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IMPACT OF CLIMATE CHANGE ON HUMAN MORTALITY PATTERNS

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Declaration

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The PhD Committee coordinates 16 Departments of the Alma Mater Studiorum – University of Bologna, encompassing a wide range of disciplines, including physics, statistics, sociology, engineering, environmental sciences, and economics. This structure reflects the programme’s strong interdisciplinary foundation, which is essential for addressing the multifaceted challenges posed by climate change. By integrating natural, social, and data sciences, the programme fosters a holistic understanding of the interactions between environmental systems and human societies.

This three-year PhD programme combines advanced academic training with original research, encouraging collaboration across disciplinary boundaries and promoting innovative approaches to complex global challenges.

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Abstract

The increasing frequency and intensity of extreme weather events pose a growing public health threat. Evidence consistently demonstrates that the mortality risks associated with weather and climate extremes are not uniformly distributed, reflecting substantial geographical and social disparities. This thesis investigates global and European patterns of mortality risks related to extreme weather events, emphasizing population heterogeneity, regional and social vulnerabilities. Specifically, the thesis advances current understanding by (1) systematically synthesizing global evidence on climate-related mortality, (2) empirically examining the determinants of temperature-related mortality across Europe, and (3) projecting future mortality under varying climate and socioeconomic scenarios.

In the first part, a systematic review of quantitative observational studies is conducted using Web of Science and Scopus, following PRISMA guidelines. The second study involves an empirical analysis of Eurostat sub-national mortality data for adults aged 65 and above across 30 European countries (2014–2023) based on Poisson fixed-effects regression. In the third study, future projections of temperature-related mortality outcomes for 28 European countries are performed using socioeconomic and greenhouse gas emissions (SSP–RCP) scenarios.

Key findings from the systematic literature review highlights higher vulnerability among females, older adults, and socioeconomically disadvantaged populations. The empirical analysis focusing on Europe shows that, cold exposure remains a stronger determinant of mortality than heat in the continent, though extreme heat exerts greater effects in southern regions, underscoring the urgent need for region-specific adaptation strategies. Air pollution amplifies both heat- and cold-related mortality, while higher GDP per capita mitigates cold-related deaths. Future projections indicate that temperature-related mortality will decline in Northern Europe but increase markedly in Southern Europe, widening regional disparities toward the end of the century.

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Chapter 1: Introduction

1.1. Overview

1.1.1. Population and Climate Change

Over the past decade, every continent on earth has experienced record-breaking climate extremes (Blunden et al., 2025; Fisher et al., 2025; WMO, 2025). Anthropogenic climate change manifests through (i) slow-onset changes—including sea-level rise, long-term warming, glacier and permafrost loss and ocean acidification—and (ii) intensifying extremes, with greater severity, duration, and frequency of events such as heatwaves, cold spell, floods, droughts, wildfires (Dey et al., 2021; LeCompte, 2022; Seneviratne et al., 2021; Wehner et al., 2017). Notable and recent events include the European heatwaves of 2022 (Ballester et al., 2023); the severe monsoon floods in northern Pakistan in June 2025 (Zachariah et al., 2025); the devastating wildfires in Greece, Türkiye, and Cyprus in July 2025 (Keeping et al., 2025); the extreme drought in Southern Africa in 2024, with rainfall deficits exceeding 80% (Kimutai et al., 2024); and the Hurricane Helene in Florida in September 2025 (Clarke et al., 2025). All these and others climate extremes are posing new concerns amongst the public as well as the scientific community.

The relationship between climate and population have been investigated by numerous studies from diverse perspectives, disciplinary approaches, and methodological frameworks. Scholars from various fields, including demography, environmental science, sociology, economics and geography, address the issue in distinct ways. However, what clearly emerges is the reciprocal and dynamic interplay between population and the climate (Lutz et al., 2005). On the one hand, humans have influenced the climate primarily by altering atmospheric composition through fossil fuel combustion, deforestation, and land-use change (Dodson et al., 2020; Jiang & Hardee, 2009; Steffen et al., 2015). On the other hand, climatic stressors have increased in frequency and severity affecting human population (Hoffmann et al., 2024; Muttarak, 2021; Thomas et al., 2019). This bidirectional relationship between climate and population forms a complex feedback loop that has raised multiple open questions, regarding present and future trajectories.

Studies investigating the role of human activities in driving climate change have extensively examined how greenhouse gas emissions from various activities affect the Earth's climate system (Liddle et al., 2014; van Dalen & Henkens, 2021). A key point debated in the literature concerns the extent to which population growth contributes to rising emissions, as larger populations increase energy demand and resource consumption (Cohen, 1995; Dietz & Rosa, 1997; Liddle, 2014; O'Neill et al., 2010). Closely related are discussions on economic growth, with several studies emphasizing that higher income levels often correlate with increased energy use and carbon intensity, despite improvements in energy efficiency (Steinberger et al., 2012; York et al., 2003). To describe the simultaneous and rapid mid-twentieth century rise in population, industrial production, energy use, and greenhouse gas emissions, scholars refer to the "Great Acceleration", a period that has profoundly intensified environmental pressures and contributed to the ongoing anthropogenic climate crisis (Steffen et al., 2015; IPCC, 2023). Also, demographic characteristics, such as age, sex, and education, have been shown to influence consumption patterns and environmental impact, revealing population heterogeneity in environmental impacts (Liddle, 2011; Zagheni, 2011). Likewise, behavioural and sustainable lifestyle choices—such as reducing animal-based food consumption and adopting clean energy sources—can significantly lower per capita emissions, while policy interventions through carbon pricing, renewable energy incentives, and land-use regulation play a pivotal role in shaping national emission trajectories (Poore & Nemecek, 2018; Berkebile-Weinberg et al., 2024; Morrison et al., 2022).

Vice versa, environmental stressors serve as significant push factors in population change dynamics. Throughout history, climate and environmental conditions - some within the bounds of normal climatic variability and others linked to anthropogenic climate change - have interacted with social, economic, and political factors. Examples of events that fall within normal climatic variability include the 1815 eruption of Mount Tambora, which dispersed volcanic ash globally and triggered widespread famine (Marshall et al., 2018), and the end of the Little Ice Age in the mid-19th century contributed to Ireland's potato blight, causing over a million deaths and mass migration to North America (Hatton & Williamson, 2009). Today, however, anthropogenic climate change is unfolding on a far greater and faster scale than past natural fluctuations, posing unprecedented risks to human societies. A growing body of literature investigate the role of climate change in shaping human life, well-being and key demographic processes including migration, mortality, and fertility responses (Entwisle, 2022; O'Neill et al., 2020). These studies explore the impacts of diverse

climate hazards, including extreme temperatures, floods, droughts, and tropical cyclones, on demographic outcomes. Literature investigating the relationship between climate extremes and population dynamics such as fertility, migration and mortality show both direct and indirect consequences. Studies focusing on climate change and fertility, suggest that extreme heat, food insecurity, and economic stress related to climatic shocks can lower conception rates and modify reproductive behaviour (Deschênes et al., 2009; Grace, 2017). Studies that link climate change with migration indicate that climate events can drive both temporary and permanent displacements (Black et al., 2011; Nawrotzki & DeWaard, 2018; Rigaud et al., 2018). Extensive research has examined the relationship between climate change and human mortality, revealing increased death rates during both cold and extreme heat periods as well as heightened flood-related mortality risks, often indirectly driven by infectious diseases and injuries, and further linking hurricanes and tropical storms to acute mortality and long-term health deterioration (Bouwer, 2019; Doocy et al., 2013; Gasparrini et al., 2015; Guo et al., 2018; Jonkman, 2005; Kishore et al., 2018; Rentschler et al., 2022; Shultz et al., 2019; Vicedo-Cabrera et al., 2021).

Most studies to date are context-specific (e.g., focused on urban areas), and primarily address epidemiological aspects without integrating broader socioeconomic and demographic determinants. Consequently, although substantial evidence exists on temperature–mortality associations and the health impacts of climatic hazards, current research remains insufficient to capture the complex interconnections among demographic, socioeconomic, and geographic heterogeneity. Furthermore, there is still limited understanding of how climate-induced mortality patterns will evolve under different socioeconomic and climatic futures. Research on future mortality is also limited in its ability to inform population projections. By addressing these gaps, this thesis aims to provide an integrated framework that links climate exposure, population characteristics, and mortality across spatial and temporal scales.

The remainder of this introductory chapter will progressively lay out the structure and rationale of this thesis, beginning with an overview of climate change and human mortality, then delve into the definition of the research questions and aims. It then reviews the main methodologies typically employed in the field, introducing the approaches adopted in analyses. Finally, the overall structure of the thesis is outlined. The present thesis explores the relationship between the human mortality and climate hazards through three main studies: (1) a global literature review with a focus

on spatial and sociodemographic heterogeneities in climate-related mortality; (2) an empirical analysis of temperature-related mortality in Europe during the period 2014-2023, (3) a projection study on future mortality under different socio-economic and greenhouse gas emission scenarios, with corresponding future temperature changes. The first study is a global systematic review of the literature, focusing on various types of climatic hazards and the geographical and sociodemographic heterogeneity in mortality. The second study examines geographical differences in temperature-related deaths, considering factors such as PM2.5 concentrations, GDP, climatic zones, and urbanization level. The third study provides a projection of future temperature-related mortality under different SSP-RCP scenarios. The three papers are standalone yet interconnected: they present a systematic review of climate-related mortality, an empirical analysis of contemporary observational data, and projections of future mortality under global climate change.

1.1.2. Climate Change Impacts on Human Mortality

External shocks, such as wars, armed conflicts, pandemics, and environmental disasters, can significantly disrupt established mortality patterns by altering the social, economic, and environmental conditions that sustain human health (Hoffmann et al., 2024; Mohiuddin et al., 2023; Pifarré i Arolas et al. 2021). A recent example is the COVID-19 pandemic, which demonstrated how a global health crisis can rapidly shift mortality rates across age groups and regions (Acosta et al., 2022; Msemburi et al., 2022). Similarly, climate change represents a major contemporary external shock, and its multifaceted impacts on human health are becoming increasingly evident.

Suboptimal temperatures, droughts, floods, and storms significantly impact global health, leading to heightened mortality risks. Because both cold and heat increase mortality risk, the temperature–mortality association is typically non-linear, commonly J-, U-, or V-shaped. (Guo et al., 2014). An estimated 5,083,173 deaths occurred annually between 2000 and 2019, with 9.43% of total global deaths attributed to cold and 0.91% to heat (Zhao et al., 2021). In particular, the proportion of heat related deaths is expected to increase, while cold-related mortality is projected to decline in some regions and increase in others (García-León et al., 2024). Overall, when considering both effects, the total proportion of temperature-related mortality is expected to rise by the end of the century (García-León et al., 2024; Gasparrini et al., 2017; Vicedo-Cabrera et al., 2021; Zhao et al., 2021). Heat exposure is linked to cardiovascular, respiratory, metabolic, and mental health disorders, including depression and suicide (Ebi et al., 2021; Kim et al., 2019), while

cold temperatures heighten risks of hypothermia, cardiorespiratory diseases, and accidents (Zhang et al., 2019). Similarly, drought-related mortality has been significant between 2000 and 2023, with 24,160 deaths recorded globally, accounting only for the direct impacts (Mani et al., 2024). This estimate does not include the indirect effects of droughts, such as exacerbated food and water insecurity or increased diarrheal incidence, which raise the total mortality count to approximately 650,000 deaths (Lloyd et al., 2007; Füssel & Kelly, 2021; WMO, 2021). Floods and storms, among the most destructive natural disasters, caused about 635,932 deaths between 1970 and 2019 (WMO, 2021). Beyond immediate injuries and drownings, these events also increase the long-term risks of non-communicable, infectious, and vector-borne diseases, as well as mental health disorders such as post-traumatic stress disorder, depression, and anxiety (Parsons et al., 2025; Paterson et al., 2018; Tiu et al., 2021). Tropical cyclones alone have resulted in approximately 1.33 million deaths and affected over 629 million people between 1980 and 2009 (Doocy et al., 2013), with additional surges observed in respiratory, infectious, and mental health issues (Konkel, 2020).

Studies on the mortality impacts of climatic hazards indicate that these effects are unevenly distributed across time, space, and population subgroups (Burgess et al. 2014; Hoffman et al., 2024; Nordio et al. 2015). It depends on various variables, such as environmental factors, individual characteristics, geographical differences, socioeconomic features, adaptation efforts and technological progresses (Lutz & Muttarak, 2017; McDermott-Levy et al., 2021). This unequal distribution underlines not only the significant disparities in exposure to climate hazards at global and local level, but also the inequalities in vulnerability (Muttarak, 2021), where vulnerability is defined according to the IPCC assessment report as a function of sensitivity¹ and adaptation capacity² (IPCC, 2014). Understanding these intersecting dimensions is essential for assessing both current and future human responses to environmental change.

The degree of population vulnerability to climate impacts is shaped by demographic and socioeconomic characteristics, such as age, sex, education, and income (Muttarak & Lutz, 2014; O'Neill et al., 2020). Several studies highlight the importance of the demographic composition as a driver of exposure and their sensitivity. Age is recognized as a major determinant of vulnerability for different climate hazards. Literature found that nearly 60% of the total temperature-related

¹ Sensitivity degree to which a system is affected or modified by climate stimuli and external disturbances.

² Adaptation Capacity of a system to adjust to a disturbance, moderate damage, take opportunities and cope with the consequences.

mortality burden occurs among individuals aged 85 years or older (Massetot et al., 2023). Older adults are more susceptible to extreme temperatures from both physiological and socio-behavioural factors, due to diminished thermoregulatory capacity (Robine et al., 2008; Gasparrini et al., 2017), and more propensity to social isolate, sleep deprivation, and energy poverty (Santamouris et al., 2014; Zhang et al., 2019). Age is also used as proxy variable for existing medical conditions underlying climate-related vulnerability. Also, gender is found to play a significant role, even though, evidence on sex differences is mixed with some studies find higher vulnerability among women, others among men, depending on the area, the type of hazard, and other underlying factors such as socioeconomic position, social networks and gender role. In contemporary populations, women generally exhibit higher life expectancy than men, and today they outnumber men, particularly at older ages (Zarulli & Salinari, 2024). However, climate change—through its differential impacts on health, vulnerability, and adaptive capacity—may challenge this long-standing trend. Other multiple socioeconomic indicators, such as income, occupation, societal and cultural norms, education, serves as proxies of disparities in vulnerabilities in climate-related health and mortality risks, and can shape differential exposure and response capacities. An example are women in rural Bangladesh whose traditional clothing and caregiving constraints can exacerbate vulnerability to floods or heatwaves (Neumayer & Plümper, 2007). An example of how occupation may interact with climate-related deaths, is that outdoors workers are more at risks of heat-related mortality than indoor workers (Rossi et al., 2025). Education also serves as fundamental driver, substantially influencing mortality rates even when differences in income are accounted for (Lutz et al., 2014). Overall, individuals with higher income and education levels have greater access to resources and technologies, enhancing their adaptive capacity and thereby reducing climate-related mortality risks (Vicedo-Cabrera et al., 2019).

Geographical location and climatic context are also crucial. First, climate change does not affect all regions equally. The same climate anomaly can have widely differing impacts depending on regional adaptation capacity and socioeconomic context (Carleton et al., 2022). Individuals or countries with low-income countries exposed to the same hazard typically have higher mortality risks than high-income individuals/countries (Grant et. al., 2025; Herold et al. 2017). In general, economies in the Global North own stronger adaptive capacities, while low-income economies typically located in the Global South face disproportionate impacts due to limited infrastructure, limits in adaptation, and limited economic resilience. However, even strong economies still

experience significant impacts, highlighting internal disparities even when accounting for the benefits of high-income level and adaptation (Carleton et al., 2022). People living in densely populated or urbanized areas are often more exposed to heat-related risks than people living in rural regions (Dimitrova et al., 2021; Li et al. 2017; Maksimenko et al., 2024). Climate change acts as a risk multiplier, exacerbating both environmental and social disparities.

Given already existing differential climate-induced mortality risks, new questions arise about the future climate-related mortality burden. The year 2024 marks the first time the global average temperature exceeded 1.5°C above pre-industrial levels, setting a record as the warmest year globally since reliable temperature measurements began (Copernicus Climate Change Service, 2025). This record is part of a long-term warming trend, which saw the ten hottest years on record have all occurred since 2014 (NASA, 2025). Such data confirms a consistent and accelerating global warming trajectory, whose primary driver is given by the accumulation of greenhouse gas (GHG) emissions in the atmosphere. It is particularly important to note the long atmospheric lifetime of carbon dioxide (CO₂) emitted from fossil fuel consumption, which averages around 100 years. This implies that the emissions produced today will persist in the atmosphere for another century, compounding with those already present. This indicates that a reduction in emissions does not immediately translate into a proportional decrease in global temperature, as the climatic response involves complex feedback mechanisms and delayed effects, resulting in multiple possible future scenarios. The future scenarios related to emissions are modelled by the so-called Representative Concentration Pathways (RCPs). They were published for the first time in IPCC Fifth Assessment Report (AR5) in 2014, covering the emissions of well-mixed GHGs such as carbon dioxide, nitrous oxide and fluorinated gases, given up to the year 2100 (IPCC, 2014). Different combinations of these assumptions lead to different levels of greenhouse gas emissions, simulating different climate response. In this context, climate models are used to project future greenhouse gas emissions, and their concentrations implicitly considered socioeconomic factors. However, there was a need to explicitly describe narratives describing socioeconomic developments. Incorporating socioeconomic indicators into future climate scenarios is essential, as they represent the fundamental drivers of both climate change and progress in mitigation and adaptation efforts. For this reason, the Shared Socioeconomic Pathways (SSPs) were first introduced to better understand how climate change and climate policies affect society and the economy. These pathways show different “what if” scenario from different combinations of assumptions about: Population Growth,

Economic Activity, Energy Intensity, Socio-economic Development, Land Use Change, Climate Policy. Consequently, the Sixth Assessment Report of the IPCC (AR6) suggests a standard combination of SSP and RCP scenarios (IPCC, 2023).

This combined framework enables researchers to assess the interactions between human development pathways and resulting climate outcomes, supporting integrated assessments of mitigation, adaptation, and impact studies. For instance, understanding these interactions requires considering global demographic trends, which continue to show sustained population growth. On 15 November 2022, the world population surpassed 8 billion, and projections indicate a rise to approximately 10.9 billion by 2100 (United Nations, 2022). Population projection is conventionally defined by demographers as “the numerical outcome of a particular set of assumptions regarding future population trends” (Isserman & Fisher, 1984; Keyfitz, 1972). In general, population projections can be developed using various methodological approaches, which can be deterministic, stochastic, probabilistic, or hybrid, including the disaggregation approach, the scenario-based approach, or the cohort-component population method, which estimate future population changes by age and sex, separating for each cohort over time the demographic components of fertility, mortality, and migration (Smith et al., 2013). Examples of official sources include the projections from the International Institute for Applied Systems Analysis (IIASA) and the Wittgenstein Centre for Demography and Global Human Capital (WICs), which provide demographic projections—including population size, age structure, and educational attainment—under each Shared Socioeconomic Pathway (SSP) scenario. However, it is important to emphasize that these projections neither account for climate-related factors nor incorporate climate feedback mechanisms in their modelling, such as temperature increases or climate-induced mortality shifts.

Demographic dynamics are not only growing at global level in size differently by locations but also changing in structure: in 2024 around 17% of the global population is aged 65 or older, and this proportion is projected to double to 33% by 2054 (United Nations, 2024). This may result in higher vulnerability to climate-stressors. According to the Working Group II assessment of the IPCC, children aged in the year 2020 are projected to experience in their older age a nearly five-fold increase under 3°C warming by 2100 (IPCC, 2022). A recent study by Grant et al. (2025) which quantifies how different generations will experience future climate extremes under various global warming scenarios, reveal a stark intergenerational and socioeconomic disparity. Children born in

2020 projected to face two to seven times more extreme weather events than those born in 1960, and with exposure being highest among populations with greater socioeconomic vulnerability (Grant et al., 2025). These findings highlight the future unequal burden of climate impacts, which are not evenly distributed across generation and society (Gualdi & Muttarak, 2025). Given the projected future differential impacts, this raises a question how mortality would like in future under climate change and consequently how this change would affect future population trends.

1.2. Study Framework: Research Aim, Data, and Empirical Strategy

1.2.1. Research Aim

This dissertation is guided by the following research question:

- *How has climate change affected mortality, and how will it affect it in the future, and how does this vary across socioeconomic, demographic, and geographic characteristics?*

The thesis addresses this question through the integration of three complementary studies: (1) a systematic literature review of global climate-related mortality; (2) an empirical study of temperature–mortality relationships among older adults in Europe; and (3) a projection analysis using SSP–RCP scenarios to estimate future mortality patterns in Europe. The dissertation aims to contribute to advancing the understanding of the relationship between climate change and population mortality across time (past–present–future) and space (Europe and the global context), while accounting for demographic, socioeconomic, and geographical factors.

In its first contribution, this thesis conducts a global systematic review to address the divergence in climate-related mortality findings. This approach allows for integrating and comparing findings across diverse settings. A systematic literature review is conducted in order to disentangle demographic, socio-economic, geographical, and climate heterogeneities and to reveal underlying patterns. By synthesizing results across different time periods, and regions, this review seeks to provide a comprehensive understanding of how climatic, demographic, and socio-economic factors intersect to shape mortality risks worldwide. The central questions guiding this research are as follow:

1. *What are the current knowledge gaps and limitations in existing research on climate-related mortality across different regions and populations?*
2. *In what ways do demographic dimensions, social and economic inequalities, geographical and climate classifications shape vulnerability to climate-related mortality?*
3. *What assumptions can we make for future climate-related mortality trajectories?*

This work contributes to systematically review the existing literature on climate-related mortality identifying where and in what ways evidence is lacking; it examines the determinants of vulnerability; and it provides a set of fundamental assumptions about climate-related mortality, which can serve as a foundation for future mortality and population projections.

Subsequently, the thesis presents an empirical analysis in the European context that combines climate information with key socio-economic variables such as urbanization level, GDP per capita, geographical location, and PM2.5 air pollution. This analysis seeks to better understand the underlying socioeconomic and geographic factors that have the potential to alter existing temperature-related mortality patterns. The research questions guiding this analysis are:

1. *How do extreme temperatures affect mortality among individuals aged 65 and older in Europe?*
2. *How does geographical heterogeneity within Europe influence temperature-related mortality among individuals aged 65 and older?*
3. *What is the role of local climate conditions, air pollution (PM2.5 levels), urbanization, and GDP per capita in temperature-related deaths of older adults?*

This study contributes to investigate the heterogeneity of temperature-related mortality across European regions, addressing a notable gap in recent research simultaneously considering geographic, demographic, and socio-economic variations at the NUTS3 level, and by identifying the direction and magnitude of these factors' interactions.

The final study focuses on climate related mortality projections. The aim is to examine how temperature variation in frequency and severity may alter mortality patterns in the coming decades. The research question guiding this analysis is:

1. *How will temperature-related mortality vary across European regions under different SSP–RCP scenarios by the end of the century?*
2. *How would current mortality rates change if exposed to the temperatures projected under the SSP–RCP scenarios?*

This exercise contributes to the understanding of how socioeconomic trajectories and climatic systems shape future human mortality which is relevant for framing future societal challenges.

In the next section, I will outline the case selection, data sources, and methods employed across the three studies.

1.2.2. Case selection, datasets & empirical strategy

The first study, reported in Chapter II, is a global systematic literature review on socio-demographic heterogeneities in climate-related mortality. It is based on the premise that mortality risks are unevenly distributed across geographic and social contexts, highlighting the need to identify and address vulnerable populations according to factors such as age, sex, income, education, and local climatic conditions. Reviews on climate-related mortality typically follow established evidence-synthesis guidelines, with one of the most widely used being PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Frameworks such as PRISMA are particularly valuable when the literature is heterogeneous or exploratory, as is the case in the present review. This approach allows for the systematic reporting of a wide array of studies, including both systematic reviews and meta-analyses, ensuring a transparent, reproducible, and credible synthesis of evidence on climate-related mortality. Concerning the literature included in the review, it was identified through the Web of Science (WoS) and Scopus databases. Mortality outcomes encompass all-cause, non-external, non-accidental, or natural-cause deaths, as well as deaths resulting from natural hazard events, measured in terms of the number of deaths, years of life lost, or changes in life expectancy. Exposure variables are categorized into extreme temperatures (extreme heat, cold, heatwaves, cold spells) and natural hazards (floods, storms, hurricanes, droughts). Based on this search, 246 quantitative observational studies published between 1985 and 2025 were identified and analyzed, covering all regions of the world. The review also highlights differences in mortality outcomes, measurement approaches, and methodologies

applied across temporal and geographic contexts. Further details on the outcomes, data sources, search strategy, and methods are provided in Section 0 (Methods & Data) of the Literature Review.

The second study, reported in Chapter III, examines geographic heterogeneity in temperature-related mortality in Europe, enhancing the understanding of the crucial roles of local climate, air pollution, urbanization, and GDP per capita. The analysis covers 2014–2023 across 30 European countries at the NUTS3 level. A panel econometric approach³ is applied to investigate the temperature–mortality relationship while accounting for geographic and socioeconomic variables, and controlling for additional covariates such as humidity, wind speed, solar radiation, age, and sex. Such models have also been applied to policy evaluation and cost–benefit analyses (Carleton et al., 2022). Climate data are drawn from the E-OBS dataset from the Copernicus Data Store, providing high-resolution gridded measurements across Europe, while mortality data for individuals aged 65 and older are obtained from Eurostat. More specific information about the method and data is present in Section 3.3 (Data & Method) of the thesis.

The third study, reported in Chapter IV, on future temperature-related deaths under climate change conducted in the European territory, use future RCP-SSP scenarios to examine the effect of future extreme temperatures on mortality across 28 European countries at regional level. It focuses specifically on the population aged 65 and older and describes potential future trajectories of European mortality related to temperature and global warming based on the four SSP-RCP scenarios. The work integrates four main datasets. s mortality and population data were obtained from the Eurostat; Meteorological data relies on ERA5-Land and E-OBS; while future temperature projections were obtained from NASA-NEX-GDDP-CMIP6, offering daily mean temperature simulations from the ACCESS-CM2 General Circulation Model under four SSP-RCP scenarios for the years 2030–2100. Together, these datasets form the basis for an empirical analysis linking historical climate and mortality data to model future temperature-related mortality risks. A typical

³ Studies on temperature-related mortality employ a variety of methods, but two main traditions dominate. **Epidemiological approaches**, commonly used in environmental health, typically rely on Distributed Lag Non-Linear Models (DLNMs) to capture non-linear and lagged effects of temperature on mortality (Gasparrini, 2011, 2013). These models estimate the optimal temperature, where mortality is lowest, and calculate excess deaths from deviations above or below it. **Econometric approaches**, common in climate econometrics, use methods such as time-series regressions, cross-sectional analyses, and panel data models to investigate non-linear relationships and causal effects between temperature and mortality (Angrist & Pischke, 2009; Auffhammer et al., 2013; Hsiang, 2016; Raimi et al., 2021). Both approaches can yield valid results describing the historical temperature–mortality relationship, and the choice depends exclusively on the scope of the study.

approach used to conduct the analysis is either epidemiological or econometric. This study chooses an econometric approach, and a counterfactual analysis is performed. Note however that the projection does not account for adaptation. More specific information about the Data and Method are present in Section 4.3 and 4.4 (Data & Method) of the thesis.

1.3. Thesis structure

The thesis is structured into three case study chapters (II–IV) and one concluding chapter (V) as follows:

Chapter II is titled “Spatial and sociodemographic heterogeneities in climate-related mortality: A systematic literature review”, and is co-authored with Sirinya Kaikeaw, William Kemp, and Raya Muttarak. This work presents a global systematic literature review on socio-demographic heterogeneities in climate-related mortality. First, it describes the pathways through which weather and climate extreme events affect human mortality, as well as the factors that moderate associated risks and impacts. Second, a detailed study selection process was conducted, resulting in a review of 246 studies. Third, the temporal distribution of papers was examined, including year of publication, study duration, median year of the study period, and the distribution of studies by scope. Subsequently, the geographic distribution of the reviewed studies was analysed for both temperature-related and natural hazard-related mortality, organized by country and Köppen–Geiger climate zones. Furthermore, the review summarizes evidence on population vulnerability and effect modification in climate-related mortality. Finally, socio-economic and climate-geographical vulnerabilities are discussed, and potential future trends in climate-related mortality are highlighted, providing guidance for future research directions.

In chapter III, I conduct a study titled “Geographic heterogeneity in temperature related deaths in Europe” in collaboration with Risto Conte Keivabu. This study focuses on the understanding of the temperature-related mortality relationship in Europe and how local climate, socioeconomic conditions, and pollution may shape it. The analysis first describes temperature-related mortality in Europe, highlighting geographical differences in relation to local climate, air pollution, urbanization, and economic development. Population and mortality data were obtained from Eurostat, while meteorological information was sourced from the E-OBS dataset of the Copernicus Climate Data Store (CDS). The study focuses on the temperature-related monthly mortality rate as

the primary outcome. Descriptive statistics were calculated for monthly observations across European NUTS3 regions. Geographical maps were then produced to display the coldest and hottest percentiles of the temperature distribution in each region, illustrating the heterogeneity in temperature exposure. The relationship between extreme temperatures and mortality among individuals aged 65 and older was estimated with 95% confidence intervals using a Poisson regression model with fixed effects. Subsequently, temperature–mortality relationships were analysed by climate region, degree of urbanization, GDP per capita, and PM2.5 ($\mu\text{g}/\text{m}^3$) air pollution. For robustness checks, the analyses were repeated using absolute, maximum, and minimum daily temperatures, as well as a balanced panel dataset.

Chapter IV presents a study titled “Projecting Future Temperature-Related Mortality in Europe under Global Climate Change” conducted with Risto Conte Keivabu, Andrea Tamburini, and Raya Muttarak. This chapter presents projections of future temperature-related deaths under different RCP–SSP scenarios. The study begins with a review of the existing literature on the topic and introduces methodological tools for projecting mortality under different temperature trajectories simulated by climate models. A historical analysis of the relationship between temperature and mortality was conducted, serving as the basis for counterfactual analyses spanning 2030–2100. Excess death rates (per 100,000 population) are calculated across NUTS2 European regions under different SSP–RCP scenarios until the end of the century. Additionally, excess death rates are estimated for the 2030–2100 period, assuming temperatures reach end-of-century levels projected under the SSP–RCP scenarios. The results are then discussed in terms of regional differences and scenario-specific patterns.

The dissertation concludes with Chapter V, in which the main findings are presented together with the study’s limitations. Finally, directions for future research are discussed, not excluding possible key policy implications.

1.4. References

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Chapter 2: Spatial and sociodemographic heterogeneities in climate-related mortality: a systematic literature review

Spatial and Sociodemographic Heterogeneities in Climate-related Mortality:

A Systematic Literature Review

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Abstract

As the climate changes, the frequency and intensity of extreme weather events are shifting globally, with considerable implications for population health. Mortality risks from these extremes vary markedly across regions and populations, highlighting the need to identify vulnerable groups. This systematic review synthesizes global evidence on heterogeneity in mortality risks associated with weather extreme events. The review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A total of 246 studies from Web of Science and Scopus were included, of which 211 were on temperature-related mortality and 35 on natural hazard-related mortality. The findings highlight that mortality risks from extreme weather events are not uniformly distributed but are shaped by demographic, socioeconomic, geographic, and climatic factors. Females, older adults, and individuals with lower education and socioeconomic status consistently experience higher mortality related to extreme temperatures and natural hazards, underscoring the need to integrate these vulnerabilities into future population dynamics. Cold exposure remains the dominant global mortality driver, though heat-related risks are intensifying with rising global mean temperature. Spatially, mortality burdens vary across regions and climate zones, with temperate areas showing stronger cold effects, while tropical regions experience increasing risks from hydrometeorological hazards such as storms. Urban populations are disproportionately impacted by the urban heat island effect. Despite these insights, major geographic and climatic research gaps exist, particularly in Africa, along with a lack of studies integrating demographic and socioeconomic vulnerabilities into analyses of natural hazard-related mortality.

KEYWORDS Weather Extremes • Mortality • Natural Hazards • Temperature • Systematic Review

2.1. Background

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 clear and persistent warming trend (Samset et al., 2023). This ongoing rise in temperature, combined with shifting weather patterns, has contributed to a marked increase in the frequency, intensity, and unpredictability of extreme events such as temperature extremes, heatwaves, cold spells, droughts, floods, and storms. These phenomena are already adversely impacting population health worldwide (Dimitrova et al., 2019; Kharb et al., 2022; Watts et al., 2019).

As extreme weather events become more frequent and severe, population exposure is also expected to increase, thereby intensifying their health consequences 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. Indirectly, extreme events can disrupt food and water systems, force population displacement, and increase the risk of conflict over scarce natural resources (Dimitrova et al., 2021; Decet & Marcucci, 2023). Among these consequences, the rise in climate-related mortality is one of the most immediate and severe outcomes.

An expanding body of epidemiological research has increasingly demonstrated strong associations between various climate-related exposures and increased mortality (Analitis et al., 2008; Basu & Ostro, 2008; Forzieri et al., 2017; Gasparrini et al., 2015). Among these, temperature exposure has emerged as the most extensively studied factor. Temperature-mortality relationships often follow U-, J-, or reverse-J shaped exposure-response curves, with the lowest mortality typically observed at an optimal temperature range and increased risks of mortality at both cold and heat extremes (Gasparrini et al., 2015). Notably, cold exposure poses a greater mortality risk than heat (Bakhtsiyarava, et al., 2023; Gasparrini et al., 2015), with effects that are more prolonged, lasting up to 3 to 4 weeks, compared to the more immediate impacts of heat (Analitis et al., 2008; Guo et al., 2014). Globally, cold-related mortality is disproportionately higher in tropical climates, whereas heat-related mortality is more pronounced in Central and Eastern Europe, with heat waves being the deadliest (Zhao et al., 2021). Yet, the effects attributable to climate-related exposures are

heterogeneous and influenced by local climatic conditions as well as sociodemographic factors such as age, sex, and socioeconomic status.

Spatial and sociodemographic factors play a significant role in determining climate-related mortality. Nonetheless, the strength and direction of these associations vary considerably across studies and geographic contexts, reflecting differences in methodologies, population characteristics, and local climatic conditions (Borrell et al., 2006; Dimitrova et al., 2021; Son et al., 2019). These inconsistencies can be an obstacle to designing targeted risk policies on those particularly vulnerable subgroups. Despite the growing number of systematic reviews on climate-related health impacts, no comprehensive synthesis of the literature has yet been conducted to investigate the mortality impacts of various extreme weather events at a global scale. In particular, the studies of temperature extremes (e.g., heatwaves, cold spells and non-optimal temperature), alongside other major natural hazards, including floods, storms, and droughts, remain understudied in an integrated framework.

Therefore, this systematic review aims to provide the global synthesis of case studies quantifying the relationship between climate events and mortality, with a particular focus on the heterogeneous effects of spatial and sociodemographic factors. Specifically, the review will examine climate-related mortality across subpopulations stratified by age, sex, socioeconomic status, and geography, in order to identify vulnerable groups and highlight critical knowledge gaps. By consolidating evidence from diverse settings, this review will enhance understanding of how climate change influences mortality patterns. Ultimately, the findings aim to inform a basis for mortality assumptions in demographic modelling to improve projections of future population dynamics under climate change.

2.2. 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 weather extreme events, exposure, and vulnerability (The Intergovernmental Panel on Climate Change (IPCC), 2022). This conceptual framework adapts the IPCC risk paradigm to illustrate the principal pathways linking climate change with mortality outcomes (Figure A.1).

In panel (a), 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 all-cause mortality by triggering acute physiological stress responses and aggravating pre-existing chronic conditions. Over time, persistent deviations in ambient temperature also led to slow-onset effects, such as a rise in the incidence and severity of chronic conditions. In contrast, rapid-onset events such as *heat waves* and *cold spells* trigger sudden physiological stress, leading to acute increases in all-cause mortality from cardiovascular, respiratory, and heat-related illnesses (Gasparrini et al., 2015; Liu et al., 2022). For natural hazards, some health impacts occur immediately during the event itself such as drowning or injury-related deaths, while others emerge as long-term outcomes, for example, increased post-disaster mortality due to infectious disease outbreaks, mental health effects, or healthcare system disruptions following storms and floods (Yang et al., 2024). Some of the indirect effects of climate change on mortality 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 (panel (a), lower section). These climate processes are interconnected: rising temperatures can intensify drought conditions, while temperature variability alters hydrological cycles and evaporation rates, amplifying the frequency and severity of floods and storms (IPCC, 2021; Watts et al., 2015).

Consequently, the magnitude and distribution of mortality risk are moderated by differential exposure and vulnerability, shaped by both geographic and sociodemographic factors (panel (b)). Geographic factors such as region, climate zone, and urban-rural setting define baseline climatic conditions and exposure intensity. Sociodemographic factors including age, sex, education, occupation, and income determine individuals' adaptive capacity and vulnerability to climate impacts. In panel (c), human mortality reflects the outcome of the interaction between the type and intensity of the hazard, and population-level exposure and vulnerability. Critically, these relationships are highly nonlinear and vary substantially across socioeconomic, geographic, and individual contexts.

Thereby, a framework is constructed to explain how climate change impacts mortality patterns across subpopulations by linking demographic composition and social vulnerability to differential risks. Ultimately, this framework identifies the basic assumptions underlying climate-related mortality (panel (d)) and supports the anticipation of future mortality patterns, strengthening demographic projections under changing climate conditions. Building on this conceptual foundation, the framework informs the design and analytical focus of this systematic review, guiding the selection and interpretation of empirical evidence aimed at explaining geographic and sociodemographic differences in climate-related mortality.

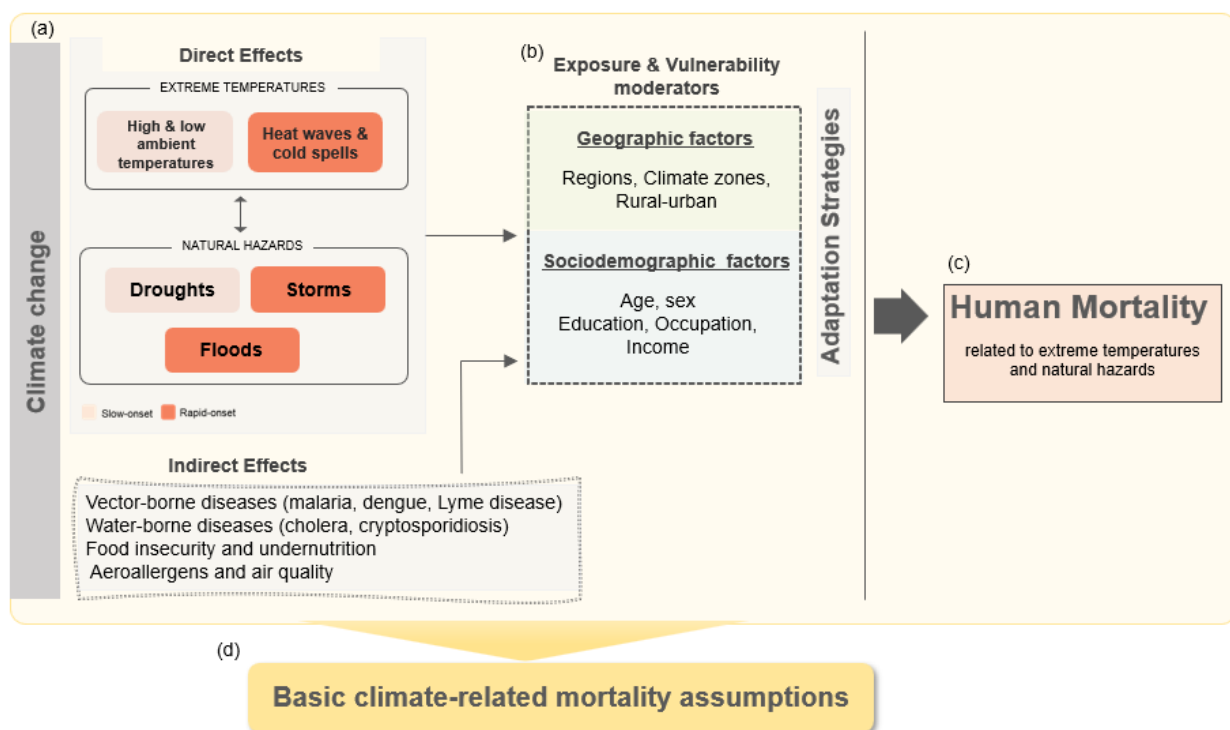


Figure A. 1 Conceptual framework of pathways linking climate change to human mortality and moderating factors

2.3. 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 (Supplementary Information Table A.S.1):

- **Population:** the general population of all ages.
- **Exposure:** extreme weather events include variations in extreme temperatures (such as high and low ambient temperatures, heat waves, and cold spells) and natural hazards (such as storms, floods, and droughts).
- **Comparators:** A comparable population unexposed to the same weather extreme 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.

2.3.1. Data search and search strategy

A systematic search of two electronic databases, including *Web of Science (WoS)* and *Scopus*, was performed. 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 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 centered on weather extremes: “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 extreme weather events and mortality may exist in various permutations and combinations (Supplementary Information Table A.S.2).

2.3.2. Study selection criteria and procedure

The initial literature search considered original and peer-reviewed articles published since 1985, indiscriminate of study location. Studies meeting the following criteria were selected: (1) quantitative observational studies, which present results for the general population, (2) based on mortality outcomes in all-cause/non-accidental/non-external/natural cause mortality and mortality from 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 according to predefined inclusion and exclusion criteria. This process yielded 655 articles for full-text assessment. Following detailed review, 367 articles met the eligibility criteria. From these articles, information on each study’s characteristics was extracted (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 A.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.

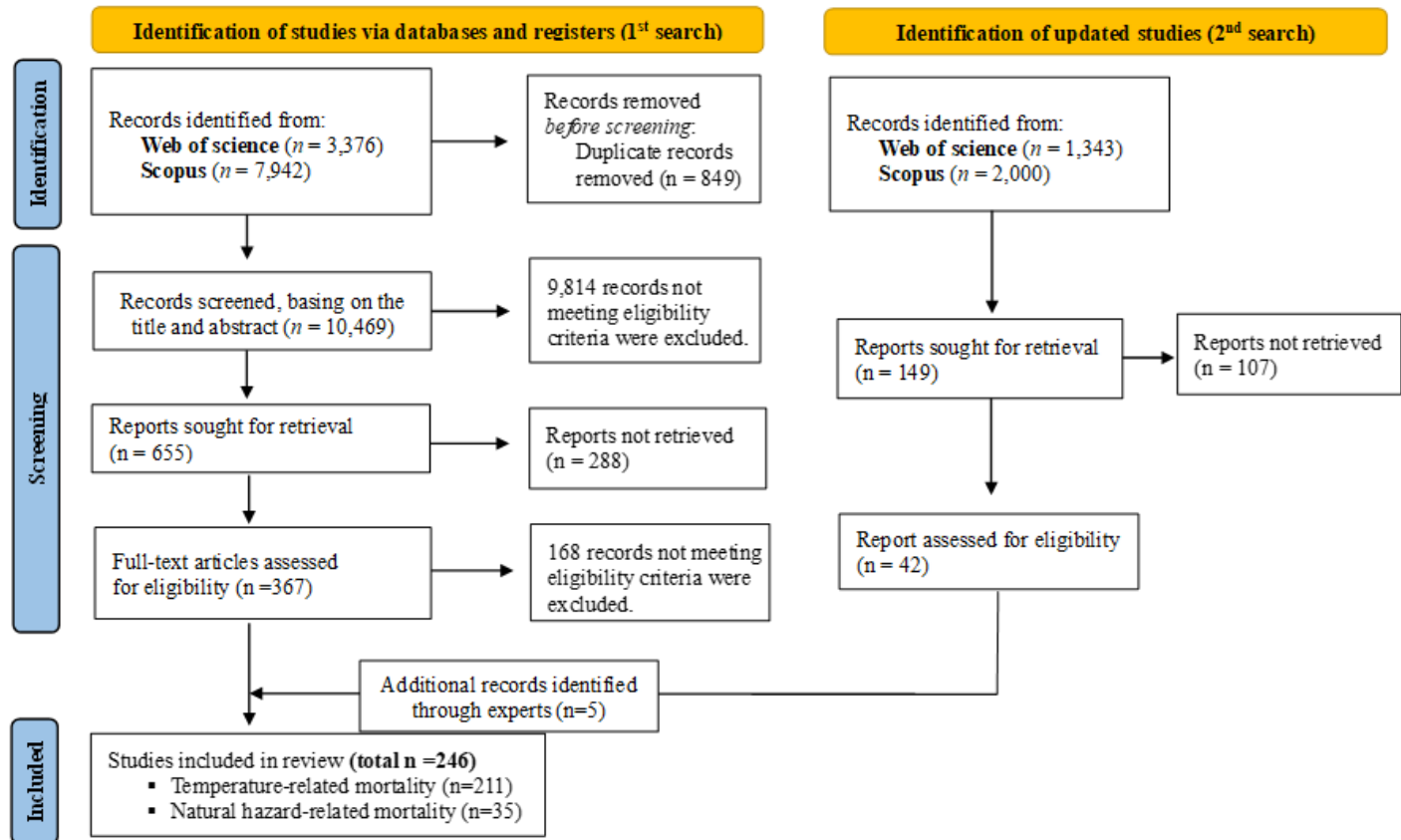


Figure A. 2 Flow chart of studies selection process

2.3.3. 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 modification⁴ 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. 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 (Supplementary Information Table A.S.4). Also, this approach allowed us to synthesize the heterogeneous effects of extreme temperatures and other natural hazards on mortality risk.

