Spatial and sociodemographic heterogeneities in climate-related mortality: a systematic literature review

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Abstract

As climate change alters the frequency and intensity of extreme weather events worldwide, mortality risks vary substantially across regions and populations. Identifying vulnerable groups is therefore essential. However, existing reviews remain fragmented, typically focusing on single hazards, primarily temperature, without integrating evidence across multiple weather extreme events or systematically examining spatial and sociodemographic heterogeneity. This systematic review addresses this gap to inform evidence-based assumptions for future population projections under climate change. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we synthesized global evidence on heterogeneity in mortality risks associated with climate extremes. A total of 246 studies from Web of Science and Scopus were included, comprising 211 on temperature-related mortality and 35 on natural hazard-related mortality. The findings show that climate-related mortality is unevenly distributed and shaped by demographic, socioeconomic, geographic, and climatic factors. Females, older adults, and individuals with lower education or socioeconomic status consistently face higher mortality risks related to extreme temperatures and natural hazards. Cold exposure remains the dominant global contributor to temperature-related mortality, although heat-related risks are increasing with rising global temperatures. Spatial patterns also vary across regions and climate zones: temperate regions show stronger cold effects, while tropical regions face increasing risks from hydrometeorological hazards such as storms. Despite these insights, major research gaps remain, particularly in Africa and in studies integrating demographic and socioeconomic vulnerabilities in natural hazard-related mortality.

Keywords: climate extremes, mortality, natural hazards, temperature, systematic review

1. Introduction

Climate change is recognized as one of the most significant global health challenges of the 21st century (The Intergovernmental Panel on Climate Change (IPCC), 2023). Over the past five decades, global surface temperatures have increased at an average rate of 0.18°C per decade, reflecting a persistent warming trend (Samset et al., 2023). This warming, together with shifting weather patterns, has contributed to more frequent and intense extreme weather events, including heatwaves, droughts, floods, storms and wildfires, which are already affecting population health worldwide (Dimitrova et al., 2019; Kharb et al., 2022; Watts et al., 2019).

As extreme events become more frequent and severe, population exposure is expected to increase, intensifying health impacts through multiple pathways. Direct effects include heat stress, dehydration, injuries, and increased transmission of vector- and water-borne diseases, particularly during floods and after storms. Indirect effects arise from disruptions to food and water systems, population displacement, and increased risks of conflict over scarce resources (Abel et al., 2019; Decet & Marcucci, 2023; Dimitrova et al., 2021;). Among these impacts, climate-related mortality represents one of the most immediate and severe consequences for human health.

An expanding body of epidemiological research demonstrates strong associations between climate-related exposures and mortality (Ballester et al., 2023; Gao et al., 2024; Gasparrini et al., 2022). Temperature exposure is the most extensively studied factor. Temperature-mortality relationships often follow U-, J-, or reverse-J shaped exposure-response curves, depending on geographic location, with the lowest mortality occurring within an optimal temperature range and increased risks at both cold and heat extremes (Gasparrini et al., 2015). Globally, cold exposure poses a greater mortality risk than heat (Bakhtsiyarava, et al., 2023; Gasparrini et al., 2015), partly because cold effects tend to persist longer, lasting up to 3 to 4 weeks, compared with the more immediate impacts of heat (Guo et al., 2014). However, the magnitude and direction of these impacts vary across regions and populations, reflecting differences in climate conditions, demographics, and socioeconomic characteristics (Borrell et al., 2006; Dimitrova et al., 2021; Son et al., 2019).

Despite the growing number of systematic reviews on climate-related health impacts (Arsad et al., 2022; Benmarhnia et al., 2015; Dimitrova et al., 2021; Son et al., 2019), the existing evidence remains fragmented. Most reviews focus primarily on temperature-related mortality and do not provide an integrated assessment across multiple climate-related hazards, such as floods, storms, and droughts. In addition, they rarely examine how mortality risks vary jointly across sociodemographic and spatial dimensions, including geographic regions and climate zones. Many reviews are also dated and may not capture recent evidence or methodological advances, particularly as climate change intensifies and alters exposure patterns and associated mortality risks. This lack of integrated and up-to-date evidence limits the ability to identify vulnerable populations and constrains the development of robust, evidence-based assumptions for demographic modelling and future population projections under climate change.

To address these gaps, this systematic review provides an updated and integrated global synthesis of studies quantifying the relationship between climate-related events and mortality across both extreme temperatures and natural hazards. The review focuses on heterogeneity across sociodemographic and spatial dimensions, examining mortality risks by age, sex, socioeconomic status, geographic region, and climatic zone to identify vulnerable groups and highlight key knowledge gaps. By synthesizing evidence across diverse settings, this review aims to improve understanding of how climate change shapes mortality patterns and to generate evidence that can inform demographic modelling and projections of future population dynamics under climate change scenarios.

2.Understanding mechanisms, and impacts of climate change on mortality

As climate change drives a shift toward rising temperature distributions, its direct impacts on human mortality operate through interconnected mechanisms involving extreme weather events, exposure, and vulnerability (IPCC, 2022). Our conceptual framework adapts the IPCC risk paradigm to illustrate the principal pathways linking climate change with mortality outcomes **(Figure 1)**.

Figure 1 demonstrates that climate change contributes to human mortality through both direct and indirect pathways. Direct effects arise from the extreme weather events themselves, including storms, droughts, floods, heatwaves, and cold spells. Extreme temperatures, including both heat and cold, directly elevate human health and mortality by triggering acute physiological stress responses and aggravating pre-existing chronic conditions. Over longer periods, persistent deviations in ambient temperature may also produce slow-onset health effects, potentially increasing the incidence and severity of chronic diseases. In contrast, rapid-onset events such as heat waves and cold spells can induce sudden physiological stress, leading to acute increases in mortality from cardiovascular, respiratory, kidney, and heat-related illnesses (Gasparrini et al., 2015; Liu et al., 2022). Natural hazards can cause immediate health impacts during the event itself, such as drowning or injury-related deaths, while others emerge as long-term outcomes, for example, infectious disease outbreaks, mental health effects, or healthcare system disruptions following storms and floods (Yang et al., 2024).

Climate change affects human health not only through direct impacts but also through indirect pathways that alter ecosystems, food systems, air quality, and social stability. Some of the indirect effects operate through multiple environmental and ecological pathways, including vector-borne diseases such as malaria, dengue, and Lyme disease; water-borne diseases including cholera and cryptosporidiosis; food insecurity and undernutrition; and changes in aeroallergen exposure and air quality. Moreover, climate shocks can exacerbate economic stress and competition over scarce resources, potentially leading to greater conflict and social instability (IPCC, 2022; Watts et al., 2015).

The magnitude and distribution of mortality risk are moderated by differential exposure and vulnerability shaped by both geographic and sociodemographic factors. Geographic factors such as region, climate zone, and urban-rural setting define baseline climatic conditions and exposure likelihood and intensity. Sociodemographic factors including age, sex, education, occupation, and income determine individuals' vulnerability and adaptive capacity in the face of climate hazards. Ultimately, human mortality reflects the outcome of the interaction between the type and intensity of the hazard, and population-level exposure and vulnerability. Climate-related mortality depends not only on the hazard itself but also on the demographic and contextual characteristics that shape vulnerability and adaptive capacity. The relationship between climate impacts and population health outcomes is nonlinear and complex, mediated by multiple intersecting dimensions.

The framework explains how climate change impacts mortality patterns across subpopulations by linking demographic composition and social vulnerability to differential risks. By identifying the core mechanisms underlying climate-related mortality, this framework supports anticipation of future mortality patterns and strengthens demographic projections under changing climate conditions. Building on this conceptual foundation, it also informs the design and analytical focus of our systematic review, guiding the selection and interpretation of empirical evidence on geographic and sociodemographic disparities in climate-related mortality.

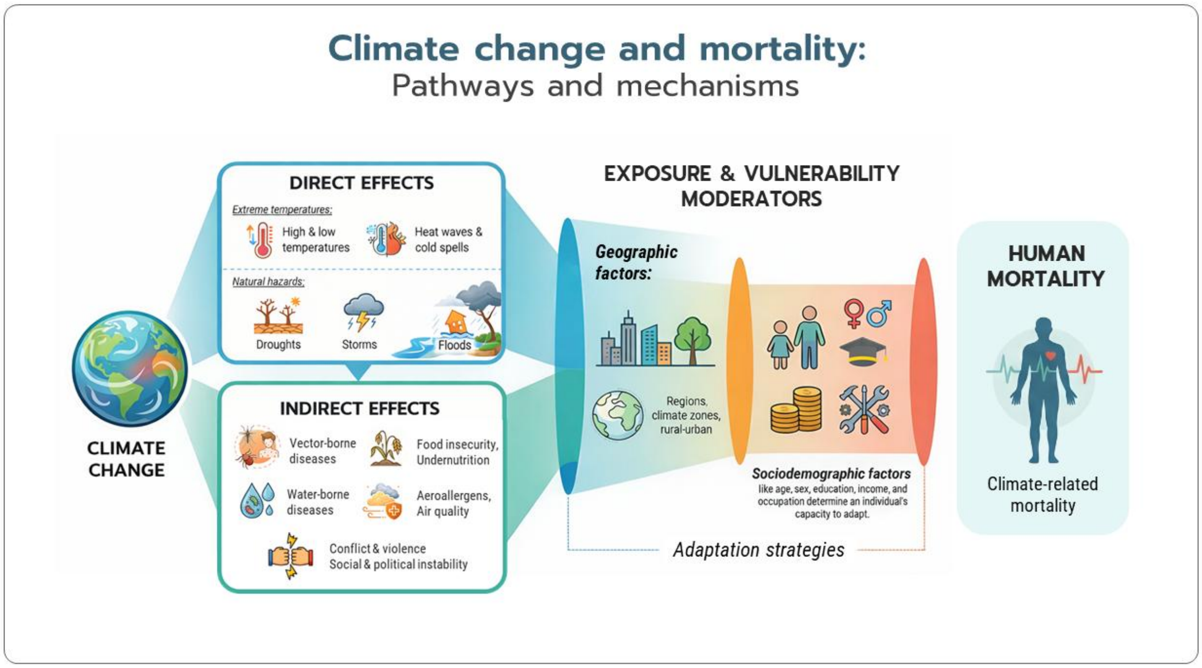

Figure 1. Conceptual framework of the pathways linking climate change to human mortality and moderating factors

3. Methodology: identification and selection of publications

A systematic literature review was performed, following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The protocol has been registered in the PROSPERO, an international prospective register of systematic reviews, with ID: CRD42024563147.

