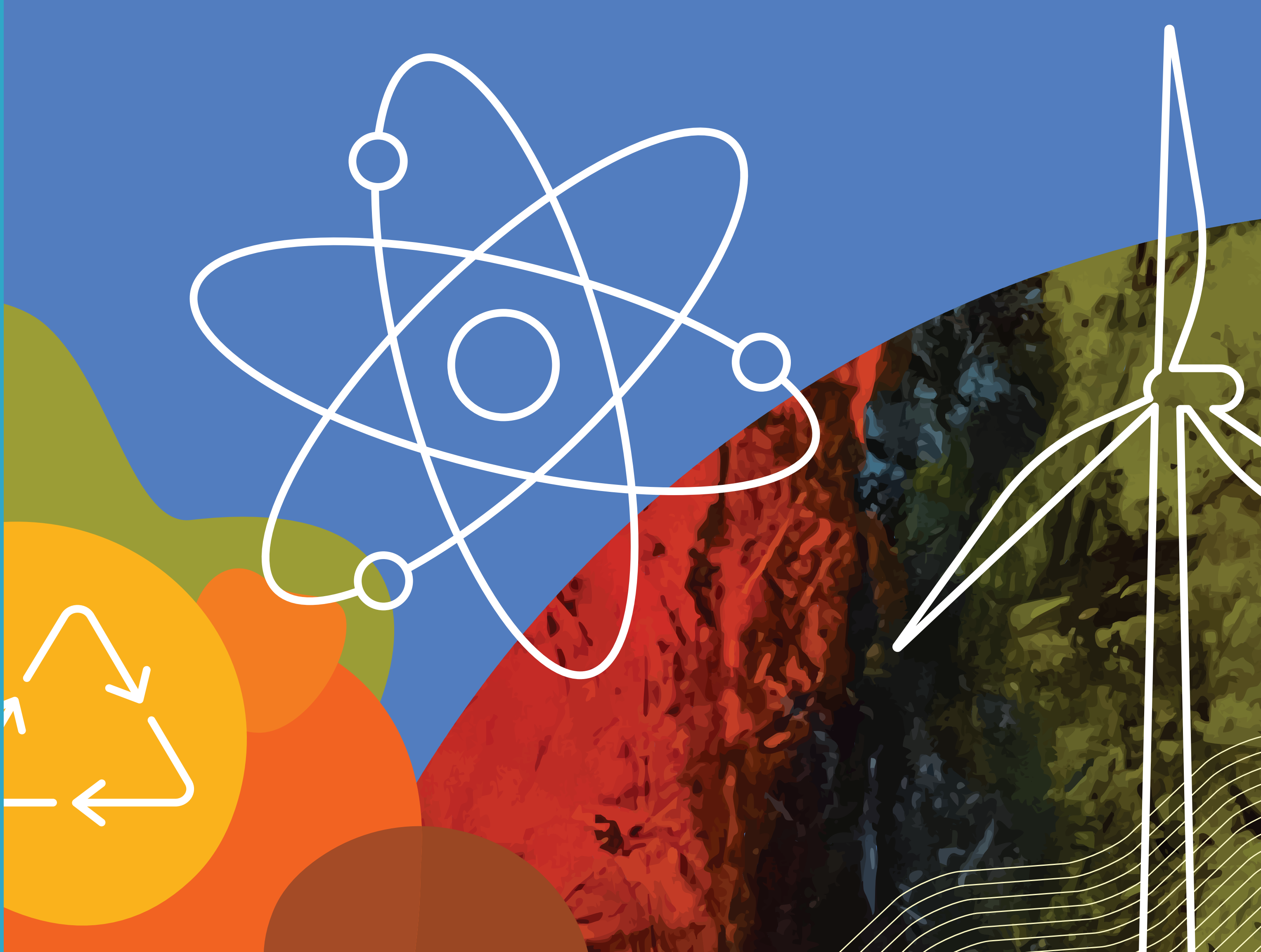

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Attribution Science Methodologies from an Actuarial Perspective

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Attribution Science Methodologies from an Actuarial Perspective

Introduction: A New Frontier for Actuarial Science

This paper represents the second installment in a broader research program dedicated to advancing the understanding and application of climate risk attribution. The first paper, an issue brief, *Attribution Science from an Actuarial Perspective*, published in November 2025, introduced the foundational principles of climate attribution science, explaining how meteorologists quantify the influence of anthropogenic climate change on the likelihood and severity of extreme weather events.

Building directly on that scientific groundwork, this paper advances a collaborative methods model that explores the convergence of climate science and actuarial risk assessment. By critically integrating actuarial expertise into attribution practice, this interdisciplinary cooperation enhances our ability to translate meteorological attribution findings into financial, health, and social risk metrics.

Through systematically examining how property & casualty, life and pension, and health actuaries can translate these models into attributable losses, prospective loss costs, and capital requirements, this paper seeks to demonstrate the practical application of actuarial perspectives in operationalizing climate attribution for robust decision-making across the insurance sector and public policy.

An Overview of Climate Attribution Methodologies

The science of climate attribution has evolved rapidly, transitioning from the study of broad, multi-decadal trends to the probabilistic assessment of climate change's role in specific extreme weather events. Formalized within the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), these methodologies do not yield a single "precise" answer given the inherently stochastic nature of climate systems. Rather, they utilize rigorous statistical models to estimate the degree to which anthropogenic climate change has altered the likelihood or intensity of a hazard. Understanding these underlying scientific frameworks is an essential prerequisite for interpreting the resulting metrics.

Detection and Attribution: Establishing the Baseline

Historically, the field relied on Detection and Attribution (D&A) studies.[1] As recognized by the IPCC, this approach utilizes regression-based "optimal fingerprinting" techniques (statistical methods that detect the unique spatial and temporal patterns, or "fingerprints" of specific climate forcings in observed data) to attribute observed multi-decadal climate trends to specific drivers, such as greenhouse gases, aerosols, and natural forcings. For instance, a D&A study might determine that a 15% increase in extreme rainfall over several decades is largely attributable to greenhouse gas forcing—a long-term trend shift frequently tracked by tools such as the Actuaries Climate Index (ACI).[2] While foundational for providing the scientific basis for long-term trend analysis in peril modeling, D&A lacks the granularity required for localized, event-specific risk assessment. This limitation in granularity motivated the development of a complementary framework: Event Attribution.