2.4. Results

2.4.1. Temporal and geographical distribution of reviewed studies

The publication years of all 246 studies are shown in Figure A.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

⁴ 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

A.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 A.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.

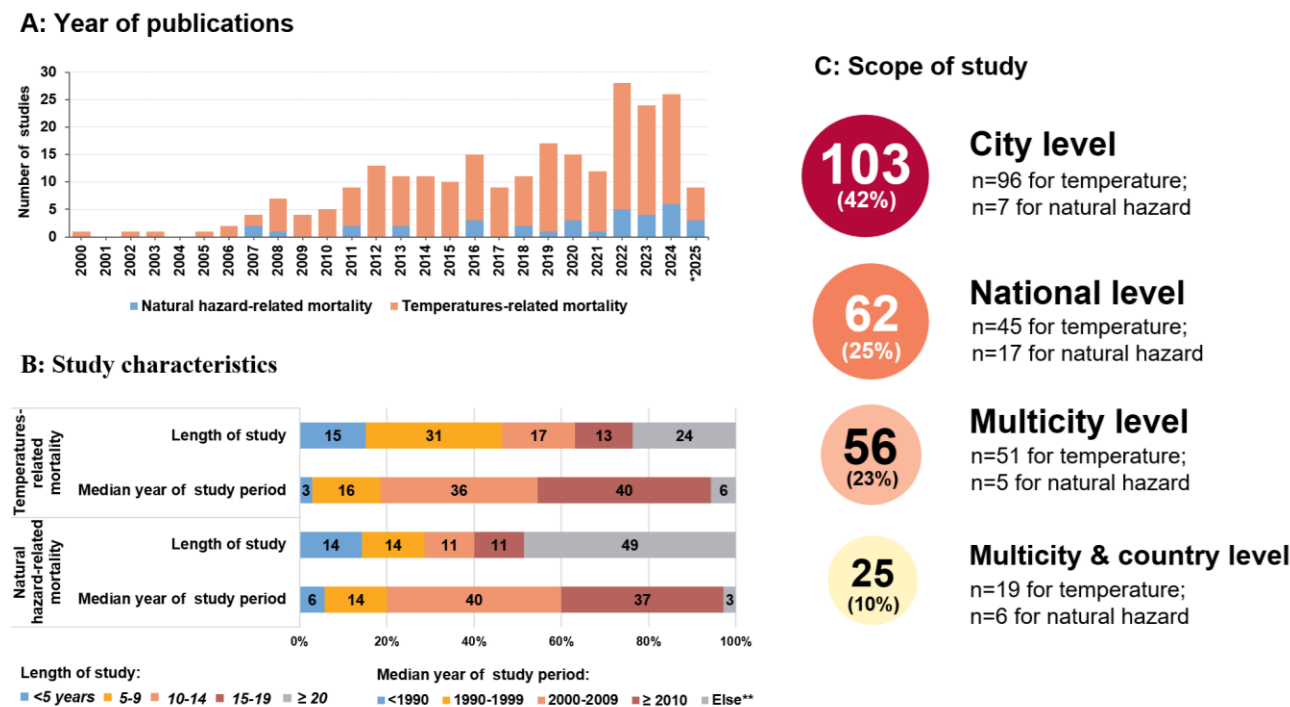


Figure A. 3 Panel A shows the distribution of papers by year of publication on climate-related mortality, Panel B shows the distribution of study characteristics based on length of study and median year of study period, and Panel C shows the distribution of papers.⁵

Understanding the geographical distribution of climate-related mortality research is essential for assessing whether existing evidence adequately captures global variations in vulnerability. Figure A.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

⁵ * Refers 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.

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, study locations fell 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 A.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). 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.

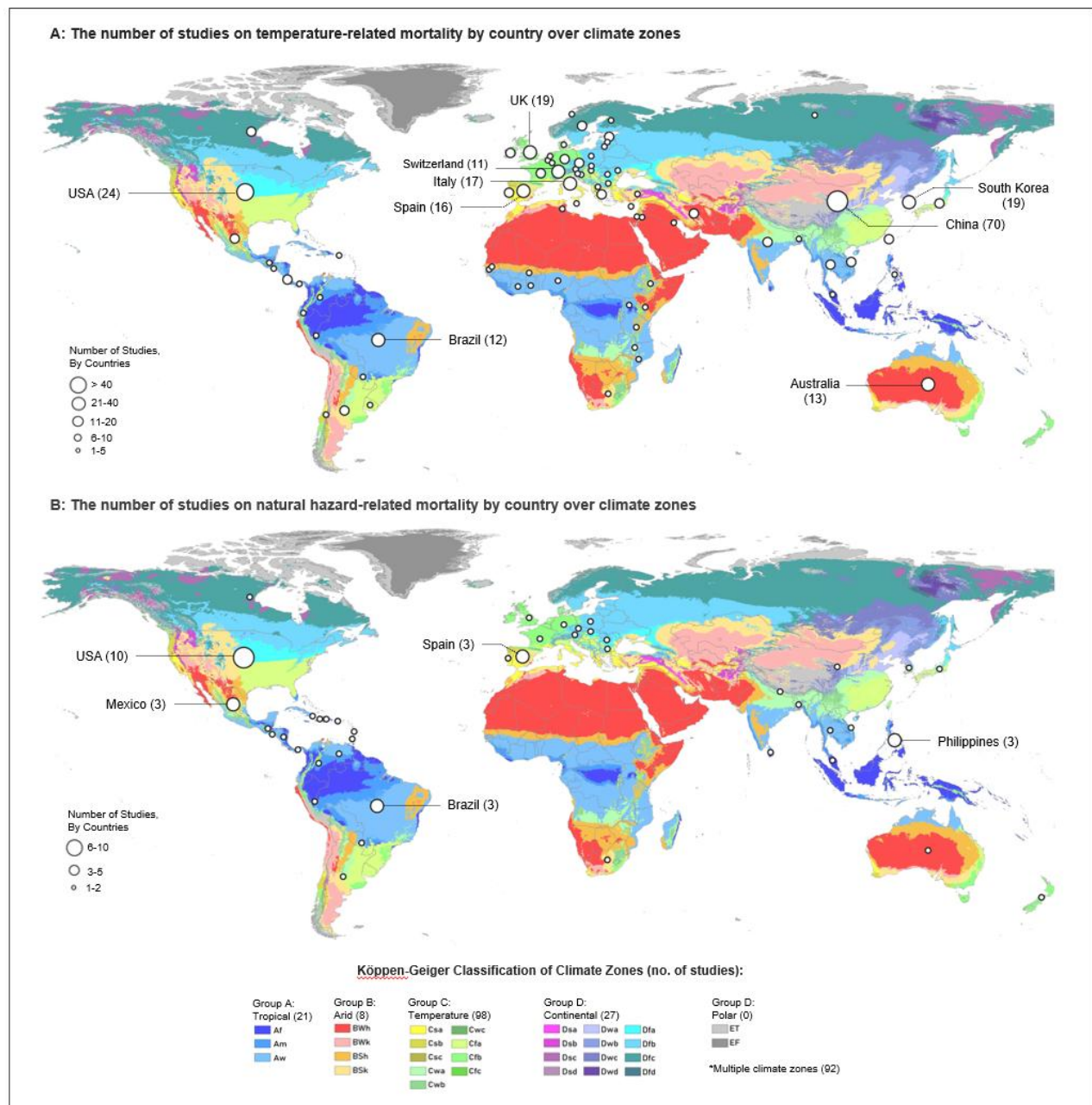


Figure A. 4 Geographic distribution of reviewed studies on temperature-related mortality (A) and natural hazard-related mortality (B) by country over the climate zones (an article can contain multiple case study locations)

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.

2.4.2. 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 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 (Supplementary Information Table A.S.3).

Regarding natural hazards, 35 studies (14% of all included studies) examined their effects on mortality. These studies predominantly focused on 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 the exposed as areas affected by flooding over periods ranging from days to months (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.

2.4.3. 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, nearly all 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.

2.4.4. 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, time-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 high 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 over dispersed 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; 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.

2.4.5. 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 A.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. After that, the overall summary effects for each factor were categorized as strong evidence, limited or suggestive evidence, weak evidence (Tables A.S.4). A complete list of the included studies is provided in the Supplementary Material (Tables A.S.5-A.S.6).

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 , ≥ 65 , ≥ 75 , or ≥ 85 years) were disproportionately affected by both heat (115 effects) and cold (76 effects) compared with younger age groups. Evidence for children under five was reported only a few studies indicated 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 several variables at both the individual and country levels, 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, evidence regarding the role of education and SES was weak but suggested that lower education and SES levels increased mortality during tropical storms and floods.

Geographic patterns were assessed by selecting studies that examined both high- and low-temperature effects and identified which exposure (heat or cold) had a stronger impact on mortality, thereby facilitating direct comparison of mortality risks across different geographic regions and climate zones. The findings reveal substantial regional heterogeneities. Strong evidence indicates that cold exposure contributes more significantly to mortality across all regions. The most extensive evidence base was found in Asia, encompassing 62 original studies, where cold-related mortality predominated, particularly in Eastern Asia (38 cold vs. 10 heat effects). A pattern similarly observed in the Americas. In Europe (24 original studies), northern regions showed suggestive evidence of greater cold-related risks (9 effects), whereas southern Europe exhibited higher heat-related mortality (4 effects). Evidence on natural hazards was far more limited but regionally varied, with most studies conducted in North America and Asia reported increased mortality associated with

tropical storms and flooding and only sparse evidence from Africa and Oceania, highlighting major global research gaps.

Across Köppen-Geiger climate zones, temperature-related mortality varied systematically, as shown in in 69 original studies. The temperate zone (Group C), characterized by mild winters and warm to hot summers, exhibited the strongest evidence, reporting in 34 effects linked to cold exposure and 15 to heat. Similarly, the arid (Group B), tropical (Group A) zones showed slightly greater cold-related (4 each) than heat-related mortality, whereas the continental zone (Group D) displayed the opposite pattern, with more heat-related (5 effects) than cold-related effects. Cold temperatures contribute to a higher mortality burden than heat across nearly all climate zones, even in typically warm or hot regions. For natural hazards, tropical regions, characterized by high temperatures and heavy rainfall, bear the greatest mortality burden from storms, while temperate zones showed the mortality risk from all hazards, particularly from floods.

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

Table A. 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	
	<i>k</i>	Heat/Heat waves	Cold/Cold spells	<i>k</i>	Tropical storms	<i>k</i>	Flood	<i>k</i>		Drought
<u>Sociodemographic characteristics</u>										
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 ↓			
<u>Geography & Climate</u>										
Continent†										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
Africa	2				2			1		
Northern										
Sub-Saharan			2 effects ↑				2 effects ↑		1 effect ↑	
Americas	14			5	7			4		

Table A. 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	
	<i>k</i>	Heat/Heat waves	Cold/Cold spells	<i>k</i>	Tropical storms	<i>k</i>	Flood	<i>k</i>		Drought
Northern		4 effects ↑	5 effects ↑		4 effects ↑		4 effects ↑		1 effect ↑; 2 null effects	Natural hazard: America faces a higher risk from storms, and floods.
Latin & Caribbean			5 effects ↑		1 effect ↑		3 effects ↑		1 effect ↑	
Asia	62			3		4				
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

2.5. Discussion

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. Through a comprehensive search of two major 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 highlights 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. Furthermore, as this systematic review ultimately aimed to inform mortality assumptions for demographic modelling, some insights are offered for future research on mortality under global climate change. Based on the observed patterns of vulnerability across demographic, socioeconomic, geographic, and climatic dimensions, key mortality assumptions can be integrated into population models.

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 (Burkart & 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). To better understand this, an analysis of gender disparities—both in biological factors and in structural inequalities, as well as context-specific social norms—may be needed, as these differences can lead to varying outcomes in mortality. Such variability may help explain why current studies have been unable to identify a consistent pattern in sex-based differences related to natural hazards.

Considering these results in literature, particularly that females are overall more vulnerable to both heat- and cold-related mortality than males across most regions, future projections should

incorporate slightly higher excess mortality rates due to extreme temperature exposure for females. This should particularly be considered in low- and middle-income settings where adaptive capacity may be limited.

Age-related vulnerability

Age consistently emerges as the most robust demographic factor modifying the relationship between extreme temperatures and mortality. The significant, higher mortality risk of both heat and cold impacts on people aged 60 years and over than those younger are evident from our findings, with numerous studies reporting the highest relative risks (RRs) (Bai et al., 2014; Deng et al., 2020; Gallo et al., 2024), the largest YLL (Liu et al., 2021), excess deaths (ED) (Scovronick et al., 2024; Thommen, 2005), and the greatest percentage increases in mortality (Baccini et al., 2008). 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. Social determinants 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 (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 observed in communities characterized by elevated poverty (Curriero et al., 2002; Sarmiento, 2023) or high deprivation index (Kim & Kim, 2017), income inequality (Gini index), and residential segregation (Bakhtsiyarava et al., 2023). Thus, the heightened vulnerability among lower educated and less SES groups to extreme temperature-related mortality is likely multifaceted. 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.

Similarly, socioeconomic factors have been shown to influence mortality risk from natural hazards; however, evidence supporting this relationship is still limited in the current review. 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 individuals with higher education (ages 15-39) faced lower mortality risks by 42% from flooding and landslides (KC, 2013), while those from low-SES households were 6.4 times more likely to experience flood-related deaths than their higher-SES counterparts (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 (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, future demographic projections should integrate education levels into mortality assumptions within the framework of Shared Socioeconomic Pathways (SSPs). 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.

Urban-rural disparities

This review further highlights that urbanization level is a significant modifier of temperature-related mortality. Urban areas are disproportionately affected by heat due to the urban heat island (UHI) effect, where densely built environments trap heat, lack vegetation, and generate additional heat from energy use, resulting in elevated temperatures compared to rural areas. (Franklin et al., 2023; Li et al., 2021; Kai Wan et al., 2022). Moreover, urban temperatures are typically 1°C to 2°C warmer than rural areas, with differences sometimes reaching up to 10°C, depending on factors such as the city's location, building density, and local weather conditions (Chapman et al., 2017). Consistent with this, numerous studies have reported stronger heat-related mortality in urban compared to rural areas, including evidence from China (Wang et al., 2018), Australia, Colombia (Sarmiento, 2023), and the UK (Gasparrini et al., 2022). Similarly, in Germany, Grize et al. (2005) reported significant excess mortality during heat waves in urban and suburban areas. Burkart et al. (2014) also found that older populations (65 and over) in urban Bangladesh were particularly vulnerable to heat-related all-cause mortality. Nevertheless, evidence is not entirely consistent. Some studies have reported stronger 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). Regarding cold exposure, findings are more mixed. Studies in China report stronger cold effects in rural areas (Hu et al., 2019; Wang et al., 2018), particularly

among older people, and females (Hu et al., 2019), while evidence from the United States suggests higher cold-related mortality in urban settings (Choi et al., 2021). 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). This vulnerability is even more pronounced among older adults; in Bangladesh, individuals aged 60 and above were nearly nine times more likely to die in tornadoes compared to younger adults (Sugimoto et al., 2011). 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 centers. 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 to rural counterparts. Additionally, urban adaptation capacity should be explicitly incorporated into future projections (e.g., air conditioning, cooling shelters). Including indicators like air conditioning coverage can substantially reduce heat-related mortality.

Regional and continental burden

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, the evidence is both the most abundant and the most consistent that cold exposure accounts for the greater share of the temperature-related mortality burden in this region, particularly in Eastern Asia. 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 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 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 found that Eastern, and Southern Europe, experience higher heat-related mortality risks compared to other parts of Europe (Baccini et al., 2008; Leone et al., 2013; Zhao et al., 2021). Within this region, Southern Europe records the highest overall heat-related mortality rates, 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—specifically in Norway—cold is the dominant driver of temperature-related deaths, with attributable fractions of 9.9% compared to 0.1% for heat (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 (4% increase during extreme heat events) (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.

In the Americas, findings are fewer but point to a dual burden of heat and cold. 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, while heat remains a growing concern, cold continues to impose a substantial mortality burden across Americas.

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 Americas, the coastal geography and warm ocean currents make the region highly susceptible to frequent and intense storm events as tropical cyclones, particularly in regions like the southeastern United States, and the Caribbean, Gulf of Mexico. The literature highlights the acute impacts of tropical cyclones such as Hurricane Katrina and Maria. Recent estimates indicate that tropical cyclones account for 3.2-5.1% of all deaths in the United States (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 States, 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 show that severe storms significantly increase mortality in Mexico (Pugatch, 2019), Philippines (Gray et al., 2022), and Bangladesh (Burkart et al., 2014), particularly among vulnerable groups 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). Conversely, 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 UK (Wu et al., 2024) and the US. (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.

Drought-related mortality impacts have been documented across the Americas, Europe, and Sub-Saharan Africa, though findings are consistently limited. In the United States, studies reported no significant associations between drought severity and all-cause mortality overall (Abadi et al., 2022). However, evidence shows 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 non-external mortality, 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.

Mortality assumptions should consider regional mortality adjustments. For example, in Europe, future projections could assume increasing temperature-related mortality rates in southern regions, while maintaining or slightly reducing cold-related mortality in northern regions due to increasingly mild winters. However, the projection should consider potential adaptation measures, such as improved infrastructure, healthcare, and early warning systems, which may help reduce mortality.

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 in studies than heat-related effects, as historical associations were stronger and cold contributed to a higher number of deaths. Similarly, this review found the same pattern across different climatic zones, with cold-related effects consistently reported more often than heat-related effects. Temperate climates are characterized by wide temperature ranges throughout the year and pronounced

seasonal variations, exposing populations to both cold winters and hot summers. Many temperate regions, including parts of Europe, North America, and East Asia (Peel et al., 2007), experience the greatest mortality burden year-round temperature variability due to exposure to both heat and cold extremes (Wen et al., 2024). A global study from Zhao and colleagues (2021) reported that excess death ratios associated with non-optimal temperatures were highest in temperate climates (excess death ratio = 10.88%), surpassing those in other climate zones (excluding polar regions). Notably, the majority of these deaths were attributed to cold exposure (9.95%), highlighting that even in regions with moderate climates, cold temperatures remain a major contributor to climate-related mortality. Furthermore, when focusing on cold spells, Gao and colleagues (2024) found that regions with temperate climates had highest excess death ratio (5.17 per 1000 deaths) than other climate zones. In some areas within temperate climates, higher mortality risks have been reported during hot summers, particularly in regions such as Hubei, China (Zhang et al., 2017b), the 15 largest cities in Germany (Rai et al., 2023), Paris, France (Schaeffer et al., 2016) and Victoria, Australia (Amoatey et al., 2024). Thus, populations in temperate climates are facing a dual burden from both heat and cold extremes, emphasizing challenges in adaptation to fluctuating temperatures and the increasing variability associated with climate change.

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.

2.6. Conclusion

This systematic review of 246 studies provides the global synthesis of spatial and sociodemographic heterogeneity in mortality risks associated with extreme temperatures and natural hazards extreme events. The evidence demonstrates that females, older adults, and individuals with lower education or socioeconomic status consistently face greater mortality risks

from extreme weather events. Despite growing evidence, major research gaps persist. Africa and low-income countries are critically underrepresented in literature, particularly in studies examining natural hazards such as floods, storms, and droughts. In addition, demographic and socioeconomic characteristics are often not considered in analyses of hazard-mortality. Spatially, temperate zones show 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.

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). Furthermore, despite efforts to account for variations across climate zones, several studies encompass areas that span multiple climate zones. This posed challenges in assigning results to a specific climate classification. Moreover, 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. In addition, no studies were identified in Polar climates for temperature and in Arid climates for natural hazards, representing a research gap. Finally, the review did not conduct a quantitative meta-analysis, which restricts the ability to generate pooled effect estimates or quantify overall effect modification in mortality risks associated with extreme temperatures and natural hazards. This limitation stems from substantial heterogeneity across studies in research methodologies and designs, statistical method, effect size types, exposure durations (e.g., lag structure and thresholds used), and the unavailability of information necessary for meta-analysis.

Future research should improve regional balance, adopt 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 human mortality from climate-related hazards.

Nevertheless, the review provides detailed information such as study locations, exposure metrics, increments, and investigated effect modifiers studied for each original study. These

findings collectively highlight consistent vulnerability patterns across populations and regions and offer a foundation for identifying priority areas for future research.

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Chapter 3: Geographical Heterogeneity in Temperature-Related Deaths in Europe

Geographical Heterogeneity in Temperature-Related Deaths in Europe

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Abstract

Climate change-induced increases in temperature extremes present new health risks for aging populations. However, the factors determining geographical heterogeneities in temperature-related mortality are not fully understood. Here, we investigate temperature-related mortality in Europe, and how environmental and socioeconomic factors determine regional heterogeneities in temperature impacts. We leverage Eurostat data on deaths on individuals aged 65 and above from 2014 to 2023 across 30 European countries at a precise geographical level. We find that both cold and hot days contribute to increased mortality rates, with cold increasing deaths more than heat. Furthermore, extreme heat is most detrimental in the hottest European climatic regions, whereas higher GDP per capita is linked to lower cold-related mortality. Additionally, both cold and heat show to be more detrimental at elevated concentrations of air pollution. Conversely, we do not observe urbanicity to shape vulnerability to cold and heat. This study enhances our understanding of the crucial roles that local climate, air pollution, urbanization, and GDP per capita play in temperature-related mortality providing critical indications on which locations should be targeted by climate adaptation policies in Europe

KEYWORDS Extreme Temperature • Mortality • Geographical Heterogeneity • Europe

3.1. Introduction

Climate change is posing new challenges on public health systems across the world, and Europe is particularly at risk from such new environmental threats (van Daalen et al. 2024). Europe has been documented to be warming at a faster rate compared to other world regions posing concerns on future developments of heat extremes in the region (Copernicus 2022; IPCC 2023a). Additionally, the rapid aging of the European population is already having a substantial impact on healthcare systems (Etman et al. 2012), and climate change is expected to worsen health risks, morbidity, and quality of life (Arsad et al. 2022; Díaz et al. 2015; Sandu et al. 2021). In this context, it is notable that the share of people aged 65 and over in the EU reached 21% in 2023 (Eurostat 2024a) and is projected to rise to around 30% by 2050 (European Union 2023). The increase in the proportion of older adults poses a challenge as this population group is most vulnerable to extreme temperatures given their greater susceptibility to health conditions such as hyperthermia or hypothermia due to their preexisting medical status (Shibasaki et al. 2013; Székely and Garai 2018), and to social disadvantages such as social isolation (Delerue Matos et al. 2021) and heating and cooling poverty (Bouzarovski 2014; Mazzone et al. 2023).

A large body of literature has documented the impact of extreme temperature on mortality in Europe (Gasparrini et al. 2015; Masselot et al. 2023; Tobías et al. 2021). For instance, a pan-European study estimated that 407,000 deaths annually were attributable to extreme temperatures in a baseline period between 1991 to 2020, with 363,500 deaths attributed to cold and 43,700 deaths attributed to heat (García-León et al. 2024). Also, a study documented how recent increases in temperature due to climate change determined a larger death toll due to heat in Europe (Vicedo-Cabrera et al. 2021). However, large geographic heterogeneities in vulnerability to extreme temperatures exist in Europe and play a relevant role in modeling temperature-related mortality risks (García-León et al. 2024; Hajat and Kosatky 2010; Kovats and Hajat 2008). These disparities can be largely attributed to demographic, climatic, and socioeconomic factors – including differences in economic development, air pollution exposure, levels of urbanization - which may shape vulnerability, exposure, susceptibility or access to medical support (Arsad et al. 2022; Benmarhnia et al. 2015; Gallo et al. 2024; Ingole et al. 2022; Santamouris et al. 2014; Smętkowski 2013). Nevertheless, research on geographical differences in the impact of temperature on

mortality among older adults in Europe remains limited, particularly regarding the key factors driving these differentials.

This study aims to investigate temperature-related impacts on mortality while considering the moderating role of climatic and sociodemographic variables in European countries at the NUTS 3 level ⁶. More precisely, we examine the role of the local climate, the urbanization level, the Gross Domestic Product (GDP) per capita, and an indicator of air pollution i.e.: Particulate Matter (PM)_{2.5}, to elucidate how these factors contribute to determine geographical differences in cold- and heat-related mortality across European areas. Our study contributes to the existing literature exploring the temperature impacts on mortality in three main ways. Firstly, we focus our research at the NUTS 3 regional level whereas much of the existing evidence on temperature-related deaths is based on the regional level (NUTS 2) (García-León et al. 2024; Gasparrini et al. 2015; Vicedo-Cabrera et al. 2021; Zhao et al. 2021), or focuses on urban areas while excluding rural regions (Baccini et al. 2009; García-León et al. 2024; Masselot et al. 2023). Additionally, we provide a comprehensive analysis on the factors that determine a moderation of the impacts of heat and cold on mortality in Europe. Previous studies have provided evidence that socioeconomic, infrastructural, and healthcare-related factors can influence temperature-related mortality, but a systematic analysis of their moderating effects across different European regions remains limited (Arsad et al. 2022; Gallo et al. 2024; Ingole et al. 2022; Santamouris et al. 2014).

The article is structured as follows. First, we describe the existing literature on temperature related mortality and the factors determining geographical disparities in vulnerability in Europe. Secondly, we describe the data and methods. Afterwards, in the results section, we document the impact of temperature on mortality in Europe over the last decade and we provide evidence on the geographical heterogeneities and specific temperature-mortality effect modifiers (urbanization,

⁶ The Nomenclature of Territorial Units for Statistics, abbreviated as NUTS, is a hierarchical system developed and regulated by the European Union that subdivides the economic territory into regions at three levels (NUTS 1, 2, and 3), moving from larger to smaller territorial units based on demographic thresholds (Eurostat, 2024c):

Level	Minimum	Maximum
NUTS 1 (major socioeconomic regions)	3 million	7 million
NUTS 2 (basic regions)	800 000	3 million
NUTS 3 (small regions)	150 000	800 000

NUTS 0 corresponds to the national boundaries (European Parliament, 2024; Eurostat, 2024).

GDP per capita, and PM_{2.5} air pollution). Finally, we conduct robustness checks and conclude with a discussion of our findings.

3.2. Background

3.2.1. Temperature-Related Mortality in Europe

Exposure to extreme temperatures directly affects human health by compromising the body's ability to regulate its internal temperature (Sarofim et al. 2016; Seltenrich 2015). A decrease or increase in body temperature ($\leq 35^{\circ}\text{C}$; $\geq 40^{\circ}\text{C}$ ⁷) can lead to severe health complications, including organ failure and premature death (Cheshire 2016; Osilla and Sharma 2020; Seltenrich 2015). Cold exposure impairs blood flow, metabolism, and brain function, potentially leading to memory loss, confusion, fatigue, and fatal hypothermia (Arbuthnott et al. 2018; Ryti et al. 2016). Conversely, excessive heat can reduce blood pressure, raise heart and respiratory rate, increasing the risk of heatstroke, hyperthermia, and damage to vital organs such as kidneys, liver, lungs, and brain (Basu and Samet 2002; Cui and Sinoway 2014; Seltenrich 2015).

Individuals aged above 65 are widely recognized as having an increased risk of respiratory and cardiovascular death during temperature extremes due to reduced thermoregulation (Aström et al. 2011; Zanasi and Conte Keivabu 2024), with many also having preexisting health conditions, limited mobility, or social isolation, which can further increase their risk (Bunker et al. 2016; Delerue Matos et al. 2021). The already high proportion of older adults in Europe poses a significant public health concern during extreme temperature events, which are expected to escalate over time due to population aging and the increasing frequency and intensity of heatwaves and cold spells (Vicedo-Cabrera et al. 2021; van Dalen et al. 2024).

Traditionally, the human mortality-temperature relationship is described as a U-, J-, or inverse J-shaped curve, defined by a temperature range of minimum mortality and increasing incidence for colder and/or warmer temperatures (Alberdi et al. 1998; Armstrong 2006; Laaidi et al. 2006; McMichael et al. 2006). A U-shaped relationship between temperature and mortality reflects the lowest death rate within a comfort zone, with increases in deaths during both extreme cold and

⁷ $\leq 95^{\circ}\text{F}$; $\geq 104^{\circ}\text{F}$

extreme heat events (Armstrong 2006; Raimi 2021). A J-shaped relationship indicates that either cold or heat -related mortality rises more sharply and is more pronounced than the other (Armstrong 2006, Gasparrini et al. 2015). The existing literature on the effects of extreme temperatures on human mortality has shown that extremely cold temperatures have the greatest impact on human health (Alahmad et al. 2025, Masselot et al. 2023; Zhao et al. 2021). This general trend is due in part to the fact that cold temperatures facilitate the spread of flu and viruses (Jaakkola et al. 2014; Arbuthnott et al. 2018), increasing the mortality rates in the colder months (Gasparrini et al. 2022; Son et al. 2019). A substantial body of literature indicates that influenza is not merely a confounder but an independent driver of winter mortality, characterized by complex dynamics (Gagnon et al., 2020; Lane et al., 2022; Towers et al., 2013)⁸. The precise timing and characteristics of viral circulation can markedly alter both the magnitude and the seasonal profile of cold-attributable mortality.

Prior to the 2000s, mortality rates attributed to cold weather received more scientific research attention than those related to heat due to the highest impact of cold temperature-related deaths across most of the world (Gasparrini et al. 2015; Rytı et al. 2015). A recent study carried out across 854 cities in Europe found that the number of cold-related deaths is around 10 times higher than that of heat-related deaths (Masselot et al. 2023), mostly as the European area is characterized by a higher prevalence of moderately cold days than of very cold days (Köppen and Geiger 1936; Moberg et al. 2006). Similar results have been found for non-EU countries (Lee and Dessler 2023; J. Liu et al. 2022). Nevertheless, after the heatwave of summer 2003 generated 70,000 additional deaths across Europe (Robine et al. 2008), interest in investigating heat-related mortality and heat policies in the European context increased (Black et al. 2004; Fouillet et al. 2006; Johnson et al. 2005). Global surface temperature records were broken in 2022-2023 (Copernicus 2023), and there were an estimated 61,672 heat-related deaths in Europe in summer 2022 (Ballester et al. 2023). The Intergovernmental Panel on Climate Change (IPCC) defined the European area as a hotspot for multiple risks of increasing temperatures and extreme heat (IPCC 2023a). Europe average warming has increased at a rate that is more than twice the global average over the past 30 years

⁸ An illustrative example is the paradoxical decline in mortality among older adults during the 2009 H1N1 pandemic, which has been attributed to prior cohort exposure to antigenically similar strains. During this pandemic, mortality among individuals aged 65 years and older decreased by approximately 50%, a counterintuitive outcome resulting from immunological protection conferred by exposure to related strains (H3N2) decades earlier (Gagnon et al., 2020).

(Copernicus 2022). Additionally, it has been pointed out that the European area is particularly vulnerable to extreme temperatures, as it has a large population and an aging demographic structure: of the 448.4 million individuals living in the EU on January 1, 2023, 98 million were over 60 years old (Eurostat 2024a), and this proportion is projected to increase. European and global studies have stressed the need to implement long-term prevention, and adaptation plans to protect populations at risk during heatwaves, including people aged 65 and over (Masselot et al. 2023; Raimi 2021).

3.2.2. Geographical Differences in Temperature-Related Mortality: Local Climate, Air Pollution, Urbanity, and Economic Development

There are various explanations for heterogeneities in temperature-related deaths across geographical areas: e.g., (1) differences in exposure due to the frequency, intensity, severity, and duration of extremely hazardous temperatures (heatwaves/cold spells) (Masselot et al. 2023; Xu et al. 2016); (2) differential sensitivity within countries and regions based on socio-demographic characteristics, such as age, gender, education, and income (Etman et al. 2012; Muttarak et al. 2016); and (3) differences in the development of policies and medical infrastructure that enable them to adapt to exposure (Carleton et al. 2022; Lutz and Striessnig 2015). Reflecting on these arguments, it is recognized that the optimal temperature and the shape of the human mortality-temperature curve vary across places, ranging from 17°C in Northern Europe, to 20°C in Central Europe, and to 23°C in Southern Europe (Tobías et al. 2021). The literature reports that the optimal temperature for humans is lower in colder regions and is higher in warmer regions of the world (Yin et al. 2019), indicating that physiological and technological adaptations help individuals to cope with cold and heat. Furthermore, most studies have found that populations living in places with warm winter climates are generally more vulnerable to variations in cold winter weather (Anderson and Bell 2009; Conlon et al. 2011; Heutel et al. 2021), whereas populations living in places with moderate summer climates are more vulnerable to hot weather stress (Basu 2009; Hajat and Kosatky 2010; McMichael et al. 2008; Yin et al. 2019), even though the hazardous temperature levels are lower. Indeed, regions that generally do not experience extreme temperature events may be less equipped to manage the consequences of such an event (Thompson et al. 2023). In these regions, a record-breaking event is likely to have a greater impact due to a lack of preparedness.

Other than the local climate other factors determine disparities in vulnerability to extreme temperatures. Factors that have been found to moderate the effects of cold and heat on mortality are: socioeconomic status proxied with income or educational attainment (López-Bueno et al. 2020; Kulhánová et al. 2014; Rydland et al. 2020; Conte Keivabu 2022); technological adaptation such as the presence or absence of air conditioning and heating (Chard and Walker 2016; Thomson et al. 2019); loneliness (Burlina and Rodríguez-Pose 2023; Elovainio et al. 2017); adverse health status (Song et al. 2017); living in an urban/rural area (Gabriel and Endlicher 2011); types and concentrations of air pollutants (Chen et al. 2024).

In our study, we focus on three of these dimensions: urbanization level, GDP per capita and PM_{2.5} air pollution. The urbanization level is correlated differently with heat- and cold-related human mortality. Most studies have reported that the risk of cold-related mortality is higher in rural areas, where populations may have limited access to healthcare facilities and heating infrastructure, as well as difficult financial situations (Rechel et al. 2016; Rygh and Hjortdahl 2007). In urban areas, by contrast, the risk of heat-related mortality may be exacerbated by the so-called urban heat island effect (UHI) (Iungman et al. 2024). Urban environments absorb and retain more heat and are slower to cool down than natural environments (Laaidi et al. 2012). Nevertheless, urban areas are not immune to the risks associated with cold-related mortality, as exemplified by findings in Scotland (Wan et al. 2022). About 75% of the EU population today is concentrated in various types of urban areas, with about 40% living in capitals or other big cities and about 35% living in towns or suburbs. The remaining 25% of the EU population live in rural regions (Lavalley et al. 2017). Rural settlements generally have lower levels of innovation than cities and frequently face critical challenges that make these areas especially sensitive and vulnerable to extreme temperature variations (European Environment Agency 2020). However, rural areas also tend to have lower population densities and greater green space coverage, which contribute to lower exposure risks to extreme heat temperatures (Luo et al. 2024). GDP per capita is expected to be inversely associated with the risk of temperature mortality (López-Bueno et al. 2022; Sakka et al. 2012; Santamouris et al. 2014). Several studies report that deaths related to extreme temperatures are particularly high among populations with low-income levels (Berg et al. 2024, Healy 2003). This inverse association accounts for contextual characteristics, such as housing energy ratings, housing type and quality (Santamouris et al. 2007; Santamouris and Kolokotsa 2015), interior air conditioning and fuel poverty (Champagne et al. 2023; Healy 2016),

highlighting the relevance to health of indoor environments and the lack of economic resources to invest in home adaptation (Achebak et al. 2023; Rudge and Gilchrist 2007). PM_{2.5} air pollution has been shown to modify the impact of extreme temperatures on mortality, exacerbating the effects of both heat and cold exposure (Iungman et al. 2024; Keatinge and Donaldson 2001). In line with numerous studies, we assume an increasing association between higher pollution and cold/heat mortality (Ingole et al. 2022; Orru et al. 2017; Stafoggia et al. 2023). Cold temperatures may affect respiratory health more severely when combined with high levels of air pollution, which tend to rise during the winter heating period due to increased emissions from residential heating systems, while temperature inversions trap pollutants close to the ground, worsening air quality (De Sario et al. 2013; Fiore et al. 2015). Moreover, several European studies have found that heatwaves tend to have a greater effect in areas where pollution levels are higher (Gryparis et al. 2004; Katsouyanni et al. 1993). In fact, heatwaves can intensify air pollution by increasing ozone and particulate matter concentrations, while pollutants like ozone and nitrogen dioxide can exacerbate the physiological stress caused by high temperatures, leading to greater health risks (Chen et al. 2018).

3.3. Data and Measures

3.3.1. Population and Mortality

We leverage Eurostat⁹ sources of data for population and death counts at the regional level. The demographic data includes information on population on 1 January by broad age group, sex and NUTS 3 region (dataset: `demo_r_pjanaggr3`, European Commission, 2013), as well as deaths by week, sex, five-year age group, and NUTS 3 region (dataset: `demo_r_mweek3`, European Commission, 2020). The data at the regional level are calculated by Eurostat based on a common methodology for all countries and regions, according to the official classification for statistics at the regional level that is in force in the given year (Eurostat 2024b).

⁹ Eurostat is the statistical office of the European Union, which provides high-quality statistics and data on Europe in cooperation with the National Statistical Institutes and other national authorities in the EU (Eurostat, 2024b).

Starting with population and deaths expressed in absolute values we first estimate the monthly exposure of the population by linearly interpolating the population on 1 January by sex, age, and NUTS 3 region. We then construct the monthly death counts by summing the weekly mortality data, using the `ISOweek2date` function to assign each weekly observation to the appropriate month for each combination of NUTS region, sex, and age group (Block, 2011; R package `ISOweek`). This procedure ensures consistency with ISO week definitions and avoids misalignment of weeks that span two calendar years or months¹⁰.

3.3.2. Meteorological Information and Temperature Bins

We obtained meteorological data from the E-OBS dataset of the Copernicus Climate Data Store¹¹. We use version 30.0e based on in-situ surface observations, provides ensemble mean information with a spatial resolution of $0.1^\circ \times 0.1^\circ$ for the period 2014–2023 (Cornes et al., 2018). We utilize mean, minimum, and maximum temperature as main variables for our analysis, while solar radiation, relative humidity, precipitation, wind speed as control variables¹².

Daily gridded climate data were overlaid with NUTS-3 administrative boundaries, using population-weighted averages, with population counts derived from the 2015 layer of the Gridded Population of the World (GPW v4) dataset at 2.5 arc-minute resolution (dataset: GPWv4, CIESIN, 2018). Daily population-weighted mean climate exposures were computed for each NUTS-3 region, weighting each grid cell by the corresponding population count and accounting for partial overlaps between grid cells and administrative boundaries¹³.

¹⁰ Weekly mortality counts were provided by Eurostat using the ISO 8601 week numbering system, in which each week starts on Monday and week 1 is defined as the week containing the first Thursday of the year (Eurostat, 2025). The `ISOweek2date` function allows to convert each ISO week identifier to the date of the corresponding Monday, from which the calendar year and month are extracted to assign each weekly observation to the appropriate month (Block, 2011; R package `ISOweek`).

¹¹ E-OBS is a daily gridded observational dataset for precipitation, temperature, sea level pressure, global radiation, humidity, and wind speed over Europe based on observation networks that are owned and operated by the National Meteorological Services and others (Copernicus Climate Change Service 2024a).

¹² These control variables are widely found by the literature to significantly alter people's thermal sensations, comfort level, and thermoregulatory efforts (Fang et al. 2004; Li et al. 2024; Yang et al. 2024).

¹³ The population raster was resampled to the climate grid using an area-preserving sum aggregation to ensure consistency between population counts and the coarser climate resolution. The use of a static weighting surface population distribution assumes that sub-regional population patterns remained relatively stable over the study period and avoids introducing additional uncertainty related to temporal interpolation of population data, which has been shown to have limited impact on short- to medium-term climate–health associations at sub-national scales.

Relative humidity was computed from air temperature, measured in Kelvin and converted to Celsius, and dew point using the Magnus formula¹⁴. Wind speed was derived as the Euclidean norm of the zonal and meridional wind components¹⁵, measured in meters per second. Precipitation was measured in meters, while solar radiation, measured in joule per square meter (J/m^2)¹⁶, was log-transformed to reduce skewness. Temperature data (mean, maximum, minimum) were converted from Kelvin to Celsius.

Next, we proceed with the creation of the temperature exposures variable, utilizing daily average temperature bins. We leverage these daily values to create temperature bins of daily average temperature based on percentiles derived from the temperature distribution specific to each NUTS 3 unit over the study period. We count the number of days in a month and NUTS 3 area that fall within 11 temperature bins: 1) equal to or below the 5th percentile; 2) between the 5th and 10th percentiles; 3) between the 10th and 15th percentiles; 4) between the 15th and 20th percentiles; 5) between the 20th and 25th percentiles; 6) above the 25th percentile but below the 75th percentile; 7) between the 75th and 80th percentiles; 8) between the 80th and 85th percentiles; 9) between the 85th and 90th percentiles; 10) between the 90th and 95th percentiles; and 11) above the 95th percentile. The category encompassing temperatures between the 25th and 75th percentiles is considered as the comfort zone, and it is excluded from the analysis. The use of such temperature bins is common in existing literature and allows us to better capture the non-linear impact of temperature on mortality (Barreca et al. 2016; Hajdu and Hajdu 2023; Hovdahl 2022; Khatana et al. 2022; Masiero et al. 2022).

3.3.4. Urbanity, Air Pollution, Income, and Climate Regions

The four main variables for which we analyze heterogeneity are: urbanization level, $\text{PM}_{2.5}$ air pollution, GDP per capita, and climatic regions, for which we provide maps in Figure S1 and S2 in Supplementary Material. Respectively we capture them as follows.

¹⁴ This formula, commonly known as the Magnus formula, is widely used in meteorology to derive relative humidity from temperature measurements. The dew point is the temperature at which air becomes saturated with water vapor and condensation begins, representing the absolute moisture content of the air.

¹⁵ the wind speed is calculated as the square root of the sum of the squares of the east–west (zonal) and north–south (meridional) wind components, representing the total wind intensity regardless of direction.

¹⁶ Joule per square meter (J/m^2) represents the direct solar energy incident on one square meter of the Earth's surface over a specified time interval.