A summary of the “Population”, “Exposure”, “Comparator”, “Outcomes”, “study design” (PECOs) framework (Morgan et al. 2018) is presented below (Table S1):

- **Population**: the general population of all ages.
- **Exposure**: extreme weather events include variations in extreme temperatures (e.g., high and low ambient temperatures, heat waves, and cold spells) and natural hazards (e.g., storms, floods, and droughts).
- **Comparators**: A comparable population unexposed to the same extreme weather events or the same population at a time when it was not exposed to such events.
- **Outcome**: mortality (e.g., number of deaths, years of life lost, change in life expectancy) for all-cause/non-accidental/non-external/natural cause mortality and mortality from natural hazard events.
- **Study design**: quantitative observational studies.

3.1 Data search and search strategy

We performed a systematic search of two electronic databases, including *Web of Science (WoS)* and *Scopus*. Date restriction was applied in the search, only peer-reviewed articles published in English between January 1985 and April 2025. The search was first undertaken on 15 August 2023 for WoS and 17 November 2023 for Scopus, and subsequently updated to include studies published up to the date of 28 April 2025. This was to identify observational studies investigating the direct relationship between extreme weather events (e.g., extreme temperature and natural hazards) and human mortality.

This systematic review used two core concepts of search terms, including extreme weather events [exposure] and mortality [outcome]. The search for exposure centred on extreme weather events: "climate change" OR "weather" OR "extreme temperature" OR "cold" OR "heat" OR "cold spell" OR "heat wave" OR "climate disaster" OR "flood" OR "storm" OR "hurricane" OR "tornado" OR "typhoon" OR "drought." Outcome was focused on mortality: "mortality" OR "death" OR "all-cause mortality" OR "years of life lost (YLL)" OR "life expectancy." These search terms of both climate events and mortality can exist in various permutations and combinations **(Table S2).**

3.2 Study selection criteria and procedure

The initial literature search considered original and peer-reviewed articles published since 1985, indiscriminate of study location. We selected studies that were: (1) quantitative observational studies, which present results for the general population, (2) based on mortality outcomes in all-cause mortality, non-accidental (non-external/natural) causes of death, or mortality attributable to natural hazard events, (3) reported information on the direction or magnitude of the relationship between climate events (e.g., extreme temperatures and natural hazards) and mortality, (4) explored the effects of spatial and sociodemographic heterogeneity on climate-related mortality, and (5) provided effect measures as relative risk/risk ratio, odds ratio, regression coefficient or percent change. Studies investigating morbidity effects and those that include the effect of air pollution, through wildfire or other indirect causes were excluded. Studies that focused on estimation/ projections for future mortality under climate scenarios, were also excluded in this review. No restrictions were placed on the duration of exposure in the studies screened.

The first search identified 11,318 records from WoS (n = 3,376) and Scopus (n = 7,942). After systematic removal of duplicates, the remaining records were imported into the artificial intelligence (AI) platform AS Review (https://asreview.nl/) for screening and data management. Titles and abstracts were independently screened by two reviewers (SK and WK) according to predefined inclusion and exclusion criteria; disagreements were resolved by a third reviewer (RG). This process yielded 655 articles for full-text assessment. Following detailed review, 367 articles met the eligibility criteria. From these articles, we extracted information on each study's characteristics (e.g., study location, time frame, study population); exposure details (e.g., temperature exposure metrics); outcome measures; data sources; statistical methods; subgroup analyses; examined effect modifiers; and the main findings, including effect modification results that related to sociodemographic heterogeneity. Ultimately, 199 articles published between January 1985 and August 2023 (WoS) and November 2023 (Scopus) were included from the first search.

To ensure comprehensive coverage, the search was updated to include studies published after the initial search dates, covering the period up to 28 April 2025 for both databases. This second search yielded 3,343 records (WoS: 1,343; Scopus: 2,000). Following deduplication and screening, 42 additional articles were identified as eligible. In addition, five further studies were obtained through expert consultation. In total, 246 articles met the inclusion criteria and were incorporated into this systematic review **(Figure 2)**.

For analytical purposes, these studies were categorized into two groups based on the type of extreme weather event investigated. The first group comprised of 211 articles (86%) on ***temperature-related mortality***, which examined variations in extreme temperatures (e.g., high and low ambient temperatures, heat waves, and cold spells). The second group comprised 35 articles (14%) on ***natural hazard-related mortality***, focusing on events such as storms, floods, and droughts.

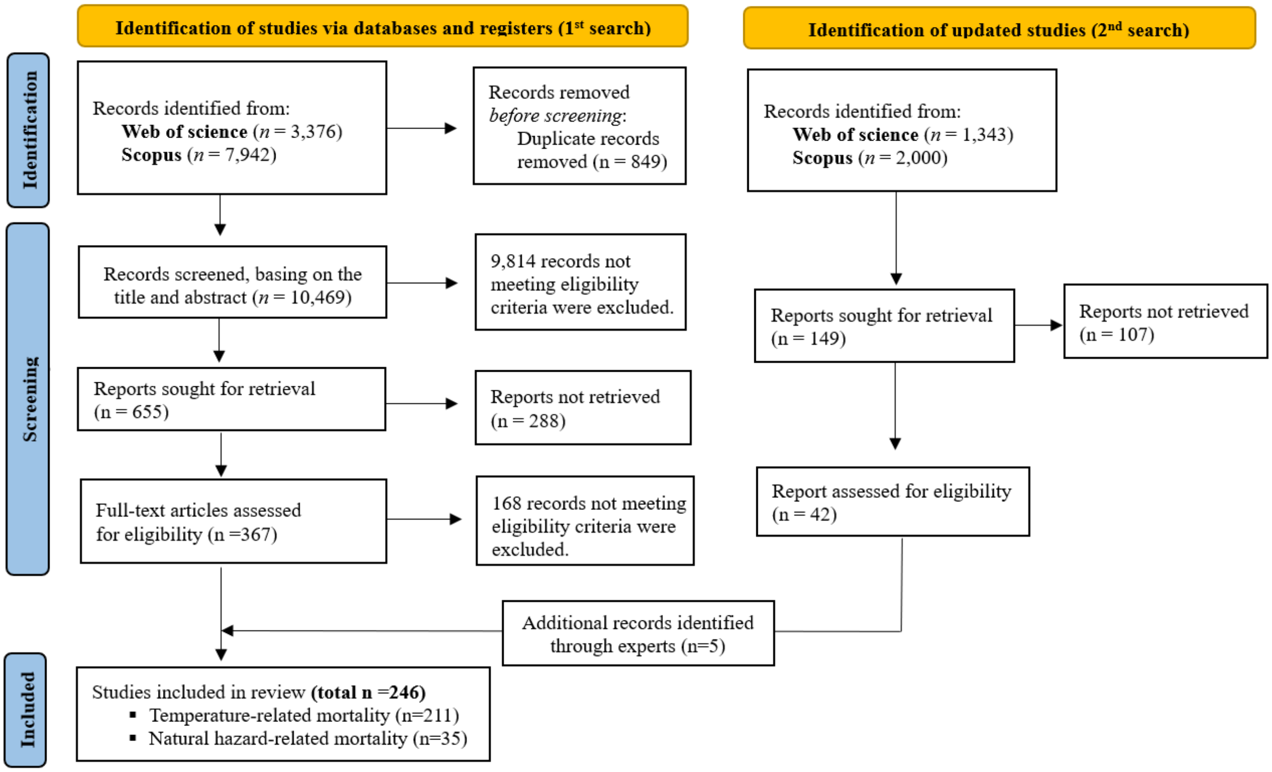

Figure 2. Flow chart of studies selection process

3.3 Data extraction and analysis

In order to understand how populations and their vulnerability to extreme weather events differ, we systematically conducted subgroup analyses. We used the key findings as reported by the original study authors and summarized the evidence on effect modification[1] based on *sex, age, socioeconomic status (education or income) and geographic areas (continent, climate zones, urban/rural areas)*. We summarized overall strength of evidence based on the number of studies presenting consistent findings relative to those showing conflicting results within the overall body of evidence (Table 1). A similar approach was used in previous studies (Son et al., 2019) which classified into strong evidence, limited or suggestive evidence, weak evidence, or no evidence (**Tables S4**). Also, this approach

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[1] Effect modification refers to the statistically significant effect (i.e. direction, size of effect, and p-values) of a climate exposure on mortality that varies across subgroups. It highlights the heterogeneity of risk, offering critical insights into which groups are most vulnerable to climate-related mortality

allowed us to synthesize the heterogeneous effects of extreme temperatures and other natural hazards on mortality risk.

4. Results

4.1 Descriptive overview of the evidence base

4.1.1 Temporal and geographical distribution of reviewed studies

The publication years of all 246 studies are shown in **Figure 3, Panel A**, illustrating a pronounced expansion in research on climate-related mortality over the past two decades. The temporal trend reveals two notable peaks in 2013 and 2019, followed by the largest surge in 2022, when 28 articles were published. This trajectory reflects the growing global recognition of climate change as a critical public health challenge.

With respect to study duration, defined as the temporal span of the dataset used in the analysis, most investigations on temperature-related mortality spanned either 5 to 9 years (66 studies; 31%) or 20 years and longer (50 studies; 24%), with the longest time series extending to 107 years in a study conducted in Stockholm, Sweden (Åström et al., 2013). Natural hazard studies more often covered the periods of 20 years or more (17 studies; 49%), including a 116-year global analysis of storm surges (Bouwer & Jonkman, 2018). Differences also emerged in median study years **(Figure 3, Panel B**). Temperature-related mortality studies were more likely to use post-2010 data (84 studies; 40%), whereas natural hazard studies clustered in the 2000-2009 decade (14 studies; 40%).