Event Attribution: Quantifying the Extremes

To assess individual catastrophic disasters, the scientific community developed Event Attribution (EA). The IPCC defines EA as the assessment of how human influence has changed the probability or intensity of specific extreme events.[3] EA generally employs two distinct methodological branches:

- **The Risk-Based (Probabilistic) Approach:** This is a primary method for quantifying shifts in likelihood. It relies on a rigorous counterfactual framework, comparing large multi-model ensembles of the "actual world" (today's climate with observed human-caused changes) against a "counterfactual world' (a hypothetical cooler climate without human influence). The core outputs of this process are key statistical metrics, primarily the Risk Ratio (RR), which quantifies how many times more likely the event has become, and the Fraction of Attributable Risk (FAR), which represents the proportion of the risk attributable to anthropogenic factors. For example, an extreme rainfall event that historically occurred once every 200 years (1-in-200) but now occurs once every 50 years (1-in-50) in the actual world yields a RR of 4, indicating a fourfold increase in likelihood.

1 Chapter 10: Linking Global to Regional Climate Change; Intergovernmental Panel on Climate Change (IPCC), Sixth Assessment Report (AR6), Working Group I; 2021.
2 Actuaries Climate Index®; Actuaries Climate Index; updated quarterly.
3 Chapter 11: Weather and Climate Extreme Events in a Changing Climate; Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), Working Group I; 2021.

- **The Storyline (Conditional) Approach:** Instead of focusing on probability, this approach focuses on the physical mechanics of a specific, observed event. Scientists hold the observed dynamic atmospheric circulation (e.g., a specific blocking pattern or storm track) fixed and perturb the thermodynamic components (e.g., atmospheric temperature and moisture levels). This simulates and isolates how the altered climate state changed the overall intensity or severity of that specific event.

To frame these attribution studies accurately, scientists rely on tools like the IPCC interactive Atlas, which defines specific regional "climate impact drivers" and indices.[4] By establishing this regional context, scientists ensure that the hazards metric being analyzed (e.g., a specific regional rainfall index or drought threshold) is the most relevant indicator for localized impacts.[5]

Key Laboratories and Rapid Screening Platforms

The operationalization of these methods relies on key research bodies and platforms. World Weather Attribution (WWA) represents the forefront of rapid, probabilistic event attribution, utilizing observations combined with models to produce event-specific RR and FAR metrics globally within days or weeks of a disaster. To support this, tools like Climate Central's Climate Shift Index (CSI) provide an immediate diagnostic screening layer, identifying real-time thermodynamic climate fingerprints before formal attribution models are finalized.

Furthermore, translating this science into policy and legal contexts is supported by institutions like the Sabin Center for Climate Change Law at Columbia University.[6] By maintaining a comprehensive Climate Attribution Database, the Sabin Center aggregates peer-reviewed studies into a central repository. For actuaries and policymakers, this database serves as a vital resource for cross-referencing attribution metrics when modeling loss, establishing liability, or navigating emerging legal and regulatory frameworks.

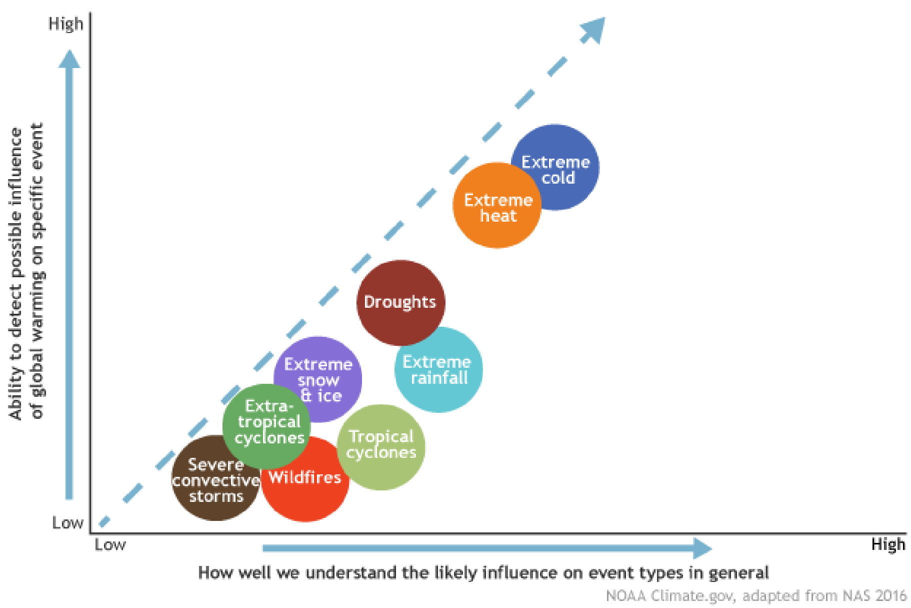
4 Chapter Atlas; Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), Working Group I; 2021.
5 Chapter 16: Key Risks Across Sectors and Regions; Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), Working Group II; 2022.
6 Sabin Center for Climate Change Law; Columbia Law School, Columbia University; 2026.

Limitations and Scientific Considerations

To effectively utilize attribution science, actuaries and risk professionals should understand its inherent limitations and uncertainties. The robustness of attribution findings varies depending on the hazard type. Attribution of extreme heat is generally highly robust due to a strong signal-to-noise ratio and excellent observational records. Conversely, events like heavy, localized rainfall or severe convective storms are associated with greater uncertainty due to the spatial and temporal resolution limits of current global climate models, which struggle to capture fine-scale dynamics—such as narrow bands of convective rainfall within a standard 100-kilometer grid. This resolution constraint adds significant uncertainty when attempting to attribute highly localized events, such as urban flash flooding. To overcome these limitations, researchers increasingly rely on high-resolution reanalysis datasets (e.g., Copernicus ERA5) to extract granular variables like hourly precipitation, layered soil moisture, and refined wind gusts.[7]

Additionally, attribution outputs are highly sensitive to event definition. How an event is framed—its specific geographic boundaries, duration, and severity thresholds (i.e., exposure and vulnerability)—can significantly alter the resulting RR or FAR. Furthermore, different modeling groups may utilize different baseline periods or forcing sets when structuring their counterfactual worlds. Therefore, transparency regarding methodological assumptions is paramount. Finally, it is important to recognize that hazard attribution strictly isolates the meteorological driver; translating this hazard change into financial loss requires additional actuarial modeling of exposure and societal vulnerability.