We analyze the role of urbanization level in temperature-related mortality using the Eurostat demographic datasets, which include the urban-rural typology information and identify each NUTS 3 region as (i) predominantly urban (more than 80% of the population live in urban clusters), (ii) intermediate (between 50% and 80% of the population live in urban clusters), or (iii) predominantly rural (at least 50% of the population live in rural grid cells) (Eurostat 2018).

Air pollution data are obtained from the Copernicus Atmosphere Monitoring Service (CAMS)¹⁷ (Copernicus 2024). We use PM_{2.5} concentrations provided at a spatial resolution of 0.75 degrees, which are derived from daily records ($\mu\text{g}/\text{m}^3$) and averaged for each NUTS 3 region. We additionally categorize PM_{2.5} exposure into quartiles to compute the heterogeneity analysis: (i) Q1, the first quartile, comprising observations in the lowest exposure range (3.26 – 10.3 $\mu\text{g}/\text{m}^3$); (ii) Q2, consisting of data falling between the first and the second quartile thresholds (10.3 – 11.3 $\mu\text{g}/\text{m}^3$); (iii) Q3, including values between the second and the third quartile thresholds (11.4 – 12.9 $\mu\text{g}/\text{m}^3$); and (iv) Q4, consisting of observations in the highest exposure range (12.9 – 20.1 $\mu\text{g}/\text{m}^3$).

We incorporate information on Gross Domestic Product (GDP) per capita at current market prices for each NUTS 3 region, using a downscaled gridded global dataset of GDP per capita at purchasing power parity (Kummu et al. 2025). We leverage annual regional GDP data at the NUTS 3 level to compute average GDP per capita for each region and categorize this variable into terciles. The GDP per capita terciles describe: (i) the low category, defined as the first third consisting of the lowest 33.3% of the data (4985 - 28818); (ii) the middle category, defined as the second third consisting of the data falling between the first and the second tercile (28825 - 39621); and (iii) the high category, defined as the last third consisting of the upper 33.3% of the data (39632 - 179805). In brackets the minimum and maximum values for each GDP per capita categorization are reported.

Finally, we incorporate data from the Köppen-Geiger classification system (Beck et al. 2018), which defines distinct climate types based on a large range of meteorological variables (Köppen and Geiger 1936). We classify NUTS 3 regions according to the Köppen-Geiger typology into

¹⁷ CAMS provides the latest global reanalysis dataset of atmospheric composition produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Inness et al. 2019).

three categories: (i) hot and arid climates, (ii) temperate climates, and (iii) cool climates, following the approach used in previous research (Beck et al. 2018; Hoffmann et al. 2022).

3.3.5. Methods

To estimate the association between temperature and mortality, we employ a Poisson regression with fixed effects (FE). We describe the equation as follows:

$$\ln[E(Y_{mrag})] = \ln(E_{mrag}) + \sum_j \theta_j TBIN_{mr}^j + X_{mr}\beta + \alpha_{mr} + \delta_m \quad (1)$$

where Y_{mr} is the monthly count of deaths in month-year m , NUTS 3 region r , age groups a , and gender group g . E_{mrag} is an offset term capturing the exposure to death risk in the NUTS 3 region r and month-year m , gender g , and age a . $TBIN_{mr}^j$ captures the number of days where temperature in month-year m in NUTS 3 region r fell into the range of bin j , i.e., one of either percentile bins $\leq 5^{\text{th}}$, $[5^{\text{th}} - 10^{\text{th}}]$, $[10^{\text{th}} - 15^{\text{th}}]$, $[15^{\text{th}} - 20^{\text{th}}]$, $[20^{\text{th}} - 25^{\text{th}}]$, $[25^{\text{th}} - 75^{\text{th}}]$, $[75^{\text{th}} - 80^{\text{th}}]$, $[80^{\text{th}} - 85^{\text{th}}]$, $[85^{\text{th}} - 90^{\text{th}}]$, $[90^{\text{th}} - 95^{\text{th}}]$, $\geq 95^{\text{th}}$ percentiles. The reference category is the comfort zone $[25^{\text{th}} - 75^{\text{th}}$ percentile]. The coefficients θ_j represent the effect on mortality of exchanging one day in the comfort zone for a day in the j -th bin. Because temperature exposures are measured as discrete counts of days within percentile bins, we compute discrete marginal effects, computed as $(\exp(\theta_j) - 1) \times 1000$, representing the relative percent change in monthly mortality rate per 1,000 population associated with exchanging one day in the comfort range for one day in the j -th temperature bin. X_{mr} are the time-varying control variables including monthly precipitation, wind speed, relative humidity, log-transformed solar radiation, PM2.5 air pollution, population density, in each NUTS 3 region with associated coefficients β . We also control for GDP per capita, sex and age categories (65-69 as reference, 70-74, 75-79, 80-84, 85-89, 90+). α_{mr} captures the NUTS 3 region-by-month fixed effects; and δ_m account for year-by-month fixed effects. The use of a fixed-effect regression model enables to capture two key sources of variation: (a) temporal variations between locations (NUTS 3), allowing us to check for variations that may differ across regions; and (b) monthly variations across years, allowing us to examine temporal changes that may vary from year to year due to specific events, such as pandemics, natural disasters, or public policies (Hsiang 2016). Also, the use of monthly data aligns with other previous

similar studies (Barreca et al. 2016; Hajdu and Hajdu 2023; Hovdahl 2022; Khatana et al. 2022; Masiero et al. 2022). We clustered standard errors at the NUTS 3 level that align with our level of exposure (Hsiang 2016).

In addition, to investigate heterogeneity in temperature-related mortality across Europe, we extend equation (1), where we include a model matrix $\mathbf{Z}_{mr}$ that corresponds to the interaction between the temperature variable $TBIN_{mr}^j$ and the variables: climatic region, urbanization, GDP per capita, and PM_{2.5} air pollution. The term $TBIN_{mr}^j$ is the number of days in temperature bin j as defined in equation (1). We estimate the following specification:

$$\ln [E(Y_{mrage})] = \ln(E_{mrage}) + \mathbf{Z}_{mr}\boldsymbol{\theta} + \mathbf{X}_{mr}\boldsymbol{\beta} + \alpha_{mr} + \delta_m \quad (2)$$

where $\mathbf{Z}_{mr}$ corresponds to the interaction term between the temperature variable $TBIN_{mr}^j$ and the individual variable of urbanization, GDP per capita, climate regions, and PM_{2.5}, with the associated coefficient vector $\boldsymbol{\theta}$. The control variables $\mathbf{X}_{mr}\boldsymbol{\beta}$, region-by-calendar month fixed effects α_{mr} , and month-year fixed effects δ_m remain as specified in equation (1). Standard errors remain clustered at the NUTS 3 level. Temperature effects for each subgroup (climate region, urbanization category, GDP per capita tercile, PM2.5 quartile) are computed as discrete marginal effects conditional on the category.

3.4. Results

3.4.1. Temperature-Related Deaths in Europe

Table B.1 provides descriptive statistics of the variables used in our analysis. On average in each NUTS 3 region, there are about 7710 [198-105545] people aged 65 or older. The total deaths per each NUTS 3 region are on average about 342 [0 - 14929] per month, with a standard deviation of about 345. The number of days falling in the ≤ 5 th temperature percentile per NUTS 3 region per month is on average 1.56 [0; 29], while the number of days falling in the ≥ 95 th percentile is on average 1.53 [0; 28].

Table B. 1 Descriptive statistics of the monthly observations for European NUTS3 regions

Variables	Mean	SD	Min	Max
Mortality and population				
Population exposures 65+	7710	8063.16	198	105545
Total deaths	342	344.76	0.00	14929
Temperature				
≤5th percentile	1.56	3.61	0.00	29.00
>5th and ≤10th percentile	1.55	2.68	0.00	20.00
>10th and ≤15th percentile	1.52	2.32	0.00	18.00
>15th and <20th percentile	1.52	2.20	0.00	15.00
≥ 20th and <25th percentile	1.51	2.12	0.00	15.00
≥ 75th and <80th percentile	1.50	2.30	0.00	19.00
≥ 80th and <85th percentile	1.52	2.40	0.00	18.00
≥ 85th and <90th percentile	1.52	2.57	0.00	21.00
≥ 90th and <95th percentile	1.52	2.83	0.00	20.00
≥ 95th	1.53	3.49	0.00	28.00
Control variables				
Relative humidity (%)	73.79	10.19	23.77	95.82
Wind speed (m/s)	1.37	1.06	0.00	10.02
Precipitation (m)	0.0024	0.007	0.00	0.0224
PM _{2.5} (μg/m ³)	11.48	4.49	0.64	164.51
GDP per capita (€)	34969	15721.15	4985	179805
Population density (persons per m ²)	5.51	17.96	0.01	290.27
Observations				
N. NUTS3	964			
N. NUTS3 – years	1,201,488			

Notes: SD refers to the standard deviation. For temperature ranges, we report average values (number of days in range) for our month-year-NUTS3 cells.

Figure B.1 shows the extreme temperature percentiles ($\leq 5^{\text{th}}$; $\geq 95^{\text{th}}$) in Europe by NUTS3 region, highlighting the different temperatures characterizing Europe. Regional differences are expected, particularly as in our analysis the regions with the highest heat levels are located in Spain, where the temperatures in the 95th percentile are above 30°C, while the regions with the highest cold levels are located in northeastern Europe, where the temperatures in the 5th percentile are mostly between 0 and -10°C. The lowest temperatures are observed in Sweden, where the temperatures in the 5th percentile are below -15°C.

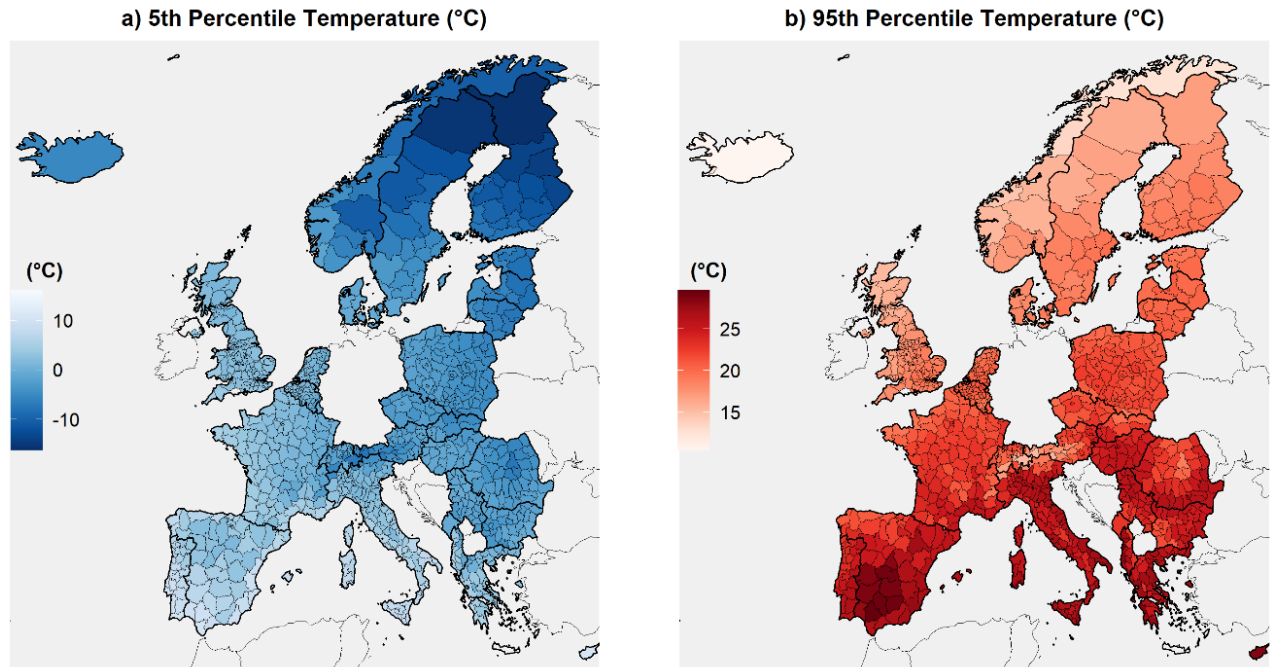


Figure B. 1 Map of European NUTS3 regions included in the analysis by the 95th and the 5th percentile of the temperature distribution

Note: The figure presents the 95th and the 5th percentile of the temperature distribution in each NUTS3 region in our sample for the study period (2014-2023).

In Figure B.2, we display the results of the model based on Equation (1). The estimated coefficients are in Table B.S.2 of the Supplementary Material. The relationship between heat and cold exposure and human mortality follows an inverse J-shaped curve. The monthly mortality rates are higher at the colder extremes of the spectrum than in the moderate and the hotter temperature ranges. In line with the literature (Masselot et al. 2023; Zhao et al. 2021), a higher peak is observed at extremely cold temperatures (5th percentile), which continue to be the most detrimental for older people. An additional day in the coldest percentile ($\leq 5^{\text{th}}$) increases the monthly mortality rate by 7.2‰ [95% Confidence Interval (CI): 6.6 – 7.7‰], while an additional day in the hottest percentile ($\geq 95^{\text{th}}$) increases the monthly mortality rate by 5.8‰ [95% CI: 5.1 – 6.5‰]. The change in monthly mortality rate is higher in general at any cold temperatures ($\leq 25^{\text{th}}$), and lower at warmer temperatures ($\geq 75^{\text{th}}$). This suggests that, in line with previous findings (Gasparrini et al. 2015, 2022; Masselot et al. 2023) cold- and heat-related mortality behave differently, with the number of deaths at moderately cold temperatures being higher than the number of deaths at moderately hot temperatures.

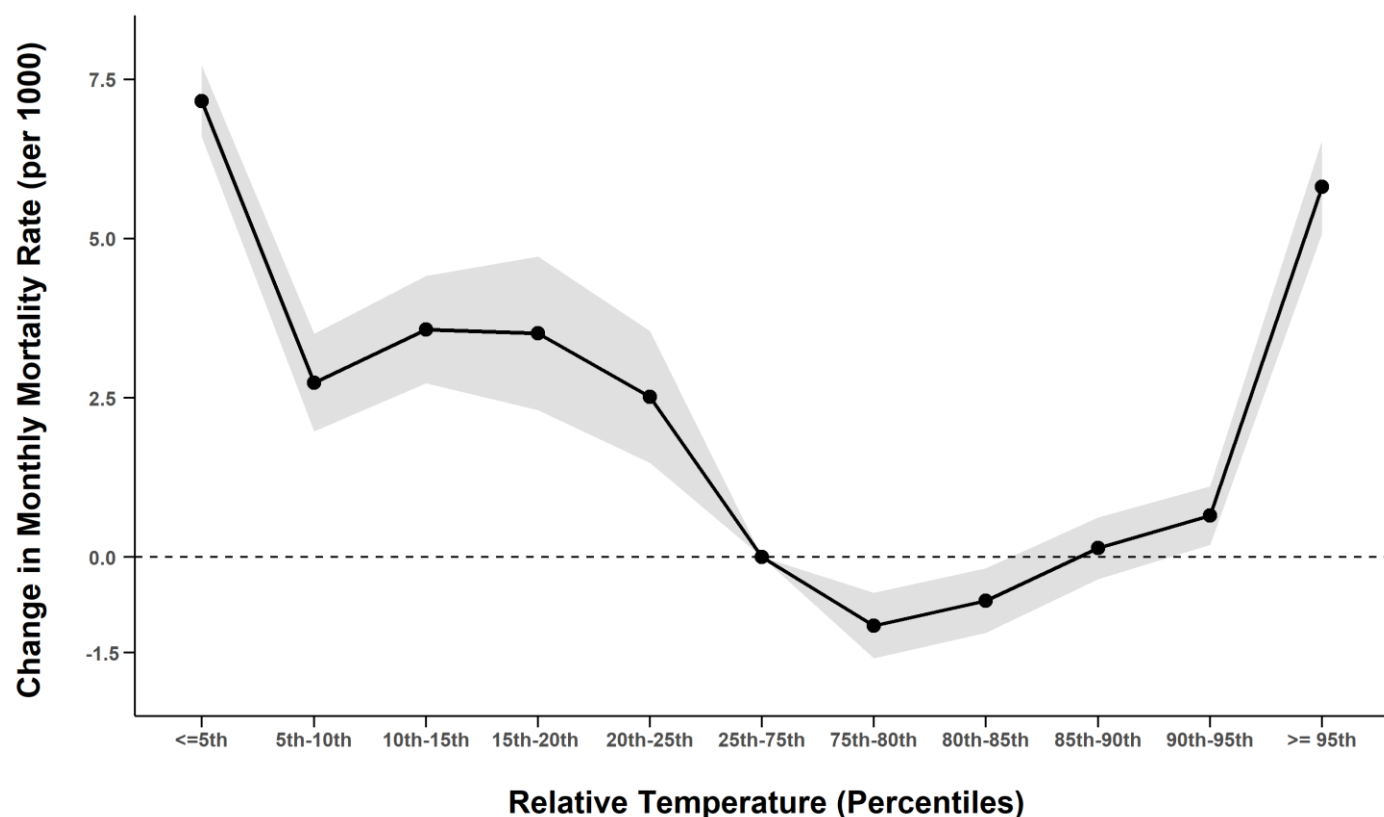


Figure B. 2 Extreme temperatures and mortality in Europe (population aged 65+)

Note: The figure shows estimates obtained by estimating equation (1). Standard errors are clustered at the NUTS3 level. 95% confidence intervals.

3.4.2. Geographical Heterogeneity in Temperature-Related Deaths in Europe

Our geographical heterogeneity analysis quantifies how temperature-related mortality is modified by local factors. In Figure B.3 (we report the coefficients in Supplementary Material Table B.S.3), we first analyze the interaction between the three climatic regions defined by the Köppen-Geiger classification (cool, temperate, and hot regions in panel (a)), then the urbanization level in panel (b), followed by the terciles of GDP per capita panel (c) and the quartiles of $PM_{2.5}$ air pollution in panel (d).

In panel (a), the interaction with climate regions shows that extreme heat is most detrimental for the hottest regions, while for extreme cold, there is no significant difference between hot and cool regions, with all regions exhibiting increases in monthly mortality rate. More

precisely, the results show that an additional day in the 5th percentile increases the monthly mortality rate by 8.3‰ [95% CI: 7.6 – 9.0‰] in cool regions, by 6.5‰ [95% CI: 5.8 – 7.2‰] in temperate regions, and by 7.4‰ [95% CI: 6.1 – 8.8‰] in hot regions, but differences between regions are not statistically significant at the 95% confidence level. Conversely, an additional day in the hottest percentile ($\geq 95^{\text{th}}$) increases the monthly mortality rate by 3.1‰ [95% CI: 2.3 – 3.9‰] in cool regions, by 5.5‰ [95% CI: 4.5 – 6.4‰] in temperate regions, and by 9.7‰ [95% CI: 8.6 – 10.8‰] in hot regions, and differences between cool regions and hot regions show to be significant at the 95% confidence level. This highlights at least two issues. (1) While individuals and infrastructure in historically warm regions are better adapted to elevated temperatures, they may not be able to cope with certain extreme heat events as those observed in the past few decades (Grant et al. 2025; Gualdi and Muttarak 2025). Indeed, according to previous research, the last 10 years have been the hottest on record (Lindsey and Dahlman 2024). (2) Political adaptation plans are lacking or are not enough to fully protect vulnerable individuals (Martínez-Solanas and Basagaña 2019). Thus, although populations in warm regions are more adapted to elevated temperatures, recent temperature extremes still show to affect them heavily (Ballester et al. 2023; Gallo et al. 2024).

Considering urbanity, in panel (b), we do not observe it to determine major disparities in the impact of cold ($\leq 5^{\text{th}}$ percentile), or heat ($\geq 95^{\text{th}}$ percentile) on mortality. Such results are contrary to our expectations, as urban areas are predominantly covered in cement and lack greenery, and were found to be more at risk with heat exposure in previous studies (Buscail et al. 2012; Gabriel and Endlicher 2011, Iungman et al. 2024).

In panel (c), GDP per capita, we observe the effect of heat to be similar across terciles, but cold to determine a larger increase in mortality in poorer regions compared with wealthier ones. More precisely, we observe cold to increase mortality by 9.4‰ [95% CI: 8.7 – 10.1‰] in regions with low GDP, by 6.6‰ [95% CI: 5.9 – 7.3‰] in regions with middle GDP, and by 5.7‰ [95% CI: 4.8 – 6.6‰] in regions with high GDP, with differences between the low and high GDP groups being statistically significant at the 95% confidence level. This result is in line with the literature and our expectations (Berg et al. 2024; López-Bueno et al. 2022).

Finally, the interaction with the PM_{2.5} air pollution in panel (d) shows heat to be more detrimental in areas with the highest level of air pollution (4th quartile) and similarly we observe for cold. Indeed, the literature has shown that air pollution patterns have a compounding effect at both extremely high and extremely low temperatures (De Sario et al. 2013; Denman et al. 2007), which may worsen the health status of older adults (Carder et al. 2008; Kenny et al. 2010). Specifically, in the coldest percentile, the estimated increase in monthly mortality rate per additional day ranges from 5.4‰ [95% CI: 4.3 – 6.5‰] in regions with low PM_{2.5} air pollution levels to 8.6‰ [95% CI: 7.7 – 9.5‰] in regions with high PM_{2.5} levels and the difference between groups is statistically significant at the 95% confidence level. Conversely, the estimated increase in monthly mortality rate per an additional day in the hottest percentile ($\geq 95^{\text{th}}$) ranges from 5.4‰ [95% CI: 3.9 – 6.9‰] in regions with low PM_{2.5} air pollution values, to 7.3‰ [95% CI: 6.4 – 8.2‰] in regions with high PM_{2.5} air pollution values and the difference between groups is statistically significant at the 95% confidence level.

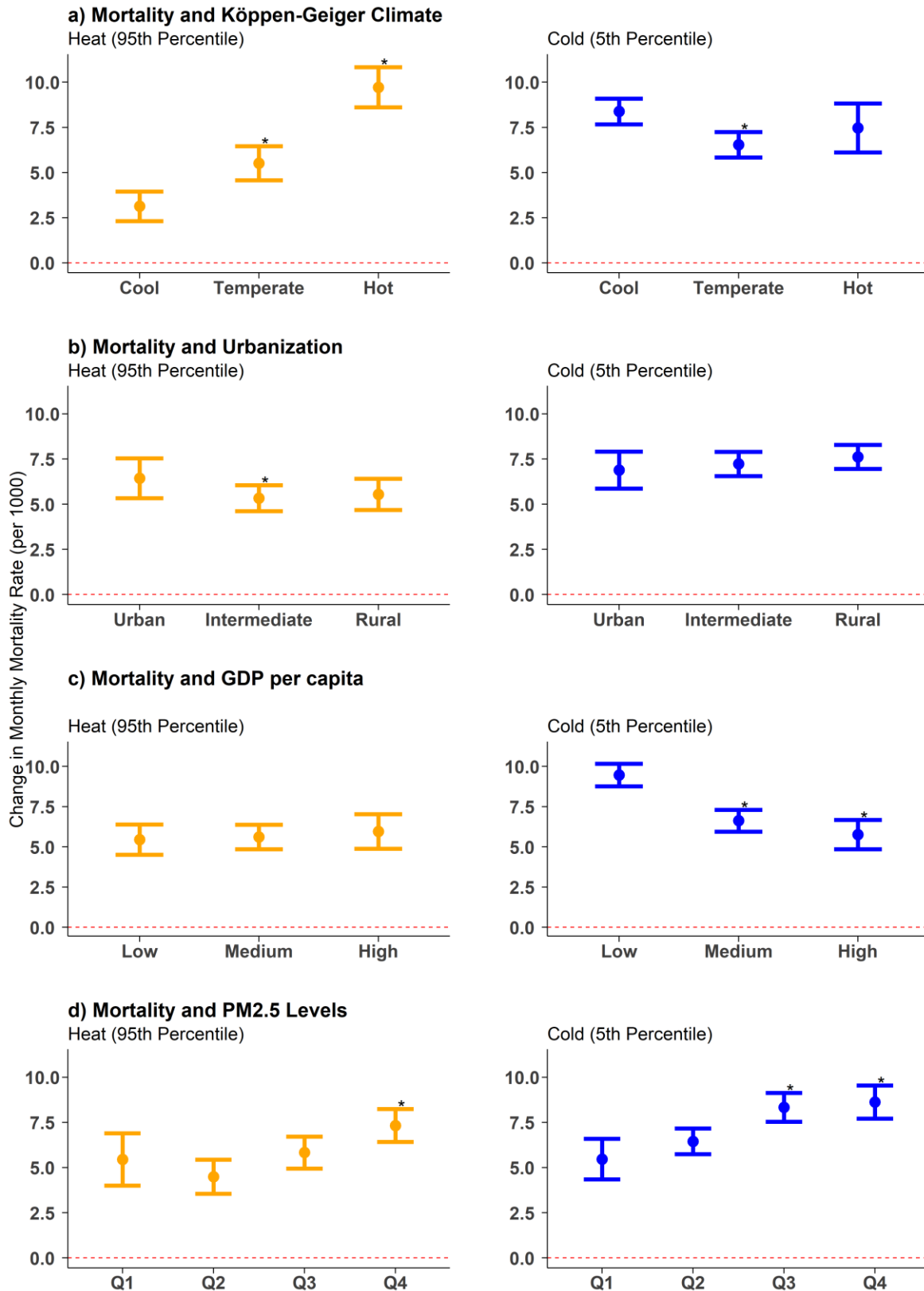


Figure B. 3 Extreme temperatures and mortality in Europe (population aged 65+) by climate region (a), urbanization (b), GDP per capita (c), and PM_{2.5} (µg/m³) air pollution (d)

Note: The figure shows estimates obtained by estimating equation (2) with respective interactions with climate regions (reference category: cool), urbanization patterns (reference category: urban), GDP per capita levels (reference category: low), and PM_{2.5} pollution levels (reference category: low). Q1, Q2, Q3, Q4 refers to quartile categorization, from lower to higher level of PM_{2.5} air pollution. Standard errors are clustered at the NUTS3 level. 95% confidence intervals. * Denotes the category as having a statistically significant ($p < 0.05$) difference relative to the baseline category.

3.5. Robustness checks

A series of robustness checks were performed to test the stability of our results. We replicated our analysis using alternative measures of temperature Figure B.S.3 and Table B.S.4 in the Supplementary Material shows the results of the model based on absolute temperatures, with temperature bins defined as $\leq -6^{\circ}\text{C}$, -6 to -3°C , -3 to 0°C , 0 to 3°C , 3 to 9°C , 9 to 15°C , 15 to 18°C , 18 to 21°C , 21 to 24°C , 24 to 27°C , and $\geq 27^{\circ}\text{C}$ ¹⁸. Overall, we observe a similar curve and consistent findings with the main results in Figure B.2, showing higher monthly mortality rates at both colder and warmer temperatures. However, values are slightly higher when using absolute categorization compared to relative categorization. Specifically, the highest absolute temperatures ($\geq 27^{\circ}\text{C}$) determine an increase of approximately 11.4 deaths per 1,000 older adults [95% CI: 1.04 – 12.5%], while an additional day in the coldest bin ($\leq -6^{\circ}\text{C}$) increases the monthly mortality rate by 9.9 per 1,000 [95% CI: 8.9 – 10.8%].

In Tables B.S.5 and B.S.6, we present the results using temperature bins based on maximum and minimum daily temperatures, which show consistent results to those obtained using average temperatures in our main analysis (Figure B.2). For instance, using maximum temperatures, we show that an additional day in the coldest percentile ($\leq 5^{\text{th}}$) increases the monthly mortality rate by 6.9% [95% CI: 6.0 – 7.7%], while an additional day in the hottest percentile ($\geq 95^{\text{th}}$) increases the monthly mortality rate by 5.1% [95% CI: 4.3 – 6.0%]. Using minimum temperatures, we find that an additional day in the coldest percentile ($\leq 5^{\text{th}}$) increases the monthly mortality rate by 6.2% [95% CI: 5.6 – 6.8%], while an additional day in the hottest percentile ($\geq 95^{\text{th}}$) increases the monthly mortality rate by 4.6% [95% CI: 4.0 – 5.1%]. Heterogeneous effects of extreme temperatures by sex and age could also be expected (Ballester et al. 2023; Folkerts et

¹⁸ These reference bins, respectively, correspond to the following Fahrenheit temperatures: $\leq 21.2^{\circ}\text{F}$, 21.2 to 26.6°F , 26.6 to 32°F , 32 to 37.4°F , 37.4 to 48.2°F , 48.2 to 59°F (reference bin), 59 to 64.4°F , 64.4 to 69.8°F , 69.8 to 75.2°F , 75.2 to 80.6°F , and $\geq 80.6^{\circ}\text{F}$.

al. 2022; Marí-Dell’Olmo et al. 2019). Sex heterogeneities in temperature related deaths remains unclear as some studies have identified women as the most vulnerable both to heat and cold (Folkerts et al. 2022; van Steen et al. 2019), whereas other have identified men at higher risk (Achebak et al. 2019) and other have found no significant differences (Marí-Dell’Olmo et al. 2019) requiring additional investigation (Fouillet et al. 2008). Conversely, the majorities of studies found older people (65+) at disproportionate risk to both heat and cold (Ballester et al. 2023; García-León et al. 2024; Wan et al. 2022), peaking for those over 85 (Masselot et al. 2023). We report in Figure B.S.4 and Table B.S.7 of the Supplementary Material the estimates on sex-specific heterogeneities. We observe cold and heat related mortality to be stratified by sex. More precisely, cold increases the death rate by 8.2‰ [95% CI: 8.0 – 8.5‰] for women and 5.9‰ [95% CI: 5.3 – 6.5‰] for men for extreme cold exposure (<5th percentile), whereas extreme heat (>95th percentile), to increases the monthly death rate by 6.9‰ [95% CI: 6.6 – 7.3‰] for women and 4.5‰ [95% CI: 3.8 – 5.2‰] for men. On age heterogeneity, we provide results in Figure B.S.5 and Table B.S.8 and we confirm the impact of cold and heat to increase linearly with age, with the highest impact observed for individuals aged above 90.

Finally, we replicated the analysis using the balanced panel dataset of countries covering the full period of analysis 2014 to 2023 to test for possible biases arising from certain countries being covered for a more limited period. We report the results in Tables B.S.9 and B.S.10 and Figures B.S.6 and B.S.7 of the Supplementary Material. Here, we observe the direction and significance of the estimates to remain consistent with our main results (Figure B.2-3), particularly with respect to climatic regions, urbanization level, and GDP per capita. For PM_{2.5}, the significance levels are slightly lower, although the overall patterns persist.

3.6. Conclusions

This study found that extreme temperatures, both high and low, significantly increase mortality rates among older adults in Europe, with cold temperatures ($\leq 5^{\text{th}}$ percentile) having a larger effect size compared to hot temperatures ($\geq 95^{\text{th}}$ percentile). The analysis revealed regional differences based on climate, urbanization, GDP per capita, and air pollution levels. Extreme heat is shown to be most harmful in regions categorized by the Köppen-Geiger classification as hot, while extreme cold is detrimental in cool, temperate and hot regions. Urban areas face higher

mortality rates during extreme heat than intermediate areas, while for extreme cold there are no significant differences. Higher GDP per capita is linked to lower cold-related mortality but shows to not attenuate the risks posed by heat. Extreme cold and heat are most detrimental in regions with elevated concentrations of PM_{2.5}, suggesting that poor air quality increases temperature-related health risks. Robustness checks confirmed these trends across various temperature metrics.

While our study offers valuable insights, it is not free from limitations. First, although we observe heterogeneous patterns between regions, we cannot claim that they have a causal moderating impact on the relationship between temperature and mortality, as other confounding factors could be at play. Relatedly, we lacked indicators on factors that are related to adaptation to cold or heat, and that could explain the heterogeneities observed. For instance, we did not have information on the proportion of households that own air conditioning or heating in each of the NUTS3 regions. Consequently, we were limited in our ability to describe the specific mechanisms underlying the heterogeneous patterns that we observed. We also lack data on the preexisting health conditions of the population aged above 65. Additionally, while we leveraged data at the NUTS3 level, i.e., at the most fine-grained geographical unit of analysis at our disposal, we acknowledge that heterogeneities in the impact of temperature on mortality could exist at a more fine-grained neighborhood level.

Future studies could improve our work in a few ways. Testing the specific mechanisms that explain the heterogeneities we observed could be relevant for guiding policies. For this purpose, empirical studies could leverage sudden changes in certain characteristics of a territory to estimate the causal impact of these factors in moderating the impact of temperature on mortality. For instance, policy-driven improvements in air quality could also lead to a decrease in temperature-related deaths. Future data collection efforts are also needed to gather information on the presence of air conditioning and heating technologies across Europe at a fine-grained resolution. In addition, to gain a more comprehensive understanding of regional differences in mortality linked to climate, future studies should expand to incorporate the missing European countries in our dataset such as Germany, Croatia, Slovenia, but also aim to extend the data collection on additional neighboring regions to Europe that are facing rapid warming such as Africa and the Middle East (IPCC 2023b).

To conclude, our findings highlight several areas for interventions aimed at diminishing geographical differences and inequalities in Europe. First, adaptation measures, especially those

targeting vulnerable regions and population subgroups with lower adaptive resources, should be enhanced. Our findings show that hot climates, such as those in the southern European regions, are among the most susceptible areas to heat, exhibiting higher peaks in mortality during hot days. Consequently, heat action plans and support for vulnerable populations such as those aged above 65 are particularly important in these areas to enhance resilience. For instance, examples of such policies are expansion of green spaces and water bodies (Shickman and Rogers 2019; Luo et al. 2024), the improvement of building design and materials (Cabeza et al. 2010, Keushkerian and Shdid 2024), the optimization of infrastructure and medical facilities (Qi et al. 2019; Luo et al. 2024), the promotion of public awareness through educational initiatives (He et al. 2022; Medina-Ramon et al. 2006), and the establishment of cooling centers (Widerynski et al. 2017). Finally, reducing PM_{2.5} concentrations may help diminish temperature-related mortality among older adults. Altogether, these strategies not only address the immediate risks posed by extreme temperatures but also lay the foundation for more equitable and climate-resilient societies across Europe.

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Chapter 4: Projecting Future Temperature-Related Mortality in Europe under Global Climate Change

Projecting Future Temperature-Related Mortality in Europe under Global Climate Change

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Abstract

Ongoing climate change, coupled with population ageing, puts Europe at risk of experiencing a disproportionately large mortality burden. To date, there has been limited work exploring the implications of climate change on mortality outcomes under different Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP), and to our knowledge, no studies have specifically examined how can be impacted differentially by changing in temperature in future. This study examines the effect of future extreme temperatures on mortality of older adults aged ≥ 65 years across 28 European countries at regional level (NUTS2). We use a combination of historical data (2014-2022), climate projections based on RCP and SSP scenarios to describe potential future trajectories of European mortality related to climate change-induced shifts in temperature (2030-2100). A Poisson regression model with fixed effects is employed to establish the baseline temperature–mortality relationships, followed by a counterfactual analysis in the SSP-RCP framework to assess future temperature-related deaths. Our findings reveal significant regional differences in temperature-related mortality across Europe, with an excess death rate projected to decline in Northern Europe but rise in Southern Europe, highlighting regional disparities exacerbated by climate change and different SSP-RCP scenarios.

KEYWORDS Extreme Temperature • Mortality Projection • SSP-RCPs • Europe

4.1. Introduction

Amid ongoing warming, concerns are growing about how extreme temperatures will shape future mortality burdens. (Gasparrini et al., 2017; Huang et al., 2011; Vicedo-Cabrera et al., 2018). Addressing this challenge is widely recognised as essential for the identification of new health risks, socioeconomic, demographic and spatial vulnerabilities, policies intervention, and adaptation strategies (García-León et al., 2024; Lloyd et al., 2023; Masselot et al., 2025; Watts et al., 2015).

Historically cold temperature has accounted for the larger share of temperature-attributable mortality (R. Chen et al., 2018; Zhao et al., 2021). However, the number of heat-stress days is rising, as indicated by the growing count of days on which the daily maximum Universal Thermal Climate Index (UTCI)¹⁹ exceeds heat-stress thresholds (Fiala et al. 2011). This shift is particularly concerning given Europe's aging population. Older adults are more susceptible to extreme temperatures (K. Chen et al., 2024; Shibasaki et al., 2013), and the share of people aged 65 and over in the EU is projected to reach around 30% by 2050 (European Union, 2023). This makes Europe particularly vulnerable to extreme temperatures and raises pressing questions about future mortality trajectories. Research on future temperature-attributable mortality spans diverse datasets, spatial scales, and methodological frameworks. Broadly, the literature clusters in three themes: (1) studies focused on exposure (heat-only, cold-only, or combined); (2) studies quantifying the role of demographic change, especially population ageing; and (3) studies assessing adaptation and policy measures that may reduce vulnerability over time. Evidence consistently indicates that extreme cold events are becoming less frequent in some areas, such as northern Europe, while still exerting substantial health impacts in mid-latitude regions. In contrast, extreme heat events are becoming increasingly common in southern and Mediterranean areas. Previous studies are primarily conducted in urban areas, often neglecting rural regions (Gasparrini et al., 2017; Zhao et al., 2021), and predominantly focus on projecting heat-related mortality, with limited attention to cold-related mortality (Basu, 2009; Hajat et al., 2009; Heiden et al., 2020). Moreover, there are still few studies that integrate SSP framework with RCP scenarios (IPCC, 2023).

¹⁹ The Universal Thermal Climate Index (UTCI) is defined as the physiological comfort of the human body under specific meteorological conditions (Bröde et al., 2012).

Our study aims to understand three key aspects of the future effects of extreme temperatures on older mortality. We start from the present European baseline, providing a reference point for the relationship between extreme temperatures and mortality among people aged 65 and above. Secondly, we assess the direction and extent to which the temperature-related deaths among older adults are expected to change across the continent by the end of the century (2030–2099) under different SSP-RCP scenarios. Third we discuss the broader demographic consequences of these future deaths providing valuable insights into the evolving risks of extreme temperatures.

To achieve this, we first model the relationship between temperature and mortality in Europe using a combination of historical population records, mortality data, and meteorological information. The historical data cover the period from 2014 to 2022 at the NUTS2 level for 28 European countries, encompassing both rural and urban areas. We then project future temperatures for the period 2030–2099 and estimate excess death rates (per 100.000) at the regional level. We incorporate RCP scenarios to account for future changes in emissions, in combination with General Circulation Models (GCMs) to capture future climate variables.

The remainder of the chapter is structured as follows. It begins by outlining the background and the framework of future scenarios, followed by a description of the data and methods employed. The subsequent sections present the results, which are then discussed. Finally, the chapter concludes with a summary of the main findings and their implications.

4.2. Background

4.2.1. Literature in the European Context

Average global temperatures continue to rise due to anthropogenic climate change (IPCC, 2023). The impact of future warming temperature on human mortality is still unclear, and many questions persist regarding how mortality patterns may evolve under global climate change. Literature is investigating whether cold-related mortality will remain dominant, be surpassed by heat-related mortality, or whether both will lead to increasingly severe mortality peaks. These outcomes depend not only on the nature of climatic hazards but also on a range of factors, including the geographical location, demographic and socioeconomic vulnerabilities, adaptive capacity, and the specific future scenarios considered (Martinez-Solanas et al., 2021; Rai et al., 2022; de

Schrijver et al., 2023). Altogether, these elements contribute to the considerable complexity of projecting future temperature-related mortality.

Numerous studies in the literature have approached this issue from different perspectives, using a variety of climate measures, datasets, geographical resolution, and methodological approaches. The literature investigating future temperature-related mortality can generally be divided into studies focusing on cold, heat, or both types of temperature exposure, which may be analysed jointly or separately. Studies investigating exclusively the heat-related mortality are predominantly concentrated in urban areas, given their higher vulnerability to heatwaves (Baccini et al., 2011; Ignjacevic et al., 2024; Wu et al., 2025). A high level of data granularity is frequently available for urban settings, making them particularly attractive for researchers studying both future cold- and heat-related mortality (Masselot et al., 2025). Other studies investigate the future effects of temperature on mortality across both urban and non-urban settings, with some focusing exclusively on heat (Relvas et al., 2025; Kendrovski et al., 2017), while others include both future cold- and heat-related mortality (Fonseca-Rodríguez et al. 2023; García-León et al., 2024; Masselot et al., 2025; Rodrigues & Carvalho, 2025).

Geographical location plays a key role in determining the impact of present and future temperature-related mortality, as it shapes the level of heat and cold hazard experienced. Studies consistently show that cold events are projected to become less severe and less frequent, above all in northern European latitudes, while extreme heat events are no longer described as rare events in the Mediterranean region (World Weather Attribution, 2024a). A recent assessment by Copernicus reports that the number of winter days classified as ‘extreme cold stress’ in northern Europe has declined from around 4% in the 1980s to about 2% in the last decade and this trend is expected to continue in the coming decades (Copernicus, 2021). However, cold temperatures are still projected to have more detrimental effect, particularly across European mid-latitude regions, whereas heat-related mortality is expected to rise substantially, especially among vulnerable populations, due to the combination of more frequent heatwaves and limited adaptive capacity in many regions (Lee et al., 2025; World Weather Attribution, 2021, 2024b).

Other studies have investigated the role of demographic change in temperature extremes future deaths. These studies highlight that in rapidly aging regions, the risk of dying for being exposed to extreme temperatures is expected to increase substantially by 2050 and the end of the century

(García-León et al., 2024; Lee & Kim, 2016). On the other end, other literature focus on the role of adaptation measures and policy interventions. They show the modifying effect the temperature–mortality relationship over time (Ballester et al. 2011; Rai et al. 2022; Wu et al. 2025). A study conducted by Vicedo-Cabrera and colleagues (2018) show that heat-related vulnerability declined faster than the rate of warming across most countries, indicating effective adaptation and increased population resilience to rising temperatures, while for the cold the behaviour remains more uncertain.

4.2.2. Scenario Framework, Methodological Approaches and Climate Modelling

Concerning the methodological approaches used to project future temperature-related mortality, they vary considerably depending on the research objectives, the variables involved, and the disciplinary perspective of the study. In environmental epidemiology, the most common approach apply exposure–response risk functions to simulated future exposure distributions generated by climate models under specific emission scenarios (García-León et al., 2024; Gasparrini et al., 2017; Martínez-Solanas et al., 2021; Vicedo-Cabrera et al., 2019). Conversely, approaches more frequently used in environmental economics and social sciences, focus primarily on establishing the causal relationship between temperature and mortality (Kathana et al., 2024; Honda et al., 2013; Hsiang, 2016; Risto Conte Keivabu et al., 2024). In these cases, projections often follow the so-called counterfactual projection method, which consists of estimating counterfactual outcomes through regression models, subtracting these counterfactuals from the observed data to obtain attributable anomalies, and then comparing these anomalies across scenarios to quantify temperature-related mortality under varying levels of anthropogenic climate change (Mahoney et al., 2017).

To understand how the future climate will unfold, key tools for predicting climate at global and regional scales are the so-called General Circulation Models (GCMs). GCMs are complex numerical models which account for physical processes of the atmosphere, oceans, and land to simulate response of global climate to the increasing greenhouse gas emission (IPCC, 2013). Climate modelling describes possible future climate outcomes, thru the greenhouse gas concentration trajectories explained by the Representative Concentration Pathways (RCP) (Moss et al., 2010). Some studies based their analyses using the RCPs (García-León et al., 2021). Other studies follow the narratives SSPs, which are described by a set of five alternative scenarios of

future societal development (O'Neill et al., 2017; Striessnig et al., 2019). The first SSP scenario “SSP1 (Sustainability)” envisions an optimistic path to sustainability, with improvements in both environmental and human well-being. The second scenarios “SSP2 (Middle of the Road)” represents the baseline scenario, where historical trends continue, posing moderate challenges for adaptation and mitigation. The third scenario “SSP3 (Regional Rivalry)” predicts slow economic growth, rising inequality, and weak institutions, hindering efforts to address environmental issues. The fourth scenario “SSP4 (Inequality)” highlights different trajectories across and within countries, where environmental policies are dominated by elites, resulting in uneven development and limited adaptive capacity for vulnerable populations. The fifth scenario “SSP5 (Fossil-Fuelled Development)” sees economic growth driven by fossil fuels achieving human development goals but facing high mitigation challenges due to a high fossil fuel dependency.