In terms of study scope **(Figure 3, Panel C)**, most temperature studies adopted micro-level designs, particularly city-level (96 studies) and multicity (51 studies) analyses. Conversely, natural hazard research more often employed national-scale assessments (17 studies). These divergences likely reflect differences in data accessibility, methodological approaches, and the nature of the exposures under study.

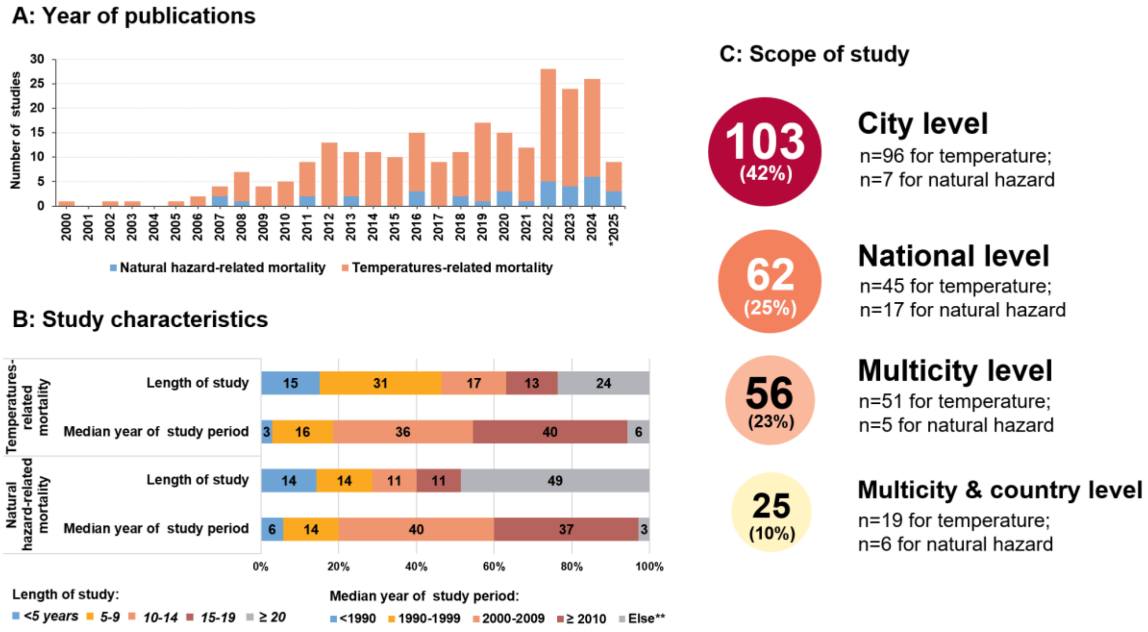

Figure 3. ***Panel A*** shows the distribution of papers by year of publication on climate-related mortality, ***Panel B*** shows the distribution of study characteristics based on length of study and median year of study period, and ***Panel C*** shows the distribution of papers by scope of study (N=246). Note: * refer to included studies published between January 1 and April 28, 2025; ** studies that used different study periods by city/country or used two separate periods.

Understanding the geographical distribution of climate-related mortality research is essential for assessing whether existing evidence adequately captures global variations in vulnerability. **Figure 4, Panel A** illustrates the geographic distribution of studies on temperature-related mortality included in this review. Altogether, the articles encompassed 80 country specific estimates and 13 global, multi-continent analyses. However, the spatial distribution of the studies reveals a marked disproportionality, reflecting limitations in data availability, as reliable temperature and mortality data are lacking for certain countries and regions. The most heavily studied regions are Asia (105 studies, particularly China and East Asia), Europe (55), and the Americas (31; largely the United States). By contrast, substantially fewer studies address lower-income regions, especially Africa, which is represented by only five articles. Moreover, among the studies included in this review, 12 focused only on urban areas, whereas only 3 examined population in rural areas.

To further examine the geographic coverage, we classified study locations into four Köppen-Geiger climate zones (Peel et al., 2007): Group A: “Tropical” (15 studies), B: “Arid” (8), C: “Temperate” (90), and D: “Continental”

(25), with no articles falling into Group E: "Polar." Seventy-three articles covered multiple climate zones due to national, cross-country, or multi-location analyses; these were recorded separately to avoid misclassification.

By comparison, research on natural hazard-related mortality **(Figure 4, Panel B)** was heavily concentrated in the Americas (15 studies), with markedly fewer studies conducted in Asia (6) and Europe (5). Africa continues to be critically underrepresented, with only two studies. The United States dominates this body of literature, appearing in 10 studies, while Brazil, Mexico, the Philippines, and Spain are each the focus of only three studies. With respect to population settings, just two studies focused exclusively on urban areas and one on rural areas. All the included studies covered only three Köppen-Geiger climate zones: Group A, "Tropical" (6); C, "Temperate" (8); and D, "Continental" (2), with 19 articles spanning multiple climate zones.

Overall, the current evidence base demonstrates a clear geographical bias towards certain regions and even certain countries. The absence of research in Africa is particularly concerning given the region's high climate vulnerability coupled with limited adaptive capacity (Centre for Research on the Epidemiology of Disasters (CRED), 2023; IPCC, 2022). One contributing factor is the disproportionately low allocation of global funding to climate research in Africa, estimated at no more than 3.8% of the global total, with only a small share directed toward academic publications on climate-related health risks (Overland et al., 2022). Furthermore, research emerging from Africa are rarely published in top-tier journals, frequently because their focus on individual countries is undervalued within global research hierarchies (Nagendra et al., 2018). These funding and publication barriers reinforce the underrepresentation of African contexts in the literature, resulting in a scarcity of empirical studies identified in this systematic review and underscoring critical knowledge gaps on climate-related mortality in the region.

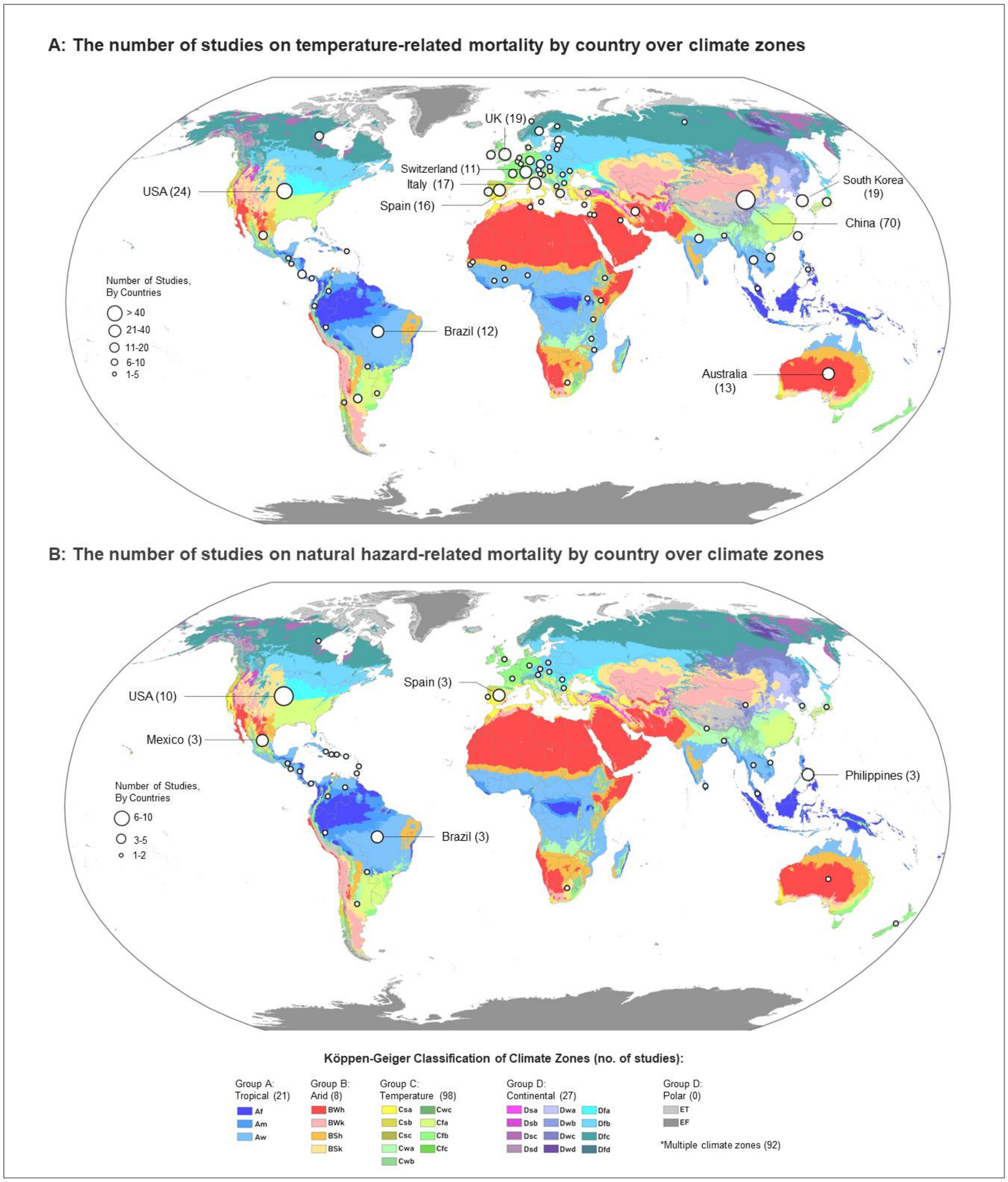

Figure 4. Geographic distribution of reviewed studies on temperature-related mortality (**A**) and natural hazard-related mortality (**B**) by country across Köppen–Geiger climate zones. Circle sizes represent the number of studies per country. Note: a single article may include multiple case study locations.

