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Quantifying Mortality and Morbidity Impacts from Climate Risks: A Practical Framework for Decision-Making

AUGUST | 2026

Quantifying Mortality and Morbidity Impacts from Climate Risks

A Practical Framework for Decision-Making

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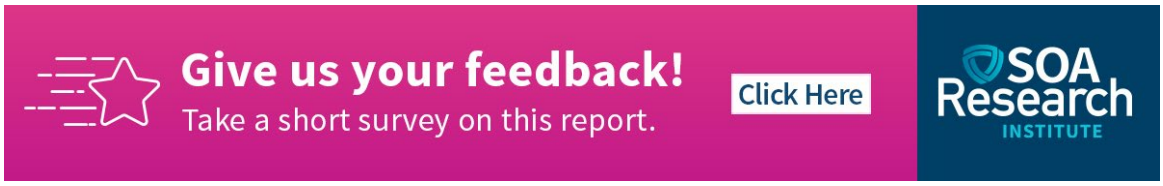

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Quantifying Mortality and Morbidity Impacts from Climate Risks

A Practical Framework for Decision-Making

Executive Summary

Climate change is becoming an increasingly material risk driver for human life, health, and the insurance sector.

Climate change is no longer a peripheral sustainability-related concern for the life and health insurance sector but is becoming a material driver of biometric risks. While the property and casualty insurance industry has long accounted for physical climate risks, life and health insurers remain generally reliant on actuarial techniques that assume stable trends derived from experience, a foundation that is increasingly untenable in a changing climate. Current scientific evidence confirms that climate change is already affecting human health, with rising heat-related mortality, expanding ranges of vector-borne diseases, and extreme weather events straining health care systems. For actuaries and for the life and health insurance industry, integrating these trends into the core assumptions underpinning pricing, reserving, risk and capital management can be challenging.

A forward-looking lens on climate-related life and health risk

This report proposes a forward-looking and scenario-based framework designed to evaluate how climate change impacts mortality and morbidity. The framework distinguishes between acute risks (such as heat domes and floods) causing immediate spikes in mortality, and chronic risks (such as sustained heat stress and air quality degradation) that alter baseline mortality trends. Climate-related risks are non-stationary (since past data cannot reliably predict future climate-driven health outcomes) and have a systemic nature (as they are correlated and can affect entire regions simultaneously). They can flow through direct pathways like injury and heat stress, as well as indirect pathways including air quality, vector-borne disease, mental health, and health care system strain. Their impacts are not uniform but are mediated by such factors as geography, socioeconomic status, age, and adaptive capacity. This research also identifies and warns against specific cognitive pitfalls in climate risk assessment, such as the over-reliance on familiar models simply because they are readily available, or the tendency to make decisions driven solely by easily measurable variables while ignoring critical qualitative drivers and emerging science-based trends.

Mapping the complex transmission channels of extreme weather events and climate-related perils

The major climate perils relevant to life and health insurance include heat waves, drought, wildfires, floods, severe storms, and sea-level rise. The report examines the specific transmission channels through which these hazards translate into health outcomes, highlighting the population groups and regions most at risk. It explores how risks compound when multiple hazards interact, how acute climate disasters can produce short-term mortality spikes followed by temporary dips, and how health care utilization may exhibit a trend bounce-back as deferred care resumes after an extreme weather event. The report also evaluates the scope and limitations of adaptation strategies, from early warning systems and climate-resilient infrastructure to public health surveillance, while cautioning against the risks of maladaptation and the uneven distribution of adaptive capacity across different socioeconomic groups.

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Operationalizing the framework: A climate-adjusted Lee-Carter model for modern actuarial practice

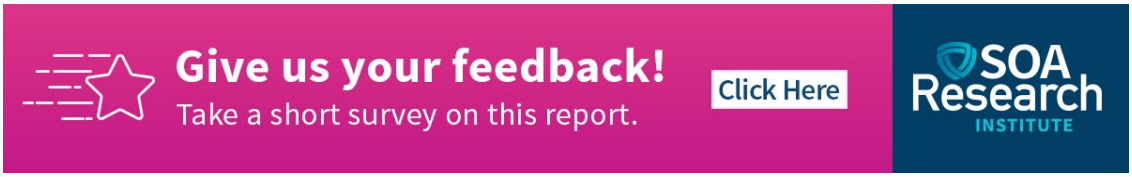
The Lee-Carter mortality model can be extended to create a climate-adjusted specification, incorporating vulnerability factors that capture how age, geography, and socioeconomic status amplify the impact of these hazards. The adjusted model is intended to enable scenario analysis under different emissions pathways and stress testing of portfolio resilience under severe conditions. A parallel framework is introduced for morbidity, modeling health care utilization rates. Recognizing that data constraints often limit the ability to estimate climate sensitivity across all socioeconomic groups, reduced-form variants of the models are also introduced that remove the socioeconomic status dependency. The modeling frameworks are designed to support actuarial applications such as pricing, reserving, capital management, Own Risk and Solvency Assessment (ORSA), and common climate-related disclosure frameworks.

Practical application: A case study for heat-related mortality risk in France, Italy and Spain

A case study applies this framework to mortality modeling in France, Italy, and Spain. Using data from 2004 to 2025 (excluding the anomalous COVID-19 years) and projecting to 2060 under a high-emissions, high-warming scenario, it illustrates how the models can be calibrated and projected to assess directional shifts in mortality under relevant climate pathways. The case study highlights the importance of interpreting results as conditional scenario outputs rather than point forecasts and underscores the need for robust validation and governance when integrating forward-looking assumptions into actuarial practice. To facilitate practical application and help ensure transparency, the full model specification, calibration routines, and a complete suite of notebooks are made available in a public online repository, allowing practitioners to run the model, adapt the framework to their own portfolios, and extend the analysis to additional geographies or scenarios.

Integrating climate scenario projections can help protect insurers and society's resilience.

Ultimately, climate change introduces structural shifts in mortality and morbidity that cannot be captured by traditional actuarial methods alone. Models and projections that include climate-related effects may better reflect plausible long-term physical conditions. By adopting forward-looking scenarios and interdisciplinary approaches, actuaries can better support decision-making, protect the balance sheet of insurers, and contribute to a more resilient financial system and society in the face of a changing climate.



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Section 1 Conceptual Framework

Climate change is not just a peripheral, sustainability-related consideration layered onto traditional mortality and morbidity drivers. Instead, it is emerging as a significant long-term driver of biometric risks, with implications for the life and health (L&H) insurance sector and the core actuarial assumptions that underpin it.

The Intergovernmental Panel on Climate Change (IPCC) WGII AR6 report concludes with high confidence that climate change is already affecting health and that heat-related mortality and morbidity increase with warming.[1]

This finding is reinforced by the World Health Organization (WHO), which documents observed climate-related health impacts and quantified indicators such as rising heat-related deaths among older adults.[2] Rising temperatures, more frequent extreme weather events, and gradual environmental degradation are already influencing health outcomes and are expected to intensify over time. Together, these developments warrant further evaluation to understand how climate-related physical risks may alter future experience, challenge long-standing biometric assumptions, and reshape the risk landscape for insurers, regulators, and policymakers.

The purpose of this conceptual framework is to provide a structured basis for evaluating how climate change affects mortality, morbidity, and longevity, and to support the development of methods for quantifying these impacts within L&H insurance. Actuarial techniques that depend primarily on historical experience and implicitly assume stable relationships between risk factors and outcomes are poorly suited to the non-stationary, path-dependent character of climate-related risks. More robust climate risk assessment involves using forward-looking scenarios and an interdisciplinary approach that integrates insights from climate science, epidemiology, and data analytics.

1.1 THE NATURE OF CLIMATE-RELATED RISKS TO HUMAN LIFE AND HEALTH

1.1.1 DEFINING CLIMATE RISKS

The Task Force on Climate-related Financial Disclosures (TCFD) formalized in its 2017 recommendations the distinction between physical and transition risks.[3] Climate-related **physical risks** encompass a broad set of environmental hazards that directly or indirectly affect human mortality and morbidity. They include extreme weather events such as heat waves, floods, hurricanes, and severe storms, as well as slower-moving environmental changes such as rising temperatures, deteriorating air quality, and the geographic expansion of vector-borne diseases (i.e., illnesses transmitted by living organisms such as mosquitoes or ticks). Each of these hazards can influence health outcomes through multiple pathways, ranging from acute injuries and heat stress to chronic respiratory, cardiovascular, infectious disease, and mental health impacts.

A key distinction for actuarial analysis is the difference between **acute and chronic** physical climate risks. Acute impacts arise from discrete, high-intensity events such as heat domes or floods, which cause immediate illnesses, injuries, and fatalities. In contrast, chronic impacts accumulate gradually over time. Long-term exposure to elevated temperatures or persistent air pollution can contribute to chronic physiological and psychological stress, alter disease prevalence, and increase baseline mortality and morbidity rates. Recent empirical evidence from the Society of Actuaries Research Institute shows that large-scale climate anomalies can impede mortality improvement for

[1] Climate Change 2022: Impacts, Adaptation and Vulnerability - Summary for Policymakers, page 11, IPCC (Pörtner et al., 2022), https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

[2] Fact Sheet - Climate Change and Health, WHO (2023), https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

[3] Recommendations of the Task Force on Climate-related Financial Disclosures, page 5, TCFD (2017), https://assets.bbhub.io/company/sites/60/2021/10/FINAL-2017-TCFD-Report.pdf

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several years after the event window, illustrating how chronic climate-related stressors can also reshape long-term mortality trajectories, in addition to producing acute shocks.[4]

While both acute and chronic climate risks can affect human life and health, the long-term, cumulative impacts of chronic exposures represent the more distinctive modeling challenge. In many developed countries, early-warning systems, resilient infrastructure, and strong emergency management can often limit direct mortality from extreme weather events. By contrast, in lower-income or politically fragile regions, acute climate hazards can still cause catastrophic loss of life (as illustrated by the 2023 dam failures in Derna, Libya, where extreme rainfall intensified by climate change combined with aging infrastructure and governance failures to produce thousands of deaths),[5] underscoring the need for context-specific modeling approaches.

Although this report focuses primarily on physical climate risks, it is important to note that **transition risks** (including economic and technological disruption, energy-system changes, and policy-driven shifts in employment or living conditions) also affect human health. These impacts can arise through factors including changes in income, access to health care, occupational exposures, or psychosocial stress. The increase in frequency and severity of events associated with physical risks tends to unfold gradually over time,[6] whereas transition risks can potentially materialize more abruptly due to policy shifts or rapid technological change. This difference in timing adds complexity to scenario design and risk assessment. While distinct from physical hazards and potentially harder to quantify, transition-related effects on human life and health form part of the broader climate risk landscape and warrant consideration in comprehensive risk assessments.

1.1.2 DISTINCTIVE RISK CHARACTERISTICS

Climate-related risks differ fundamentally from the types of risks traditionally assessed in life and health insurance. Their unique characteristics challenge traditional enterprise risk management (ERM) processes, such as insurers' Own Risk and Solvency Assessment (ORSA), which are primarily designed to address known and quantifiable risks and, therefore, may require adaptation to capture the emerging, systemic, and deeply uncertain nature of climate-related L&H risks.

Climate risks are **non-stationary**: the environmental conditions that influence mortality and morbidity are shifting over time, and past data becomes less reliable over time as the sole basis for projecting future experience. Climate change alters both the variability and the long-term trend of mortality and morbidity. Increased climate volatility raises short-term risk levels and affects risk assumptions, while gradual environmental degradation influences long-term best-estimate assumptions. In addition, changes in variability and trend also combine to lead to the occurrence of unprecedented extreme events, as illustrated in figure 1.1 in the case of rising temperatures.

[4] Climate Anomalies' Enduring Impacts on U.S. Health Landscape, SOA Research Institute (Xu et al., 2025), https://www.soa.org/globalassets/assets/files/resources/research-report/2025/2025-12-cc219-climate-anomalies.pdf

[5] Aging Infrastructure, Climate Change, and Political Instability Fueled Catastrophic Dam Collapse in Libya, United Nations University Institute for Water, Environment and Health (2025), https://unu.edu/inweh/news/aging-infrastructure-climate-change-and-political-instability-fueled-catastrophic-dam

[6] Except where physical thresholds are crossed and irreversible tipping points are triggered, leading to non-linear damage functions

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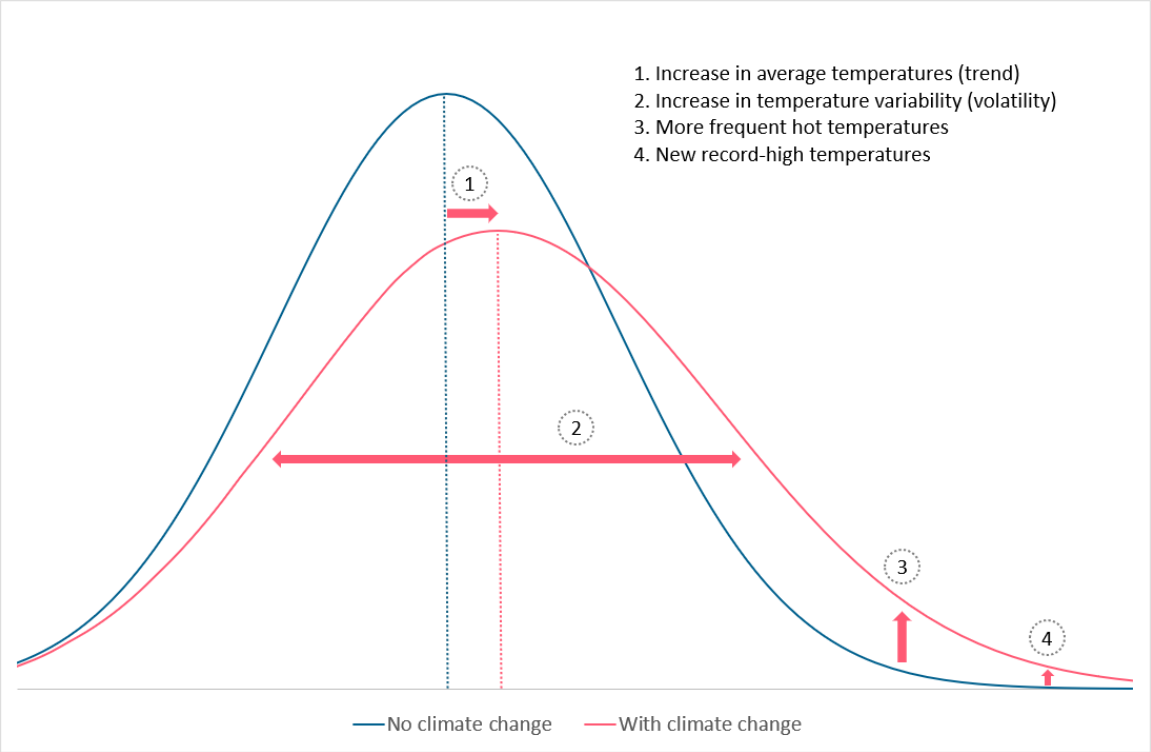
Figure 1.1
EFFECT ON TEMPERATURE DISTRIBUTION WHEN THE MEAN AND VOLATILITY INCREASE



Climate risks are increasingly **systemic**. Unlike idiosyncratic life and health risk drivers that affect individuals independently, climate-related hazards can influence entire regions, populations, and health systems at the same time. Like other catastrophic L&H shocks (such as pandemics or large-scale accidents), extreme heat waves, wildfire smoke episodes, and climate-amplified infectious disease outbreaks can generate concentrated surges in mortality and morbidity. As such extreme events become more frequent and chronic stressors intensify, correlations across exposures may grow stronger, reducing the potential for diversification within L&H insurance portfolios and increasing the likelihood of concentrated losses.[7] The systemic nature of these risks is further shaped by broader societal factors, including infrastructure resilience, public-health capacity, and socioeconomic vulnerability.

Climate risks also exhibit **non-linear** dynamics, including feedback loops, cascading effects, and potential tipping points. These dynamics can amplify health impacts in ways that are difficult to anticipate using linear models calibrated on historical data, underscoring the need for approaches that can accommodate discontinuities and systemic interactions rather than assuming smooth trend evolution.[8]

Climate risks can be considered **novel risks**. They do not fit neatly into established categories such as stable, historically observable risks or hypothetical emerging risks. Like cyber-related risks, climate-related health impacts are already materializing, yet their future trajectory remains uncertain and is shaped by complex interactions among

[7] GROWING LIFE AND HEALTH INSURANCE INDUSTRY RISKS FROM CATASTROPHIC EVENTS AND HOW INDUSTRY WILL MODEL THEM, SOA Research Institute (Montgomery & Stryker, 2024), https://www.soa.org/globalassets/assets/files/resources/research-report/2024/lifehealth-catastrophic-event-risks.pdf

[8] Introduction to Climate-Related Scenarios, International Actuarial Association (Dionne et al., 2021), https://actuaries.org/app/uploads/2025/04/CRTF_Introduction_Climate_Scenarios.pdf

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hazard, exposure and vulnerability factors. This combination of gradual emergence over time, deep uncertainty and local impacts places climate risks outside the scope of most traditional actuarial and risk management toolkits.

1.1.3 CLIMATE RISK AWARENESS ACROSS THE INSURANCE SECTOR

Within the insurance sector, climate-related risk awareness has historically been concentrated primarily in **property and casualty** (P&C[9]) portfolios and, to some extent, in investment activities. Natural catastrophe insurance, in particular, has faced mounting challenges as the frequency and severity of extreme weather events have increased. This has contributed to a well-documented crisis of insurability and affordability. In the United States, for example, the share of uninsured homes rose from 5% in 2019 to 12% in 2024[10], reflecting deteriorating affordability and availability of coverage in states repeatedly affected by hurricanes, wildfires, and floods, such as California, Florida, and Louisiana.[11] A more detailed discussion about the impact of climate change on P&C insurance can notably be found in the SOA Research Institute paper "Availability, Affordability, and Adequacy of Insurance in Areas Impacted by Climate-related Risks."[12]

By contrast, **life and health** insurers have so far experienced only limited direct impacts from climate-related risks.[13] For instance, among all supervisory climate scenario analysis exercises performed at the time of writing, only the French ACPR/Banque de France climate stress test (2023-2024) has explicitly incorporated selected life and health dimensions (namely heat waves, air pollution, and vector-borne diseases).[14] However, there is broad consensus among experts that climate impacts on life and health insurance will become increasingly material in the years ahead.[15] In Switzerland, for instance, risks to human health have been rated as the highest of all climate-related risks in the country's latest climate risk analysis.[16]

The magnitude and timing of future impacts will depend on multiple factors, including geographic location, demographic and socioeconomic characteristics of insured populations, preparedness, and the resilience of health care systems. The extent of future L&H risks associated with climate change will also depend heavily on how health care systems respond. Differences in public-health preparedness, emergency response capacity, access to primary care, and the resilience of hospital and long-term care infrastructure can significantly amplify or mitigate climate-related mortality and morbidity. As a result, countries or regions with similar hazard profiles may experience very different health outcomes depending on the strength and adaptability of their health system responses.

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[9] Also known as general insurance (e.g., in the UK and Australia) or non-life Insurance (e.g., in European and international contexts)

[10] Tackling the Insurance Protection Gap, WWF Policy Brief (Hess, Crugnola-Humbert et al., 2025), https://wwfint.awsassets.panda.org/downloads/wwf--insurance-protection-gap-policy-brief_1_1.pdf

[11] The 13th National Risk Assessment - Climate, The 6th "C" of Credit, First Street (2025), https://assets.riskfactor.com/media/The%2013th%20National%20Risk%20Assessment%205_23_25

[12] Availability, Affordability, and Adequacy of Insurance in Areas Impacted by Climate-related Risks, SOA Research Institute (Sousounis, 2024), https://www.soa.org/globalassets/assets/files/resources/research-report/2024/ins-availability-climate-risk-areas.pdf

[13] CLIMATE CHANGE: What does the future hold for health and life insurance?, page 25, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[14] Main results of the climate exercise for the insurance sector, ACPR / Banque de France (2025), https://acpr.banque-france.fr/en/publications-and-statistics/publications/main-results-climate-exercise-insurance-sector

[15] CLIMATE CHANGE: What does the future hold for health and life insurance?, pages 6-7, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[16] Climate Risk Analysis for Switzerland, Figure 2 page 9, Federal Office for the Environment (2025), https://www.bafu.admin.ch/dam/en/sd-web/74m-J2D7NNzh/klima-risikoanalyse.pdf

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1.2 METHODOLOGICAL CHALLENGES AND COGNITIVE PITFALLS

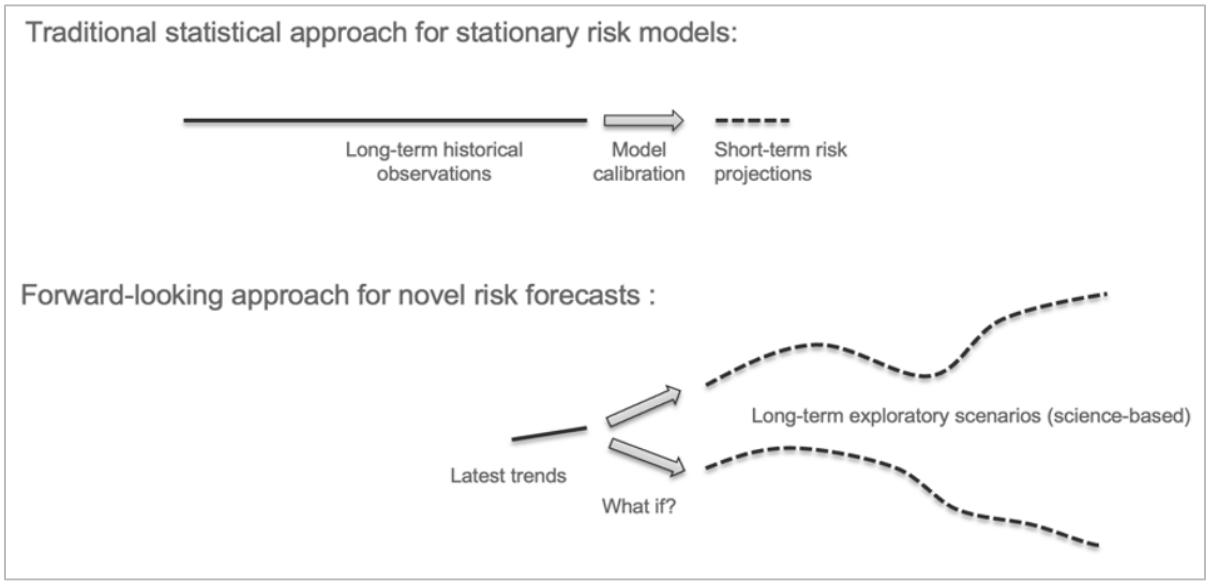
1.2.1 LIMITS OF HISTORICAL DATA AND USE OF FORWARD-LOOKING METHODS

Traditional L&H actuarial methods rely on stable historical datasets and the assumption that past experience provides a reliable basis for projecting future mortality and morbidity. As discussed earlier, the non-stationary nature of climate risks challenges this foundation: environmental conditions are evolving, and past data no longer reflect the risk environment that insurers may face in the coming decades.

These limitations can motivate greater use of **forward-looking** modeling approaches. Long-term exploratory scenario development can be useful for understanding how mortality and morbidity may evolve under different greenhouse gas emissions and climate pathways. Climate scenarios are not forecasts but structured explorations of plausible futures, combining climate pathways with socioeconomic assumptions.

They typically combine a physical climate pathway, localized physical hazard projections, assumptions about emissions and technological evolution, and socioeconomic narratives, over short-, mid- and long-term time horizons.[17] Such approaches acknowledge that future conditions may fall outside the range of historical experience and that climate-related risks interact with demographic, environmental, and socioeconomic factors in ways that traditional models were not designed to capture. For actuaries, addressing these challenges can involve integrating the latest insights from climate science and epidemiology and explicitly accounting for uncertainty in both hazard evolution and population exposure and vulnerability.

Figure 1.2
STATISTICAL VS. FORWARD-LOOKING APPROACH TO RISK MODELING



Source: Crugnola-Humbert (reproduced with permission from the copyright holder)[18]

[17] Climate-Related Scenarios Applied to Insurers and Other Financial Institutions, International Actuarial Association (Musulin et al., 2021), https://actuaries.org/app/uploads/2025/04/CRTF_Application_Climate_Scenarios.pdf

[18] Climate & Sustainability Risk Management: The Need for New Approaches, Swiss Association of Actuaries (Crugnola-Humbert, 2024), https://www.actuaries.ch/document/download/97

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1.2.2 THE STREETLIGHT EFFECT

A common pitfall in climate-risk assessment is linked to the Streetlight Effect, i.e., the tendency to search for answers where data are easiest to obtain rather than where the underlying risk is most significant.[19] The term originates from a well-known anecdote in which a drunk man looks for his lost keys under a streetlight, not because he dropped them there, but because the light is better there at night. In the context of climate-risk assessment, this effect manifests when analysts rely on familiar datasets or established actuarial tools simply because they are readily available, even if they are poorly suited to capturing climate-related dynamics. Such practices risk creating a misleading sense of precision and may obscure the true drivers of climate-related health impacts. Effective assessment may benefit from developing new tools and data structures, rather than relying on legacy models that were not designed to capture these novel risks.

1.2.3 THE QUANTITATIVE FALLACY

Another pitfall is the Quantitative Fallacy, which arises when decision-making is driven primarily or solely by those variables that can be easily measured. Likewise, climate-related life and health risks involve many qualitative or hard-to-quantify factors (such as social resilience, governance quality, adaptive capacity, and systemic interactions) that play a critical role in shaping future outcomes. Over-emphasizing measurable variables, such as temperature or historical L&H claims data, while neglecting these broader determinants can lead to incomplete or misleading risk assessments, particularly in a domain characterized by deep uncertainty and complex causal pathways. Recognizing the importance of qualitative drivers can contribute to meaningful climate risk assessment.

1.2.4 BIASES ASSOCIATED WITH LONG HORIZONS IN LIFE AND HEALTH CLIMATE RISK ASSESSMENT

Life and health insurance liabilities often develop over multi-decade horizons, while climate change is itself a slow-moving and cumulative process. This creates additional cognitive pitfalls that can distort long-term risk assessment. Present bias and excessive discounting may lead to underweighting climate-related impacts that materialize beyond typical financial planning cycles. They can make future climate-related health risks feel abstract or less urgent, reducing their perceived relevance for today's assumptions. Disproportionate focus on recent events (such as a single extreme heat season) can also lead to overlooking slow-building chronic risks and increasing the risk tolerance. These biases are particularly relevant for L&H actuarial modeling, where small changes in long-term mortality or morbidity trends can compound significantly over time.

1.2.5 IMPLICATIONS FOR ACTUARIAL JUDGMENT AND MODEL GOVERNANCE

These challenges have important consequences for actuarial and risk management practice. Assessing climate-related L&H risks and integrating them into ERM and ORSA-type processes requires new modeling approaches that explicitly incorporate non-stationarity, deep uncertainty, and correlated vulnerabilities. It also requires interdisciplinary data integration, drawing on climate projections, geospatial hazard information, and epidemiological research. Given the limitations of available data and the complexity of emerging risks, supplementing quantitative analysis with qualitative expert judgment can be beneficial.

From a model governance perspective, the proposed framework emphasizes transparency regarding models' intended uses and limitations. It explicitly identifies parameter, model, and scenario uncertainty and presents that uncertainty alongside model outputs. The framework also recognizes that key assumptions—particularly those informed by expert judgment—may evolve as scientific understanding develops and is structured to accommodate

[19] Streetlight Effect, Wikipedia (retrieved 2026), https://en.wikipedia.org/wiki/Streetlight_effect

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periodic review of those assumptions. In short, climate change challenges not only actuarial tools and data, but also the judgment and model governance frameworks that underpin actuarial decision-making.

1.3 RISK TRANSMISSION CHANNELS IN LIFE AND HEALTH INSURANCE

Climate-related hazards influence mortality, morbidity and longevity through both direct and indirect pathways.

Direct pathways involve acute mechanisms linked to short-duration, high-intensity events. They notably include injuries, acute illnesses, and fatalities resulting from extreme events such as heat waves, floods, hurricanes, and severe storms. These events can cause immediate spikes in mortality and morbidity, particularly among vulnerable populations such as older adults and those with limited access to cooling or emergency services.

Short-term spikes in mortality due to acute climate-related events such as heat waves, particularly among individuals with pre-existing conditions, may be followed by a temporary reduction in mortality in subsequent weeks or months as some of the individuals who died during the event might have otherwise done so anyway in the near term.[20] Similar effects can be observed for morbidity and health care usage, where vulnerable individuals' health events (such as hospital admissions) are brought forward by exposure to extreme weather events such as floodings.[21] This mortality and morbidity displacement is called the harvest effect and can also be observed during pandemics, such as COVID-19. It can partially offset the long-term impact of acute events, but it does not mitigate the broader chronic health burdens associated with sustained climate stressors. Conversely, extreme weather events can also lead to a short-term decrease in non-urgent health care utilization due to deferred care (for instance, due to difficult-to-use preventive services or diagnostics), followed by a trend bounce-back effect once the situation normalizes and people can resume accessing health care services and facilities.

Indirect pathways operate through chronic environmental and ecological changes that affect baseline life and health risks. Examples include increasing daily temperatures,[22] deteriorating air quality due to wildfires, shifts in mosquito or tick habitat that expand the geographic range of the diseases they transmit, and disruptions to ecosystems that influence food security or water quality. These mechanisms can contribute to chronic respiratory and cardiovascular disease burdens, increased infectious disease prevalence, and long-term physiological stress. Such mechanisms build up risk gradually over time, ultimately altering long-term trends in baseline mortality, morbidity and longevity. These indirect pathways can also be shaped by socioeconomic factors, for example, when climate-related adaptation demands draw resources away from health and social services.

1.4 HAZARD, EXPOSURE AND VULNERABILITY DETERMINANTS

Climate-related L&H impacts arise from the interaction of three core dimensions: climate hazards themselves, the exposure of populations to those hazards, and the vulnerability of individuals and systems to adverse outcomes. As climate change progresses over time, hazards are intensifying, exposure patterns are shifting (for instance, when new regions become increasingly exposed to climate perils that they were traditionally safe from in the past), and vulnerability is shaped by a complex set of factors. Climate risks also exhibit strong geographic, demographic and socioeconomic patterns. Climate-related events, such as heat waves or flooding episodes, often produce highly

[20] Mortality risk attributable to high and low ambient temperature: a multi-country observational study, The Lancet (Gasparrini et al., 2015), https://www.thelancet.com/action/showPdf?pii=S0140-6736%2814%2962114-0

[21] Effects of extreme climate events on the morbidity of a sample of medical scheme lives in South Africa, South African Actuarial Journal (Smith et al., 2025), https://www.actuarialsociety.org.za/wp-content/uploads/2025/11/2025-ASSA-KotzenSmithCo-FIN.pdf

[22] Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits, The Quarterly Journal of Economics (Carleton et al., 2022), https://academic.oup.com/qje/article/137/4/2037/6571943

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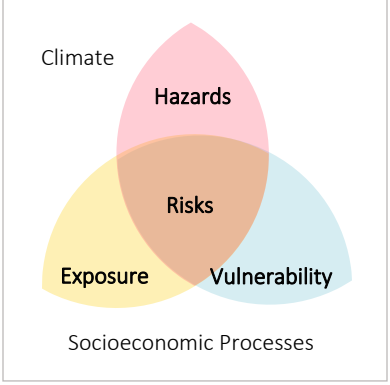
uneven impacts across regions and population groups, reinforcing the usefulness of decision-making with a granular and localized assessment of hazard, exposure, and vulnerability.

Figure 1.3
RISKS, HAZARDS, EXPOSURE AND VULNERABILITY



Source: Adapted by the authors from the IPCC Sixth Assessment Report [23]

The populations most at risk from climate-related health impacts are those with high exposure to hazards (such as outdoor workers, coastal and urban residents), greater biological vulnerability (including children, older adults, pregnant women, and individuals with pre-existing health conditions), or limited adaptive capacity (such as low-income groups, marginalized or remote communities, and migrants). These overlapping factors compound climate hazards and contribute to unequal health outcomes across populations.

1.4.1 GROWING CLIMATE HAZARDS

The underlying climate hazards are changing over time as extreme climate-related events become more frequent, more severe, and more prolonged. Rising temperatures increase the likelihood and duration of extreme heat events, while warmer oceans contribute to more intense hurricanes and heavier precipitation. Wildfire seasons are lengthening, and air quality degradation is becoming more persistent in many regions. Vector-borne diseases are expanding into new geographic areas as ecological conditions shift. These evolving hazards mean that future L&H risks cannot be inferred from historical patterns alone, as the baseline risk drivers are undergoing structural change.

1.4.2 DETERMINANTS OF EXPOSURE

Exposure refers to the degree to which individuals or populations encounter climate-related hazards. Geographic location is the primary determinant, but its relevance is evolving as hazards expand into regions where they were previously rare. Urbanization patterns, land use decisions, and occupational environments also shape exposure. Urban heat islands amplify temperature-related risks, while outdoor workers face heightened exposure to extreme heat and air pollution. For insurers, understanding exposure patterns is critical for assessing geographic concentration risk and anticipating shifts in regional mortality and morbidity trends.

1.4.3 DETERMINANTS OF VULNERABILITY

Vulnerability reflects the susceptibility of individuals or groups to adverse health outcomes when exposed to climate-related hazards. It is shaped by a complex combination of demographic, socioeconomic, and behavioral factors (such as time spent outdoors). Older adults, infants, and individuals with chronic cardiovascular or

[23] IPCC Sixth Assessment Report, Figure 16.1, IPCC (2022), https://www.ipcc.ch/report/ar6/wg2/figures/chapter-16/figure-16-001

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respiratory diseases are more vulnerable to heat stress and air pollution. Lower-income populations may face higher vulnerability due to limited access to cooling, health care, or resilient housing. For instance, studies of hurricane-related health impacts show that morbidity surges disproportionately affect older adults, low-income populations, individuals with chronic conditions, and those with limited mobility or access to transportation.[24] Recent analysis by the Institute and Faculty of Actuaries and the UK Government Office for Statistics Research further highlights how housing quality and income deprivation act as critical multipliers for heat-related mortality in specific demographics.[25] These findings underscore how climate-related events interact with pre-existing social and health vulnerabilities.

Adaptive capacity is a critical mitigant of vulnerability. It reflects the ability of individuals, communities, and systems to adjust to climate-related hazards, mitigate potential harm, and recover from adverse events. Access to health care, availability of cooling or heating, quality of housing, and the resilience of infrastructure all contribute to adaptive capacity. Public-health interventions, early-warning systems, and community-level preparedness can also reduce the severity of climate-related health impacts.[26] A distinctive feature of L&H risks is that human beings, more so than fixed physical assets, can adjust their behavior and location in both the short and long term, whether through immediate protective actions during acute events or through longer-term adaptations such as lifestyle changes or climate-related migration. At the individual level, behavioral adaptations (such as hydration practices, avoidance of outdoor activity during extreme heat, or use of air filtration) play an important role. For insurers, adaptive capacity influences both the magnitude and variability of future claims and introduces uncertainty as adaptive measures can evolve over time in response to policy, technology, and social behavior.

Differences between the insured and general population, where such differences exist, are also an important consideration for L&H insurers. Insured lives are generally less vulnerable to climate-related risks than the uninsured and under-insured (e.g., those who have insurance but with significant deductibles and exclusions). For example, cold-related mortality, such as deaths from hypothermia, disproportionately affects people experiencing homelessness or living in severely inadequate housing. These groups are often under-represented in insured portfolios, making these cold-related impacts less directly relevant for most L&H insurers. The resilience of insured lives typically stems from greater affluence and resources for adaptation, reduced exposure to climate impacts through better living conditions, and healthier lifestyles supported by good access to health care. For life insurance and for non-mandatory health insurance, medical underwriting further strengthens this by selecting healthier cohorts.[27] However, even well-insured populations are not immune to climate-related risks. Geographic concentration, aging policyholder cohorts, and the prevalence of chronic conditions can still contribute to risk elevation. Moreover, indirect effects (such as strain on health care systems or economic disruption) can influence insured lives as well.