Relative Confidence in Attribution of Different Extreme Events



7 ERA5 hourly data on single levels from 1940 to present; Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts; 2018.

The Actuarial Value-Add: Extending Climate Attribution to Financial Impacts

While meteorologists quantify physical hazards, actuaries are increasingly applying their specialized risk quantification expertise to translate these physical shifts into measurable financial impacts. This translation is built upon established actuarial frameworks that utilize curated historical data adjusted for current economic and demographic environments. By utilizing climate attribution models and methods, actuaries can effectively assess and estimate financial impacts, insured losses, and evolving peril profiles across property & casualty, life and pension, and health domains.

This section outlines the three-layer conceptual framework that clearly distinguishes actuarial work from meteorological science and bridges the gap between climate science and applied financial risk management.

The integration of these models depends on the confidence levels associated with different perils (as illustrated in the preceding graph: Relative Confidence in Attribution of Different Extreme Events). For perils with high confidence level, such as extreme heat, attribution metrics are mature enough for direct integration into baseline pricing and mortality tables. Perils with moderate confidence level, such as heavy precipitation, drought, and tropical cyclones, are highly suitable for scenario analysis, Own Risk and Solvency Assessment (ORSA) reporting, and adjusting tail-risk capital requirements. Conversely, perils with a relatively low confidence level, such as severe convective storms, can be utilized cautiously, serving primarily as inputs for exploratory stress-testing rather than for definitive pricing or reserving.

Conceptual Chain for Actuarial Application

To operationalize attribution science, actuaries can apply a structured “Hazard × Exposure × Vulnerability” framework, aligned with the methodology of the IPCC Working Group II.[8] This establishes a clear, quantifiable pathway from a physical weather event to its ultimate financial impact.[9]

8 “Climate Change 2022: Impacts, Adaptation and Vulnerability”; Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), Working Group II; 2022.
9 Chapter 16: Key Risks Across Sectors and Regions; Intergovernmental Panel on Climate Change, Sixth Assessment Report (AR6), Working Group II; O’Neill, B. et al.; 2022.

The pathway can be visualized as the Climate Signal Chain:

Climate Forcing: the underlying driver (e.g., anthropogenic greenhouse gas emissions)

→ *Hazard Change*: The physical meteorological event, with its altered intensity and frequency quantified using event attribution results (e.g., RR or FAR).

→ *Exposure*: The inventory of assets and populations in harm's way, ranging from insured properties and infrastructure to demographic populations and supply chains.

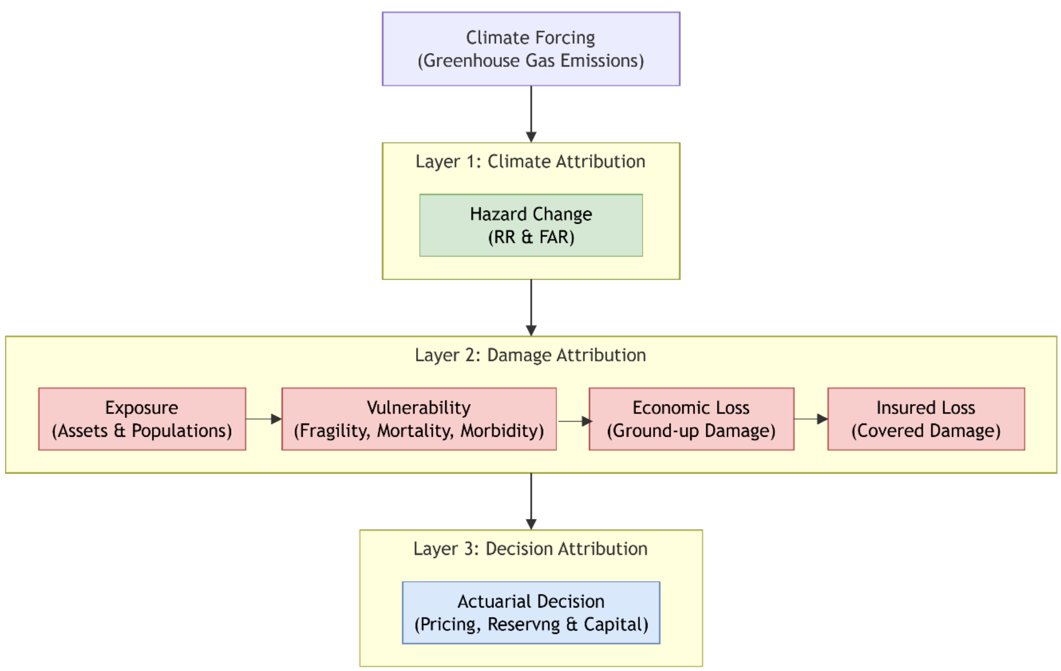
→ *Vulnerability*: The susceptibility of those exposed assets to damage, captured by engineering-based fragility curves or mortality and morbidity functions.

→ *Economic Loss*: The resulting ground-up societal and financial damage.

→ *Insured Loss*: The specific portion of the ground-up economic loss transferred to insurers, representing covered claims for property damage, or health care utilization, or casualty events.

→ *Actuarial Decision*: The ultimate application of the loss data to inform pricing, reserving, and capital strategy.

Actuarial Climate Signal Chain



By systematically isolating the *Hazard Change* from changes in *Exposure* and *Vulnerability,* actuaries assess actual climate impacts and separate socioeconomic trends such as population growth, urban development, or inflation. This prevents both overestimation and underestimation of climate risk.