Af=tropical rainforest climate. Am=tropical monsoon climate. Aw=tropical savanna climate. BWh=hot desert climate. BWk=cold desert climate. BSh=hot semi-arid climate. BSk=cold semi-arid climate. Csa=hot-summer Mediterranean climate. Csb=warm-summer Mediterranean climate. Csc=cold-summer Mediterranean climate. Cwa=monsoon-influenced humid subtropical climate. Cwb=subtropical highland climate or Monsoon-influenced temperate oceanic climate. Cwc=cold subtropical highland climate or Monsoon-influenced subpolar oceanic climate. Cfa=humid subtropical climate. Cfb=temperate oceanic climate. Cfc=subpolar oceanic climate. Dsa=Mediterranean-influenced hot-summer humid continental climate. Dsb=Mediterranean-influenced warm-summer humid continental climate. Dsc=Mediterranean-influenced subarctic climate. Dsd=Mediterranean-influenced extremely cold subarctic climate. Dwa=Monsoon-influenced hot-summer humid continental climate. Dwb=Monsoon-influenced warm-summer humid continental climate. Dwc=Monsoon-influenced subarctic climate. Dwd=Monsoon-influenced extremely cold subarctic climate. Dfa=hot-summer humid continental climate. Dfb=warm-summer humid continental climate. Dfc=subarctic climate. Dfd=extremely cold subarctic climate. ET=tundra climate. EF=ice cap climate.

4.1.2 Types of climate exposures assessed of reviewed studies

The evidence base in this systematic review was overwhelmingly dominated by studies on temperature-related mortality (211 studies; 86% of all included studies). Of these, 114 studies (46%) investigated both high- and low-temperature effects, allowing comparative risk estimates across thermal extremes. About one-third (80 studies; 33%) focused exclusively on heat, either high temperatures (46 studies) or heat waves (34 studies), whereas only 17 studies (7%) examined cold-related outcomes (7 on low temperatures and 10 on cold spells).

These studies employed various forms of air temperature as the exposure measures. Mean daily ambient temperature accounting for the effects of both heat and cold on human health, was the most common exposure (123 studies). It is often considered the standard baseline metric, especially in multi-country studies (Gasparrini et al., 2015; Zhao et al., 2021). To capture acute heat stress, 23 studies incorporated daily maximum temperature. In contrast, the 34 heatwave studies employed diverse definitions, using different temperature indices (e.g., maximum, minimum, or mean), threshold temperatures, and durations ranging from 1 to 20 days. Likewise, the 10 cold-spell studies typically relied on daily minimum or mean temperature, combined with thresholds and varying durations, to characterize cold spells. There exists no standard definition of a “hot” or “cold” day, or a “heatwave” or “cold spell,” either in scientific research or policy frameworks. A further 21 studies employed two or more temperature metrics, highlighting the methodological complexity of quantifying temperature effects. In addition, 12 studies used diurnal temperature range (DTR), defined as the difference between daily maximum and minimum temperatures, to account for within-day variability. Recognizing that temperature alone is often regarded as an inadequate indicator of thermal stress, 11 studies adopted apparent temperature (AT), a composite index combining air temperature, relative humidity, and wind speed, to better reflect human thermal discomfort. This measure may be more relevant when comparisons of thermal exposure are required. This diversity of metrics reflects the wide variation in approaches used to characterize temperature-related exposures across contexts. Consequently, the choice of exposure metric should be determined not only by its contextual relevance, but also by data availability and methodological suitability **(Table S3).**

Regarding natural hazards, 35 studies (14% of all included studies) examined their effects on mortality. These studies predominantly focused on extreme weather events, including storms (hurricanes, tornadoes, cyclones, and typhoons) (15 studies; 6%), floods (13; 5%), and droughts (7; 3%). Standardization in hazard exposure measurement proved even more difficult than for temperature. Storm-related studies alternated between indicators such as wind speed along a storm’s trajectory and simple event occurrence (Gray et al., 2022; Huang et al., 2024). Similarly, flood studies typically relied on event-based records, defining exposure as areas affected by flooding over periods ranging from days to months, with no direct measurement of inundation levels (Yang et al., 2023). In contrast, drought analyses more frequently applied standardized indices such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), which capture drought severity across short-term (e.g. 1- 6 month measures) to long-term timescales (e.g.12-15 month measures) (Gwon et al., 2023; Salvador et al., 2021). More recently, the Evaporative Demand Drought Index (EDDI) has been introduced, which measures drought conditions based on atmospheric evaporative demand (Abadi et al., 2022). These indices offer a more consistent framework for assessing drought severity and duration in relation to mortality outcomes.

Taken together, these findings reveal a field heavily skewed toward temperature exposures, with heat far more frequently investigated than cold, and with relatively few studies addressing natural hazards. At the same time, the wide diversity of metrics underscores the methodological barriers to comparability and the persistent absence of standardized approaches.

4.1.3 Mortality outcomes and measurement approaches

Across the reviewed studies, mortality outcomes were overwhelmingly measured as daily death counts. Among temperature-related mortality studies, 203 studies relied on death counts, while only a small minority employed alternative health indicators such as Years of Life Lost (YLL; 8 studies), with three combining deaths and YLL. Similarly, natural hazard-related studies (34 studies) measured mortality as deaths, with only one incorporating YLL. This dominance of crude mortality counts reflects the accessibility of death registration data but also constrains the ability to capture premature or adult mortality and broader population health impacts.

This systematic review focused on all-cause mortality as the primary outcome. Causes of death were identified using the *International Classification of Diseases* (ICD), 9th and 10th revisions (ICD-9 and ICD-10). A total of 104 studies explicitly analysed all-cause mortality, defined as ICD-9 codes 000-999 or ICD-10 codes A00-Z99/U99. Where such all-cause mortality counts were unavailable, many studies used non-external, non-accidental, or natural causes of death as proxies (ICD-9: 001-799; ICD-10: A00-R99), which applied to 107 studies. In addition, 12 studies specifically examined deaths directly or indirectly associated with natural hazards such as cyclones, typhoons, hurricanes, tornadoes, and floods. These studies assessed mortality at different temporal scales, including event-based, monthly, and annual analyses. For drought exposure, all-cause mortality was the most frequently applied outcome metric (7 studies).

Most studies analysed mortality across all age groups (187 studies on temperature-related mortality; 32 on natural hazard-related mortality). These studies further stratified analyses by age groups, thereby providing insights into effect modification and highlighting differential vulnerabilities across populations. Nevertheless, only 12 temperature-related studies examined specific age groups, primarily older adults (≥60 years), and very few addressed young children, with just one study each addressing ages 0-4 in relation to temperature or flood events.

4.1.4 Study designs and statistical methods applied

To understand how a changing climate affects human mortality, researchers have employed various statistical approaches to quantify the relationship between environmental exposures and mortality outcomes. This relationship commonly referred to as the exposure-response relationship. In this systematic review, the most frequently applied approaches were time-series, case-crossover, and case-series study designs.

For temperature exposure, **t**ime-series approaches were commonly used to assess short-term associations between daily temperature fluctuations and mortality. In these models, daily mortality was treated as the dependent variable, with daily temperature, humidity, or weather variables included as predictors, while adjusting for confounders such as air pollution, day of the week, and holidays. Risk estimates were typically reported as dose-response functions, expressed as percentage change or relative risk (RR) of mortality per unit increase in temperature. In addition, some studies have given estimates of the attributable burden, reporting either absolute excess deaths (counts) or relative excess deaths (fractions) attributable to non-optimal temperatures.

As the mortality data rarely follow a normal distribution, most analyses employed ***generalized linear models (GLMs)*** (133 studies) or ***generalized additive models (GAMs)*** (34 studies), to estimate exposure-response relationships. Within these frameworks, mortality was typically modelled as a count outcome using Poisson or quasi-Poisson regression, which provided an appropriate basis for estimating daily death counts. These regression models were often fitted with natural cubic spline function, allowing flexible estimation of non-linear relationships. With this analysis, researchers estimate the minimum mortality temperature (MMT), representing the temperature at which all-cause mortality is lowest, then sum the additional deaths resulting from deviations in temperature above and below this threshold. Several studies defined city-specific temperature cut-offs, such as the 90th or 10th percentiles of daily temperature, to capture the increased risks linked to extreme heat and cold events. A substantial number of studies (110 studies) further incorporated *distributed lag non-linear models (DLNMs)* within GLMs or GAMs, as proposed by Gasparrini (2010), to simultaneously capture both the non-linear shape of the temperature-mortality relationship and the lagged effects, which describe the delayed impact of exposure on mortality. Lag structures commonly ranged from 1-3 days for hot temperatures up to 28 days for cold temperatures. In addition, multi-location or multi-country analyses used hierarchical models, often implemented as *multivariate meta-analyses*, to pool the estimated location-specific overall cumulative exposure-response association in each location (Gasparrini et al., 2015; Guo et al., 2014; Scovronick et al., 2024).

Similarly, studies on natural hazards and mortality frequently employed multilevel approaches, most often using regression and time-series methods. Mortality impacts were typically quantified through measures of association, including relative metrics such as risk ratios, odds ratios, and incidence rate ratios (IRRs), alongside absolute measures such as excess deaths (ED). Moreover, GLMs were the most widely applied statistical framework, used in 27 of the reviewed studies. Poisson GLMs, as well as overdispersed quasi-Poisson or negative binomial specifications, were applied to modelling count data such as daily or event-based mortality arising from storms, floods, and droughts. Storm-related studies used these models to link mortality counts with indicators such as storm occurrence, maximum wind speed, or rainfall (Gray et al., 2022; Huang et al., 2024), while flood-related studies relied on event-based records capturing duration, severity, and geographic extent to estimate excess deaths by comparing populations in flood-affected versus non-affected areas (Chu et al., 2025). In addition, several studies examined lagged effects following storms or floods to determine whether elevated mortality risks often persist for long-term impacts (Parks et al., 2022; Yao Wu et al., 2024). Drought-related studies most often incorporated continuous drought indices such as SPI, SPEI, and EDDI, within Poisson models to quantify the impact of droughts on daily mortality and to capture both short-term and prolonged risks (Abadi et al., 2022; Salvador et al., 2020). A smaller number of studies (n = 6) further incorporated DLNMs within GLM frameworks to capture lagged effects, recognizing that mortality may occur not only during the acute phase of hazards but also in the days or weeks that follow.