[24] Health and Hurricanes - Studying Disparate Health Impact of Extreme Climate Events, 2017-2020, SOA Research Institute (Webb et al., 2024), https://www.soa.org/globalassets/assets/files/resources/research-report/2022/health-hurricanes-studying-impact.pdf

[25] Heat, Health and Inequality, Institute and Faculty of Actuaries & UK Government Office for Statistics Research, June 2026, https://actuaries.blog.gov.uk/2026/06/09/heat-health-and-inequality/

[26] Intergovernmental Panel on Climate Change (IPCC), Summary for Policymakers, in Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, ed. H.-O. Pörtner et al. (Cambridge, UK: Cambridge University Press, 2022), 3–33, https://doi.org/10.1017/9781009325844.001.

[27] The risk of a lifetime: mapping the impact of climate change on life and health risks, Swiss Re Institute (Meier et al., 2023), https://www.swissre.com/dam/jcr:b851c59c-d3e0-4f87-817c-62691b985bc5/2022-11-sri-expertise-publication-impact-of-climate-change-life-health-risks.pdf

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1.5 DATA AND MEASUREMENT CHALLENGES

These limitations affect the ability of actuaries to quantify climate-related risks, calibrate forward-looking models, and interpret observed experience.

1.5.1 LACK OF GRANULAR, LONGITUDINAL, AND INTEGRATED DATA

Robust climate-health assessment requires data that are granular, longitudinal, and integrated across disciplines.[28] Many health datasets lack the spatial or temporal resolution needed to link specific climate hazards to health outcomes. For instance, even foundational elements such as the geographical distribution of L&H portfolios are often insufficiently understood. Mortality and morbidity data are often aggregated at regional or national levels, masking local variations in exposure and vulnerability. Long-term datasets that track individuals or cohorts over time are also limited, making it difficult to assess how shifting chronic climate stressors, such as long-term heat exposure or persistent air pollution, influence mortality and morbidity trends across locations and population groups. In addition, climate, environmental, demographic, and health data are typically collected by different institutions using different standards. Integrating these datasets requires harmonization of formats, definitions, and timeframes, which is resource-intensive and methodologically complex. Given these multiple constraints, one possible approach is to work iteratively, starting small and exploring emerging climate-health linkages with available data, while simultaneously expanding data collection efforts to progressively close the most material data gaps.

1.5.2 MEASUREMENT AND ATTRIBUTION LIMITATIONS

Even when data is available, measurement challenges complicate the **attribution** of climate-related health impacts. Causes of death and illness are often coded using broad categories that do not explicitly capture climate-related factors. Climate-related mortality is frequently under-reported because death certificates typically record the immediate medical cause of death rather than the environmental conditions that contributed to it.[29] Heat-related deaths, for example, may be recorded under cardiovascular or respiratory causes, leading to systematic under-estimation of climate impacts. A high-profile illustration is the case of acclaimed movie director, David Lynch, who died during the January 2025 Los Angeles wildfires and whose official cause of death was simply recorded as cardiac arrest due to chronic obstructive pulmonary disease, with dehydration listed as a significant contributing factor.[30] This example reflects a broader pattern: while acute climate impacts on life and health (e.g., drowning deaths during floods) can generally be captured, other climate-related factors often remain invisible in statistics because they manifest through underlying medical conditions.

Measurement challenges also arise from inconsistent reporting standards across regions and countries, which complicate cross-regional comparisons and global assessments. Long-term exposures, such as cumulative heat stress or persistent air pollution, are difficult to quantify accurately, especially when monitoring networks are sparse or unevenly distributed. Because the current level of climate-related mortality and morbidity is already embedded in historical experience data, care is also needed to avoid double-counting when projecting future impacts. It may be helpful for future projections to distinguish between incremental climate effects already captured in the base period and additional impacts expected under future climate pathways. Temporal attribution is further complicated by short-term mortality displacement (the harvest effect), which can obscure the net impact of acute events when mortality spikes are followed by short-term mortality deficits.

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[28] CLIMATE CHANGE: What does the future hold for health and life insurance?, page 7, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[29] CLIMATE CHANGE: What does the future hold for health and life insurance?, page 10, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[30] Where there's fire, there's smoke: David Lynch's death and the climate crisis, The Vermont Cynic (Kaminski, 2025), https://vtcynic.com/opinion/where-theres-fire-theres-smoke-david-lynchs-death-and-the-climate-crisis/

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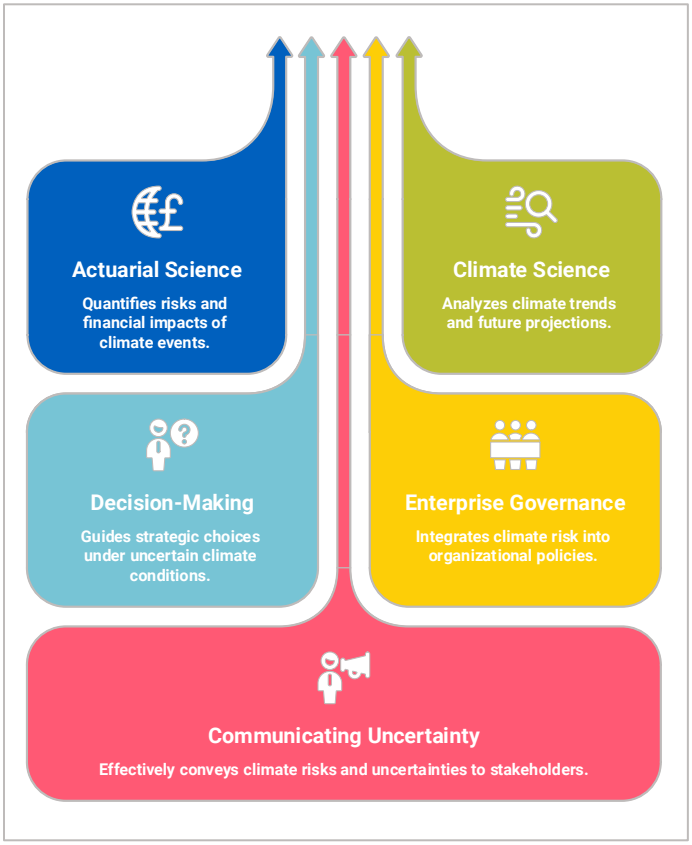
1.6 TOWARD AN INTEGRATED FRAMEWORK FOR LIFE AND HEALTH CLIMATE RISK ASSESSMENT

Climate change introduces new dynamics into mortality and morbidity risk that cannot be captured through traditional actuarial methods alone. A forward-looking, interdisciplinary framework can help to integrate actuarial science, climate science, epidemiology, and systems thinking, supported by strong governance and transparent communication.

Figure 1.4
TOWARD AN INTEGRATED FRAMEWORK FOR LIFE AND HEALTH CLIMATE RISK ASSESSMENT



1.6.1 PRINCIPLES OF A FORWARD-LOOKING FRAMEWORK

The frequency, severity, and geographic distribution of climate hazards are shifting, and the associated health impacts are expected to intensify or evolve over time. The proposed framework and analytical methods can accommodate a wide range of plausible futures rather than relying only on point estimates or narrow confidence intervals. The use of a central, baseline climate risk scenario is more accurately understood as a decision-useful narrative anchor, rather than a probabilistic best estimate.[31] It is different from traditional actuarial best estimate assumptions. While standard practice often treats the central projection as the most likely outcome, the exclusion of climate drivers in baseline projections would not represent a best estimate for the future. Rather, it serves as a neutral counterfactual against which incremental climate-related impacts can be measured. For practical applications, this climate component will typically be overlaid onto best estimate biometric assumptions to avoid

[31] Developing central climate scenarios, Institute and Faculty of Actuaries (2026), https://blog.actuaries.org.uk/developing-central-climate-scenarios-initial-workshop-findings/

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misestimating liabilities, acknowledging that a trajectory without climate change is increasingly unlikely to reflect the evolving risk environment.

Long-term horizons are essential as many climate-related health impacts unfold gradually over decades, while acute shocks may occur intermittently and with increasing intensity. A robust framework integrates both short-term volatility and long-term structural change. Long-term climate impacts also raise questions about the choice of discount rates, as traditional financial discounting may hide the significance of health impacts that materialize over multi-decade horizons.[32]

Climate-related risks interact with broader economic, political, and social systems, creating feedback loops and cross-sector dependencies. As scientific understanding, global policy environments, and technological pathways evolve, actuaries will typically want to revisit their climate scenarios periodically. This iterative approach ensures that climate scenario analysis remains aligned with emerging evidence and integrates **systems thinking**. It is also important to note that climate change is only one of several structural forces shaping future mortality and morbidity. Medical innovation (such as the adoption of GLP-1 or mRNA-based therapies[33]), demographic transitions, lifestyle trends, and the evolution of health care systems introduce additional long-term uncertainties alongside climate-related risks, but those fall outside the scope of this report.

1.6.2 COMBINING ACTUARIAL SCIENCE WITH CLIMATE SCIENCE

An integrated framework involves the systematic incorporation of climate science into actuarial analysis. Developing meaningful climate-related scenarios can require actuaries to become more climate-literate and engage in more interdisciplinary collaboration. Actuaries increasingly work alongside climate scientists, epidemiologists, health economists, and other experts to ensure that scenario assumptions reflect both physical climate science and the socioeconomic context in which health impacts unfold. This interdisciplinary approach is essential given the complexity and uncertainty inherent in climate-health interactions. In this context, important sources of information notably include the reports of the United Nations' Intergovernmental Panel on Climate Change (IPCC) and the climate scenarios from the Network for Greening the Financial Sector (NGFS). Given that L&H impacts can vary markedly across alternative climate and socioeconomic trajectories, relying on established scenario frameworks (such as those developed by the IPCC and the NGFS, despite their current limitations around the integration of potential tipping points[34]) can help ensure that actuarial analyses reflect a broad spectrum of plausible futures.

To translate climate projections into biometric impacts, modeling may follow either a bottom-up, peril-specific approach or a broader top-down assessment of aggregated climate-related impacts, depending on the model's purpose and the availability of suitable data. This may involve, for instance, linking projected changes in temperature, air quality, vector ecology, or extreme weather events to established epidemiological relationships. For example, temperature and mortality curves can be combined with projected heat wave frequency to estimate future heat-related mortality burdens. Similar approaches can be applied to wildfire smoke, flooding, and vector-borne diseases.

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[32] Social Discounting - Application to the Risk Management of Climate Change, SOA Research Institute (Gutterman, 2020), https://www.soa.org/globalassets/assets/files/resources/research-report/2020/social-discounting-climate-change.pdf

[33] GLP-1 (glucagon-like peptide-1) is a natural gut hormone that regulates appetite and blood sugar; an mRNA is a vaccine that teaches cells how to make a protein. https://medlineplus.gov/genetics/understanding/therapy/mrnavaccines/

[34] The Emperor's New Climate Scenarios, Institute & Faculty of Actuaries / University of Exeter (Trust et al., 2023), https://actuaries.org.uk/media/5d1j5tud/the-emperor-s-new-climate-scenarios.pdf

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1.6.3 DECISION-MAKING UNDER DEEP UNCERTAINTY

Given the deep uncertainty surrounding future climate trajectories and their potential L&H impacts, attributing likelihoods and severities to physical and transition risk developments is a particularly difficult task. Decision-making may, therefore, rely on methods that apply across a wide range of plausible futures. Scenario analysis is a key tool in this context. Exploratory modeling approaches, such as stress testing, sensitivity analysis, and science-informed expert judgment, can help identify potential tail risks and assess the resilience of insurance portfolios under various plausible conditions. These methods support ERM by highlighting vulnerabilities, informing strategic planning, and guiding the development of adaptation strategies.

Actuaries have a central role in integrating climate insights into insurance models and decision-making. This includes adjusting baseline mortality and morbidity assumptions, developing scenario-based stress tests, and evaluating implications for pricing, reserving, and capital management. A coherent framework connects climate hazards to exposure and vulnerability, health impacts and, ultimately, insurance outcomes, while allowing for potential feedback effects from adaptation measures, socioeconomic change, and technological evolution.

1.6.4 EMBEDDING CLIMATE RISK IN ENTERPRISE GOVERNANCE

Climate-related L&H risks expose several governance vulnerabilities familiar to those involved in performing Own Risk and Solvency Assessments (ORSA).[35] A key challenge is the risk of incompleteness, since predefined risk models can only address 'known unknowns' and often focus on reporting past events rather than conducting genuinely forward-looking assessments. At the same time, insurers face the risk of unnecessary complexity if they devote excessive attention to an ever-expanding list of risks regardless of their actual materiality. There is also a risk that scenario analysis remains mostly a risk-reporting exercise and remains insufficiently connected to actual business decisions. Together, these governance risks underscore the importance of technically robust climate-related L&H assessments that are meaningfully embedded in strategic and operational decision-making across pricing, reserving, capital management, and long-term business planning.

1.6.5 COMMUNICATING UNCERTAINTY

Policymakers, regulators, supervisors, boards, rating agencies, investors, clients and other insurance stakeholders increasingly expect insurers to articulate how climate-related risks may affect long-term financial performance or the future availability and cost of insurance. Clear communication of uncertainty, acknowledging what is known, what is unknown, and how assumptions may evolve, can support maintaining transparency and informed decision-making. Effective communication may also require going beyond single-point estimates to include the variance or distribution of possible L&H effects, offering stakeholders a more transparent understanding of the uncertainty around projected climate-related impacts.

[35] Deriving Value from ORSA - Board Perspective, International Actuarial Association (2015), https://actuaries.org/app/uploads/2025/04/PublishCopy_DerivingValuefromORSA_BoardPerspective_March2015Final.pdf

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Section 2 Qualitative Analysis

This section examines how climate hazards translate into concrete mortality and morbidity impacts. It reviews the major climate perils relevant to L&H insurance (heat waves, drought, wildfires, floods, severe storms, and sea-level rise) and describes the main pathways through which they can influence health outcomes, also highlighting the population groups and the regions that are most at risk. It also explains the common transmission channels across hazards, such as air quality degradation, vector-borne diseases, mental health impacts, and health system strain, and considers how risks can compound when multiple hazards interact. It concludes with a discussion of adaptation and risk mitigation measures that can moderate these impacts.

2.1 MACRO-LEVEL TRENDS IN CLIMATE-RELATED HEALTH RISK

With global average temperatures having risen by approximately 1.5°C / 2.7°F above pre-industrial levels by 2024, climate change is emerging as a significant threat to human health in the 21st century. Recent global estimates found that heat-related illnesses now contribute to more than 540,000 deaths per year, representing an increase of around 63% since the 1990s and around 0.9% of all deaths globally recorded that year, while hospitals and health facilities face a 41% higher risk of damage from climate-related extreme weather than in 1990.[36] These trends indicate that climate change is not only a hypothetical long-term driver of excess mortality and morbidity, but that it is already reshaping the environment in which health systems and insurers operate.

According to a study by the World Economic Forum, by 2050 climate change may cause an additional 14.5 million deaths worldwide, i.e., around 560,000 deaths per year on average. Climate-induced impacts will account for an additional USD $1.1 trillion in extra costs to health care systems, creating a significant additional burden on already strained medical infrastructures and resources. These projections underscore the scale of future additional climate-related pressures on global health systems and illustrate why some life and health insurers are already incorporating forward-looking scenario analysis into their long-term strategy and risk management.[37]

[36] COP30 SPECIAL REPORT ON HEALTH AND CLIMATE CHANGE, page 1, COP30 Brazil (2025), https://cdn.who.int/media/docs/default-source/climate-change/cop30-special-report-on-health-and-climate-change.pdf

[37] Quantifying the Impact of Climate Change on Human Health, page 4, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

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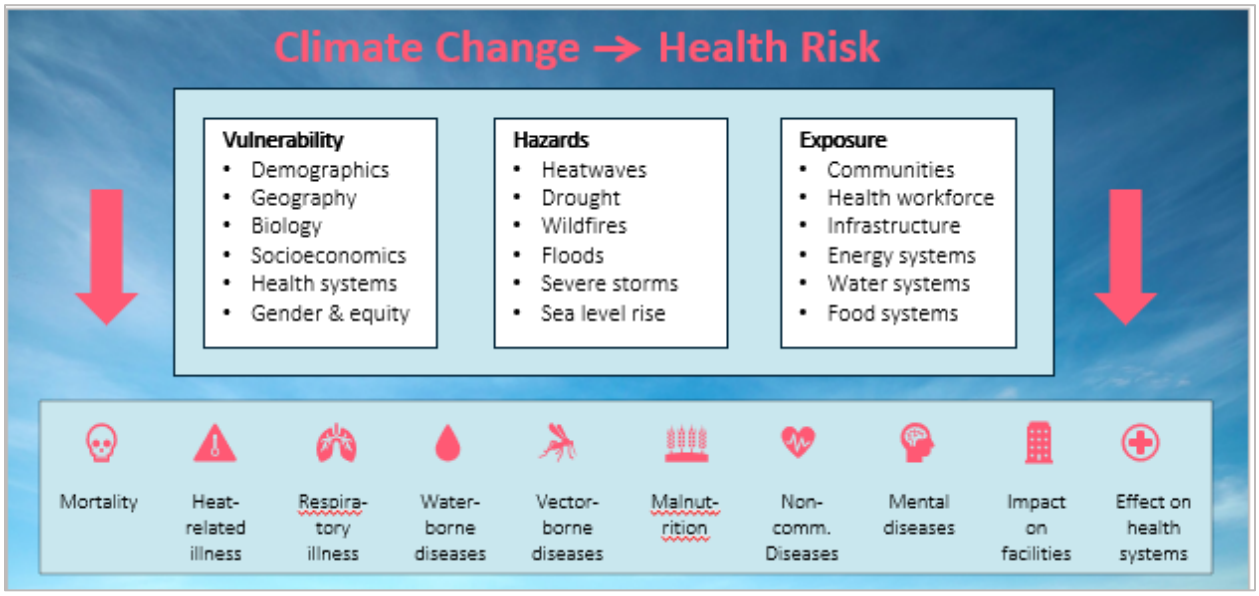
figure 2.1 illustrates the many pathways through which climate change affects human life and health. It shows how the impacts from climate-related hazards combine with preexisting exposure and vulnerability factors to cause both direct and indirect effects on health outcomes and health systems.

Figure 2.1
OVERVIEW OF CLIMATE-SENSITIVE HEALTH RISKS, EXPOSURE PATHWAYS AND VULNERABILITY FACTORS



Source: Adapted by the authors from World Health Organization[38]

Table 2.1 highlights the scale of climate-related excess mortality that could emerge over the coming decades under different global emissions pathways, according to projections from Swiss Re, a global reinsurer. The analysis, drawing on IPCC scenarios, shows that mortality outcomes diverge substantially depending on the speed and effectiveness of global mitigation efforts. Under lower-emissions pathways, excess mortality remains limited, whereas under higher-emissions trajectories, the projected mortality increases materially by mid-century and accelerates toward 2100.

Table 2.1
EXPECTED GLOBAL EXCESS MORTALITY BY CLIMATE SCENARIO

IPCC Scenario	Description	Temperature Increase 2100	Global Excess Mortality 2050	Global Excess Mortality 2100
RCP 2.6	Rapid emissions cuts, net-zero 2050 (highly optimistic)	Under +2ºC	Minimal	0.75% annually
RCP 4.5	Emissions peak mid-century, then decline (central scenario)	Around +2.5ºC	0.75% annually	1% annually
RCP 8.5	Rising emissions all century (high-end stress-test)	Over +3.5ºC	1.5% annually	5% annually

Source: Adapted from Swiss Re [39]

[38] World Health Organization, Climate Change, WHO Newsroom: Fact Sheets (October 12, 2023), https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

[39] The risk of a lifetime: mapping the impact of climate change on life and health risks, page 19, Swiss Re (Meier et al., 2023), https://www.swissre.com/dam/jcr:b851c59c-d3e0-4f87-817c-62691b985bc5/2022-11-sri-expertise-publication-impact-of-climate-change-life-health-risks.pdf

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Unlike mortality, there is no comparable set of authoritative RCP-specific projections that quantify how total health care expenditures will evolve solely as a result of climate change. Health system costs are shaped by a wide range of factors, including local demographics, medical technology, coverage structures, pricing dynamics, and regulation, which makes isolating the climate-attributable component analytically challenging. Many published cost estimates also combine health-system expenditures with broader economic impacts, such as productivity losses, complicating the extraction of stand-alone health care cost impacts. Nevertheless, emerging research provides early indications of the potential scale of climate-related cost pressures. For example, an analysis by Allianz suggests that the rising frequency and severity of heat waves alone could increase per-capita hospitalization costs in Europe by an average of 4.9% by 2035 in a medium-impact scenario.[40] Recent analysis in Switzerland also demonstrates that heat-related hospital admissions already create material annual costs and are projected to increase by a factor of 2.5 to 5 by 2060 under high-emission scenarios.[41]

Exposure and vulnerability factors reinforce and amplify climate-driven disparities in mortality and morbidity. Climate-related health impacts are distributed unevenly across populations, with low-income and marginalized communities being more exposed to extreme weather events, food and water shortages, and health hazards.[42] Vulnerable communities often face additional challenges to accessing health services, such as living farther from health services and facilities, relying on emergency staff and vehicles that may not be available during extreme weather circumstances, and having to pay higher out-of-pocket costs as a proportion of their available income for access to medical supplies and treatment. They also generally have less access to climate adaptation measures. These differentials in access to high-quality care can perpetuate the disparities in health outcomes, widening the gap between the levels of mortality and morbidity experienced by socioeconomically disadvantaged populations and more privileged groups, both in general and in relation to the outcomes of climate disasters.[43]

2.2 HOW INDIVIDUAL CLIMATE HAZARDS AFFECT HUMAN HEALTH

Climate-related impacts on human life and health arise through diverse mechanisms, and their significance varies across geographies, populations, and time horizons. While broad global trends illustrate the scale of the challenge, understanding how climate change affects mortality, morbidity and longevity in practice requires examining the specific hazards that drive these outcomes. Each major climate peril presents its own set of pathways, uncertainties, and compounding factors, and together they form the basis for how climate risks manifest within life and health insurance portfolios.

[40] Climate change and the double impact of aging, page 15, Allianz (Grimm et al., 2024), https://www.allianz-trade.com/content/dam/onemarketing/aztrade/allianz-trade_com/en_gl/erd/publications/pdf/2024-06-13-Heath-climate-change-AZT.pdf

[41] Quantifying the financial burden of heat-related hospital admissions in Switzerland under a changing climate: A scalable analytical framework, BMC Global and Public Health (Vaghefi et al., May 2026). https://doi.org/10.1186/s44263-026-00275-w

[42] CLIMATE CHANGE: What does the future hold for health and life insurance?, pages 5, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[43] Quantifying the Impact of Climate Change on Human Health, page 10, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

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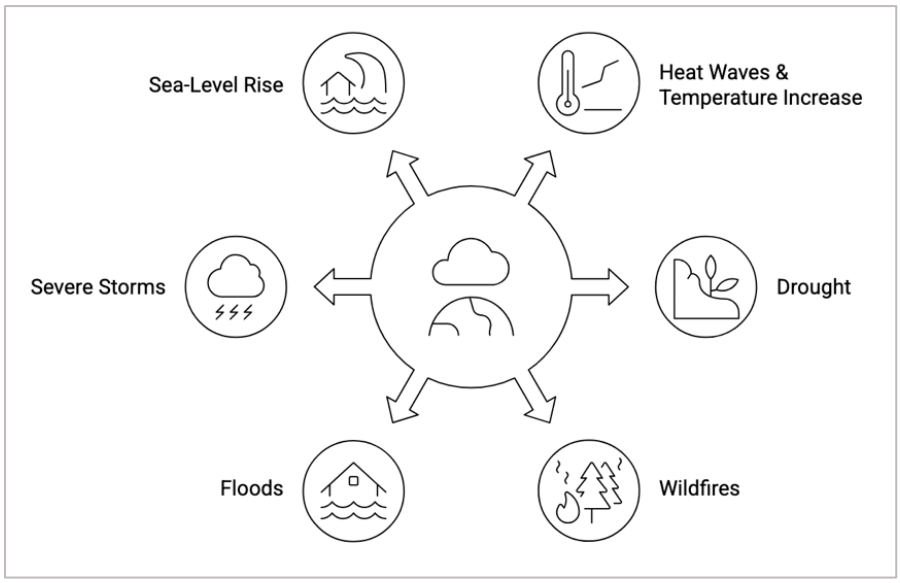
Figure 2.2
CLIMATE HAZARDS



2.2.1 HEAT WAVES AND TEMPERATURE INCREASE

Direct impacts: Evidence consistently links higher temperatures to adverse health outcomes, though impacts vary by region, population, and disease profile. Heat stress notably strains the heart, worsening existing conditions and raising risks of heat exhaustion, stroke, and mortality. With global warming and aging populations, heat-related cardiovascular risks are expected to further increase.[44] Importantly, the health burden of heat waves is driven not only by peak daytime temperatures but also by how little temperatures drop at night, the duration of the heat event, and the level of humidity. High nighttime temperatures prevent the body from recovering, prolonged multi-day heat waves compound physiological stress, and high humidity reduces the effectiveness of sweating, making it harder for the body to cool itself.

The 1995 heat wave in the U.S. Midwest notably led to over 739 heat-related deaths in Chicago over a period of five days, with most of the victims found among the elderly, poor residents of the city.[45] The 2003 European heat wave is another key example of how harmful extreme heat can be. Paris, France, reported 39.5°C / 103.1°F temperatures that summer, and an excess death rate of 141%, with a 250% increase in out-of-hospital cardiac arrests.[46] Overall, the July-August 2003 heat wave in Europe led to an estimated death toll of over 70,000 people, mostly among people over 80. The summer 2021 heat dome in the U.S. and Canada provides yet another striking example. In late June 2021, an unprecedented heat wave struck the Pacific Northwest region of North America. This heat dome broke all-time maximum temperature records across the region, with Canada reporting a new national record temperature of 49.6°C / 121.3°F in Lytton, British Columbia (the same town was engulfed by a wildfire the following

[44] Heat exposure and cardiovascular health outcomes: a systematic review and meta-analysis, The Lancet (Liu et al., 2022), https://research.monash.edu/en/publications/heat-exposure-and-cardiovascular-health-outcomes-a-systematic-rev/

[45] Heat Wave: A Social Autopsy of Disaster in Chicago, Chicago University Press (Klinenberg, 2002)

[46] The risk of a lifetime: mapping the impact of climate change on life and health risks, page 9, Swiss Re Institute (Meier et al., 2023), https://www.swissre.com/dam/jcr:b851c59c-d3e0-4f87-817c-62691b985bc5/2022-11-sri-expertise-publication-impact-of-climate-change-life-health-risks.pdf

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day). Government sources confirm that 619 people lost their lives due to heat in the summer of 2021, making it the deadliest extreme weather event in Canada's history.[47]

Large-scale empirical analyses show that mortality risk increases at both very low and very high temperatures, forming what is generally described as a U-shaped relationship between temperature and mortality.[48] Historically, temperature-related mortality has been mostly dominated by cold-related deaths but, with global warming, the gap has started to narrow with heat-related deaths.[49] Climatological temperature increases also result in milder winter temperatures, thus improving the cold-related mortality during the winter (notably for the homeless or those living in severely inadequate housing) and, hence, the net impact of higher temperatures on mortality and life expectancies can differ by geographical location. This has notably been observed in scenario studies relating to temperature trends and mortality trends in the UK.[50] Globally and throughout this century, deaths caused by extreme cold are anticipated to decrease in some temperate regions, while heat-related mortality is expected to rise globally. However, the magnitude and direction of cold-related changes vary by region, and the net effect is not uniform across all climate zones.[51] In a scenario without future demographic changes and adaptation to a changing environment, the U.S. Global Change Research Program found a net increase in projected future mortality, with the increased mortality from heat being higher than the offset through reductions in cold-related mortality.[52] Although the relationship between temperature and mortality is often described as U-shaped, its asymmetry—where cold-related mortality rises gradually, while heat-related mortality increases sharply beyond a threshold—suggests that, in many locations, it is more accurately characterized as an "inverse-J" shape, as illustrated in figures 2.3 and 2.4.

[47] CLIMATE CHANGE: What does the future hold for health and life insurance?, page 16, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[48] Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits, The Quarterly Journal of Economics (Carleton et al., 2022), https://academic.oup.com/qje/article/137/4/2037/6571943

[49] Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019, The Lancet (Zhao et al., 2021), www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00081-4/fulltext

[50] Mortality Insights from GAD, UK Government Actuary's Department (2023), https://www.gov.uk/government/publications/mortality-insights-from-gad-april-2023/mortality-insights-from-gad-april-2023

[51] Projections of temperature-related excess mortality under climate change scenarios, The Lancet (Gasparrini et al., 2017), https://pubmed.ncbi.nlm.nih.gov/29276803/

[52] The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, Ch. 2: Temperature-Related Death and Illness, U.S. Global Change Research Program (Sarofim et al., 2016), https://www.researchgate.net/publication/299864019_Ch_2_Temperature-Related_Death_and_Illness

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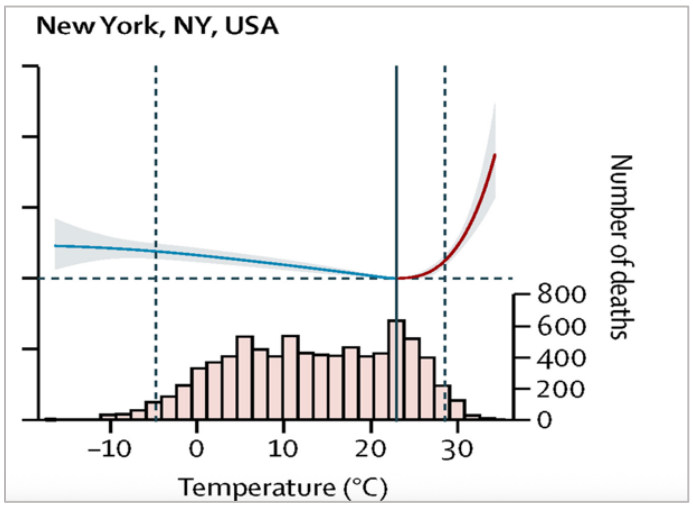
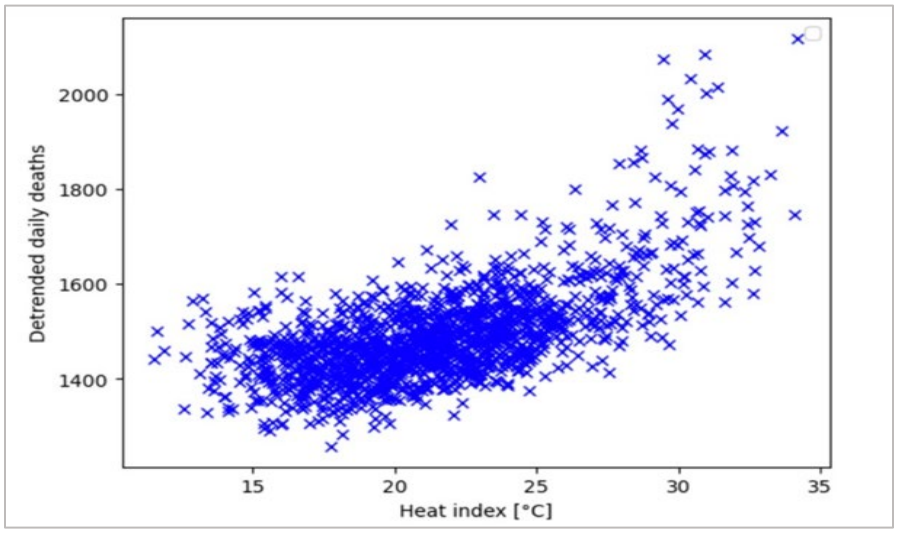
Figure 2.3
OVERALL CUMULATIVE EXPOSURE-RESPONSE CURVE FOR NEW YORK CITY, USA (1985—2006)



Source: National Library of Medicine[53] (reproduced with permission from the copyright holder)

Figure 2.4
EVOLUTION OF THE NUMBER OF DAILY EXCESS DEATHS IN THE SUMMER MONTHS, FRANCE (1970—1990)



Source: CNP assurances & DIALog chair[54] (reproduced with permission from the copyright holder)

Similar to mortality outcomes, there is a U-shaped or J-shaped association between temperature and morbidity. Exposure to extreme cold leads to higher rates of respiratory-related health care utilization, with delayed impacts that persist for several days. In contrast, exposure to extreme heat results in increased visits and admissions for circulatory, endocrine, nephrology, and trauma-related conditions, with the most pronounced effects observed

[53] Mortality risk attributable to high and low ambient temperature: a multicountry observational study, National Library of Medicine (Gasparrini et al., 2015), https://pubmed.ncbi.nlm.nih.gov/26003380/

[54] Risque climatique et impact en assurance (in French), page 21, CNP assurances & DIALog chair (Garrido, Anani et al., 2024), https://www.cnp.fr/cnp/content/download/11584/file/Livre-vert-Risque-climatique-et-impact-en-assurance-juin2024.pdf

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among older adults.[55] Excess heat notably causes stress to the renal system, which is sensitive to dehydration. A higher outdoor temperature increases the body's water consumption. If there is no adjustment in water intake, this can be detrimental to health, especially to the kidneys.[56] Extreme heat can also fuel mood and anxiety disorders, and lead to suicide, interpersonal violence, and aggression.[57]

However, milder winters are not an unqualified benefit for morbidity. Although they may reduce cold-related mortality stress, they also disrupt natural seasonal defense cycles that normally suppress insect and pest populations. Warmer winters enable mosquitoes, ticks, and other vectors to survive in greater numbers and expand into new regions, increasing the incidence of vector-borne diseases such as West Nile virus, Lyme disease, and malaria. They can also favor fungal growth and allergen persistence, exacerbating respiratory conditions.

Importantly, climate change does not only imply a simple upward shift in average temperatures, but it also increases weather volatility. This means that even as winters become milder on average, severe cold spells can still occur. Recent events, such as the January 2026 cold outbreak in the United States, illustrate how sudden Arctic air intrusions can strain electrical grids, disrupt heating systems, and create health risks for exposed populations.

Indirect impacts: Heat-related health risks extend far beyond the direct physiological effects from acute heat waves and include a wide range of indirect pathways that influence long-term mortality, morbidity, and longevity. Elevated temperatures and recurring heat waves year after year can increase the baseline mortality and morbidity rates and negatively impact life expectancies. Prolonged exposure to elevated temperatures can contribute to cumulative physiological deterioration and accelerated biological aging, with chronic heat stress impairing cardiovascular, renal, and metabolic function over time. For instance, large-scale climate patterns, such as El Niño–Southern Oscillation (ENSO), can intensify heat and humidity over extended periods. These conditions have been linked to persistent increases in cardiovascular mortality and to multi-year slowdowns in mortality improvement. The effects arise from both direct thermal stress and indirect mechanisms such as degraded air quality.[58]

The effects of increased temperatures are often intensified by psychosocial stressors associated with hot environments, including disrupted sleep, reduced outdoor physical activity, and chronic discomfort. Persistent heat exposure also affects mental health, with evidence from the IPCC,[59] World Health Organization,[60] and multiple peer-reviewed studies linking high temperatures to increased anxiety, irritability, cognitive impairment, and higher rates of emergency psychiatric visits, particularly among individuals with pre-existing mental health conditions.

The risks to human life and health from rising temperatures are further compounded by interacting environmental and societal factors. Demographic changes (including aging populations, urbanization, and migration into hotter regions) increase the number of people exposed and vulnerable to heat. At the same time, biodiversity loss and land-use change reduce natural cooling, disrupt ecological controls on disease vectors, and weaken food and water

[55] Effects of extreme climate events on the morbidity of a sample of medical scheme lives in South Africa, South African Actuarial Journal (Smith et al., 2025), https://www.actuarialsociety.org.za/wp-content/uploads/2025/11/2025-ASSA-KotzenSmithCo-FIN.pdf

[56] Actuarial Insights on Heat-Related Mortality and Morbidity, The Actuary Magazine (Hogekamp, 2024), https://www.theactuarymagazine.org/actuarial-insights-on-heat-related-mortality-and-morbidity/

[57] Association Between Ambient Heat and Risk of Emergency Department Visits for Mental Health Among US Adults, JAMA Psychiatry (Nori-Sama et al., 2022), https://jamanetwork.com/journals/jamapsychiatry/fullarticle/2789481

[58] Climate Anomalies' Enduring Impacts on U.S. Health Landscape, SOA Research Institute (Xu et al., 2025), https://www.soa.org/globalassets/assets/files/resources/research-report/2025/2025-12-cc219-climate-anomalies.pdf

[59] IPCC Sixth Assessment Report, Chapter 7: Health, Wellbeing and the Changing Structure of Communities, IPCC (2022), https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-7/

[60] Fact Sheet - Climate Change and Health, WHO (2023), https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

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system resilience, further amplifying heat-related health risks. Strained health care systems, particularly during peak demand periods, can further exacerbate heat-related morbidity and mortality.