When exploring future population dynamics, the RCPs and the Shared Socioeconomic Pathways scenarios (SSPs) can be integrated to form the SSP-RCP scenarios. The SSP-RCP (‘SSPX-Y’) scenarios are used in the last IPCC assessment report (IPCC, 2023) and combine baseline SSPs with RCP radiative forcing levels to impose global warming targets, where ‘X’ refers to the baseline SSP scenario and ‘Y’ refers to the RCP radiative forcing levels. For example, the SSP components of the SSP1-2.6 SSP-RCP scenario envisions an optimistic path to sustainability, with improvements in both environmental and human well-being (“SSP1 - Sustainability”), and the RCP components impose a 2.6 W m^{-2} level of radiative forcing in 2100, which corresponds with a related level of global warming (IPCC, 2023).

The SSP-RCP framework used in this study allows testing of different combinations of socioeconomic development and emissions, producing a range of quantitative projections:

- SSP1-2.6 ($\sim 1.5^\circ\text{C}$ warming): A green-growth scenario with low emissions and sustainable socio-economic practices.
- SSP2-4.5 ($\sim 2.7^\circ\text{C}$ warming): A “middle-of-the-road” scenario with moderate emissions, assuming current global development trends continue with some mitigation.
- SSP3-7.0 ($\sim 3^\circ\text{C}$ warming): A high-emission scenario characterized by fragmentation and inequality.
- SSP5-8.5 ($\sim 4.9^\circ\text{C}$ warming): A high-emission, fossil-fuel-intensive pathway with limited climate policies, leading to extreme warming.

Recent studies adopting combined SSP–RCP frameworks incorporate both emission trajectories and socioeconomic development patterns, following IPCC recommendations (Chen et al., 2024; Hajat et al., 2023; Masselot et al., 2025; Rai et al., 2022).

While the literature on temperature-related mortality projections is extensive and methodologically diverse, to our knowledge, few studies have applied an econometric approach with a counterfactual fixed-effects analysis to project temperature-related mortality across Europe. This thesis provides a baseline estimate of the potential impacts of future temperature variations on mortality without adjusting for future adaptation and demographic change. The analysis includes both urban and rural regions, offering a comprehensive understanding of spatial heterogeneity in temperature–mortality relationships. All four SSP-RCP scenarios are considered, covering a relevant spectrum of climate futures, which is particularly useful for risk assessments and policy discussions. Given identified research gaps, the focus is specifically on older adults aged 65 years and above, as they are the most vulnerable to temperature extremes. The study is conducted at a fine spatial resolution (NUTS2), incorporating daily temperature variations for both heat and cold exposures.

4.3. Data

4.3.1. Mortality and Population Data

We collected observed weekly mortality data by age group, sex, and NUTS2 from Eurostat. As population exposures, we gathered the annual population data from Eurostat, available from the Eurostat by age group, sex, and NUTS2. We compiled the file at a monthly level covering the historical period 2014 – 2022. We computed monthly mortality rates as the ratio of death counts to monthly population exposures.

4.3.2. Current and Projected Meteorological Data

For the daily meteorological information, we used the E-OBS from Copernicus Climate Data Store (CDS) with a version 29.0e gridded at $0.1^\circ \times 0.1^\circ$ for the period 2014 to 2022 (Copernicus Climate Change Service, 2024; Cornes et al., 2018). As control variables we utilized the solar radiation, relative humidity, precipitation, and wind speed recorded in each NUTS2 region. These listed variables are widely found to significantly alter people’s thermal sensations, comfort level,

and thermoregulatory efforts (Fang et al. 2004; Li et al. 2024; Yang et al. 2024). We used the temperature data to compute the average number of days in each temperature range. Section 4.4 of the Research Methods describes how the average number of days in each temperature range was calculated.

For the projected daily temperatures, we used the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) dataset, which provides a global downscaled climate scenario (NCCS, 2024a). The NEX-GDDP-CMIP6 is derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Intercomparison Project Phase 6 (CMIP6) and across all four “Tier 1” greenhouse gas emissions scenarios known as Shared Socioeconomic Pathways (SSPs) (NCCS, 2024b). Using thresholds fixed to the current period, we calculated the monthly mean number of projected extreme-temperature days across four climate change scenarios: RCP2.6, RCP4.5, RCP7.0 and RCP8.5.

4.4. Methods

To estimate the overall relationship between temperature and human mortality in Europe, a Poisson regression is employed with region by month, and year by month Fixed Effects (FE). The equation can be described as follows:

$$\ln[E(Y_{mrag})] = \ln(E_{mrag}) + \sum_j \theta_j TEMP_{mr}^j + \mathbf{X}_{mr}\boldsymbol{\beta} + \alpha_{mr} + \delta_m \quad (\text{Equation 1})$$

where Y_{mrag} is the monthly counts of deaths in month-year m , NUTS2 region r , age groups a , and gender group g . E_{mrag} is an offset term capturing the exposure to death risk in the NUTS2 region r month-year m , age groups a , and gender group g . $TEMP_{mr}^j$ captures the number of days in temperature range j , in month-year m and NUTS2 region r ; the coefficients θ_j is the effect on mortality of exchanging one day in the comfort zone for a day in the j -th bin; the covariates $\mathbf{X}_{rm}$ are the control variables with associated coefficients $\boldsymbol{\beta}$; α_{rm} captures NUTS2 region by month fixed effects; δ_m account for year by month fixed effects. The standard errors are clustered at the NUTS2 level.

Daily average temperature bins were created using absolute temperature distribution for each NUTS2 unit over the study period. We counted the number of days per month in each NUTS2 that fell within a temperature range. Eleven ranges were established: ≤ -6 , $(-6, -3]$, $(-3, 0]$, $(0, 3]$, $(3, 9]$, $(9, 15)$ (comfort zone, excluded from analysis), $[15, 18)$, $[18, 21)$, $[21, 24)$, $[24, 27)$, $\geq 27^\circ\text{C}$.

The temperature–mortality relationship among older adults is estimated to project excess deaths under future climate scenarios. We perform a counterfactual analysis by replacing observed temperature exposures with projected temperature distributions for future 10-year periods (2030–2039, 2040–2049, to the end of the 21st century) under different SSP–RCP scenarios, while holding all other covariates and estimated coefficients fixed.

Let $\hat{Y}_{mrag}$ denote the fitted monthly deaths from equation (3), and $\tilde{Y}_{mrag}$ denote the counterfactual deaths obtained by replacing the temperature covariate $TEMP_{rm}^j$ of the historical period 2014–2022 with the projected future temperature exposures (keeping all estimated coefficients $\theta_j, \beta, \alpha_{rm}, \delta_m$ fixed). Excess deaths are given by $\hat{d}_{mrag} = \tilde{Y}_{mrag} - \hat{Y}_{mrag}$, and the excess mortality rate is computed as $\frac{\hat{d}_{mrag}}{Emrag} \times 100,000$ representing the number of excess deaths per 100,000 older adults.

To derive confidence intervals for projected excess mortality, we employ a simulation approach that accounts for regression uncertainty. Specifically, we simulate death counts from a Poisson distribution with expected value equal to $\hat{Y}_{mrag}$. Using this new set of simulated deaths, we refit the same model specification (equation 3) and compute excess mortality under the counterfactual temperature scenario. Repeating this process 100 times (Monte Carlo iterations) generates 100 simulations of excess mortality that incorporate coefficient uncertainty. 95% confidence intervals are derived from the empirical percentiles (2.5th and 97.5th) of these simulations.

4.5. Results

4.5.1 Future temperature related deaths and regional disparities

The projected change in temperature-related mortality rates vary considerably by location. Figure C.1 shows the excess death rates (per 100.000) across NUTS2 European regions under the

four climate and socio-economic scenarios. The map highlights substantial regional differences in projected excess death rates related to temperatures. The greatest reduction in temperature-related mortality is projected for Northern Europe, with Finland experiencing decreases of 6.21 and 7.85 excess deaths per 100,000 older adults under SSP1-2.6 and SSP2-4.5, respectively, and northern Sweden showing an even larger reduction of 11.71 and 13.75 deaths per 100,000 under SSP3-7.0 and SSP5-8.5 scenarios. In contrast, Southern Europe faces the highest increase in temperature-related mortality, particularly in Portugal, where excess death rates rise by 9.55 under SSP2-4.5 and 14.26 per 100,000 under SSP5-8.5, and in Italy with an increase in excess death ratios of 10.73 under SSP1-2.6, and 13.05 under SSP3-7.0 scenarios.

Figure C.2 extends the historical mortality series into the future (2030–2099), assuming stable population dynamics and considering all the four SSP-RCP scenarios. The projections reveal distinct patterns for the scenarios:

- Under SSP1-2.7, excess death rates decrease and remain stable around zero, reflecting a mortality level like that experienced in historical years.
- Under SSP2-4.5, excess death rates initially decline until reaching a minimum of 0.002 per 100,000 in the period 2050–2059. However, after this point, mortality rates gradually rise, peaking at 1.585 per 100,000 by the end of the century.
- Under SSP3-7.0, excess mortality follows an increasing trend, reaching its peak of 3 per 100,000 in 2080–2089, before declining by the end of the century.
- Under SSP5-8.5, excess mortality follows a continuously increasing trend, reaching its highest value of 4.72 per 100,000 by the end of the century.

A discussion of these results follows in the next section.

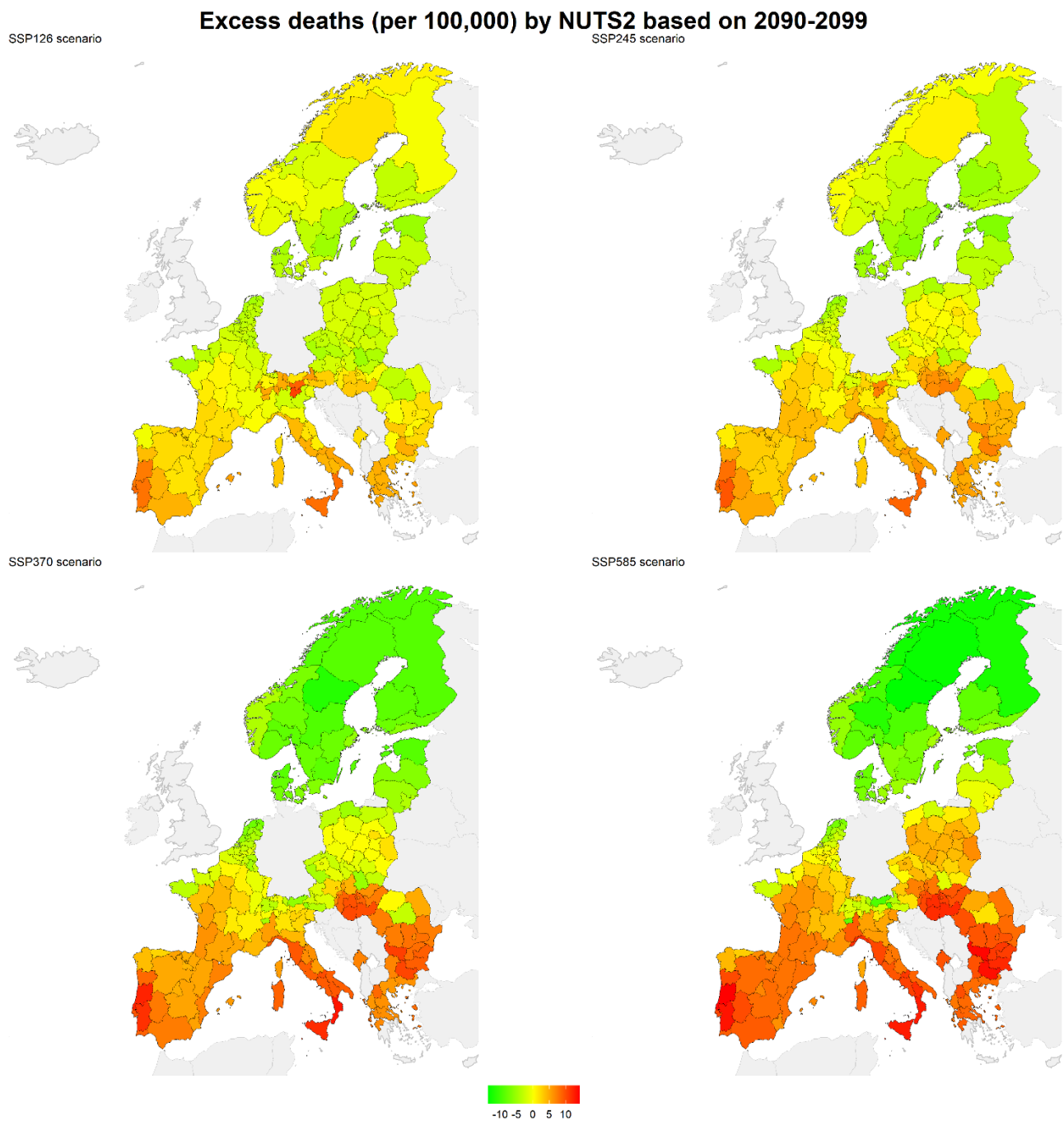


Figure C. 1 Excess death rates (per 100,000) across NUTS2 European regions under different SSP-RCP scenarios at the end of the century (2090–2099).

Note: The excess death rates range from -7.66 to +10 under SSP2-4.5 and from -13.98 to +15.22 under SSP5-8.5.

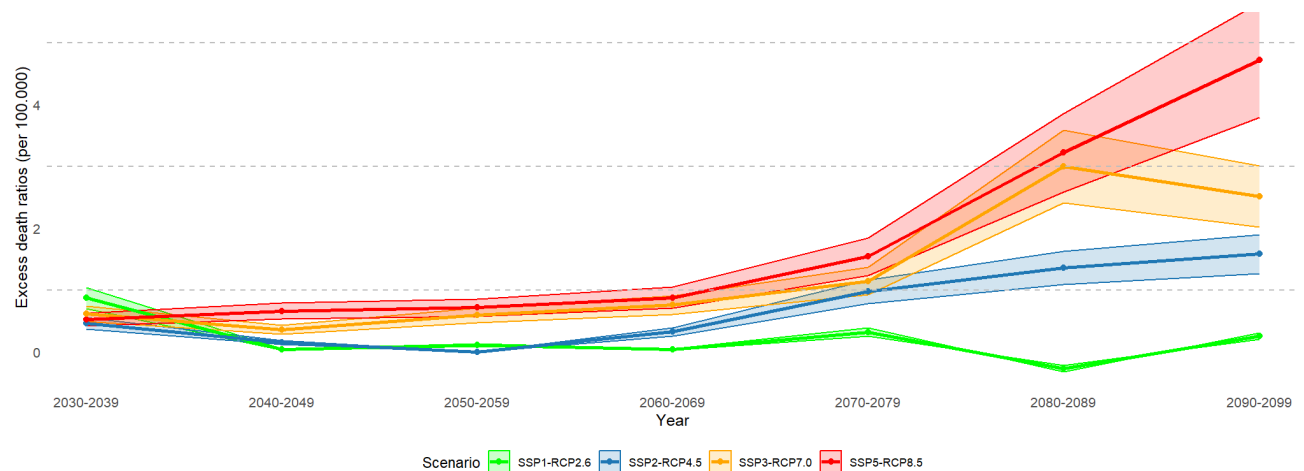


Figure C. 2 Excess death rates (per 100,000) if temperatures in 2014-2022 were as high as the end-century levels projected in the SSP-RCP scenarios

4.6. Discussion

Regional differences highlighted in Figure C.1 emphasize that under different emission and socio-economic scenarios, climate change can exacerbate internal disparities across Europe. While populations and infrastructure in historically warm regions are generally better adapted to high temperatures, Southern Europe appears insufficiently prepared for the unprecedented extreme heat events projected under different SSP-RCP scenarios (Marí-Dell’Olmo et al., 2019; Martínez-Solanas et al., 2022). Indeed, several studies predict a decline in cold-related deaths particularly at higher latitudes, such as in Northern Europe, and an increase in heat-related deaths particularly at lower latitudes (Carleton et al., 2022; Sarofilm et al., 2016; Seltenrich, 2015). The findings suggest a spatial redistribution of temperature-related mortality rather than a simple seasonal displacement within the same populations. Projected mortality declines in Northern Europe are accompanied by increases in Southern Europe, indicating a geographical shift in the burden of temperature-related deaths. However, the direct physiological effects of extreme temperatures on older adult mortality represents only one dimension of climate change’s total health burden. Many other outcomes exhibit temperature–response relationships that differ markedly from the classic U-shaped mortality curve, and do not appear to benefit from reduced cold exposure.

The pattern described in Figure C.2 highlights that under the SSP2-RCP4.5 emission scenario, we observe a reduction in temperature-attributable mortality during the first half of the century,

primarily because fewer deadly cold days lower cold-related mortality. In some regions, this decline initially offsets heat-related deaths, creating a temporary benefit before mortality rates begin to rise from the mid-2050s onward, increasingly rapidly. SSP1-RCP2.6 yields the smallest projected rise in excess mortality, staying close to the historical baseline. In contrast, under the SSP3-RCP7.0 and SSP5-RCP8.5 scenarios, the overall mortality effect follows a consistently increasing trend (Carleton et al. 2022).

Our findings raise several considerations. First, we have to consider that the calculation of the future excess death rates per 100,000 is performed as the difference between (i) the number of deaths that would have occurred if temperatures had remained at the levels observed during the historical period (2014–2022), and (ii) the deaths projected under different socio-economic and emissions scenarios. Since these differential references a historical period (2014–2022) during which climate change has already occurred and has already produced some consequences on human health and wellbeing, the starting point already reflects relatively high temperature-attributable mortality. On the other hand, this approach has the advantage of grounding projections in present conditions, thereby showing how impacts may evolve in the future starting from today's climate reality.

The analyses of future temperature-related mortality in European regions highlight several converging concerns. First, the projected increased in heat-related mortality is driven by the intensification of heat extremes. This exacerbates physiological stress and elevates mortality risk, particularly among vulnerable populations. Second, there is an uneven spatial distribution of temperature-mortality effects across the region. In fact, some areas, such as Southern Europe, are negatively impacted, whereas Northern Europe experiences comparatively lower impacts. Thirdly, substantial within and cross-country heterogeneities in social, economic, demographic, and climatic factors further shape vulnerability and resilience. Differences in age structure, socioeconomic status, access to healthcare, housing quality, and adaptive capacity can amplify or mitigate the health burden of heat exposure, resulting in complex, population-specific outcomes (Benmarhnia et al., 2015; García-León et al., 2024; Martínez-Solanas et al., 2021; Masselot et al., 2025; Relvas et al., 2025; Smętkowski, 2013). Collectively, these factors must be considered, as they may not only amplify existing inequalities but also exacerbate temperature–mortality

disparities between and within countries and population subgroups (Balakrishnan et al., 2022; Guan et al., 2021)

Given our results on projected changes in temperature-related mortality, an open discussion on broader demographic implications that could reshape population structures across Europe is needed. In Southern Europe, population ageing amplifies vulnerability to extreme heat, leading to higher heat-attributable mortality (Carleton et al., 2022; Martínez-Solanas et al., 2021). This shift could strain healthcare systems, social services, and pension schemes, particularly in countries with limited adaptive capacity. Selective mortality could reduce the size of the older population in the most affected regions, paradoxically slightly lowering old-age dependency ratios in the short term, but at the cost of increased health and social vulnerabilities among survivors (Benmarhnia et al., 2015; Carleton et al., 2022). Conversely, reductions in cold-related deaths in Northern Europe may partially offset these pressures but are unlikely to fully counterbalance the long-term demographic impacts of heat extremes. Such reductions may allow a larger proportion of older adults to survive, increasing the old-age dependency ratio and placing additional long-term demands on healthcare and social support systems (García-León et al., 2024; Martínez-Solanas et al., 2021). These results raise the question of whether anthropogenic climate change will produce net health benefits for European populations. The broader evidence base points in the opposite direction. First, rising temperatures could enable the spread of disease vectors into new regions, as well as alter pathogen circulation and increase the likelihood of emerging viruses and bacteria (Parsons et al. 2025). Second, many other health outcomes exhibit temperature-response relationships that differ fundamentally from the U-shaped mortality curve, and the deterioration in other health indicators may translate into higher mortality risks over time. For outcomes such as acute care utilization, primary care demand, pregnancy loss, neonatal health, psychiatric conditions, and sleep quality, the continued warming is likely to generate net health deterioration, as heat-related harms accumulate without compensatory gains from reduced cold exposure, given that low temperatures appear to exert limited adverse effects on these indicators. Climate change may also compromise agricultural productivity and alter nutritional quality of food crops, with downstream consequences for population health and mortality.

Moreover, areas with higher socio-economic vulnerability may experience compounded health, labour, and economic consequences (Benmarhnia et al., 2015; García-León et al., 2024).

These projections highlight that climate-driven mortality is both a public health concern and a critical demographic challenge, potentially shaping age structure, dependency ratios, and long-term societal resilience across Europe. The uneven spatial distribution of these effects underscores how climate-induced mortality could exacerbate demographic imbalances, amplifying regional inequalities in labour force participation, public service demand, and social resilience, while emphasizing the urgent need for targeted adaptation, health interventions tailored to local population vulnerabilities, and for equitable climate mitigation strategies to reduce intergenerational and societal disparities in future health outcomes (Grant et al., 2025).

4.7. Conclusion

This study finds that the change in temperature-related mortality rates is projected to vary considerably across subnational regions in Europe and SSP-RCP scenarios. Specifically, the change in temperature-related mortality rates is projected to decrease in Northern Europe, particularly Finland and northern Sweden, while increasing in Southern Europe, especially Portugal and Italy. Furthermore, projections through 2030–2099 indicate that under low-emission scenarios (SSP1-2.6 and SSP2-4.5), excess death rates remain low or even temporarily decrease, whereas in high-emission scenarios (SSP3-7.0 and SSP5-8.5) mortality continues to rise. Overall, these findings highlight significant regional disparities driven by both climatic extremes and socio-economic factors, suggesting that vulnerable populations in Southern Europe will bear the greatest burden of future temperature-related mortality.

This study is not free from limitations. First, the present analysis focuses on direct associations between temperature and mortality. However, climate change may also influence mortality through indirect and delayed pathways that fall outside the scope of this study. Second, this analysis does not account for demographic changes in the future population and is based on the population structure of the historical reference period. Moreover, the assumption of no adaptation could result in either underestimation or overestimation of impacts. Additionally, we do not consider potential changes in the Atlantic Meridional Overturning Circulation (AMOC). Data availability is another limitation, as some European regions such as lack complete death counts. Furthermore, model confidence intervals could be improved by integrating a broader range of temperature projection models.

These findings also point to new important questions. First, the results raise the question of how climate effects may impact future populations, particularly how older adults' mortality due to extreme temperatures could influence the structure and composition of the population over time. Second, deaths among older adults may be reallocated across seasons (e.g., fewer in winter, more in summer). The possibility of temporal displacement of deaths across seasons warrants further investigation. Testing for such seasonal displacement requires monthly, not annual, analyses. Third, future analyses could examine age subgroups in greater detail, such as <5, 5–65, and 65–75 years, but also very old categories ≥ 90 years and centenarians. This would allow exploration of longevity under prolonged exposure to high temperatures, and whether countries historically characterized by high proportions of centenarians may experience shifts or changes. Analyses stratified by sex would also allow investigation of gender differentials in reaching centenarian ages. Furthermore, life expectancy itself may be affected by changing temperature-related mortality, a question deserving specific investigation. Ultimately, the role of adaptation should be considered. Although findings in the literature may suggest that adaptation could have only limited effects (Vicedo-Cabrera et al., 2018), progressively more severe warming is likely to encounter limits to adaptation - physiological, infrastructural, and socioeconomic - making the scale and distribution of residual mortality risk a priority for further study.

This study contributes to a growing body of research on the future impacts of extreme temperatures on human health by examining how warming driven by anthropogenic climate change will shape future mortality patterns in Europe, considering geographical heterogeneity at the subnational level by different climate scenarios.

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Chapter 5: Conclusion

5.1. Main contributions & Findings

The central focus of this dissertation is to provide a comprehensive study of climate-related mortality. The analysis begins with a systematic review of scientific studies in English conducted from 1985 up to April 2025, followed by an empirical analysis of present-day temperature-related mortality among older adults in Europe (from 2014 to 2023), and concludes with a forward-looking study projecting potential future temperature-related deaths across Europe (from 2030 to 2100) under different warming scenarios. In this way, the dissertation traces mortality patterns associated with extreme weather events worldwide across temporal and geographic scales, following a coherent thread from past to present and future. A further central focus, which connects all chapters, is the investigation of interactions among demographic, geographic, and socioeconomic factors under climate change. Specifically, the thesis contributes to:

- (1) Synthesizing the evidence from the existing literature on climate-related mortality using systematic review, examining determinants of vulnerability, and providing a set of foundational assumptions that can inform future mortality and population projections.
- (2) Assessing the heterogeneity of temperature-related mortality across European regions by analysing geographic, demographic, and socioeconomic variations, and identifying the direction and magnitude of the interactions among these factors.
- (3) Evaluating how temperature variability in frequency and severity may alter mortality patterns in the coming decades throughout the end of the century in Europe under different SSP-RCP scenarios.

The global systematic literature review on socio-demographic heterogeneities in climate-related mortality, is presented in the second chapter of the thesis. This analysis identified current knowledge gaps and limitations in the existing research, clarified how demographic, social, and economic inequalities, as well as geographical and climatic factors, shape vulnerability, and provided assumptions for future studies. The results highlight some gaps in literature and reveal

notable patterns. First, research on natural hazard-related mortality (floods, storms, droughts) is limited compared with studies on temperature-related mortality. Second, several geographical areas remain largely unexplored, including the African continent, West Asia, and the majority of low-income countries. This disparity is particularly striking given that these populations have contributed substantially less to historical and current global CO₂ emissions than Europe and other high-income nations (Davis and Caldeira, 2010; Friedlingstein et al., 2023). Third, mortality burdens vary across regions and climate zones: cold-related deaths dominate in East Asia and parts of Europe, while heat-related mortality is most pronounced in Southern Europe and temperate regions, and is expected to increase sharply with ongoing global warming. Additionally, certain population subgroups, such as females, older adults, and individuals with lower education levels, are found to be at higher risk during extreme temperatures and natural hazards. Finally, several studies fail to adequately account for demographic and socioeconomic vulnerabilities.

The third chapter of the thesis presents an empirical analysis of temperature-related mortality among older adults in 28 European countries. The objective was to assess how extreme temperatures affect mortality among individuals aged 65 and older, and how geographic heterogeneity within and across countries in Europe shapes these outcomes, investigating the role of local climate conditions, air pollution (PM_{2.5}), urbanization, and GDP per capita. Results indicate that both cold and heat increase mortality, with cold having a stronger overall effect. Importantly, we underline how geographical differences in temperature are influenced by factors such as the severity of heatwaves or cold spells, urbanization level, GDP per capita. We found that extreme heat is most harmful in the warmest European regions, while higher GDP per capita is associated with lower cold-related mortality. Furthermore, mortality risks from both cold and heat are amplified by elevated air pollution, whereas urbanicity does not significantly affect temperature-related deaths.

The fourth chapter of the dissertation presents projections of future temperature-related mortality under different RCP–SSP scenarios in Europe. It investigates how variations in temperature frequency and severity may alter mortality patterns across European subnational regions under different SSP–RCP scenarios until the end of the century. Results suggest that climate change could exacerbate existing inequalities between territories and populations. It indicates populations in Southern Europe as the one who bear the heaviest burden of future

temperature-related mortality primarily due to substantial increase in warmer days, while Northern Europe is expected to experience reductions in temperature-related mortality due to a decline in extreme cold days. The results reveal a geographical redistribution of temperature-related mortality, with projected declines in Northern Europe accompanied by increasing burdens in Southern regions. However, climate change is also expected to affect population health through additional pathways – including the spread of infectious diseases, disruptions to agricultural systems - those points to a more concerning trajectory.

Overall, all three studies emphasize that climate-related mortality is not uniformly distributed but shaped by underlying demographic, socioeconomic, and geographic vulnerabilities. The literature review identifies global evidence, the European empirical study confirms these patterns by showing that temperature-related mortality among older adults varies with economic conditions and environmental exposures such as air pollution, the projection study suggest that existing inequalities will likely widen, with Southern Europe bearing the greatest burden.

5.2. Limitations & Future Research

This thesis is not free from limitations. The evidence from the systematic literature review demonstrates that climate-related mortality is influenced by multiple interacting factors such as demographic, socioeconomic, geographic, and climatic factors. However, the spatial coverage of the included studies both in terms of geographic location and climate zones was limited. Most available evidence is concentrated in high- and middle-income countries, particularly in Asia, Europe, and North America, while low-income countries, particularly those in Africa are critically underrepresented. This imbalance may bias the global evidence base and limit the generalizability of findings. Additionally, the review included only peer-reviewed articles published in English, which may have introduced language and publication bias by excluding relevant studies in other languages. Notably, no studies were identified in Polar climates for temperature-related mortality or in Arid climates for natural hazards. Finally, the review did not include a quantitative meta-analysis, which restricts the ability to derive pooled effect estimates or to quantify overall effect modification of mortality risks associated with extreme temperatures and natural hazards.

The second paper, reported in Chapter III, on geographical heterogeneity in temperature-related mortality, revealed varying patterns across regions but cannot infer a causal moderating

effect of regional characteristics. Unobserved confounding factors may contribute to these differences, such variables related to population adaptation to extreme temperatures as the prevalence of air conditioning or heating within households in the NUTS3 regions, which could help explain the observed variability. Furthermore, information on pre-existing health conditions among individuals aged 65 and older was unavailable, preventing adjustment for important vulnerability factors. While our study utilized data at the NUTS3 level, which is the most detailed geographic unit available, heterogeneities in temperature impacts may exist at finer scales, such as neighbourhoods, which cannot be captured in this analysis. Last but not least, complete death records are unavailable for certain European regions.

The limitations of the projection paper reported in Chapter IV, on future temperature-related mortality under global climate change, stem from not accounting for future demographic changes and potential adaptation measures, which could lead to either under- or overestimation of the impacts. Confidence intervals for our models could also be strengthened by incorporating a broader range of temperature projections. While older adults remain particularly vulnerable, these projections are limited by their reliance on annual summaries. If the timing of deaths shifts across seasons more than overall exposure changes, annual estimates may be biased; modelling at monthly intervals would better capture these dynamics. Additionally, some European regions lack complete death counts. A further limitation concerns the interpretation of projected mortality reductions under warmer scenarios. Attributing these gains primarily to declines in cold-related mortality may be problematic, as a substantial share of winter deaths is influenced by viral dynamics that do not necessarily respond to temperature in a linear or predictable manner. This complicates projections of future mortality benefits in a warming climate. Moreover, the present analysis does not fully capture the possibility of reaching limits to physiological and infrastructural adaptation, or broader systemic disruptions. These include, for example, pressures on food systems, ecosystem degradation, and other climate-related instabilities that may affect population health through pathways not reflected in temperature–mortality curves. Consequently, the projected reductions in cold-related mortality should be interpreted with caution.

Overall, in all three studies, limitations related to incomplete or uneven geographic coverage both in terms of data availability and scientific publications are highlighted. For both historical and future projections, gaps in death counts represent a consistent limitation. All studies are limited

in fully accounting for adaptation measure or demographic change in future may underestimate or overestimate risk in vulnerable groups.

Future research could build on this work in several important ways. Concerning the literature review, future work may increase regional representation by including non-English literature assisted by assisted by large language models (LLM) multilingual searches which may help identify and summarize relevant studies, enhancing methodological consistency in defining exposures, and further incorporating dimensions of vulnerability, including factors such as adaptation measures. Concerning the historical study on temperature-related mortality, future empirical studies could consider policy interventions or adaptation measures in territorial characteristics to estimate their causal role in moderating the effects of temperature on mortality. For example, improvements in air quality resulting from policy interventions or capturing the presence and distribution of air conditioning and heating technologies across Europe at a fine-grained spatial scale, may reduce temperature-related deaths. The third paper, on projections of future temperature-related mortality, could further investigate how climate effects may influence future population trends, particularly by examining how older mortality due to extreme temperatures could affect population structure and composition over time. Another future research question is the temporal distribution of deaths, specifically, whether seasonal patterns may shift, which could be explored by moving from annual to monthly analyses. Additionally, future studies should move beyond temperature–mortality curves by incorporating explicit models of infectious disease dynamics, adaptation constraints, and broader systemic risks, in order to better capture the non-linear and indirect pathways through which climate change may influence population health.

Overall, the three studies collectively suggest that future research should incorporate adaptation measures, fine-grained data, and comprehensive geographic coverage. Research may also combine climate mitigation and population adaptation strategies to better understand past-present-future temperature-mortality risks. To achieve a more complete understanding of regional differences in climate-related mortality, future studies should also include countries missing from the current dataset, such as Germany, Croatia, and Slovenia, and consider extending analyses to neighbouring regions experiencing rapid warming, including broader territory, for example, the entire Mediterranean area, which includes parts of Africa and the Middle East (IPCC 2023b).

5.3. Conclusions

Overall, our analyses contribute to the growing body of research on the impacts of extreme weather events on human mortality, highlighting how climatic changes, in combination with geographical and socio-economic heterogeneity, are likely to shape mortality patterns across the Globe and in Europe. The three studies form a coherent continuum: the literature review identifies global knowledge gaps and major vulnerable population subgroups; the historical study quantifies spatial and demographic heterogeneity in temperature-related mortality, and the final study extends these insights by projecting mortality trends under future scenarios.

As observed across all three studies, socio-economic vulnerability strongly modulates climate exposure. For instance, individuals with lower incomes consistently experience higher levels of climate-related mortality, as shown in both the literature review and the European case study, particularly in relation to cold temperatures, where a significant interaction between low and high GDP per capita levels was found. Additionally, projection study suggests and confirms regional differences in future temperature-related mortality, with a slight decrease of death rates in Northern European countries but high vulnerability of the Southern regions, which is projected to experience the largest increases, particularly under high-emission scenarios (SSP3-7.0 and SSP5-8.5).

Targeted policy interventions are therefore essential. In Southern Europe, where populations are already exposed to high baseline temperatures, adaptation strategies should prioritize heat-health action plans, early warning systems, and urban greening initiatives to mitigate heat stress. Enhancing the energy efficiency of housing and expanding access to cooling infrastructure can further reduce mortality risks among vulnerable groups. At the same time, national and regional governments should invest in strengthening health surveillance systems, improving public awareness, and integrating climate risk assessments into urban and regional planning. Coordinated mitigation policies, such as accelerating the transition to renewable energy and reducing air pollution, would not only limit future warming but also deliver co-benefits for public health. Furthermore, unless strong mitigation and adaptation measures are implemented, most European regions may experience an increase of their temperature-related mortality burden. Under sustainability-oriented scenarios (SSP1–2.6), projected increases are moderate, highlighting the substantial health benefits of pursuing low-carbon pathways. However, without such efforts, high-emission scenarios could exacerbate existing regional inequalities in climate vulnerability. This

dissertation can provide valuable insights for broader analyses on economic planning, and climate policies, thereby informing decision-making processes in both the public and private sectors.

Appendix A: Supplemental Information

A.1. Details on inclusion criteria, search strategy, and definitions

Table A.S. 1 Inclusion and exclusion criteria based on the PECOs Framework.

PECOS	Inclusion	Exclusion
Population	The general human population, including at-risk subgroups such as children, pregnant women, and older adults, with no geographical restrictions.	Not performed on human populations
Exposure	Rapid onset and long-term exposure to climate change, extreme temperatures (heat and cold), heatwaves and cold spells, and natural disasters such as floods, storms, and droughts.	Air pollutants: Ozone, PM10, PM2.5; environmental factors: wildfire, carbon emissions, snow, and the greenhouse effect.
Comparator	Exposure of interest change in the same population; Exposure of interest by demographic heterogeneity including age, gender, education, income, urban-rural; Exposure of interest by geographical heterogeneity e.g. across countries, within a country across subnational regions,	Distinct population subgroups, each not representative of the general population in their designated areas.
Outcome	Number of death (all-cause, non-accidental, non-external, natural cause, and natural hazard-related) or excess mortality (daily, weekly, monthly, yearly, duration, peak month/year, mortality rate); Years of life lost (YLL); Life expectancy.	Investigated morbidity instead of mortality
Study	Human epidemiological studies, including cohort studies, quantitative research, time-series regression, and case-crossover designs; Examined spatial and sociodemographic heterogeneity in climate-related mortality; Published in peer-reviewed English-language journals with full-text access; Reported effect measures such as odds ratio (OR), relative risk (RR), regression coefficients, or percent change with 95% confidence intervals (CI) or standard error (SE).	Qualitative studies; Reviews and methodological papers; Studies lacking statistical measures (RR, OR, percent change, CI, or SE); Non-English publications; Articles without full-text access; Projection or estimation studies.

Table A.S. 2 Search strategy: terms, databases and number of articles for review.

Databases	Strategy	Number
Web of Science (WoS)	<u>Search 1</u>	
Date (publication): 1980-2023	TI=((("climate change" OR weather OR "atmospheric pressure" OR "climatic change" OR "global warming" OR "environmental change" OR "climate disaster" OR "greenhouse effect" OR "climate variability" OR flood* OR storm* "climatic variability" OR "carbon emission" OR cold OR cool OR cooling OR heat OR humid* OR ice OR precipitation OR rain* OR season* OR snow* OR *storm* OR hazard * OR *fire OR hurricane OR temperature OR warm OR warming OR wind OR" natural disaster*" OR drought* OR tornado*) AND (mortality OR death* OR "years of life lost" OR YLL OR life expectancy OR heat stroke OR thermal stress NOT plant NOT animal)))	10,817
Search date: 15/8/2023	<u>Search 2</u>	
	10,817 without any of the "and Ecology or Surgery or Biochemistry Molecular Biology or Mechanics or Forestry or Cell Biology or Marine Freshwater Biology or Plant Sciences or Engineering Mechanical or Thermodynamics or Zoology or Entomology or Transplantation or Fisheries or Biophysics or Critical Care Medicine or Medicine Legal or Biodiversity Conservation or Neurosciences or Physics Applied or Engineering Electrical Electronic or Energy Fuels or Oncology or Clinical Neurology or Metallurgy Metallurgical Engineering or Engineering Multidisciplinary or Construction Building Technology or Oceanography or Urology Nephrology (Exclude – Web of Science Categories) and Article (Document Types) and Sport Sciences or Veterinary Sciences or Geosciences Multidisciplinary or Toxicology or Agriculture Dairy Animal Science or Water Resources or Food Science Technology or Pharmacology Pharmacy or Pediatrics or Ornithology or Agronomy or Horticulture (Exclude – Web of Science Categories) and Physics Nuclear or Physics Atomic Molecular Chemical or Physics Condensed Matter or Literary Theory Criticism or Materials Science Characterization Testing or Hematology or Parasitology (Exclude – Web of Science Categories)	3,376
	<i>Same search strategy</i>	
		1,343
<u>Update search</u>		
Date (publication): 15/8/2023-28/4/2025		
Search date: 28/4/2025		

Scopus	TITLE-ABS-KEY ((("climate change" OR weather OR "atmospheric pressure" OR "climatic change" OR "global warming" OR "environmental change" OR "climate disaster" OR "greenhouse effect" OR "climate variability" OR flood* OR storm* "climatic variability" OR carbon* OR cold OR cool OR cooling OR heat OR humid* OR ice OR precipitation OR rain* OR season* OR snow* OR storm* OR hazard* OR hurricane OR temperature OR warm OR warming OR wind OR " natural disaster*" OR drought* OR tornado*) AND (mortality OR death* OR "years of life lost" OR yll OR "life expectancy" AND NOT plant AND NOT animal))) AND PUBYEAR > 1979 AND PUBYEAR < 2024 AND (EXCLUDE (PUBSTAGE , "aip")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "ENGI") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "NURS") OR EXCLUDE (SUBJAREA , "CHEM") OR EXCLUDE (SUBJAREA , "NEUR") OR EXCLUDE (SUBJAREA , "PHYS") OR EXCLUDE (SUBJAREA , "VETE") OR EXCLUDE (SUBJAREA , "AGRI")) AND (EXCLUDE (EXACTKEYWORD , "Virology") OR EXCLUDE (EXACTKEYWORD , "Cytokine Release Syndrome") OR EXCLUDE (EXACTKEYWORD , "Angiotensin Converting Enzyme 2") OR EXCLUDE (EXACTKEYWORD , "Tocilizumab") OR EXCLUDE (EXACTKEYWORD , "Diabetes Mellitus") OR EXCLUDE (EXACTKEYWORD , "Cytokine") OR EXCLUDE (EXACTKEYWORD , "C Reactive Protein") OR EXCLUDE (EXACTKEYWORD , "Interleukin 6") OR EXCLUDE (EXACTKEYWORD , "Nonhuman"))	7,942
Date (publication): 1980-2023		
Search date: 17/11/2023		
<i>Same search strategy</i>		2,000
<u>Update search</u>		
Date (publication): 17/11/2023-28/4/2025		
Search date: 28/4/2025		

Table A.S. 3 Frequency and definitions of temperature exposure metrics applied in the review (n = 211)

Meteorological Variable	Form of variable or indices	Number (%)	Measurement
Temperature index	Mean Temperature (Tmean)	123 (58.3)	The average of the minimum and maximum temperatures over a specific period (day, week, month, or year).
	Maximum Temperature (Tmax)	23 (10.9)	The highest temperature recorded during a specific period (day, week, month, or year), typically measured over a 24-hour interval.
	Minimum Temperature (Tmin)	3 (1.4)	The lowest temperature recorded during a specific period (day, week, month, or year), typically measured over a 24-hour interval.
	Diurnal Temperature Range (DTR)	12 (5.7)	The difference between the daily maximum and minimum temperatures, representing the range of temperature variation within a day.
	Temperature Variability (TV)	10 (4.7)	The standard deviation (SD) of daily (hourly) maximum and minimum temperatures (Tmax and Tmin) during the defined exposure period.
	Temperature Anomaly (TA)	1 (0.5)	The difference between the observed temperature at a specific location and time and a reference or baseline temperature (usually a long-term average).
	Used two or more metrics of temperature index	21 (10.0)	Using multiple temperature indicators, based on daily mean, minimum, maximum, and the diurnal temperature range. These metrics were then used to compare and evaluate variations in temperature exposure across different indicators.
Temperature and humidity index	Apparent temperature (AT, max, mean or min)	11 (5.2)	The perceived temperatures over a specific period (day, week, month, or year), typically derived from air temperature, relative humidity, and wind speed.
	Humidex	2 (0.9)	A Canadian index reflecting perceived heat by combining air temperature and humidity, indicating thermal discomfort.
	Wet bulb globe temperature (WBGT)	1 (0.5)	Heat stress on the human body by taking into account the combined effect of temperature, humidity, wind speed, sun angle, and cloud cover
	Heat index	2 (0.9)	Represents perceived temperature by combining air temperature and relative humidity; commonly used to assess heat-related stress.
	Universal Thermal Climate Index (UTCI)	2 (0.9)	An advanced index estimating thermal stress on humans in outdoor settings, based on temperature, humidity, wind speed, and solar radiation.

Table A.S. 4 Criteria for categorizing the overall summary of evidence for effect modification

Categorization	Criteria
Strong evidence	-The results across studies are generally aligned in terms of direction and magnitude of effect or degree of association. -There is a substantial body of research supporting these findings, with consistent evidence drawn from <u>at least 30 independent studies</u>, in contrast to any conflicting results.
Limited/Suggestive evidence	- A small number of studies - Consistent evidence drawn from <u>at least 4 independent studies</u>, in contrast to any conflicting results.
Weak evidence	-A limited number of studies. -There is consistent support from <u>at least 1 independent study</u>, despite the presence of conflicting findings.
No evidence	- An insufficient number of studies, with no consistent findings available.