Overall, research on climate-related mortality has advanced from basic regression models to more complex methods such as DLNMs and hierarchical meta-analyses, enabling the capture of non-linear, lagged, and spatially heterogeneous effects. These methods are especially valuable for capturing the complex climate-mortality relationships that vary by geographic areas, climate zone, and population vulnerability. Nonetheless, the continued reliance on GLM-based approaches highlights their enduring importance, given their adaptability in analysing count-based mortality data and their capacity to integrate diverse exposure metrics, ranging from daily temperature to event-based hazard indicators such as floods, storms, and drought indices.

4.2 Empirical evidence and vulnerability in climate-related mortality: Effect modification

This section synthesizes evidence on effect modification in climate-related mortality across sociodemographic and geographic characteristics. **Table 1** presents the number of effects from original studies reporting statistically significant associations, including the direction and size of effects, between mortality and both temperature extremes and natural hazards, along with those reporting no significant associations. In some cases, multiple effects were counted from a single study when significant results were observed across different subgroups. For example, if heat exposure was significantly associated with increased mortality in males while cold was significant in females, each subgroup effect was counted separately. Subsequently, we combined all reported effects within each factor to derive the overall summary effect for that factor. These overall summary effects were then categorized as strong evidence, limited or suggestive evidence, or weak evidence **(Tables S4).** We determined the category based on the quantity of studies reporting consistent findings with those presenting conflicting results in the overall summary of evidence. This approach was used in previous studies (Son et al., 2019). A complete list of the included studies is provided in the Supplementary Material **(Tables S5-S6).**

The findings reveal pronounced demographic heterogeneities in temperature-related mortality. Sex-based differences were evident, as shown by 133 original studies reporting effect modification, providing strong evidence that females experience higher risks from both heat (67 effects) and cold (33 effects). For natural hazards, findings were less consistent: males were more vulnerable during tropical storms (4 effects), whereas females showed greater risks from floods (4 effects) and droughts (3 effects).

Effect modification by age was consistently observed and emerged as one of the strongest modifiers of climate-related mortality. Although the categorization of age varied across studies, evidence from 179 original studies consistently showed that older adults (≥60 years) were disproportionately affected by both heat (115 effects) and cold (76 effects) compared with younger age groups. Evidence for children aged under five was reported only a few studies, which indicated an increased risk (8 effects for heat). For natural hazards, older adults still showed highest mortality risk during tropical storms (8 effects).

Socioeconomic status (SES) and education further influenced vulnerability. Evidence from 38 original studies reporting effect modification across different education groups showed that individuals with no or low education consistently faced higher risks from both heat (23 effects) and cold (16 effects). Similarly, SES groups, defined by individual-level indicators (e.g., income, occupation, social class) and country-level measures (e.g., poverty index, GDP, Gini index, regional development), were examined in 27 studies. Across these studies, low-SES groups consistently showed greater vulnerability to both heat (12 effects) and cold (8 effects). For natural hazards, the evidence on education and SES was limited; however, it suggested that lower educational attainment and lower SES were associated with increased mortality during tropical storms and floods.

Regional analyses revealed substantial geographic variation. Strong evidence indicates that cold contributes more to mortality than heat across most regions. The largest evidence base was in Asia (62 original studies), where cold-related mortality predominated, particularly in Eastern Asia (38 cold vs. 10 heat effects), where most studies were conducted. A similar pattern was observed in the Americas. In Europe (24 studies), northern regions showed suggestive evidence of greater cold-related risks (9 effects), whereas southern Europe showed higher heat-related mortality (4 effects). Evidence on natural hazards was limited and concentrated in North America and Asia, reported increased mortality associated with tropical storms and flooding and only sparse evidence from Africa and Oceania.

Across Köppen-Geiger climate zones, temperature-related mortality varied systematically (69 original studies). The temperate zone (Group C) showed the strongest evidence, with 34 cold-related and 15 heat-related effects. Arid (Group B) and tropical (Group A) zones also showed slightly more cold-related mortality (4 effects each) than heat-related mortality, whereas the continental zone (Group D) showed the opposite pattern, with more heat-related (5 effects) than cold-related effects. Overall, cold exposure contributed more to mortality across most climate zones. For natural hazards, tropical regions experienced the highest storm-related mortality, while temperate zones showed elevated mortality risks across hazards, particularly floods.

Urban-rural contrasts were observed in 37 original studies. Urban areas showed higher heat-related (22 effects) and cold-related (8 effects) mortality. Conversely, rural areas were more affected by storms (2 effects), with drought-related risks evident in urban contexts (2 effects).

Table 1 Summary of evidence for population vulnerability and effect modification in climate-related mortality

Effect modifier	Temperature-related mortality			Natural hazards-related mortality						Summary of evidence
	k	**Heat/Heat waves**	**Cold/Cold spells**	***k***	**Tropical storms**	***k***	**Flood**	***k***	**Drought**	
Sociodemographic characteristics										
Sex	**133**			**9**		**7**		**6**		***Temperature:*** strong evidence that females are at higher risk from heat and cold. ***Natural hazard:*** limited evidence indicating that males may be at higher risk during tropical storms, while females may face a higher risk during droughts.
Female		67 effects ↑; *15 null effects*	33 studies ↑; *16 null effects*		3 effects ↑; *2 null effects*		4 effects ↑; *1 null effect*		3 effects ↑; *2 null effects*	
Male		27 effects ↑	13 studies ↑		4 effects ↑		2 effects ↑		2 effects ↑	
Age	**179**			**11**		**7**		**7**		***Temperature:*** strong evidence that older people are at higher risk from heat and cold. ***Natural hazard:*** limited evidence indicating that older people may be at higher risk during tropical storms and droughts.
Older people (60+)		115 effects ↑; 5 *null effects*	76 studies ↑; 5 *null effects*		8 effects ↑; *1 null effect*		2 effects ↑; *1 null effect*		3 effects ↑; *1 null effect*	
Children (≤ 5)		8 effects ↑	2 studies ↑		2 effects ↑		2 effects ↑		1 effect ↑	
Adults		13 effects ↑	12 studies ↑				2 effects ↑		2 effects ↑	
Education	**38**			**2**		**2**				***Temperature:*** suggestive evidence of higher risk with none or low education for heat and cold. ***Natural hazard:*** weak evidence for education levels.
None or low		23 effects ↑; *5 null effects*	16 effects ↑; *2 null effects*		2 effects ↑					
High		2 effects ↑; 1 effect ↓	2 effects ↑; 1 effect ↓				1 effect ↑; 1 effect ↓			
SES*	**27**			**2**		**4**				***Temperature:*** limited evidence of higher risk with low SES for heat and cold. ***Natural hazard:*** weak evidence for SES levels.
Low		12 effects ↑; *3 null effects*	8 effects ↑; *3 null effects*		2 effects ↑		2 effects ↑			
High		3 effects ↑; 1 effect ↓	1 effect ↑; 1 effect ↓				1 effect ↑; 1 effect ↓			
Geographic characteristics										***Temperature:*** strong evidence shows that cold contributes more to mortality across regions, particularly Eastern Asia, Europe and Americas. Europe, cold effects found in the north, while heat is more pronounced in the south
Continent†										
Africa	**2**					**2**		**1**		
Northern										
Sub-Saharan			2 effects ↑				2 effects ↑		1 effect ↑	
Americas	**14**			**5**		**7**		**4**		
Northern		4 effects ↑	5 effects ↑		4 effects ↑		4 effects ↑		1 effect ↑; *2 null effects*	
Latin & Caribbean			5 effects ↑		1 effect ↑		3 effects ↑		1 effect ↑	

Table 1 Summary of evidence for population vulnerability and effect modification in climate-related mortality

Effect modifier	Temperature-related mortality			Natural hazards-related mortality						Summary of evidence
	k	**Heat/Heat waves**	**Cold/Cold spells**	***k***	**Tropical storms**	***k***	**Flood**	***k***	**Drought**	
Asia	**62**			**3**		**4**				***Natural hazard:*** America faces a higher risk from storms, and floods.
Eastern		10 effects ↑	38 effects ↑				2 effects ↑			
Southeastern			2 effects ↑		1 effect ↑					
Southern		4 effects ↑	3 effects ↑		2 effects ↑		2 effects ↑			
Western		2 effects ↑	3 effects ↑							
Europe	**24**					**4**		**2**		
Eastern		1 effect ↑	2 effects ↑				1 effect ↑			
Northern		3 effects ↑	9 effects ↑							
Southern		4 effects ↑	2 effects ↑				1 effect ↑		2 effects ↑	
Western		2 effects ↑	1 effect ↑				2 effects ↑			
Oceania & pacific	**3**	3 effects ↑				**1**	1 effect ↑			
Climate zone †	**69**			**6**		**4**		**2**		***Temperature:*** temperate climate showed the strongest mortality evidence from both cold and heat. ***Natural hazard:*** suggestive evidence showing tropical regions face risks from storms, whereas temperate zones show elevated risks across multiple hazards.
Group A: Tropical		3 effects ↑	4 effects ↑		4 effects ↑		1 effect ↑			
Group B: Arid			4 effects ↑							
Group C: Temperate		15 effects ↑	34 effects ↑		2 effects ↑		3 effects ↑		1 effect ↑	
Group D: Continental		5 effects ↑	4 effects ↑						*1 null effect*	
Urban-rural	**37**			**3**				**3**		***Temperature:*** suggestive evidence of higher risk with urban areas for heat. ***Natural hazard:*** weak evidence for urban-rural areas.
Rural		7 effects ↑; *2 null effects*	2 effects ↑		2 effects ↑				1 effect ↑	
Urban		22 effects ↑	8 effects ↑		1 effect ↓				2 effects ↑	

Note: ***k***= the total number of original studies that reported effect modification; * SES groups are based on several variables at both the individual level (e.g., income, occupation, social class, residential area) and the country level (e.g., poverty index, gross domestic product [GDP], Gini index, regional development level); † For temperature-related mortality studies, we selected only those that reported the effects of both heat and cold exposure, then we compared the direction and size of these effects. The meanings of the arrows and symbols are as follows: ↑ indicates a higher or increased risk of mortality; ↓ indicates a lower or reduce risk of mortality; and "*null effect*" denotes no statistically significant difference, no effect, or no effect modification.