Food safety can deteriorate as temperatures rise. Warmer and more humid conditions facilitate bacterial and fungal contamination, increasing the risk of food-borne illnesses such as Salmonella or mycotoxin exposure. Human activities add further risks through pesticide residues and other pollutants entering the food chain. For example, the concentration of toxic mercury in fish can increase as water temperatures rise, posing additional long-term health hazards.[61]

Extreme heat imposes substantial economic and labor market impacts. According to the International Labor Organization, at least 2.4 billion workers are exposed to excessive heat, resulting in an estimated 22.8 million injuries and 18,970 deaths annually,[62] and generating global economic losses exceeding USD $361 billion.[63] Heat exposure also significantly raises workplace injury risks across sectors, with higher temperatures linked to more accidents, reduced productivity, and long-term health impacts (such as kidney disease). Outdoor and manual labor sectors are especially vulnerable and face higher workplace injury rates, including from indirect causes such as falls or cuts, due to impaired physical and cognitive function. This can be seen as preventable bodily injuries and employers' failure to mitigate heat risks may trigger casualty insurance claims or, in some cases, management liability (D&O) insurance.[64] Vulnerability also depends on the measures taken by governments to protect workers. For example, in 2023 Spain introduced a ban on certain outdoor work if the State Meteorological Agency issues an alert for high temperatures and when employers cannot guarantee workers protection.[65]

Most vulnerable populations: Heat-related health risks are highly uneven across populations. Older adults, children, pregnant women, and individuals with chronic cardiovascular, respiratory, or renal conditions face the greatest physiological vulnerability as their bodies are less able to regulate temperature or respond to heat stress. Urban residents, particularly in dense neighborhoods with limited green space, are disproportionately affected by the urban heat island effect (where urban areas are significantly warmer than surrounding rural areas due to buildings, roads, and other infrastructure absorbing and retaining heat, and due to a lack of vegetation providing cooling). This effect is most pronounced at night and during calm weather, increasing energy demand, air pollution, and heat-related illnesses. Low-income households, individuals without access to air conditioning, and those living in poorly insulated or overcrowded housing experience the highest exposure to indoor heat. Agricultural and outdoor workers, athletes, and the homeless face prolonged exposure to extreme temperatures and often have limited ability to reduce heat stress. For instance, in the U.S., the construction industry accounts for 37% of occupational heat-related mortality nationwide, with construction workers at 13-times-higher risk of heat-related fatality compared to workers in other industries.[66]

[61] The Relevance of Climate Change for Life Insurance, Part 1 – The Risk Manager's View, page 5, SCOR (Merk, 2022), https://www.scor.com/en/expert-views/relevance-climate-change-life-insurance

[62] Ensuring safety and health at work in a changing climate, International Labour Organization (Scott et al., 2024), https://www.ilo.org/sites/default/files/2024-07/ILO_SafeDay24_Report_r11.pdf

[63] Heat at work: Implications for safety and health, International Labour Organization (Flouris et al., 2024), https://www.ilo.org/sites/default/files/2024-07/ILO_OSH_Heatstress-R16.pdf

[64] European Heatwaves – Impact on Life Risks and Casualty Insurance, Moody's (2025), https://www.moodys.com/web/en/us/insights/physical-transition-risk/european-heatwaves-impact-on-life-risks-and-casualty-insurance.html

[65] Spain: High temperatures will mean employers must adopt preventive measures in order to protect employees, Garrigues (2023), https://www.garrigues.com/en_GB/new/spain-high-temperatures-will-mean-employers-must-adopt-preventive-measures-order-protect

[66] Assessing Heat Stress and Health among Construction Workers in a Changing Climate: A Review, International Journal of Environmental Research and Public Health (Acharya et al., 2018), https://www.mdpi.com/1660-4601/15/2/247

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Most exposed regions: Heat exposure is increasing across all world regions, but the greatest risks are concentrated in areas where rising temperatures combine with high humidity, rapid urbanization, or limited adaptive capacity. India, the Middle East, and parts of Southeast Asia are among the most exposed regions, with "wet bulb" temperatures (a combined measure of heat and humidity) increasingly approaching levels that challenge human survivability. In the U.S., the projected heat wave exposure is expected to surge between 168 billion and 535 billion person-days by 2050, with a concentration of the risk in the Eastern and Southwestern U.S.[67] Already hotter regions of the U.S. are more resilient to heat waves compared to more temperate regions, with heat-related mortality risk being higher in the U.S. Northeast and Midwest than in the South.[68] Likewise, the temperature thresholds leading to higher mortality have been shown to be significantly higher in Brazil than in France.[69]

On a more anecdotal basis, it is also worth noting that the populations of different countries self-report very heterogenous thresholds for the temperatures they consider warm, as illustrated for Europe in figure 2.5. Resilience to increasing temperatures is influenced by the degree of preparedness, including access to cooling. In many temperate regions, such as Canada and Northern Europe, many existing buildings were not designed for extreme heat and lack adequate air conditioning or ventilation, increasing the risk of dangerous indoor temperatures during prolonged heat events.

[67] Quantifying the Impact of Climate Change on Human Health, page 26, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

[68] The Relevance of Climate Change for Life Insurance, Part 1 – The Risk Manager's View, page 7, SCOR (Merk, 2022), https://www.scor.com/en/expert-views/relevance-climate-change-life-insurance

[69] Risque climatique et impact en assurance (in French), page 25, CNP assurances & DIALog chair (Garrido, Anani et al., 2024), https://www.cnp.fr/cnp/content/download/11584/file/Livre-vert-Risque-climatique-et-impact-en-assurance-juin2024.pdf

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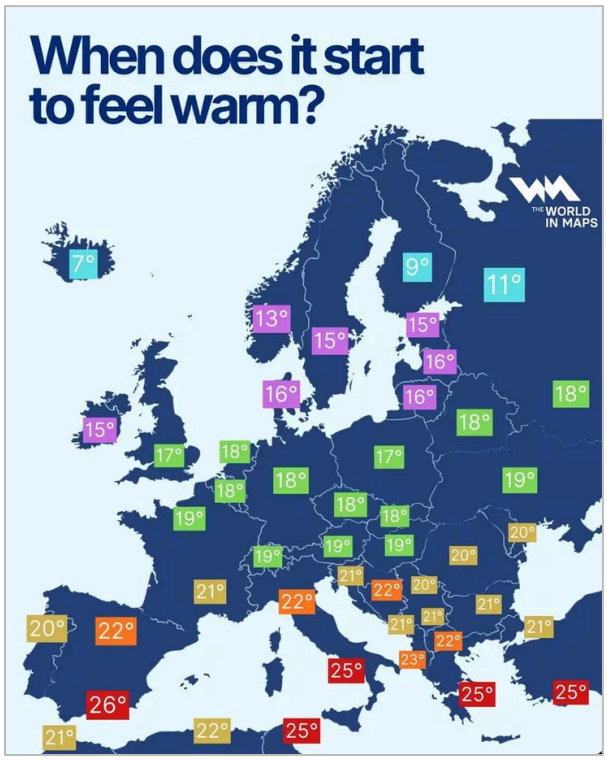
Figure 2.5
HOW EUROPE DEFINES “WARM WEATHER” DIFFERENTLY (TEMPERATURES IN DEGREES CELSIUS)



Source: The World In Maps[70] (reproduced with permission)

2.2.2 DROUGHT

Direct impacts: Droughts can directly affect human health by reducing the availability of safe water for drinking, cooking, and sanitation. Limited access to clean water increases the risk of dehydration and heightens the spread of water-borne diseases such as cholera or dysentery. Prolonged dry conditions also reduce crop yields and degrade soil quality, immediately threatening food availability for communities dependent on local agriculture. These direct impacts depend on the length of the drought and are most acute in low-income regions where water-treatment infrastructure, sanitation systems, and emergency response capacity are limited, and where households have fewer buffers to absorb sudden declines in food and water security.

Indirect impacts: Beyond these immediate effects, prolonged drought generates a wide range of longer-term health risks. Persistent food insecurity can lead to chronic malnutrition, stunted growth, and developmental challenges in children. Soil degradation, loss of livestock and declining agricultural productivity undermine livelihoods, increasing economic stress and contributing to mental health burdens such as anxiety and depression. Drought conditions can also increase the likelihood and severity of wildfires, further degrading air quality and exacerbating respiratory and cardiovascular risks. Drought and desertification can also drive population displacement as households migrate in search of water, food, or employment, placing additional strain on receiving communities and health systems. These indirect pathways often unfold over months or years, amplifying the cumulative health burden associated with

[70] How Europe Defines 'Warm Weather' Differently, The World In Maps (2026), https://theworldinmaps.co/article/how-europe-defines-warm-weather-differently

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prolonged water scarcity. Historical examples illustrate how such climate-related pressures can interact with broader socioeconomic and political stresses. For instance, the prolonged 2006–2010 drought in Syria contributed to large-scale migration from rural to urban areas and heightened social vulnerability in the years preceding the civil war, as noted by the IPCC.[71]

Most vulnerable populations: Children, older adults, people with disabilities, low-income households, and individuals whose livelihoods depend on farming are particularly vulnerable to drought-related health impacts. Farmers and agricultural laborers face heightened risks due to direct dependence on rainfall and soil conditions, while low-income households may struggle to secure adequate nutrition or safe water during extended dry periods.

Most exposed regions: Drought risk is projected to intensify in several regions over the coming decades. Western North America, the Mediterranean basin, southwestern South America, and western southern Africa are identified as areas where rising temperatures and shifting precipitation patterns are expected to increase the frequency, duration, and severity of drought episodes.[72]

2.2.3 WILDFIRES

Direct impacts: Wildfires pose immediate threats to human life and health through direct exposure to flames and smoke. These hazards can cause burns, asphyxiation, traumatic injuries, and fatalities, particularly when fires spread rapidly or evacuation routes are limited. Firefighting personnel face especially high risks due to extreme heat, falling debris, and unpredictable fire behavior. In addition, wildfires can destroy homes, critical infrastructure, and transportation networks, creating acute dangers for individuals attempting to evacuate or shelter in place. Wildfire risks are especially important when they are accompanied by high winds, high temperatures, and dry conditions, exacerbated by poor forest/tree management, as well as increasing residential construction close to forests, and where health care facilities are at risk.

Indirect impacts: The observed increase in the frequency and intensity of wildfires threatens human health, not only through direct fire destruction but also through the release of toxic air pollutants. Wildfires generate substantial amounts of fine particulate matter, notably $PM_{2.5}$ (with diameters of less than 2.5 micrometers in size), which is of greatest concern due to its ability to penetrate deep into the lungs and enter the bloodstream.[73] Exposure to $PM_{2.5}$ is a known cause of mortality and cardiovascular disease and is linked to the onset and worsening of respiratory conditions (including asthma), as well as mental and behavioral disorders. As climate change exacerbates wildfire risk, $PM_{2.5}$ emissions from wildfires have surged, contributing nearly half of the national annual average $PM_{2.5}$ across the United States in recent years and reversing air quality improvements in several regions.[74] Large wildfires can degrade air quality over thousands of square kilometers and sometimes far from their point of origin, as illustrated by the 2023 Canadian wildfires, which produced the poorest air quality ever recorded in Washington, D.C. and triggered air quality alerts across multiple U.S. states.[75]

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[71] IPCC Sixth Assessment Report, Chapter 16, IPCC (2022), https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-16/

[72] Quantifying the Impact of Climate Change on Human Health, page 22, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

[73] The Impact of Wildfire-Related and Environmental Air Pollution on Morbidity, SOA Research Institute (Yi et al., 2025), https://www.soa.org/resources/research-reports/2025/wildfireimpact-usinsurers-morbidity/

[74] Anthropogenic climate change contributes to wildfire particulate matter and related mortality in the United States, Nature (Law et al., 2025), https://www.nature.com/articles/s43247-025-02314-0

[75] Wildfires in Canada led to dangerous air quality in parts of the US for the first time, CNN (Choi & Shveda, 2025), https://edition.cnn.com/2023/09/17/us/air-quality-wildfire-pollution-allergy-dg/index.html

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Beyond respiratory and cardiovascular impacts, wildfires can cause food insecurity, displacement, and loss of livelihoods, driving stress, anxiety, and other mental health challenges. The destruction of forests also impairs critical ecosystem services such as air purification and temperature moderation, provisioning services such as clean water, and cultural or recreational benefits. The loss of these regulating services can exacerbate heat exposure, worsen air quality, disrupt local water systems, and reduce opportunities for physical and psychological restoration, thereby amplifying the long-term health burden associated with wildfire events.

Most vulnerable populations: Firefighters, low-income households, older adults, people with disabilities and pre-existing cardiovascular and pulmonary conditions, hospitalized patients, and communities living in forested areas (including indigenous tribes) are particularly vulnerable to wildfire-related health impacts. These groups may face greater exposure to smoke, reduced ability to evacuate, limited access to health care, or heightened sensitivity to air quality degradation. Structural inequities, geographic isolation, and dependence on local natural resources can further amplify vulnerability.

Most exposed regions: Wildfire risk is projected to increase in several regions over the coming decades. Western United States and Canada, the Mediterranean basin, the Amazon, and Australia are among the most exposed areas, reflecting a combination of rising temperatures, prolonged drought conditions, and forested landscapes.[76] These regions are, therefore, expected to face growing health burdens associated with both direct fire hazards and widespread smoke exposure. In some places, the risk is further amplified by high concentrations of homes and infrastructure in fire-prone zones. In California, for instance, the expansion of the wildland–urban interface and the vulnerability of many buildings to ember ignition significantly heighten exposure and overall vulnerability.

2.2.4 FLOODS

Direct impacts: Floods and heavy rainfall events pose immediate threats to human health through drowning, hypothermia, and physical injuries caused by fast-moving water, debris, or damaged infrastructure such as exposed live electric wires. These events can also impede access to medical care by blocking roads, isolating communities, restricting the mobility of health care workers, and damaging emergency vehicles, thereby delaying treatment for both acute flood-related injuries and other unrelated medical needs. As a result, flooding can simultaneously increase the demand for health care services and reduce the capacity of health systems to respond, amplifying short-term mortality and morbidity risks. It is also important to note that exposure patterns differ across coastal, riverine, and flash floods, which occur in distinct geographic and hydrological settings and, therefore, affect different populations and regions.

Indirect impacts: Floods also generate a wide range of secondary health risks that extend well beyond the immediate event window. Contaminated floodwaters can carry sewage, industrial waste, agricultural runoff, and other hazardous materials, increasing the likelihood of gastrointestinal illness and other infections. Standing water left behind after flooding creates favorable conditions for mosquitoes, heightening the risk of vector-borne diseases. Residual moisture in flooded homes and buildings can promote mold growth, and the resulting airborne spores may trigger respiratory problems ranging from allergic reactions to more serious infections, particularly among individuals with pre-existing conditions.[77] In addition, the loss of homes, livelihoods, and community infrastructure can have lasting effects on mental health, with many affected individuals experiencing traumatic stress, anxiety, or

[76] Quantifying the Impact of Climate Change on Human Health, page 31, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

[77] The Relevance of Climate Change for Life Insurance, Part 2 – The Medical Director's View, page 6, SCOR (Bagul & Merk, 2022), https://www.scor.com/en/expert-views/relevance-climate-change-life-insurance-part-2

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depression long after the physical hazards have receded.[78] Property insurance coverage gaps often compel households to return to damaged, devalued properties because affordable alternatives are unavailable, subjecting them to chronic psychological distress and increased risk of physical injuries.

Most vulnerable populations: Children, older adults, people with disabilities or other pre-existing conditions, and individuals without stable housing (i.e., people experiencing homelessness or living in temporary, overcrowded, or structurally unsafe accommodations) are particularly vulnerable during flood events. These groups may have limited ability to evacuate quickly, secure safe shelter, or access essential medical care, increasing the likelihood of both acute harm and longer-term health complications. Physical mobility constraints, reliance on medical equipment, and reduced access to transportation further heighten vulnerability, while unstable housing conditions can expose individuals to prolonged contact with contaminated water, mold, and other post-flood hazards.

Most exposed regions: Assessments of climate-related health vulnerability identify South and South-East Asia, northern South America, and parts of Middle Africa as among the most exposed areas to recurrent and severe flooding in the coming decades, reflecting a combination of rising physical hazard levels, dense populations, and constrained adaptive capacity.[79] Areas at high flooding risk also include mountain regions facing deglaciation, while major coastal cities like Houston and New Orleans face heightened exposure from hurricane-driven storm surges.[80]

2.2.5 SEVERE STORMS

Direct impacts: Tropical cyclones (including hurricanes and typhoons), winter storms, and severe convective storms (such as thunderstorms, hailstorms and tornadoes) pose immediate threats to human life and health. High winds, storm surge (i.e., a storm-driven rise of seawater that floods coastal areas), and intense precipitation can cause deaths and injuries through collapsing infrastructure (such as bridges, for instance), airborne debris, flooding and, in the case of convective storms, increasingly large and damaging hail. Tropical storms, hurricanes, and major winter storms typically affect large geographic areas and are generally foreseeable several days in advance. Severe convective storms, by contrast, tend to be highly localized and develop rapidly, and while meteorologists can forecast the general weather conditions, which are conducive to severe convective storm formation, the precise timing, location, and severity of individual storm cells remain difficult to predict.

Indirect impacts: The health burden of severe storms extends well beyond the immediate event window and is shaped by both environmental and social factors. True mortality tolls exceed the official death counts, which typically record only immediate fatalities from drowning or trauma.[81] Excess deaths often occur weeks or months later, uncounted in official statistics. Severe storms can also trigger cascading health crises. Extended power outages, contaminated water supplies, blocked roads, and food shortages can create hazardous living conditions and impede access to medical care. When hospitals lose power, treatments like dialysis and chemotherapy are interrupted, and vulnerable patients with chronic conditions face heightened risks. Disruptions to routine and preventive care can also exacerbate chronic illnesses.

Post-storm risks also include injuries during cleanup, infections linked to unsafe or crowded living conditions, contaminated water, and respiratory issues arising from mold growth in water-damaged homes. Analyses of recent

[78] Impact of repeat flooding on mental health and health-related quality of life: a cross-sectional analysis of the English National Study of Flooding and Health, British Medical Journal (French et al., 2019)

[79] Quantifying the Impact of Climate Change on Human Health, page 19, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

[80] Flood Risk, International Actuarial Association (Gutterman et al., 2019), https://actuaries.org/app/uploads/2025/04/REWG_Flood_Risk.pdf

[81] The Hidden Devastation of Hurricanes, The New Yorker (Dalton, 2025), https://www.newyorker.com/news/the-lede/the-hidden-devastation-of-hurricanes

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U.S. hurricanes show that carbon monoxide poisoning consistently increases in the weeks following major storms, largely due to the use of small fuel-powered generators during prolonged power outages (which can produce dangerous concentrations of carbon monoxide when operated indoors or near enclosed spaces).[82] In some cases, storms can lead to direct air contamination, such as the release of pollutants from industrial facilities during Hurricane Harvey in 2017.[83] Displacement and stressful living environments also contribute to adverse mental health outcomes, including depression, anxiety, PTSD, and substance abuse. Long-term psychological effects were notably documented among survivors of Hurricane Katrina, which devastated New Orleans in 2005.[84] Severe storms can also hinder economic development and productivity, reducing resources available for education, health systems, and climate adaptation.

Most vulnerable populations: Children, older adults, people with disabilities, individuals with chronic illnesses, and those without resilient housing or reliable transportation face heightened risks during severe storms. These groups may struggle to evacuate quickly, secure safe shelter, or access essential medical care, increasing the likelihood of both acute harm and longer-term health complications. Evidence from recent hurricane events shows that secondary impacts are highly uneven across populations. Older adults, low-income households, individuals with chronic conditions, and those with limited mobility or transportation face higher risks during and after storms.[85] These groups are more likely to experience disruptions in access to care, prolonged exposure to unsafe living conditions, and greater mental health burdens.

Most exposed regions: The frequency and intensity of severe storms are projected to increase in several regions over the coming decades. North America, Central America and the Caribbean, as well as Asia for tropical cyclones, are identified as among the most exposed areas, reflecting a combination of rising hazard levels and dense coastal populations.[86]

2.2.6 SEA-LEVEL RISE

Direct impacts: Sea-level rise does not typically cause direct health impacts on its own as it is a gradual process. However, by raising baseline water levels, it intensifies the effects of floods and storms, allowing storm surges and high tides to reach farther inland and cause greater damage. Even small increases in sea level can turn previously manageable high tides into destructive flooding events, while hurricanes and cyclones push water higher and deeper into coastal areas than they once did. These changes heighten the risk of drowning and injuries during high tides and storm surges. Rising water levels can also compromise roads, sanitation systems, and buildings, even in the absence of major storms.

Indirect impacts: Sea-level rise threatens human health through multiple indirect pathways. Saltwater intrusion increases groundwater salinity, contributing to hypertension and cardiovascular disease. Coastal flooding expands mosquito habitats and elevates infectious disease risks, while contamination of drinking water systems and wastewater infrastructure increases exposure to pathogens and pollutants. Beyond physical illness, displacement and the loss of homes, land, or livelihoods heighten stress, anxiety, and depression, particularly in communities

[82] Health and Hurricanes - Studying Disparate Health Impact of Extreme Climate Events, 2017-2020, SOA Research Institute (Webb et al., 2024), https://www.soa.org/globalassets/assets/files/resources/research-report/2022/health-hurricanes-studying-impact.pdf

[83] Nearly 1 Million Pounds of Seven Deadly Air Pollutants Released by Texas Refineries During Harvey Floods, Center for Biological Diversity (2017), https://www.biologicaldiversity.org/news/press_releases/2017/air-pollution-09-01-2017.php

[84] The Psychological Impact From Hurricane Katrina: Effects of Displacement and Trauma Exposure on University Students, National Library of Medicine (Thompson et al., 2009), https://pmc.ncbi.nlm.nih.gov/articles/PMC3374339/

[85] Health and Hurricanes - Studying Disparate Health Impact of Extreme Climate Events, 2017-2020, SOA Research Institute (Webb et al., 2024), https://www.soa.org/globalassets/assets/files/resources/research-report/2022/health-hurricanes-studying-impact.pdf

[86] Quantifying the Impact of Climate Change on Human Health, page 28, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

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facing repeated inundation or long-term uninhabitability and in areas where sea-level rise coincides with land subsidence. Additionally, ocean acidification compounds coastal ecosystem degradation, indirectly affecting food security and community health.

Most vulnerable populations: Low-income coastal communities, farmers in low-lying areas, and populations with limited access to safe drinking water are especially vulnerable. These groups often lack the financial resources, infrastructure, or mobility needed to adapt to rising water levels, and may face disproportionate risks from salinization, flooding, and displacement.

Most exposed regions: The regions that are most at risk from sea-level rise in the coming decades include major river deltas (such as those in Bangladesh), small island states (such as the Maldives), and low-lying coastal cities combining high physical exposure with dense populations (including Miami, New York City, Shanghai, Shenzhen, Hong Kong, and Jakarta where relocation plans are already underway due to the combination of sea-level rise and land subsidence).

Table 2.2 below summarizes the main impacts, vulnerabilities and exposures for each of the six perils analyzed in this section:

Table 2.2
OVERVIEW OF THE MAIN IMPACTS, VULNERABILITIES AND EXPOSURES BY PERIL

Peril	Direct Impacts	Indirect Impacts	Most Vulnerable Populations	Most Exposed Regions
Heat waves and temperature increase	Heat stress; cardiovascular collapse	Air quality; chronic heat strain; mental health	Elderly; chronically ill; urban poor; outdoor workers	Asia; Middle East; temperate regions lacking cooling
Drought	Dehydration; food loss	Malnutrition; mental stress; wildfire risk; displacement	Children; elderly; farmers; low-income households	Mediterranean; Western North America; Africa; South America
Wildfires	Burns; smoke inhalation; trauma	Air pollution; respiratory/cardiac disease; displacement	Firefighters; elderly; respiratory patients; low-income communities	Western North America; Mediterranean; Amazon; Australia
Floods	Drowning; injuries; hypothermia	Waterborne disease; mold; mental health; disrupted care	Children; elderly; disabled; poorly housed	Asia; Northern South America; Middle Africa
Severe storms	Trauma; storm surge; debris injuries	Power outages; contaminated water; disrupted care	Elderly; chronically ill; low-income; mobility-limited	Caribbean & Central America; North America; Asia
Sea-level rise	Amplified coastal flooding; storm-surge injuries	Salinized water; vector habitat expansion; displacement	Low-income coastal communities; farmers in low-lying areas	Deltas; small islands; major coastal cities

2.3 CROSS-PERIL TRANSMISSION CHANNELS AFFECTING HUMAN HEALTH

Climate hazards affect human life and health through a set of interconnected transmission channels that cut across individual perils: direct physical injury; degradation of air quality; shifts in ecological and disease-vector dynamics; disruptions to water, food, energy, and health care systems; and cascading social and economic stresses that undermine mental and physical well-being. These mechanisms often operate simultaneously, interact with one another, and compound pre-existing vulnerabilities, meaning that the complete life and health impacts of climate change cannot be understood by examining each peril in isolation. Whereas the previous section organized climate-

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related risks by type of peril, this section reorganizes the same risk landscape by type of consequence, as illustrated in figure 2.6 below.

Figure 2.6
TWO COMPLEMENTARY VIEWS OF CLIMATE-RELATED HEALTH RISKS

By Climate Peril

- Temperature increase
- Drought
- Wildfires
- Floods
- Severe Storms
- Sea Level Rise

By Transmission Channel

- Direct Injury
- Air Quality
- Vector-Borne Diseases
- Mental Health
- Health Care Services
- Socioeconomic Disruption

2.3.1 DIRECT INJURY AND MORTALITY

Extreme weather events can cause immediate injury and mortality through a range of direct physical mechanisms. Acute heat exposure can lead to heatstroke, dehydration, and cardiovascular collapse, particularly among individuals with pre-existing conditions or limited access to cooling. Floods pose risks of drowning, trauma from debris, collapsing structures, and electrocution as water interacts with damaged electrical systems. Severe storms expose populations to flying debris, structural failures, storm surges, and flash flooding, all of which can result in sudden and severe injuries. Wildfires create life-threatening conditions through burns, smoke inhalation, and entrapment as fire fronts move rapidly and unpredictably.

However, it is important to note that direct deaths and injuries represent only a small fraction of the overall health burden associated with climate hazards, especially in high-income countries. For health systems and insurers, the more consequential impacts arise from the way climate-related stressors accelerate the onset and progression of certain chronic conditions that are sensitive to sustained heat exposure, poor air quality, and other environmental changes (including asthma, chronic pulmonary disease, cardiovascular disease, and kidney disease). As a result, the long-term actuarial implications of climate change are driven more by chronic morbidity pathways than by the acute mortality and injury spikes associated with individual events.

2.3.2 AIR QUALITY DEGRADATION

Climate hazards also affect health through widespread degradation of air quality, a mechanism that operates across heat waves, drought and wildfire conditions. High temperatures accelerate the formation of ground-level ozone and intensify smog episodes, while also altering the timing, duration, and intensity of pollen seasons. Drought dries soil and vegetation, increasing the frequency of dust storms and elevating wildfire risk, both of which contribute to particulate matter pollution. Wildfires are a major source of fine particulate matter ($PM_{2.5}$), carbon monoxide, ozone precursors, and toxic combustion by-products, often exposing populations far beyond the fire zone to hazardous smoke. These air quality impacts can trigger or exacerbate a wide range of diseases, including asthma and other

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respiratory illnesses, cardiovascular disease, type-2 diabetes, antibiotic resistance, and certain mental health conditions.[87]

2.3.3 VECTOR-BORNE DISEASES

Climate hazards also reshape ecological conditions in ways that expand the geographic range, seasonal activity, and transmission intensity of vector-borne diseases, i.e., illnesses transmitted by living organisms such as mosquitoes or ticks. A striking illustration of these shifts occurred in 2025, when mosquitoes were detected in Iceland for the first time, as warming temperatures made the country newly hospitable to species that had previously been unable to survive there. Until then, Iceland and Antarctica were the only places on Earth without native mosquito populations, highlighting how rapidly vector ranges can expand under changing climatic conditions.[88]

Rising temperatures accelerate mosquito and tick life cycles, extend transmission seasons, and allow diseases such as malaria, dengue, Zika, chikungunya [89], West Nile virus, Lyme disease, and tick-borne encephalitis to spread into regions that were previously too cool to sustain them, including parts of Europe and the United States. Drought can also shift vector habitats by altering ecosystems, concentrating hosts and vectors around scarce water sources, and increasing human–vector contact. Floods can create areas of standing water that serve as breeding grounds for mosquitoes, while sea-level rise and storm surges increase saltwater intrusion into wetlands, enabling salt-tolerant mosquito species to thrive in new areas. Taken together, these changes are expected to place as many as 500 million additional people at risk of exposure to vector-borne diseases by 2050.[90]

2.3.4 IMPACTS ON MENTAL HEALTH

Climate hazards can also affect mental health through both acute traumatic shocks and chronic stress pathways. Sudden extreme events such as severe storms, floods, wildfires, and even heat waves can trigger post-traumatic stress disorder, acute anxiety, and stress reactions linked to trauma, displacement, loss of housing or livelihoods, and disruption of social networks. Gradual climate stressors, including rising temperatures, sea-level rise, and prolonged drought, can also create persistent psychological burdens that contribute to chronic anxiety, eco-anxiety, depression, and substance use disorders, particularly in communities facing marked livelihood insecurity or environmental degradation. Mental health impacts also arise through physiological transmission channels: hot weather can exacerbate symptoms of pre-existing conditions, such as depression or dementia, while sleep disruption during heat waves further impairs emotional regulation. Importantly, the psychological toll of climate hazards extends far beyond those who experience direct physical harm; for every person injured or displaced, many more are affected indirectly through fear, uncertainty, community disruption, and prolonged recovery periods.[91]

2.3.5 STRAIN ON HEALTH CARE ACCESS AND PUBLIC SERVICES

Climate hazards undermine health outcomes by disrupting health care systems and essential public services, with indirect but potentially significant consequences for mortality and morbidity. Extreme weather events can force

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[87] CLIMATE CHANGE: What does the future hold for health and life insurance?, page 17, Geneva Association (Bhattacharya-Craven, 2024), https://www.genevaassociation.org/sites/default/files/2024-02/cch-report_web-270224.pdf

[88] Mosquitoes found in Iceland for first time as climate crisis warms country, The Guardian (Horton, 2025), https://www.theguardian.com/environment/2025/oct/21/mosquitoes-found-iceland-first-time-climate-crisis-warms-country

[89] Excruciating tropical disease can now be transmitted in most of Europe, study finds, The Guardian (Carrington, 2026), https://www.theguardian.com/science/2026/feb/18/tropical-disease-chikungunya-transmitted-europe-study

[90] Quantifying the Impact of Climate Change on Human Health, page 4, World Economic Forum & Oliver Wyman (Eitelwein et al., 2024), https://www3.weforum.org/docs/WEF_Quantifying_the_Impact_of_Climate_Change_on_Human_Health_2024.pdf

[91] How Extreme Weather Events Affect Mental Health, American Psychiatric Association (Haase, 2023), https://www.psychiatry.org/patients-families/climate-change-and-mental-health-connections/affects-on-mental-health

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hospitals and clinics to evacuate, close temporarily, or operate under degraded conditions due to structural damage, flooding, or prolonged power outages. Transportation disruptions (such as damaged roads, bridges, or transit systems) can prevent patients and health care workers from reaching medical facilities. For instance, health care utilization was disrupted during the 2022 KwaZulu-Natal floods in South Africa, with visits and admissions dropping significantly at the height of the rainfall as access to services was curtailed. Once conditions stabilized, utilization rebounded, though the overall impact was compounded by infrastructure damage to clinics, hospitals, utilities, and transport systems, which magnified the morbidity consequences of the disaster.[92] The closure of even a single major hospital can overload neighboring institutions, with overcrowding and the boarding of patients in emergency departments being generally associated with decreased quality of care. For instance, when Hurricane Sandy struck New York City in 2012, Bellevue Hospital, which serves more than 500,000 patients annually, was forced to close temporarily and move patients elsewhere.[93]

Supply chain vulnerabilities further compound these pressures. Severe storms and floods can interrupt the production or distribution of essential medicines and medical devices, as seen when Hurricane Maria damaged a major saline manufacturing plant in Puerto Rico, triggering nationwide shortages of a critical medical supply.[94] Over the longer term, rising health impacts from climate change may also drive up long-term costs, making it harder for public and private insurance schemes to provide quality care for all. In the United States, for instance, exposure to wildfire smoke pollution has been linked to increased municipal borrowing costs for health care facilities, resulting in additional financial pressures on hospitals.[95]

Extreme weather events also alter health care utilization patterns in other complex ways. During acute events, such as hurricanes, wildfires, or severe storms, overall health care use often declines temporarily as individuals defer routine, chronic, and preventive care. Once conditions stabilize, however, deferred care tends to rebound, sometimes with higher severity due to delayed treatment. This trend **bounce-back effect** has important implications for health insurers and actuaries, as it can distort short-term claims experience, affect reserve adequacy, and complicate the interpretation of post-event morbidity trends.[96]

2.3.6 SOCIOECONOMIC DISRUPTION, RESOURCE STRESS, AND DISPLACEMENT

Climate hazards also generate far-reaching socioeconomic disruptions that indirectly affect mortality and morbidity across populations. Extreme weather events can damage water infrastructure, contaminate freshwater supplies, and reduce agricultural productivity, contributing to food scarcity and nutritional stress. In some regions, prolonged drought, soil degradation, or sea-level rise can render traditional modes of subsistence non-viable, leading to outright famine. Such conditions have direct and severe impacts on mortality and morbidity, particularly among children, older adults, and individuals with pre-existing health vulnerabilities. These pressures are often compounded by rising living costs, loss of livelihoods, and displacement of households from the affected regions.

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[92] Effects of extreme climate events on the morbidity of a sample of medical scheme lives in South Africa, South African Actuarial Journal (Smith et al., 2025), www.actuarialsociety.org.za/wp-content/uploads/2025/11/2025-ASSA-KotzenSmithCo-FIN.pdf

[93] To Be High Performing, the U.S. Health System Will Need to Adapt to Climate Change, The Commonwealth Fund (Blumenthal & Seervai, 2018), https://www.commonwealthfund.org/blog/2018/be-high-performing-us-health-system-will-need-adapt-climate-change

[94] Saline Shortages — Many Causes, No Simple Solution, The New England Journal of Medicine (Mazer-Amirshahi & Fox, 2018), https://www.nejm.org/doi/full/10.1056/NEJMp1800347

[95] Up in Smoke: The Impact of Wildfire Pollution on Healthcare Municipal Finance, Federal Reserve Bank of Dallas (Lopez et al., 2025), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5101773

[96] An Introduction to Climate Change for Health Actuaries, SOA Research Institute (Barrett & Owen, 2025), https://www.soa.org/globalassets/assets/files/resources/research-report/2025/climate-change-act-practice-articles/climate-change-act-practice-barrett-owen.pdf

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As communities compete for increasingly scarce resources, such as arable land, clean water, or safe housing, social tensions may intensify, heightening the risk of conflict and political instability. In this context, resource stress is not only a driver of socio-political conflict but also a pathway through which climate hazards translate into acute health crises. These dynamics can undermine public health conditions, reduce access to essential services, and exacerbate existing inequalities, with the greatest burdens falling on low-income and marginalized groups.