Attribution of Damages Methods

Using this conceptual chain, actuaries embed hazard-side attribution metrics into catastrophe models to estimate the climate-attributable share of financial losses. The Attribution of Damages (AoD) generally follows two methodological approaches:

- **Risk-Based Loss Attribution:** This approach takes a probabilistic view by running catastrophe models under two distinct hazard ensembles: the "Actual" (factual, with anthropogenic forcing) and the "Counterfactual" (without anthropogenic forcing). By comparing the expected losses under each scenario, actuaries can quantify how climate change has systematically shifted the risk profile. The primary metric derived is the Attributable Loss Fraction (ALF), calculated as:

$$\mathrm{ALF} = \frac{\mathrm{E}[\mathrm{L}_{\mathrm{actual}}] - \mathrm{E}[\mathrm{L}_{\mathrm{counterfactual}}]}{\mathrm{E}[\mathrm{L}_{\mathrm{actual}}]}$$

**E[L] represents the Expected Loss under each respective climate scenario*

  For example, an ALF of 0.30 would indicate that 30% of the expected loss under current climate conditions is attributable to anthropogenic climate change.

- **Storyline Loss Attribution:** Rather than assessing long-term probabilities, this method focuses on quantifying the incremental financial impact of a specific historical catastrophe. Building upon the meteorological storyline approach, actuaries rerun established catastrophe models, such as a vendor's or the company's proprietary models, using the modified, counterfactual weather inputs (e.g., reducing the wind speed or precipitation footprint of a recent hurricane to match a pre-industrial climate). By comparing the resulting modeled loss against the reported insured loss of the historical event, actuaries can isolate and quantify the incremental financial damage caused solely by the climate-driven intensification of that single storm.

An Operational Workflow for Actuarial Attribution

To translate these methodologies into practical application, actuaries can utilize a structured, three-phase workflow that integrates rapid scientific screening with deep financial impact modeling. A detailed step-by-step methodological guide for this workflow is provided in Appendix A.

- **Phase 1: Rapid Screening and Event Definition (24–72 Hours).** The process begins immediately following a catastrophic event with a precise event definition. Within the first 24 to 72 hours, rapid diagnostic tools—such as the Climate Shift Index (CSI)—are applied to screen whether the event's thermodynamic environment was amplified by climate change. This early screening establishes a preliminary physical storyline before formal attribution studies are completed (See Appendix A, Steps 1-2).

- **Phase 2: Formal Hazard Attribution (Weeks to Months).** As comprehensive observational data and climate model ensembles become available, the workflow shifts to rigorous probabilistic attribution. This phase involves estimating historical return periods, comparing actual versus counterfactual climate simulations, and deriving the core hazard metrics: RR and Intensity Change (see Appendix A, Steps 3-5).

- **Phase 3: Impact Interpretation and Decision Outputs.** The final phase represents the core actuarial translation, where the meteorological attribution outputs from Phase 2 are converted into measurable financial impacts. The actuary isolates the climate-attributable hazard signal from the broader loss drivers—including exposure growth, socioeconomic vulnerability, and infrastructure changes—and translates that isolated signal into actionable decision outputs for pricing, reserving, capital management, and catastrophe model calibration. The detailed step-by-step methodology for this translation is provided in Appendix A (Steps 6–8).

Quantifying Attributable Impacts: Actuarial Perspectives on Climate Risk

Climate attribution science provides the tools to estimate how much anthropogenic climate change has altered the likelihood or severity of specific weather events. Yet, translating these scientific findings into financial, health, and social risk metrics requires specialized actuarial expertise. Property & casualty, life and pension, and health actuaries each can apply distinct analytical frameworks to this challenge, converting attribution probabilities into tangible quantifications of climate-attributable impacts across society.

- **Property & Casualty (P&C): Translating Physical Hazards to Quantifiable Losses**
  P&C actuaries are well-equipped to embed attribution studies directly into established catastrophe risk models. For flood risk, actuaries can integrate rainfall attribution metrics—such as the RR and FAR—into hydrologic and hydraulic models (e.g., HEC-HMS, HEC-RAS) to generate counterfactual flood depths, representing conditions that would have occurred without anthropogenic climate change.[10] By comparing these counterfactual depths to observed flood events, actuaries can recalculate insured losses and economic damages, isolating the climate-attributable portion of flood risk. This process relies on catastrophe-loss normalization to ensure the evolving concentration of exposure is cleanly separated from the changing meteorological hazard. This quantification supports more robust pricing, reserving, and reinsurance negotiations.

  Attribution science also can offer valuable insights for tropical cyclone modeling, where the interaction of multiple perils creates complex loss dynamics. In tropical cyclone modeling, attribution findings on rainfall intensification and sea-level rise provide the basis for estimating the incremental damage from storm surge and flooding. While acknowledging the greater uncertainty in attributing changes in storm frequency, this approach allows actuaries to distinguish between baseline risk and climate-driven severity enhancements. This distinction can help actuaries isolate the trending components of risk, support more accurate capital allocation, and make forward-looking solvency assessments that reflect evolving climate conditions rather than solely relying upon historical experience. The Hurricane Harvey (2017) case study illustrates this application: attribution studies estimated that a substantial share of the approximately $90 billion in economic losses, roughly $67 billion was estimated to be climate-attributable, largely due to intensified rainfall.[11] By embedding attribution

10 Hydrologic Engineering Center; U.S. Army Corps of Engineers, Institute for Water Resources; 2026.
11 Frame, D. J., Wehner, M. F., Noy, I. et al.: "The economic costs of Hurricane Harvey attributable to climate change." Climatic Change, 160, 271–281; 2020. doi:10.1007/s10584-020-02692-8.

findings into modelling, actuaries can demonstrate how climate change materially alters catastrophe outcomes—equipping insurers, reinsurers, and policymakers with a stronger actuarial basis for refining pricing models, assessing capital adequacy, and prioritizing targeted resilience investments.