*Noted: This criterion has been adapted from Son et al., 2019. Temperature-related mortality: a systematic review and investigation of effect modifiers. *Environmental Research Letters*, 14(7), 073004.

A.2. Main findings temperature-related mortality studies included

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
Africa (n=5)										
[1]	Azongo et al., 2012	Kasena-Nankana, Ghana (Aw)	1995-2010	All-cause	Heat	Mean temperature	GLM	Age (0–4, 5–19, 20–59, 60+), sex	The thresholds for the 25th (27.4°C) and 75th (30.6°C) percentiles for the lag strata; 1°C above/below the threshold temperature	Males had 2% higher mortality than females when temperatures exceeded 30.6°C. For children under 5 and ages 5–19, temperatures above 30.6°C raised mortality by 0.7% at lag weeks 1–2. For adults 60+, temperatures around 27.4°C increased mortality by 0.29% at lag days 0–1.
[2]	Bettaieb et al., 2020	Tunisia (Csa)	2005-2007: May–October	All-cause	Heat	Maximum temperature	GEE	Age (0–14, 15–64, 65+), sex	1°C increase in daily maximum temperature above the threshold (31.5°C)	A 1°C increase in daily maximum temperature led to a 2% increase in daily mortality (95% CI: 0.68–3.16). The effect was stronger in females (3.11%) and in the 0–14 age group (3.06%) and aged 65+ (2.28%).
[3]	Brimicombe et al., 2024	Gambia, Senegal, Ghana, Burkina Faso, Nigeria, Côte d'Ivoire, Ethiopia, Kenya, Tanzania, Uganda, Malawi, Mozambique, and South Africa (Multi)	1993-2016	All-cause	Heat	Mean daily maximum wet bulb globe temperature (WBGT)	a quasi-PGLM & DLNM	Age (neonate: <28 days, post-neonate: 28 days to 1 year, and child: >1 year and <5 years), region, and season	The increase from the median value of exposure for WBGT, known as the centroid, to the 95th percentile.	In Ethiopia, mortality risk ratios were 1.14 for neonates, 0.99 for post-neonates, and 0.79 for children. Child mortality risk increased notably in eastern Africa (RR = 1.27) and Senegal/The Gambia (RR = 1.11). During the hottest season, relative risk rose significantly in South Africa, eastern Africa, and the Sahel.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[4]	Faye et al., 2021	Bandafassi, Senegal (Aw)	1973-2012	All-cause	Heat wave	Used two or more metrics	PGAM & DLNM	Age (0–5, 6– 54, 55+), sex	During heat wave based in different duration and intensities	Heatwaves defined by ≥ 3 consecutive days above the 90th percentile showed the best model fit, with a significant increase in total mortality risk (RR=1.4). Females (RR=1.609) and those aged 55+ (RR=1.67) faced higher risks than males and younger age groups.
[5]	Wiru et al., 2020	Kintampo, Ghana (Aw)	2005-2015	All-cause	Heat, cold	Mean apparent temperature	PGLM & DLNM	Age (0-4, 5- 19, 20-59, 60+), sex	RR at varies apparent temperature (18°C, 23°C, 26°C, 31°C) vs the reference apparent temperature (24.8°C)	Low apparent temperature (18°C) showed the highest mortality risk (RR = 1.61) at lag 3. Females were more vulnerable to cold (RR = 4.88), while males were sensitive to both temperature extremes (RR= 2.21 for cold; RR= 2.19 for heat) at lag 2–4.
Americas (n=31)										
[6]	Anderson & Bell, 2009	U.S. (Multi)	1987-2000	Non- external	Heat, cold, Heat waves	Mean temperature	PGAM	Age (0-64, 65–74, 75+), cities	Cold effect: the 1st and 10th percentile temperatures, lag 0- 25; heat effect: the 99th and 90th percentiles, lag 0-1; heat wave: a heatwave event vs non-heatwave days	Mortality risk increased by 4.2% for cold (lag 0–25), exceeding the 3.0% (2.4%–3.6%) rise for heat (lag 0–1). Heatwave impacts increased with intensity or duration, reaching 10.6% at the ≥ 99.5 th percentile for ≥ 4 days. Heat, heatwave, and cold effects were highest in those aged 75+ (8.2% for heatwaves).
[7]	Aschidamini & Leon, 2025	Brazil (Multi)	2000-2014	Non- accidental	Heat, cold	Mean temperature	GLMs & DLNM	Age (all, 60+), region	Extreme heat: 99th percentile; and low (1st percentile)	In metropolitan area, cold effects (RR=1.26) were stronger than heat (1.09) in general population, particularly older adult groups (cold RR=1.30 vs. heat RR=1.13). Both heat- and cold-related mortality were highest in Southeast and South Brazil.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[8]	Bakhtsiyarava et al., 2023	Argentina, Brazil, Chile, Costa Rica, Salvador, Guatemala, Mexico, Panama, Peru (Multi)	2002-2015	All-cause	Heat, cold	Mean temperature	PGLM & DLNM	Age (0-64, 65+), climate zone, population density	a 1 °C change in temperature below the 5th (cold) or above the 95th percentile (heat)	Heat-related mortality was just 0.67% (95% CI: 0.58–0.74) of temperature-related deaths, much lower than cold-related mortality. Poverty is linked to higher cold-related excess mortality among the elderly.
[9]	Basu & Ostro, 2008	California, U.S. (Multi)	1999–2003: May - September	Non-accidental	Heat	Mean apparent temperature	Conditional logistic regression	Age (0-1, 2-5, 65+, 75+, 85+), sex, educational level (high school, non-high school)	A 10°F (4.7°C) increase in mean daily apparent temperature	The rise in non-accidental mortality risk was especially notable in infants, with a 4.9% increase per 10°F (4.7°C) rise in mean daily apparent temperature (95% CI: 1.8–11.6), and in young children aged 5 or under, with a 4.2% increase. No sex and education significant difference.
[10]	Bell et al., 2008	Mexico City, Mexico; Sao Paulo, Brazil; Santiago, Chile (Cw/Cfa/Csa)	1998-2002	Non-accidental	Heat	Mean apparent temperature	Conditional logistic regression	Age (0–15, 16–64, 65+), sex, education (none, primary, secondary, university), cause, city	Heat effect: % increase in mortality risk at 95th percentile vs at 75th percentile	Heat increased mortality by 4.43% in São Paulo, 1.82% in Santiago, and 1.26% in Mexico. Those 65+, risks were 6.51% in São Paulo, 3.22% in Mexico, 2.69% in Santiago. Females (1.75%) in Mexico had higher risks. In São Paulo, less-educated were more vulnerable (7.45%).
[11]	Chen et al., 2017	Texas, U.S. (Multi)	1990-2011	Non-accidental	Cold	Mean temperature	PGAM & DLNM	Age (0–64, 65–74, 75+), Cause	a 1 °C decrease in temperature below the cold threshold.	A 1 °C decrease in temperature was associated with a 1.58% increase in mortality risk. The impact was greatest among individuals aged 75+ (1.86%).
[12]	Chesini et al., 2022	Argentina (Cfa / BSh)	2013-2014	Natural causes	Heat wave	Used two or more metrics	Not show	Age (0-19, 20-39, 40-59, 60-79, 80+), sex	Heat wave (>95th percentile) vs the reference period	During heatwaves, mortality rose by 23% (1,877 excess deaths). Risk increased with age, especially for those 60–79 and

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
										80+. Gender patterns varied across time and regions.
[13]	Choi et al., 2021	North Carolina, U.S. (Cfa/ Cfb)	2000-2016	Non-external	Heat, cold	Mean temperature	a quasi-PGAM & DLNM	Urban-rural, SES, city	Cold effect: 1st (−3.7°C) to 10th (2.9°C) percentiles; heat effect: 99th (28.2°C) to 90th (25.5°C) temperature percentiles	Overall cold-mortality risk for relative effects was 1.019. The heat mortality risk was not statistically significant. Cold-mortality risk was higher in urban areas (1.023) than rural areas (1.012). Cold risks were higher in wealthier counties (RRR 1.72). Significant cold effects were seen in Coastal Plains (1.019), Piedmont (1.021), and Mountains (1.014).
[14]	Curriero et al., 2002	U.S. (Multi)	1973-1994	Non-external	Heat, cold	Mean temperature	PGAM	Age (0-64, 65-74, 75+), cities, %poverty, % aged 65+, % not completing high school	% change in mortality per 10°F	A 10% increase in the 65+ population raised cold-related mortality by 3.97% per 10°F decrease. A 10% increase in poverty increased mortality by 4.26% per 10°F above the MMT, while high % of those not completing high school raised mortality by 3.13%.
[15]	Geirinhas et al., 2020	Rio de Janeiro, Brazil (Af)	2000-2015	Natural causes	Heat	Used two or more metrics	NBGLM	Age (0-14, 15-29, 30-59, 60+), sex	Heat: above the 90th percentile	Mortality tend to increase significantly for extremely hot conditions for all populations (Tmax: 0.43, Tmean: 0.41, EHF: 0.43). Females experienced a 47% excess in deaths, with higher than males. Aged 60+ (Tmax: 0.42; Tmean: 0.39; EHF: 0.43) showed significantly highest correlations at lag 0.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[16]	Goldberg et al., 2011	Montreal, Canada (Dfb)	1984-2007	Non-accidental	Heat, cold	Maximum temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex, cause	Cold: the 1st percentile (−16.3 °C) to 10th (−5.3 °C); heat: the 99th (31.8 °C) to the 75th (22.5 °C) and to the 90th (26.9 °C)	Non-accidental mortality rose by 28.4% as temperatures increased from 22.5 to 31.8 °C. Cold showed a modest risk increase (lag 2–5 days) but no impact over 30 days. No sex differences.
[17]	Guo et al., 2023	Texas, U.S. (Multi)	1990-2011	All-cause	Heat	Mean temperature	a quasi-PGAM	Age (0-64, 65-74, 75+), Cause, Cities	1 °C increase in temperature above the threshold of heat.	A 1 °C rise above the heat threshold increases all-cause mortality risk by 0.60% overall and 1.10% for aged 75+.
[18]	Harlan et al., 2014	Maricopa County, Arizona, U.S. (BWh)	2000-2008: May–October	Non-external	Heat	Maximum apparent temperature	GLM	age (0-64, 65+), sex	1 °F above threshold	On the hottest days, Relative risk was elevated for all cause deaths in females both younger (ATmax = 107 °F, RR = 1.02) and older (ATmax = 107 °F, RR = 1.01) with a one-day lag effect.
[19]	Hattis et al., 2012	Massachusetts, U.S. (Dfb)	1990-2008	All-cause	Heat	Mean apparent temperature	Linear regression model	Age (% aged 65+, %Infant)	the association with the mortality anomaly on hot days	Areas with more elderly (65+) show higher mortality on hot days (p=0.006), with a 1% rise in elderly population increasing mortality on hot days by 0.487%.
[20]	Healy et al., 2023	U.S. (Multi)	2000-2016	All-cause	Heat, cold	Mean temperature	Difference-in-Differences	Age (65+)	1°C increase in the SD of warm and cold season temperature	The mortality rate increased by 1.54% in warm season temperature and 0.69% in cold season temperature in aged 65+.
[21]	Hovdahl, 2022	U.S. (Multi)	1970-2004	All-cause	Heat	Mean temperature	GLM	Age (0, 1-44, 45-64, 65+)	% increase per 1°C rise in daily temperature	A 1°C rise in daily temperature variability increased mortality by 0.206 per 100,000 (0.28% monthly) and 1.351 deaths among those 65+.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[22]	Isaksen et al., 2016	King County, Washington, U.S. (Csb)	1980-2010	All-cause	Heat wave	Humidex	PGLM & DLNM	Age (0–4, 5–14, 15–44, 45–64, 65–84, 85+), sex, cause, education	99th percentile heat days (36.1 °C or 97.0 °F) vs non-heat day	On heat days, the risk of death increased by 10% for all ages (RR=1.10, 1.06–1.14). The risk was higher for the 65–84 age group (6%, RR=1.06) and the 85+ age group (18%, RR=1.18). No statistically significant in sex and high school graduation.
[23]	Joe et al., 2016	California, U.S. (Multi)	2006	All-cause	Heat wave	Maximum temperature	DLNM	Age (0-4, 5-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65-74, 75-84, 85+), sex, location	18-day heat wave period vs the reference period	During heat wave, deaths increased by 5% (582 excess deaths, RR = 1.05). Mortality risk was highest among ages 35–44 (RR = 1.18), 45–54 (RR = 1.08), and 55–64 (RR = 1.12), exceeding risks for those 65+. No sex differences.
[24]	Kephart et al., 2022	Argentina, Brazil, Chile, Costa Rica, El Salvador, Guatemala, Mexico, Panama, and Peru (Multi)	2002-2015	All-cause	Heat, cold	Mean temperature	Conditional Poisson regression & DLNM	Age (0-64, 65+)	Extreme heat: ≥95th percentiles; extreme cold: ≤5th percentiles	Cold-related excess death fractions (EDF) were higher (5.09%, 95% CI: 4.64–5.47%) than heat-related EDF (0.67%, 95% CI: 0.58–0.74%). Risk increased by 1.057 per 1°C rise in extreme heat and by 1.034 per 1°C drop in extreme cold. Among those 65+, cold-related EDF was highest at 6.28% (95% CI: 6.41–7.18).
[25]	Kosatsky et al., 2012	Vancouver, Canada (Cfb)	2009	Non-accidental	Heat	Maximum temperature	logistic regression	Age (0-64, 65–74, 75–84, 85+), Sex, pop density	N/A	During hot weather, mortality risk was highest in the 65–74 age group (OR=1.47) compared to 85+ and 0-64 (OR=1.10). Males faced higher risk than females (OR=1.12).

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[26]	Liu et al., 2022	115 cities, U.S. (Multi)	1962-2016	All-cause	Heat, cold	Temperature anomaly (TA)	a quasi-PGLM & GAM	Age (0-24, 25-44, 45-64, 65+)	Extreme heat: 99th temperature anomaly (TA) percentile, Extreme cold: 1st TA percentile	Extreme heat had a higher mortality risk (RR = 1.036, 95% CI: 1.030–1.041) compared to extreme cold (RR = 1.024, 95% CI: 1.017–1.031). Older aged 65+ had higher risks at 1.039 (95% CI: 1.028–1.050) for cold and 1.059 (95% CI: 1.048–1.069) for heat
[27]	Medina-Ramon & Schwartz, 2007	U.S. (Multi)	1989-2000	All-cause	Heat, cold	Used two or more metrics	Conditional logistic regression	City	Cold effect: %change in mortality per each degree of maximum daily temperature below 17°C; heat effect: % change in mortality per each degree of minimum daily temperature above 17°C	Mortality rose by 1.59% in extreme cold and 5.74% in extreme heat, with smaller increases at milder temperatures.
[28]	O'Neill et al., 2003	U.S. (Multi)	1986-1993	Non-external	Heat, cold	Mean temperature	GLM	Age (0-64, 65+), sex, education (high school or less, any post-high school)	% change in mortality at 29°C apparent temperature (heat) and at -5°C relative to 15°C (cold)	Cold effects (10.1%) exceeded heat effects (5.0%), with higher cold-related risks for males (10.9%), under 65 (11.7%), and lower education (6.9%). Heat effects were higher for lower education (5.2%), unaffected by sex or age.
[29]	Quick, 2024	Montréal, Québec, Surrey, Toronto, Canada (Multi)	2000-2020: summer	Non-accidental	Heat wave	Humidex	GAM	Age (0-64, 65+), cities/region	Extreme heat event days (95th percentile heat days) vs non-extreme heat event days	Across 12 cities, about 670 excess non-accidental deaths were linked to extreme heat events. Older adults (65+) in Montréal, Québec, Surrey, and Toronto showed significantly higher mortality risks during extreme heat days.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[30]	Roca-Barcelo et al., 2022	São Paulo, Brazil (Cfa)	2000-2018	Non-external	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (65-79, 80+, sex, ethnic group (white and non-whites), and years of education (≤ 3 , 4-11, >11 years).	Extreme heat: cRR at 99th percentile; moderate heat: 90th percentile; moderate cold: 10th percentile; extreme cold: 1st percentile vs. MMT	The cRR for extreme heat significantly increased from 1.14 in 2000 to 1.22 in 2018, while the cRR for cold slightly decreased from 1.33 in 2000 to 1.31 in 2018. Mortality risk from extreme heat and cold rose for those aged ≥ 80 (heat: 1.29 to 1.46; cold: 1.48 to 1.45). Females saw an increase in cRR for heat and a slight decrease for cold.
[31]	Sarmiento, 2023	Colombia (Multi)	1993-2016	All-cause; YLL	Heat, cold	Mean temperature	GLM	Age (0-4, 5-9, 10-19, 20-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80+), urban-rural, rich-poor area	N/A	A day above 27°C increases mortality by 0.7% of monthly rates, while cold-related deaths account for 3.4% of average monthly deaths. Heat effects are only significant in urban and rich municipalities.
[32]	Schwarz et al., 2025	Mexico (Multi)	1998–2019	All-cause	Heat	Used two or more metrics	Spatial Bayesian hierarchical model	Age (% 65+), %education, %employment, region	Extreme heat day (the 99th percentile of the same-day maximum temperature: above 35 °C) vs. non-extreme heat day	Extreme heat increased overall mortality risk (OR = 1.061), with the highest impact in Tabasco (OR = 1.23). The strongest effects occurred along the eastern, southwestern, and Sonora coasts. Municipalities with larger elderly populations (65+) and lower education levels faced greater heat-related risks.
[33]	Shrestha et al., 2024	British Columbia (BC), Canada (Multi)	2001-2021	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Regions	Extreme cold and heat: below the 2.5th or above the 97.5th percentiles Moderate cold and heat: fall between the 2.5th percentile,	In BC, 7.17% of deaths were linked to non-optimal temperatures, mostly from cold (6.24% moderate, 0.38% extreme). The Island region had the highest impact (9.19%), while Northern had the lowest (3.31%).

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
									MMT, and the 97.5th percentile	Fraser, Vancouver Coastal, and Island regions more affected.
[34]	Silveira et al., 2023	Brazil (Multi)	2000-2018	Non-external	Heat wave	Used two or more metrics	Conditional Poisson regression & DLNM	age (0-64, 65+), sex	Heat waves vs non-heat wave days	Mortality risk rose with heat wave, ranging from RR=1.03 (1.01–1.06) for less intense waves to 1.18 (1.04–1.33) for the most intense. Females (RR=1.24) were more vulnerable compared to males (RR=1.11). Older aged 65+ were most affected (RR=1.34) during heat waves, compared to younger individuals (RR=1.03).
[35]	Yu et al., 2022	45 cities in U.S. (Multi)	1987-2000	All-cause	Heat, cold	Temperature variability (TV)	a quasi-PGLM & DLNM	Age (0-64, 65-74, 75+)	1 °C increase in TVdaily or TVhourly	A 1 °C rise in TV at lag 0–7 days was associated with an increase of RR 0.55% (TVdaily, 0.41–0.70%) and 0.51% (TVhourly, 0.35–0.66%) in all-cause mortality. People over 75 years old were relatively more vulnerable to TV-related mortality risks (RR of TVdaily=0.67; TVhourly=0.64%)
[36]	Zhang et al., 2015	Houston, Texas, U.S. (Cfa)	August 2, 2011 - August 30, 2011	All-cause	Heat wave	Mean temperature	a quasi-PGLM & DLNM	Age (0-5, 6-64, 65+)	% increase in excess mortality risk of heat waves vs warm months	The 2011 Houston heat wave increased overall mortality risk by 0.6%, with the highest impact observed in individuals aged 6–65 years (3.4%).
Asia (n=105)										

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[37]	Aboubakri et al., 2023	8 cities, Kurdistan, Iran (Multi)	2008–2014; 2015–2022	All-cause	Heat, cold	Mean temperature	GAM & DLNM	Age (0–64, 65+), sex, city	Extreme cold effect: 3th percentile; Extreme heat effect: the 99th percentile.	Heat-related mortality increased in recent years, while cold had no significant effect. From 2015–2022, heat and extreme heat caused more deaths than cold, with extreme heat RR rising to 1.56 (vs. 0.88 in 2000–2014), particularly in men (RR = 1.64), the young (RR = 1.88), and the elderly (RR = 1.40). Heat increased mortality in Qorveh, Saqez, and Sanandaj.
[38]	Alahmad et al., 2024	5 districts in Cyprus (Csa)	2004–2019	All-cause, non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	City	Cold effects: the 1st, 2.5th, and 5th percentiles to the optimal temperature; heat effects: the 95th, 97.5th and 99th percentiles	Cold showed mortality risks of 1.55 (1st percentile), 1.41 (2.5th), and 1.32 (5th). Heat risks were 1.10 (95th), 1.17 (97.5th), and 1.29 (99th). Cold days contributed to 8 deaths for every 100 deaths, while heat days accounted for 1.3 deaths. Not find evidence of heterogeneity between 5 districts.
[39]	Alam et al., 2012	Bangladesh (Aw)	1983–2009	All-cause	Heat, cold	Mean temperature	GLM & DLNM	Age (0, 1–4, 5–19, 20–59, 60+), sex	1°C decrease in temperature below the 25th percentile (23.0°C), between the 25th and 75th percentile (23.0 and 29.6°C), above the 75th percentile (29.6°C).	Mortality risk increased by 2.3% for every 1°C drop below the 25th percentile and by 2.4% between the 25th and 75th percentiles. For females, mortality increased by 4.3% below the 25th percentile and by 3.8% between the 25th and 75th percentiles. Low temperature-mortality risk was significantly higher for age groups 5–19 and 20–59 years below the 75th percentile.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[40]	Alwadi et al., 2024	Amman, Jordan (Multi)	2000-2018	All-cause	Heat, cold	Mean temperature	GLMs & DLNM	Sex, nationality	Heat: temperatures above the MMT Cold: temperatures below the MMT for each category	Females showed greater vulnerability to temperature extremes, with a higher heat- attributable mortality fraction of 2.59% compared to 1.17% for males. They also had a higher cold-attributable mortality fraction (6.23%) than males (5.1%).
[41]	Bai et al., 2014	Tibet (BSk)	2008-2012	Non- accidental	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65+), sex, education (illiterate and non-illiterate people), city	Cold: 1st percentile (- 4.4 °C) relative to the 25th (3.4 °C); heat effect: 99th (21.7 °C) relative to the 75th (15.5 °C) of temperature.	Cold (lags 0-14) strongly increased non-accidental deaths (RR=2.251) in Jiangzi. No heat or cold effects in Chengguan and Naidong. Males, elderly, and illiterate individuals were more vulnerable to temperature extremes.
[42]	Bi et al., 2022	Shanghai, China (Cfa)	2002 -2004	Non- accidental	Heat waves, cold spells	Temperature variability (TV)	Linear regression	Age (0-44, 45-59, 60-74, 75-89, 90+), cause	During the heatwave/cold spell vs the reference periods	Heatwaves significantly impacted total non-accidental deaths (RR=16% for the 1st heatwave; 3% for the 2nd heatwave, not statistically significant). Cold spell mortality risk increased by 10%. Aged 75+ were more sensitive to temperature variation.
[43]	Burkart et al., 2014	Bangladesh (Aw)	2007	All-cause	Heat	Universal thermal climate index (UTCI)	PGAM & DLNM	Age (0-65, 65+), sex, urban/rural, SES area (low, high)	1°C increase in UTCI above threshold; the 99th percentiles (35.5 °C UTCI), the median equivalent temperature (26.6 °C UTCI)	Heat-related mortality increased by 31.3% overall, with the highest impact in older adults (32.0%). Older males (45.9%) and urban residents (46.3%) experienced stronger effects. High SES areas showed a 41.6% increase for older adults.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[44]	Cao et al., 2023	Shandong, China (Dwa)	2013-2018; June– September	All-cause	Heat	Mean temperature	Conditional logistic regression & DLNM	Age (0-64, 65-74, 75+), sex, education (junior high school and below, and high school and above), Urban-rural	Extreme heat: the 97.5th percentile of the temperature range compared to MMT	Extreme heat effects significantly declined from OR 3.52 to 2.85 between early and late warm seasons. Females (OR= 4.03) and the aged 75+ (OR= 5.06) were significantly most vulnerable, with higher risks also seen among those with lower education (OR= 3.43). No significant urban-rural differences.
[45]	Chan et al., 2012	Hong Kong, China (Cwa)	1998-2006: May and October	Non- accidental	Heat, cold	Mean temperature	PGAM	Age (0-74, 75+), sex, urban/rural, SES area (low, medium, high)	3.0°C increase above/decrease below 28.2°C	A 1°C rise above 28.2°C increased non-accidental mortality by 1.8%. Females (RR=1.068) were more sensitive to a 3°C rise than males (RR=1.045). Adults 75+ were more affected by temperature drops below 28.2°C (RR=1.040). No significant differences by residence or SES.
[46]	Chen et al., 2019	31 cities in China (Multi)	2007-2013	Non- accidental	Cold spells	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65-74, 75+), sex, educational level	Cold spell: at least two consecutive days with temperature below the 5th percentile (the best)	Cold spells increased mortality risk at lag 0-27 (RR=1.55). A stronger impact on those aged 75+ (RR=1.62) compared to ages 0-64 (RR=1.33). Less-educated individuals were more vulnerable (RR=1.63) than those with higher education (RR=1.37). No sex differences.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[47]	Chen et al., 2020	364 locations, China (Multi)	2006-2017	Non- accidental ; YLL	Heat, cold	Mean temperature	DLNM	Age (0-64, 65+), sex, SES (high- development regions: HDR, low- development regions: LDR)	Extreme cold: 2.5th percentile; nationwide: -8.2 °C Extreme heat: 97.5th percentile; nationwide: 30.3 °C	Cold-related AFs or life loss per death were much higher than heat-related AFs, with moderate cold contributed to majority of mortality burden. Males suffer with cold more than females. People aged 65+ showed higher AFs due to cold (HDRs = 12.6% vs. LDRs = 14.4%), while those aged 0-64 had higher AFs in heat (HDRs = 1.3% vs. LDRs = 2.0%). Attributable YLL rates for cold were higher in LDRs (10.4%) than in HDRs (8.5%).
[48]	Chen et al., 2021	Guangzhou, China (Cwa)	2010-2018	Non- accidental	Cold spells	Mean temperature	GLM & DLNM	Age (0-64, 65+), Sex	Cold spells: <the 5th percentile with ≥ 2 consecutive days	Cold spells significantly increased all-cause mortality (lag 0-27, RR=1.57), with higher risks for females (RR=1.66) and those aged 65+ (RR=1.65) compared to males (RR=1.50) and younger individuals (RR=1.33).
[49]	Chen et al., 2024	A low-latitude plateau area in Yunnan, China (Cwb)	2014-2020	Non- accidental ; YLL	Heat, cold	Mean temperature	GLMs & DLNM	Age (0- 74,75+), sex, occupation (farmer, staff, or other), education level (junior college and above, below junior college).	Cold and heat: temperatures below and above the temperatures with the lowest YLL.	Cold had a significant impact on YLL for non-accidental deaths (650.99 overall; 403.16 for cold). Temperature-related deaths accounted for AF=7.45%, mainly from cold (4.61%) versus heat (2.84%). Males and younger (<75 years) individuals were more affected to cold, with YLLs of 302.93 (AF= 5.87%) and 403.63 (AF= 5.78%), respectively. Mortality effects were higher among those with lower education (7.42%) and farmers (7.74%).

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[50]	Chen et al., 2025	Guiyang, China (Cwb)	2013-2023	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex	Extreme cold and heat effect: temperatures below the 2.5th percentile (0.9°C) and above the 97.5th percentile (25.8°C)	Extreme low temperatures showed a higher and longer-lasting mortality risk (RR = 1.24%) than extreme high temperatures (RR = 1.18%). Males were more vulnerable (RR = 1.27% for extreme cold; 1.20% for extreme heat), and adults aged 65+ were especially sensitive to extreme heat (RR = 1.28%).
[51]	Choudhary et al., 2023	Delhi, Varanasi, and Chennai, India (Multi)	1979-2020	Non-accidental	Heat	Heat Index	a quasi-PGAM	Age (0-18, 19-44, 45-64, 65+), sex, cities	RR per 1°C increase in India heat index (IHI)	Each unit increase in IHI led to higher all-cause mortality: 3.1% in Chennai, 3.2% in Delhi, and 6.8% in Varanasi. Females (3.7–6.9%) and adults over 64 years (5.7%, 4.2%, and 7.5% respectively) were most affected by heat stress.
[52]	Chung et al., 2018	Japan (Multi)	1972-2012	All-cause	Heat, cold	Used two or more metrics	a quasi-PGLM & DLNM	Age (0-4, 5-9, 65+), sex, time, cities	1°C increase in temperature above and below MMT (27.5°C); cold effect: the 1st percentile of temperature vs. the MMT; heat effect: the 99th percentile	Cold-related mortality risk was higher than heat. A higher percentage of elderly people (65+) was associated with higher MMT and higher cold risk.
[53]	Cui et al., 2016	Chengdu, China (Cfa)	2011-2014	Non-accidental	Heat, cold	Minimum temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex	Extreme cold and heat: below the 2.5th or above the 97.5th percentiles; Moderate cold and heat: fall between the 2.5th, MMT, and the 97.5th percentile	Temperature-related deaths accounted for 10.93% of mortality, with cold 9.96% and heat 0.97%. Most deaths were due to moderate temperatures (8.54%). Older adults (65+) had a higher cold-attributable fraction (12.13%) than younger (7.66%). No sex differences.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[54]	Dang et al., 2016	Hue, Vietnam (Am)	2009-2013	All-cause	Heat, cold	Used two or more metrics	NBGLM & DLNM	Age (0-65, 65+), sex	Heat: the 99th percentile (32.4°C) to the 50th (26.3°C); Cold: the 1st (15.8°C) to the 50th (26.3°C) percentile	Low temperatures posed a higher mortality risk (RR=1.78, 95% CI: 1.10–2.88) than high temperatures (RR=1.28, 95% CI: 1.04–1.58). Cold effects were stronger in females (RR=2.19, 95% CI: 1.14–4.21) than males. Older adults (65+) faced increased risk from both low (RR=2.0, 95% CI: 1.13–3.52) and high temperatures (RR=1.42, 95% CI: 1.11–1.83).
[55]	Dang et al., 2019	Ho Chi Minh, Vietnam (Aw)	2010-2013	Non- external	Heat wave	Mean temperature	a quasi- PGLM &DLNM	Age (0-14, 15-64, 65+), sex	Heat waves: 97th percentile (30.9 °C) in ≥2 consecutive days	Heatwave effects significantly increased female mortality (RR = 1.11, 95% CI: 1.04–1.18), elderly mortality (65+) with RR = 1.43 (95% CI: 1.34–1.53).
[56]	Deng et al., 2019	Yuxi, China (Cwb)	2009-2016	Non- accidental	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (0–64, 65–74, 75+), sex, occupation (farmer and non-farmer)	Extreme cold: below the 2.5th percentile (5.4°C) Extreme heat: above the 97.5th percentile (23.1°C)	Cold temperatures contributed most to the mortality (attributable risk 4.08%). The cold-related burden was slightly higher for females (4.66%). Older (75+) faced a greater burden (1.71%) from extreme cold. Farmers, representing low SES, had a higher cold-related burden (4.66%) than non-farmers.
[57]	Deng et al., 2020	Hefei, China (Cfa)	2014-2017	Non- accidental	Heat, cold	Used two or more metrics	PGLM & DLNM	Age (0-64, 65+), sex	The thresholds for the 75th (24.4 °C) percentiles for the lag strata; 1°C above/below the threshold temperature	Non-accidental mortality rose by 1.8% at 24.4°C (95% CI: 0.7–3.0%) and by 1.4% at lag 6 with a DTR of 11.3°C (95% CI: 0.1–2.7%). Females were more susceptible to high DTR effect (2.8%) than males. Older (65+) are more susceptible to daily mean temperature effects (2.4%) and DTR (1.3%) than younger.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[58]	Ding et al., 2015	Yuxi, China (Cwb)	2007 - 2013	Non- accidental	Heat, cold	Diurnal temperature range	GLMs & DLNM	Age (0-74, 75+), Sex, Cause	Extreme high DTR effect: 99th percentile of DTR distribution (18.4 °C for the full year, 18.9 °C for the cold season and 17.3 °C for the warm season) vs the reference DTR of 10.2 °C	Non-accidental mortality showed higher RRs with extreme high DTR at lag 0–21 days in the full year (RR= 1.33), especially in the cold season (RR=2.05). Males (RR=1.60) and those under 75 (RR=1.69) were more susceptible to extreme high DTR compared to females and older.
[59]	Ding et al., 2016	Yuxi, China (Cwb)	2009-2014	Non- accidental	Cold	Mean temperature	a quasi- PGLM & DLNM	Age (0-74, 75+), sex, occupation (farmer or non-farmer)	Cold effect: 1st to 10th percentile (4.2 °C vs. 9.6 °C); Hot effect: 99th to 90th percentile (23.7 °C vs. 21.8 °C); a 1°C below a cold threshold (9.1 °C)	Cold temperatures increased non- accidental mortality (RR 1.40, 95% CI: 1.19–1.66) over lag 0–21 days. A 1°C drop below the cold threshold raising mortality by 7.35% (3.75–11.09). This effect was not significantly modified by sex, age, or occupation.
[60]	Ding et al., 2016	Yuxi, China (Cwb)	2007-2014	Non- accidental	Heat, cold	Diurnal temperature range	a quasi- PGLM & DLNM	Age (0-64, 65–74, 75–84, 85+), sex, educational groups (low, high)	High DTR days were defined as ≥ 90th percentile of DTR; risk of mortality on high DTR days compared with the reference group	DTR was higher in the cold season than the warm season. Mortality risk on high DTR days was significantly elevated for those aged 75–84 (OR=1.07) and 85+ (OR=1.16), with older adults (85+) particularly vulnerable in both cold and warm seasons. No effect modification was observed by sex or education.
[61]	Fang et al., 2023	China (Multi)	2006-2017	Non- accidental	Heat	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65-84, 85+), sex, region, urban-rural	% change of excess rates (ER)	Non-accidental mortality risk was higher during dry-hot events (ER = 10.18%), with greater vulnerability among females (ER = 13.91%), the older aged 85+ (ER = 17.96%), central China

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										residents (ER = 13.33%), and urban populations (ER = 11.59%).
[62]	Fu et al., 2018	India (Aw/BSh)	2001-2013	All-cause	Heat, cold	Mean temperature	DLNM	Age (0–29, 30–69, 70+), areas	Cold effect: the 1st percentile thresholds; heat: the 99th percentile thresholds vs MMT	Cold (6.8%) posed a higher risk than hot (0.5%). Moderately cold (6.3%) carried greater risk than extreme cold, moderate, or extreme heat (all <0.6%). Risks of moderately cold were higher in ages 70+ (12.5%) compared to 30–69 years (7.6%).
[63]	Gao et al., 2023	Hulunbuir, China (Dwb/Dwc)	2014-2018	Non-accidental	Heat, cold	Mean temperature	PGAMs & DLNM	Age (0–64, 65+), sex	The optimum ambient temperature (MMT) = 15 °C; Cold effect: the 1st percentile (–33 °C), heat effect: the 99th percentile (27 °C)	Heat increased non-accidental mortality (RR=1.111, 95% CI: 1.031–1.198). Heat effects were stronger in females (RR=1.252) than males (RR=1.187). Older (65+) faced higher risks from heat (RR=1.215, lag 0–5) and cold (RR=1.487, lag 2–14) than younger individuals.
[64]	Goggins et al., 2013	Kaohsiung, Taiwan (Aw)	1999-2008: May to October	Natural causes	Heat	Mean temperature	GAM & DLM	Age (0-64, 65-74, 75+)	1°C above/below 29°C	Each 1°C increase in mean temperature above 29.0°C significantly associated with 3.4% (95% CI 0.6, 6.3%) increase in natural mortality. Older aged 75+ show a stronger effect, with each 1 °C rise in mean temperature was significantly associated with a 2.3% (95% CI: 0.3-2.5%) rise in natural mortality.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[65]	Guo et al., 2012	Chiang Mai, Thailand (Aw)	1999-2008	Non- external	Heat, cold	Used two or more metrics	a quasi- PGLM &DLNM	Age (0-64, 65-74, 75-84, 85+)	cold: 1st percentile relative to 25th percentiles (19.35°C vs. 24.7°C); heat: 99th vs. 75th percentiles (31.7°C vs. 28°C)	Cold (RR = 1.29, 95% CI: 1.16-1.44) had a stronger impact on non-external mortality than heat (RR = 1.11, 95% CI: 1.16-1.44) for lags 0–21. Heat and cold effects were acute for all age groups. The highest RR for hot temperatures was 1.33 in ages 75–84, and for cold temperatures, it was 1.62 in ages 85+.
[66]	Ha & Kim, 2013	Seoul, South Korea (Dwa)	1993-2009: June– August	Non- accidental	Heat	Mean temperature	PGLM	Age (all ages, 65+), time periods	A 1 °C increase in summer temperature (lag 0-1) above the threshold	Summer temperature was associated with increases in mortality for aged 65+ of 7.31 % (95 % CI, 5.83–8.81 %) for the entire summer.
[67]	Ha et al., 2011	Seoul, Daegu, and Incheon, South Korea (Multi)	1991-2008: summer (June, July, and August)	Non- accidental	Heat	Mean temperature	PGLM & DLM	Age (0-14, 15-64, 65+), cities	1°C increment above threshold	High temperatures affected mortality for 5 days, with lasting effects for 30 days in Seoul and Incheon. Older aged 65+ are at highest risk at lag 0, but cumulative effect over 30 days, they have a lower risk compared to all-ages population in Seoul.
[68]	Heo et al., 2016	South Korea (Dwa/Cfa)	1996-2000 and 2008- 2012	All-cause; non- accidental	Heat	Maximum temperature	PGAM	Age (0-20, 20–74, 75+), sex, occupation (White-collar, blue-collar), education (none, elementary, ≥6th grade)	a 1°C change in daily temperature above the threshold	The all-cause mortality risk per 1°C rise above 33.5°C was RR=1.05 in 1996–2000 and 1.03 in 2008–2012. The risk for aged 75+ fell slightly (RR=1.05 to 1.04). Risks for those with no education (RR=1.02 to 1.04) and blue-collar workers (RR=1.06, 2008–2012) increased over time. No sex differences.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[69]	Ho et al., 2020	Hong Kong (Cwa)	January- March 2016	All-cause; non- accidental	cold spells	Mean temperature	PGLM	Age (0-64, 65-74, 75-84, 85+), sex, employment	Cold wave vs the comparison period	The adjusted IRR for weeks 2–5 after the first cold wave were 1.16, 1.31, 1.19, and 1.27. Economically inactive individuals had higher mortality in week 5 (OR=1.43) than economically active. No sex, age differences.
[70]	Ho et al., 2023	Hong Kong (Cwa)	2010-2019	Non- external	Heat wave	Mean temperature	a quasi- PGAM & DLNM	Age (0-74, 75+), cause	Urban heat island under extreme heat vs non-extreme heat	Temperature-mortality risk was significant for those 75+ during extreme heat, especially in high UHIdh areas, while younger groups showed no significant increase.
[71]	Hu et al., 2019	Zhejiang, China (Cfa)	2009-2015	All-cause; non- accidental	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65+), sex, urban-rural	Heat: 99th percentile vs. MMT; cold: 1st percentile vs. MMT	Cold more effect than heat. Mortality risks were higher in rural areas (16.4% for cold, 0.9% for heat) compared to urban areas (7.0% for cold, 0.8% for heat). Cold effect for the elderly (65+) was higher in rural areas (RR=2.18) than urban (1.59). For heat, rural elderly also had higher (1.20 vs 1.11 for urban elderly).
[72]	Hua et al., 2024	Suzhou, China (Cfa)	2008–2022	Non- accidental	Heat, cold	Mean temperature	Conditional logistic regression & DLNM	Age (0-64, 65+), sex, educational attainment (0- 9 years and 10+ years)	Extreme cold (<2.5th percentile) and extreme heat (>97.5th percentile)	Extreme cold posed a higher mortality risk (RR=1.37) than extreme heat (RR=1.09). Females were more affected by both cold (OR=1.45) and heat (OR=1.11). Elderly showed higher risks for extreme cold (OR=1.42) and heat (OR=1.09), while lower education was more sensitive to extreme cold (OR=1.43 vs. 1.19 higher education).