Importantly, many of the most significant health consequences may arise not from the climate hazards themselves but from the broader environmental, ecological, and social changes they set in motion.[97] Economic disruption, unemployment, and prolonged uncertainty can worsen mental health outcomes and contribute to higher rates of chronic disease, substance use, and premature mortality. The International Actuarial Association notes that because mortality and morbidity are highly sensitive to unemployment and mental health, climate- related transition risks such as job losses, energy system shifts, or rising living costs may have more material impacts on L&H insurers' risk profiles than short-term physical climate risks.[98] These socioeconomic pathways highlight the need for a holistic understanding of climate risk that integrates physical, environmental, and transition-related drivers of health outcomes.

2.3.7 COMPOUNDING RISK DRIVERS AND CLIMATE SYSTEM VARIABILITY

Climate-related risks to human life and health are amplified when multiple hazards or environmental stressors occur simultaneously. For instance, exposure to extreme heat combined with dryness and elevated particulate-matter pollution from wildfires significantly increases the risk of cardiovascular mortality, far beyond the effect of either hazard alone. The likelihood of death from cardiovascular disease has been found to rise by more than 20% when individuals are exposed to both high temperatures and poor air quality (which often coincides with heat waves), compared with a 5-6% increase associated with each condition independently.[99] Elevated heat also interacts with humidity to create dangerous "wet bulb" conditions, in which the body's cooling mechanisms fail because sweat cannot evaporate effectively. This can lead to dangerous rises in core body temperature, heat exhaustion, and potentially fatal heatstroke, particularly among older adults, outdoor workers, and individuals with chronic illnesses.

Compounding risks also arise from large-scale climate system patterns that influence multiple hazards at once. The El Niño–Southern Oscillation (ENSO) is a prominent example: shifts in sea surface temperatures in the tropical Pacific can alter temperature, humidity, rainfall, and air quality conditions across vast regions, including much of the United States. These remote climate influences can produce correlated increases in heat stress, storm activity, wildfire smoke exposure, and respiratory risks. Emerging evidence indicates that strong El Niño events can slow mortality improvement for several years, underscoring the importance of accounting for climate system variability as a cross-peril amplifier.[100]

2.3.8 POTENTIAL BENEFICIAL OR OFFSETTING EFFECTS

Although the expected impacts of climate change on mortality and morbidity are predominantly adverse, a small number of potentially beneficial or offsetting effects have been identified in the literature. As previously noted, the

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[97] The Relevance of Climate Change for Life Insurance, Part 2 – The Medical Director's View, page 3, SCOR (Bagul & Merk, 2022), www.scor.com/en/expert-views/relevance-climate-change-life-insurance-part-2

[98] Climate-Related Scenarios Applied to Insurers and Other Financial Institutions, page 20, International Actuarial Association (Musulin et al., 2021), https://actuaries.org/app/uploads/2025/04/CRTF_Application_Climate_Scenarios.pdf

[99] The Effects of Coexposure to Extremes of Heat and Particulate Air Pollution on Mortality in California, American Journal of Respiratory and Critical Care Medicine (Rahman et al., 2022), https://pubmed.ncbi.nlm.nih.gov/35727303/

[100] Climate Anomalies' Enduring Impacts on U.S. Health Landscape, SOA Research Institute (Xu et al., 2025), https://www.soa.org/globalassets/assets/files/resources/research-report/2025/2025-12-cc219-climate-anomalies.pdf

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most consistently projected benefit is a decline in cold-related mortality in several temperate regions, driven by milder winters. These reductions, however, are highly region- and population-specific, and they are generally outweighed on a global scale by the expected rise in heat-related mortality. Beyond direct health outcomes, some high-latitude regions (such as Alaska, Canada, and Northern Russia) may experience temporary gains in agricultural productivity as warming extends growing seasons,[101] supported by longer frost-free periods and, in some contexts, CO_2-fertilization effects that can enhance plant growth. However, these localized gains are expected to be temporary and limited, and to remain a net negative globally due to declines in crop yields in lower latitudes.

It is also important to distinguish between the impacts of climate change itself and the health co-benefits of climate mitigation and adaptation. While not directly caused by warming, actions such as reducing fossil fuel combustion, improving urban design, enhancements to health care and emergency response systems, and promoting active mobility (e.g., walking and cycling for daily transport) could lead to substantial improvements in air quality and population health. Similarly, the acceleration of innovation and adaptation, such as advances in heat-resilient infrastructure, climate-smart agriculture, or early-warning systems, may support public health resilience. Recognizing these possible co-benefits offers a fuller understanding of the climate risk landscape, while noting that such advantages may arise indirectly from societal responses addressing climate change, rather than from climate change itself. It is also important to avoid undue "transition optimism" biases, for instance, by implicitly assuming that anticipated air quality improvements from decarbonization will offset the deterioration in long-term heat-related mortality.[102]

2.4 RISK MITIGATION AND CLIMATE ADAPTATION STRATEGIES

As climate-related health risks intensify, effective adaptation and risk mitigation strategies can help reduce mortality, morbidity, and pressure on health systems. Adaptation measures range from early warning systems and resilient infrastructure to training and preparation for medical services, disease surveillance, occupational protections, and mental health support. Together, they can substantially moderate the impacts of both acute events and chronic climate stressors. For instance, Japan's long-standing investment in building codes, public alerts, and school curricula for earthquakes and typhoons illustrates how preparedness can substantially reduce both human and economic impacts.[103] Likewise, the lessons learned from the 2003 heat wave in France and the subsequent adaptation plan have contributed to significantly lower mortality from subsequent heat events.[104] However, adaptation is unevenly distributed, subject to financial and institutional constraints, often location-specific in its effectiveness, and cannot fully offset all climate-related health burdens. Understanding the scope, effectiveness, and limitations of available adaptation strategies can help L&H insurers assess future risks using forward-looking scenarios.

2.4.1 PUBLIC AWARENESS AND EARLY WARNING SYSTEMS

Effective climate adaptation may typically begin with data gathering, timely information and clear guidance that enables individuals, communities, and institutions to take protective action. Public education campaigns, such as

[101] Wilderness areas under threat from global redistribution of agriculture, Current Biology (Gardner et al., 2023), https://www.cell.com/action/showPdf?pii=S0960-9822%2823%2901229-0

[102] Climate forecast: Looking beyond net-zero mortality predictions, Milliman (Drew et al., 2026), https://media.milliman.com/v1/media/edge/images/millimaninc5660-milliman6442-prod27d5-0001/media/Milliman/PDFs/2025-Articles/2-27-25_0207PC_Climate-forecast-Looking-beyond-net-zero-mortality-predictions.pdf

[103] From Risk to Resilience. Closing the Climate Insurance Protection Gap, Council on Economic Policies (Crugnola-Humbert, 2025), https://www.cepweb.org/from-risk-to-resilience-closing-the-climate-insurance-protection-gap/

[104] Risque climatique et impact en assurance (in French), page 22, CNP assurances & DIALog chair (Garrido, Anani et al., 2024), https://www.cnp.fr/cnp/content/download/11584/file/Livre-vert-Risque-climatique-et-impact-en-assurance-juin2024.pdf

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guidance on how to stay safe during heat waves, poor air quality episodes, hurricanes, wildfires or flood events, play a critical role in reducing exposure and preventing avoidable health impacts. These initiatives are most effective when they translate scientific risk assessments and complex data into simple, actionable messages tailored to vulnerable groups, including older adults, outdoor workers, and people with chronic illnesses.

Early warning systems provide a critical layer of protection by detecting emerging hazards and issuing alerts before conditions become dangerous. Early warning systems typically integrate four core components:

(1) risk knowledge, including scientifically-defined thresholds for activation, escalation, and deactivation;
(2) detection, monitoring, analysis, and forecasting, supported by meteorological and environmental data;
(3) warning dissemination, using channels such as SMS push alerts for exposed and vulnerable populations,[105] mobile applications, broadcast media, and community networks; and
(4) preparedness and response capacity, ensuring that individuals and institutions know how to act once an alert is issued.[106]

When these elements function together, early warning systems can substantially reduce climate-related health risks, particularly for vulnerable populations.

Evidence shows that countries with comprehensive early warning coverage experience, such as Japan for instance, dramatically lower disaster-related mortality than countries with limited systems. Building such systems requires robust data infrastructure, typically at least a decade of weather and health data to calibrate thresholds and validate predictive models. In settings where epidemiological data are sparse or cannot be modelled reliably, more narrowly hazard-based forecasting methods can serve as an interim approach.[107] Overall, strengthening public awareness and early warning systems is widely recognized as one of the most proven and cost-effective strategies.[108] For many acute weather hazards, such as typhoons, flash floods or fast-moving wildfires, timely warnings and rapid evacuation can be a decisive factor in reducing loss of life.

2.4.2 CLIMATE-RESILIENT INFRASTRUCTURE

The built environment is central to climate adaptation, as both man-made and natural infrastructure determines the level of exposure to climate hazards and the capacity of communities to withstand them. Updated building standards that account for higher temperatures, stronger storms, and increased flood risk can reduce structural damage, maintain habitability during extreme events, and protect indoor environmental conditions. Urban design measures, such as expanding tree cover, green roofs, shaded public spaces and permeable surfaces, can significantly reduce urban heat island effects and lower ambient temperatures during extreme heat events, as well as improve air quality, stormwater management, and overall urban livability. Access to cooling through air conditioning, community cooling centers, or passive cooling design plays a vital role in preventing heat-related illness. Air filtration systems, including high-efficiency particulate air (HEPA) filters, can also help reduce indoor exposure to wildfire smoke and other pollutants, providing an important layer of protection during prolonged air quality episodes.

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[105] City-County send first joint Wireless Emergency Alert on heat, Multnomah County, Oregon (2021), https://multco.us/news/archives-city-county-send-first-joint-wireless-emergency-alert-heat

[106] COP30 SPECIAL REPORT ON HEALTH AND CLIMATE CHANGE, page 24, COP30 Brazil (2025), https://cdn.who.int/media/docs/default-source/climate-change/cop30-special-report-on-health-and-climate-change.pdf

[107] COP30 SPECIAL REPORT ON HEALTH AND CLIMATE CHANGE, pages 24-25, COP30 Brazil (2025), https://cdn.who.int/media/docs/default-source/climate-change/cop30-special-report-on-health-and-climate-change.pdf

[108] Early Warnings for All, United Nations Office for Disaster Risk Reduction (retrieved 2026), https://www.undrr.org/implementing-sendai-framework/sendai-framework-action/early-warnings-for-all

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Nature-based solutions also play an important role in strengthening climate-resilient infrastructure. Measures such as restoring wetlands, expanding urban tree canopies, protecting coastal ecosystems, and creating green corridors can reduce flood risk, moderate extreme heat, improve air quality, and enhance mental well-being. These interventions often deliver multiple co-benefits, supporting biodiversity, reducing energy demand, and improving urban livability while avoiding some of the long-term drawbacks associated with hard infrastructure. As such, nature-based solutions may represent a cost-effective and sustainable complement to engineered adaptation measures.[109]

2.4.3 REDUCING EXPOSURE AND VULNERABILITY IN WORK AND CARE ENVIRONMENTS

Protecting individuals during periods of extreme heat, poor air quality, or other hazardous conditions requires targeted measures that reduce direct exposure and support safe living and working environments. Adjusting working hours, modifying workloads, implementing mandatory rest and providing hydration are among the most effective strategies for safeguarding outdoor and high-exertion workers during heat waves. Occupational safety protocols (such as heat stress monitoring, shaded rest areas, and access to cooling) can significantly reduce the risk of heat exhaustion, heatstroke, and other acute health events. These measures are particularly important for sectors such as construction, agriculture, transportation, and emergency response, where climate-related exposures are unavoidable.

Beyond workplaces, protective measures are equally important in settings that house or serve vulnerable populations. Schools may need to adjust schedules, limit outdoor activities, or activate cooling and air filtration protocols during extreme conditions. Elderly care facilities and assisted-living centers require enhanced monitoring, reliable cooling, and contingency plans for power outages, as older adults face disproportionately high risks during heat and air quality emergencies. Similar considerations apply to hospitals, shelters, and correctional facilities, where residents have limited ability to self-protect.

2.4.4 PUBLIC HEALTH SURVEILLANCE AND EMERGENCY RESPONSE

Disease surveillance and public health preparedness are among the approaches prominently discussed in the literature for addressing health risks associated with a changing climate. Rising temperatures, shifting precipitation patterns, and ecological disruption are expanding the geographic range and seasonality of vector-borne diseases such as dengue, West Nile virus, Lyme disease, and malaria. Surveillance systems that combine entomological monitoring, environmental data, and real-time reporting of cases can facilitate early detection of outbreaks and inform timely public health interventions. Complementary measures, including mosquito control programs, the use of insect repellents or bed nets, and the development of vaccines and treatments can help reduce transmission and protect high-risk populations.

Preparedness for climate-related or climate-amplified emergencies can typically involve planning across multiple components of the health system. Extreme weather events can overwhelm emergency services, disrupt supply chains, and impair access to essential medical care. Health system preparedness may include considerations such as surge capacity, maintaining strategic reserves of critical supplies, and strengthening logistics and distribution networks, which can influence system resilience during emergency events. Hospitals, emergency responders, and public health agencies may also develop coordinated response plans that account for more frequent and severe climate-related shocks.

[109] Tackling the Insurance Protection Gap, WWF Policy Brief (Hess, Crugnola-Humbert et al., 2025), https://wwfint.awsassets.panda.org/downloads/wwf--insurance-protection-gap-policy-brief_1_1.pdf

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2.4.5 INTEGRATING MENTAL HEALTH AND SOCIAL RESILIENCE INTO ADAPTATION PLANNING

Climate-related hazards affect more than physical health and can impose substantial psychological and social burdens that could persist long after an event has passed. Integrating mental health considerations into climate adaptation strategies is, therefore, essential for a comprehensive response. This includes ensuring access to psychological first aid after disasters, strengthening community-based mental health services, and embedding mental health expertise into emergency response planning. Building social resilience is equally important. Strong social networks, community organizations, and local support systems can significantly reduce the health impacts of climate-related shocks by improving communication, facilitating access to resources, and providing emotional and practical support. Targeted outreach to isolated or vulnerable individuals (such as older adults, people with disabilities, or those living alone) helps ensure that protective measures reach those most at risk.

2.4.6 LIMITS OF ADAPTATION AND RISKS OF MALADAPTATION

Adaptation and risk mitigation measures can substantially reduce climate-related mortality and morbidity, but they cannot eliminate all risks, and their effectiveness varies widely across regions, populations, and hazard types. While ignoring future adaptation overestimates the long-term climate-related life and health risks, assuming full or uniform adaptation can conversely lead to significant underestimation of risk. Many of the most damaging climate impacts on health, such as chronic heat exposure, long-term air quality degradation, and the spread of vector-borne diseases, accumulate gradually and are difficult to fully offset through behavioral or infrastructural interventions. Moreover, adaptation capacity is unevenly distributed: wealthier communities can invest in resilient infrastructure, cooling, and health care, while low-income or marginalized groups often face financial, institutional, or geographic barriers that limit their ability to access and benefit from protective measures. For instance, evidence from global mortality studies shows that adaptation can substantially reduce heat-related mortality, but that these measures require investments that are not equally accessible across populations.[110]

Adaptation can have limits, costs and potential secondary effects such as the risk of maladaptation, i.e., responses that inadvertently increase long-term vulnerability or create new risks. For example, widespread reliance on energy-intensive air conditioning can strain power grids during heat waves and increase greenhouse gas emissions, unless it is paired with clean energy transition and efficiency measures. Built infrastructure solutions, such as sea walls or flood barriers, may protect one area while shifting risks to neighboring communities. Overuse of insect repellents can further damage biodiversity and reduce ecosystem services. Even well-intentioned public health measures can have unintended consequences if they are not designed with sustainability and long-term economic, social, health, and environmental system dynamics in mind. Recognizing these limits and potential trade-offs can help to develop realistic climate-health scenarios and ensure that adaptation strategies strengthen resilience rather than create new vulnerabilities.

[110] Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits, The Quarterly Journal of Economics (Carleton et al., 2022), https://academic.oup.com/qje/article/137/4/2037/6571943

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Section 3 Modeling Climate-Related Mortality and Morbidity Risks

This section develops a forward-looking, scenario-based quantitative framework for assessing how climate change may affect mortality and morbidity over time, building on established actuarial practice while explicitly addressing non-stationarity and deep uncertainty.

The approach extends traditional mortality modeling based on an augmented Lee–Carter specification to separate baseline health trends from incremental climate-driven effects using exogenous hazard pathways, a globally governed climate sensitivity parameter, and potential group-specific vulnerability adjustments by geography, demographic characteristics and socioeconomic status. It details the necessary data inputs and calibration approach, emphasizes scenario analysis and stress testing rather than pathway forecasting, and may support the application of results in pricing, reserving, product development, capital management, ORSA, and climate-related disclosure frameworks, including the International Sustainability Standards Board (ISSB),[111] the Corporate Sustainability Reporting Directive (CSRD),[112] and the Task Force on Climate-related Financial Disclosures (TCFD)[113] (which has been effectively integrated into the ISSB standards). The section also sets out model limitations, key sensitivities, validation checks, and model governance controls to help ensure the framework remains transparent, auditable, and suitable for professional use.

The models presented in this section are purpose-driven, rely on transparent and externally-sourced inputs where appropriate, explicitly disclose limitations and uncertainty, and are intended to support actuarial judgment rather than replace it.

Finally, as noted in subsection 1.1.1, climate risk is commonly decomposed into physical risk (arising from direct climate impacts and weather events) and transition risk (which reflects the economic and financial consequences of the transition to a low-carbon economy). The modeling framework developed in this report focuses exclusively on physical risk. While transition risk is also relevant (as noted in subsection 2.3.6), it is driven by a complex and evolving set of factors, including regulatory changes, technological innovation, market dynamics, and shifts in consumer behavior, as well as the consequences of the climate transition on growth, inflation and employment, which are all inherently difficult to isolate and represent with a tractable quantitative mortality or morbidity modeling framework.

3.1 PURPOSE AND SCOPE OF QUANTITATIVE MODELING

In the context of climate-related mortality and morbidity risk, quantitative modeling is intended not to produce precise point forecasts, but rather to provide a structured and internally consistent framework for studying the effects on mortality and morbidity rates under an assumed plausible climate pathway.

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[111] The International Sustainability Standards Board (ISSB) develops global sustainability disclosure standards under the IFRS Foundation. In particular, IFRS S2 *Climate-related Disclosures* establishes requirements for the identification, assessment, and disclosure of climate-related risks and opportunities, including the use of scenario analysis and the disclosure of assumptions and methodologies. Where referenced in this report, ISSB refers to IFRS S2 and related sustainability reporting guidance issued by the IFRS Foundation.

[112] The Corporate Sustainability Reporting Directive (CSRD) is a European Union Directive that establishes enhanced sustainability reporting requirements for companies operating within its scope. It requires disclosure of environmental, social, and governance (ESG) information, including climate-related risks and impacts, in accordance with the European Sustainability Reporting Standards (ESRS). References to CSRD in this report pertain to its climate-related disclosure requirements and the associated expectations regarding scenario analysis, risk assessment, and transparency of assumptions.

[113] The Task Force on Climate-related Financial Disclosures (TCFD) was established by the Financial Stability Board to develop voluntary, consistent climate-related financial risk disclosures for use by companies, banks, and investors. The TCFD recommendations provide a framework for reporting climate-related governance, strategy, risk management, metrics, and targets, including the use of scenario analysis to assess resilience under different climate pathways. References to TCFD in this report relate to its guidance on climate-risk identification, scenario analysis, and disclosure practices.

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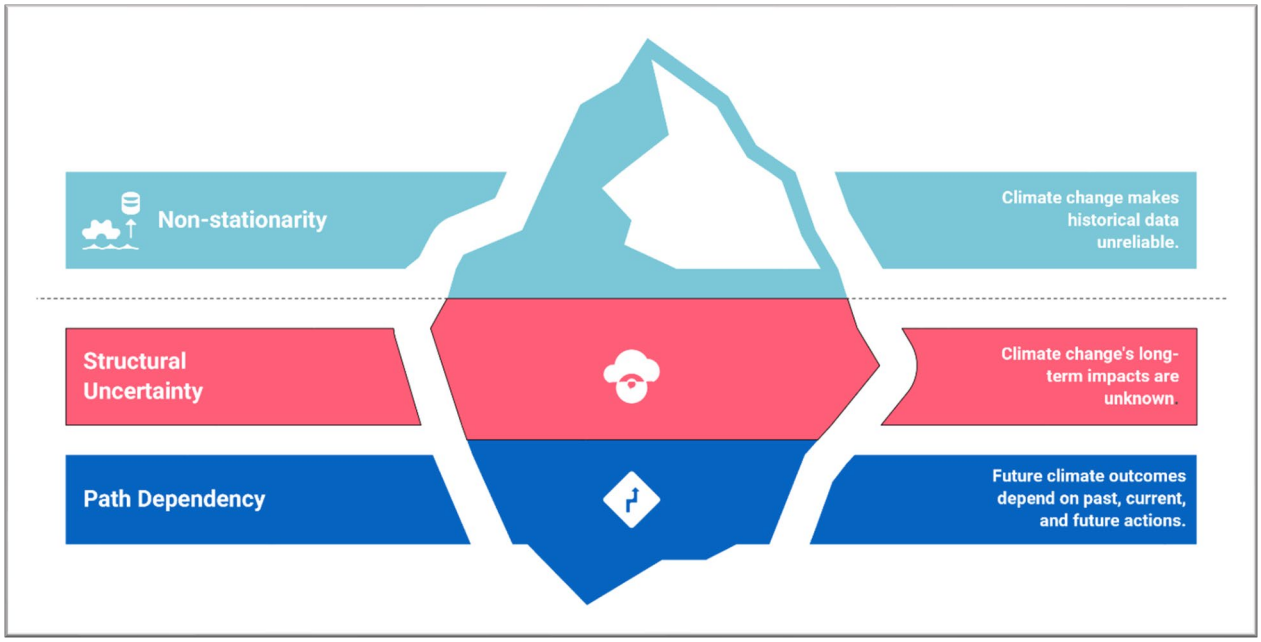
3.1.1 DIFFERENCES WITH RESPECT TO TRADITIONAL ACTUARIAL MODELING

In contrast to many traditional actuarial applications, where stable historical relationships and long time series support statistical extrapolation, climate change introduces non-stationarity, structural uncertainty, and path dependency that require a different modeling mindset described below.

Figure 3.1
CLIMATE CHANGE CHALLENGES ACTUARIAL MODELING



Non-stationarity

Climate-related hazards, such as temperature extremes, air pollution, and wildfire smoke, are not expected to evolve as stationary processes fluctuating around fixed long-term means. Rather, their future dynamics are shaped by scenario-dependent trajectories driven by physical climate processes, greenhouse gas emission pathways, and socioeconomic development.

While the stochastic processes used in actuarial modeling can, in principle, accommodate trends, regime shifts, and cyclical behavior, the future evolution of climate hazards is not well captured by models calibrated solely on historical mortality or morbidity experience. Accordingly, climate variables are treated in this framework as exogenous, inputs informed by externally governed climate scenarios. These inputs are intended to reflect both systematic changes in long-term mean conditions and the evolving variability around those means, recognizing that climate change alters the whole probabilistic distribution, i.e., not only central expectations but also the frequency and severity of tail events.

Structural Uncertainty

Certain relationships, such as the physiological response of humans to extreme heat or air pollution, are informed primarily by epidemiological and medical research and are expected to be relatively stable across populations. Other aspects, such as vulnerability by geography or socioeconomic group, are more context-specific and uncertain. The framework distinguishes among these layers explicitly, allowing global sensitivity parameters to be treated differently from relative vulnerability adjustments. This hierarchy supports both disciplined calibration and meaningful sensitivity analysis.

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Path Dependency

The climate-adjusted modeling frameworks presented in this report are primarily designed for scenario analysis, reflecting the inherently path-dependent character of climate-related risk.

In traditional actuarial modeling, uncertainty is often represented by stochastic processes in which future outcomes are described by probabilistic dynamics calibrated to historical data. By contrast, climate-related mortality and morbidity risk depends on the cumulative evolution of physical climate variables, technological change, socioeconomic development, and adaptive responses from human societies over time. These drivers influence one another sequentially, so that outcomes depend materially on the particular pathway followed rather than solely on terminal conditions or stationary probability distributions.

Accordingly, climate scenarios are not assigned likelihoods within the models, nor are outputs interpreted as expected values in a probabilistic sense. Instead, the models are used to examine how mortality and morbidity trajectories evolve under alternative, internally consistent pathways that combine physical climate assumptions with broader socioeconomic contexts.

This framing recognizes the path-dependent nature of long-term health outcomes and is consistent with forward-looking, scenario-based climate-risk analysis.

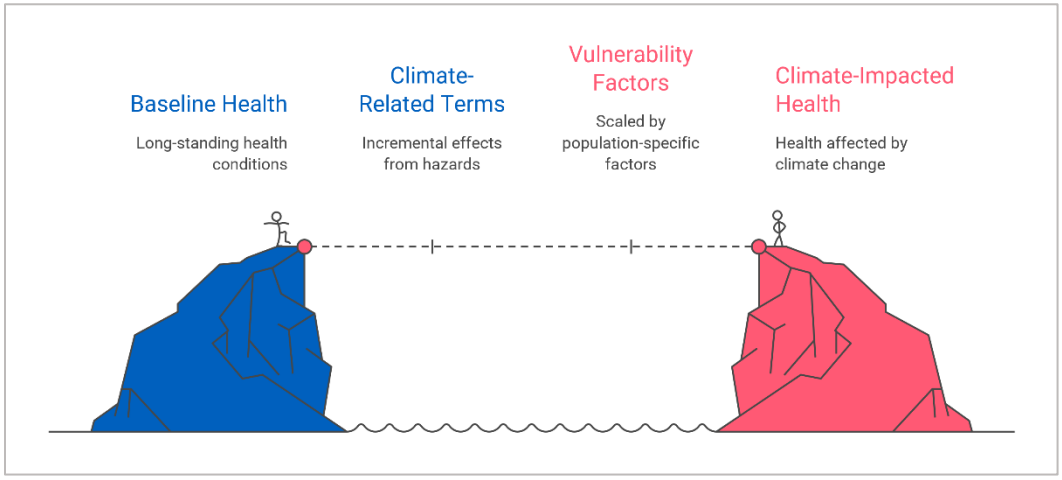
3.1.2 SEPARATION OF HAZARD, VULNERABILITY, EXPOSURE, AND RESPONSES

Climate change affects health outcomes through physical hazards (such as heat stress, air pollution, and wildfire smoke) that interact with population exposure (such as geographic location and environmental context), population vulnerability (such as age, socioeconomic status, and pre-existing health conditions), and adaptive or systemic responses. The modeling framework adopted in this report is designed to keep these components conceptually distinct:

- Baseline mortality and morbidity reflect underlying health conditions, demographic and socioeconomic characteristics, and prevailing levels of adaptation, as captured in historical experience.
- Climate-related terms represent incremental effects driven by externally defined, scenario-based exposure to evolving climate hazard, scaled by population-specific vulnerability factors.

Figure 3.2

FROM BASELINE TO CLIMATE-IMPACTED HEALTH



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Responses—such as behavioral adaptation, infrastructure, health care capacity, and government interventions—are reflected implicitly through scenario assumptions and, where appropriate, through the calibration and interpretation of vulnerability parameters rather than through explicit dynamic-response modeling.

This structured separation enhances interpretability and reduces the risk of double counting or misattribution of climate-related effects.

3.1.3 PARSIMONY

Given the limited availability of long, reliable time-series-linking climate variables to mortality and morbidity outcomes, overly complex statistical models' risk may provide a false sense of precision. The proposed mortality modeling framework, therefore, builds on the well-understood Lee–Carter model and extends it in a controlled and transparent way to incorporate climate effects. Each additional parameter is introduced only where it serves a clear conceptual role and can be supported by external evidence or professional judgment. Similar tenets are maintained for the morbidity modeling framework.

Within this research project, quantitative modeling serves three primary objectives:

1. Translates high-level climate narratives and physical risk pathways into actuarially interpretable metrics, such as age-specific mortality and morbidity rates;

2. Enables comparative analysis across scenarios, socioeconomic population groups, regional classes, and time horizons, allowing actuaries to assess relative impacts rather than relying on single deterministic projections; and

3. Provides a decision-support tool for actuarial applications including, for instance, pricing, reserving, capital management, ORSA, and climate-related disclosure frameworks (including ISSB, CSRD, and TCFD), while remaining transparent about uncertainty and model limitations.

3.1.4 SCOPE

The scope of the quantitative modeling framework presented here is deliberately limited. The mortality and morbidity models are designed to operate at the population or portfolio level, rather than at the individual policyholder level, and to support long-term strategic analysis rather than short-term forecasting. They focus primarily on the physical impacts of climate change on mortality and morbidity, such as heat stress, air pollution, and related health outcomes, and do not attempt to model transition risks or second-order economic feedback effects explicitly within the mortality or morbidity equations themselves. While the underlying hazard-exposure-vulnerability logic shares conceptual similarities with catastrophe modeling, this report focuses primarily on population-level biometric trends and does not address the more granular, event-based modeling typical of catastrophe applications. Where relevant, such effects are considered qualitatively or through scenario interpretation.

The framework is intended for portfolios of sufficient scale and diversification to support population-level analysis. It may not be appropriate for very small or highly concentrated portfolios where random fluctuation or concentration risk may dominate systematic climate effects. For example, a small employer-sponsored life portfolio concentrated in a single industry and geographic region may experience year-to-year mortality volatility that materially exceeds the modeled climate adjustment. In such cases, the usefulness of climate-adjusted projections may depend on the extent to which they are considered alongside a supplemental, qualitative assessment.

A key design principle underlying this work is the explicit separation of baseline health trends from climate-related effects. Baseline mortality and morbidity dynamics reflect long-standing drivers such as medical progress,

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socioeconomic development, and demographic and behavioral changes. Climate-related effects are introduced as incremental, scenario-driven adjustments that modify these baseline trajectories rather than replace them. This approach allows the modeling framework to remain anchored in established actuarial practice while accommodating forward-looking climate information.

Importantly, the absence of a climate-informed scenario does not necessarily imply a neutral or best estimate assumption. A projection that excludes climate-related effects is unlikely to reflect plausible long-term conditions and represents only a neutral counterfactual against which climate-related impacts can be incrementally measured. While uncertainty remains regarding the precise future pathway—whether defined under specific SSP–RCP combinations or NGFS scenarios—the scientific consensus indicates that some material degree of climate-related physical impact is expected. Accordingly, incorporating climate-informed scenarios does not merely increase uncertainty in a probabilistic sense; it also introduces potential structural shifts in long-term mortality and morbidity trends. Climate change, therefore, affects both the variability around projections and the trajectory of central trend assumptions.

The quantitative framework is not intended to predict the “most likely” future, or to assign probabilities to climate scenarios. Instead, it supports exploratory and stress-testing analyses, helping actuaries understand how sensitive outcomes are to key assumptions about climate hazards, exposure, and vulnerability. Within this framework, results are conditional on the chosen scenarios and assumptions rather than representing unconditional forecasts. The choice of central climate scenario to incorporate into best-estimate assumptions depends on the emissions trajectory that the world is considered to be following at a given point in time. Further discussion of this judgment is outside the scope of this report.

Finally, the scope of this modeling exercise reflects the professional context in which actuaries operate. The framework is designed to be auditable, explainable, and responsive to alternative changes in conditions or expectations, with clear links among assumptions, data sources, and outputs. It is intended to complement (but not replace) actuarial judgment, governance processes, and qualitative assessments. In this sense, quantitative modeling is positioned as one component of a broader climate-risk assessment toolkit, providing analytical structure while recognizing the inherent uncertainty and evolving nature of climate-related health risks.

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3.2 CLIMATE-ADJUSTED MORTALITY MODELING FRAMEWORK

3.2.1 ORIGINAL LEE-CARTER MODEL

The Lee-Carter model[114] captures time-dependent mortality evolution driven, for instance, by socioeconomic and medical improvements. However, the model does not incorporate exogenous hazards such as climate impacts. The Lee-Carter model takes the following form:

$$\log m_{x,t} = a_x + b_x k_t + \varepsilon_{x,t}$$

Where

- $m_{x,t}$ is the central death rate at age x during calendar year t;
- a_x is the average log-mortality at age x;
- k_t is the mortality index at time t, representing the general level of mortality in the population;
- b_x is the age-specific sensitivity of mortality to the mortality index k_t; and
- $\varepsilon_{x,t}$ is the random error capturing the residual variation not explained in the model.

3.2.2 HIGH-LEVEL METHODOLOGICAL APPROACH

The Lee-Carter model is used as the foundation for the climate-adjusted mortality framework because it is a well-established, transparent, and widely used structure for modeling age-specific mortality dynamics over time. Its log-linear specification provides a parsimonious decomposition of mortality into an age component and a time-varying trend component, making it particularly suitable for separating long-standing demographic improvements from incremental climate-related effects.

However, there is an important potential distinction between general population mortality and the actual mortality experienced in specific insurance or pension portfolios. Insured lives and pension scheme members may exhibit materially different mortality characteristics from the wider population due to underwriting selection, employment status, benefit eligibility, socioeconomic profile, access to health care, lifestyle factors, and a potentially lower prevalence of co-morbidities. As a result, portfolio mortality may be lower, less volatile, or differently distributed by age, gender, region, or socioeconomic group than population mortality. These differences are particularly relevant when assessing climate-related mortality impacts, as vulnerability to heat, air pollution, humidity extremes, and other environmental stressors may vary significantly across socioeconomic and health-status groups.

The model's interpretability and stability allow climate variables to be incorporated as structured extensions rather than ad hoc adjustments, while permitting calibration to the specific experience of an insured or pension portfolio.[115] This preserves continuity with established actuarial practice while recognizing that population-based climate-mortality relationships may require adjustment before being applied to select portfolios.

In addition, the Lee–Carter model has been widely adopted in academic research, actuarial literature, and practical applications in life insurance, pensions, and longevity risk management, which facilitates communication, peer

[114] Lee, Ronald D; Carter, Lawrence R (September 1992). Modeling and Forecasting U.S. Mortality. Journal of the American Statistical Association. 87 (419): 659–671 https://www.tandfonline.com/doi/abs/10.1080/01621459.1992.10475265

[115] See, for example, Lee-Carter Model, Wikipedia (retrieved 2026) https://en.wikipedia.org/wiki/Lee%E2%80%93Carter_model

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review, validation, and governance within actuarial practice.[116] By adjusting a well-established actuarial mortality modeling framework with an additional climate-related component, rather than introducing an entirely new structure, the framework maintains methodological credibility while accommodating forward-looking, scenario-based climate inputs.

The adjusted Lee–Carter climate model is used to project mortality rates under both non-climate drivers (e.g., medical progress, socioeconomic changes) and climate-related risks (e.g., rising temperatures, air pollution, humidity extremes).

The model notably supports:

- long-term mortality projections
- climate-risk scenario analysis (IPCC, NGFS)
- stress testing
- portfolio segmentation by geography, age, and socioeconomic status (SES)

The climate-adjusted mortality and morbidity models are fully specified in subsections 3.2.3 and 3.3.3, respectively.

3.2.3 MORTALITY MODEL STRUCTURE

While the standard Lee-Carter model captures long-term demographic trends, it treats mortality as a function of time alone. This framework is extended by explicitly decoupling the baseline mortality trend (implicitly driven by medical and socioeconomic progress over time) from a dynamic climate-specific risk component. This augmentation allows the model to project how intensifying climate hazards alter mortality trajectories beyond standard demographic improvements.

The climate adjustment is not uniform: it incorporates a vulnerability scaling factor that accounts for how age, geography, and socioeconomic status (SES) amplify or mitigate risk. This ensures that the model can reflect that identical climate events can have different mortality consequences depending on a population's demographic profile, location and adaptive capacity. The specification below formalizes this approach, defining how these drivers are combined to calculate central death rates.

