uncertainty, this expansion of the actuarial approach is essential to preserve the relevance and robustness of the discipline in the face of emerging challenges.

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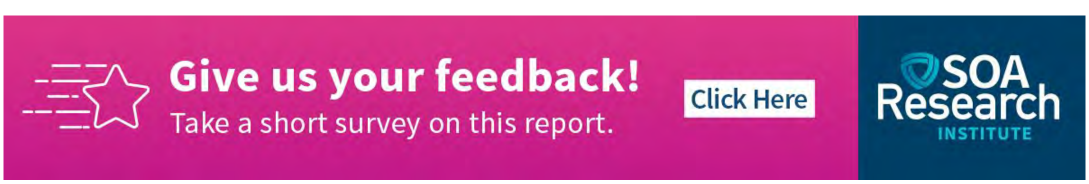
Jorge Skotiuk is an independent actuarial consultant. He can be reached at jmskotiukp@gmail.com.

Julio Skotiuk is a financial risk management consultant with broad experience in the identification, management, quantification, and monitoring of market, credit, and liquidity risk. He can be reached at juliosk24@gmail.com.



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8770 W Bryn Mawr Ave, Suite 1000
Chicago, IL 60631
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