- **Life and Pension: Assessing Mortality and Asset Vulnerability**
  Life and pension actuaries extend attribution science into the critical domain of human longevity risk and long-term financial sustainability. By incorporating climate-driven temperature anomalies from attribution studies into mortality and morbidity models, actuaries can estimate the attributable portion of excess deaths and hospitalizations during extreme events. The 2021 Pacific Northwest heat dome illustrates this application: a World Weather Attribution study concluded that this event would have been virtually impossible without human-caused climate change, and that anthropogenic warming increased the event's peak temperatures by approximately 2°C.[12] The event was associated with an estimated 1,400 excess deaths across the United States and Canada. By embedding such attribution findings into mortality and morbidity models, actuaries can quantify mortality and morbidity impacts on vulnerable populations, providing insurers and pension funds with a forward-looking view of climate-related longevity risk.

  Furthermore, pension funds and life insurers often hold significant real asset portfolios—such as real estate and infrastructure—that are directly exposed to climate-driven physical damage. Attribution studies can help actuaries quantify the climate-attributable damage to these holdings, whether from flooding, wildfire, or prolonged heat stress on physical infrastructure (e.g., power grid strain, pavement degradation). By integrating these estimates into asset-liability management, actuaries can refine long-term solvency projections and adjust investment strategies to account for physical climate risk.

  Beyond acute events, chronic climate-attributable health stresses—such as respiratory conditions from persistent wildfire smoke or cardiovascular strain from recurring heatwaves—can systematically reduce life expectancy, alter retirement patterns, and catalyze population relocation in affected regions. These compounding effects significantly alter the geographic distribution, health profiles, and risk concentration of a pension plan's participant base. For example, a pension fund heavily concentrated in a region prone to intensifying heatwaves or coastal flooding may need to reassess assumptions regarding workforce participation patterns, retirement age, payout

12 Philip, S. Y., S. F. Kew, G. J. van Oldenborgh, et al., "Rapid attribution analysis of the extraordinary heat wave on the Pacific Coast of the U.S. and Canada in June 2021." *Earth System Dynamics*, 13, 1689–1713; 2022.

duration, and geographic risk concentration to maintain long-term sustainability. Actuaries can incorporate these attribution-based projections into longevity and migration models to anticipate potential shifts in annuity payouts and system solvency.

- **Health: Quantifying the Financial Burden on Health Care Systems**
  Health actuaries can provide an essential link between climate attribution and the financial realities of health care. By connecting event attribution studies—such as those analyzing heatwaves or wildfire smoke exposure—to health claims data, actuaries can calculate the attributable fraction of health care costs for specific outcomes like heat stroke, respiratory illness, or cardiovascular stress. This quantification enables insurers and public health systems to measure the direct financial burden of climate change on health delivery and infrastructure.

  At a systemic level, actuaries can move beyond individual claims to assess how climate-attributable health burdens translate into broader financial risks. Actuaries analyze how repeated climate-driven health shocks may increase insurance premiums and alter long-term morbidity trends, while simultaneously straining public health budgets and safety-net programs. This quantification connects meteorological attribution with health care financing, offering policymakers and insurers a clearer view of long-term climate-related health costs.

  Importantly, attribution studies also offer insights into mitigation and prevention strategies. By estimating avoided health care costs under counterfactual scenarios (i.e., modeling claims without anthropogenic warming), actuaries can quantitatively evaluate the cost-effectiveness of preventive interventions. This includes assessing the return on investment for measures such as implementing cooling centers, supporting wildfire smoke filtration programs, or deploying early warning systems. For instance, modeling the reduction in heat-related claims attributable to widespread cooling center access can quantitatively demonstrate the actuarial value of public health resilience investments and inform evidence-based policy decisions on adaptation measures. Similarly, quantifying the reduction in respiratory claims following the deployment of community air filtration systems during wildfire events can demonstrate the financial return on targeted public health investments.

Together, these perspectives illustrate a comprehensive actuarial approach to climate risk: P&C actuaries derive attributable loss fractions, Life and pension actuaries measure attributable mortality and asset damage, and health actuaries calculate attributable health care costs. Importantly, these practice-area perspectives are not siloed. A single climate-attributable event may simultaneously generate P&C insured losses, excess mortality affecting life and pension obligations, and a surge in health care utilization—underscoring the need for the systemic integration of attribution-informed risk assessment. This collective effort provides the foundational metrics that allow actuaries to move beyond qualitative assessments and incorporate climate change explicitly into the quantitative frameworks that underpin financial risk management across all practice areas.

Best Practices for Reporting and Communication

The practical utility of climate attribution analysis depends not only on the rigor of the underlying science but also on the clarity, transparency, and discipline with which results are communicated to stakeholders. To transform complex scientific outputs into reliable financial metrics, actuaries can adopt a structured reporting framework that prioritizes precision in event definition, methodological transparency, and the explicit clarification of uncertainty.

Effective reporting begins with a clear and unambiguous definition of the event under analysis—specifying the event class, primary peril, geographic boundaries, time window, and the severity metric used to characterize the extreme. This specificity ensures that stakeholders understand exactly what is being attributed and prevents the misinterpretation of results across different event definitions. In accordance with ASOP No. 41 (*Actuarial Communications*), practitioners can provide further transparency through the clear disclosure of the observational datasets, climate model ensembles, counterfactual baseline definitions, and attribution methodologies used to derive the results. This includes an explicit discussion of the modeling boundaries—such as constraints related to spatial resolution, temporal granularity, or the specific hazard types analyzed—ensuring that the findings are interpreted within their appropriate scientific and financial context.

Given the stochastic nature of the climate system, a thorough risk assessment extends the analysis well beyond central estimates. Applying the professional rigor outlined in ASOP No. 23 (*Data Quality*), ASOP No. 38 (*Catastrophe Modeling*), and ASOP No. 56 (*Modeling*), actuaries provide a robust quantification of uncertainty by presenting results as ranges with explicit confidence intervals, acknowledging structural model dependencies, and clearly distinguishing between what the model results signify and what they do not. This disciplined treatment of uncertainty ensures that decision-makers understand both the strength of the climate signal and the bounds within which the results can be reliably interpreted.