[116] See, for example, CNP assurances & DIALog chair (Garrido, Anani et al., 2024) https://www.cnp.fr/cnp/content/download/11584/file/Livre-vert-Risque-climatique-et-impact-en-assurance-juin2024.pdf, Modelling the impact of climate risks on mortality (Milliman, 2022) https://media.milliman.com/v1/media/edge/images/millimaninc5660-milliman6442-prod27d5-0001/media/Milliman/PDFs/2022-Articles/12-16-22_Modelling-the-impact-of-climate-risks-on-mortality.pdf and Modeling the Impact of Wildfire-Related Air Pollution on Mortality, SOA Research Institute (Titon et al., 2025) https://www.soa.org/globalassets/assets/files/resources/research-report/2025/ml241-impact-wildfire.pdf

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The baseline augmented Lee-Carter mortality climate model takes the following form:

$$\log m_{x,t,r,s} = a_{x,r,s} + b_x k_t + \lambda_{x,r,s} C_{t,r} + \varepsilon_{x,t,r,s}$$

where

$m_{x,t,r,s}$ is the central death rate at age x during calendar year t for geographical region r and socioeconomic status s;

$a_{x,r,s}$ is the group-specific baseline, non-climate related log-mortality at age x for geographical region r, and socioeconomic status s. This parameter shifts the baseline mortality up or down as follows: $a_{x,r,s} = a_x + \alpha_r + \alpha_s$ where α_r captures mortality differences driven by geographical region (health system, pollution, etc.), and α_s the mortality differences driven by socioeconomic level (the more affluent will have a higher α_s);

k_t is the mortality index at time t, representing the general level of mortality in the population;

b_x is the age-specific sensitivity of mortality to the mortality index k_t;

$C_{t,r}$ is the climate exposure at time t for geographical region r (rising acute and chronic hazards, floods, droughts, air quality, etc.);

$\lambda_{x,r,s}$ is the vulnerability scaling to climate hazards at age x for geographical region r and socioeconomic status s. This parameter encodes the biological sensitivity and adaptive capacity of the population by age, geography and across socioeconomic segments defined by income, education, occupation, housing conditions, access to health care, and broader forms of social and cultural capital. In effect, $\lambda_{x,r,s}$ reflects pre-existing health conditions by age (e.g., prevalence of cardiovascular disease, diabetes/obesity), but also reflects age structures (i.e., older populations), lack of air conditioning during heat waves, weak housing insulation, or poor adaptive capacity. $\lambda_{x,r,s}$ can then be interpreted as how strongly regional and socioeconomic-related health disadvantages amplify the effect of climate hazards on mortality at different ages. In summary, $\lambda_{x,r,s} \geq 1$ means more vulnerable populations, $\lambda_{x,r,s} \approx 1$ means "average vulnerability," and $\lambda_{r,s} \leq 1$ means more resilient populations. $\lambda_{x,r,s}$ can also be defined as $\lambda_{r,s} = \lambda_x \cdot \lambda_r \cdot \lambda_s$; and

$\varepsilon_{x,t,r,s}$ is the random error capturing the residual variation not explained in the model.

As a complement to this baseline specification, subsection 3.2.5 introduces a simplified variant in which SES is removed from the climate sensitivity term, i.e., $\lambda_{x,r,s}$ is replaced by $\lambda_{x,r}$. This alternative formulation is motivated primarily by considerations of parsimony and data availability. As explained in section 2, empirical evidence supports the inclusion of the socioeconomic status as an underlying risk vulnerability driver, but in some practical applications, reliable and sufficiently granular data to support robust estimation of climate sensitivity across SES groups may be limited or inconsistent across regions. By reducing the dimensionality of the model, the simplified specification improves stability and interpretability while retaining the ability to capture age- and geography-specific climate effects. It is, therefore, presented as a pragmatic option for implementation, particularly in settings where data constraints or governance considerations favor a more streamlined approach.

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3.2.4 REPRESENTATION OF GEOGRAPHY AND SOCIOECONOMIC STATUS (SES)

In addition to traditional age-related parameters, the model uses a two-dimensional population segmentation:

- r: geographical region (e.g., country, climate zone)
- s: SES group defined using structured segmentation variables (e.g., income band, educational attainment, occupational category, housing conditions, area-level deprivation index, health care access indicators, or related proxies capturing economic resources, human capital, and adaptive capacity)

Geography and SES are represented explicitly to reflect heterogeneity in both climate exposure and population vulnerability. Geographic differentiation is introduced through region-specific climate hazard variables, allowing the model to capture spatial variation in physical climate stress over time. Socioeconomic status is represented separately through baseline mortality differentials and relative vulnerability factors, reflecting differences in underlying health, access to health care, housing quality, and adaptive capacity. This structure preserves the core Lee–Carter formulation, while enabling climate effects to vary systematically across populations without conflating baseline health differences with climate sensitivity. By distinguishing geography as a driver of exposure and SES as a driver of vulnerability, the framework supports interpretable, scenario-based analysis and reduces the risk of double counting or misattribution of climate-related effects.

In practice, SES may be either operationalized using observable proxies available in actuarial or public datasets or removed as in the simplified variant included below in subsection 3.2.5. In the baseline model, these proxies may include income bands, education level, occupation class, area-based deprivation indices, housing characteristics, access-to-health care indicators, or other demographic segmentation variables. Where direct individual-level measures are unavailable, geographic proxies (e.g., census tract deprivation scores) may be used, subject to appropriate disclosure of limitations. The objective is not to classify individuals normatively, but to capture systematic differences in adaptive capacity and baseline health conditions that may mediate the impact of climate hazards on mortality and morbidity outcomes.

In summary, the framework allows:

- Geographic variation to enter via baseline mortality $\alpha_{x,r,s}$, climate exposure $C_{t,r}$ and regional baseline differences $\lambda_{r,s}$
- SES variation to enter via baseline mortality $\alpha_{x,r,s}$ and differential climate vulnerability $\lambda_{x,r,s}$

3.2.5 CLIMATE-ADJUSTED LEE-CARTER MORTALITY MODEL (REDUCED FORM)

As a complement to the baseline specification of subsection 3.2.3, a more parsimonious version of the climate-adjusted mortality model is considered. In this alternative formulation, the climate sensitivity parameter is simplified by removing the SES dimension, replacing $\lambda_{x,r,s}$ with $\lambda_{x,r}$. The resulting specification can be expressed as:

$$\log m_{x,t,r,s} = a_{x,r,s} + b_x k_t + \lambda_{x,r} C_{t,r} + \varepsilon_{x,t,r,s}$$

A primary motivation is that, for application purposes, particularly when multiple geographical regions are involved, sufficient granular and consistent data to support robust estimation of climate sensitivity across SES groups may be limited. Estimating a fully disaggregated $\lambda_{x,r,s}$ may lead to instability, overfitting, or reliance on strong assumptions.

This simplification preserves the core structure of the model. Age-specific and geographic variation in climate sensitivity are retained, while SES differences continue to be reflected in the baseline mortality term $a_{x,r,s}$.

A further practical simplification of the proposed modeling framework may be achieved by modeling age in age bands rather than at single-year ages. Under this approach, both baseline mortality and climate sensitivity parameters are estimated for grouped age intervals (e.g., 0–19, 20–44, 45–64, 65–79, 80+), thereby reducing the

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dimensionality of the model. While some granularity is lost, the use of age bands remains consistent with the overall modeling framework and can be appropriate for high-level analysis, scenario testing, or applications where interpretability and tractability are prioritized over fine age resolution.

3.3 EXTENSION TO MORBIDITY MODELING

3.3.1 OVERVIEW AND RATIONALE

To ensure consistency across the mortality and morbidity components of the framework, the quantitative structure developed for mortality may be extended to morbidity by modeling health care utilization as an age-specific rate influenced by long-term trends and climate hazard variables. The same conceptual decomposition applies: baseline health dynamics are separated from incremental, scenario-driven climate effects.

Morbidity modeling has broad application across health care, disability, and long-term care, each of which reflects a different dimension of health-related risk. In health care, morbidity models are used to estimate the incidence, prevalence, severity, and cost progression of diseases and medical conditions, supporting pricing, reserving, care management, and public health strategy. In disability, morbidity assumptions inform the likelihood, duration, and recovery patterns associated with income interruption due to illness or injury. In long-term care, they help assess the onset and progression of functional limitations, cognitive impairment, and the resulting need for sustained support services. While the specific benefit structures, data sources, and risk drivers vary across these applications, the underlying modeling considerations are closely related: each requires a robust view of health status transitions, demographic variation, trend, heterogeneity, and uncertainty. For this reason, the discussion that follows focuses primarily on health care morbidity, while recognizing that many of the same principles can be adapted to disability and long-term care contexts.

For morbidity related to health care, the preferred modeling variable is a utilization rate per person-year, rather than health care cost. Utilization measures are more directly linked to underlying health events, whereas health care costs are influenced by additional factors such as reimbursement systems, pricing, medical inflation, and technological change. These monetary factors have a dynamic of their own, which can obscure the relationship between climate hazards and health outcomes, making utilization a more suitable basis for isolating climate-related morbidity effects. This distinction is well recognized in health economics literature, which separates the volume of care from price and institutional drivers of expenditure.[117]

3.3.2 DEFINITION OF THE MORBIDITY VARIABLE

Let $h_{x,t,r,s}$ denote a health care utilization rate at age x, time t, region r, and socioeconomic status s. This variable represents the expected number of health care events per person-year and is modeled on a log-rate scale.

Candidate definitions for $h_{x,t,r,s}$ include:

- Annual rate of inpatient hospital admission per person—this measure has strong clinical relevance and is generally widely available in administrative datasets. Both the number of admissions and total duration in days of the combined admissions within a year would be appropriate.

[117] Price Setting and Price Regulation in Health Care (OECD, 2019), https://www.oecd.org/en/publications/price-setting-and-price-regulation-in-health-care_ed3c16ff-en.html

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- Annual rate of emergency department visits per person—this measure is particularly responsive to acute climate events, such as heat waves, and is supported by epidemiological evidence linking, for instance, temperature extremes to increased emergency visits.

- Annual rate of total health care utilization per person, including primary care, specialist visits, emergency visits, and hospitalizations—this broader measure better captures both acute and chronic morbidity burdens, including those associated with longer-term exposures such as air pollution. However, it may be more sensitive to non-climate factors, such as access to care and provider behavior, and may not have the same data availability or quality.

Because $h_{x,t,r,s}$ is defined as a rate rather than a probability, values exceeding one (as may be the case, for instance, for total health care utilization per person) are not necessarily problematic within a log-rate modeling framework.

Empirical evidence supports the use of hospital admissions and emergency visits as climate-sensitive morbidity indicators. For example, exposure to air pollution has been associated with increased hospital admissions and emergency visits,[118] and elevated temperatures have been linked to higher rates of emergency department utilization.[119]

3.3.3 MORBIDITY MODEL STRUCTURE

A baseline morbidity analogue of the climate-adjusted Lee-Carter *mortality* model presented in subsection 3.2 can be written as follows:

$$\log h_{x,t,r,s} = \alpha_{x,r,s} + \beta_x \kappa_t + \lambda^{(H)}_{x,r,s} C^{(H)}_{t,r} + \varepsilon^{(H)}_{x,t,r,s}$$

where:

$h_{x,t,r,s}$ is the health care utilization rate at age x, time t, region r, and socioeconomic group s;

$\alpha_{x,r,s}$ is the baseline morbidity level for each age-region-SES cell;

β_x is the non-climate morbidity trend over time;

κ_t is the morbidity index at time t, representing the general level of morbidity in the population;

$C^{(H)}_{t,r}$ is the climate hazard variable relevant to morbidity in region r at time t;

$\lambda^{(H)}_{x,r,s}$ is the group-specific vulnerability multiplier for morbidity at age x; and

$\varepsilon^{(H)}_{x,t,r,s}$ is the residual term.

This specification mirrors the structure of the climate-adjusted mortality model but replaces the mortality rate with a health care utilization rate. The term $\alpha_{x,r,s}$ captures baseline morbidity differences across age, geography, and socioeconomic status; κ_t captures long-term non-climate changes in morbidity or health care utilization; and the

[118] Health Impacts of Air Pollution (World Health Organization), https://www.who.int/teams/environment-climate-change-and-health/air-quality-energy-and-health/health-impacts

[119] Climate Change and Human Health: Heat and Health Technical Report (U.S. Environmental Protection Agency), https://www.epa.gov/climate-research/human-health-and-climate-change-research

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climate term $\lambda_{x,r,s}^{(H)} C_{t,r}^{(H)}$ represents the incremental effect of climate hazards on morbidity. The superscript (H) is used to distinguish morbidity-specific climate sensitivity and vulnerability parameters from their mortality counterparts, recognizing that the relevant climate-health pathways and magnitudes may differ.

Analogously to the simplified variant introduced for the mortality modeling framework (subsection 3.2.5), a simplified variation of the morbidity baseline modeling framework is included in subsection 3.3.5.

3.3.4 CLIMATE VARIABLES MOST RELEVANT FOR MORBIDITY

While heat is expected to play a major role in both mortality and morbidity, morbidity may be influenced by a broader set of climate-sensitive pathways, many of which are likely more pronounced for illness than for death. Examples include air pollution (e.g., $PM_{2.5}$, ozone) or prolonged precipitation (e.g., leading to gastrointestinal infections, humidity-induced respiratory infections, mental health impacts, and disruptions in health care access). These climate–morbidity pathways have implications over different time horizons: acute exposures influence short-term utilization, whereas chronic exposures contribute to long-term shifts in disease burden and system capacity. Because the pathways can differ from those driving mortality (in nature, in timing or in magnitude of impact), the optimal climate variables for morbidity may not be fully identical to those used in the mortality model, even though the overall modeling structure remains the same.

3.3.5 CLIMATE-ADJUSTED LEE-CARTER MORBIDITY MODEL (REDUCED FORM)

As a complement to the baseline specification of subsection 3.3.3 (and to keep consistency with the mortality modeling framework presented in this report), a more parsimonious version of the climate-adjusted morbidity model is considered. In this alternative formulation, the climate sensitivity parameter is simplified by removing the SES dimension, replacing $\lambda_{x,r,s}$ with $\lambda_{x,r}$. The resulting specification can be expressed as:

$$\log h_{x,t,r,s} = \alpha_{x,r,s} + \beta_x k_t + \lambda_{x,r}^{(H)} C_{t,r}^{(H)} + \varepsilon_{x,t,r,s}$$

A primary motivation is that, for application purposes, particularly when multiple geographical regions are involved, sufficient granular and consistent data to support robust estimation of climate sensitivity across SES groups may be limited. Estimating a fully disaggregated $\lambda_{x,r,s}$ may lead to instability, overfitting, or reliance on strong assumptions. This simplification preserves the core structure of the model. Age-specific and geographic variation in climate sensitivity are retained, while SES differences continue to be reflected in the baseline morbidity term $\alpha_{x,r,s}$.

Likewise, a further practical simplification of the framework may be achieved by modeling age in age bands rather than at single-year ages. Under this approach, both baseline mortality and climate sensitivity parameters are estimated for grouped age intervals (e.g., 0–19, 20–44, 45–64, 65–79, 80+), thereby reducing the dimensionality of the model. While some granularity is lost, the use of age bands remains consistent with the overall modeling framework and can be appropriate for high-level analysis, scenario testing, or applications where interpretability and tractability are prioritized over fine age resolution.

3.4 CLIMATE HAZARD VARIABLES AND SCENARIO INPUTS

3.4.1 ROLE OF CLIMATE HAZARD VARIABLES IN THE MODELING FRAMEWORK

Climate hazard variables (such as temperatures, wind speeds, humidity or levels of rainfall) provide the quantitative link between externally defined climate scenarios and actuarial mortality and morbidity models. In the framework adopted in this report, climate hazards represent physical manifestations of climate change that may affect population health outcomes over time and across geographies. These variables are introduced as exogenous drivers,

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ensuring that climate risk enters the model through transparent and traceable inputs rather than through indirect inference from historical mortality or morbidity experience.

3.4.2 EXTERNAL SCENARIO FRAMEWORKS AND DATA SOURCES

Climate hazard variables are sourced exclusively from externally governed and widely recognized scientific frameworks. These sources are selected for their credibility, transparency, and relevance to long-term climate-risk assessment. They include actuarial, regulatory, and scientific bodies that provide scenario-consistent climate pathways and observational datasets suitable for population-level analysis.

The use of multiple external sources reflects differences in geographic coverage, variable availability, and scenario design. Where scenario-based projections are required, preference is given to internally consistent frameworks that explicitly articulate underlying assumptions regarding emissions, socioeconomic development, and physical climate response.

The main data sources, which can be incorporated into the models without modification, notably include:

- Actuaries Climate Index
- Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) of the Sixth Assessment Report (AR 6) of the IPCC (or collectively, "IPCC AR6 SSP-RCP Pathways")
- Copernicus Climate Change Service
- National Oceanic and Atmospheric Administration (NOAA)

Actuaries Climate Index (ACI)

The Actuaries Climate Index—developed by the American Academy of Actuaries, Canadian Institute of Actuaries, Casualty Actuarial Society, and Society of Actuaries—tracks changes in climate extremes and sea levels in the United States and Canada.[120] It provides an aggregated, actuarially oriented set of indicators designed to track changes in extreme weather and climate conditions over time. It combines multiple components—such as temperature extremes, heavy precipitation, drought, and sea level—into a standardized index that is readily interpretable by actuarial practitioners. In this report, the ACI is referenced as a high-level indicator of physical climate stress, supporting comparative and trend-based analysis rather than detailed physical modeling. This is an example of a multivariable, aggregate measure that focuses on extreme outcomes.

The ACI has inspired comparable initiatives and adaptations in other jurisdictions, demonstrating the portability of its underlying methodology. Notably, the Australian Actuaries Climate Index (AACI),[121] applies a similar framework tailored to regional climate conditions and data availability. More broadly, the ACI methodology is designed to be replicable in other countries where suitable, high-quality climate data exist. The ACI sponsors have highlighted its adaptability, and feasibility work has explored extensions to additional regions, including the UK, Spain, France, and Colombia,[122] to name a few. These developments underscore the potential for constructing consistent, region-specific climate indicators that support actuarial analysis while maintaining alignment with a common methodological foundation.

Finally, although the ACI is useful as a broad climate indicator, additional hazard variables may be needed for life and health applications. Indeed, the structure of the ACI suggests a stronger orientation toward physical hazard

[120] Actuaries Climate Index, https://actuariesclimateindex.org/home/

[121] Australian Actuaries Climate Index, https://www.actuaries.asn.au/climate-index

[122] Colombian ACI (in Spanish) (Asociación Colombiana de Actuarios, retrieved in 2026), https://icacolombia.netlify.app/

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monitoring than toward life and health pathways. Its components align naturally with catastrophe and property-related climate exposures while, for instance, no explicit air-pollution component is included.

IPCC AR6 SSP-RCP Pathways

The Sixth Assessment Report[123] (AR6) of the IPCC provides forward-looking climate projections structured around combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). These pathways describe internally consistent futures linking emissions, socioeconomic development, and physical climate response. In this report, SSP–RCP pathways are used to anchor long-term climate hazard trajectories and ensure alignment with internationally recognized scientific scenarios.

Copernicus Climate Change Service

The Copernicus Climate Change Service is a European Union initiative that delivers authoritative, open-access data and analyses on the Earth's climate. It supports adaptation and mitigation policies across Europe and globally by providing consistent, quality-assured climate information based on satellite, in-situ observations, and advanced modeling.[124] Copernicus provides high-quality observational data and reanalysis products for a wide range of climate variables, including temperature, air quality, and atmospheric composition. The datasets compiled by Copernicus offer consistent spatial and temporal coverage across regions, making them suitable for population-level exposure analysis. In this research project, Copernicus data are used to inform regional climate hazard measures and support consistency between observed climate patterns and scenario-based projections.

National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration (NOAA) is a scientific and regulatory agency of the United States Department of Commerce. It focuses on understanding and predicting changes in climate, weather, oceans, and coasts, and on managing and conserving marine and coastal resources.[125] NOAA provides authoritative observational climate and environmental data, including temperature records, air quality indicators, and extreme weather statistics. The datasets compiled by NOAA are widely used in climate and public-health research and support historical context for climate hazard analysis. In this framework, NOAA data serve as an additional observational reference for climate variables relevant to mortality and morbidity modeling, complementing scenario-based inputs.

[123] Sixth Assessment Report, IPCC, https://www.ipcc.ch/assessment-report/ar6/

[124] Copernicus, https://climate.copernicus.eu/

[125] National Oceanic and Atmospheric Administration, https://climate.copernicus.eu/

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Table 3.1
CLIMATE HAZARD VARIABLES, INDICATIVE MEASURE, AND RELEVANCE TO MORTALITY & MORBIDITY

Variable	Indicative Measure	Example of Relevance to Mortality & Morbidity
Temperature anomaly	Deviation from historical mean temperature	Heat stress, cardiovascular and respiratory mortality
Extreme heat days or heat wave duration	Frequency or number of consecutive days above temperature thresholds[126]	Acute mortality, hospital admissions, heat-related indices
$PM_{2.5}$ concentration	Ambient fine particulate matter levels[127]	Respiratory and cardiovascular mortality and morbidity
Wildfire smoke exposure index	Smoke or aerosol indices linked to wildfires	Respiratory morbidity, excess short-term mortality[128]
Composite climate index	Aggregated indicator of several physical climate stress variables	Broad proxy for climate-related health stress

The variables listed in table 3.1 above represent a core set of climate hazard indicators selected for parsimony and direct relevance to mortality and morbidity outcomes. Depending on geographic context, data availability, and intended application, additional non-core variables may be considered. These may include extreme precipitation and flooding indices, drought severity measures, sea-level rise indicators, tropical cyclone intensity metrics, vector suitability indices, humidity or wet-bulb temperature measures, and other region-specific physical risk factors. Materiality, data quality, and consistency with the overall modeling framework are among the considerations that may influence the inclusion of additional variables.

3.4.3 SELECTION OF CLIMATE HAZARD VARIABLES RELEVANT TO LIFE AND HEALTH OUTCOMES

The climate hazard variables used in this report are selected based on documented relevance to mortality and morbidity outcomes in epidemiological and public health literature. Variables are chosen to capture key physical pathways—such as heat stress, air quality degradation, and wildfire exposure—while remaining sufficiently aggregated for actuarial modeling purposes.

The framework is flexible with respect to the specific hazard variables used, allowing for substitution or extension as data availability and scientific understanding evolve. In addition to heat stress, air quality degradation, and wildfire exposure, other climate hazards may also be relevant to mortality and morbidity outcomes depending on calendar year, geographic context, and portfolio characteristics. These may include extreme precipitation and flooding indices, drought severity measures, sea-level rise indicators for coastal populations, tropical cyclone intensity metrics, humidity or wet-bulb temperature measures, and vector suitability indices linked to climate-sensitive infectious diseases. Such variables reflect additional physical pathways through which climate change may affect health, including waterborne disease risk, infrastructure disruption, displacement, food and water insecurity, and vector-borne transmission dynamics. While these hazards are not necessarily included in the core modeling set for

[126] See the **Heat wave** entry in Wikipedia for illustrative definitions of heat waves, https://en.wikipedia.org/wiki/Heat_wave#Definitions

[127] This includes not only wildfire smoke but also chronic air pollution from traffic and industry, residential heating, or agricultural burning, and wildfires.

[128] Wildfire smoke exposure should be added only if wildfire activity is material in the modeled geography, and it should be considered a subset of $PM_{2.5}$ to avoid double counting.

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reasons of parsimony and data consistency, the framework allows for their incorporation where material, supported by credible data sources, are aligned with the intended purpose of the analysis.

From a modeling perspective, climate hazards may be incorporated either as individual (single hazard) variables or as part of a composite (multi-hazard) index, such as those developed in the ACI. A single-hazard approach allows for clearer interpretation of the relationship between a specific climate driver and health outcomes, facilitating sensitivity analysis. However, it may not fully capture the interacting effects of multiple hazards. In contrast, multi-hazard indices aggregate several climate indicators into a unified measure of climate stress, offering a more holistic representation of overall climate conditions.[129] This approach can be useful for high-level monitoring, benchmarking, or communication, but may obscure the contribution of individual hazards and introduce additional modeling assumptions through the aggregation process. The choice between single- and multi-hazard representations depends on the purpose of the analysis, data availability, and the balance between interpretability and comprehensiveness. In this report, the emphasis is primarily on single-hazard variables to preserve transparency, while recognizing that composite indices may serve as complementary tools.

The aim of this research paper is not to exhaustively model all possible climate-health pathways, but to represent material drivers in a manner that is consistent with the scope and purpose of the analysis.

3.4.4 SCENARIO TRACEABILITY AND TREATMENT OF CLIMATE INPUTS

Climate hazard inputs are incorporated into the model as externally sourced data, without internal modification or statistical adjustment aimed at improving model fit. This approach helps to ensure that results remain fully traceable to the underlying climate scenarios and data sources. However, in certain cases, these inputs are subject to limited and transparent preprocessing before being used in the modeling framework. Such preprocessing is intended to help ensure consistency, comparability, and numerical stability rather than to enhance model performance. For example, outliers may be normalized, variables may be transformed, and units may be standardized. These steps are applied in a controlled and documented manner to preserve the interpretability of the climate inputs.

Climate scenarios are typically treated as plausible alternative futures, not as probabilistic forecasts. The framework does not assign likelihoods to scenarios or combine them into a single expected outcome. Instead, results are interpreted comparatively across scenarios to assess sensitivity and potential ranges of impact.

3.4.5 LIMITATIONS OF CLIMATE HAZARD INPUTS

Climate hazard datasets differ in spatial resolution, temporal coverage, and underlying modeling assumptions. In addition, available indicators may only partially capture the complexity of climate-health interactions. Documenting these limitations may be helpful because they provide important context for interpreting results and conclusions, sensitivity analysis and model validation. The presence of such limitations reinforces the role of professional judgment and supports the use of scenario-based analysis rather than point estimation.

A further consideration arises when models are used for long-term predictions (such as the impact of climate risk on life expectancy). To help ensure consistency with scenario-based projections, the climate variables used to calibrate the model would ideally be available within established scenario frameworks, such as those developed by the IPCC or the NGFS. In practice, however, not all relevant health-related climate indicators—particularly more complex or derived variables, such as certain air quality (e.g., $PM_{2.5}$)—are consistently available across such scenarios. This

[129] Notwithstanding, it may be useful to check the correlation among individual hazards, e.g., extreme heat can lead to more wildfires; tropical depressions can lead to more flooding, etc.

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creates a trade-off between relevance for the calibration and ability to implement for long-term projections. While the modeling framework is not restricted to variables such as temperature or precipitation, acknowledging these data availability constraints and reflecting them in model design, interpretation and use may be helpful.

3.5 CALIBRATION APPROACH

The calibration of climate-adjusted mortality and morbidity models differs fundamentally from calibration exercises in traditional actuarial modeling. The challenges arise from the non-stationary nature of climate hazards, the limited length and relevance of historical data, and the reliance on forward-looking scenarios rather than experience-based extrapolation. Calibration is, therefore, guided by the intended purpose of the model, the availability and quality of data, and the need for transparency in the use of assumptions and expert judgment.

3.5.1 CALIBRATION PRINCIPLES

For this framework, actuarial models are designed to be appropriate for their intended purpose, to use reasonable model assumptions, and to be accompanied by clearly communicated uncertainty and limitations. In the context of climate-related mortality and morbidity modeling, these principles imply that calibration prioritizes plausibility, interpretability, and robustness over statistical fit.

Calibration in this report is not intended to identify a single best estimate of expected climate impact, as uncertainties surrounding future climate pathways and the potential for physical climate tipping points make it inappropriate to rely on any single point estimate. Instead, it seeks to establish defensible reference parameter values and ranges that behave consistently under scenario analysis and sensitivity testing. Model outcomes are intended to be understood in light of their reliance on assumptions, data constraints, and expert judgment, particularly when historical data are insufficient to support traditional calibration techniques.

3.5.2 CALIBRATION OF BASELINE MORTALITY AND MORBIDITY COMPONENTS

Parameters governing baseline mortality and morbidity—patterns with respect to age and sex, geographic and socioeconomic differentials, and non-climate temporal trends—are calibrated primarily using historical actuarial data and established demographic techniques.[130] These components are intended to capture long-standing demographic, socioeconomic, and health system influences that are not explicitly climate-driven. Calibrating these baseline elements independently of climate hazard variables preserves continuity with traditional actuarial practice and supports clearer attribution of incremental effects arising from climate-related exposures.

The calibration of baseline components may be conducted independently of climate variables to the extent practicable. This separation helps avoid confounding baseline health differences with climate effects and supports clearer interpretation of results. Data sources, methods, and limitations are documented, and any material data deficiencies are disclosed.

3.5.3 CALIBRATION OF CLIMATE HAZARD INPUTS

Climate hazard variables are treated as exogenous inputs to the model and are derived from externally defined climate scenarios rather than inferred from mortality or morbidity experience. This reflects the recognition that future climate conditions cannot be reliably extrapolated from historical variability alone.

[130] Some well-established techniques include extensions of the Lee-Carter model for mortality forecasting, graduation and smoothing techniques, time-series and trend models, credibility and experience-based methods.

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The selection and use of these inputs are guided by the model's purpose and credibility of the external sources. Calibration in this context does not involve statistical estimation of climate trajectories, but rather the consistent translation of externally specified climate pathways into actuarially usable inputs. The provenance, scope, and limitations of these inputs should be explicitly documented.

3.5.4 CALIBRATION OF CLIMATE-RELATED PARAMETERS

Climate-related parameters are calibrated using a step-wise approach that separates baseline mortality from climate-driven effects. The calibration is performed sequentially, allowing each component of the model to be identified using appropriate data sources. Once baseline mortality parameters are estimated, climate-related effects are calibrated by linking deviations in mortality to selected climate hazard variables, which also may be combined into multi-hazard indices. This approach improves parameter stability, enhances interpretability, and reduces the risk of overfitting, especially in the presence of limited data.

The calibration period requires careful consideration. In particular, practitioners may choose to exclude the years 2020–2021 or even 2020–2022 due to the extraordinary mortality patterns associated with the COVID-19 pandemic. These years reflect a structural shock driven by non-climate factors, which may distort the estimation of underlying climate–mortality relationships if included without adjustment. Vulnerability is not necessarily static and may change over time. Empirical evidence suggests that adaptive capacity can evolve. In Western Europe, for instance, reductions in heat-related mortality following the deadly heat wave of the summer 2003[131] indicate that populations may become less vulnerable as awareness, preparedness, and response mechanisms improve. The choice of the calibration period may, therefore, reflect, where feasible, structural changes in vulnerability rather than assuming that historical relationships remain constant.

Population- or segment-specific differences in climate response are introduced through relative vulnerability factors $\lambda_{x,r,s}$. These factors are calibrated as multipliers rather than as independent absolute effects, consistent with the conceptual separation between baseline health status and incremental climate vulnerability.

Normalization and identifiability constraints are applied to the climate variables $C_{t,r}$ where necessary to help ensure that climate-related parameters are well defined and aggregate and disaggregated results remain consistent.

3.5.5 ROLE OF EXPERT JUDGMENT AND USE OF PARAMETER RANGES

Given the absence of long historical calibration periods for climate-related health effects, expert judgment plays an important role in calibration. The framework intends for such judgment to be explicitly documented, justified, and subjected to review and challenge.

Parameter estimates are not treated as precise point values. Instead, calibration establishes reference values and plausible ranges, which are subsequently explored through sensitivity and stress testing. This approach reflects the scenario-based nature of the analysis and supports responsible use of model outputs as decision-support tools rather than deterministic forecasts.

3.5.6 DOCUMENTATION, REVIEW, AND RECALIBRATION

The framework intends for all calibration choices—including data sources, external references, assumptions, constraints, and expert judgments—to be fully documented. Calibration is subject to review as part of the model

[131] Death toll exceeded 70,000 in Europe during the summer of 2003 (Robine et al, 2007), https://pubmed.ncbi.nlm.nih.gov/18241810/

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governance framework described later in this report, consistent with modeling expectations regarding transparency and model risk management.

The calibration is intended to be revisited periodically as new scientific evidence, improved data, or updated climate scenarios become available. This helps ensure that the model remains relevant and fit for purpose as the understanding of climate-related health risks evolves.

3.6 RESULTS INTERPRETATION, SENSITIVITY, AND STRESS TESTING

The outputs of climate-adjusted mortality and morbidity models are intended to be interpreted as conditional, scenario-dependent outcomes, rather than as unconditional forecasts or point estimates of future experience. Unlike traditional actuarial projections that extrapolate historical trends under implicit stationarity assumptions, results from the climate-adjusted framework reflect the interaction between baseline health dynamics and externally-specified climate pathways. Accordingly, interpretation emphasizes relative effects, directional insights, and sensitivities rather than numerical precision.

A structured interpretation begins with decomposing results into their principal components. Baseline mortality or morbidity levels reflect long-standing demographic, socioeconomic, and health system factors embedded in the underlying actuarial model. The non-climate time component captures expected improvements or deteriorations unrelated to climate change, such as medical progress or behavioral change. The climate component represents an incremental adjustment driven by the assumed evolution of climate hazards, scaled by age-specific sensitivity and population vulnerability. This decomposition does not eliminate attribution uncertainty, since climate-related effects may interact with broader demographic, behavioral, medical, and socioeconomic trends. However, it provides a clearer analytical framework for distinguishing modeled climate adjustments from familiar actuarial drivers, identifying where attribution is more or less robust, and supporting sensitivity testing around areas of uncertainty.

The analytical value of the framework lies primarily in comparative analysis across scenarios, population segments, and time horizons. Differences between milder and more severe climate pathways illuminate potential ranges of impact, while variation across geographies, socioeconomic groups, and age cohorts highlights the role of exposure and vulnerability. Age-specific analysis is particularly important as climate effects may be concentrated among older ages or populations with pre-existing health vulnerabilities. Aggregate indicators alone (e.g., life expectancy at birth for the mortality framework) may obscure material distributional effects.

When interpreting short-term model outputs, the possibility of a harvest effect or a trend bounce-back may be relevant. For example, hurricanes can suppress short-term health care utilization due to deferred care, while heat waves may generate a sharp spike followed by a temporary dip as the system normalizes. For health insurance applications, it may be helpful to interpret results across both short- and long-term horizons, recognizing that acute events primarily affect near-term financial outcomes, while chronic climate stressors shape long-term disease burden and infrastructure needs.

Sensitivity and stress testing are integral to responsible interpretation. Given the forward-looking and scenario-driven nature of climate modeling, results are inherently sensitive to assumptions regarding climate sensitivity, vulnerability multipliers, and hazard selection. Sensitivity analysis evaluates how incremental changes in key parameters affect outcomes, helping identify which assumptions materially influence projections. Stress testing extends this analysis by examining severe but plausible combinations of assumptions, such as higher physical risk pathways, elevated vulnerability, and limited adaptive capacity. This testing exercise is particularly relevant for long-term risk management applications, including capital adequacy assessments and ORSA, where resilience under adverse conditions is central.

A key principle in conducting sensitivity and stress testing is internal consistency. Within this framework, climate hazard trajectories, vulnerability assumptions, and baseline trends are intended to vary coherently with the

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underlying scenario narratives. Using arbitrary parameter combinations may produce misleading conclusions if they are not aligned with internally-consistent scenario assumptions. The sensitivity analysis presented here is multidimensional, assessing variation across age, geography, socioeconomic status, and projection horizon to capture distributional and long-term effects.

Importantly, neither baseline results nor stress outcomes are interpreted probabilistically unless explicitly stated. The objective is not necessarily to identify a "most likely" or "worst-case" outcome, but to assess the range of potential impacts and the robustness of conclusions under alternative assumptions. However, where the application requires an expected, best-estimate, or decision-useful central outcome (such as for pricing or reserving), this will require the development and documentation of an appropriate probabilistic or weighting framework. This may involve assigning scenario probabilities, using exposure-weighted assumptions, developing a central best-estimate scenario, or applying credibility and expert judgment to translate scenario results into actionable assumptions. Within the framework presented in this report, results are communicated in a manner consistent with their intended use and supported central estimates where required for pricing or underwriting decisions. In all cases, the framework also intends for the communication to disclose the key drivers, uncertainties, limitations, and the extent to which the results reflect judgment rather than statistically-calibrated probabilities.

In this way, interpretation and sensitivity analysis of results together support informed actuarial judgment, prudent risk management, and transparent communication, while avoiding false precision in the face of deep uncertainty and structural change.