5. Discussion: Interpretation of findings, underlying mechanisms, and key assumptions

This systematic review provides an updated synthesis of the effects of extreme weather events on mortality risk and represents one of the first global efforts to integrate evidence across multiple hazards. It encompasses both temperature-related exposures (including heat, cold, heatwaves, and cold spells) and natural hazards (such as storms, floods, and droughts), with a particular focus on identifying factors that shape population vulnerability and outlining key assumptions for future population projection under climate change conditions. Through a comprehensive search of two major scientific databases, 246 eligible studies were identified, spanning a wide range of study designs, populations, exposure and outcome definitions, and methodological approaches. The synthesis of these studies provides consistent evidence of climate-mortality associations while also revealing important gaps and heterogeneities. To facilitate interpretation, the discussion is structured around two key dimensions of vulnerability, including sociodemographic and spatial characteristics as summarized below.

5.1 Sociodemographic heterogeneities in climate-related mortality

Sex-based differences

Sex significantly modifies the temperature-mortality relationship, with strong evidence indicating that females are generally more vulnerable to both heat- and cold-related mortality than males. Elevated risks among females during extreme heat and heatwaves have been consistently documented across diverse contexts, including China (Gao et al., 2023; Huang et al., 2015; Yang et al., 2012), India (Singh et al., 2019); Italy (Ellena et al., 2022), Belgium (Demoury et al., 2022), and Ghana (Wiru et al., 2020). Beyond heat, European studies also highlight a greater mortality risk for females during periods of extreme cold (Arbuthnott et al., 2020; Laaidi et al., 2006). These disparities have been attributed to physiological factors such as higher percentage of body fat, reduced sweat production, and hormonal fluctuations related to the menstrual cycle and menopause, all of which may impair thermoregulatory capacity and exacerbate heat stress (Wickham et al., 2021). Nevertheless, some evidence suggests that contextual factors, including housing conditions, residential environment, and social roles, may confound these associations (Bell et al., 2008). A minority of studies reported no sex differences (Åström et al., 2013). Conversely, some studies reported higher mortality risks among males during periods of heat (Ngarambe et al., 2022; Otrachshenko et al., 2018) and cold (Liu et al., 2021; Riahi & Khorsandi, 2025). This elevated risk is often attributed to males' greater engagement in outdoor activities, particularly during heatwaves, as well as are often occupied in heavy labour such as construction, agriculture, and emergency response (Burkart et al., 2014).

Evidence on sex-based differences in mortality linked to natural hazards is inconsistent across studies. Studies have shown varying results regarding gender susceptibility, with some indicating significant differences while others report null associations. Several studies suggest higher male mortality during storms such as typhoons in the Philippines (Gray et al., 2022), cyclones in the United States (Parks et al., 2023), and hydro-metrological disasters in 63 countries (Zagheni et al., 2015), as well as during flash floods in the United States (Terti et al., 2017) and flooding events in Hunan, China (Li et al., 2007). This heightened risk for males may be attributed to greater involvement in rescue operations or emergency services and high-risk activities during disasters (Li et al., 2007). By contrast, other studies report higher female mortality from flood (Chu et al., 2025; Lynch et al., 2025; Pradhan et al., 2007), and tornadoes in the United States (Chiu et al., 2013), cyclones in Bangladesh (Burkart & Kinney, 2016), a pattern partly explained by female's greater likelihood of being indoors and thus more exposed to building collapse or limited access to evacuation routes (Katrin Burkart & Patrick Kinney, 2016). In many contexts, female face restricted mobility during disasters due to caregiving responsibilities which can reduce survival chances (Lynch et al., 2025). In the case of droughts, findings remain mixed: some studies identify females as more vulnerable, with findings from metropolitan areas in Brazil (Salvador et al., 2022) and Nebraska, United States (Abadi et al., 2022), while others report greater male vulnerability (Salvador et al., 2021) or no significant sex differences (Lynch et al., 2020). These findings highlight that gender disparities in natural hazard mortality are not solely biological but are deeply rooted in structural inequalities and context-specific social norms.

Considering these results in literature, particularly the consistent finding that females are generally more vulnerable than males to both heat- and cold-related mortality across most regions, future projections should incorporate slightly higher excess mortality risks from extreme temperature exposure among females. This consideration is especially important in low- and middle-income settings, where adaptive capacity may be more limited.

Age-related vulnerability

Age consistently emerges as the most robust demographic factor modifying the relationship between extreme temperatures and mortality. The significantly higher mortality risk associated with both heat and cold among people aged 60 years and over, compared with younger populations, is well documented in the literature. Numerous studies have reported the highest relative risks (RRs) (Bai et al., 2014; Deng et al., 2020; Gallo et al., 2024), the largest YLL (Liu et al., 2021), greater excess deaths (ED) (Scovronick et al., 2024; Thommen, 2005), and the greatest percentage increases in mortality (Baccini et al., 2008) in this age group. These findings are often reflected in the characteristic "U-shaped" exposure-response curves, where mortality risk rises sharply at both temperature extremes. Importantly, the oldest age groups contribute the largest share to the overall mortality burden from non-optimal temperatures (Huang et al., 2022; Masselot et al., 2023; Yu et al., 2011). This elevated vulnerability is not unexpected, given the age-related decline in the body's thermoregulatory capacity, including reduced sweat gland function, impaired blood circulation, weakened immune systems, and a reduced ability to detect dehydration during periods of high temperature (Scovronick et al., 2024; Vardoulakis et al., 2014; Zeng et al., 2022). Additionally, older adults often present additional risk factors for temperature sensitivity, including the presence of pre-existing chronic diseases and the use of certain pharmacological treatments that interfere with thermoregulation. Sociological factors also play a critical role in exacerbating vulnerability, including social isolation (Lin et al., 2019; Zhang et al., 2017), lower socioeconomic status (Bakhtsiyarava et al., 2023; Bettaieb et al., 2020), and substandard housing conditions, particularly the lack of access to adequate heating or air conditioning—more common among older females—have been linked to higher heat-related mortality (D'Ippoliti et al., 2010). At the other end of the age spectrum, infants aged 0-4 years exhibit an elevated relative risk of mortality during heat waves in India (Singh et al., 2019), and high temperature in Ghana (Azongo et al., 2012) and 13 countries across Africa (Brimicombe et al., 2024), attributable to a combination of physiological immaturity, environmental exposure, and socioeconomic disadvantage. In contrast, a higher proportion of infants in this age group in Japan are associated with increased cold-related mortality, largely due to seasonal peaks in respiratory infections such as influenza and pneumonia (Chung et al., 2018). Together, these findings emphasize the heightened vulnerability of both the youngest and oldest age groups to temperature extremes, underscoring the importance of age-targeted strategies in climate-related health interventions.

Evidence from natural hazards reinforces these patterns. Both older adults and young children show disproportionate mortality risks following storms, floods, and droughts. This vulnerability is often attributed to limited mobility, reduced resilience to post-disaster illnesses, and heightened susceptibility to malnutrition and respiratory impacts (Salvador et al., 2022). In Bangladesh, individuals aged 60 years and older were nearly nine times more likely to die from tornadoes (Sugimoto et al., 2011), while similar findings were observed among those aged ≥75 during Hurricane Katrina in the United States (Joan Brunkard et al., 2008). Zagheni et al. (2015) further demonstrated that children and older adults, particularly females, face higher risks of death during hydro-meteorological disasters. Flood exposure has also been associated with increased infant mortality in Africa, with each flood event linked to an additional 5.35 deaths per 1,000 live births (Zhu et al., 2024). By contrast, floods appear to disproportionately affect adults of working age, as shown in Hunan, China (Li et al., 2007). Evidence links drought-related mortality disproportionately to older adults, with studies in Spain (Salvador et al., 2020) and Portugal (Salvador et al., 2021) and a multicity analysis in Brazil (Salvador et al., 2022) showing the highest excess mortality risks among older women (65-74 years), followed by children.

While temperature-related mortality and deaths from natural hazards may contribute to accelerated population aging and a modest reduction in life expectancy among older cohorts under severe climate scenarios, these groups already exhibit lower survival probabilities. Consequently, no specific adjustments are recommended at this stage; however, further investigation into seasonal variations in older adults' mortality would be valuable.

Socioeconomic status and education

Further characteristic underlying of vulnerability considered in this review include education level, income, and occupation, which are commonly used as proxies for socioeconomic status (SES). Numerous studies demonstrate that educational level shapes heterogeneous mortality risks from extreme temperatures. Specifically, individuals with no or low educational levels consistently face a higher burden of extreme temperatures from both heat and cold effects. For example, a higher risk of low educational attainment has been documented across diverse contexts, including Europe (Keivabu, 2022; Marí-Dell'Olmo et al., 2019; Ragettli et al., 2024), Asia context (Hua et al., 2024; Kim & Kim, 2017), and the United States (O'Neill et al., 2003). Furthermore, both heat and cold effects-associated YLL were higher in persons with low education than those with higher educational level (Chen et al., 2024; Yang et al., 2015). Individuals with low SES face elevated risks of heat-related mortality (Liu et al., 2020; Longden, 2019; Yang et al., 2013). Occupation further modifies risk. Blue-collar workers, for example, face significantly higher heat-related mortality in South Korea (Heo et al., 2016), and evidence from Guangzhou, China indicates that they are more susceptible than white-collar workers not only to heatwaves (Yang et al., 2013) but also to both heat and cold extremes (Chen et al., 2024; Yang et al., 2012).