A distinguishing feature of rigorous actuarial reporting is the explicit disaggregation of loss drivers. By clearly separating the climate-attributable hazard amplification from the financial impacts driven by exposure growth and vulnerability changes, actuaries prevent the conflation of climate signals with socioeconomic trends. This approach directly aligns with established catastrophe-loss normalization methodologies, such as those utilized by the NOAA Billion-Dollar Disasters report and the FEMA National Risk Index.[13] This disaggregation enables stakeholders to make targeted decisions—whether for pricing adjustments, capital allocation, or public policy—grounded in a clear understanding of the distinct forces shaping overall loss outcomes.

Finally, effective communication connects attribution findings to specific business or policy decisions rather than presenting results in isolation. The actuary articulates the implications for pricing, reserving, capital adequacy, or resilience investments while providing appropriate context to ensure that conclusions remain proportionate to the strength of the evidence. By maintaining these standards of reporting, actuaries transform complex climate signals into reliable, decision-grade information that strengthens financial risk management frameworks and supports evidence-based investments for critical infrastructure and climate mitigation systems.

13 Billion-Dollar Weather and Climate Disasters; National Oceanic and Atmospheric Administration, National Centers for Environmental Information; updated 2026.

Applications in Actuarial Practice and Public Policy

The quantification of climate-attributable impacts, as detailed in the previous section, unlocks a new dimension of strategic insight for the insurance industry and public policymakers. By moving beyond general climate projections to event-specific, financially material metrics, actuaries can guide stakeholders in embedding climate risk directly into core decision-making processes. This transition from abstract science to concrete application enhances financial resilience and informs strategic responses to an evolving risk landscape.

Insurance Applications: Integrating Attribution into Core Functions

For insurers, the primary value of attribution science lies in its ability to refine the traditional actuarial feedback loop—pricing, reserving, capital modeling, and product design—to reflect a non-stationary climate.

In the domains of pricing and underwriting, attribution metrics allow actuaries to augment historical averages with a forward-looking view of risk. Conceptually, this actuarial integration can be expressed as a trend decomposition framework:

Future Risk = Historical Baseline x Climate Trend Shift x Extreme Event Amplification

This approach illustrates how actuaries can combine the traditional data (*Historical Baseline*) with two distinct branches of attribution science, Trend Attribution (*Climate Trend Shift*) and Event Attribution (*Extreme Event Amplification*).

- *Historical Baseline:* Selected historical loss data, normalized for current economic and demographic exposure
- *Climate Trend Shift (Trend Attribution):* Utilizing Detection and Attribution (D&A) to capture long-term, decadal shifts in peril frequency (e.g., rising baseline sea level or 10-year drought trends)
- *Extreme Event Amplification (Event Attribution):* Utilizing Event Attribution (EA) to calibrate severity models for specific, high-impact tail risks (e.g., the increased rainfall intensity of a specific hurricane)

By utilizing both long-term trend data (D&A) and extreme event attribution (EA), P&C actuaries can calibrate climate-adjusted rates that reflect the heightened severity of perils like floods and convective storms, while life and health actuaries can incorporate "climate loads" into premiums to account for projected trends in climate-driven mortality and morbidity. This integration can help ensure that pricing signals remain adequate to cover evolving exposures, preventing market dislocation.

Simultaneously, attribution science equips actuaries to strengthen reserving and capital modeling. In reserving, it can help actuaries interpret recent loss experience, distinguishing between random volatility and systemic climate-driven shifts in claims frequency or severity. This distinction is essential for setting appropriate reserves for recent catastrophes. For capital modeling, attribution findings provide the empirical basis for rigorous stress testing and scenario analysis, including for the purpose of the Own Risk and Solvency Assessment (ORSA). By modeling counterfactual scenarios of extreme events—intensified by thermodynamic changes—insurers can better assess their solvency positions against "tail risks" that historical data alone may not fully capture.

Furthermore, these insights drive product development. Understanding the drivers of climate risk enables the creation of innovative solutions, such as parametric insurance triggered by attribution-defined hazard thresholds or resilience-linked products that incentivize risk reduction.

Public Policy and Regulatory Implications

Beyond the balance sheet, actuarial application of attribution science provides the quantitative evidence to support effective public policy and regulatory frameworks for addressing climate change.

A key application is in climate-related financial disclosures. As regulators and standards bodies like the Task Force on Climate-related Financial Disclosures (TCFD) and the International Sustainability Standards Board (ISSB) mandate more rigorous reporting, qualitative descriptions of risk are no longer sufficient. Attribution analysis allows insurers to provide auditable, quantitative evidence of their physical risk exposure, demonstrating specifically how climate change impacts their asset portfolios and insurance liabilities. This transparency is essential for maintaining stakeholder confidence and market stability.

Additionally, attribution science is becoming a pivot point in litigation and liability. Legal proceedings increasingly rely on establishing a causal link between emissions and specific damages. Actuaries can utilize attribution findings to objectively quantify the extent to which anthropogenic climate change contributed to a specific disaster, thereby informing liability assessments and potential settlements.

These metrics guide land-use planning and building codes. By quantifying the climate-attributable portion of risk, actuaries provide the cost-benefit analysis needed to justify investments in adaptation. Whether it is strengthening flood defenses or revising zoning laws in heat-prone areas, the ability to isolate the specific financial cost of climate change provides guidance that helps policymakers prioritize which risks to address first, thereby maximizing the impact of resilience projects that offer the greatest protective value to society.

Conclusion: The Way Forward

Taken together, the insights from the three actuarial domains—property & casualty, life and pension, and health—illustrate a robust interdisciplinary framework for climate risk quantification. Meteorologists provide the rigorous scientific attribution of climate signals, while actuaries systematically convert those signals into quantifiable impacts on insured losses, human longevity, and health care costs. This collaborative model fundamentally bridges the gap between cutting-edge climate science and applied financial risk management.