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[73]	Huang et al., 2010	Shanghai, China (Cfa)	July 19, 2003 - August 6, 2003	All-cause	Heat wave	Maximum temperature	Not show	Age (0-4, 5-44, 45-64, 65+), sex, cause	RR of mortality on heat days vs non-heatwave	During the heat wave, total mortality increased by 13% (RR=1.13, 95% CI: 1.06–1.20), with the elderly (65+) being most vulnerable (RR=1.13, 95% CI: 1.06–1.21). No sex differences.
[74]	Huang et al., 2015	China (Multi)	2006-2011	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0–64, 65–74, 75–84, 85+), sex, education	1°C increase above the MMT (heat effect) or a 1°C decrease below the MMT (cold effect).	Excess mortality risk was higher for cold (3.44%) than heat (1.04%), with the highest cold-related risk in aged 85+ (4.11%). Heat risk increased in aged 85+ (1.72%), females (1.36%), low education (1.38%). Cold effects were strongest in North and Central regions, while heat effects peaked in South.
[75]	Huang et al., 2022	Nantong, China (Cfa)	2012-2017	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (65–69, 70–74, 75–79, 80–84, 85–89, 90–94, 95–99, 100+)	Cold spell: temperature below the 5th percentile (1.9 °C); heat wave: temperature above the 95th percentile (30.4 °C)	Heat wave had much higher relative risk than cold spell compared with moderate high and low temperature, especially for the groups 85+. Low temperature is the main risk for oldest old, with 18.3% of 90–94 years, 16.1% of 95–99 years and 19.1% of 100+
[76]	Ingole et al., 2012	Vadu, India (Aw)	2003-2010	All-cause	Heat, cold	Mean temperature	GLM	Age (0–4, 5–19, 20–59, 60+), Sex	1°C increase in temperature	Mortality is linked to daily ambient temperatures, with children under 5 being especially vulnerable to both heat and cold. Adults aged 20–59 face higher mortality on hot days.
[77]	Ingole et al., 2015	Vadu, India (Aw)	2003-2012	All-cause	Heat, cold	Maximum temperature	a quasi-PGLM	Age (12-59, 60+), sex, cause	Cold: 2nd percentile (<25 °C); heat effect: 98th percentile (>39 °C)	Heat days increased total mortality by 33%, significantly affecting males (RR=1.38), aged 12–59 (RR=1.43). No cold affect.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[78]	Jang et al., 2020	Seoul, South Korea (Dwa)	2011-2017	All-cause	Heat	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65+), sex	Percentile increase (PI) in heat risks per 0.1 °C changes in the urban heat.	Heat-related mortality risk was higher in females (14.56%) than males (9.65%) and greater in those aged 65+ (17.28%) compared to 0-64 (0.08%).
[79]	Jiao et al., 2019	Wuhan, China (Cfa)	2009 -2012	Non- accidental : YLL	Heat wave	Mean temperature	GLM	Age (0-74, 75+), sex, cause	Change in YLL (years) per interquartile range (IQR) increase of daily excess hourly heat	The most intense effect on YLL was found in non-accidental deaths (20.11 years, 95% CI: 8.90-31.33) at lag 0-1. Males had more significant results (11.31 years at lag 1). People aged 0-74 years experienced a higher YLL burden due to high temperatures (14.13 years at lag 1).
[80]	Jin et al., 2024	Shanghai, China (Cfa)	2016-2020	Non- accidental	Cold spells	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65-74, 75-84, 85+), sex, education (low, high)	Cold spell: different temperature thresholds (10th, 7.5th, 5th, 3rd, and 2.5th) and duration days (≥ 2 , ≥ 3 , ≥ 4), compared to risks of non-cold spell days	The highest cumulative relative risk (CRR = 1.122) occurred during cold spells lasting at least two days below the 5th temperature percentile. Higher attributable fractions during cold spells were seen among females (1.34% vs. 1.26% in males), the 75-84 age group (2.36%), and low-education groups (1.58%).
[81]	Kang et al., 2020	South Korea (Dwa/Cfa)	2011-2017: June- September	All-cause	Heat wave	Mean temperature	GLM & DLM	Age (0-64, 65+), rural- urban	Heatwave days vs non-heatwave days	Heatwave-related mortality risk was 1.11 overall, slightly higher in rural areas (RR=1.23) than urban areas (RR=1.10). People aged 65+ had higher risks (RR=1.13) compared to those under 65 (RR=0.98). Among those aged 65+, rural residents had a higher risk of 1.20 than urban residents (RR=1.13)

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[82]	Kim & Kim, 2017	Seoul, South Korea (Dwa)	2009-2012: June to August	Non-accidental	Heat wave	Mean temperature	Conditional logistic regression	sex, education	During heat wave vs non-heat wave days	A lower education group had significantly a higher vulnerability to heat wave-related mortality (OR: 1.261, 95% CI: 1.034–1.538) than those with advanced degrees.
[83]	Kim et al., 2023	Japan (Multi)	1973- 2015	All-cause	Heat	Minimum temperature	a quasi-PGLM & DLNM & DLM	Age (0-14, 15–64, 65+), cause of death, district	Hot nights: $\geq 25^{\circ}\text{C}$ and $\geq 95^{\text{th}}$ percentile vs non-hot night.	All-cause mortality increased by 9–10% during hot nights in comparison with nonhot nights (RR=1.09–1.10). Elderly (≥ 65 years) experienced the longest lag effects.
[84]	Kysely & Kim, 2009	South Korea (Dwa/Cfa)	1991-2005	All-cause	Heat wave	Used two or more metrics	Not show	Age (0-14, 15-59, 60-69, 70-79, 80+), sex	N/A	Mortality was larger in children aged 0-14 and 15-59 years, males during severe heat wave.
[85]	Lan et al., 2012	Harbin, China (Cwa)	2010	Non-accidental	Heat wave	Maximum temperature	Not show	Age (0–64, 65–74, 75+), Sex	RR for deaths during the heat wave vs the reference period	During the heat wave, total mortality increased by 41% (RR = 1.41). Females had higher mortality risk (RR = 1.55) than males (RR = 1.31), with the 0-64 age group (RR = 1.55) and 75+ (RR = 1.36) showing significant increases
[86]	Lei et al., 2022	China (Multi)	2013-2015: cool seasons (i.e., from November to March)	Non-accidental	cold spells	Mean temperature	a quasi-PGAM & DLM	Age (5-64, 65+), sex	Cold-spell: daily mean temperatures of 2.5th, 5th, 7.5th, and 10th percentiles and duration of ≥ 2 , ≥ 3 , and ≥ 4 days durations; $< 5^{\text{th}}$ with ≥ 4 -d duration ($P5_{\geq 4d}$) defined as the main analysis.	Cold spells definition of $P5_{\geq 4d}$ were associated with increased non-accidental mortality risk, with RR=1.39 (95% CI: 1.15, 1.69). Older (65+) were particularly vulnerable (RR 1.77, 95% CI: 1.43–2.20) compared to younger groups (RR=1.41, 95% CI: 1.06–1.88). No sex difference

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[87]	Li et al., 2014	Harbin, Nanjing, Shenzhen and Chongqing, China (Multi)	2004-2012	All-cause	Heat	Maximum temperature	GAM	Age (0-5, 0-14, 15-29, 30-54, 55-64, 65-74, 75+), sex, urban areas of four cities	1°C increase over the threshold.	A 1°C increase in temperature brought approximately a 4.5%, 3.2%, 4.0% and 5.5% increase in daily all-cause mortality in Harbin, Nanjing, Shenzhen and Chongqing, respectively. Females were slightly higher risk for heat than males in the four study areas. Adults aged 30-54 and 55+ found heat-mortality associations.
[88]	Li et al., 2017	Jinan, China (Cwa)	2007–2013: May- September	Non-accidental	Heat	Used two or more metrics	a quasi-PGAM	Age (0-64, 65+), sex, education	1 °C increase above the threshold temperature (Tmax=32°C/ Tmean=28°C/ Tmin=24 °C)	A 1°C rise above the threshold increased non-accidental mortality for Tmax (2.8%), Tmean (5.3%), and Tmin (4.8%). Effects for Tmax were stronger in females (RR=1.034), older adults 65+ (RR=1.038), and those with low education (RR=1.031).
[89]	Li et al., 2017	Ningbo, China (Cfa)	2008-2015	Non-accidental ; YLL	Heat, cold	Mean temperature	GLMs & DLNM	Age (0-74, 75+), sex, time period	Cold:5th (3.0°C) vs MMP; Hot:95th (30.4°C) vs MMP	Heat increased YLL due to non-accidental mortality (RR=1.08 in 2008–2013, and 1.44 in 2013–2015), while cold effects showed a stronger association (RR=1.90, and 1.34). Females had a higher cold-related death risk (RR=2.06) than males. Elderly individuals had higher YLL from temperature extremes than younger ones.
[90]	Li et al., 2021	Guangzhou, China (Cwa)	2011-2017	Non-accidental	Heat	Used two or more metrics	a quasi-PGLM & DLNM	Age (0-64, 65-74, 75+), Sex, Region (Urban/Suburban)	Compound hot extremes as a hot day/night when TMax/TMin was higher than its historical 90th percentile	Compound hot extremes increase mortality risk (RR=1.43, 95% CI: 1.28–1.59) over lag 0–7, with higher risks for females (RR=1.54) and older people (RR=1.41 for 65–74 years, RR=1.63 for 75+ years) compared to males (RR=1.32) and those under 65 (RR=1.01). Urban areas

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
										(RR=1.41) had a higher mortality risk than suburban (RR=1.35).
[91]	Lim et al., 2012	6 cities in South Korea (Dwa/Cfa)	1992-2007	Non-accidental	Heat, cold	Diurnal temperature range (DTR)	PGLM	Age (0-74, 75+), sex, city, education (≤ 6 years or >6 years)	% change of mortality per 1°C increase in DTR	The pooled effect of DTR on mortality was 0.5% per 1°C increase. Gwangju showed the highest mortality increase at 0.8%, while Busan had the lowest at 0.1%. Mortality risk was higher in females (0.6%), aged 75+ (0.6%), and individuals with ≤ 6 years of schooling (0.6%), particularly in the fall season.
[92]	Lin et al., 2011	Taiwan (Cfa)	1994-2007	Non-accidental	Heat, cold	Mean temperature	PGLM & DLNM	Age (65+)	% mortality risk per 1°C temperature change at 18 °C (cold) and 30 °C (heat) vs at 26 °C	Mortality risk in the older aged 65+ is higher in cold (RR= 1.13) than to hot (RR= 1.07).
[93]	Lin et al., 2019	Guangzhou, China (Cwa)	2012-2015	Natural causes	Heat, cold	Mean temperature	NBGLM & DLNM	Age (0-64, 65-74, 75+), sex	Extreme heat: degree-hour >27.8 °C; extreme cold: degree-hour <24.3 °C	An interquartile range (IQR) increase in hot degree-hours raised total mortality by 2.11%, while an IQR increase in cold raised it by 2.42%. Females showed a slightly stronger effect from cold (2.58%) than males (2.36%). Aged 75+ faced the highest risk from extreme temperatures (3.00% in heat, 3.04% in cold).
[94]	Lin et al., 2019	Taiwan (Cfa)	1995-2011	All-cause	Heat, cold	Mean temperature	GLMs & DLNM	Age (all, 65+)	Cold effect: the 5th percentile temperature; heat	Low temperatures increase mortality risk more (RR=1.71) than heat (RR=1.10). Elderly

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
									effect: the 95th percentile temperature	living low-income family significantly influence cold-related mortality risks.
[95]	Liu et al., 2019	Lanzhou, China (BSk)	2014-2017	Non-accidental ; YLL	Heat, cold	Mean temperature	DLNM with meta-analyses	Age (0-64, 65+), Sex	Cold effect: YLL changes per 1°C decrease from 25th to 1st percentile; hot effect: YLL changes per 1 °C increase from 75th to 99th percentile of temperature	Cumulative cold effects (lag 0–30) increased YLL by 246.87 years, while heat effects (lag 0–7) added 88.19 years. Males were more affected by heat (133.58 YLL), females by cold (246.41 YLL). Aged 65+ experienced the strongest effects for heat (89.82 YLL) and cold (121.85 YLL).
[96]	Liu et al., 2020	Hong Kong (Cwa)	2007-2015	Non-accidental	Heat, cold	Mean temperature	PGAMs & DLNM	Age (0-64, 65+), sex, cause, SES (highest-lowest)	Cold effect: 2.5th percentile at lag 0–21 (12.9 °C); heat effect 97.5th percentile at lag 0–3, 30.3 °C,) vs MMT 27 °C	Cold has a stronger impact (RR=1.463, lag 0–21) compared to heat (RR=1.035, lag 0–3). Heat increases mortality risk more in females than males. Older aged 65+ are more vulnerable to extreme temperatures, mostly cold. Heat affects the lowest SES groups (RR=1.040), while cold significantly impacts all SES groups.
[97]	Liu et al., 2021	China (Multi)	2006-2017	Non-accidental ; YLL	Heat, cold	Used two or more metrics	DLNM with meta-analyses	Age (0–64, 65–74, 75 +), sex, region	Extreme cold (≤2.5th percentile), moderate cold (2.5th to MYT 27.4°C), moderate heat (MYT to 97.5th), extreme heat (>97.5th.	Cold increased YLL per death (0.98) more than hot (0.04), with moderate cold having the largest impact (0.84). Cold caused larger YLLs in males (1.12) than females (0.82), and the highest YLLs were in those aged 65–74 (1.27).
[98]	Liu et al., 2023	China (Multi)	2013-2015	Non-accidental	Heat, cold	Temperature variability (TV)	a quasi-PGLM	Age (5-64, 65-74, 75+), sex	Every 1°C increase in TV	TV at 0–7 days increased non-accidental mortality risk by 0.79%. Effect of TV0–7 on daily total mortality were larger in the warm season than cold season.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
										The attributable fraction was higher in females (6.77%) than males (2.49%). Mortality was highest in those aged 75+ (5.78%).
[99]	Lv et al., 2020	Hunan, China (Cfa)	2013- 2017	Non-accidental	Heat, cold	Mean temperature	DLNM with meta-analyses	Age (0-64, 65+), sex	Extreme cold: <the 2.5th percentile (10.41 °C); Extreme heat: > the 97.5th percentile (24.74 °C); Moderate heat and cold: between 17.74°C vs extreme heat/cold	Cold temperatures accounted for most of the YLL burden, with 10.27% for non-accidental mortality, including 9.26% from moderate cold. YLLs were higher in older adults (14.06% for cold; 0.86% for heat) and females (14.59% for cold; 0.39% for heat).
[100]	Meng et al., 2022	Shenzhen, China (Cwa)	2013-2017	All-cause; non-accidental	cold spells	Mean temperature	a quasi-PGLM & DLNM	age (0-64, 65+), sex	Cold spell: 3rd percentile in ≥3 consecutive days	Cold spells increased all-cause mortality risk by 1.54 (95% CI: 1.20–1.98) and non-accidental mortality by 1.43 (95% CI: 1.11–1.84) at lag 0–14 days. Females had a higher risk (RR=1.55) than males (RR=1.36) for non-accidental deaths. Those aged 0–64 faced a higher risk (RR=1.46) than those aged 65+ (RR=1.40).
[101]	Ngarambe et al., 2022	Seoul, South Korea (Cwa)	1999-2018	Non-accidental	Heat wave	Maximum temperature	GAM	Age (0-64, 65+), sex, education (low, high education)	N/A	The influence of HWs on mortality is more apparent in Males (RR = 0.40, 95% CI: 0.23–0.54) and aged 65+ (RR = 0.10, 95% CI: 0.002–0.18). Low-educated groups showed higher mortalities than high-educated groups.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[102]	Onozuka et al., 2015	Fukuoka, Japan (Cfa)	1973–2012	Non-external	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0–14, 15–64, 65–79, 80+), sex	Extreme cold effect: < 2nd percentile (5.0 °C), Lag 0–25; Extreme heat effect: >the 98th percentile (30.0 °C), Lag 0–1	Both heat (RR=1.06, 95% CI: 1.00–1.13) and cold (RR=1.06, 95% CI: 1.03–1.08) extremes increased mortality risk. Females were more affected by both heat (RR=1.10) and cold (RR=1.07). Those aged 80+ faced higher risks from heat (RR=1.15) and cold (RR=1.12) extremes.
[103]	Ou et al., 2013	Guangzhou, China (Cwa)	2003–2011	All-cause	Cold	Mean temperature	GLM	Age (0–64, 65–74, 75+), sex, educational groups (no education, primary, higher education)	A 1 °C decrease/increase in monthly mean temperature	A 1°C decrease in monthly mean temperature increased mortality by 1.38% (95% CI: 0.34%–2.40%). Excess winter mortality was higher in females (1.13%, 95% CI: 0.22%–2.04%), the elderly (75+) (1.33%, 95% CI: 0.35%–2.29%), and those with low education (2.19%, 95% CI: 0.98%–3.39%).
[104]	Park & Chae, 2023	Seoul, Incheon, Daegu, and Gwangju, Korea (Multi)	1999–2018: during summer	Non-external	Heat	Maximum temperature	PGLM & DLNM	Age (0–64, 65+), education, cities	Mild heat days: Tmax in the 60th–90th percentile range; Moderate heat: the 90th–99th; Severe heat: 99th or more percentile	Older adults had a 7.05% RR increase (95% CI: 4.74–9.69) in Seoul and 3.00% (95% CI: 0.77–5.69) in Incheon. Less-educated individuals experienced a 2.91% RR increase per 1°C on moderate heat days and 4.49% on severe heat days in Seoul.
[105]	Pehlivan et al., 2024	South Korea (Dwa/Cfa)	2011–2021	All-cause	Heat, cold	Temperature variability	a quasi-PGLM & DLNM	Age (0–64, 65+), sex, seasons	% change in mortality per interquartile range (IQR) increase in each TV index.	TV-related mortality risks were consistently high in spring and generally high in summer. Interday TV was generally associated with female (IQR=0.49%) and aged 65+ mortality (IQR=0.32%)

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[106]	Revich & Shaposhnikov, 2010	Yakutsk, Russia (Dfd)	1999-2007	Non-accidental	Heat waves, cold spells	Mean temperature	Pearson correlation coefficient	Age (30-64, 65+)	During heat waves (cold spells) days vs non-heat waves (cold spells) days	Mortality rose by about 50% during three heat waves. While per one wave analyzed, cold spells produced more effects than heat waves. Heat waves increased only mortality in those aged 30–64 (RR=1.27), while cold spells significantly affected those 65 and older (RR=1.33).
[107]	Rezace et al., 2023	Iran (Multi)	2008-2014, 2015-2022: summer	All-cause	Heat wave	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex, cities	Heat wave days: mean temperatures above (95th, 98th percentiles) and duration days (≥ 2 , ≥ 3 , ≥ 4) vs not heat wave days	In 2015-2022, the risk due to severe heat waves declined, higher mortality risk based on the least severe (RR 1.29) and less severe heatwaves (RR=1.25). Effects were strongest among females (RR=1.6) and older adults (RR=1.48), with no significant impact on males or younger groups. Elderly in Sanandaj were the most vulnerable to heatwaves.
[108]	Riahi & Khorsandi, 2025	Tehran, Iran (BSh)	2012-2019	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex	Extreme cold and heat: at the 2.5th (2.4°C) and 97.5th (33.9°C) percentiles of the temperature distribution.	Cold had a stronger effect on non-accidental mortality (RR=1.67) than heat (RR=0.24). Cold was linked to higher male mortality (RR=1.11). Older adults (≥ 65) were more affected by extreme cold (RR=1.20), while younger individuals (0–64) faced greater risk from extreme heat (RR=1.10).
[109]	Seposo et al., 2015	Manila City, Philippines (Af)	2006-2010	All-cause	Heat	Mean temperature	PGLM & DLNM	Age (0-14, 15-64, 65+), sex	Per 1°C increase; mortality in 1st, 5th, 95th, and 99th temperature percentiles and respective MMTs	Females (RR=1.47, 95% CI: 1.27–1.69) and older adults (65+) (RR=1.53, 95% CI: X) had the highest temperature-related mortality risks.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[110]	Sharma et al., 2024	Ahmedabad, India (BSh)	2002–2018	All-cause	Heat	Maximum temperature	DLNM	Sex	Extreme heat day (above 40 °C, 41 °C, 45 °C.) vs non-extreme heat day	All-cause mortality risk rises significantly at high temperatures, with a 30% (RR=1.30) increase at 40 °C and over triple (RR= 3.08) at 45 °C. Females were more vulnerable, showing higher risks than males (RR = 1.40 vs. 1.25 at 40 °C) and greater mortality during severe heatwaves (RR = 3.11 at ≥45 °C).
[111]	Singh et al., 2019	Varanasi, India (Cwa)	2009-2016	All-cause	Heat, cold	Used two or more metrics	a quasi-PGLM & DLNM	Age (0-4, 5-44, 45-64, 65+), sex	Heat wave: equal or above the 95th percentile (≥34.5 °C) for at least 3 consecutive days during summer Cold spell: equal to or below the 5th percentile (≤14.7 °C) for at least 3 consecutive days during winter	Daily temperature increased mortality by 5.61% in summer (95% CI: 4.69–6.53%) and 1.53% in winter (95% CI: 0.88–2.18%). Heat waves raised mortality by 12.02% (95% CI: 4.21–19.84%). Females had higher risk (RR=1.22, 95% CI: 1.09–1.37). The most heat-sensitive group was 0–4 years (RR=1.39, 95% CI: 1.16–1.69), and cold spells impacted ages 45–64 most (RR=1.17, 95% CI: 1.03–1.33).
[112]	Son et al., 2011	Seoul, South Korea (Dwa)	2000-2007	Non-external	Heat, cold	Mean temperature	GLM	Age (0–14, 15–64, 65–74, 75+), sex, cause, educational (none, 0-12, 12+)	Cold effect: the 10th percentile (-1°C) vs the 50th percentile (15°C); Heat effect: at the 90th percentile (25°C) vs the 50th percentile (15°C)	Mortality risk increased more in cold (12.17%) than heat (10.16%). Females (16.88% for cold; 12.33% for heat), those aged 75+ (16.44% for cold; 16.16% for heat), and no education (28.68% for cold; 16.11% for heat) were more affected.
[113]	Son et al., 2012	7 cities in South Korea (Multi)	2000-2007	All-cause	Heat wave	Mean temperature	GLM & DLNM	Age (0-14, 15–64, 65–74, 75+), sex, education level (none,	Every 1°C increase in average daily mean temperature during heat waves	Total mortality increased by 4.1% during heat waves compared with non-heat-wave days, and by 8.4% in Seoul. In Seoul, higher mortality risks were observed for females (15%), older adults

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
								1–12, > 12 years), city		(14.8%), and those with no education (24.8%), though these were not statistically significant.
[114]	Song et al., 2023	18 cities in China (Multi)	2014-2018	All-cause	Cold spells	Mean temperature	Conditional Poisson regression & DLNM	Age 0–44, 45–59, 60–74, 75–89, 89+), sex, urbanisation (rural-urban), climate zone	Cold spells: temperature thresholds (1 st , 3 rd , 5 th , & 10 th percentile) and lasting ≥2-3 consecutive days for the 1st and 3rd percentiles, and ≥2-5 days for the 5 th & 10 th percentiles vs. non- cold spell days	Cold spells significantly increased all-cause mortality (CRR=1.38). Women (CRR=1.40 vs 1.38 for men) and the oldest adults (89+, CRR=1.57) were most affected, with risk rising with age. Rural areas (AF=2.85%) and subtropical monsoon zones (AF=3.36%) showed greater vulnerability.
[115]	Sun et al., 2014	Pudong New Area, China (Cfa)	2008-2013	All-cause	Heat wave	Maximum temperature	GAM	Age (0-64, 65-79, 80+), sex	During 2013 heat waves	During the 2013 heat wave, excess mortality reached 10.51%, with females (11.79%) more affected than males (10.43%). The highest impact was observed in individuals aged 80+ (16.64%).
[116]	Torkian et al., 2021	Kerman, Iran (BWh)	2006-2016	All-cause	Heat, cold	Diurnal temperature range (DTR)	a quasi- PGLM & DLNM	Age (0-18, 18-59, 60+), Sex	High extreme DTR: 90 th (23°C) to 99 th (26°C) vs. 50 th (19°C); Low extreme DTR: 1 st (5°C) to 10 th (12°C) on total mortality.	Mortality increased at the 90 th DTR percentile (CRR=1.16, lag 0–21) and the 10th percentile (CRR=1.27, lag 0–13; CRR=1.35, lag 0–21). At the 10 th percentile, higher mortality was noted in the elderly (CRR=1.26, lag 0–13) and males (CRR=1.38, lag 0–13; CRR=1.54, lag 0–21). At the 90 th percentile, mortality increased more in males (CRR=1.21, lag 0– 21).

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[117]	Wang et al., 2017	China (Multi)	2007-2012	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Climate zone, GDP	RR below/above the MMT	Cold-related mortality risk (1.63, 0–21 lag) was higher than heat-related risk (1.15, 0–3 lag). The highest cold risk (1.92) occurred in the middle subtropics, while the highest heat risk (1.21) was in the warm temperate zone. Heat risks were higher in wealthier areas, and cold risks in middle-income regions.
[118]	Wang et al., 2018	China (Multi)	2007-2012	Non-external	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Rural-urban	RR below/above the MMT	Cold effect was stronger in rural areas (RR: rural 1.69 vs. urban 1.51), while heat effect was stronger in urban areas (RR: rural 1.01 vs. urban 1.12).
[119]	Wang et al., 2019	Hong Kong (Cwa)	2006-2015	All-cause	Heat	Mean temperature	GAM	Age (0-18, 19–64, 65+), sex	% increased risks of mortality	A single hot night increased mortality by 2.74% in females and 2.53% in those aged 65+. Prolonged hot nights (>5) raised mortality risk to 6.06% for females, 4.70% for males, and 5.33% for those aged 65+.
[120]	Wang et al., 2021	Yunnan, China (Cwb)	2013-2015	Non-accidental	Heat, cold	Diurnal temperature range (DTR)	a quasi-PGLM & DLNM	Age (0-74, 75+), sex, occupation (farmer or non-farmer)	Extremely low and extremely high DTR (the 1st and 99th percentile of DTR distribution)	DTR was higher in the cold season. Non-accidental mortality attributable to DTR accounted for 15.52%, with high DTR contributing the majority (14.48%). DTR was slightly greater for males (16.35%), those aged 75+ (20.41%) and non-farmers (27.16%).
[121]	Xia et al., 2024	4 cities in Sichuan Basin, China (Cwa)	2016-2021	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65+), sex, education level (low and high)	Extreme cold and heat: (below the 1st percentile), and above the 99th; moderate cold and	Overall, 10.16% of non-accidental deaths were attributed to non-optimal temperatures, mainly cold (9.10%) and less from heat (1.06%). Most deaths

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
									heat: the 1st percentile to MMT, and MMT to the 99th	were linked to moderate cold (6.23–12.30%), with minimal impact from extreme cold (0.24–0.48%) and heat (0.10–0.37%). Higher burdens to heat and cold were seen in females (AF = 12.37%), those under 65 (AF = 12.42%, mainly moderate cold), and individuals with low education (AF = 10.54%).
[122]	Xiao et al., 2021	Shenzhen, China (Cwa)	2013-2017	Non-accidental	Heat, cold	Diurnal temperature range (DTR)	a quasi-PGLM & DLNM	Age (0-64, 65+), sex	The 99th percentile of DTR distribution (10.8 °C for the full year, 11.5 °C for the cold season and 8.8 °C for the warm season)	Extreme large DTR (99th) in cold seasons raised mortality risk (RR=1.407, Lag 0–7), with no significant effects in warm seasons. Elderly (RR=1.548) and females (RR=1.587) were more sensitive to temperature changes, especially in cold seasons
[123]	Xuan et al., 2014	Hanoi, Vietnam (Cwa)	2005-2010	All-cause	Heat, cold	Mean temperature	a quasi-PGAM	Age (60+), Sex	N/A	Deaths aged 60+ increased by 21% in the cold season compared to the warm season, with a higher rise among females (IRR=1.23) than males (IRR=1.18).
[124]	Yan et al., 2022	China (Multi)	2017	All-cause	Heat wave	Mean temperature	PGLM	Age (0–64, 65–74, 75+). Sex	Heat wave days in 2017 vs non-heatwave days	The 2017 heatwaves increased all-cause mortality (RR=1.23), with higher risks for females (RR=1.31) and those aged 65–74 and 75+, compared to males (RR=1.18) and younger individuals.
[125]	Yang et al., 2012	Guangzhou, China (Cwa)	2003-2007	Non-accidental	Heat, cold	Mean temperature	PGLM & DLNM	Age (0–64, 65–74, 75–84, 85+), sex, education, occupation (unemployed,	Cold: 1st (8.2°C) relative to 10th percentile (13.8°C); heat: 99th (29.9°C) vs. the 90th percentile (32.0°C)	Cold effect was stronger (RR=20.39%) than heat. Females had higher heat risk (OR=1.192). Aged 85+ increased risks (heat: OR=1.195, cold: OR=1.187). Blue-collar workers were more

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
								blue-collar, white-collar)		vulnerable (heat: OR=1.095, cold: OR=1.104), with no education differences.
[126]	Yang et al., 2013	Guangzhou, China (Cwa)	2003-2010	Non- accidental	Heat, cold	Diurnal temperature range (DTR)	a quasi- PGLM & DLNM	Age (0–64, 65–74, 75+), sex, education (no education, primary, higher)	a 1 °C increase in DTR	A 1°C increase in DTR at lag 0–4 days increased mortality by 0.47%. Females were more sensitive to DTR (1.22%) than males. Older adults (65-74: 0.83%) were more sensitive than youth (0–64). Low education had higher risk (1.21%).
[127]	Yang et al., 2013	Guangzhou, China (Cwa)	2003-2006	Non- accidental	Heat wave	Mean temperature	Conditional logistic regression	Age (0-64, 65-74, 75+), sex, employment, education	Excess deaths and rate ratio (RR) of death in heat wave vs non-heat wave	Heatwaves increased mortality (RR=1.23). Females (RR=1.46), the elderly aged 75+ (RR=1.49), and those with no education (RR=1.52) were most vulnerable. Blue-collar workers (RR=1.39) faced a greater risk than white- collar workers.
[128]	Yang et al., 2015	Guangzhou, China (Cwa)	2003-2007	Non- accidental ; YLL	Heat, cold	Mean temperature	GLMs	Age (0-74, 75+), sex, education (low, high)	Cold effect: YLL changes per 1°C decrease from 25th to 1st percentile; heat effect: YLL changes per 1 °C increase from 75th to 99th percentile of temperature	Cold effects were stronger than heat, with a 31.15 YLL increase (95% CI: 20.57–41.74) for non- accidental deaths, compared to 12.71 YLL for heat. Cold impacts were higher in males (17.81 YLL), those under 75 years (18.83 YLL), and low education (14.76 YLL). Heat-related YLL were significant in females (10.12 YLL), aged 75+ (5.97 YLL), low education (15.76 YLL).

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[129]	Yang et al., 2019	31 cities in China (Multi)	2007-2013: May– September	Non- accidental	Heat wave	Maximum temperature	GLM	Age (0-64, 65-74, 75+), sex, education (none, primary, higher), cities	During heatwave days vs non- heatwave days	Heatwaves increased mortality, with the highest risks at lag 0–10 (RR=1.10). Females (RR=1.14 vs 1.07 for males), the older aged 75+ (RR=1.17), and those with lower education (RR=1.18) were most vulnerable. Risk was highest in Jinan (RR=1.34) and lowest in Chongqing (RR=0.91).
[130]	Yang et al., 2021	31 cities in China (Multi)	2007-2013	Non- accidental	Heat, cold	Hourly temperature variability (HTV)	a quasi- PGLM & DLNM	Age (0-64, 65+), sex, education (low: illiterate or primary school; high: secondary school or higher)	% change of mortality per 1 °C increase of HTV	Each 1 °C rise in HTV (lag 0–17) increases mortality by 1.38% (95% CI: 0.77–1.99), with 5.47% of such deaths attributable fraction (AF) to HTV. The females (AF= 6.99%), the older (AF= 6.80%), and low education level (AF= 9.47%) were significantly more susceptible to HTV than their counterparts.
[131]	Yang et al., 2024	13 cities in Jiangsu, China (Cfa/Cwa)	2014-2022	All-cause	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (0-64, 65–75, 75+)	Extreme cold and heat: at the 2.5th and 97.5th percentiles	Extreme cold had a greater impact (CRR = 1.43) than extreme heat (CRR = 1.18). The highest risks occurred in those over 75 years (CRR = 1.59 for cold; 1.25 for heat).
[132]	Yatim et al., 2021	Klang Valley, Malaysia (Af)	2006-2015	Natural causes	Heat, cold	Mean temperature	GLM & DLNM	Age (0-14, 15-59, 60+), Sex	Cold: 1st percentile (25.2 °C) Heat: 99th percentile (30.2 °C)	High temperatures had immediate mortality effects (lags 0–3 days, RR=1.09), while cold effects were delayed (lags 0–28 days, RR=1.26). Females and older adults were more vulnerable, with RRs of 1.21 (1.08–1.34) and 1.15 (1.03–1.27), respectively.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[133]	Yin et al., 2018	China (Multi)	2013 -2015	Non- accidental	Heat wave	Mean temperature	GAM & DLM	Age (5–64, 65–74, 75+), sex, education (low, high: >9 years)	Heatwave days vs non-heatwave days	Heat risks typically occurred immediately and lasted 3–5 days. During heatwaves (≥ 97.5 th percentile for ≥ 2 consecutive days), RR of total mortality was 1.07 (1.03–1.10), higher in females, the elderly (≥ 75 years), and less-educated individuals.
[134]	Zeng et al., 2022	China (Multi)	2006-2017	Non- accidental ; YLL	Heat, cold	Mean temperature	DLNM	Age (0-64, 65–74, 75+), region	Extreme cold: below the 2.5th percentile (-8.2°C) Extreme heat: above the 97.5th percentile (30.3°C)	The YLL rates attributable to extreme cold were much greater (YLL rates=5.0, 95 % CI: 4.1-5.9) than that attributed to extreme heat (0.4, 95 % CI: 0.3-0.6). The overall YLL rates due to cold and hot temperature were larger for the older (aged 65–74 and 75+) than the younger population.
[135]	Zhang et al., 2014	Beijing, Shanghai, and Guangzhou, China (Multi)	2001-2008	All-cause	Heat, cold	Mean temperature	PGLM & DLNM	Age (0-64, 65+), city	Cold effect: 1°C decrease in temperature below the cold threshold; heat effect: 1°C increase in temperature above the heat threshold	Cold effect was higher in those aged 0–64 in Beijing (RR=22.11) but greater in those aged 65+ in Shanghai (RR=3.72), Guangzhou (RR=13.86). Heat effects were higher in aged 65+ in Beijing (RR=1.30), Shanghai (RR=2.21), Guangzhou (RR=2.96).
[136]	Zhang et al., 2017	Wuhan, China (Cfa)	2009-2012	Non- accidental ; YLL	Heat, cold	Diurnal temperature range (DTR)	a quasi- PGLM &DLNM	Age (0–74, 75+), sex, education (0– 6, 7+ years)	1°C increase in DTR	Higher DTR increased mortality by 0.65%. Females greater increases in mortality (1.26%) and YLL (1.46%). Aged 75+ had increased YLL (0.72%). Those with 7+ years of education found higher mortality (1.18%) and YLL (1.25%) due to large DTR.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[137]	Zhang et al., 2017	Hubei, China (Cfa)	2009-2012	All-cause	Heat, cold	Heat index	a quasi- PGLM & DLNM	Age (0-74, 75+), sex, cause, education (low, high), urban-rural	Extreme cold effect: 1st percentile; extreme heat: 99th percentile	Cold effects (RR=1.828 at lag 0–21) were much larger than heat (RR=1.097 at lag 0–2). Higher mortality risks were found among females (1.910 for cold; 1.134 for heat), aged 75+ (2.241 for cold; 1.164 for heat), and higher education (2.028 for cold; 1.134 for heat). Heat effects were slightly higher in rural, while cold-related mortality impacts were stronger in urban.
[138]	Zhang et al., 2017	Hubei, China (Cfa)	2009-2012	Non- accidental	Heat, cold	Temperature variability (TV)	a quasi- PGLM & DLNM	Age (0–74, 75 +), sex, education attainment (low, high), city, urban- rural	% increase in mortality per 1 °C increase in TV	A 1°C increase in TV0–7 raised mortality by 1.19% annually, 1.94% in the warm season, and 0.87% in the cold season. Effects were stronger in the warm season for males (2.24%), those aged 75+ (2.05%), and highly educated individuals (1.84%). Urban areas showed greater mortality.
[139]	Zhang et al., 2018	Hubei, China (Cfa)	2009-2012	Non- accidental ; YLL	Heat, cold	Mean temperature	GLM & DLNM	Age (0-74, 75+), sex, education (low, high)	Cold effect: % changes of YLL per 1°C decrease from 25th to 1st percentile at lag 0– 21 days; hot effect: per 1 °C increase from 75th to 99th percentile of temperature at lag 0–2 days	Cold effects increased YLL from non-accidental deaths by 5.09% (95% CI: 2.79–7.40), surpassing heat effects at 1.91% (95% CI: 0.83–3.00). Cold impacts were higher in females (5.51%) and the elderly (1.20%), while heat effects were greater in males (1.98%) and younger individuals (1.12%). Stronger heat and cold effects were consistently observed in low-educated individuals (5.11% for cold, 2.33% for heat).

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[140]	Zhou et al., 2014	China (Multi)	2001-2010	Non-accidental	Heat, cold	Diurnal temperature range (DTR)	GAM	Age (1-64, 65+), sex	A risk of mortality on 1 °C increase of DTR	A 1°C increase in DTR on lag-day 1 increased non-accidental mortality by 0.42% (95% CI: 0.14–0.70) in cool seasons. Females had a stronger association with DTR (0.51% in cold seasons). The association was stronger for those aged 65+ (0.46% in cold seasons) compared to younger individuals (0.10%).
[141]	Zhou et al., 2014	36 cities in China (Multi)	2006-2010: December to February	Non-accidental	Cold spells	Mean temperature	DLNM	Age (0-64, 65-74, 75-84, 85+), sex, urban-rural, region	Cold spell: >5 consecutive days with temperature below the 5th percentile	The 2008 cold spell increased mortality by 43.8% (95% CI: 34.8%–53.4%), with the highest impact in southern (53.2%) and central China (53.8%). Females (48.9%) faced higher risk than males (38.5%). Older adults (85+ years) were most affected (65.4%) compared to younger populations (17.9%). Urban areas (46.0%) had slightly higher mortality than rural areas (42.7%).
Europe (n=50)										
[142]	Almeida et al., 2010	Lisbon and Oporto, Portugal (Csa/Csb)	2000-2004: April - September	Non-external	Heat	Mean apparent temperature	a quasi-PGAM	Age (all age, 65+), cities	1°C increase in mean apparent temperature	A 1°C rise in daily apparent temperature increased all-cause mortality by 2.7% in Lisbon and 1.5% in Oporto. Aged 65+, mortality rose by 2.7% (95% CI: 2.2–3.2) in Lisbon and 1.8% (95% CI: 1.2–2.3) in Oporto.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[143]	Analitis et al., 2008	Greece, Spain, Hungary, Ireland, Finland, Slovenia, United Kingdom, Italy, France, Czech Republic, Sweden, Switzerland (Multi)	1990-2000: cold season (October–March)	Natural causes	Cold	Minimum apparent temperature	GEE	Age (0–14, 15–64, 65–74, 75+)	1°C decrease in minimum apparent temperature (average of lags 0–15)	A 1°C drop in temperature was linked to a 1.35% (95% CI: 1.16–1.53) rise in daily natural deaths, with stronger effects in older age groups: 1.67% (95% CI: 1.45–1.90) for ages 75+ and 1.02% (95% CI: 0.78–1.26) for ages 65–74. Colder temperatures had a stronger impact in warmer southern cities, with effects lasting up to 23 days.
[144]	Arbuthnott et al., 2020	Greater London, West Midlands (including Birmingham), Greater Manchester, England (Cfb)	1996-2013	All-cause; YLL	Heat, cold	Mean temperature	PGLM & DLM	Age (0–65, 65–74, 75+), sex, cause, city	Cold effects: each 1 °C below the cold threshold (35th percentiles) at lag 0-27; heat effect: each 1 °C above the heat-threshold (91st percentiles) at lag 0-2	Heat increased mortality by 3.9% and YLL increased by 3.0% in London, and cold increased mortality by 3.1% in the West Midlands, with similar YLL increases. Heat effects were higher in females in London and Manchester, and cold effects were slightly higher in females in London and West Midlands. Aged 75+ faced the highest mortality risks in heat and cold.
[145]	Aringstrom et al., 2016	Estonia (Dfb)	1997-2013	All-cause	Heat	Maximum temperature	GLM & DLNM	Age (0-74, 75+), sex, regions	the 75th vs. the 99th percentiles of daily maximum temperature	High summer temperatures significantly increased mortality. Heat effect was RR=1.12 in coastal regions and 1.28 in inland regions. Older adults (75+) in inland regions had the highest RR (lag 0–2: 1.45; lag 0–10: 1.38). Sex did not modify mortality risk.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[146]	Åström et al., 2013	Stockholm, Sweden (Dfb)	1901-2009	All-cause	Heat, cold	Mean temperature	GLM	Age (0–14, 14–64, 65+), sex	Extreme cold: below the 2nd percentile (–6.9°C) at lag025 Extreme heat: above the 98th percentile (20.8°C) at lag01	Heat extremes showed higher RRs than cold extremes in all decades. RRs increased for those over 65 during both heat and cold extremes throughout the period. Sex did not modify mortality risk
[147]	Åström et al., 2019	Tallinn (Estonia), and Riga (Latvia) (Dfb)	1997-2015	All-cause	Cold	Minimum temperature	PGLM & DLNM	Age (0-74, 75+), cause	Cold effect: at the 5th percentile; modestly cold: the 2.5th percentile vs MMT; extremely cold: below the 2.5th percentile	Cold temperatures significantly increased mortality by 41% (RR=1.41) in Riga and by 28% (RR=1.28) in Tallinn. Significantly increased mortality was observed in the 75+ age group (RR = 1.64) in Tallinn. The AFs for modestly cold were 6.9% and 7.8% for extremely cold.
[148]	Baccini et al., 2008	15 Cities in 12 European countries (Multi)	1990-2000: April-September	Natural causes	Heat	Maximum apparent temperature	GEE	Age (15–64, 65–74, 75+), cities, region	1°C increase in maximum apparent temperature above the threshold (29.4°C: Mediterranean cities, 23.3°C: north-continental cities)	A 1°C rise in maximum apparent temperature above thresholds increased mortality by 3.12% in the Mediterranean region and 1.84% in the north-continental region. Heat effect was largest in the older aged 75+, with 4.2% for the Mediterranean region and of 2.1% for the north-continental region.
[149]	Can et al., 2019	Istanbul, Turkey (Csa)	2013-2017: June–August	Non-accidental	Heat wave	Mean temperature	Not show	Age (0–14, 15–64, 65–74, 75+), sex	During the heat wave (above the 95th percentile with three added lag days) vs during the reference period.	Extreme heat waves in 2015, 2016, and 2017 increased mortality risk by 6% to 21%. Female mortality risk was higher, with RR=1.25 in 2015 and RR=1.29 in 2016. Aged 75+ faced higher risk, with RR=1.16 in 2015 and RR=1.38 in 2017.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[150]	de Schrijver et al., 2022	Switzerland (Multi)	1969-2017	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65-79, 80+)	Cold effect: at the 1st percentile of the temperature distribution; heat effect: at the 99th percentile	Cold-related mortality accounted for 8.91% of deaths, much higher than heat (0.28%). The 80+ age group had the highest burden (10.99% for cold; 0.42% for heat).
[151]	de'Donato et al., 2013	Italy (Multi)	January 2012 - February 2012	All-cause	cold spells	Mean temperature	PGLM	Age (65+, 75+), cause	Excess mortality during cold spell episodes	An overall 1578 (+25%) excess deaths among the 75+ age group was recorded in the 14 cities that registered a cold spell in February 2012. A statistically significant excess in mortality was observed in several cities ranging from +22% in Bologna to +58% in Torino.
[152]	Demoury et al., 2022	9 largest municipalities, Belgian (Cfb)	2010-2015	Natural causes	Heat, cold	Maximum temperature	CLR & DLNM	Age (0-64, 65-74, 75-84, 85+), sex	Cold effects: the 2.5th percentiles (-1.3 °C); Heat effects: 97.5th percentiles (28.6°C)	Cold temperatures had a stronger effect on mortality (OR=1.42, 95% CI: 1.30-1.57) than heat (OR=1.17, 95% CI: 1.12-1.21). Females were at higher risk for heat effects (OR=1.20). People aged 85+ experienced significantly higher cold effects (OR=1.57) compared to heat effects (OR=1.19).
[153]	Demoury et al., 2022	Belgium (Cfb)	2010-2015	Natural causes	Heat, cold	Maximum temperature	a quasi-PGLM & DLNM	Age (0-64, 65-74, 75-84, 85+), sex, %higher-education graduates (low and high), cause	Cold effect: at 1st percentile (-1.7 °C) and 5th percentile (2.3 °C) vs MMT (23.1°C); Heat effect: 6.7 °C (95th percentile) and 31.3 °C (99th percentile) vs MMT	Mortality risk was 1.32 at cold and 1.21 at heat. Heat effects were stronger in females (RR=1.29) than males (RR=1.10) and highest for ages 0-64 (RR=1.46). Cold effects were greater in ages 75-84 (RR=1.34), 85+ (RR=1.44), and in high-education areas (RR=1.55). No differences in heat effects by education level.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[154]	D'Ippoliti et al., 2010	Athens (Greece), Barcelona, Valencia (Spain), Budapest (Hungary), London (UK), Milan, Rome (Italy), Munich (Germany), Paris (France) (Multi)	1990-2004	All-cause	Heat wave	Used two or more metrics	GEE	Age (65-74, 75-84, 85+), sex, city	% increase in daily mortality during heat wave days vs non heat wave days	Heatwave days increased mortality by 7.6% in Munich to 33.6% in Milan, with up to 3-fold higher mortality during prolonged, intense episodes. The highest effect was observed among females aged 75-84, 85+ years, especially in Mediterranean cities.
[155]	Ellena et al., 2020	Turin, Italy (Cfa)	1982-2018	All-cause	Heat	Mean temperature	a quasi-PGLM & DLNM	Age (0-64, 65-74, 75-84, 85+), sex, education (less than primary, secondary, more)	Heat effect: at the 99th percentile of temperatures	Mortality risk is higher in females (RR=1.88) than males (RR=1.56). The highest risk in females is seen in those aged 85+ (RR=2.13) and with lower education levels (RR=1.93). For males, the highest significant effect is among those with higher education (RR=1.66).
[156]	Ellena et al., 2022	Turin, Italy (Cfa)	1982-2018	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (65-84, 85+), sex, education (until primary, higher), time period	Cold: the 1st percentile Heat: the 99th percentile	Heat posed a greater mortality risk (1.51% in 1982-2006 to 1.59% in 1994-2018) than cold (1.15% to 1.24%). Risks were higher for females (heat: 1.68%-1.25%, cold: 1.19%-1.23%), aged 85+ (heat: 1.83%-1.78%, cold: 1.39%-1.35%), and those with less education (heat: 1.55%-1.57%, cold: 1.18%-1.26%).