Beyond individual-level vulnerabilities, socioeconomic disparities manifest at an aggregated level, where regions or areas with lower socioeconomic status consistently experience greater impacts from heat or heatwave mortality (Franklin et al., 2023; Ngarambe et al., 2022; Ragettli et al., 2024; Yang et al., 2021). Moreover, higher excess mortality from non-optimal temperatures is observed in communities characterized by elevated poverty

(Curriero et al., 2002; Sarmiento, 2023) high deprivation index (Kim & Kim, 2017), income inequality (Gini index), and residential segregation (Bakhtsiyarava et al., 2023). Contributing factors include poorer baseline health, limited access to healthcare, inadequate housing, and a lack of preventive knowledge and less resilient in coping strategies when faced with extreme heat or cold. Thus, the heightened vulnerability among lower educated and less SES groups to extreme temperature-related mortality likely reflects multiple interacting social, environmental, and health-related factors.

With respect to natural hazards, there is limited evidence on how socio-economic factors influence mortality risks. A few existing evidence present consistent findings that low SES have higher mortality risks. For example, lower education levels were associated with higher mortality following Hurricane Maria (Marazzi et al., 2022) and during typhoons in the Philippines (Gray et al., 2022). Evidence from Nepal shows that communities with higher educational attainment among young adults (aged 15-39) experienced 42% lower mortality risks from floods and landslides (KC, 2013), whereas individuals from low-SES households were 6.4 times more likely to experience flood-related deaths than those from higher-SES households (Pradhan et al., 2007). At the macro level, flood-related mortality is markedly higher in disadvantaged settings, with rates up to 22 times greater in low-GDP countries (Lindersson et al., 2023) and stronger associations observed in countries with low income levels and low human development indices (Yang et al., 2023). Consistent with these findings, subnational analyses of Hurricane Maria revealed that mortality was disproportionately concentrated in municipalities with lower socioeconomic status (Carlos Santos-Burgoa et al., 2018). These results highlight the amplifying role of socioeconomic disadvantage in shaping vulnerability to natural hazards across both global and local scales.

Reflecting the evidence reported across studies, lower education is consistently linked to increased vulnerability to climate risk, while higher education provides protective effects through improved awareness, adaptive capacity, and access to resources. To capture this dynamic, it is possible to adjust future projections by climate-related mortality and by education level (KC & Lutz, 2017). For instance, higher climate-related death rates can be applied to populations with lower education levels or lower rates among those with higher educational attainment.

5.2 Spatial heterogeneities in climate-related mortality

Regional and continental burden

The mortality impacts of climate change are far from uniform across the globe, highlighting the critical importance of spatial heterogeneity when assessing population-level risks. A clear research concentration emerges in Asia and Europe, where a relatively large body of evidence documents both heat- and cold-related effects. In contrast, studies from other world regions such as Africa and Oceania remain scarce, leaving substantial uncertainty about the global distribution of risks.

In Asia, most of the available evidence comes from Eastern Asia, particularly China, and consistently indicates that cold exposure accounts for a larger share of the temperature-related mortality burden in this region. A large multi-country analysis across diverse climatic contexts reported the highest attributable mortality from cold effects in China (10.36%), Japan (9.81%), South Korea (6.93%), and Taiwan (3.89%) (Gasparrini et al., 2015). National- and city-level studies in China (Chen et al., 2020; Zhang et al., 2017a) and Japan (Chung et al., 2018) reinforce this pattern, showing that cold spells contribute disproportionately to mortality risk and years of life lost (YLL) compared to heat effects. Notably, cold-related effects often manifest with a delayed onset, extending over several days to weeks, thereby compounding their cumulative burden (Guo et al., 2014). While Eastern Asia dominates the literature, emerging studies from Southeastern, Southern, and Western Asia suggest that even in warmer climates, cold exposure can exert measurable mortality effects such as in Chiang Mai, Thailand (RR=1.29 vs 1.11 for heat) (Guo et al., 2012), India (attributable risk=6.8% vs 0.5% for heat) (Fu et al., 2018), Tehran, Iran (RR=1.67 vs 0.24 for heat) (Riahi & Khorsandi, 2025). These findings emphasize that in Asia, cold temperatures remain the dominant driver of climate-related mortality. This result reflects limited adaptive capacity, both physiological and infrastructural, to moderate drops in temperature, and the following extended periods of warmth (Analitis et al., 2008; Zhao et al., 2021).

Europe exhibits a more balanced distribution in terms of the studies conducted within the region. Historically, cold-related deaths have significantly outnumbered heat-related deaths across Europe (attributable fractions: 6.63% for cold vs 0.69% for heat) (Masselot et al., 2023). However, heat has emerged as the more acute threat in recent decades, with projections indicating a substantial future increase in heat-related mortality, especially during extreme temperature events such as heatwaves, alongside an overall decline in cold-related effects over the coming decades (García-León et al., 2024). This pattern is not homogeneous across Europe; several studies have reported that Eastern, and Southern Europe experience higher heat-related mortality risks compared with other parts of the continent (Baccini et al., 2008; Leone et al., 2013; Zhao et al., 2021). Within this context, Southern Europe was estimated to experience the highest overall heat-related mortality rates in 2023, particularly in Greece (393 deaths per million), followed by Bulgaria (229), Italy (209), Spain (175), Cyprus (167), and Portugal (136) (Gallo et al., 2024). These elevated risks have been attributed to a combination of factors, including Europe's rapidly aging population and high burden of chronic diseases, compounded by infrastructural constraints such as the low prevalence of air conditioning, which limits effective adaptation to extreme heat in many countries (Chen et al., 2024). Despite growing concerns about heat, multiple studies indicate that extreme cold poses a greater overall mortality risk than extreme heat, both in regions with severe cold hazards and in those where such hazards are less pronounced (Alahmad et al., 2025). For instance, in Northern Europe, cold is the dominant driver of temperature-related deaths, with attributable fractions of 9.9% for cold versus only 0.1% for heat in Norway (Fernández et al., 2025). Similar patterns are observed in Scotland, where the relative risk is higher for extreme cold (RR=1.09) compared to heat (RR=1.04) (Wan et al., 2023), and in Belgium, where mortality risks are greater at extreme cold (RR = 1.32 at −1.7 °C) than at extreme heat (RR = 1.21 at 31.3 °C) (Demoury et al., 2022). Populations in Southern Europe continue to experience acute mortality risks during both extreme heat and cold events. These patterns highlight the complex interplay of vulnerabilities different across Europe in relation to both heat and cold extremes (de Schrijver et al., 2022; Gasparrini et al., 2022; Masselot et al., 2023).

Fewer studies have focused on the Americas, but existing evidence points to a dual burden of both heat- and cold-related mortality. North America reported effects from both heat and cold, while Latin America and the Caribbean yielded only cold-related effects. Multi-city studies across the United States show that both extremes increase deaths, with heat often contributing the larger share (Liu et al., 2022; Medina-Ramon & Schwartz, 2007). Yet, some locations reveal stronger cold effects, for example, in North Carolina (RR = 1.019 for cold; heat not significant) (Choi et al., 2021) and in British Columbia, Canada, where 7.2% of all deaths were attributable to non-optimal temperatures, mostly moderate cold (6.2%) (Shrestha et al., 2024). In Latin America and the Caribbean as tropical region, more limited evidence indicates that cold continues to represent the primary mortality risk: a nine-country study attributed 5.1% of deaths to cold versus 0.7% to heat (Kephart et al., 2022). Studies from São Paulo and Colombia support this pattern, though recent decades suggest declining cold effects alongside gradually increasing heat impacts (Aschidamini & Leon, 2025; Roca-Barceló et al., 2022; Sarmiento, 2023). Overall, cold continues to impose a substantial mortality burden across Americas, while heat has become a growing concern

For *natural hazards*, the evidence on storm-, flood-, and drought-related mortality is far more limited but exhibits important regional contrasts. Most epidemiological studies on storm-related mortality have been conducted at national or regional scales, primarily in the Americas (mostly from the USA). In this region, the coastal geography and warm ocean currents make the area highly susceptible to frequent and intense storm events as tropical cyclones, particularly in regions like the South-eastern of United States, the Caribbean, and Gulf of Mexico. The literature highlights the acute impacts of tropical cyclones such as Hurricane Katrina in 2005 and Maria in 2017. Recent estimates indicate that tropical cyclones account for 3.2-5.1% of all deaths in the United State (Young & Hsiang, 2024). Post-hurricane deaths rose sharply, injuries by 33% and overall mortality by 3.7%, mainly among infants and the older people (Marazzi et al., 2022; Parks et al., 2022). However, mortality risks associated with storms and tropical cyclones have shown a declining trend in the United State, likely reflecting improved early warning systems and disaster preparedness in this region (Bouwer & Jonkman, 2018; Huang et al., 2024). In contrast, a global study found that Latin America and the Caribbean, Southeast Asia, and South Asia had the highest and growing tropical cyclone-related mortality burdens, measured by excess death rates and ratios, largely attributable to the region's high exposure to natural disasters and socioeconomic vulnerability (e.g., relatively low GDP per capita and high population density) (Huang et al., 2023). For example, studies have shown that severe storms significantly increase mortality in Mexico (Pugatch, 2019), the Philippines (Gray et al., 2022), and Bangladesh (Burkart et al., 2014), with particularly pronounced impacts among vulnerable populations such as infants and older adults. Overall, these patterns underscore the uneven global burden of storm-related mortality, driven by differences in geography, exposure, socioeconomic vulnerability, and adaptive capacity.

For flood-related mortality, impacts were observed across the Americas, Europe, and Asia. Global evidence indicates that the highest annual relative mortality from floods occurs in lower-income countries, particularly in regions of Latin America and the Caribbean, Africa, and Asia, both in terms of mortality rates and absolute fatality counts (Alfieri et al., 2020; Lindersson et al., 2023). Moreover, flood exposure was significantly associated with increased infant mortality in Africa (Zhu et al., 2024), and child mortality in Nepal (Pradhan et al., 2007). In high-income regions such as Europe and North America, studies have identified long-term associations between flood exposure and mortality, with flood events linked to increased all-cause mortality in the 12 months following the event in the United Kingdom (Yao Wu et al., 2024) and the United States (Chu et al., 2025). These findings suggest that while floods pose a universal mortality risk, their burden is disproportionately concentrated in low-income and developing regions.