3.7 MODEL VALIDATION, REASONABLENESS CHECKS, AND GOVERNANCE

Validation and governance are components of the quantitative analysis of climate-related mortality and morbidity risks presented in this report. Given the forward-looking, scenario-dependent, and inherently uncertain nature of climate risk modeling, validation approaches differ in some respects from those commonly applied to traditional experience-based actuarial models. While standard actuarial tools such as back-testing, sensitivity analysis, and residual diagnostics remain relevant, their interpretation reflects the characteristics of scenario-based modeling. Within the framework presented here, validation is intended to assess appropriateness for purpose, internal coherence, plausibility, and responsible use, rather than statistical optimality or predictive accuracy alone.

3.7.1 VALIDATION FRAMEWORK

Model validation techniques include back-testing against selected historical events where feasible, sensitivity analysis of key parameters, and residual analysis of baseline components. Back-testing provides limited historical context but cannot establish predictive accuracy under future climate conditions. Sensitivity analysis evaluates how results respond to changes in climate sensitivity parameters, vulnerability multipliers, and hazard assumptions, supporting robustness and interpretability. Residual diagnostics help assess structural soundness of the baseline mortality or morbidity components.

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Beyond these technical tools, this validation framework incorporates cross-checks and triangulation:

- Cross-checks assess whether results are internally coherent across geographies, population groups, and scenarios, including whether the direction and relative magnitude of impacts are plausible.
- Triangulation compares outputs with multiple independent sources of evidence, such as published studies, expert judgment, and alternative model formulations, to test whether conclusions are robust rather than driven by any single assumption or dataset.

Within the framework presented in this report, model outputs are assessed for high-level consistency with external scientific and epidemiological evidence, including qualitative findings from bodies such as the IPCC and scenario narratives from the NGFS. These comparisons serve as plausibility benchmarks rather than calibration targets, confirming that modeled impacts are broadly aligned with current scientific understanding. As part of this assessment, the model user may also define reasonable ranges, tolerance thresholds, or trigger points for key outcomes. Results falling outside these ranges would not necessarily indicate that the model is incorrect, but they may reflect differences in scenarios, assumptions, data, methodology, or applications, and may, in some cases, indicate the need for revised assumptions, additional sensitivity testing, or management action. This approach supports both scientific consistency and practical model governance by identifying when emerging results are sufficiently different from expectations to warrant escalation or refinement.

Given the interdisciplinary nature of climate-related health risk analysis, the reasonableness assessment presented in this framework incorporates perspectives beyond actuarial review. Dialogue with climate scientists, epidemiologists, public health experts, and environmental data specialists can strengthen conceptual soundness and may mitigate the risk of misinterpreting scientific findings. Independent actuarial review and professional judgment also remain integral elements of the validation process in order to emphasize transparency, disclosure of limitations, and context-appropriate validation methods.

The validation framework comprises multi-layered and purpose-driven components. Back-testing provides historical context, sensitivity analysis assesses robustness, residual analysis supports structural checks, and interdisciplinary plausibility review enhances scientific alignment. Together, these elements may support responsible actuarial application while acknowledging the structural uncertainty inherent in climate-related risk assessment.

Structured Validation Process

Implementation of the models described in this report are intended to be subject to a structured validation process. Prior to use in actuarial analysis, scenario assessment, or decision support, model implementations are intended to satisfy documented validation criteria confirming that they are fit for purpose, internally consistent, appropriately governed, and aligned with professional standards of practice. A formal validation checklist may provide a practical framework for documenting validation activities and supporting professional judgment.

3.7.2 GOVERNANCE FRAMEWORK

The proposed quantitative framework for climate-related mortality and morbidity risk is underpinned by a governance structure. Model design, assumptions, and data inputs and outputs are documented in relation to their intended purpose and reviewed regularly as scientific knowledge, data availability, and external guidance evolve.

Model Purpose and Scope

The quantitative framework for climate-related mortality and morbidity risk aims to be suitable for long-term, population-level analysis, including scenario analysis, stress testing, pricing sensitivity analysis, reserving considerations, capital assessment, and ORSA applications. Models may be application-specific and may deal with a selected range of scenarios. Neither model is intended for short-term forecasting, individual underwriting, or clinical inference. Use is intended to be restricted to contexts consistent with these objectives.

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Ownership and Accountability
Clear ownership resides within the actuarial function, with defined responsibility for model development, maintenance, documentation, and appropriate use. Accountability includes a periodic review of assumptions, updating of external climate inputs, and transparent communication of limitations.

Assumptions and Parameter Governance
Within the framework presented in this report, key assumptions—including climate hazard selection, choice of central and alternative scenario pathways, calibration of climate sensitivity parameters, and specification of vulnerability multipliers—are explicitly documented. Assumptions derived from scientific or epidemiological sources are referenced and periodically reviewed. Material changes are subject to formal approval, documentation, and version control.

Data Governance, Quality, and External Climate Inputs
Climate hazard variables and scenario pathways used in this mortality and morbidity modeling framework may be drawn from externally governed sources, such as the NGFS and IPCC, to promote consistency with established scientific benchmarks. Within this framework, the selection, use, and reliance on these inputs are subject to professional judgment, documentation, and disclosure of limitations. Because many climate variables are forward-looking, modeled, or scenario-based rather than purely observational, information on their provenance and quality is included and assists with transparency.

To support structured disclosure and comparability, climate inputs may be categorized using a simple data-quality tiering framework:

- Tier 1 – Direct Observational Data:
  Measured, instrument-based climate or air-quality observations (e.g., historical temperature records, monitored $PM_{2.5}$ concentrations) from recognized meteorological or environmental agencies.

- Tier 2 – Reanalysis or Harmonized Datasets:
  Data products combining observations with physical climate models to provide consistent spatial and temporal coverage.

- Tier 3 – Modeled Scenario Outputs:
  Forward-looking climate projections derived from structured scenario frameworks (e.g., SSP–RCP pathways, NGFS scenarios), reflecting internally consistent assumptions about emissions, socioeconomic development, and physical climate response.

- Tier 4 – Proxy or Derived Indicators:
  Constructed indices or aggregated measures (e.g., composite climate stress indicators, deprivation-based exposure proxies) developed to align scientific variables with actuarial modeling requirements.

For each material climate input, the data source, update frequency, geographic coverage, methodological basis, and known limitations are documented. Where reliance is placed on third-party datasets or models, this reliance is disclosed, including any material constraints on independent verification.

Where climate data are unavailable, insufficiently granular, temporally inconsistent, or otherwise not fit for the intended purpose, proportionate alternatives may be used, including proxy indicators, interpolation, scenario-aligned assumptions, or expert judgment, subject to clear documentation and disclosure of associated uncertainty. Conversely, where particular variables are not relevant or material to the exposure, geography, peril, or projection horizon being assessed, they may be excluded on a reasoned basis to avoid unnecessary complexity and spurious precision.

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The purpose of this tiering approach is to enhance transparency regarding input characteristics and potential limitations. The structure is conceptually similar to tiered data-quality disclosure approaches used in climate-related financial reporting frameworks, such as the data quality scoring methodology developed by the Partnership for Carbon Accounting Financials[132] (PCAF). This structured documentation is intended to support informed interpretation of results, facilitate validation and review, and strengthen governance over externally-sourced climate data used in climate-related mortality and morbidity modeling.

Model Peer Review and Change Management
Validation focuses on structural reasonableness, robustness, and consistency with external evidence rather than backward-looking fit alone. Independent peer reviews, second opinions, and challenges are integral to the validation process. All material changes—including structural modifications, recalibration, or scenario updates—are intended to be subject to formal change management procedures, with version histories maintained to help ensure auditability and traceability.

Use of Expert Judgment
Given the evolving scientific landscape and limited historical calibration data, interdisciplinary expert judgment can play a central role in model design and interpretation. This framework's governance processes include documentation of such judgment, its rationale, and any associated sensitivity testing where appropriate.

Communication and Responsible Use
Model outputs are intended to be communicated with contextual information regarding assumptions, uncertainty, and limitations. Results are intended to be presented as conditional on climate scenarios rather than as probabilistic forecasts, taking care to avoid false precision and support informed actuarial decision-making rather than mechanical reliance on model outputs.

Modelers may want to pay particular attention to ensuring consistency between quantitative outputs and narrative disclosures, especially in relation to scenario analysis, risk assessment, and long-term resilience. This alignment can facilitate stakeholder clarity and responsible integration of climate-related health risk analysis within broader financial and sustainability reporting.

3.8 PRACTICAL IMPLICATIONS FOR ACTUARIAL PRACTICE

The preceding sections have outlined the quantitative framework, key assumptions, sensitivities, and governance considerations underpinning the climate-adjusted mortality and morbidity models used in this research report. While these elements help to ensure methodological soundness and appropriate model use, their relevance ultimately depends on how they inform real actuarial decisions. For example, climate-related risks may have indirect effects on asset values, investment returns, discount rates, and broader asset-liability management considerations, particularly where physical or transition risks affect economic conditions, sector exposures, or market valuations. This section shifts the focus to practical actuarial applications across product lines and enterprise functions, illustrating how climate-informed risk modeling can support actuarial judgment in pricing, reserving, capital assessment, ORSA, and other related applications. The discussion below emphasizes use cases, interpretation, and professional judgment rather than technical detail, reflecting the applied nature of actuarial work.

[132] Partnership for Carbon Accounting Financials (PCAF), Global GHG Accounting and Reporting Standard for the Financial Industry (https://carbonaccountingfinancials.com/files/standard-launch-2025/PCAF-PartA-2025-Full-Document-Clean.pdf), which introduces a Data Quality Score (DQS) framework for classifying the quality of emissions data inputs.

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3.8.1 LIFE INSURANCE PRODUCTS

Climate change creates a new driver of longevity and mortality risk for life insurers. Short-term events such as heat waves or severe storms can generate mortality spikes, particularly among individuals with pre-existing health conditions. However, in line with qualitative climate risk analysis, climate-related effects may be most material for long-duration products such as annuities, term life policies, and guaranteed lifetime income contracts. For such long-term products, traditional actuarial techniques rely on historical mortality improvement patterns to inform future biometric risks.

Climate-related hazards, such as sustained heat stress, persistent air pollution, and vector-borne disease, may disrupt these statistical patterns by increasing baseline mortality rates or slowing future improvements in longevity, especially at older ages and for vulnerable populations. Climate-related mortality impacts may also interact with socio-economic factors, potentially altering the composition and risk profile of insured populations. Climate-related physical and transition risks can also affect life insurers through economic impacts on asset values (e.g., stranded assets), discount rates, inflation, lapse rates, or profit-sharing mechanisms based on investment income.[133]

These effects can influence price setting, reserving adequacy, long-term risk management and capital requirements, especially for products with long durations or embedded guarantees.[134] Climate scenario analysis can highlight how alternative futures (e.g., 1.5°C vs 3°C temperature pathways) may shift expected mortality improvements and longevity exposures, and stress testing can identify potential adverse outcomes beyond the range implied by historical experience alone. Life actuaries may consider climate-adjusted mortality models (for example, the climate-augmented Lee–Carter model presented in this report) to assess scenario impacts on mortality trends under different climate pathways.

3.8.2 HEALTH INSURANCE PRODUCTS

Health insurance products are more directly exposed to climate-related morbidity impacts. Climate change is already associated with increased rates of heat exhaustion, respiratory distress related to air pollution, and vector-borne diseases.[135] Extreme weather events (for example, hurricanes[136]) can place sudden pressure on health care systems, resulting in a mix of surges in emergency care, hospitalizations, and post-event complications while, at the same time, temporarily reducing non-urgent care and elective procedures and leading to a subsequent catch-up period once services resume (trend bounce-back).

Chronic climate-related stressors can also increase the prevalence and severity of respiratory, cardiovascular, and heat-related illnesses, leading to higher health care utilization and claims. Over time, climate-related morbidity trends can influence medical cost inflation, utilization patterns, and the incidence of chronic disease. Traditional morbidity models are often built on historical hospitalization, diagnosis, and claims data, and may not fully capture such climate-related risk dynamics. Incorporating climate hazard variables (e.g., extreme heat days, ozone / $PM_{2.5}$ levels) into morbidity incidence models can, therefore, help quantify potential shifts in utilization and cost trends.

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[133] A detailed discussion of these investment-side considerations falls outside the direct scope of this report.

[134] For products with non-guaranteed elements, insurers may also adjust certain parameters after issue, which can partially mitigate these effects.

[135] In some geographic settings, short-term climate-related effects may also be favorable, for example, where milder winters or fewer cold-related events contribute to reduced hospitalization or lower near-term morbidity incidence. These effects may partially offset adverse impacts in the near term, although they are not uniform across geographies, populations, or perils.

[136] Health and Hurricanes - Studying Disparate Health Impact of Extreme Climate Events, 2017-2020, SOA Research Institute (Webb et al., 2024), https://www.soa.org/resources/research-reports/2022/health-hurricanes-impact/

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From a pricing perspective, including climate risk considerations in morbidity models can inform adjustments to expected claim frequency and severity assumptions. From a reserving perspective, climate-related scenarios can help assess whether adverse development patterns may emerge and current reserves remain adequate under a range of plausible future conditions. Within the framework presented in this report, scenario analysis serves as one input to reserve-related analysis rather than the sole basis for reserve assumptions. The selection of scenarios or assumption set used for reserve setting is intended to be based on the applicable reserving framework, the purpose of the reserve, the credibility of the evidence, and expert judgment regarding best-estimate assumptions and any required margins or provisions for adverse deviation. Different climate scenarios may be used for different analytical purposes; for example, stress or adverse climate scenarios may be applied in reserve adequacy testing, sensitivity analysis, capital assessment, or ORSA, while the booked reserve would typically be supported by a clearly documented rationale for the selected morbidity trend, claim frequency, severity, and uncertainty margins.

For annually renewable policies, the immediate impact on pricing and short-term reserving may not be immediately obvious, given the relatively gradual evolution of most climate-related health trends and predominance of near-term experience and expected year-to-year variations in premium settings. However, climate-related risk dynamics can be of critical importance for long-term health insurance products and strategic planning within health insurers, where scenario-based analysis can provide valuable insight into emerging risk patterns, potential shifts in disease burden, and evolving exposure profiles. Importantly, there may be a cumulative effect on the underlying health infrastructure needed to provide care to patients (a dimension that distinguishes health insurers from life insurers, as they not only provide financial coverage but also support a complex care delivery infrastructure). For health insurance, climate-related forecasting distinguishes between short-term financial impacts driven by acute utilization shocks, and long-term planning considerations, which relate to evolving disease burden and the resilience of health care infrastructure.

3.8.3 HYBRID LIFE AND HEALTH PRODUCTS

Hybrid life and health products such as accelerated death benefits, critical illness coverage, long-term care insurance, and disability income insurance are exposed to both mortality and morbidity pathways. Climate-related risks can affect the timing, frequency, and severity of claims across multiple benefit types. Acute events may trigger simultaneous mortality and morbidity claims, while chronic exposures may increase the incidence of conditions that lead to disability, long-term care needs, or critical illness claims. The correlated nature of climate-related health impacts can reduce diversification benefits within hybrid portfolios and increase the importance of understanding how mortality and morbidity pathways interact under different climate scenarios.

3.8.4 PENSIONS

For pension actuarial valuations, climate-related mortality changes can affect longevity assumptions used in valuation, funding, and risk management.

Pension obligations are typically among the longest-duration liabilities in the financial system, often extending several decades into the future. As a result, even gradual, structurally persistent shifts in mortality trends may have material implications over time. Many pension plans use standard mortality improvement scales[137] that do not

[137] For example, the Mortality Projections Model, CM:2024 (released in 2025) by the Continuous Mortality Investigation, a body within the Institute and Faculty of Actuaries, incorporates data from 2024 and introduces a "fitted overlay" to better account for the impact of the COVID-19 pandemic (https://actuaries.org.uk/news-and-media-releases/news-articles/2025/jun/30-jun-25-cmi-publishes-cmi_2024-mortality-projections-model/#:~:text=The%20CMI%20has%20published%20CMI_2024,available%20in%20this%20registration%20document) The Society of Actuaries produces "MP" (Mortality Projection) scales (RPEC 2024 Mortality Improvement Update, https://www.soa.org/globalassets/assets/files/resources/research-report/2024/rpec-mort-improvement-update.pdf).

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incorporate exogenous climate drivers. Climate-adjusted mortality models can provide alternative improvement scales or adjustment factors under defined climate scenarios, enhancing the relevance of assumptions for long-term liabilities. In addition, climate risks may affect pension plans indirectly through economic channels (e.g., investment returns, inflation, and discount rates), which interact with mortality risk.

3.8.5 PORTFOLIO-LEVEL CONSIDERATIONS

Climate-related risks often involve multiple interacting drivers, such as, for example, extreme heat coinciding with air-quality degradation, power outages, or strained emergency services. Such multifactor events can trigger simultaneous impacts across life, health, disability, long-term care and pension products, reducing diversification benefits and increasing the likelihood of correlated claims across the portfolio. These dynamics underscore the importance of understanding cross-product dependencies when assessing climate-related L&H risks.

Climate-related mortality and morbidity impacts can vary substantially across insurance portfolios depending on geographic concentration, age distribution, socioeconomic characteristics, and product mix. Portfolios with higher concentrations of older adults, individuals with chronic conditions, or policyholders residing in high-risk regions may experience disproportionately large climate-related impacts.

Conversely, portfolios with younger or more geographically diversified populations may exhibit lower sensitivity. Assessing the portfolio-specific climate exposure may be necessary for developing credible assumptions. Broader balance sheet implications may be assessed in coordination with asset/liability managers to form a holistic view of climate-related risks across underwriting and investment portfolios.

3.8.6 CORE CROSS-PRACTICE THEMES

Across all areas of actuarial practice and all types of L&H insurance products:

- Integrating external scientific data (e.g., climate scenarios, epidemiological evidence) into models can be helpful to support the modeling frameworks.
- Scenario analysis and stress testing can be core tools for assessing climate risk, both for liabilities linked to mortality and/or morbidity risks and for their interaction with economic assumptions.
- Explicitly addressing the non-stationary nature of climate drivers, scenario choice, and limited historical calibration data can be integral to model risk management and validation.
- When communicating model results to stakeholders, it may be helpful to highlight the conditional nature of the forecasts and the uncertainty inherent in long-term climate pathways, consistent with actuarial commentary standards.

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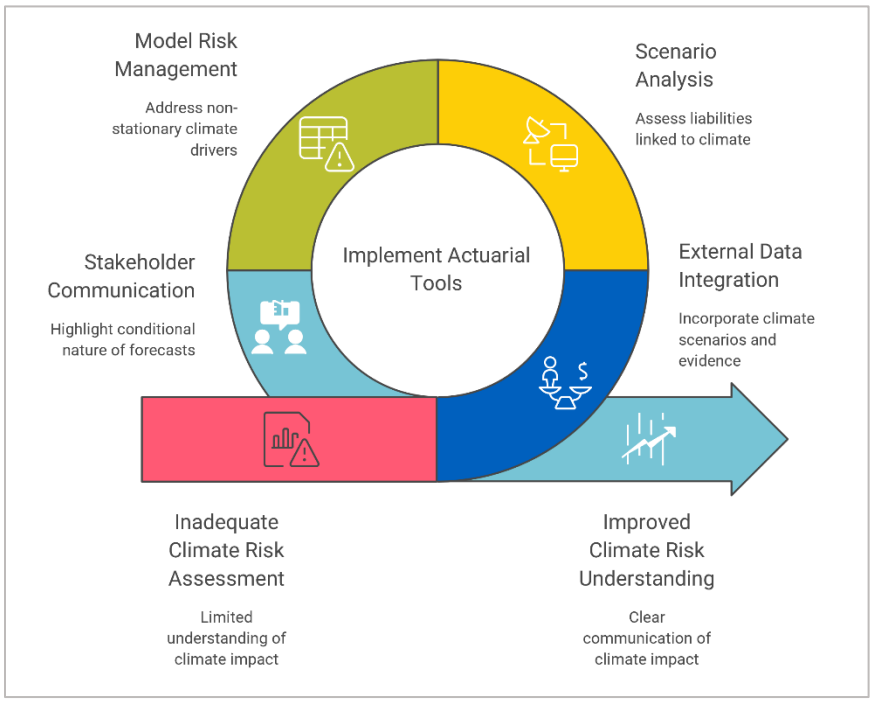
Figure 3.3
CORE CROSS-PRACTICE THEMES



3.8.7 VALIDATION CHECKLIST

The validation checklist presented below provides a structured mechanism to help ensure that the climate-adjusted mortality and morbidity models are conceptually sound, appropriately governed, and fit for their stated purpose. It establishes a technical and governance foundation that may be a component of responsible model deployment. However, validation and governance are not ends in and of themselves. Once a model has met these standards, the focus shifts to how its outputs are integrated into enterprise workflows and decision-making processes.

Table 3.3
VALIDATION CHECKLIST FOR CLIMATE-ADJUSTED MORTALITY AND MORBIDITY MODELS

Area	Objective	Checks	Pass?	Review?
Purpose	Ensure model is fit for its purpose	• Purpose clearly stated	☐	☐
Soundness	Confirm structural coherence	• Separation of baseline trends, non-climate improvements, climate hazards, and vulnerability • Climate variables treated as exogenous • No double counting of SES effects	☐	☐
Data	Assess data quality and origin	• Mortality/morbidity data sources documented • Climate inputs sources from recognized bodies • Data gaps and proxies disclosed	☐	☐
Back-Testing	Establish historical reasonableness *(where possible and relevant)*	• Directional checks during past climate stress periods • Results interpreted qualitatively • Disclosure of limitations	☐	☐
Sensitivity Analysis	Test robustness of key assumptions	• Sensitivities on climate and vulnerability parameters • Smooth, monotonic response to parameter changes • No implausible parameter dominance	☐	☐

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Area	Objective	Checks	Pass?	Review?
Stress Testing	Assess resilience under adverse scenarios	• Scientifically and politically plausible selection of climate pathways • Internal consistency of assumptions • Results reviewed by age, geography, SES, and time horizon	☐	☐
Residual Analysis	Diagnose structural issues	• Residuals reviewed for baseline components • No systematic bias or unexplained structure • Residuals not interpreted as climate evidence	☐	☐
Plausibility	Cross-check against external sources	• Direction/magnitude broadly consistent with epidemiological data • Alignment with IPCC conclusions and NGFS narratives • Used as plausibility checks only	☐	☐
Expert Review	Apply professional judgment	• Peer review performed • Independent actuarial review performed • Expert judgment explicitly documented • Key assumptions challenged and justified	☐	☐

Climate-related assumptions often involve forward-looking considerations and expert judgment in addition to experience data. In these circumstances, documentation and governance can provide context for the assumptions, particularly where historical patterns alone do not fully support them.

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Section 4 Climate-Adjusted Mortality Case Study

This section illustrates how the qualitative assessment and quantitative modeling described in the preceding sections can be applied in a practical case study.

The qualitative component identifies the principal risks associated with projecting mortality metrics under climate-related uncertainty and evaluates their potential materiality.

The quantitative component identifies the principal risks associated with projecting mortality metrics under climate-related uncertainty and assesses their potential materiality. The quantitative component describes the analytical techniques used to construct climate-related inputs, calibrate the mortality model, and generate outputs that are credible, decision-relevant, and suitable for actuarial interpretation.

The primary objectives of the case study are to demonstrate how a climate augmented Lee-Carter mortality model can:

- Quantify directional shifts in long-term mortality change under selected climate pathways;
- Highlight regional heterogeneity across selected European countries/regions;
- Assess the sensitivity results to climate-index construction, calibration choices, and model assumptions; and
- Support climate-risk narratives for actuarial analysis, governance, and disclosure purposes.

The case study is intended as an illustrative application rather than a production model. Its purpose is to show how actuaries may structure a transparent and reproducible workflow for incorporating climate-related physical risk into long-term mortality analysis, while recognizing the limitations of available data, the uncertainty of climate pathways, and the need for applying professional judgment to fine-tune the model calibration and interpret projections.

4.1 ACTUARIAL TOOLKIT: CORE MODELING FRAMEWORK

The actuarial toolkit provides the quantitative engine for modeling climate-adjusted mortality in the context of long-term liabilities. It implements the reduced-form climate-adjusted Lee–Carter mortality model (cf. 3.2.5), in which climate sensitivity varies by age and geography, but not explicitly by SES (although it may be extended to do so if sufficiently supported by data). This specification is adopted as the primary modeling framework for the case study, balancing conceptual relevance, statistical robustness, and ease of implementation.

At its core, the toolkit delivers a modular implementation of the mortality model, enabling actuaries to estimate, calibrate, and project mortality rates under alternative climate scenarios. The selected specification captures baseline mortality dynamics through the standard Lee–Carter structure, while introducing a climate component that allows mortality to respond to exogenous hazard variables in an age- and region-specific manner. This ensures that key dimensions of heterogeneity—particularly demographic structure and geographic exposure—are preserved within the model.

The decision to adopt the reduced-form specification reflects several practical considerations:

- While SES is an important determinant of vulnerability, sufficiently granular and consistent data across countries and time are limited. Attempting to estimate fully disaggregated climate sensitivity parameters by age, geography, and SES may lead to instability, overfitting, or reliance on strong assumptions.

- SES differences remain partially captured within the baseline mortality term, ensuring that inequalities are not entirely omitted, even if they are not explicitly modeled in the climate response.

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The toolkit is organized around a sequence of functional components. These include:

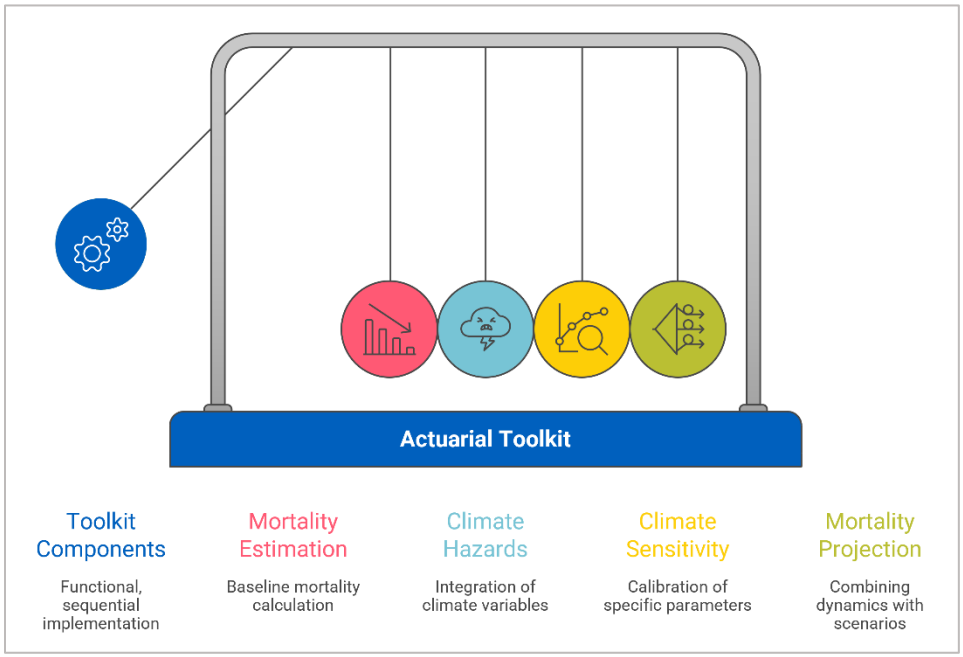
a) baseline mortality estimation,

b) construction and integration of climate hazard variables,

c) calibration of age- and region-specific climate sensitivity parameters using a structured, staged approach, and

d) projection modules that combine mortality dynamics with externally-defined climate scenarios. Each component is implemented in a configurable manner, with separation among inputs, assumptions, and outputs.

Figure 4.1
ACTUARIAL TOOLKIT COMPONENTS



The toolkit also incorporates diagnostic and validation features to support appropriately cautious model use. These include residual analysis, sensitivity testing, and scenario comparisons, enabling actuaries to understand key drivers of results, and evaluate the impact of alternative assumptions. Where appropriate, the toolkit facilitates cross-checks against external data and supports documentation of assumptions and limitations.

In summary, the actuarial toolkit is designed with reproducibility and governance in mind. Model configurations, parameter selections, and data transformations are explicitly documented, allowing results to be traced, reviewed, and replicated. This supports internal validation, external review, and alignment with modeling practices and communication.

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4.2 JUPYTER NOTEBOOK SUITE

The Jupyter[138] notebook suite provides an end-to-end implementation of the climate-adjusted mortality modeling framework, from data ingestion to projection, sensitivity analysis, and validation. It is designed to support transparency and reproducibility, allowing actuaries to follow each step of the modeling process, and adapt individual components to specific analytical purposes. The notebook suite is available through a separate Git repository, as described in subsection 4.7.

The notebooks are organized as a structured pipeline. The workflow begins with data ingestion and preparation, followed by the construction of climate hazard variables, estimation of the baseline mortality model, calibration of climate sensitivity parameters, projection of climate-adjusted mortality rates, and sensitivity and validation analysis. Each notebook has a defined role, with clear inputs and outputs, so that users can review, rerun, modify, or replace individual components without disrupting the overall framework.

The suite reflects the structure of the model. Baseline mortality parameters are estimated first using historical mortality data. Climate effects are then calibrated separately using the residuals from the baseline Lee-Carter model and the constructed climate hazard index $C_{t,r}$. This sequencing helps preserve the intended separation between long-standing demographic mortality trends and incremental climate-related effects.

The sensitivity and validation notebook provides additional controls around model use. It tests alternative weights for the composite climate index $C_{t,r}$, alternative k_t projection methods, selected shocks to $\lambda_{x,r}$, and residual diagnostics. It also includes reasonableness checks by country, age, year, and scenario. These tests are intended to support actuarial judgment and to identify outputs that require further review before being used in report exhibits or decision support.

The notebook sequence is as follows:

[138] A Jupyter notebook is an open source interactive computing environment that combines executable Python code, narrative text, tables, and graphs within a stand-alone document.

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Table 4.1
JUPYTER NOTEBOOK SUITE

Notebook	Purpose	Key Outputs
01_data_ingestion_and_preparation.ipynb	Loads, checks, and prepares the mortality and climate input datasets for the case study countries	Processed mortality data; processed historical and projected climate data
02_climate_features.ipynb	Constructs the composite climate hazard variable $C_{t,r}$ from temperature anomaly, extreme heat days, and heat wave duration	Historical and projected $C_{t,r}$; standardization parameters; climate feature files.
03_baseline_mortality_model.ipynb	Estimates the non-climate Lee–Carter baseline mortality model	$a_{x,r}$, b_x, k_t, fitted baseline mortality, and baseline residuals
04_climate_calibration.ipynb	Calibrates the age- and country-specific climate sensitivity parameter $\lambda_{x,r}$	Calibrated $\lambda_{x,r}$, climate calibration panel, climate-adjusted fitted mortality, and calibration diagnostics
05_projection_engine.ipynb	Produces no-climate baseline and climate-adjusted mortality projections for 2030–2050	Projected k_t, projected baseline mortality, climate-adjusted mortality, and impact summaries
06_sensitivity_and_validation.ipynb	Tests sensitivity and reasonableness of the projected results	Sensitivity results, residual diagnostics, reasonableness flags, and validation summaries

The notebooks are documented through code comments and diagnostic visualizations. Key intermediate and final outputs are saved as structured files, enabling traceability from inputs to outputs. This design supports replication, auditability, and efficient review by actuaries and technical users.

The notebook suite is intended for research, educational, and illustrative purposes. It is not intended to constitute actuarial advice or a production-ready modeling system without further validation, customization, and governance by the user. Any operational use would require appropriate controls over data quality, assumptions, parameter selection, version control, validation, documentation, and communication of limitations.

4.3 CURATED DATASETS

The case study is supported by a set of curated datasets that organize the mortality, climate, and model-output information required to implement the climate-adjusted mortality framework. These datasets are not intended to replace the original source data. Rather, they provide a controlled analytical layer that converts raw or externally sourced inputs into standardized, model-ready files. This allows users to trace the workflow from data ingestion through feature construction, baseline mortality estimation, climate calibration, projection, and validation.

The curated datasets are designed around the three European countries included in the case study: mainland Spain, mainland France, and Italy. These countries were selected to provide a practical and diverse European case study for climate-adjusted mortality modeling. Together, these countries offer variation in geography, climate exposure, and demographic structure. The selection includes southern European countries with greater exposure to heat-related hazards (mainland Spain, Italy), and a more temperate country with a variety of climates (mainland France). This mix allows the case study to illustrate how the same modeling framework can be applied across countries with different climate profiles. France and Spain's overseas territories were not included due to their sometimes markedly different climate (e.g., French Polynesia); in the rest of the case study, "France" and "Spain" will be used to refer to the mainland.

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The historical calibration period is 2004–2025, excluding the atypical 2020-2021 years where mortality patterns were heavily disrupted by COVID-19, while the projection period is 2030–2060. The datasets are structured at the country/year/age level for mortality modeling and at the country-year level for climate variables.

The first group of curated files consists of processed mortality data. These files provide the age-specific central mortality rates used to estimate the baseline Lee–Carter model. Where exposure and death counts are available, they are retained to support weighting, diagnostics, and credibility checks. The resulting mortality dataset is the main input to **03_baseline_mortality_model.ipynb**.

The second group consists of processed climate feature files. These files include historical and projected climate variables such as temperature anomaly, extreme heat days, and heat wave duration:

- the **temperature anomaly** is the annual difference between a country's average daily maximum temperature in a given year and that country's average daily maximum temperature over the historical calibration-period.
- **Extreme heat days** are the annual number of days in a country where the daily maximum temperature exceeds the country-specific historical threshold. In this iteration, the threshold is based on the historical 95th percentile of daily maximum temperatures.
- **Heat wave duration days** are the annual number or days that belong to heat wave episodes. In this iteration, a heat wave episode is defined as a run of at least six consecutive days where the daily maximum temperature exceeds the country-specific historical 95th percentile.

These variables are standardized[139] and combined into the composite climate hazard variable $C_{t,r}$. The construction of $C_{t,r}$ is documented in **02_climate_features.ipynb**, and the resulting files are used in both calibration and projection.

The third group consists of model parameter and diagnostic files. These include the estimated Lee–Carter baseline parameters $a_{x,r}$, b_x, and k_t, the calibrated climate sensitivity parameters $\lambda_{x,r}$, fitted values, residuals, and validation summaries. These outputs allow users to review the intermediate results before relying on the final projection outputs.

The final group consists of projection and sensitivity files. These datasets compare baseline mortality projections with climate-adjusted mortality projections for 2030–2060. They also include summaries of the impact of climate adjustments by country, age, year, and scenario, as well as sensitivity and validation outputs. These files support interpretation, reporting, and further actuarial analysis.

[139] Variables are expressed relative to a common scale by subtracting their mean and dividing by their standard deviation.

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Table 4.2
CURATED DATASETS

Dataset Group	Key Output CSV Files	Purpose
Processed mortality data	mortality_country_age_year_2004_2025_excl_2020_2021	Provides country-age-year mortality rates for baseline mortality estimation
Climate feature data	C_tr_core_country_annual_combined_era5_cmip6_ssp5_8_5	Provides the historical and projected composite climate hazard variable $C_{t,r}$
Baseline mortality parameters	baseline_parameters_a_xr_2004_2025_excl_2020_2021 baseline_parameters_b_x_2004_2025_excl_2020_2021 baseline_parameters_k_t_2004_2025_excl_2020_2021	Stores the estimated non-climate Lee–Carter baseline parameters
Baseline fitted values and residuals	baseline_fitted_mortality_2004_2025_excl_2020_2021 baseline_residuals_2004_2025_excl_2020_2021 baseline_residual_diagnostics_2004_2025_excl_2020_2021	Provides fitted baseline mortality rates and residuals used to calibrate climate sensitivity
Climate calibration outputs	climate_parameters_lambda_xr_2004_2025_excl_2020_2021 climate_calibration_panel_2004_2025_excl_2020_2021 climate_adjusted_fitted_mortality_2004_2025_excl_2020_2021 climate_calibration_diagnostics_2004_2025_excl_2020_2021	Stores calibrated $\lambda_{x,r}$, calibration diagnostics, and historical climate-adjusted fitted values
Projection outputs	projected_k_t_2030_2060 projected_mortality_baseline_and_climate_adjusted_2030_2060 projected_mortality_impact_summary_2030_2060 projected_mortality_by_country_year_2030_2060	Provides projected baseline and climate-adjusted mortality rates, together with impact summaries
Sensitivity and validation outputs	sensitivity_projection_panel_2030_2060 sensitivity_summary_by_experiment_2030_2060 validation_reasonableness_flags_2030_2060 validation_reasonableness_flag_summary_2030_2060 residual_validation_diagnostics_2004_2025_excl_2020_2021	Supports sensitivity testing, residual analysis, and reasonableness checks

The curated datasets are intended to improve transparency and reproducibility. Each file is generated by a specific notebook, and the file-naming convention links the dataset to the modeling step, period, and scenario where applicable. This makes it easier to audit the workflow, reproduce results, and identify which inputs or assumptions drive specific outputs.