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[157]	Fernández et al., 2025	Seven cities in Norway (Multi)	1996-2018	Non-accidental	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0–74, 75+), sex	Cold and heat effects: at the 1st and 99th percentiles of relative to the MMT	About 5.3% of deaths were linked to non-optimal temperatures, mainly moderate cold(AF=4.9%). Females and adults aged 75+ showed significant mortality associations with non-optimal weather, while those aged 0–74 was affected only by cold.
[158]	Fernández et al., 2025	Norway (Multi)	1996-2018	Non-accidental	Heat, cold	Mean temperature	Conditional Poisson regression & DLNM	Age (proportion of aged 65+), sex, region, degree of urbanisation, quintiles of tertiary education, and income	Cold and heat effects: at the 1st and 99th percentiles of relative to the MMT	Most temperature-related deaths were from cold (AF = 9.9%) vs heat (0.1%). Higher education and high income reduced vulnerability (56.32 cold, 0.54 heat deaths per 100,000 person-years). Rural areas had higher heat mortality, peaking in the southeast for heat and central-east for cold. No sex differences.
[159]	Gabrie & Endlicher, 2011	Germany (Cfb)	1990-2006	All-cause	Heat wave	Used two or more metrics	N/A	Age (0-49, 50+), sex, urban/rural	Heat-stressed days vs non-heat-stressed days.	Females, aged 50+, showed greater heat vulnerability, with deaths exceeding expectations by 54.9% in Berlin. Mortality rates rose by up to 67.2% during extreme heat waves, both in the urban of Berlin.
[160]	Gallo et al., 2024	35 countries in Europe (Multi)	2000-2023	All-cause	Heat	Mean temperature	a quasi-PGLM & DLNM	Age (0–64, 65-79, 80+), sex, countries	Heat effect: temperature 95th and 99th centile	Southern Europe showed the highest heat-related mortality, particularly in Greece (393 deaths per million), Bulgaria (229), Italy (209), Spain (175), Cyprus (167), and Portugal (136). Women (ratio = 1.55) and the elderly (80+/65–79 years = 8.68) faced greater risks across most European regions.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[161]	Gasparri et al., 2022	England and Wales, UK (Cfb)	2000-2019	All-cause	Heat, cold	Mean temperature	Conditional Poisson regression & DLNM	Age (0-64, 65-74, 75-84, 85+), cities	Cold effect: at 1st temperature percentile vs MMT; heat: 99th temperature percentile vs MMT	Annually, cold-related deaths (60,753) greatly exceed heat- related deaths (791). Susceptibility to non-optimal temperatures increases with age, with older adults (RR=1.553 for cold; 1.072 for heat) facing higher risks than those aged 0-64 (RR=1.249 for cold; 1.038 for heat).
[162]	Gemmell et al., 2000	Scotland, UK (Cfb)	1981-1993	All-cause	Heat, cold	Mean temperature	PGLM	Age (0-9, 10- 59, 60-69, 70- 79, 80+), sex, SES	% change in deaths per 1°C a fall in temperature at lag 0-5 week	A 1°C drop in mean temperature led to a 1% rise in deaths after one week. Between 1981 and 1993, annual seasonal mortality increased by 29% for females and 34% for males. No clear for SES and mortality.
[163]	Gomez- Acebo et al., 2012	Cantabria, Spain (Cfb)	2003-2006	All-cause	Heat, cold	Used two or more metrics	PGLM	Age (25-64, 65-74, 75-84, 85-89, 90+), sex	Each 1°C increase/decrease	Mortality rose by 2.0% in Tmax and by 2.5% in Tmin increased by 1°C during the warm season, but no effect in mortality on the cold season. Females are more sensitive to higher temperatures, with increases of 4.69% for Tmax and 8.23% for Tmin. People aged 65-74 were more easily affected by Tmax (6.48%)
[164]	Green et al., 2016	England and Wales, UK (Cfb)	2013	All-cause	Heat wave	Mean temperature	GLM	Age (0-44, 45-64, 65-74, 75-84, 85+)	During heatwave 2013	Cumulative excess deaths in aged 65+ during the heatwave period in 2013 were low (195 excess deaths) and did not reach significance.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[165]	Grize et al., 2005	Basel, Berne, Geneva, Lausanne, Lugano, and Zürich, Switzerland (Cfa/Cfb)	1990-2003: June-August	All-cause	Heat wave	Used two or more metrics	PGLM	Age (20-39, 40-59, 60-79, 80+), sex, urban-rural, cities	% increase in mortality associated with the heat episodes	During June-August 2003, mortality increased by 7%, with females (7.5%) slightly more affected than males (6.1%). Mortality was highest among those aged 80+ (8.8%). Excess mortality was mainly observed in suburban areas (10.2%) and urban (7.9%). Significant impacts were observed north of the Alps (7.1%), particularly in Basel (24.4%), Geneva (17.5%), and Lausanne (13.5%).
[166]	Hajat et al., 2016	England, UK (Cfb)	1993-2006	All-cause	Cold	Mean temperature	PGLM	Age (0-14, 15-64, 65-74, 75-84, 85+), region	%change in mortality per 1 °C fall in temperature	All-cause deaths rose by 3.44% per 1°C drop below thresholds, with the greatest risk among the very elderly (4.34% for 75–84 years; 4.96% for 85+). The highest regional effects were in the North East (4.17%), North West (4.33%), and London (4.20%).
[167]	Hutter et al., 2007	Vienna, Austria (Cfb)	1998-2004: May – September	All-cause	Heat wave	Maximum temperature	GAM	Age (0, 65+), sex	Heat wave days vs non-heat wave days	Heatwave days was approximately a 13% increase in deaths (RR=1.13; 1.09–1.17). The risk was higher for females (RR=1.15) than males (RR=1.10) and significantly affected those aged 65+ (RR=1.12). Female elderly had the highest risk (RR=1.15).
[168]	Ishigami et al., 2008	Budapest (Hungary), London (UK), Milan (Italy) (Multi)	1993-2004	All-cause	Heat	Mean temperature	PGLM	Age (0-74, 75+), sex, city	Every 1°C change above the heat cut- point	Heat effects are greater in females than in males. Older people (75+) are more at risk from heat-related mortality than the non-older (0-74) age groups.

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[169]	Janos et al., 2024	Czech Republic (Multi)	1987-2019	All-cause	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (65-74, 75-89, 90+), sex, region	Cold and heat effect: temperatures below or above the MMT. Extreme cold and heat: temperatures below the 2.5th or above the 97.5th percentile.	Heat and cold accounted for 8.35% of all deaths, mainly from moderate cold (AF=7.34%). Heat- related mortality inequalities rose over time, while cold-related ones remained stable. No sex difference was seen for cold, but women had higher heat-related risk (AF=0.36% vs. 0.09% in men). Mortality risk increased with age, peaking in aged 90+
[170]	Keivabu, 2022	Spain (Multi)	2012-2018	All-cause	Heat, cold	Mean temperature	PGLM	Age (25-64, 65-74, 75-84, 85+), sex, educational groups (none, elementary, higher)	Cold: below or equal to the 5th percentile Heat: above or equal to the 95th percentile	Cold days increase monthly mortality rates more (coef.= 0.007 or 7 per 1,000) than hot days (0.005 or 5 per 1,000). Older women found a stronger effect of heat and especially cold than men. The strongest effect seen in aged 85+ in both extreme cold and heat. Extreme cold and hot days increase mortality rates among Low education and Medium (elementary) SES individuals.
[171]	Kendrovski, 2006	Skopje, Macedonia (Cfa)	1996-2000	All-cause	Heat, cold	Mean temperature	Multiple Regression	Sex	1°C increase in temperature	Daily deaths were 13% higher during cold periods compared to warm periods. Total mortality decreases, with each 1°C rise in temperature associated with a 0.19 decrease in the mortality rate (b = -0.19). Females was greater mortality in cold than males.
[172]	Laaïdi et al., 2012	Paris, France (Cfb)	1-13 August 2003	All-cause	Heat wave	Used two or more metrics	Conditional logistic regression	Age (65+), residential zone	Per 0.37°C increase in average mean temperature	Mortality risk among aged 65+ increased significantly with minimum temperatures: a 0.41°C rise had an OR of 2.17, and a

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ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
										0.51°C rise (day of death + 6 days prior) had an OR of 2.24.
[173]	Mari-Dell'Olmo et al., 2019	Barcelona (Csa)	1992-2015	Non-external	Heat, cold	Maximum temperature	PGLM & DLNM	Age (25–64, 65–74, 75–84, 85+), sex, education (no, primary education, more than primary)	Cold effect: 5th percentile vs 25 °C; heat effect: 95th vs 25 °C; extreme cold: 1st vs 5th percentile; extreme heat: 99th vs 95th percentile.	Females had a higher heat-related mortality risk (RR=1.14), while aged 75–84 faced the strongest cold effect (RR=1.40). Educated males were more vulnerable to temperature extremes (cold: RR=1.31, heat: RR=1.20). Females non-education were more at risk from heat (RR=1.31) and cold (RR=1.28).
[174]	Masselot et al., 2023	30 European countries (Multi)	2000-2019	Non-external	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (20–44, 45–64, 65–74, 75–84, 85+), cities	Cold: the 1st percentile Heat: the 99th percentile	Cold contributed more to mortality (AF = 6.63%) than heat (AF = 0.69%). The oldest aged 85+ had the highest RR for cold (1.36%) and heat (1.27%). Cold risks were found in London, UK (RR = 2.05), Dublin, Ireland (RR = 1.73), and Valletta, Malta (RR = 1.70). The highest heat risk was in Paris, France (RR = 1.60).
[175]	Otrachshenko et al., 2018	Russia (Multi)	1989-2014	All-cause; YLL	Heat, cold	Diurnal temperature range (DTR)	GLM	Age (20–29, 30–39, 40–49, 50–59, 60–69, 70+), sex	Extreme cold: below –23 °C; extreme hot: above 25 °C temperature.	A single day, extreme hot mortality by 12.32 per million females and 20.86 per million males, while extreme cold raises mortality by 16.06 per million females and 25.51 per million males. Extreme heat affects females 40–69 and males 40–59, while single cold days have no impact, but consecutive cold days harm females 70+ and males 40+.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[176]	Perčič et al., 2018	Slovenia (Cfb)	2003 & 2015	All-cause	Heat wave	Maximum temperature	Not show	Age (0-4, 5-74, 75+), sex, urban-rural	During heat waves in 2015 and 2003	In 2015, heatwaves caused 10% excess deaths in those 75+ (115 deaths, RR=1.11), higher than ages 5–74. Females saw 10% excess deaths (RR=1.1), males 6% (RR=1.04). Urban-rural differences were insignificant.
[177]	Ragettli et al., 2017	Basel, Berne, Lucerne, St. Gallen, Zurich, Geneva, Lausann Lugano, Switzerland (Cfa/Cfb)	1995-2013	Non-external	Heat	Used two or more metrics	a quasi-PGLM & DLNM	Age (0-74, 75+), sex, cities	Hot days: the 98th percentile (32 °C)	Mortality risk increased most for extreme minimum temperatures (RR = 1.23), with a significant rise above the 90th percentile (18°C). Heat effect was stronger in females (Tmin RR=1.30) and older aged 65+ (Tmin RR=1.29).
[178]	Ragettli et al., 2024	Switzerland (Multi)	2003-2016	All-cause mortality	Heat	Maximum temperature	Conditional logistic regression & DLNM	Age (0-74, 75-84, 85+), sex, education (compulsory or less, upper secondary, tertiary), socioeconomic position (low, medium, high)	Extreme heat effect: the 98th percentile of the warm season Tmax (33 °C)	Extreme heat increased all-cause mortality (OR = 1.21), though the risk was lower in 2009–2016 than in 2003–2008. The most vulnerable groups were adults ≥75 years (OR = 1.25), individuals with low education, older women in low socioeconomic areas, and men under 75 with low socioeconomic status.
[179]	Rai et al., 2023	15 largest cities in Germany (Cfb)	1993 -2016	Non-accidental	Heat, cold	Mean temperature	PGLM & DLNM	Age (0-64, 65-74, 75+), sex, time period	Cold: 1st percentile (-6.0 °C) relative to 25th percentile (4.9 °C); Heat: 99th percentile (25.1 °C) relative to 75th percentile (15.9 °C)	Both cold and heat were associated with all death, the heat effects were stronger (RR= 1.28 in 1993–2004, and 1.29 in 2005–2016) than cold (RR= 1.08 in 1993–2004, 2005–2016). Males became more vulnerable to cold over time, and younger age groups (<75 years) showed increasing susceptibility to cold for non-accidental mortality.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[180]	Revich & Shaposhnikov, 2008	Moscow, Russia (Dfb)	2000-2006	Non-accidental	Heat waves, cold spells	Mean temperature	DLM	Age (all, 75+)	During heat waves and cold spells vs non-heat waves/cold spells days	Daily all non-accidental deaths during the 2001 heat wave rose 33% above the seasonal average for all and 45% for aged 75+. During the 2006 cold spell, mortality among aged 75+ increased by 9% with seasonal long-term expected value.
[181]	Schaeffer et al., 2016	Paris, France (Cfb)	2000-2006	Non-accidental	Heat, cold	Temperature variability (TV)	PGAM	Age (all ages, 0-74, 75+)	Cold effect: the 1st percentile vs the 10th percentile; heat effect: the 99th (very hot days) vs the 90th (hot days)	Heat showed a significantly increased risk. Heat effect was significant among aged 75+ (RR = 1.10), while cold was more marked among aged under 75 years (RR = 1.04) than aged 75+.
[182]	Schumann et al., 2013	Uppsala, Sweden (Dfb)	1749-1824	All-cause	Heat, cold	Mean temperature	a quasi-PGLM	Sex	% change of death numbers for an increase in seasonal temperature (°C)	The relative risk of mortality increased by 3.6% for every 1°C rise in temperature (RR = 1.036).
[183]	Shartova et al., 2019	Arkhangelsk, Russia (Dfc)	1999-2016	Non-external	Heat, cold	Else	PGLM & DLNM	Age (30-64, 65+), sex, cause	% increases in mortality per 1°C increase in exposure	Cold temperatures had a greater impact on mortality than heat. Males had lower heat tolerance and higher cold-related mortality. Men aged over 65 were more sensitive to heat exposure.
[184]	Stafoggia et al., 2006	Bologna, Milan, Rome, Turin, Italy (Cfa)	1997 - 2003	Non-accidental	Heat	Mean apparent temperature	Conditional logistic regression	Age (35-64, 65-74, 75-84, 85+), Sex, City	Increase in odds ratios (ORs) of dying at 30 °C (apparent temperature) relative to 20 °C	ORs of dying on days were 1.34. Females had higher risk (OR=1.45) than males (OR=1.24). Mortality was higher among those aged 75+ (OR=1.36 for 75-84, 1.49 for 85-94, 1.58 for 95+). No effect for area-based income.
[185]	Stafoggia et al., 2009	London, UK (Cfb)	2007-2016	All-cause	Heat	Mean temperature	Conditional logistic regression	Age (0-39, 40-64, 65-84, 85+), sex, SES	Increase in ORs of dying per 1°C increase in temperature	Heat-related mortality rose with increasing temperature (OR=1.039 per 1°C increase). No significant by age, sex, or SES.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[186]	Vésier & Urban, 2023	Czech Republic (Cfb)	1995-2019: May-September	All-cause	Heat	Mean temperature	a quasi-PGLM & DLNM	Age (0–64, 65–74, 75–84, 85+), sex	Extreme heat: the 99th percentile (25.5 °C)	Females were generally more at risk by heat (RR=1.25) than males (1.16). Older age 75+ more risk than younger; the highest risk in older females than 85+ (1.42)
[187]	Vicedo-Cabrera et al., 2016	Switzerland (Multi)	2005-2015: June–August	All-cause	Heat	Maximum apparent temperature	Linear regression model	Age (0-19, 20–39, 40–64, 65–74, 75–84, 85+), sex, region	Heat: the 95th and 99th percentiles	In summer 2015, mortality increased by 5.4%. Excess mortality was 6.0% in males and 5.0% in females. For those aged 75-84, excess mortality was 9.7%.
[188]	Výberčí et al., 2018	Slovakia (Dfb)	1996-2015	All-cause	Heat wave	Mean temperature	PGLM	Age (65+), sex	During the 2015 summer heat spells	The 2015 summer heat spells caused a 14.0% rise in total mortality in Slovakia, with a higher increase in males (15.5%) than females (12.5%). Mortality among those aged 65+ increased more significantly by 17.6%.
[189]	Wan et al., 2022	Scotland, UK (Cfb)	1974-2018	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (0–64, 65–74, 75–84, 85+), sex, city/region	Cold effect: the 1st percentile of temperature distributions vs the 10th percentile; heat effect: the 99th vs the 90th percentile.	All-cause mortality increased by 9% in extreme cold (RR=1.09) and 4% in extreme heat (1.04). Males were more affected by cold, while females, especially the elderly, were more vulnerable to heat. The elderly had the highest risk under both extremes.
[190]	Wicki et al., 2024	8 Swiss cities, Switzerland (Cfb)	2003-2016	All-cause	Heat	Maximum temperature	a quasi-PGLM & DLNM	Age (0-75, 75+), sex, SEP (socioeconomic position), urban-non urban	Heat effect: the 99th percentile (35 °C) vs 22.5 °C (MMT)	Mortality risk rose by 31% (RR= 1.31) during the warm season, with higher heat-related risks in females (RR = 1.38 vs 1.21 for males), aged 75+ (RR = 1.38). Low-SEP was associated with an increased heat risk in aged below 75 years. Heat risk at 35 °C was 26% higher in urban heat island areas than in non-UHI regions.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[191]	Zeka et al., 2014	Ireland (Cfb)	1984 -2007	Non-accidental	Cold	Maximum temperature	Conditional logistic regression & DLM	Age (18-64, 65-74, 75+), sex, region (North Ireland and Republic Ireland)	Percentage (%) change in mortality per 1°C decrease in weekly average of daily maximum temperature.	Mortality was strongest in the week before death, lasting 3–5 weeks. A 1°C drop in weekly mean of maximum temperature led to a cumulative mortality increase of 6.4% in the Republic of Ireland and 4.5% in Northern Ireland. Mortality increases in aged 65+. No sex differences.
Oceania & pacific (n=7)										
[192]	Amoatey et al., 2024	Victoria, Australia (Multi)	2000–2019	All-cause mortality	Heat, cold	Diurnal temperature range	a quasi-PGLM & DLNM	Age (0–65, 65–85, 85+), sex, seasons	1°C increase in DTR	Mortality risk rose by 0.33% per 1°C increase in daily DTR, peaking at 0.55% over lag0-1 days. The risk was higher in warmer months and greatest among those aged 85+ (0.39%), followed by ages 65-84 (0.31%).
[193]	Franklin et al., 2023	Queensland, Australia (Cfa/Aw)	2010-2019	All-cause	Heat wave	Mean temperature	Not show	Age (0-4, 5-19, 25-59, 60-64, 65-79, 80+), SES areas, rural-urban	Heatwave days vs non-heatwave days	Heatwaves increase mortality by 5%. Older aged 80+ had the highest mortality risk, especially during severe (RR=1.09) and extreme heatwaves (RR=1.06). Those living in lower SES regions were most impacted by heatwave mortality. Those in urban centers (RR = 1.06) were most impacted
[194]	Longden, 2019	Australia (BWh/ Cfa)	2006-2017	All-cause; non-external	Heat	Mean temperature	PGAMs & DLNM	Climate zone, socio-economic index	Cold effect: >the 2.5th percentile; Heat effect: the 97.5th percentile.	Extreme heat significantly impacts mortality (13.8% for heat vs. 1.4% for cold), with strongest effects in warmer climate zones. The impact is most pronounced in areas with the lowest socio-economic index (22.7% for heat vs. -0.2% for cold).

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[195]	Qiao et al., 2015	Brisbane, Australia (Cfa)	1996-2004: January 1996 to 30 November 2004	Non- accidental	Heat wave	Mean temperature	GAM	Age (15-64, 65+, 65-84, 85+), season (winter/ summer)	a 1°C temperature (mean temperature, lag 0–1) increase above the threshold (28°C)	A 14.14 % increase in non- accidental mortality (95% CI: 10.15, 18.28%) with a 1°C increase in mean temperature above a 28°C threshold in all summers. Heat risk was highest in those aged 85+ with an 18.18% increase (95% CI: 11.29–25.49) compared to younger age groups.
[196]	Tong et al., 2015	3 largest cities, Australia (Cfa/Cfb)	1988-2009	Non- accidental	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Age (0-74, 75+), sex, cities	During heat waves vs non-heat waves	Heat waves affected females more than males in Brisbane (female = 1.52) and Melbourne (female = 1.17), while in Sydney, males were more affected (male = 1.49). Heat waves affected aged 75+ in males (1.69 in Sydney) and females (1.54 in Brisbane)
[197]	Yu et al., 2010	Brisbane, Australia (Cfa)	1996-2004	All-cause; non- external	Heat, cold	Mean temperature	GLM & DLM	Age (0–64, 65–74, 75–84, 85+), sex, SES groups (low, high)	% increase in mortality per 1°C increase above the threshold temperature.	Heat significantly increased mortality by 13.81% (95% CI: 4.62%–21.74%) in those aged 85+, higher than in the 0–64. A higher risk of dying was found among females (11.21%) than males (0.56%). No effect in SES.
[198]	Yu et al., 2011	Brisbane, Australia (Cfa)	1996-2004	Non- external	Heat	Mean temperature	GAM	Age (15-64, 65-84, 85+)	Heat effect: 1°C of temperature increase above 24°C; Cold effect: 1°C of temperature decrease below 24°C.	Heat has acute effects (4.7% increase for lag 0), while cold has longer lag effects (2.0% increase for lag 0-20). The very old people (85+) were most vulnerable to heat stress (7.2%) and cold temperature (3.9%)
Multi-continents studies (n=13)										

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[199]	Gao et al., 2024	1,960 locations across 59 countries (Multi)	2000-2019	All-cause mortality	Cold spells	Mean temperature	a quasi- PGLM & DLNM	Countries, Region	Cold spell: different temperature thresholds (2·5th, 5th, 7·5th) and duration days (≥ 2 , ≥ 3 , ≥ 4).	Globally, cold spells caused an estimated 205,932 excess deaths annually (3.81 per 1,000 deaths) from 2000–2019. The highest excess death rates occurred in Europe and the lowest in Africa, with temperate climates most affected.
[200]	Gasparrini et al., 2015	Australia, Brazil, Canada, China, Italy, Japan, South Korea, Spain, Sweden, Taiwan, Thailand, UK, and U.S. (Multi)	1985-2012	All-cause; non- external	Heat, cold	Mean temperature	a quasi- PGLM & DLNM	Country	Cold effect: below the optimum temperature; heat: above the optimum temperature; extreme cold: temperatures lower than the 2.5th; extreme heat: higher than the 97.5th.	Non-optimum temperatures caused 7.71% of deaths, mostly from cold (7.29%), with moderate cold contributing 6.66% and heat only 0.42%. The highest temperature-related risk was in China (11.00%), Italy (10.97%), and Japan (10.12%), while the lowest was in Thailand (3.37%), Brazil (3.53%), and Sweden (3.87%).
[201]	Guo et al., 2011	Brisbane, Australia and Los Angeles, U.S. (Multi)	Brisbane: 1996-2004 (Dec–Feb), LA: 1987-2000 (Jan-Aug) in summers	Non- external	Heat, cold	Mean temperature	PGAM	Age (0-64, 65-74, 75+), sex, city	Temperature change: a drop of more than 3°C; a rise of more than 3°C; a change in either direction of less than 3°C.	Females were more sensitive to cold for non-external mortality (RR 1.186) than males in Brisbane. People under 65 were vulnerable to sharp temperature increases (RR 1.667) in LA. Aged 65–74 in Brisbane (RR 1.442) and 75+ in Los Angeles (RR 1.254) were sensitive to sudden temperature drops.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[202]	Guo et al., 2014	Australia, Brazil, Thailand, China, Taiwan, South Korea, Japan, Italy, Spain, UK., U.S., Canada (Multi)	1972-2011	Non- accidental	Heat, cold	Mean temperature	DLNM	Countries	Cold: 1st percentile vs. minimum- mortality temperatureHeat: 99th percentile vs. MMT	Cold temperatures have a prolonged, stronger impact on mortality than heat, with Taiwan, Italy, and Spain showing higher sensitivity to both extremes.
[203]	Lee et al., 2018	U.S., UK, Spain, South Korea (Multi)	1972-2013	All-cause; non- external	Heat, cold	Diurnal temperature range (DTR)	a quasi- PGLM & DLNM	Location	% increases in mortality risk per 10°C	DTR increased mortality risk (3.1%) and AF of deaths (2.5%), with highest risks in South Korea (6%), Spain (4.4%), and Brazil (4.2%). Colombia (−1.2%) and Ireland (0.3%) showed the lowest.
[204]	Leone et al., 2013	Italy, Israel, Spain, Portugal, Greece, Turkey, Tunisia (Multi)	1991-2007: the summer season (April- September)	Natural causes	Heat	Maximum apparent temperature	PGAM	Age (0–14, 5– 64, 65+), city	1°C increase above the maximum apparent temperature (Tappmax) of city- specific threshold	European cities (except Bari) the greatest effect is recorded in older people, while in the Eastern- Southern cities the greatest effect is among the youngest age groups (0–14 and 15–64 years).
[205]	Muggeo & Hajat, 2009	Santiago, Chile & Palermo, Italy (Multi)	1997-2001 for Palermo and 1989- 1991 for Santiago.	Non- external	Heat, cold	Mean temperature	GAM	Age (0–64, 65+)	Cold: a 1 °C decrease in temperature below the threshold; heat: a 1 °C increase in temperature above the threshold	Cold increases mortality by 2.36% in the 65+ in Santiago, compared to 1.11% (0.09%– 2.14%) in Palermo. Heat effects are higher in Palermo (17.6%) than in Santiago (5.48%) for the same age group.

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
[206]	Revich & Shaposhnikov, 2022	Murmansk, Archangelsk (Europe); Magadan, Yakutsk (Asia) (Multi)	1999–2019	Natural causes	Heat, cold	Mean temperature	PGLM	Age (30–64, 65+), city,	% changes in mortality associated with cold spells and heat waves	Cold spells posed greater health risks than heat waves in Murmansk, Archangelsk, and Magadan, while heat waves were more harmful in Yakutsk. Older adults (65+) were particularly vulnerable to both cold (RR=1.12) and heat extremes.
[207]	Scovronick et al., 2024	532 cities in 33 countries (Multi)	1980-2018	All-cause	Heat, cold	Mean temperature	a quasi-PGLM & DLNM	Age (30–44, 45–59, 60–74, 75–100), cities	Extreme cold and heat: at 1st and 99th temperature percentile.	Cold increased all-cause mortality risk (RR = 1.22), while extreme heat also raised risk (RR = 1.11). Mortality risks from both heat and cold were highest at age 85+, with excess deaths increasing steadily with age for cold but were more variable for heat, though still highest in the oldest age group.
[208]	Wen et al., 2024	758 locations in 47 countries or regions (Multi)	1972-2020	All-cause	Heat, cold	Temperature variability (TV)	a quasi-PGLM & DLNM	Climate area, season, climate type	%change per interquartile range [IQR] increase in TV	All-cause mortality rose by 0.59% per IQR increase in intra-day TV0–7 (0.9 °C) and 0.22% per inter-day TV0–7 (1.6 °C). Inter-day variability was highest in the USA and Canada, lowest in Southeast Asia; and intra-day variability peaked in South Africa, lowest in Western Europe. Mortality risks from both were greater in dry and polar climates.
[209]	Wu et al., 2022	717 locations from 36 countries (Multi)	1972-2018: warm season	All-cause; non-external	Heat	Temperature variability (TV)	GLM	Country, regional, and global levels.	The MMTs for different quartiles of TV: Q1 (17.62°C), Q2 (17.62°C), Q3 (18.39°C), Q4 (19.80°C)	Increased TV poses a greater mortality risk due to heat, accounting for 0.70% (Q1), 1.34%, 1.99%, and 2.73% (Q4) of total deaths. Central Europe showed the highest attributable fractions (AFs) for total deaths in

Table A.S. 5 Characteristics and main findings of studies of temperature exposure and mortality included in the review (n=211)

ID	Authors	Location (Köppen Climate)	Period	Mortality	Exposure Type	Exposure metrics	Statistical Method	Effect Modification	Exposure Increment	Summary of findings
										Q4 of TV at 7.68%, while North America had the lowest at 1.74%.
[210]	Wu et al., 2022	750 locations in 43 countries (Multi)	2000-2019	All-cause; non- external	Heat, cold	Temperature variability (TV)	a quasi- PGLM & DLNM	Region	Each 1°C increase in temperature variability	Global TV caused 3.4% of all deaths. Asia, Australia, and New Zealand have a higher percentage excess in mortality than the global mean. Mortality from TV rose by 4.6% per decade, with the largest increases in Australia and New Zealand (7.3%), Europe (4.4%), and Africa (3.3%).
[211]	Zhao et al., 2021	750 locations in 43 countries (Multi)	2000-2019	All-cause; non- external	Heat, cold	Mean temperature	DLNM	Region	Cold and hot: temperatures either lower or higher than the MMT	Globally, non-optimal temperatures contributed 9.43% of all deaths, with 8.52% cold-related and 0.91% heat-related. Asia accounted for 51.5% of excess deaths. Eastern Europe had the highest heat-related death rate, while Sub-Saharan Africa had the highest cold-related rate.

Abbreviations: YLL= years of life lost; MMT=minimum mortality temperature; MMP= minimum mortality percentile; GAM = generalized additive model; PGAM= poisson generalized additive model; GLM = generalized linear model; PGLM= poisson generalized linear model; DLNM=, distributed lag nonlinear model; DLM=distributed lag linear model; CLR= conditional logistic regression; GEE = generalized estimating equation; NBGLM = negative-binomial generalized linear model; RRs= risk ratio; IRRs = incidence rate ratio/s; ORs= odds ratio; AFs=attributable fractions; ER = excess risk; NA= not show.

Köppen climate classification: **Group A-Tropical:** Af=tropical rainforest climate. Am=tropical monsoon climate. Aw=tropical savanna climate; **Group B-Arid:** BWh=hot desert climate. BWk=cold desert climate. BSh=hot semi-arid climate. BSk=cold semi-arid climate; **Group C-Temperate:** 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; **Group D-Continental:** 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; **Multi=multi-climate zones.**

A.3. Main findings temperature-related mortality studies included

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
Tropical storms (Hurricanes/Tornado/ Typhoon) (n=15)								
Americas (n=8)								
[212]	Brunkard et al., 2008	Louisiana, USA (Cfa)	2005	Hurricane-related mortality (by event)	Hurricane event	Pearson chi-square and Fisher exact tests	Age (0-18, 19-29, 30-44, 45-54, 55-64, 65-74, 75+), sex, race	Hurricane Katrina caused 971 deaths in Louisiana and 15 among evacuees. Major causes were drowning (40%), injury/trauma (25%), and heart conditions (11%). Nearly half (49%) of victims were 75+ years old. Among victims, 53% were men, 51% were Black, and 42% were White. In Orleans Parish, Black adults had a mortality rate 1.7 to 4 times higher than Whites. Older adults (75+) were significantly more likely to die ($P < .0001$).
[213]	Chiu et al., 2013	Alabama, USA (Cfa)	April 27 to December 31, 2011	Tornado-related mortality, both directly or indirectly (by event)	Tornado event on April 27, 2011	N/A	Age (0-4, 5-14, 15-24, 25-34, 35-44, 45-54, 55-64, 65-74, 75-84, 85+), sex, urban-rural	Females were 40% more likely to suffer a tornado-related death than males ($RR = 1.39$; 95% $CI = 1.08, 1.80$). Risk increased with age, with those 85+ nearly 4 times more likely to die ($RR = 3.85$; $CI = 2.05, 7.26$). Rural residents faced nearly 3 times the risk of death at the time of the tornadoes compared to urban residents ($RR = 2.90$; $CI = 2.18, 3.87$).
[214]	Marazzi et al., 2022	US. (Multi)	2012-2018	All-cause mortality (monthly)	Hurricane event	Difference-in- differences	Age (0-39, 40-64, 65+), sex, education (not complete high school, high school, higher education or more)	Mortality rose 3.7% (95% $CI: 2.5\% - 4.9\%$) in the six months post-hurricane. Among those 65+, excess deaths were higher for males (7.3%) and females (6.4%). Older adults with lower education were most vulnerable, with the highest excess deaths among females with less than high school (243) and males with a high school diploma (175).
[215]	Parks et al., 2022	US. (Multi)	1988-2018	Specific cause of mortality (monthly) following Tropical Cyclones	Tropical cyclone (≥ 34 knots), hurricanes (≥ 64 knots)	a quasi-PGLM & DLNM	Age (0-24, 25-44, 45-64, 65-84, 85+), sex, Social Vulnerability Index (SVI) (1 =low to 3=high)	Highest overall increases were observed in injury-related mortality (such as drowning) after tropical cyclones, peaking 1 month after cyclone (3.7%) and the month of a hurricane (33.4%). Females had a higher relative increase in injury deaths during hurricanes (46.5%) compared to males (27.6%). Older adults (65+) saw the largest increases in the first two months post-cyclone, with a 6.4% rise one

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
								month later, compared to a 2.7% increase for those under 65.
[216]	Parks et al., 2023	US. (Multi)	1988-2019	All-cause mortality (yearly)	Tropical cyclone (days when peak sustained winds reach ≥ 34 knots (63 km/h). Gale to violent storms range from 34 to <64 knots, while hurricanes have winds ≥ 64 knots (119 km/h).	PGLM	States, type of tropical cyclones	Hurricane Katrina (2005) was the deadliest tropical cyclone, causing 1,491 excess deaths ($>99\%$ probability), including 719 in Orleans Parish, LA. Regions with $>95\%$ probability of excess deaths saw 3,112 post-hurricane force and 15,590 post-gale to violent storm force deaths, with most (83.1% and 70.0%, respectively) occurring from 2004–2019.
[217]	Pugatch, 2019	Mexico (Multi)	1990-2011	All-cause mortality (daily)	Tropical storms (originate over tropical oceans with sustained winds exceeding 33 knots (61 km/h))	GLM	Age (0, 1-4, 5-14, 15-29, 30-49, 50-69, 70+), sex	The strongest storm could increase the mortality rate by 3.12 deaths per thousand, a 68% rise over the baseline. Infants and the elderly (70+) are most vulnerable to storms. The strongest storms increase infant mortality by 25.5 per thousand (1.4 times the mean) and elderly mortality at a similar magnitude, both significant at 10%. No significant differences in sex.
[218]	Santos-Burgoa et al., 2018	Puerto Rico (Af)	2010-2018	All-cause mortality (monthly)	Hurricane Maria	GLM & GAM	age (0–39, 40–64, 65+), sex, Municipal Socioeconomic Development Index (SEI)	Six months post-disaster, mortality impact was greater for men, with the highest observed-to-expected ratio in males 65+ (1.33, 95% CI: 1.30–1.37). The greatest impact was on those in the lowest SES areas had 43% higher mortality (1.43, 95% CI: 1.39–1.46).
[219]	Young & Hsiang, 2024	US. (Multi)	1930-2015	All-cause mortality (monthly)	Tropical cyclone events	GLM	Age (<0 , 1–44, 45–64, 65+)	Tropical cyclones accounted for 3.2–5.1% of all U.S. deaths, with the highest impacts along the Atlantic coast, 13% in Florida, 11% in North Carolina, 9% in South Carolina, and 8% in Louisiana. Tropical cyclone contributes significantly to mortality among younger age groups, accounting for 25% of infant deaths and 15% of deaths among those aged 1–44.

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
Asia (n=3)								
[220]	Burkart & Kinney, 2016	Bangladesh (Aw/Am)	2003-2007	All-cause mortality	Precipitation (mm) above specific threshold	a quasi-PGLM	Age (1–14, 15–44, 45–64, 65+), sex, season	During the dry season, cyclone-related deaths rose, especially for females (+18.7%, 95% CI: 3.8–35.6%) per mm above 5 mm). A dry effect later increased elderly mortality (+4.4%, 2.6–6.2%) per mm decrease).
[221]	Gray et al., 2022	Philippines (Af/Am/Aw)	2005-2015	Typhoon-related mortality (by event)	the total number of typhoons to impact the municipality between 2005 and 2015.	NBGLM	Age (% of Population under 5, % of population aged 65+), sex, urban-rural, % of Population Literate, Poverty Incidence (%)	From 2005 to 2015, male typhoon mortality was nearly double that of females, with 188 male deaths for every 100 female deaths. Mortality rates were higher in areas with more elderly 65+ (IRR = 1.227), more infants (IRR = 1.294), lower literacy (IRR = 0.985), higher poverty (IRR = 1.150), whereas mortality decreases with the level of urbanisation (IRR = 0.843)
[222]	Sugimoto et al., 2011	Bangladesh (Aw/Am)	August and October 2005	Tornado-related mortality (by event)	Tornado event in 2005 (a 27.1 square kilometer ‘tornado-affected’ area)	Multiple logistic regression	Age (0-4, 5–14, 15–24, 25–60, 60+), sex	Adults 60+ were 8.9 times (95% CI: 3.9–20.2) more likely to die in a tornado than those aged 15–24, with no increased risk in other age groups. No sex differences.
Multi-continents studies (n=4)								
[223]	Bouwer & Jonkman, 2018	Every continent (Multi)	1900-2015	Storm surge-related mortality (by event)	Storm surge events	Multiple regression	Continent	The average event mortality is 0.006 for all recorded events (100 out of 121). There is a consistent decrease in event mortality for all global regions, except South East Asia.

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
[224]	Huang et al., 2023	341 locations from 14 countries (Multi)	1980-2019	All-cause mortality; non-external mortality (daily)	Tropical cyclone day (a day with maximum sustained wind speed associated with cyclones ≥ 17.5 m/s) over lags of 0–14 days	a conditional quasi-PGLM & DLNM	Country, region, time period	Tropical cyclone exposure was linked to a 6% (95% CI: 4–8) increase in mortality, resulting in approximately 97,430 excess deaths per decade from 1980 to 2019 at lag 0-14. East and South Asia had the highest excess deaths cyclones (28,744 and 27,267 per decade, respectively) from 1980 to 2019, while Southeast Asia and Latin America and the Caribbean had the highest excess death ratios and rates.
[225]	Huang et al., 2024	494 locations in 18 countries (Multi)	1980-2019	All-cause mortality (daily)	Tropical cyclones exposure days (a day with maximum sustained wind speed associated with cyclones ≥ 34 knots)	PGLM	Country	Tropical cyclones increased all-cause mortality risk (RR = 1.04–1.42). The highest risks occurred in Guatemala (all-cause), Brazil, Vietnam, and South Korea (cardiovascular), and New Zealand and Australia (respiratory). From 1980–2019, cyclone-related mortality declined in the Philippines, Taiwan, and the USA but increased in Japan.
[226]	Zagheni et al., 2016	Every continent (Multi)	1995-2011	Storm-related mortality (yearly)	Hydro-meteorological disasters	Principal Component Analysis (PCA), a first-difference type model	Age (0-14, 15–44, 45+), sex, level of development	Males had consistently higher mortality than females across all age groups, with a greater gender gap among adults. Age group coefficients were not statistically significant, but HDI interaction was negative for ages 0–15 and positive for 45+.
Flooding (n=13)								
Africa (n=1)								
[227]	Zhu et al., 2024	37 African countries (Multi)	2000-2020	Infant mortality (yearly)	Flood events	a quasi-PGLM	Age (<0), Regions	In Africa, flood exposure significantly increased infant mortality, causing 5.35 additional deaths per 1,000 live births, highest in West (16.04) and Central Africa (12.23). From 2000–2020, floods were linked to 3.42 extra infant deaths per 1,000 births, with elevated risks lasting up to four years and 1.7 times higher than short-term exposure.

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
Americas (n=4)								
[228]	Chu et al., 2025	US. (Multi)	2000-2020	All-cause (Daily: flood day)	Flood day (flash vs non-flash event)	a quasi-PGLM	Age (0-64, 65+), sex, ethnicity	Each flood day led to 8.3 excess all-cause deaths per 10 million people, including 5.9 from external causes. Females had more excess all-cause (12.8) than males and non-external deaths (9.1), while males had more external deaths (9.8 vs. 1.1 for females). In the post-flood year, those aged ≥65 had the highest excess all-cause (48.2) than younger individuals, non-external (33.3), and external (13.3) deaths.
[229]	Lynch et al., 2025	US. (Multi)	2001-2018	All-cause and cause-specific (infectious and parasitic diseases, injuries) (monthly)	Flood events: % changes in death rates per unit increase in flood events in a month	a quasi-PGLM	Age (0-64, 65+), sex	Severe heavy rain-related floods increased all-cause mortality by 1.5% during the flood month and continued up to two (1.0%) and three months (0.6%) after the event. Very severe floods raised deaths from injury deaths (15.3%), with highest among adults ≥65 years (24.9% vs 10.2% for people <65 years) and females (21.2% vs 12.6% for males).
[230]	Terti et al., 2016	US. (Multi)	1996-2014	Flood-related mortality (by event)	Flash flood events	NA	Sex	Males comprised 61% of victims, a statistically significant overrepresentation ($p \leq 0.05$).
Asia (n=3)								
[231]	Li et al., 2007	Hunan, China (Cfa)	1999	Flood-related mortality; YLL (by event)	River flood vs no-flood groups	NA	Age (1–64), sex	Floods raise mortality and YPLL, mainly from injury, poisoning, and cancer, with males and aged 30–45 years most affected.
[232]	Pradhan et al., 2007	Sarlahi, Nepal (Aw)	1993	Flood-related mortality (daily)	Post-flood	NA	Age (2-5, 6-9, 15-24, 25-34, 35-44, 45-55, 56+), sex, SES (low, high)	Flood death rates were higher for girls (13.3/1,000) than boys (9.4/1,000) and for women (6.1/1,000) than men (4.1/1,000). Child mortality was six times higher than pre-flood rates (RR=5.9). Higher death risk was linked to low socioeconomic status (RR=6.4)
[233]	Samir, 2013	Nepal (Multi)	2000-2009	Flood and landslide-related mortality (by event)	Floods and landslides	PGLM	Education, SES	Higher education levels (ages 15–39) were linked to a 42% decline in the number of deaths during flooding and landslides (Coefficients= -0.55(0.58))

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
Europe (n=3)								
[234]	Milojevic, et al., 2011	England & Wales, UK (Cfb)	1994-2005	All-cause mortality (daily)	Post- vs. pre-flood changes in flooded postcodes to nearby non-flooded areas (within 5 km of a flood).	Conditional Poisson regression models	Age (0-64, 65-74, 75-84, 85+), sex	Flooded areas saw a post-/pre-flood mortality ratio of 0.90 (95% CI: 0.82–1.00), indicating fewer deaths post-flood than in adjacent areas. No difference in sex and age.
[235]	Valavani et al., 2025	Greece (Multi)	2015-2019	All-cause (Excess) mortality (weekly)	Flood events	a quasi-PGLM	Cities	During the flood week, mortality increased sharply in Fthiotida (57%), Karditsa/Trikala (40%), and Magnesia (39%), resulting in an estimated 54 excess deaths that week and 335 total excess deaths over the next 90 days.
[236]	Wu et al., 2024	UK (Cfb)	2000-2020	All-cause and cause-specific mortality (yearly)	Flood-affected areas vs. not flood-affected areas; flood index: per unit increase in flood index	Conditional logistic regression & DLNM	Education, SES	All-cause mortality rose by 6.7% (OR = 1.067) per unit increase in flood index. Long-term exposure to floods is associated with an increased risk of mortality. Females, those under 64 faced, individuals with higher education or income faced greater estimated risk of death from most causes in association with flooding exposure.
Multi-continent studies (n=3)								
[237]	Alfieri et al., 2020	Every continent (Multi)	1980-2018	Flood-related mortality (by yearly)	Presence of river flood disaster/event	NA	Region, income class	Global river floods affect 54 million people yearly, causing 6,120 deaths, with 63% from summer floods in Asia and 13% from November–April floods in South America and Africa.
[238]	Lindersson et al., 2023	67 countries (Multi)	1990-2018	Flood-related mortality per flood disaster (by yearly)	Flood events	NBGLM	Countries	Flood mortality was highest in Africa, Asia, and the Americas, both in rates and total deaths. High-GDP countries had 22 times lower mortality rates than low-GDP nations, and countries with low income inequality (low Gini) had 26 times lower rates than those with high inequality.