Evidence on drought-related mortality remains limited and mixed. For example, a study in the United States reported no significant association between drought severity and all-cause mortality overall (Abadi et al., 2022). However, other studies in the United States suggest that severe and prolonged droughts can increase all-cause mortality, with higher risks observed over 6, 12 months during extreme events (Gwon et al., 2024; Lynch et al., 2020). In Brazil, drought events were associated with incremental increases in mortality from non-external causes, rising with drought severity (RRs = 1.003-1.010) (Salvador et al., 2022). Similarly, in Spain, droughts significantly increased natural deaths, particularly during short- to medium-term events (RR = 1.017) (Salvador et al., 2020). More recent evidence from South Africa further supports these findings, where droughts were positively associated with all-cause mortality, particularly during prolonged events (RR = 1.098) (Salvador et al., 2024). Overall, these results suggest that while droughts tend to have a smaller and slower impact on mortality compared to acute hazards as storms and flooding, their effects accumulate over time, especially under conditions of prolonged water scarcity, food insecurity, and environmental stress.

Climatic zones (Köppen-Geiger classification)

Climate zones play a crucial role in shaping climate-related mortality, as they determine the baseline exposure of populations to temperature extremes, influence the prevalence of heat- and cold-related health risks, and interact with local socioeconomic and infrastructural factors that can mitigate or exacerbate vulnerability. Cold-related effects were more frequently reported across studies than heat-related effects, reflecting historically stronger associations with mortality and a greater number of attributable deaths. A similar pattern was observed across climatic zones in this review. However, this finding may also reflect the uneven distribution of available evidence, as a large proportion of studies were conducted in temperate regions where cold-related mortality has historically been more pronounced. Temperate climates are characterized by wide temperature ranges and strong seasonal variability, exposing populations to both cold winters and hot summers. A global study by Zhao et al. (2021) found that excess death ratios associated with non-optimal temperatures were highest in temperate climates (10.88%), surpassing those in other climate zones, including continental (10.68%), arid (8.78%), and tropical (7.22%) regions (excluding polar areas). Many temperate regions, including parts of Europe, North America, and East Asia (Peel et al., 2007), experience substantial mortality burdens due to year-round exposure to both heat and cold extremes (Wen et al., 2024). Notably, most temperature-related deaths are attributed to cold exposure (9.95%), indicating that cold remains a major contributor to climate-related mortality even in moderate climates, with temperate regions also showing the highest excess mortality during cold spells (Gao et al., 2024). increased mortality during hot summers has also been documented in several temperate regions, including China, Germany, France, and Australia (Amoatey et al., 2024; Rai et al., 2023; Schaeffer et al., 2016; Zhang et al., 2017b), suggesting a dual burden from both cold and heat extremes.

Regarding mortality from natural hazards across different climatic zones, available evidence remains limited but suggests that tropical regions face high risks from storms and floods, particularly in Bangladesh, the Philippines, Nepal, and Puerto Rico (Burkart & Kinney, 2016; Gray et al., 2022; Pradhan et al., 2007; Santos-Burgoa et al., 2018; Sugimoto et al., 2011). This pattern reflects the higher frequency of tropical cyclones in these regions, fuelled by warm ocean temperatures that drive cyclone formation and intensification and often bring torrential rainfall, floods, and landslides (Peduzzi et al., 2012; IPCC, 2021). Dense coastal populations, limited infrastructure, and socioeconomic vulnerability further amplify exposure and mortality risks (IPCC, 2022). In contrast, studies conducted in temperate regions report elevated mortality risks across multiple hazards, including storms (Brunkard et al., 2008; Chiu et al., 2013) , floods (Li et al., 2007; Wu et al., 2024), and droughts (Salvador et al., 2021), likely reflecting the greater climatic variability of these regions.

Future research on mortality projections in temperate climates should account for the dual burden of heat and cold extremes, as populations are exposed to wide temperature variability throughout the year, and explicitly integrate these factors into the modelling. Cold-related mortality remains the dominant contributor even in moderate climates, although it is expected to decrease over time. Regarding mortality from natural hazards, few studies currently account for climatic zones, making it difficult to draw assumptions for future projections.

Urban-rural disparities

This review highlights urbanization as an important modifier of temperature-related mortality. Urban areas are often more affected by heat due to the urban heat island (UHI) effect, where dense built environments, limited vegetation, and anthropogenic heat sources elevate temperatures compared with surrounding rural areas (Franklin et al., 2023; Li et al., 2021; Wan et al., 2022). Moreover, urban temperatures are typically 1-2°C warmer than rural areas, and can occasionally exceed differences of 10°C depending on local conditions (Chapman et al., 2017). Consistent with this, numerous studies have reported stronger heat-related mortality in urban areas, including in China (Wang et al., 2018), Australia, Colombia (Sarmiento, 2023), the UK (Gasparrini et al., 2022), and Germany (Grize et al., 2005), with older populations (65 and over) in urban Bangladesh also showing high vulnerability (Burkart et al., 2014). However, evidence is not entirely consistent, as some studies report higher heat-related risks in rural populations, such as in Hubei, China (Zhang et al., 2017a) and South Korea, particularly among older adults (Kang et al., 2020). Findings on cold exposure are similarly mixed, with stronger cold effects observed in rural China (Hu et al., 2019; Wang et al., 2018), particularly among older people, and females (Hu et al., 2019), while higher cold-related mortality reported in urban areas of the United States (Choi et al., 2021). Overall, these findings highlight the complexity and context-dependence of urban-rural disparities in temperature-related mortality.

Evidence regarding natural hazards is more limited but suggests that rural populations may be particularly vulnerable during tropical storms. In the United States, individuals residing in rural areas were nearly three times more likely to die from tornadoes than their urban counterparts (RR = 2.90) (Chiu et al., 2013). Similarly, in the Philippines, mortality risk from typhoons was substantially higher in rural than in urban municipalities, underscoring the disproportionate burden faced by rural populations (Gray et al., 2022). These findings point to the disproportionate risks faced by rural populations, potentially linked to weaker infrastructure, reduced access to health services, and slower disaster response compared to urban. When focusing on slow-onset events such as droughts, evidence indicates that both rural and urban populations in the United States experience elevated risks of all-cause mortality (Abadi et al., 2022; Gwon et al., 2024). In rural areas, risks were largely linked to agricultural disruption and food insecurity (Abadi et al., 2022), while in urban areas they were associated with water scarcity, higher food prices, and compounded heat stress (Salvador et al., 2022).

These findings indicate the need to incorporate higher temperature-related death rates in densely populated urban regions compared with rural counterparts when developing future mortality assumption. Urban adaptation capacity should be explicitly incorporated into projection models, including factors such as air conditioning coverage and access to cooling shelters, which can substantially reduce heat-related mortality. At the same time, projections should account for climate-related hazards affecting rural areas, where exposure to natural hazards and limited adaptive capacity may also influence future mortality risks.

6. Limitation

Limitations should be acknowledged. Firstly, this systematic review considered only peer-reviewed articles published in English, which may have introduced language and publication bias by excluding relevant studies published in other languages or in the grey literature (e.g. reports from government or non-profit or international organisations). Secondly, inconsistent evidence in socio-economic heterogeneity in hazard related mortality is partly due a lack of research. As climate change drives more frequent and diverse extreme events, understanding how multiple hazards interact with social and demographic factors to shape mortality risks is warranted.

Third, the spatial coverage of the included studies was limited in terms of both geographic representation and climate zones, despite including research from several countries with diverse climatic conditions. Most available evidence is concentrated in high- and middle-income regions, particularly Asia, Europe, and North America, while low-income regions, especially Africa, remain critically underrepresented. This imbalance may bias the global evidence base and limit the generalizability of findings. One possible explanation is that countries in higher-income regions have greater research capacity and resources to conduct and publish studies on climate-related mortality. Future research should therefore aim to improve regional representation, particularly by increasing evidence from Africa.

Fourth, although this review attempted to account for differences across climate zones, several included studies were conducted at national, multicity, or multicountry scales that encompassed areas spanning multiple climate zones. This posed challenges in assigning results to a specific classification. Furthermore, while some studies reported climate-mortality associations by individual location, others presented aggregated results across regions or countries, limiting the ability to accurately attribute findings to particular climate zones. Finally, no studies were identified in Polar climates for temperature-related mortality or in Arid climates for natural hazards, highlighting important gaps in the current literature.

7. Conclusion

This systematic review of 246 studies provides the global synthesis of spatial and sociodemographic heterogeneity in mortality risks associated with extreme temperatures and climate-related natural hazards. The evidence demonstrates that climate-related mortality is influenced by multiple interacting factors such as demographic, socioeconomic, geographic, and climatic factors. In particular, the consistent evidence is that females, older adults, and individuals with lower education or socioeconomic status consistently face greater mortality risks from extreme weather events.

Spatially, mortality burdens vary substantially across regions and climate zones. The strongest evidence base originates from Asia and Europe, with temperate zones showing the highest number of temperature-mortality associations. Cold-related deaths are more prevalent in East Asia and parts of Europe, whereas heat-related mortality dominates in Southern Europe and other temperate regions. Even though cold exposure continues to be the primary cause of mortality on a global scale, heat-related deaths are expected to rise sharply with ongoing global warming. Continuous monitoring of both heat impacts and other extreme weather events is therefore essential as them threaten population health.

Despite growing evidence, major research gaps persist. Africa and low-income countries critically underrepresented in the literature, particularly in studies examining natural hazards such as floods, storms, and droughts. In addition, demographic and socioeconomic characteristics are often not taken into account in analyses of hazard-mortality. Future research should adopt a more balanced geographic and climate coverage, improve methodological consistency in exposure definitions, and expand the integration of vulnerability dimensions. Such advancements are essential to improve understanding of population susceptibility and to inform targeted adaptation strategies for reducing climate-related mortality risks.

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