These curated datasets are intended as analytical artifacts created for the case study and may not be suitable for other uses due to completeness, source consistency, licensing restrictions, update frequency, or suitability for the intended actuarial purpose.

4.4 CLIMATE SCENARIO AND MAPPING LAYER

The climate scenario and mapping layer provide the link between externally-sourced climate data and the mortality modeling framework used in the case study. Their purpose is to convert gridded historical and projected climate datasets into country-year climate indicators that can be used consistently in the construction of the climate hazard variable $C_{t,r}$.

The framework uses a mapping layer because climate data are typically provided on a spatial grid, while the mortality model is specified at the country-age-year level. The notebook workflow, therefore, aggregates climate variables from gridded files into country-level annual metrics for France, Italy, and Spain. This creates a common analytical geography between the climate and mortality data.

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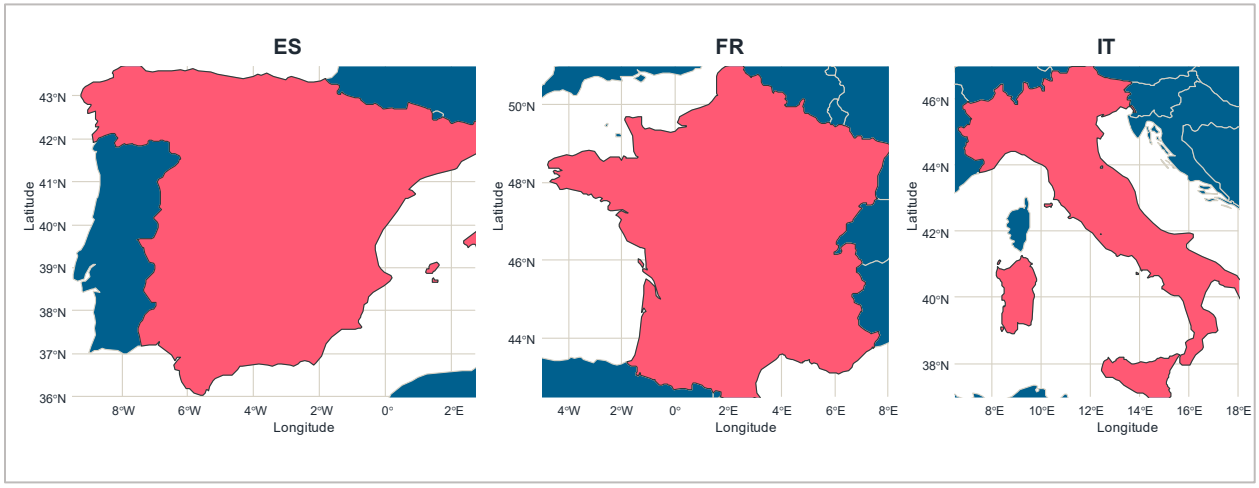
Figure 4.2
COUNTRY MAPS BASED ON BOUNDING COORDINATES



Note: The country panels are shown with country-specific latitude and longitude scales. As a result, the visual size of each map is not directly comparable across panels; countries may appear similar in size though their actual areas differ: mainland Spain ≈ 506K km^2; mainland France ≈ 552K km^2; and Italy ≈ 302K km^2

The case study distinguishes between historical climate data and forward-looking climate projections. Historical climate data are used for the calibration period. Projected climate data are used for the projection period. This distinction is important because the model requires historical climate variables to estimate the relationship between mortality residuals and climate conditions, while forward-looking climate variables project mortality under selected climate pathways.

For the current implementation:

- The historical layer is based on the fifth-generation global climate weather reanalysis dataset (ERA5) produced by the European Centre for Medium-Range Weather Forecasts.
- The projection layer is based on the Coupled Model Intercomparison Project Phase 6[140] (CMIP6) climate projections produced by the World Climate Research Programme.[141] The current scenario implementation uses **SSP5-8.5** as the illustrative projection pathway.[142] SSP5-8.5 is a high-emissions climate scenario used in CMIP6 and IPCC AR6-style climate analysis and combining SSP5 and RCP8.5. SSP5-8.5 represents a future with unconstrained, fossil-fueled economic development leading to extreme warming.[143] While this pathway is not necessarily the central scenario given the rapid development of renewables, it remains a useful high-end stress test to illustrate this case study.

[140] CMIP6 remains the most recent CMIP phase available at the time of writing, while CMIP7 is the latest phase under implementation. CMIP7 data are expected in late 2026 (source: Coupled Model Intercomparison Project, https://wcrp-cmip.org/cmip-overview/)

[141] Datasets are available at the Climate Data Store (https://cds.climate.copernicus.eu/) of the EU Copernicus Programme.

[142] The structure of the notebook suite allows additional scenarios to be added where equivalent projected variables are available. This is important because scenario analysis, rather than point forecasting, is central to the climate-adjusted mortality framework.

[143] Explainer: Scenarios for CMIP7, World Climate Research Programme (2026), https://wcrp-cmip.org/explainer-scenarios-for-cmip7/

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Figure 4.3 below presents projected annual maximum daily temperatures for Spain, France, and Italy under the selected climate scenario. Presenting the projected temperature paths separately helps distinguish the physical climate signal from the subsequent actuarial transformation into $C_{t,r}$, $\lambda_{x,r}$, and projected mortality impacts.

Figure 4.3

PROJECTED ANNUAL MAXIMUM TEMPERATURE[144]

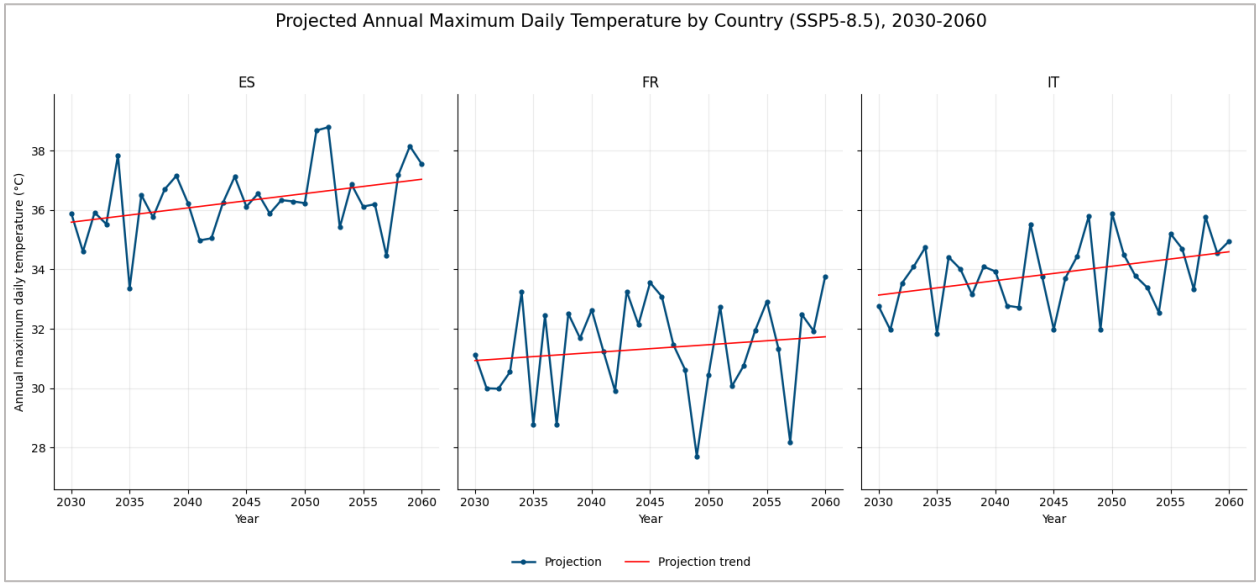

Figure 4.3 illustrates that projected temperature paths are not monotonic year by year. Even under a high-emissions scenario, annual maximum temperatures may rise, fall, or spike in individual years because climate model outputs preserve interannual variability. The trend line is, therefore, useful for summarizing the broader direction of the projection, while the annual points highlight volatility around that trend. This distinction is important for interpretation: the climate-adjusted mortality results are driven not only by long-term warming, but also by the timing, frequency, and intensity of projected heat extremes.

The climate variables used in the mapping layer are selected to support the construction of the composite climate index variable $C_{t,r}$. In the current case study, the core components are temperature anomaly, extreme heat days, and heat wave duration. These variables are first calculated or extracted at the country-year level, then standardized, and finally combined using the selected weights:

$$C_{t,r} = w_1 \cdot Z\left(\text{TempAnomaly}_{t,r}\right) + w_2 \cdot Z\left(\text{ExtremeHeatDays}_{t,r}\right) + w_3 \cdot Z\left(\text{HeatWaveDuration}_{t,r}\right)$$

The base weighting scheme used in the case study is:

$$w_1 = 0.20, \qquad w_2 = 0.70, \qquad w_3 = 0.10$$

[144] Temperatures in this figure are shown in degrees Celsius (°C). An equivalent version expressed in degrees Fahrenheit (°F) is provided in appendix B.

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The above index gives 20% weight to long-term warming, 70% weight to frequency of extreme heat, and 10% weight to persistence of heat episodes. The rationale for this first-pass structure is that mortality (and morbidity) impacts are likely driven by both the overall warming trend and acute heat extremes. The lower weight on heat wave duration reflects the fact that duration partly overlaps with the extreme-heat-day count.[145]

Figure 4.4 below presents the three heat-related components used to construct the composite climate index $C_{t,r}$.

Figure 4.4
HEAT METRIC COMPONENTS[146]

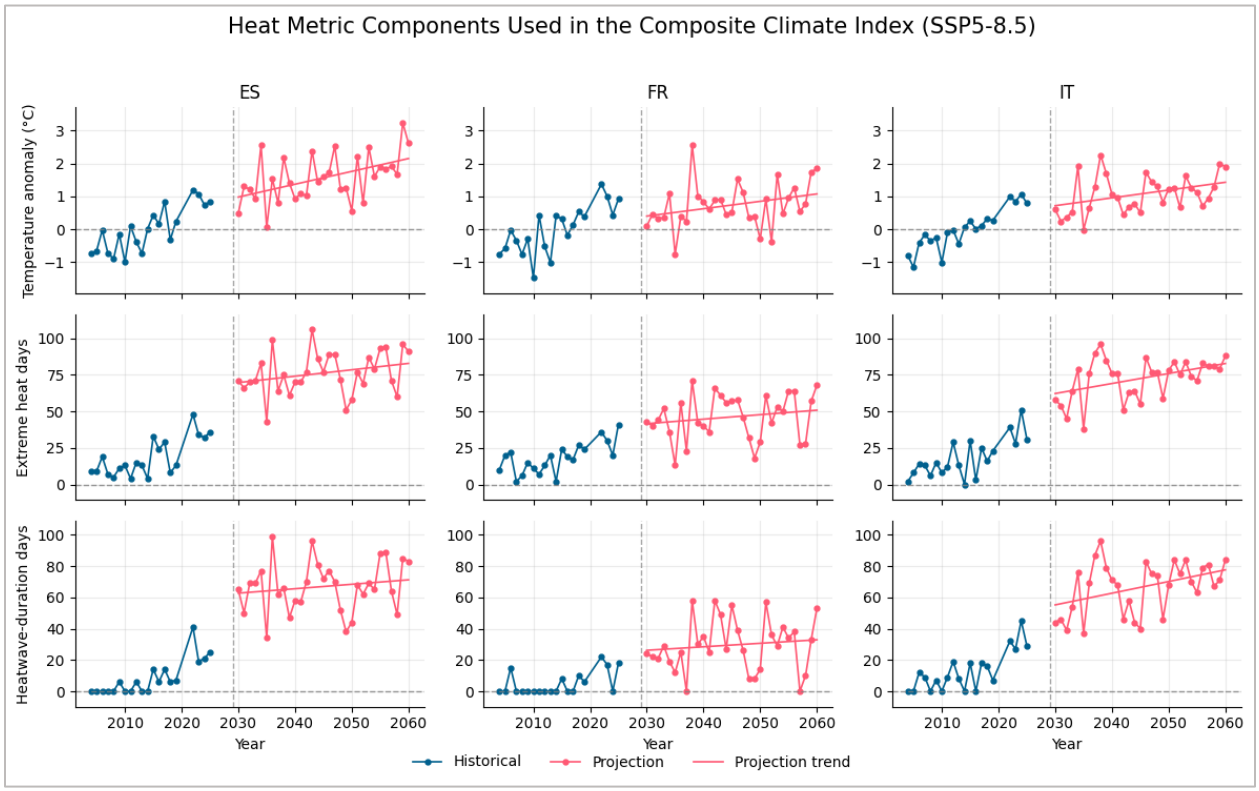

Figure 4.4 above confirms that the components of $C_{t,r}$ do not necessarily move in parallel. A country-year may show a higher annual temperature anomaly with a limited increase in heat wave duration or may experience a high number of extreme heat days without a sustained six-day heat wave episode. This is expected and reinforces the rationale for using a composite index rather than a single climate variable. At the same time, the exhibit highlights the importance of interpreting $C_{t,r}$ as an annual hazard index, not as a monotonic measure of climate change. Year-to-year variation, particularly in the projection period, reflects the selected scenario pathway, the climate-model output, and the threshold definitions used in the analysis. For this reason, the subsequent mortality analysis emphasizes multi-year patterns and relative impacts rather than relying on any single projection year.

[145] The initial weight values should be treated as an assumption, and this assumption is subsequently tested through sensitivity analysis in the notebook 06_sensitivity_and_validation.ipynb

[146] Temperatures in this figure are shown in degrees Celsius (°C). An equivalent version expressed in degrees Fahrenheit (°F) is provided in appendix B.

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Figure 4.5 below presents the composite heat-related climate index $C_{t,r}$ by country. Because each component is standardized before aggregation, the index is a relative measure of heat stress within the modeling framework rather than as a direct physical temperature measure. Higher values indicate years in which the combined heat signal is stronger relative to the historical calibration period.

Figure 4.5
COMPOSITE CLIMATE INDEX

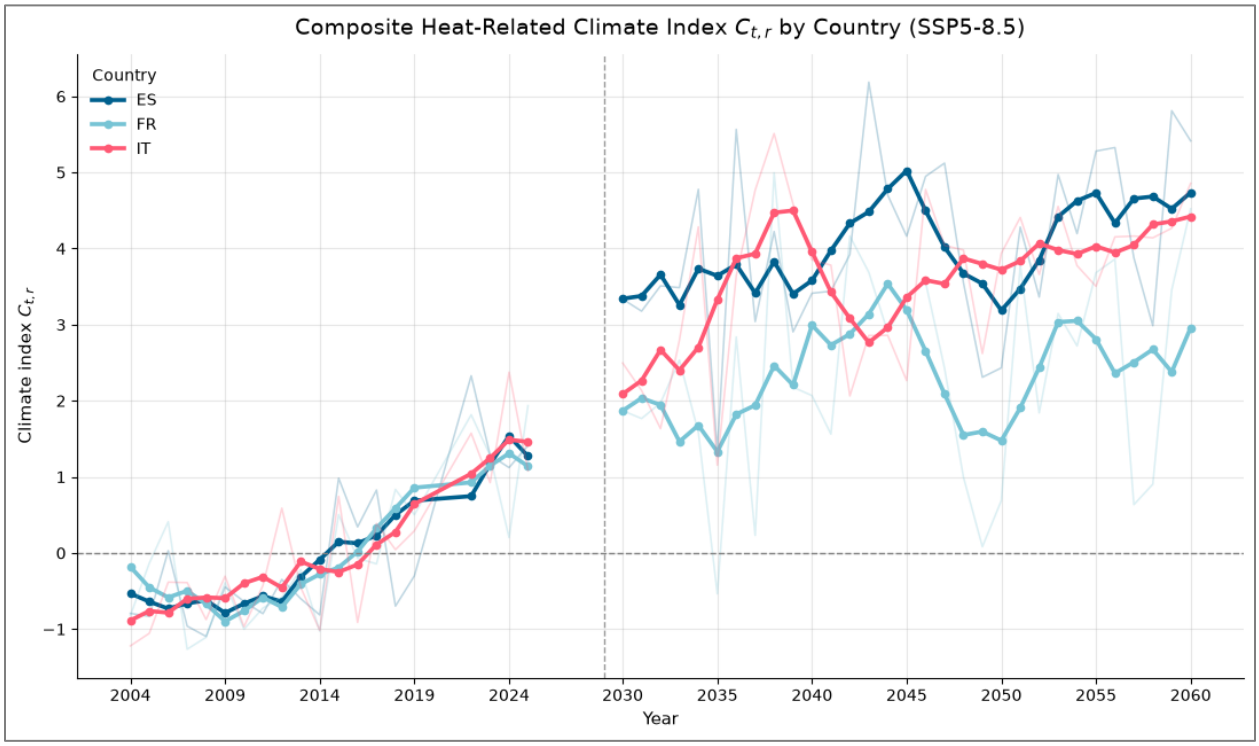

Figure 4.5 above shows that $C_{t,r}$ varies by country and year, reflecting both differences in projected heat exposure and the interaction among the three index components. As noted before, the index does not necessarily increase monotonically because annual climate-model outputs can fluctuate and because temperature anomaly, extreme heat days, and heat wave duration do not always move together. The mapping layer, therefore, performs three functions. It aligns climate:

- data spatially by converting gridded data into country-level indicators;
- data temporally by producing annual metrics for the historical and projection periods; and
- variables analytically by creating standardized inputs that can be combined into $C_{t,r}$.

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Table 4.3
MAPPING LAYER

Layer	Description	Key Output
Historical climate layer	Converts ERA5 historical climate data into country-year indicators	Historical temperature anomaly, extreme heat days, and heat wave duration by country and year
Projection climate layer	Converts CMIP6 projected climate data into country-year indicators	Projected temperature anomaly, extreme heat days, and heat wave duration by country and year
Scenario layer	Identifies the climate pathway used in the projection period	Scenario-tagged climate records
Mapping layer	Aggregates gridded climate data to the country level	Country-year climate metrics compatible with the mortality model
Composite hazard layer	Standardizes and combines the selected climate variables into $C_{t,r}$	Country-year climate feature file (see below)

The main output of this section of the workflow is the country-year climate feature file:

C_tr_core_country_annual_combined_era5_cmip6_ssp5_8_5.csv

This file is used in two downstream modeling steps. In **04_climate_calibration.ipynb**, the historical portion of $C_{t,r}$ is merged with baseline mortality residuals to estimate $\lambda_{x,r}$. In **05_projection_engine.ipynb**, the projected portion of $C_{t,r}$ is combined with projected baseline mortality and calibrated $\lambda_{x,r}$ to generate climate-adjusted mortality projections.

The mapping layer is modular. The country definitions, spatial aggregation method, climate variable definitions, standardization approach, and scenario labels should be documented in the notebook outputs. This allows users to review how raw climate data are transformed into actuarial model inputs and replace or refine individual components where more granular geography, improved exposure mapping, or additional climate scenarios are available.

The framework treats the climate scenarios and mapping layers as an analytical bridge rather than as a source of independent climate science. The credibility of the layer depends on the quality, suitability, and traceability of the underlying climate datasets. Before applying the framework in an operational setting, users will likely want to review the selected climate scenario, spatial aggregation method, variable definitions, and consistency between historical and projected data.

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4.5 APPLICATION LAYER

4.5.1 PURPOSE OF THE APPLICATION LAYER

The application layer translates the outputs of the climate-adjusted mortality model into interpretable actuarial results. Its purpose is to organize the projection outputs into tables, charts, and diagnostics that support actuarial judgment, scenario analysis, and communication with decision-makers.

In this case study, the application layer compares baseline projected mortality rates with climate-adjusted projected mortality rates for the target countries over the 2030–2060 projection period. Results are shown by country, year, and age group. The primary metric used in this section is the relative impact of the climate adjustment on projected mortality rates:

$$100 \times \left(\frac{m_{x,t,r}^{climate}}{m_{x,t,r}^{baseline}} - 1 \right) = 100 \times \left[\exp\left(\lambda_{x,r} \cdot C_{t,r} \right) - 1 \right]$$

This metric measures the percentage difference between the climate-adjusted mortality projection and the baseline Lee-Carter projection. The results are intended to be interpreted as conditional scenario outputs, not as point forecasts.

The application layer consolidates the main outputs of the projection engine, sensitivity analysis, and validation workflow into a set of exhibits and CSV files that can be reviewed, reproduced, and extended by users. These outputs are intended to support both technical review and actuarial communication. They include detailed projection panels, summary views of the incremental climate impact, sensitivity exhibits, and validation diagnostics. Table 4.4 below summarizes the principal application components and corresponding output files produced by the notebook suite.

Table 4.4
APPLICATION COMPONENTS

Component	Output
Projection exhibits	Presents baseline and climate-adjusted mortality projections by country, age, and year
Impact summaries	Shows incremental climate impacts in absolute and relative terms
Sensitivity views	Compares results under alternative assumptions for $C_{t,r}$, k_t,and $\lambda_{x,r}$
Validation views	Displays residual diagnostics and reasonableness flags

The remainder of this section uses these outputs to present selected results from the case study.

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4.5.2 COUNTRY-LEVEL RESULTS

At the country level, the model produces heterogeneous impacts. Table 4.5 summarizes the average relative mortality impact by country. These numbers are unweighted across modeled ages and, therefore, are intended to be model outputs, not exposure-weighted portfolio impacts.

Table 4.5
AVERAGE RELATIVE MORTALITY IMPACT

Country	Average Impact, 2030—2060	Average Impact, 2040—2060	Average Impact, 2050—2060
Spain	0.39%	0.41%	0.42%
France	3.59%	3.90%	4.03%
Italy	3.59%	3.73%	4.14%

Table 4.5 above indicates that the projected climate-related mortality impact is materially higher for France and Italy than for Spain in the current implementation. Over the full 2030–2060 projection period, the average relative impact is approximately **0.39% for Spain**, compared with **3.59% for both France and Italy**. This suggests that, under the selected climate scenario and calibration assumptions, the mortality impact is not driven by climate exposure alone, but by the interaction among the composite climate index $C_{t,r}$, the calibrated country-age sensitivity parameter $\lambda_{x,r}$, and the underlying baseline mortality structure. Spain's lower modeled impact may reflect a relatively lower vulnerability to extreme heat as the country is already accustomed to heat waves and temperature extremes, and also has a relatively younger population than Italy's.

The results also show a gradual increase in projected impact as the averaging window shifts toward the later years of the projection horizon. For Spain, the average impact increases from **0.39%** over 2030–2060 to **0.41%** over 2040–2060 and **0.42%** over 2050–2060. For France, the corresponding values increase from **3.59%** to **3.90%** and **4.03%**. For Italy, the increase is from **3.59%** to **3.73%** and **4.14%**. This pattern is consistent with the model's use as a long-term scenario analysis tool: climate-related effects become more visible when the analysis places greater weight on later projection years, although the magnitude of the impact remains country-specific.

These results are intended to be interpreted as conditional outputs, not as forecasts. They reflect the selected climate pathway, the construction of $C_{t,r}$, the calibration of $\lambda_{x,r}$, and the treatment of the mortality trend in the baseline (i.e., non-climate-adjusted) Lee-Carter model. The table is intended to be a high-level summary complemented by country-level trend plots, age-band exhibits, and sensitivity tests.

Figure 4.6 below presents the average climate-related projected mortality impact by country over the projection period. The impact is measured as the relative difference between the climate-adjusted mortality rates and the baseline mortality rates generated by the projection engine. In this graph, the baseline projection reflects the continuation of the fitted mortality trend without the explicit climate component, while the climate-adjusted projection incorporates the country-year climate index $C_{t,r}$ and the calibrated age- and country-specific sensitivity parameter $\lambda_{x,r}$. The results are intended to be interpreted as incremental scenario-conditioned impacts compared to the traditional Lee-Carter model, not as standalone mortality forecasts. Figure 4.6 is intended to show the direction, timing, and relative magnitude of climate-related effects across countries.

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Figure 4.6
AVERAGE CLIMATE-RELATED PROJECTED MORTALITY IMPACT

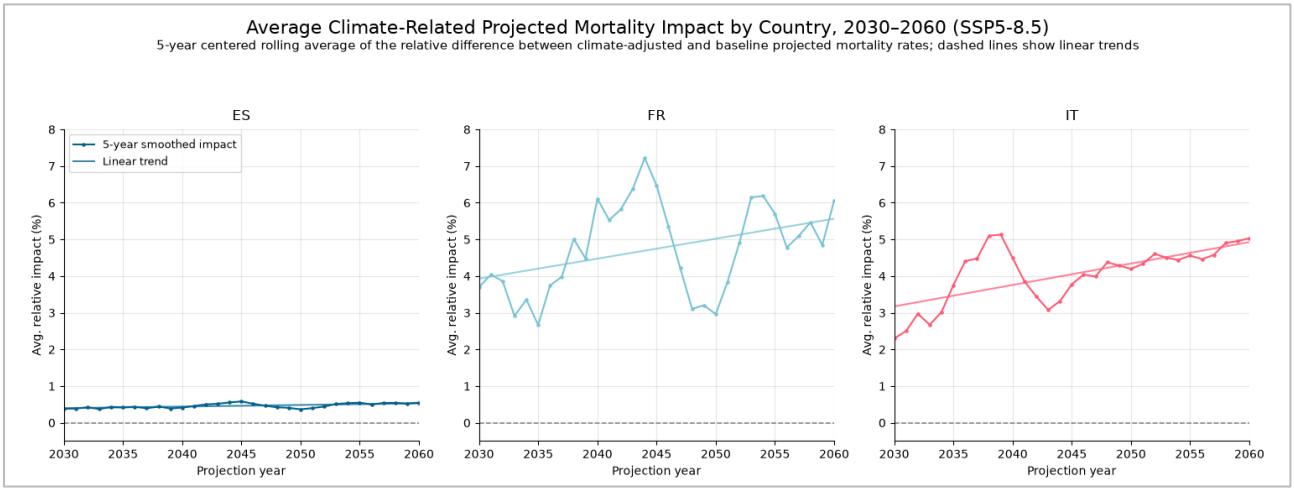

Figure 4.6 above illustrates that the projected climate-related mortality impact varies by country and over time. This variation reflects differences in the projected heat-related climate index, the calibrated sensitivity parameter $\lambda_{x,r}$, and the age composition embedded in the averaging process.

- **Spain (ES)**: The projected impact is positive but modest and relatively stable. The five-year smoothed average remains mostly around 0.3%–0.5%, with annual averages generally below 0.6%.
- **France (FR):** France shows the strongest and broadest climate-related mortality impact among the three countries. The five-year smoothed impact rises above 5% around the mid-2040s, then moderates before increasing again toward 2060.
- **Italy (IT):** Italy shows a material and persistent impact, less broadly distributed than France. The five-year smoothed impact increases from about 2% in the early 2030s to more than 4% by 2060.

4.5.3 AGE-BAND RESULTS

The age-band view provides a more stable interpretation than single-age results because it reduces the visibility of age-by-age noise while preserving the main age pattern of the climate impact.

Table 4.6
AVERAGE RELATIVE MORTALITY IMPACT BY AGE BAND

	Spain			France			Italy		
Projection	20—44	45—64	65—85	20—44	45—64	65—85	20—44	45—64	65—85
2030—2060	0.58%	0.39%	0.40%	8.66%	0.83%	3.99%	5.24%	4.21%	2.52%
2040—2060	0.61%	0.42%	0.42%	9.42%	0.90%	4.33%	5.45%	4.37%	2.62%
2050—2060	0.63%	0.43%	0.43%	9.75%	0.93%	4.48%	6.04%	4.85%	2.90%

Note: Values show the average relative difference between climate-adjusted and baseline projected mortality rates. Results are unweighted across ages and years within each period.

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Among the three countries shown:

- **Spain (ES)**: The projected climate-related mortality impact is modest across all age bands, most likely reflecting Spain's traditional adaptation to extreme heat through various mechanisms, such as passive cooling (e.g., shutters, white-washed façades, shaded streets and patios) and lifestyle modifications (e.g., shifting activity to cooler hours).

- **France (FR)**: France shows the strongest incremental impact in ages 20–44 and 65–85. This indicates a more uneven age pattern, with climate sensitivity concentrated outside the middle-age band. Younger populations may face elevated risk due to a higher prevalence of precarious, temporary contracts in heat-exposed sectors (such as tourism and construction), while the middle-aged cohort often benefits from stronger permanent employment protections and better-insulated housing.

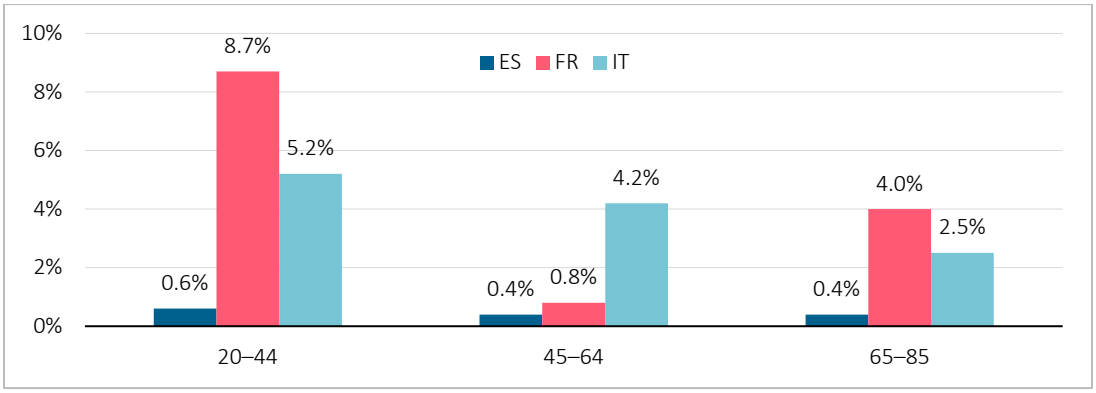
- **Italy (IT)**: Italy's incremental impact is concentrated most clearly in the working ages 20–64. This cohort represents the core of the agricultural and manufacturing workforce in the South of Italy where high heat exposure might intersect with weaker SME-level safety enforcement and lower adaptive capacity. The age band 65–85 band exhibits a lower impact but still material. France and Italy also have distinct labor market structures, adaptation mechanisms, and socioeconomic disparities. Cultural adaptation habits and stronger multi-generational support in Italy might also offer the elderly a protective buffer, which is not as prevalent in France, particularly among its urban elderly population.

Finally, Table 4.6 above supports the conclusion that the climate-adjusted mortality impact is country-specific and age-specific. However, the current results would require more research to interpret age dependencies, test alternative explanations, assess the robustness of the output, and reduce the risk of confirmation bias. These results are intended to be treated as scenario-conditioned model outputs, not as best-estimate mortality assumptions. For actuarial application, these impacts may need to be translated into portfolio-weighted measures, such as changes in life expectancy, annuity factors, etc.

Figure 4.7

CLIMATE-RELATED MORTALITY IMPACT BY COUNTRY AND AGE BAND (SSP5–8.5), 2030–2060

AVERAGE RELATIVE DIFFERENCE BETWEEN CLIMATE-ADJUSTED AND BASELINE PROJECTED MORTALITY RATES



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4.5.4 MODELING CONSIDERATIONS

Several modeling considerations are important when interpreting these application-layer results:

- **The results shown in the preceding sections are unweighted across ages**. This is useful for model diagnostics and comparison across countries, but it is not equivalent to insured portfolio, pension plan, or national population impacts. A practical implementation would likely apply relevant exposure weights such as insured lives, annuitants, pensioners, or population counts.

- **The projection engine floors negative values of the climate sensitivity parameter $\lambda_{x,r}$ at zero**. This is a judgment-based modeling constraint, not a statistical requirement. Its purpose is to avoid allowing potentially confounded negative residual relationships in the calibration data to generate persistent beneficial climate effects in the projection. In this implementation, the climate adjustment is, therefore, treated primarily as an adverse-risk overlay, consistent with the focus of the countries in scope.[147]

- **Annual climate impacts may be volatile**. This is expected because the composite climate index includes annual heat-related components, such as temperature anomaly, extreme heat days, and heat wave duration. For actuarial interpretation, rolling averages, period averages, and scenario comparisons are more informative than isolated annual peaks.

- **The model uses annual all-cause mortality**. This is transparent and practical, but it may dilute climate-health effects that are seasonal, acute, regional, or concentrated among vulnerable populations. Heat-related mortality, for example, may be strongest during specific summer weeks or months in the Northern Hemisphere and may vary substantially within a country. As a result, annual national mortality rates may understate localized or short-duration climate-related health impacts.

- **The current case study does not include sex, socioeconomic status, pre-existing health conditions, or subnational geography**. These dimensions are relevant to climate vulnerability. Their omission is a limitation of the current case study rather than a conclusion that such factors are immaterial.

- **The results depend on the selected climate scenario, construction of the climate index and underlying climate variables** (e.g., definition of temperature anomalies or what qualifies as a heat wave)**, and the calibration period**. These assumptions are intended to be tested through sensitivity analysis before the results are used for pricing, reserving, capital, or strategic planning. Subsequent research could also test the inclusion of additional variables in the climate index. This includes, for instance, the levels of air pollution related to fine particle matters and wildfire smoke (see table 3.1.) where such data is available for both historical calibration and prospective scenario analysis.

[147] However, this constraint should not be interpreted as a general principle that climate change cannot produce offsetting or beneficial effects in specific populations, regions, seasons, or causes of morbidity or mortality. In colder geographies, such as the Nordic European countries, Canada, or Northern U.S., warming may plausibly reduce some cold-related risks, at least over certain time horizons. For such applications, the floor on $\lambda_{x,r}$ may be reconsidered, removed, or replaced with a more granular structure that separately models heat-related and cold-related effects, supported by region-specific evidence and sensitivity testing.

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4.6 SENSITIVITY, STRESS TESTING, AND RESIDUAL ANALYSIS

The sensitivity and validation notebook[148] extends the projection workflow by assessing how results respond to selected modeling choices and parameter assumptions. The objective is to evaluate whether the conclusions are robust, interpretable, and suitable for actuarial use. In this case study, the analysis focuses on three areas: sensitivity to the construction of the composite climate index $C_{t,r}$, sensitivity to the climate sensitivity parameter $\lambda_{x,r}$, and residual diagnostics before and after climate calibration.

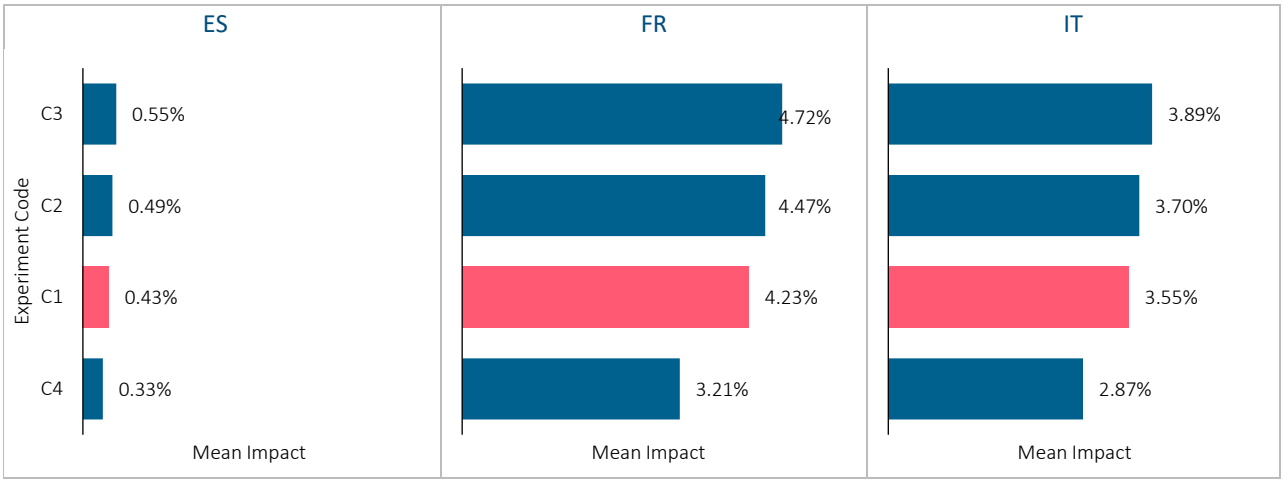
Sensitivity results are summarized using the mean relative mortality impact, i.e., the average percentage difference between climate-adjusted and baseline projected mortality rates across the modeled age-year cells (cf. 4.5.1). These averages are unweighted and, therefore, are intended to be interpreted as diagnostic indicators, not portfolio-weighted impacts.