By enabling insurers, pension funds, health care systems, and public policymakers to understand not only how climate change alters the probabilities of extreme events but also how it materially reshapes financial exposures and social outcomes, this actuarial perspective is an essential element of risk management. Integrating attribution science into actuarial practice establishes a more comprehensive and systematic approach to climate risk quantification. Such an approach strengthens resilience planning, optimizes capital allocation, informs regulatory frameworks, and supports society's critical adaptation efforts in the face of a changing climate.

Appendix A: Detailed Operational Workflow for Actuarial Climate Attribution

This appendix expands upon the operational workflow introduced in Section 3.3, providing step-by-step guidance for practitioners. It integrates rapid thermodynamic screening tools with attribution methods, ultimately translating meteorological signals into actionable actuarial outputs. A guiding principle throughout this workflow is that while the weather hazard may be partly attributable to climate change, the ultimate financial losses depend on both exposure and vulnerability.

Phase 1: Rapid Climate Signal Screening (24–72 Hours Post-Event)

The objective of the initial phase is to establish a preliminary physical storyline and detect immediate climate fingerprints before formal models are finalized.

- **Step 1: Define the Disaster Precisely.** The workflow begins by defining the event using specific parameters: the geographic footprint (e.g., the most impacted basin or region), the time window, and the primary hazard metric that best captures the extreme (e.g., 3-day maximum temperature (TX3x), 1-day basin-averaged rainfall, or storm-track wind intensity).

- **Step 2: Apply Early Diagnostic Layers.** Actuaries utilize rapid screening tools, such as Climate Central's Climate Shift Index (CSI), as an initial diagnostic layer. This involves applying the specific diagnostic relevant to the peril: the local Air CSI for heat events, the Ocean CSI for marine and coastal hazards, or the dedicated Tropical Cyclone CSI to assess whether the background thermal state was thermodynamically amplified. A highly elevated CSI (e.g., a value of 3 or higher on Climate Central's 5-point scale) may indicate same-day evidence that climate change likely acted as a significant driver of the event's environmental conditions.

Phase 2: Formal Hazard Attribution (Weeks to Months)

This phase aligns with the rigorous probabilistic frameworks utilized by major attribution laboratories, such as World Weather Attribution (WWA), to quantify shifts in likelihood and intensity.

- **Step 3: Observational Rarity and Trend Analysis.** Using historical observations, weather station records, or reanalysis datasets (such as the Copernicus C3S ERA5), practitioners estimate the return period of the event in today's climate. This step often involves fitting non-stationary extreme-value models to detect emerging trends in event frequency or severity over time.[14]

- **Step 4: Counterfactual Climate Modeling.** Practitioners utilize multi-model ensembles of climate simulations to compare two distinct states: the actual World (today's observed climate) and the counterfactual world (a hypothetical baseline climate without anthropogenic greenhouse gas and aerosol forcing).

- **Step 5: Synthesis and Hazard Metrics.** By comparing the factual and counterfactual simulations, practitioners extract the two core attribution metrics: the RR—quantifying how many times more likely the event has become—and the Intensity Change—quantifying the change in magnitude of precipitation, wind speed, or temperature attributable to anthropogenic forcing. These findings are synthesized with the observational data from Step 3 to produce a consolidated hazard attribution estimate. To ensure robustness, practitioners should then triangulate this estimate with the initial rapid screening data from Step 2, confirming that the underlying thermodynamic signals reinforce the formal probabilistic outputs.

Phase 3: Impact Interpretation and the Actuarial Layer

This final phase focuses on the actuarial application—translating the meteorological attribution outputs into measurable financial impacts. The actuary disaggregates the disaster, separating climate-attributable hazard amplification from financial impacts driven by exposure growth and socioeconomic vulnerability. Overlaying this isolated hazard signal onto structured loss frameworks requires sorting the parametric components of actuarial catastrophe models to separate the climate risk factors from non-climatic drivers. This generates actionable decision outputs—informing pricing adjustments, reserve adequacy assessments, and the calibration of catastrophe models.

14 ERA5 hourly data on single levels from 1940 to present; Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts; 2018.

- **Step 6: Disaggregate the Disaster.** The total disaster impact is explicitly disaggregated to ensure the climate signal is neither overstated nor obscured by concurrent socioeconomic drivers. Actuaries overlay the isolated hazard attribution metrics—RR and the Intensity Change derived in Step 5—onto exposure data (the assets or populations in harm's way) and vulnerability data (fragility, preparedness, and building codes). To establish these baseline damage ratios, actuaries often utilize structured historical loss databases, such as SHELDUS[15] for U.S. data or EM-DAT[16] for global disasters.

- **Step 7: Translate to Cost Implications.** Using the attribution-adjusted hazard parameters from Step 6, actuaries rerun catastrophe models or loss estimation frameworks to generate two loss estimates: one reflecting the factual climate state and one reflecting the counterfactual state. The difference between these estimates isolates the climate-attributable loss increment. Separately, actuaries quantify the contribution of socioeconomic factors—such as inflation, urban development, building code changes, and demographic shifts—to the total observed loss. By applying these loss normalization techniques, actuaries ensure that the historical baselines are adjusted to current exposure levels and that climate and non-climate drivers are independently measured.

- **Step 8: Generate Decision Outputs.** The resulting actuarial interpretation feeds directly into core insurance and risk management functions. The outputs from this workflow provide the quantitative basis for:
    - **Pricing Adjustments:** Integrating forward-looking, climate-informed loads into rate development.
    - **Reserve Adequacy:** Assessing the climate signal within recent catastrophic loss development.
    - **Catastrophe Model Calibration:** Adjusting baseline frequency and severity assumptions within internal models.
    - **Capital and Reinsurance Strategy:** Refining stress testing and scenario analysis (e.g., ORSA) and tailoring reinsurance purchasing based on attribution-adjusted risk assessments.
    - **Broader Financial Impacts:** Quantifying climate-attributable exposures across corporate financial operations, including asset-liability management (ALM), investment portfolio volatility, and long-term financial stability.
    - **Regulatory and disclosure applications:** Supporting the relevant regulatory climate disclosure requireme

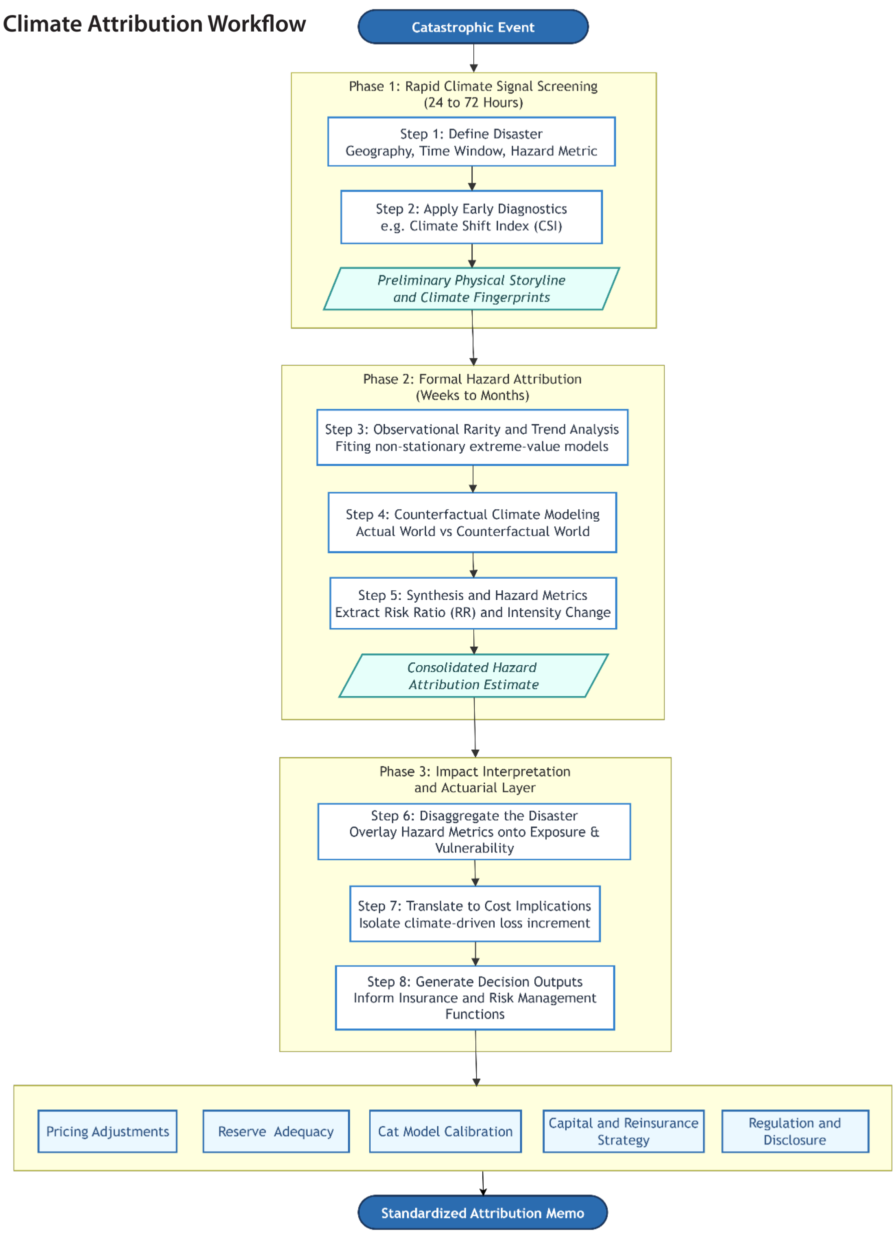
15 Spatial Hazard Events and Losses Database for the United States; Center for Emergency Management and Homeland Security, Arizona State University; 2026.
16 EM-DAT: The International Disaster Database; Centre for Research on the Epidemiology of Disasters, UCLouvain; 2025.

Standardized Output Format

To maintain the standards of transparency and clarity outlined in Section 3.5, the results of this workflow can be documented in a standardized attribution memo. A robust template includes:

1. Event definition and impacts summary.
2. Physical pathway linking climate change to the event.
3. Rapid CSI screening results.
4. Observational trend analysis and factual vs. counterfactual model comparisons.
5. Separation of hazard attribution from exposure/vulnerability amplification.
6. Summary of business implications and decision outputs.
7. Disclosure of model limitations, uncertainty bounds, and caveats.

Actuarial Climate Attribution Workflow



Appendix B: Attribution Research References

- IPCC Assessment Reports
- World Weather Attribution studies
- Peer-reviewed journals

  -*Nature Climate Change*

  -*Journal of Climate*

Appendix C: Attribution Data analytics Sources

- ERA5 hourly data on single levels from 1940 to present
- ORAS5 global ocean reanalysis monthly data from 1958 to present
- NOAA/NWS datasets
- Climate Central's Billion-Dollar Disasters
- Spatial Hazard Event and Loss Data for the U.S.
- Global Disaster data

Appendix D: Exploring Attribution Studies

For readers interested in exploring the results of specific attribution studies conducted on various extreme weather events around the world, several resources compile and present this information in accessible formats:

- **World Weather Attribution (WWA):** This international initiative conducts rapid attribution analysis of extreme weather events shortly after they occur. Their website provides summaries and full reports of their peer-reviewed studies, categorized by event type and region. It's an excellent resource for timely analyses of recent events.
- **Carbon Brief – Attribution Map:** Carbon Brief, a UK-based website covering climate science, maintains an interactive map and database of extreme event attribution studies published in peer-reviewed journals globally. Users can filter by event type, region, and study outcome.
- **Bulletin of the American Meteorological Society (BAMS) – Explaining Extreme Events Reports:** Annually (typically in January), BAMS publishes a special supplement presenting peer-reviewed analyses of extreme weather and climate events from the previous year, assessing the role of climate change. These reports offer detailed case studies from around the globe.

These resources can provide valuable context and specific examples of how the methodologies described above are applied to understand the impact of climate change on real-world extreme events relevant to actuarial work and policy decisions. While the IPCC reports synthesize the overall state of attribution science, the links above offer more direct access to studies on individual events.

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