4.6.1 SENSITIVITY TO THE COMPOSITE CLIMATE INDEX $C_{t,r}$

The first sensitivity test evaluates the effect of changing the weights assigned to the three components of the composite climate index: temperature anomaly, extreme heat days, and heat wave-duration days. The base weighting gives 20% to temperature anomaly, 70% to extreme heat days, and 10% to heat wave duration. Alternative specifications include equal weights, a duration-heavy index, and a temperature-heavy index.

Figure 4.8 below compares results by country under alternative weights assigned to the temperature anomaly, extreme heat days, and heat wave-duration days.

Figure 4.8
SENSITIVITY TO COMPOSITE CLIMATE INDEX WEIGHTS $C_{t,r}$



Notes: C3: temperature anomaly = 25% | extreme heat days = 35% | heatwave duration = 40%.
C2: temperature anomaly = 33% | extreme heat days = 33% | heatwave duration = 33%.
C1: temperature anomaly = 20% | extreme heat days = 70% | heatwave duration = 10% (baseline).
C4: temperature anomaly = 60% | extreme heat days = 25% | heatwave duration = 15%.

[148] 06_sensitivity_and_validation.ipynb

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The results show that the choice of climate-index weights affects the magnitude of the projected mortality impact, but not the broad direction of the results or country ranking. Across Spain, France, and Italy, the heat wave duration-heavy specification produces the largest average impact, while the temperature-heavy specification produces the lowest.

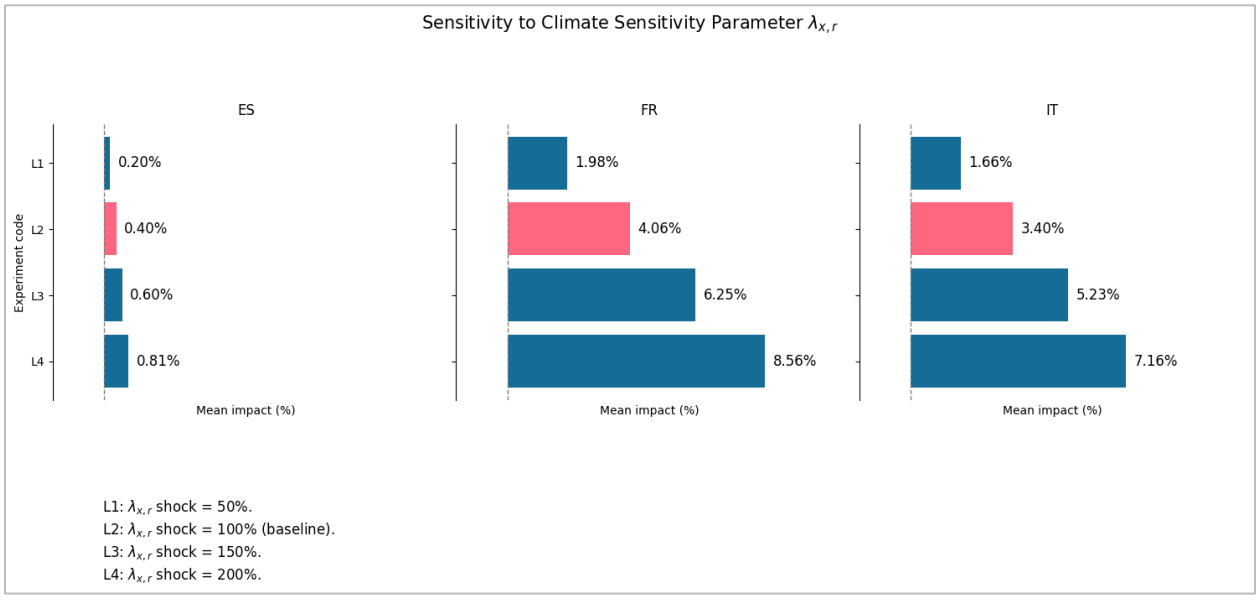
From a modeling perspective, this reinforces the importance of documenting the rationale for the selected $C_{t,r}$ weights. The weights encode an implicit judgment about which climate-health pathways and variables are most relevant for the intended actuarial application. The sensitivity results, therefore, support retaining the base specification while disclosing that alternative weighting structures can materially affect the level of projected impact. As discussed in the subsequent goodness-of-fit analysis of the weighting experiments (see subsection 4.6.3), within this framework, this judgment is not intended to rest on projected impacts alone, but also to consider whether alternative weight structures improve historical residual fit, remain interpretable, and are consistent with the intended use of the model. This provides a more balanced basis for selecting and documenting the composite climate index specification.

4.6.2 SENSITIVITY TO THE CLIMATE SENSITIVITY PARAMETER $\lambda_{x,r}$

The second sensitivity test evaluates selected shocks to $\lambda_{x,r}$, the age- and country-specific parameters that translate the climate index into a mortality adjustment. Because $\lambda_{x,r}$ is calibrated from limited historical experience and may be affected by data quality, model structure, and the selected calibration period, it is appropriate to test proportional changes to this parameter.

Figure 4.9 below compares the effect of applying 50%, 100%, 150%, and 200% of the calibrated sensitivity parameter.

Figure 4.9
SENSITIVITY TO LAMBDA



The results behave as expected (i.e., scaling the $\lambda_{x,r}$ parameters has a roughly linear impact) under the model structure and show that the $\lambda_{x,r}$ parameter uncertainty can be a material driver of results, particularly for countries with higher calibrated climate sensitivity. These tests are intended to be interpreted as model-risk diagnostics, not as alternative best-estimate assumptions. In practical use, material sensitivity to $\lambda_{x,r}$ may support additional review of the calibration period, residual structure, and age pattern of the parameter.

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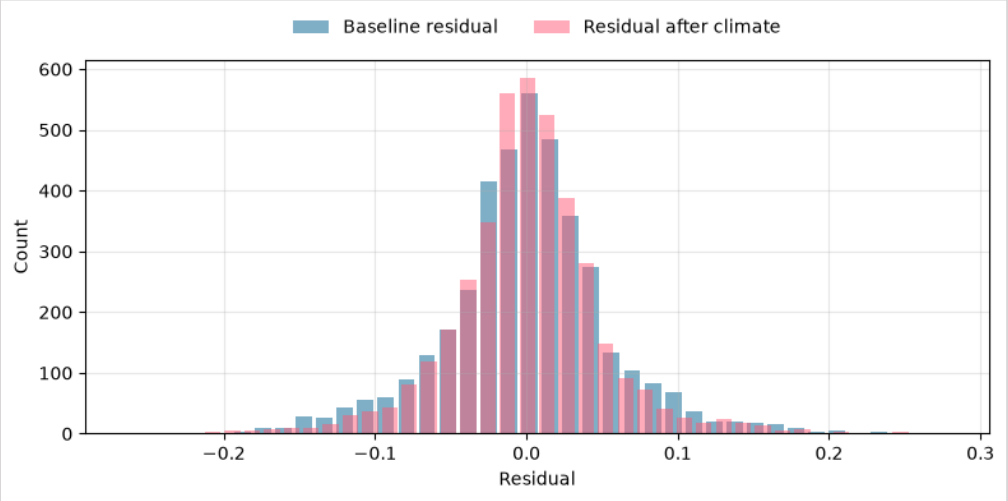
4.6.3 RESIDUAL ANALYSIS BEFORE AND AFTER CLIMATE CALIBRATION

Residual analysis provides a complementary diagnostic by comparing the distribution of baseline mortality residuals before and after the climate component is introduced. The purpose is to assess whether the climate calibration reduces systematic residual structures associated with climate variables, and whether the remaining residuals appear reasonable for the intended use of the model.

Figure 4.10 below compares baseline residuals with residuals after introducing the calibrated climate component.

Figure 4.10
DISTRIBUTION OF RESIDUALS BEFORE AND AFTERE CLIMATE CALIBRATION



A validated result shows that residuals after climate calibration are more centered around zero and less dispersed. Conversely, if the residual distribution does not improve, or if the climate-adjusted residuals introduce new skewness, fat tails, or country-specific anomalies, this would indicate that the climate term may be incomplete, unstable, or insufficiently aligned with the observed mortality variation.

Table 4.7 below summarizes residual-based goodness-of-fit measures. These measures are intended to assess whether the climate term improves the in-sample fit during the calibration period, not to establish causality or rank future projection scenarios.

Table 4.7
GOODNESS-OF-FIT METRICS

	Mean Absolute Error (MAE)		Root Mean Squared Error (RMSE)		Sum of Square Errors (SSE)	
	Baseline	**Climate-adjusted**	Baseline	**Climate-adjusted**	Baseline	**Climate-adjusted**
Spain	0.054	0.049	0.079	0.072	8.21	6.83
France	0.032	0.028	0.041	0.036	2.23	1.75
Italy	0.037	0.033	0.051	0.045	3.38	2.69
ALL	**0.041**	**0.036**	**0.059**	**0.053**	**13.82**	**11.27**

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Table 4.8 expresses the goodness-of-fit comparison in relative terms. Positive values indicate that the climate-adjusted specification reduces residual error relative to the baseline model.

Table 4.8
IMPROVEMENT IN GOODNESS-OF-FIT METRICS

	% Improvement in MAE	% Improvement in RMSE	% Improvement in SSE
Spain	9.5%	8.8%	16.9%
France	13.4%	11.4%	21.6%
Italy	12.6%	10.8%	20.5%
ALL	**11.4%**	**9.7%**	**18.5%**

The results show consistent improvement across all countries and all three error measures. At the combined level, the climate-adjusted model reduces MAE by 11.44%, RMSE by 9.72%, and SSE by 18.50%. France shows the largest percentage improvement across the three countries, followed closely by Italy, while Spain shows a smaller but still meaningful reduction in residual error. The larger percentage improvements in SSE are expected because SSE gives more weight to larger residuals, suggesting that the climate component is particularly helpful in reducing larger unexplained deviations.

Table 4.9 evaluates whether the construction of the composite climate index $C_{t,r}$ materially affects the historical calibration fit of the climate-adjusted mortality model:

Table 4.9
IMPROVEMENT IN GOODNESS-OF-FIT METRICS FOR VARIOUS WEIGHTING STRUCTURES

	w_1	w_2	w_3	% Improvement in MAE	% Improvement in RMSE	% Improvement in SSE
C1	0.20	0.70	0.10	5.02%	2.89%	5.70%
C2	1/3	1/3	1/3	4.83%	2.80%	5.52%
C3	0.25	0.35	0.40	4.70%	2.72%	5.37%
C4	0.60	0.25	0.15	5.01%	2.89%	5.70%

Notes: w_1--weight assigned to "temperature anomaly"
w_2--weight assigned to "extreme heat days"
w_3--weight assigned to "heat wave duration days"

Table 4.9 indicates that all composite climate-index weighting experiments improve residual fit relative to the baseline model (i.e., non-climate-adjusted). The differences across experiments are relatively small. Experiments C1 and C4 produce the strongest goodness-of-fit improvements, with C1 (baseline weighting structure) showing the highest MAE and RMSE improvement and C4 producing nearly identical results. C2 and C3 also improve fit, but by slightly smaller margins. This pattern supports the robustness of the overall modeling approach: **the inclusion of the climate index matters more than the precise choice among these tested weighting schemes.**

These results are not intended to be interpreted as proving that one weighting structure is definitively "correct." Rather, they provide evidence that the climate-adjusted model is directionally stable across plausible climate-index constructions. The selected weighting structure is intended to be justified by both goodness-of-fit and interpretability.

Overall, these diagnostics indicate that the climate term reduces in-sample error, which is an expected mathematical outcome when adding parameters to a regression model. However, this improvement alone does not distinguish a genuine climate signal from the model simply fitting noise or historical patterns. Consequently, the

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reported reduction in error metrics are intended to be interpreted as a necessary, but not sufficient, condition for model validation. To confirm that the climate term captures a robust signal rather than overfitting, future applications beyond this initial case study could add out-of-sample validation (e.g., calibrating on an earlier period and testing on later years) wherever data length permits. Until such out-of-sample confirmation is available, the model's reliability can be assessed through a holistic combination of sensitivity testing, residual analysis, and reasonableness checks, rather than relying solely on in-sample goodness-of-fit.

4.6.4 REASONABLENESS TESTS AND STRESS TESTING

The validation notebook also produces reasonableness checks. These checks are designed to identify projected mortality rates that are invalid, unusually large relative climate impacts, large climate components in log-mortality terms, large year-on-year changes, and potential age-pattern anomalies. The resulting flags are intended to support actuarial review rather than automatically accept or reject results. Examining flagged results may determine whether some or all are valid under a severe scenario or for a specific age-country cell.

Stress testing complements the sensitivity analysis by considering more adverse combinations of assumptions. Examples include assigning greater weight to acute heat metrics, increasing sensitivity factor $\boldsymbol{\lambda_{x,r}}$, or reviewing results under a severe climate pathway. These tests are useful for understanding model behavior under adverse but plausible conditions, especially where the outputs are used for long-term risk management, ORSA-style analysis, capital assessment, or strategic planning.

In summary, the sensitivity and validation results indicate that the climate-adjusted mortality framework is responsive to the construction of the composite climate index $C_{t,r}$ and the calibration of the sensitivity factor $\lambda_{x,r}$. The results are directionally coherent, but they also show that assumptions matter. For actuarial use, this supports a governance approach in which the base results are presented together with sensitivity ranges, residual diagnostics, and reasonableness flags. The model is, therefore, intended to be treated as a structured decision-support tool and not a deterministic forecasting engine.

4.7 GIT REPOSITORY

The case study is accompanied by a Git repository containing a Jupyter notebook suite, documentation, and selected input/output files required to reproduce the quantitative workflow. The repository is intended to provide a transparent and auditable implementation of the modeling framework described in this report, including data preparation, construction of climate hazard variables, baseline mortality modeling, climate calibration, projection, sensitivity testing, validation, and application-layer exhibits.

Table 4.9
GIT REPOSITORY

Item	Description
Repository	Society-of-actuaries-research-institute/CC230-Quantifying-Mortality-and-Morbidity-Impacts-From-Climate-Risks: A toolkit for quantifying mortality and morbidity impacts arising from climate risks
Contents	Jupyter notebooks, documentation, supporting files, and output files
Purpose	Reproducible implementation of the case study workflow

The repository is organized to support reproducibility and review. Each notebook corresponds to a defined stage of the modeling pipeline and includes comments, intermediate checks, and output references. The folder structure separates raw inputs, processed datasets, model outputs, figures, and documentation, so that users can trace the flow from source data to final exhibits. The repository also serves as a practical implementation guide for actuaries

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who wish to adapt the framework to other countries, climate scenarios, calibration periods, or portfolio structures. Users may modify selected components.

The repository materials are not intended to replace professional judgment, model governance, or independent validation. They are intended to be viewed as research and educational tools that illustrate one possible implementation of the climate-adjusted mortality framework. Before any operational use, users will likely want to review data quality, assumptions, calibration choices, parameter stability, sensitivity results, and limitations in light of their own modeling purpose and applicable professional requirements.

Disclaimer: The Jupyter notebooks available through the Git repository are provided for research, educational, and illustrative purposes only. They are not intended to constitute actuarial advice or represent production-ready systems without further validation, customization, and governance by the user. While reasonable efforts have been made to ensure accuracy and consistency, no guarantee is given as to completeness, fitness for a particular purpose, or compliance with applicable actuarial standards or regulatory requirements. Users are responsible for assessing the suitability of the materials for their specific use cases and implementing appropriate controls, validation, and documentation prior to any operational use.

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Section 5 Conclusions and Additional Insights

Climate change is gradually becoming a material driver of life and health insurance risk and is no longer a peripheral sustainability consideration. Climate-related hazards can affect mortality and morbidity through both acute pathways, such as heat waves, floods, storms, and wildfire events, and chronic pathways, such as sustained heat stress, air quality deterioration, vector-borne disease, mental health effects, and pressure on health care systems. Crucially, the health burden is distributed unevenly: direct injury and fatality represent only a fraction of the total impact in many developed countries, while indirect transmission channels (particularly air quality degradation, expanding vector ranges, and strain on healthcare access) can generate more persistent and cumulative effects. Vulnerability is strongly influenced by age, geography, socioeconomic status, pre-existing health conditions, and adaptive capacity, meaning that the same climate hazards can produce very different outcomes across populations. These effects are non-stationary over time, meaning that traditional actuarial approaches that rely primarily on historical experience and stable long-term trends may be insufficient to capture plausible future biometric risk under changing climate conditions.

Adaptation and its limits also deserve explicit attention. Early warning systems, climate-resilient infrastructure, and public health surveillance can substantially moderate climate-related health impacts. However, adaptation capacity is unevenly distributed: wealthier communities can invest in resilience, while marginalized groups face financial, institutional, and geographic barriers. Adaptation can also have limits and potential secondary effects, including the risk of maladaptation (i.e., responses that inadvertently increase long-term vulnerability), such as energy-intensive air conditioning straining power grids during heat peaks. Scenario assumptions regarding adaptive capacity can reflect these nuanced realities rather than assuming either optimal protection, or no adaptation at all.

This research paper proposes using forward-looking, scenario-based actuarial models that explicitly incorporate climate-related drivers into mortality and morbidity assumptions. The proposed climate-adjusted Lee-Carter framework, and the parallel extension to morbidity modeling, provide a practical structure for translating climate hazards, geographic exposure, and population vulnerability into actuarial projections. The framework is not intended to replace actuarial judgment or established experience-based methods. Rather, it is designed to enhance them by introducing a structured mechanism for testing how mortality and morbidity outcomes may evolve under alternative climate pathways, vulnerability assumptions, and adaptation conditions.

The case study for heat-related mortality risk in France, Italy, and Spain demonstrates that the framework can produce interpretable outputs for actuarial review, scenario analysis, and model governance. A key analytical conclusion is that climate-adjusted results depend on the interaction between projected climate hazards and calibrated mortality sensitivity. A high value of a given climate hazard index does not, by itself, imply a large mortality impact; the actual impact depends on how strongly the relevant age and country cells respond to the climate variable (i.e., on the modeled population's exposure and vulnerability). Conversely, populations with higher calibrated sensitivity may show more material projected impacts even when the climate index is less extreme. This reinforces the importance of reviewing age-band, geography-specific, and scenario-specific results rather than relying solely on aggregate headline measures.

For actuarial practice, the results are generally interpreted as conditional scenario outputs rather than point forecasts, unless a probabilistic or best-estimate framework has been explicitly developed. The model is most useful for identifying directional impacts, comparing patterns across countries and age groups, testing sensitivity to key assumptions, and supporting governance discussions around climate-related uncertainty. Where the application requires a central best estimate, such as pricing, reserving, underwriting, or financial reporting, the practitioner can document how scenario outputs have been translated into selected assumptions, including the use of weighting, margins, credibility, expert judgment, or other decision rules.

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The report also highlights that climate risks have enterprise-wide implications. Climate-informed mortality and morbidity assumptions may have implications for pricing, reserving, capital assessment, ORSA, underwriting, product design, reinsurance, risk appetite, and climate-related disclosure. In addition, climate change may affect insurers indirectly through asset values, investment returns, discount rates, liquidity, and broader asset-liability management considerations. A comprehensive assessment would, therefore, consider both liability-side biometric impacts and their potential interaction with asset-side and enterprise-risk exposures. Effective climate risk management may require embedding these analyses within enterprise risk management frameworks, helping to ensure that scenario analysis drives strategic decisions rather than serving merely as a compliance exercise. Clear communication of uncertainty distinguishing among what is known, what is unknown, and how assumptions may evolve can also be helpful for stakeholder management and informed decision-making.

Several additional insights follow from this research:

- Insurers could benefit from incorporating climate-related mortality and morbidity considerations into their governance and risk assessments, including where data limitations require simplified or reduced-form models. Qualitative risk identification and mapping of transmission channels precede and inform quantitative efforts.

- Closing data gaps and strengthening interdisciplinary collaboration is generally helpful. Granular, longitudinal data that links climate hazards to health outcomes remain limited, and progress may require partnerships with climate scientists, epidemiologists, and public health agencies.

- The societal dimension of risk reduction warrants acknowledgment. Just as the property and casualty insurance sector faces growing challenges of insurability and affordability in a changing climate, reducing climate-related life and health burdens ultimately involves a wide range of actions, from infrastructure and urban planning to public health and social protection, that extends beyond what insurers can do alone.

- Projection results are supported by sensitivity testing, alternative scenario views, and clear disclosure of uncertainty, limitations, and model judgment. It is important to distinguish among scenario analysis, stress testing, reserve adequacy testing, and assumption setting. Adverse climate scenarios may be appropriate for resilience testing, capital assessment, or ORSA.

- Model outputs are intended to be reviewed alongside the underlying climate metrics, calibrated sensitivity parameters, residual diagnostics, external scientific evidence, and reasonableness checks before being used in business decisions. The treatment of climate sensitivity parameters, vulnerability factors, adaptation assumptions, and any modeling constraints is intended to be transparent and subject to governance review. Where results are sensitive to these choices, the uncertainty is intended to be communicated explicitly.

Finally, the framework proposed in this research paper can be treated as a platform for continued development rather than a final endpoint. Future work may extend the analysis to additional countries, hazards, time horizons, socioeconomic segments, morbidity applications, adaptation pathways, and multi-peril interactions. It may also further explore the integration of scientific evidence, epidemiological research, and actuarial experience data. By adopting forward-looking, interdisciplinary, and scenario-based approaches, actuaries can better support insurer resilience, improve risk management, and contribute to a more robust understanding of how climate change may affect mortality, morbidity, and the financial and social security systems that depend on them.

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Section 6 Acknowledgments

The researchers' deepest gratitude goes to those without whose efforts this project could not have come to fruition: the Project Oversight Group and others for their diligent work overseeing questionnaire development, analyzing and discussing respondent answers, and reviewing and editing this report for accuracy and relevance.

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Appendix A Glossary

Acute climate impacts: Short-term effects of extreme weather events (e.g., floods, hurricanes, heat waves) on life, health and property.

Adaptive capacity: The ability of individuals, communities, or systems to adjust and respond effectively to climate-related risks and impacts, thereby reducing potential harm or taking advantage of opportunities.

Affordability: The extent to which insurance premiums remain within the financial means of households and businesses.

Biometric risks: Uncertainty around actual mortality, longevity, morbidity (illness or injury), or disability experience.

Chronic climate impacts: Long-term, cumulative health effects from sustained environmental changes (e.g., air pollution, vector-borne disease, sea-level rise).

Climate adaptation: Actions aimed at adjusting systems and behaviors to reduce harm from climate impacts.

Climate mitigation: Efforts to limit or prevent greenhouse gas emissions to slow climate change.

CMIP: Coupled Model Intercomparison Project, a collaborative framework where international climate modeling centers run standardized simulations under various emission scenarios (e.g., temperature, precipitation).

Copernicus: European Union's Earth observation program that provides open, operational data and services on climate, atmosphere, oceans, land, and emergency management.

Early warning system: A coordinated system that monitors climate and environmental conditions, forecasts emerging hazards, and issues timely alerts so that people and institutions can take protective action.

ERM: Enterprise Risk Management, an organizational framework for identifying, assessing, and managing risks across portfolios.

Exposure: The degree to which populations, assets, or systems are subject to climate hazards (for instance, due to their location).

Forward-looking: Scenario-based actuarial approaches anticipating future risk evolution rather than relying on historical data.

Harvest effect: Short-term surge in deaths among frail individuals (e.g., during climate or pandemic shocks), followed by a temporary dip. Also known as mortality displacement.

Hazard: A potentially damaging process, phenomenon, or human activity that poses a specific threat to life, health, property, infrastructure, or the environment (such as floods, wildfires, or heat waves). See also 'Peril' below.

Heat dome: Meteorological phenomenon where high-pressure systems trap heat over a region, causing extreme temperatures.

ICD coding system: International Classification of Diseases, the global standard for coding diagnoses and health conditions.

Insurability: The extent to which risks can be effectively priced and underwritten within insurance markets.

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Insured lives: Individuals covered under life or health insurance policies, often representing healthier cohorts due to underwriting selection.

IPCC: Intergovernmental Panel on Climate Change, a United Nations body providing scientific assessments on climate change, its impacts, and potential adaptation and mitigation strategies.

ISSB: International Sustainability Standards Board, an IFRS Foundation body issuing global sustainability-related disclosure standards, incorporating and building on the TCFD framework for climate-related reporting.

L&H: Life & health insurance provides financial protection against mortality, morbidity, and longevity risks, and may also include savings or investment-linked components.

Longevity: Actuarial measure of the expected lifespan within a population, influenced by mortality and morbidity trends.

Maladaptation: Adaptation measure that unintentionally increases vulnerability or creates new risks, ultimately making people or systems less rather than more resilient to climate impacts.

Morbidity: Incidence of illness or disease within a population.

Mortality: Incidence of death within a population.

Nature-based solutions: Climate adaptation or mitigation measures that harness natural assets and ecosystem services (e.g., wetlands for flood control).

NGFS: Network for Greening the Financial Sector, an international coalition of central banks and financial supervisors sharing best practices for the development of environment and climate risk management.

NOAA: The National Oceanic and Atmospheric Administration is the U.S. federal agency responsible for monitoring and forecasting weather, climate, oceans, and atmospheric conditions.

Non-stationary risks: Risks whose statistical properties change over time, making past data unreliable for future projections.

Novel risks: Risks that do not fit into traditional categories of stationary or emerging risks (e.g., climate change, cyber).

ORSA: The Own Risk and Solvency Assessment is an insurer's internal, forward-looking process to evaluate its material risks and overall solvency needs.

P&C: Property and casualty insurance contracts cover property damage and liability risks. P&C insurance is also known as non-life insurance or general insurance in some regions.

Parametric insurance: Insurance contracts that pay out based on predefined triggers (e.g., rainfall levels) rather than actual losses.

Peril: A potentially damaging process, phenomenon, or human activity that poses a specific threat to life, health, property, infrastructure, or the environment (such as floods, wildfires, or heat waves). See also 'Hazard' above.

Physical risks: Climate-related risks directly arising from acute weather events (e.g., storms, floods, wildfires, heat waves) or chronic environmental changes (e.g., rising temperatures, sea-level rise, drought).

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$PM_{2.5}$: Fine particulate matter with diameter $\leq$ 2.5 microns, harmful to human health when inhaled. A major source is wildfire smoke, which significantly increases cardiovascular and respiratory risks.

Protection gap: The difference between insured losses and total economic losses, often widened by climate hazards.

RCP: Representative Concentration Pathways are IPCC scenarios projecting future temperature increases and climate impacts.

Resilience: Capacity of populations, systems, or insurers to absorb and adapt to adverse shocks.

Risk transmission channels: Mechanisms through which hazards affect human life, health and property (e.g., the causal effects from heat on cardiovascular stress).

Severe convective storms: A category of fast-developing, highly localized storms driven by atmospheric convection, including severe thunderstorms, hailstorms, tornadoes, and damaging straight-line winds.

SSP: Shared Socioeconomic Pathways are IPCC scenarios describing alternative future population, economic development, technology, and policy conditions that shape greenhouse gas emissions and climate-related risks.

Storm surge: Temporary rise in sea level generated by a storm's winds and low atmospheric pressure, which pushes seawater onto coastal land and can cause coastal flooding, especially when combined with high tides.

Stranded assets: Investments that lose economic value abruptly or prematurely due to climate-related physical or transition risks, such as policy changes, technological shifts, or market repricing.

Streetlight Effect: Tendency to search for answers where data and modeling is easiest rather than most relevant.

Subsidence: Gradual sinking or downward settling of land caused by factors such as groundwater loss, soil drying or shrinkage, natural compaction, or other geological processes.

Systemic risks: Risks that affect entire regions, economies, or populations simultaneously, making them impossible to diversify across portfolios.

Systems thinking: Approach that examines how individual risks interact within larger interconnected systems, recognizing that changes in one part can influence outcomes across populations, environments, and economies.

TCFD: Taskforce on Climate-related Financial Disclosures, an international framework (now incorporated into ISSB) offering guidance to enhance climate disclosures, covering governance, strategy, risk management, and metrics.

Tipping points: Critical thresholds in climate, environmental, or social systems at which a small additional change in external conditions triggers a large and often irreversible shift in the system's overall state.

Transition risks: Climate-related risks stemming from the transition to a low-carbon economy, such as policy, technology, market, and socio-economic changes. Transition risks also include reputational and litigation risks.

Trend bounce-back: A short-term dip followed by a rebound in health care utilization that follows an acute climate-related shock, reflecting deferred care rather than a true underlying change in health trends.

Urban heat island: Elevated temperatures in cities caused by infrastructure heat absorption and reduced vegetation.

Vector-borne diseases: Illnesses transmitted by living organisms such as mosquitoes or ticks (e.g., malaria, dengue, Lyme disease).

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Vulnerability: The sensitivity of populations or systems to harm, shaped by age, health, environment, and socioeconomic factors.

Wet bulb temperature: A combined measure of heat and humidity indicating how well the body can cool itself through sweating. Sustained wet-bulb levels near 35 °C / 95 °F are potentially life-threatening.

WHO: World Health Organization, a United Nations agency responsible for global public health, providing guidance, standards, and evidence on health risks, disease prevention, and health care system resilience.

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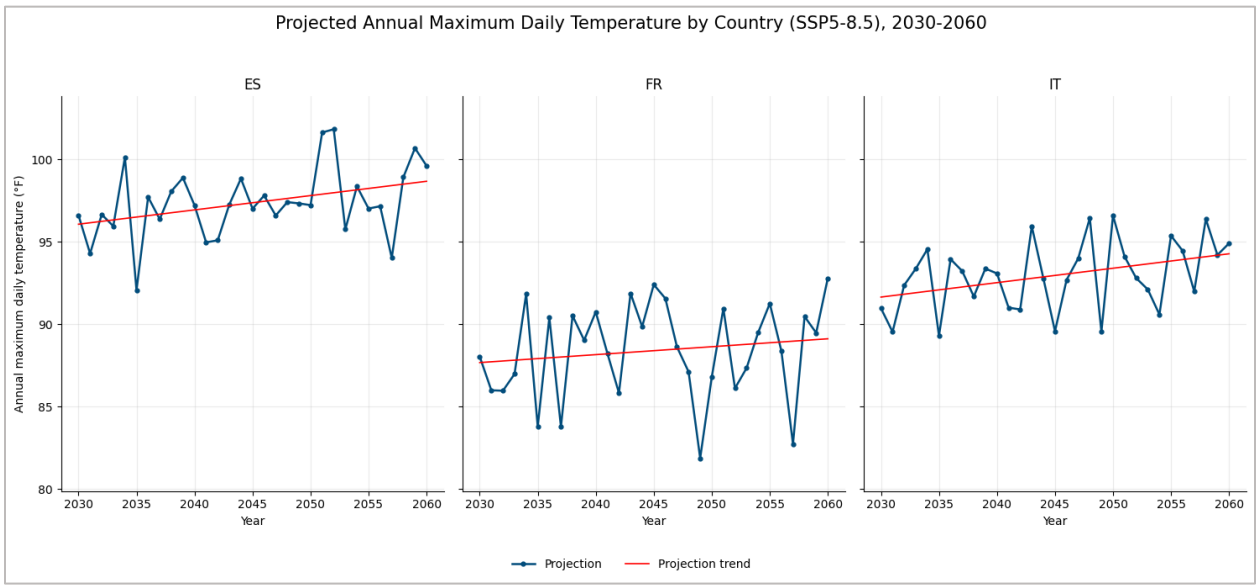
Appendix B Selected Graphs in Fahrenheit Degrees

Temperature metrics are reported in degrees Celsius (°C) in the main body of the report for consistency with the underlying climate datasets and European reporting conventions.[149]

The corresponding Fahrenheit (°F) versions of these exhibits are provided below.

Figure 4.3

PROJECTED ANNUAL MAXIMUM DAILY TEMPERATURE



[149] Certain climate variables used in CMIP6/IPCC-derived datasets are reported in kelvin (K), particularly temperature variables such as air temperature, near-surface air temperature, daily maximum and minimum near-surface air temperature, and sea-surface temperature. The kelvin is the SI unit of thermodynamic temperature. Where Celsius values are required for presentation or actuarial interpretation, values expressed in kelvin may be converted to degrees Celsius by subtracting 273.15. To convert Celsius to Fahrenheit, multiply by 1.8 and add 32 to the result.

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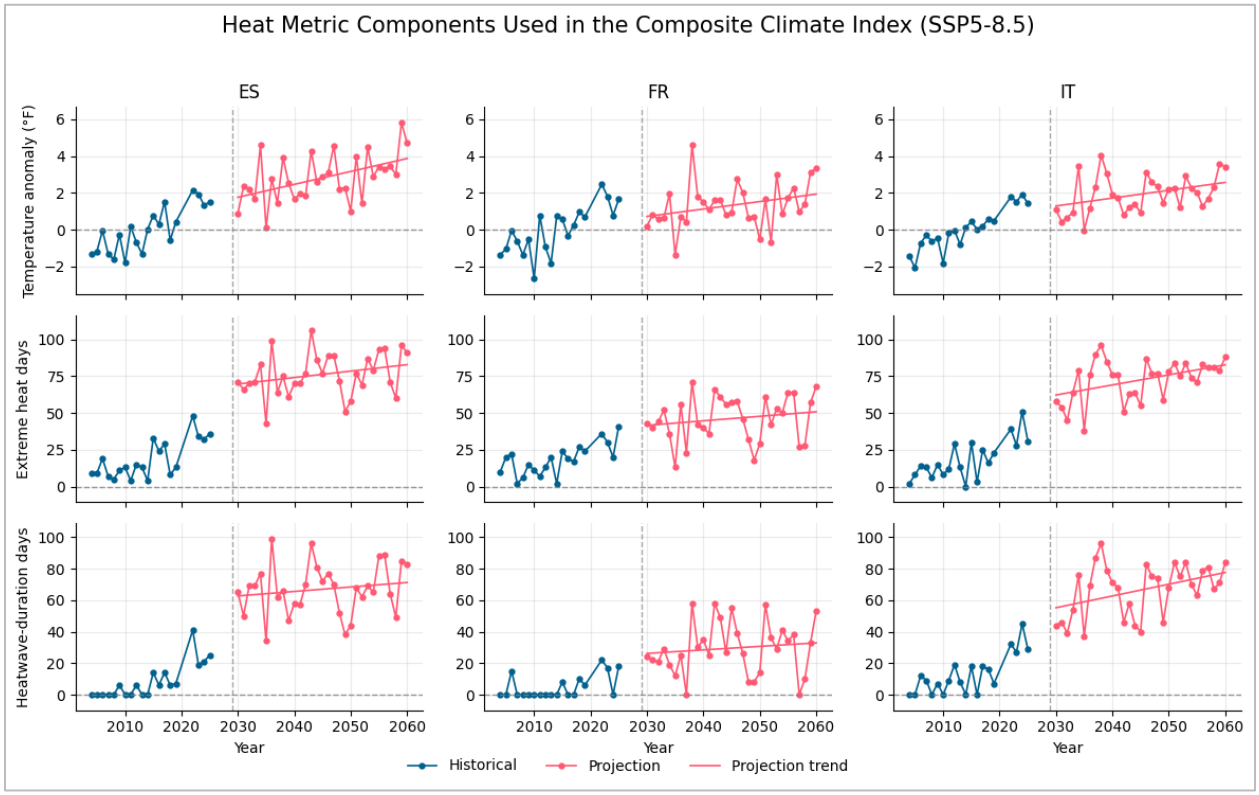
Figure 4.4
HEAT METRICS COMPONENTS



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Main References

The report provides detailed source attribution through footnotes at the point where each reference is used. This section highlights a selected set of core references that underpin the research.

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