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
[239]	Yang et al., 2023	35 countries (Multi)	2000-2019	All-cause, cardiovascular, and respiratory mortality	Flooded days: days from the start date to the end date of flood events.	a quasi-PGLM &DLNM	Climate zone, country's income class	Globally, floods increased mortality for up to 60 days (CRR: 1.021 all-cause, 1.026 cardiovascular, 1.049 respiratory), with strongest impacts in the Americas, Eastern Asia, Australia/New Zealand, and Eastern Europe. Floods accounted for up to 0.10% of all-cause deaths. Effects were greater in low-income and low-HDI populations (CRR = 1.24).
Drought (n=6)								
Africa (n=1)								
[240]	Salvador et al., 2024	South Africa (Multi)	2009-2016	All-cause and cause-specific mortality (weekly)	Standardised Precipitation Evapotranspiration Index (SPEI-1, 2, 6, 12, 15)	a quasi-PGLM &DLNM	Age (0-4, 5-24, 25-44, 45-64, 65+), sex	Droughts were linked to higher all-cause mortality, with the strongest impact during prolonged events (RR = 1.098 for SPEI-15). No significant differences in sex or age groups.
Americas (n=4)								
[241]	Abadi et al., 2022	Nebraska, US. (Dfa/Dfb)	1980-2014	All-cause mortality (daily)	Evaporative Demand Drought Index (EDDI)	Bayesian zero-inflated censored negative binomial (ZICNB) regression model	Age (0, 1-4, 5-9, 10-14, 15-19, 20-24, 25-34, 35-44, 45-54, 55-64, 65-74, 75-84, 85+), sex, race, metro vs non-metro	Droughts have a negligible impact on overall mortality. Drought increased mortality in white adults, especially females aged 45-54 in non-metro (incidence rate ratios or IRR: 1.016 for long-term drought) and males aged 55-64 in metro areas (IRR: 1.007 for long-term drought). Mortality increased in sub-populations across both metro and non-metro areas.
[242]	Gwon et al., 2024	Montana, Wyoming, North Dakota, South Dakota, and Nebraska in US.	2000-2018	All-cause mortality (Daily)	The United States Drought Monitor (USDM); The Standardized Precipitation-Evapotranspiration Index (SPEI);	a quasi-PGLM	Age (0-19, 20-39, 40-64, 65+), sex, rural-urban	Severe drought increased all-cause mortality, with risk ratios of 1.050 (USDM), 1.033 (6-SPEI), 1.023 (12-SPEI), 1.035 (6-EDDI), and 1.040 (12-EDDI). Females showed higher risks at 6-EDDI (1.054) and 12-EDDI (1.059). Elderly individuals were more affected under USDM (1.056), 6-SPEI (1.043), and 6-EDDI (1.054). Both rural and urban areas

Table A.S. 6 Characteristics and main findings of studies of natural hazards and mortality included in the review (n=35)

ID	Authors	Location (Köppen Climate)	Period	Mortality (number)	Exposure	Statistical Method	Effect Modification	Summary of findings
		(Multi)			Evaporative Demand Drought Index (EDDI)			experienced elevated mortality during severe droughts.
[243]	Lynch et al., 2020	US. (Multi)	1968-2014	All-cause mortality (daily)	Standardized Precipitation Evapotranspirati on Index (SPEI)	NBGLM	Age (25–34, 35–44, 45–54, 55–64, 65– 74, 75–84, 85+), sex, region, race	Mortality rates increased slightly with higher drought severity for ages 45–54 (IRR=1.002) and 55–64 (IRR=1.001). Significant drought-mortality increases were observed in the Southwest, South, and West regions (IRR=1.004, 0.997, and 0.998, respectively). No sex differences.
[244]	Salvador et al., 2022	13 macro urban areas, Brazil (Multi)	2000-2019	Non-external mortality (weekly)	Standardized Precipitation Evapotranspirati on Index (SPEI)	a quasi- PGLM &DLNM	Age (0–9, 10–44, 45–64, 65–74, 75+), sex	Drought exposure was positively associated with non-external mortality, with RRs between 1.003 (moderate) and 1.010 (extreme drought conditions). For extreme drought conditions, females (RR= 1.017; AF=1.67%), children aged 0-9 (RRs= 1.029; AF= 2.82%), and the elderly aged 75+ (RR=1.016; AF= 1.57%) were the populations more at risk.
Europe (n=2)								
[245]	Salvador et al., 2021	Lisbon, Portugal (Csa)	1983-2016	Natural causes (daily)	Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspirati on Index (SPEI)	PGLM	Age (45-64, 65-74, 75+), sex	The SPEI was a more effective indicator of drought-related mortality risk (RR=1.011) compared to the SPI (RR=1.006). The 75+ age group faced the highest mortality risks, with males more affected than females.
[246]	Salvador et al., 2020	Spain (Multi)	2000-2009	Natural causes (daily)	Standardised Precipitation Index (SPI-1-3) and Standardised Precipitation Evapotranspirati on Index (SPEI- 1-3)	PGLM	Age (%population aged 65+), climate	Higher RR values for natural deaths were observed during short-to-medium-term droughts (RR=1.017 for SPEI-3/SPI-3). The regions with the highest proportion of people aged 65+ reflected faced the highest daily natural mortality risk (RR=1.024 for SPEI-3/SPI-3).

Abbreviations: YLL= years of life lost; GAM = generalized additive model; PGAM= poisson generalized additive model; GLM = generalized linear model; PGLM= poisson generalized linear model; DLNM=, distributed lag nonlinear model; DLM=distributed lag linear model; NBGLM = negative-binomial generalized linear model; RRs= risk ratio; IRRs = incidence rate ratio/s; ORs= odds ratio; NA= not show.

Köppen climate classification: Group A-Tropical: Af=tropical rainforest climate. Am=tropical monsoon climate. Aw=tropical savanna climate; Group B-Arid: BWh=hot desert climate. BWk=cold desert climate. BSh=hot semi-arid climate. BSk=cold semi-arid climate; Group C-Temperate: 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; Group D-Continental: 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; Multi=multi-climate zones.

A.4. List of included studies by study ID

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Appendix B: Supplemental Information

B.1. Details on Countries involved

Table B.S. 1 List of the European Countries per NUTS3 involved in the study

Country	NUTS3 (Counties)	Coverage period
Albania	Dibër (AL011), Durrës (AL012), Kukës (AL013), Lezhë (AL014), Shkodër (AL015), Elbasan (AL021), Tirana (AL022), Berat (AL031), Fier (AL032), Gjirokastrë (AL033), Korçë (AL034), Vlorë (AL035).	2015-2021
Austria	Mittelburgenland (AT111), Nordburgenland (AT112), Südburgenland (AT113), Mostviertel-Eisenwurzen (AT121), Niederösterreich-Süd (AT122), Sankt Pölten (AT123), Waldviertel (AT124), Weinviertel (AT125), Nordteil (AT126), Südteil (AT127), Vienna (AT130), Klagenfurt-Villach (AT211), Oberkärnten (AT212), Unterkärnten (AT213), Graz (AT221), Liezen (AT222), Östliche Obersteiermark (A2239, Oststeiermark (AT224), West und Südsteiermark (AT225), Westliche Obersteiermark (AT226), Innviertel (AT311), Linz-Wels (AT312), Mühlviertel (AT313), Steyr-Kirchdorf (AT314), Traunvierte (AT315), Lungau (AT321), Pinzgau-Pongau (AT322), Salzburg und Umgebung (AT323), Außerfern (AT331), Innsbruck (AT332), Osttirol (AT333), Tiroler Oberland (AT334), Tiroler Unterland (AT335), Bludenz-Bregenzer Wald (AT341), Rheintal-Bodenseegebiet (AT342).	2014-2023
Belgium	Arr. de Bruxelles-Capitale/Arr. Brussel-Hoofdstad(BE100), Arr. Antwerpen(BE211), Arr. Mechelen(BE212), Arr. Turnhout(BE213), Arr. Tongeren(BE223), Arr. Hasselt(BE224), Arr. Maaseik(BE225), Arr. Aalst(BE231), Arr. Dendermonde(BE232), Arr. Eeklo(BE233), Arr. Gent(BE234), Arr. Oudenaarde(BE235), Arr. Sint-Niklaas(BE236), Arr. Halle-Vilvoorde(BE241), Arr. Leuven(BE242), Arr. Brugge(BE251), Arr. Diksmuide(BE252), Arr. Ieper(BE253), Arr. Kortrijk(BE254), Arr. Oostende(BE255), Arr. Roeselare(BE256), Arr. Tielt(BE257), Arr. Veurne(BE258), Arr. Nivelles(BE310), Arr. Mons(BE323), Arr. Tournai-Mouscron(BE328), Arr. La Louvière(BE329), Arr. Ath(BE32A), Arr. Charleroi(BE32B), Arr. Soignies(BE32C), Arr. Thuin(BE32D), Arr. Huy(BE331), Arr. Liège(BE332), Arr. Waremme(BE334), Arr. Verviers — communes francophones(BE335), Bezirk Verviers — Deutschsprachige Gemeinschaft(BE336), Arr. Arlon(BE341), Arr. Bastogne(BE342), Arr. Marche-en-Famenne(BE343), Arr. Neufchâteau(BE344), Arr. Virton(BE345), Arr. Dinant(BE351), Arr. Namur(BE352), Arr. Philippeville(BE353)	2014-2023
Bulgaria	Vidin(BG311), Montana(BG312), Vratsa(BG313), Pleven(BG314), Lovech(BG315), Veliko Tarnovo(BG321), Gabrovo(BG322), Ruse(BG323), Razgrad(BG324), Silistra(BG325), Varna(BG331), Dobrich(BG332), Shumen(BG333), Targovishte(BG334), Burgas(BG341), Sliven(BG342), Yambol(BG343), Stara Zagora(BG344), Sofia (stolitsa)(BG411), Sofia(BG412), Blagoevgrad(BG413), Pernik(BG414), Kyustendil(BG415), Plovdiv(BG421), Haskovo(BG422), Pazardzhik(BG423), Smolyan(BG424), Kardzhali(BG425)	2014-2023
Switzerland	Vaud(CH011), Valais(CH012), Genève(CH013), Bern(CH021), Freiburg(CH022), Solothurn(CH023), Neuchâtel(CH024), Jura(CH025), Basel-Stadt(CH031), Basel-Landschaft(CH032), Aargau(CH033), Zürich(CH040), Glarus(CH051), Schaffhausen(CH052), Appenzell Ausserrhoden(CH053), Appenzell Innerrhoden(CH054), St. Gallen(CH055), Graubünden(CH056), Thurgau(CH057), Luzern(CH061), Uri(CH062), Schwyz(CH063), Obwalden(CH064), Nidwalden(CH065), Zug(CH066), Ticino(CH070)	2014-2023
Cyprus	Kýpros(CY000)	2015-2020

Country	NUTS3 (Counties)	Coverage period
Czechia	Hlavní město Praha(CZ010), Středočeský kraj(CZ020), Jihočeský kraj(CZ031), Plzeňský kraj(CZ032), Karlovarský kraj(CZ041), Ústecký kraj(CZ042), Liberecký kraj(CZ051), Královéhradecký kraj(CZ052), Pardubický kraj(CZ053), Kraj Vysočina(CZ063), Jihomoravský kraj(CZ064), Olomoucký kraj(CZ071), Zlínský kraj(CZ072), Moravskoslezský kraj(CZ080)	2014-2023
Denmark	Byen København(DK011), Københavns omegn(DK012), Nordsjælland(DK013), Bornholm(DK014), Østsjælland(DK021), Vest- og Sydsjælland(DK022), Fyn(DK031), Syddjylland(DK032), Vestjylland(DK041), Østjylland(DK042), Nordjylland(DK050)	2014-2023
Estonia	Põhja-Eesti(EE001), Lääne-Eesti(EE004), Lõuna-Eesti(EE008), Kesk-Eesti(EE009), Kirde-Eesti(EE00A)	2014-2022
Greece	Dytikos Tomeas Athinon(EL302), Anatoliki Attiki(EL305), Dytiki Attiki(EL306), Peiraias, Nisoi(EL307), Lesvos, Limnos(EL411), Evros(EL511), Xanthi(EL512), Rodopi(EL513), Drama(EL514), Thasos, Kavala(EL515), Imathia(EL521), Thessaloniki(EL522), Kilkis(EL523), Pella(EL524), Pieria(EL525), Serres(EL526), Chalkidiki(EL527), Grevena, Kozani(EL531), Kastoria(EL532), Florina(EL533), Arta, Preveza(EL541), Thesprotia(EL542), Ioannina(EL543), Karditsa, Trikala(EL611), Larisa(EL612), Magnisia, Sporades(EL613), Zakynthos(EL621), Kerkyra(EL622), Ithaki, Kefallinia(EL623), Lefkada(EL624), Aitolokarnania(EL631), Achaia(EL632), Ileia(EL633), Voiotia(EL641), Evvoia(EL642), Evrytania(EL643), Fthiotida(EL644), Fokida(EL645), Argolida, Arkadia(EL651), Korinthia(EL652), Lakonia, Messinia(EL653)	2015-2023
Spain	A Coruña(ES111), Lugo(ES112), Ourense(ES113), Pontevedra(ES114), Asturias(ES120), Cantabria(ES130), Araba/Álava(ES211), Gipuzkoa(ES212), Bizkaia(ES213), Navarra(ES220), La Rioja(ES230), Huesca(ES241), Teruel(ES242), Zaragoza(ES243), Madrid(ES300), Ávila(ES411), Burgos(ES412), León(ES413), Palencia(ES414), Salamanca(ES415), Segovia(ES416), Soria(ES417), Valladolid(ES418), Zamora(ES419), Albacete(ES421), Ciudad Real(ES422), Cuenca(ES423), Guadalajara(ES424), Toledo(ES425), Badajoz(ES431), Cáceres(ES432), Barcelona(ES511), Girona(ES512), Lleida(ES513), Tarragona(ES514), Alicante/Alacant(ES521), Castellón/Castelló(ES522), Valencia/València(ES523), Eivissa y Formentera(ES531), Mallorca(ES532), Menorca(ES533), Almería(ES611), Cádiz(ES612), Córdoba(ES613), Granada(ES614), Huelva(ES615), Jaén(ES616), Málaga(ES617), Sevilla(ES618), Murcia(ES620), Ceuta(ES630), Melilla(ES640), El Hierro(ES703), Fuerteventura(ES704), Gran Canaria(ES705), La Gomera(ES706), La Palma(ES707), Lanzarote(ES708), Tenerife(ES709)	2014-2023
Finland	Keski-Suomi(FI193), Etelä-Pohjanmaa(FI194), Pohjanmaa(FI195), Satakunta(FI196), Pirkanmaa(FI197), Helsinki-Uusimaa(FI1B1), Varsinais-Suomi(FI1C1), Kanta-Häme(FI1C2), Päijät-Häme(FI1C3), Kymenlaakso(FI1C4), Etelä-Karjala(FI1C5), Etelä-Savo(FI1D1), Pohjois-Savo(FI1D2), Pohjois-Karjala(FI1D3), Keski-Pohjanmaa(FI1D5), Lappi(FI1D7), Kainuu(FI1D8), Pohjois-Pohjanmaa(FI1D9), Åland(FI200)	2014-2023
France	Paris(FR101), Seine-et-Marne(FR102), Yvelines(FR103), Essonne(FR104), Hauts-de-Seine(FR105), Seine-Saint-Denis(FR106), Val-de-Marne(FR107), Val-d'Oise(FR108), Cher(FRB01), Eure-et-Loir(FRB02), Indre(FRB03), Indre-et-Loire(FRB04), Loir-et-Cher(FRB05), Loiret(FRB06), Côte-d'Or(FRC11), Nièvre(FRC12), Saône-et-Loire(FRC13), Yonne(FRC14), Doubs(FRC21), Jura(FRC22), Haute-Saône(FRC23), Territoire de Belfort(FRC24), Calvados(FRD11), Manche(FRD12), Orne(FRD13), Eure(FRD21), Seine-	2014-2023

Country	NUTS3 (Counties)	Coverage period
	Maritime(FRD22), Nord(FRE11), Pas-de-Calais(FRE12), Aisne(FRE21), Oise(FRE22), Somme(FRE23), Bas-Rhin(FRF11), Haut-Rhin(FRF12), Ardennes(FRF21), Aube(FRF22), Marne(FRF23), Haute-Marne(FRF24), Meurthe-et-Moselle(FRF31), Meuse(FRF32), Moselle(FRF33), Vosges(FRF34), Loire-Atlantique(FRG01), Maine-et-Loire(FRG02), Mayenne(FRG03), Sarthe(FRG04), Vendée(FRG05), Côtes-d'Armor(FRH01), Finistère(FRH02), Ille-et-Vilaine(FRH03), Morbihan(FRH04), Dordogne(FRI11), Gironde(FRI12), Landes(FRI13), Lot-et-Garonne(FRI14), Pyrénées-Atlantiques(FRI15), Corrèze(FRI21), Creuse(FRI22), Haute-Vienne(FRI23), Charente(FRI31), Charente-Maritime(FRI32), Deux-Sèvres(FRI33), Vienne(FRI34), Aude(FRJ11), Gard(FRJ12), Hérault(FRJ13), Lozère(FRJ14), Pyrénées-Orientales(FRJ15), Ariège(FRJ21), Aveyron(FRJ22), Haute-Garonne(FRJ23), Gers(FRJ24), Lot(FRJ25), Hautes-Pyrénées(FRJ26), Tarn(FRJ27), Tarn-et-Garonne(FRJ28), Allier(FRK11), Cantal(FRK12), Haute-Loire(FRK13), Puy-de-Dôme(FRK14), Ain(FRK21), Ardèche(FRK22), Drôme(FRK23), Isère(FRK24), Loire(FRK25), Rhône(FRK26), Savoie(FRK27), Haute-Savoie(FRK28), Alpes-de-Haute-Provence(FRL01), Hautes-Alpes(FRL02), Alpes-Maritimes(FRL03), Bouches-du-Rhône(FRL04), Var(FRL05), Vaucluse(FRL06), Corse-du-Sud(FRM01), Haute-Corse(FRM02)	
Hungary	Budapest(HU110), Pest(HU120), Fejér(HU211), Komárom-Esztergom(HU212), Veszprém(HU213), Győr-Moson-Sopron(HU221), Vas(HU222), Zala(HU223), Baranya(HU231), Somogy(HU232), Tolna(HU233), Borsod-Abaúj-Zemplén(HU311), Heves(HU312), Nógrád(HU313), Hajdú-Bihar(HU321), Jász-Nagykun-Szolnok(HU322), Szabolcs-Szatmár-Bereg(HU323), Bács-Kiskun(HU331), Békés(HU332), Csongrád(HU333)	2014-2023
Italy	Torino(ITC11), Vercelli(ITC12), Biella(ITC13), Verbano-Cusio-Ossola(ITC14), Novara(ITC15), Cuneo(ITC16), Asti(ITC17), Alessandria(ITC18), Valle d'Aosta/Vallée d'Aoste(ITC20), Imperia(ITC31), Savona(ITC32), Genova(ITC33), La Spezia(ITC34), Varese(ITC41), Como(ITC42), Lecco(ITC43), Sondrio(ITC44), Bergamo(ITC46), Brescia(ITC47), Pavia(ITC48), Lodi(ITC49), Cremona(ITC4A), Mantova(ITC4B), Milano(ITC4C), Monza e della Brianza(ITC4D), L'Aquila(ITF11), Teramo(ITF12), Pescara(ITF13), Chieti(ITF14), Isernia(ITF21), Campobasso(ITF22), Caserta(ITF31), Benevento(ITF32), Napoli(ITF33), Avellino(ITF34), Salerno(ITF35), Taranto(ITF43), Brindisi(ITF44), Lecce(ITF45), Foggia(ITF46), Bari(ITF47), Barletta-Andria-Trani(ITF48), Potenza(ITF51), Matera(ITF52), Cosenza(ITF61), Crotone(ITF62), Catanzaro(ITF63), Vibo Valentia(ITF64), Reggio di Calabria(ITF65), Trapani(ITG11), Palermo(ITG12), Messina(ITG13), Agrigento(ITG14), Caltanissetta(ITG15), Enna(ITG16), Catania(ITG17), Ragusa(ITG18), Siracusa(ITG19), Sassari(ITG2D), Nuoro(ITG2E), Cagliari(ITG2F), Oristano(ITG2G), Sud Sardegna(ITG2H), Bolzano-Bozen(ITH10), Trento(ITH20), Verona(ITH31), Vicenza(ITH32), Belluno(ITH33), Treviso(ITH34), Venezia(ITH35), Padova(ITH36), Rovigo(ITH37), Pordenone(ITH41), Udine(ITH42), Gorizia(ITH43), Trieste(ITH44), Piacenza(ITH51), Parma(ITH52), Reggio nell'Emilia(ITH53), Modena(ITH54), Bologna(ITH55), Ferrara(ITH56), Ravenna(ITH57), Forlì-Cesena(ITH58), Rimini(ITH59), Massa-Carrara(ITI11), Lucca(ITI12), Pistoia(ITI13), Firenze(ITI14), Prato(ITI15), Livorno(ITI16), Pisa(ITI17), Arezzo(ITI18), Siena(ITI19), Grosseto(ITI1A), Perugia(ITI21), Terni(ITI22), Pesaro e Urbino(ITI31), Ancona(ITI32), Macerata(ITI33), Ascoli Piceno(ITI34), Fermo(ITI35), Viterbo(ITI41), Rieti(ITI42), Roma(ITI43), Latina(ITI44), Frosinone(ITI45)	2014-2023

Country	NUTS3 (Counties)	Coverage period
Island	Höfuðborgarsvæði(IS001), Landsbyggð(IS002)	2014-2023
Liechtenstein	Liechtenstein (LI000)	2014-2023
Lithuania	Vilniaus apskritis(LT011), Alytaus apskritis(LT021), Kauno apskritis(LT022), Klaipėdos apskritis(LT023), Marijampolės apskritis(LT024), Panevėžio apskritis(LT025), Šiaulių apskritis(LT026), Tauragės apskritis(LT027), Telšių apskritis(LT028), Utenos apskritis(LT029)	2014-2023
Luxemburg	Luxembourg (LU000)	2014-2023
Latvia	Kurzeme(LV003), Latgale(LV005), Rīga(LV006), Pierīga(LV007), Vidzeme(LV008), Zemgale(LV009)	2014-2023
Montenegro	Crna Gora(ME000)	2014-2022
Netherlands	Oost-Groningen(NL111), Delfzijl en omgeving(NL112), Overig Groningen(NL113), Noord-Friesland(NL124), Zuidwest-Friesland(NL125), Zuidoost-Friesland(NL126), Noord-Drenthe(NL131), Zuidoost-Drenthe(NL132), Zuidwest-Drenthe(NL133), Noord-Overijssel(NL211), Zuidwest-Overijssel(NL212), Twente(NL213), Veluwe(NL221), Zuidwest-Gelderland(NL224), Achterhoek(NL225), Arnhem/Nijmegen(NL226), Flevoland(NL230), Utrecht(NL310), Kop van Noord-Holland(NL321), IJmond(NL323), Agglomeratie Haarlem(NL324), Zaanstreek(NL325), Het Gooi en Vechtstreek(NL327), Alkmaar en omgeving(NL328), Groot-Amsterdam(NL329), Agglomeratie 's-Gravenhage(NL332), Delft en Westland(NL333), Agglomeratie Leiden en Bollenstreek(NL337), Zuidoost-Zuid-Holland(NL33A), Oost-Zuid-Holland(NL33B), Groot-Rijnmond(NL33C), Zeeuwsch-Vlaanderen(NL341), Overig Zeeland(NL342), West-Noord-Brabant(NL411), Midden-Noord-Brabant(NL412), Noordoost-Noord-Brabant(NL413), Zuidoost-Noord-Brabant(NL414), Noord-Limburg(NL421), Midden-Limburg(NL422), Zuid-Limburg(NL423)	2015-2023
Norway	Innlandet(NO020), Trøndelag(NO060), Nordland(NO071), Troms og Finnmark(NO074), Oslo(NO081), Viken(NO082), Vestfold og Telemark(NO091), Agder(NO092), Rogaland(NO0A1), Vestland(NO0A2), Møre og Romsdal(NO0A3)	2014-2023
Poland	Miasto Kraków(PL213), Krakowski(PL214), Tarnowski(PL217), Nowosądecki(PL218), Nowotarski(PL219), Oświęcimski(PL21A), Częstochowski(PL224), Bielski(PL225), Rybnicki(PL227), Bytomski(PL228), Gliwicki(PL229), Katowicki(PL22A), Sosnowiecki(PL22B), Tyski(PL22C), Pilski(PL411), Koniński(PL414), Miasto Poznań(PL415), Kaliski(PL416), Leszczyński(PL417), Poznański(PL418), Miasto Szczecin(PL424), Koszaliński(PL426), Szczecinecko-pyrzycki(PL427), Szczeciński(PL428), Gorzowski(PL431), Zielonogórski(PL432), Miasto Wrocław(PL514), Jeleniogórski(PL515), Legnicko-głogowski(PL516), Wałbrzyski(PL517), Wrocławski(PL518), Nyski(PL523), Opolski(PL524), Bydgosko-toruński(PL613), Grudziądzki(PL616), Inowrocławski(PL617), Świecki(PL618), Włocławski(PL619), Elbląski(PL621), Olsztyński(PL622), Ełcki(PL623), Trójmiejski(PL633), Gdański(PL634), Słupski(PL636), Chojnicki(PL637), Starogardzki(PL638), Miasto Łódź(PL711), Łódzki(PL712), Piotrkowski(PL713), Sieradzki(PL714), Skierniewicki(PL715), Kielecki(PL721), Sandomiersko-jędrzejowski(PL722), Bialski(PL811), Chełmsko-zamojski(PL812), Lubelski(PL814), Puławski(PL815), Krośnieński(PL821), Przemyski(PL822),	2014-2023

Country	NUTS3 (Counties)	Coverage period
	Rzeszowski(PL823), Tarnobrzieski(PL824), Białostocki(PL841), Łomżyński(PL842), Suwalski(PL843), Miasto Warszawa(PL911), Warszawski wschodni(PL912), Warszawski zachodni(PL913), Radomski(PL921), Ciechanowski(PL922), Płocki(PL923), Ostrołęcki(PL924), Siedlecki(PL925), Żyrardowski(PL926)	
Portugal	Alto Minho(PT111), Cávado(PT112), Ave(PT119), Área Metropolitana do Porto(PT11A), Alto Tâmega(PT11B), Tâmega e Sousa(PT11C), Douro(PT11D), Terras de Trás-os-Montes(PT11E), Algarve(PT150), Oeste(PT16B), Região de Aveiro(PT16D), Região de Coimbra(PT16E), Região de Leiria(PT16F), Viseu Dão Lafões(PT16G), Beira Baixa(PT16H), Médio Tejo(PT16I), Beiras e Serra da Estrela(PT16J), Área Metropolitana de Lisboa(PT170), Alentejo Litoral(PT181), Baixo Alentejo(PT184), Lezíria do Tejo(PT185), Alto Alentejo(PT186), Alentejo Central(PT187), Região Autónoma da Madeira(PT300)	2014-2023
Romania	Bihor(RO111), Bistrița-Năsăud(RO112), Cluj(RO113), Maramureș(RO114), Satu Mare(RO115), Sălaj(RO116), Alba(RO121), Brașov(RO122), Covasna(RO123), Harghita(RO124), Mureș(RO125), Sibiu(RO126), Bacău(RO211), Botoșani(RO212), Iași(RO213), Neamț(RO214), Suceava(RO215), Vaslui(RO216), Brăila(RO221), Buzău(RO222), Constanța(RO223), Galați(RO224), Tulcea(RO225), Vrancea(RO226), Argeș(RO311), Călărași(RO312), Dâmbovița(RO313), Giurgiu(RO314), Ialomița(RO315), Prahova(RO316), Teleorman(RO317), București(RO321), Ilfov(RO322), Dolj(RO411), Gorj(RO412), Mehedinți(RO413), Olt(RO414), Vâlcea(RO415), Arad(RO421), Caraș-Severin(RO422), Hunedoara(RO423), Timiș(RO424)	2015-2023
Serbia	City of Belgrade(RS110), Zapadnobačka oblast(RS121), Južnobańska oblast(RS122), Južnobačka oblast(RS123), Severnobańska oblast(RS124), Severnobačka oblast(RS125), Srednjobanatska oblast(RS126), Sremska oblast(RS127), Zlatiborska oblast(RS211), Kolubarska oblast(RS212), Mačvanska oblast(RS213), Moravička oblast(RS214), Pomoravska oblast(RS215), Rasinska oblast(RS216), Raška oblast(RS217), Šumadijska oblast(RS218), Borska oblast(RS221), Braničevska oblast(RS222), Zaječarska oblast(RS223), Jablanička oblast(RS224), Nišavska oblast(RS225), Pirotka oblast(RS226), Podunavska oblast(RS227), Pčinjska oblast(RS228), Toplička oblast(RS229)	2017-2023
Sweden	Stockholms län(SE110), Uppsala län(SE121), Södermanlands län(SE122), Östergötlands län(SE123), Örebro län(SE124), Västmanlands län(SE125), Jönköpings län(SE211), Kronobergs län(SE212), Kalmar län(SE213), Gotlands län(SE214), Blekinge län(SE221), Skåne län(SE224), Hallands län(SE231), Västra Götalands län(SE232), Värmlands län(SE311), Dalarnas län(SE312), Gävleborgs län(SE313), Västernorrlands län(SE321), Jämtlands län(SE322), Västerbottens län(SE331), Norrbottens län(SE332)	2014-2023
Slovakia	Bratislavský kraj(SK010), Trnavský kraj(SK021), Trenčiansky kraj(SK022), Nitriansky kraj(SK023), Žilinský kraj(SK031), Banskobystrický kraj(SK032), Prešovský kraj(SK041), Košický kraj(SK042)	2014-2023
United Kingdom	Hartlepool and Stockton-on-Tees(UKC11), South Teesside(UKC12), Darlington(UKC13), Durham CC(UKC14), Northumberland(UKC21), Tyneside(UKC22), Sunderland(UKC23), West Cumbria(UKD11), East Cumbria(UKD12), Manchester(UKD33), Greater Manchester South West(UKD34), Greater Manchester South East(UKD35), Greater Manchester North West(UKD36), Greater Manchester North East(UKD37), Blackburn with Darwen(UKD41), Blackpool(UKD42), Lancaster and Wyre(UKD44), Mid Lancashire(UKD45), East Lancashire(UKD46), Chorley and West Lancashire(UKD47), Warrington(UKD61),	2015-2019

Country	NUTS3 (Counties)	Coverage period
	Cheshire East(UKD62), Cheshire West and Chester(UKD63), East Merseyside(UKD71), Liverpool(UKD72), Sefton(UKD73), Wirral(UKD74), Kingston upon Hull, City of(UKE11), East Riding of Yorkshire(UKE12), North and North East Lincolnshire(UKE13), York(UKE21), North Yorkshire CC(UKE22), Barnsley, Doncaster and Rotherham(UKE31), Sheffield(UKE32), Bradford(UKE41), Leeds(UKE42), Calderdale and Kirklees(UKE44), Wakefield(UKE45), Derby(UKF11), East Derbyshire(UKF12), South and West Derbyshire(UKF13), Nottingham(UKF14), North Nottinghamshire(UKF15), South Nottinghamshire(UKF16), Leicester(UKF21), Leicestershire CC and Rutland(UKF22), West Northamptonshire(UKF24), North Northamptonshire(UKF25), Lincolnshire(UKF30), Herefordshire, County of(UKG11), Worcestershire(UKG12), Warwickshire(UKG13), Telford and Wrekin(UKG21), Shropshire CC(UKG22), Stoke-on-Trent(UKG23), Staffordshire CC(UKG24), Birmingham(UKG31), Solihull(UKG32), Coventry(UKG33), Dudley(UKG36), Sandwell(UKG37), Walsall(UKG38), Wolverhampton(UKG39), Peterborough(UKH11), Cambridgeshire CC(UKH12), Suffolk(UKH14), Norwich and East Norfolk(UKH15), North and West Norfolk(UKH16), Breckland and South Norfolk(UKH17), Luton(UKH21), Hertfordshire(UKH23), Bedford(UKH24), Central Bedfordshire(UKH25), Southend-on-Sea(UKH31), Thurrock(UKH32), Essex Haven Gateway(UKH34), West Essex(UKH35), Heart of Essex(UKH36), Essex Thames Gateway(UKH37), Camden and City of London(UKI31), Westminster(UKI32), Kensington & Chelsea and Hammersmith & Fulham(UKI33), Wandsworth(UKI34), Hackney and Newham(UKI41), Tower Hamlets(UKI42), Haringey and Islington(UKI43), Lewisham and Southwark(UKI44), Lambeth(UKI45), Bexley and Greenwich(UKI51), Barking & Dagenham and Havering(UKI52), Redbridge and Waltham Forest(UKI53), Enfield(UKI54), Bromley(UKI61), Croydon(UKI62), Merton, Kingston upon Thames and Sutton(UKI63), Barnet(UKI71), Brent(UKI72), Ealing(UKI73), Harrow and Hillingdon(UKI74), Hounslow and Richmond upon Thames(UKI75), Berkshire(UKJ11), Milton Keynes(UKJ12), Buckinghamshire CC(UKJ13), Oxfordshire(UKJ14), Brighton and Hove(UKJ21), East Sussex CC(UKJ22), West Surrey(UKJ25), East Surrey(UKJ26), West Sussex (South West)(UKJ27), West Sussex (North East)(UKJ28), Portsmouth(UKJ31), Southampton(UKJ32), Isle of Wight(UKJ34), South Hampshire(UKJ35), Central Hampshire(UKJ36), North Hampshire(UKJ37), Medway(UKJ41), Kent Thames Gateway(UKJ43), East Kent(UKJ44), Mid Kent(UKJ45), West Kent(UKJ46), Bristol, City of(UKK11), Bath and North East Somerset, North Somerset and South Gloucestershire(UKK12), Gloucestershire(UKK13), Swindon(UKK14), Wiltshire CC(UKK15), Somerset(UKK23), Cornwall and Isles of Scilly(UKK30), Plymouth(UKK41), Torbay(UKK42), Devon CC(UKK43), Isle of Anglesey(UKL11), Gwynedd(UKL12), Conwy and Denbighshire(UKL13), South West Wales(UKL14), Central Valleys(UKL15), Gwent Valleys(UKL16), Bridgend and Neath Port Talbot(UKL17), Swansea(UKL18), Monmouthshire and Newport(UKL21), Cardiff and Vale of Glamorgan(UKL22), Flintshire and Wrexham(UKL23), Powys(UKL24), Aberdeen City and Aberdeenshire(UKM50), Caithness & Sutherland and Ross & Cromarty(UKM61), Inverness & Nairn and Moray, Badenoch & Strathspey(UKM62), Lochaber, Skye & Lochalsh, Arran & Cumbræ and Argyll & Bute(UKM63), Na h-Eileanan Siar (Western Isles)(UKM64), Orkney Islands(UKM65), Shetland Islands(UKM66), Angus and Dundee City(UKM71), Clackmannanshire and Fife(UKM72), East Lothian and Midlothian(UKM73), Edinburgh, City of(UKM75), Falkirk(UKM76), Perth & Kinross and Stirling(UKM77), West Lothian(UKM78), East Dunbartonshire, West Dunbartonshire and Helensburgh & Lomond(UKM81), Glasgow City(UKM82), Inverclyde, East Renfrewshire and Renfrewshire(UKM83), North	

Country	NUTS3 (Counties)	Coverage period
	Lanarkshire(UKM84), Scottish Borders(UKM91), Dumfries & Galloway(UKM92), East Ayrshire and North Ayrshire mainland(UKM93), South Ayrshire(UKM94), South Lanarkshire(UKM95), Belfast(UKN06), Armagh City, Banbridge and Craigavon(UKN07), Newry, Mourne and Down(UKN08), Ards and North Down(UKN09)	
The NUTS3 subdivision refers to the current period 2021 – 2024 (more details can be reached here: https://ec.europa.eu/eurostat/web/nuts/history/).		

B.2. Coefficients details and additional tables

Table B.S. 2 Coefficients Temperature and Older Mortality (65+) in Europe

Variables	Estimates	[CI]
≤5th percentile	0.0072*** (0.0003)	[0.0066 – 0.0077]
>5th and≤10th percentile	0.0027*** (0.0004)	[0.0020 – 0.0035]
>10th and≤15th percentile	0.0036*** (0.0004)	[0.0027 – 0.0044]
>15th and<20th percentile	0.0035*** (0.0006)	[0.0023 – 0.0047]
≥ 20th and<25th percentile	0.0025*** (0.0005)	[0.0015 – 0.0035]
≥ 75th and<80th percentile	-0.0011*** (0.0003)	[-0.0016 - -0.0005]
≥ 80th and<85th percentile	-0.0007** (0.0003)	[-0.0012 - -0.0002]
≥ 85th and<90th percentile	0.0001 (0.0002)	[-0.0004 – 0.0006]
≥ 90th and<95th percentile	0.0007** (0.0002)	[0.0002 – 0.0011]
≥ 95th percentile	0.0058*** (0.0004)	[0.0051 – 0.0065]
Females	-0.4012*** (0.0031)	
Age 70-74	0.4170*** (0.0029)	
Age 75-79	0.9183*** (0.0052)	
Age 80-84	1.507*** (0.0073)	
Age 85-89	2.153*** (0.0093)	
Age ≥ 90	2.929*** (0.0128)	
Solar radiation	-0.0277*** (0.0039)	
Precipitation	-1.844*** (0.4975)	
Relative humidity	0.0007* (0.0003)	
Wind speed	0.0028*** (0.0008)	
PM _{2.5}	-0.0001 (0.0002)	
Population density	-0.0017 (0.0025)	
NUTS3	964	
Observations	1,201,488	

Note: Estimates are obtained by estimating Equation (1) on the values in the NUTS3, month, year and demographic group (age groups and sex) cells. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 3Temperature and Older Mortality by Climate regions, Urbanization level, GDP per capita, and PM_{2.5} air pollution

Climate Regions variables	Estimates	Effect Rate [CI]
≤5th percentile	0.0083 (0.0004)	8.3793 [7.671-9.081]
≤5th percentile * Temperate	-0.0018*** (0.0004)	6.5375 [5.836-7.238]
≤5th percentile * Hot	-0.0009 (0.0008)	7.4639 [6.107-8.822]
≥ 95th percentile	0.0031 (0.0004)	3.1307 [2.314-3.948]
≥ 95th percentile * Temperate	0.0024*** (0.0005)	5.5105 [4.565-6.456]
≥ 95th percentile * Hot	0.0065*** (0.0005)	9.7176 [8.611-0.824]
Urbanization level variables		
≤5th percentile	0.0069 (0.0005)	6.887 [5.867-7.907]
≤5th percentile * Intermediate	0.0003 (0.0006)	7.229 [6.561-7.897]
≤5th percentile * Rural	0.0007 (0.0006)	7.619 [6.959-8.280]
≥ 95th percentile	0.0064 (0.0006)	6.4374 [5.339-7.536]
≥ 95th percentile * Intermediate	-0.0011* (0.0005)	5.333 [4.612-6.055]
≥ 95th percentile * Rural	-0.0009 (0.0005)	5.5440 [4.677-6.410]
GDP per capita variables		
≤5th percentile	0.0094 (0.0004)	9.462 [8.761-10.163]
≤5th percentile * Medium	-0.0028*** (0.0004)	6.629 [5.953-7.305]
≤5th percentile * High	-0.0037*** (0.0005)	5.764 [4.852-6.677]
≥ 95th percentile	0.0054 (0.0005)	5.451 [4.514-6.389]
≥ 95th percentile * Medium	0.0002 (0.0005)	5.614 [4.850-6.378]
≥ 95th percentile * High	0.0005 (0.0006)	5.961 [4.888-7.035]
PM _{2.5} air pollution variables		
≤5th percentile	0.0055 (0.0006)	5.470 [4.346-6.595]
≤5th percentile * Q2	0.0010 (0.0007)	6.453 [5.749-7.158]
≤5th percentile * Q3	0.0028*** (0.0007)	8.336 [7.538-9.134]
≤5th percentile * Q4	0.0031*** (0.0007)	8.622 [7.706-9.538]
≥ 95th percentile	0.0054 (0.0007)	5.449 [3.999-6.902]
≥ 95th percentile * Q2	-0.0009 (0.0007)	4.497 [3.552-5.442]
≥ 95th percentile * Q3	0.0004 (0.0007)	5.829 [4.942-6.717]
≥ 95th percentile * Q4	0.0019* (0.0007)	7.328 [6.415-8.241]
NUTS3	964	
Observations	1,201,488	

Note: Estimates are obtained by estimating Equation (2) values in interaction with Climate regions (reference category: cool), Urbanization level (reference category: urban), GDP per capita (reference category: low), and PM_{2.5} air

pollution (reference category: low) in the NUTS3, month, year and demographic group (age groups and sex) cells. The 95 % confidence interval around each coefficient is calculated by taking the point estimate and adding to or subtracting from it the appropriate margin of error. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 4Temperature and Older Mortality (65+) in Europe – Absolute Temperatures

Variables	Coefficients	CI (95%)
<= - 6 C°	0.0099*** (0.0005)	[0.0089 – 0.0108]
-6 to -3 C°	0.0092*** (0.0005)	[0.0081 – 0.0102]
-3 to 0 C°	0.0078*** (0.0004)	[0.0070 – 0.0086]
0 to 3 C°	0.0048*** (0.0003)	[0.0043 – 0.0053]
3 to 9 C°	0.0042*** (0.0003)	[0.0036 – 0.0048]
15 to 18 C°	-0.0011*** (0.0002)	[-0.0016 - -0.0006]
18 to 21 C°	-0.0006** (0.0002)	[-0.0011 - -0.0002]
21 to 24 C°	0.0005 (0.0003)	[-0.0001 – 0.0012]
24 to 27 C°	0.0030*** (0.0004)	[0.0021 – 0.0038]
>= 27 C°	0.0114*** (0.0005)	[0.0104 – 0.0125]
Females	-0.4012*** (0.0031)	
Age 70-74	0.4170*** (0.0029)	
Age 75-79	0.9183*** (0.0052)	
Age 80-84	1.507*** (0.0073)	
Age 85-89	2.153*** (0.0093)	
Age ≥ 90	2.929*** (0.0128)	
Solar radiation	-0.0214*** (0.0038)	
Precipitation	-1.352** (0.4959)	
Relative humidity	0.0004 (0.0003)	
Wind speed	0.0034*** (0.0007)	
PM _{2.5}	-0.0004* (0.0002)	
Population density	-0.0014 (0.0025)	
NUTS3	964	
Observations	1,201,488	

Note: Estimates are obtained by estimating Equation (1) considering absolute temperatures. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 5Temperature and Older Mortality (65+) in Europe – Maximum Temperatures

Variables	Coefficients	CI
≤5th percentile	0.0069*** (0.0004)	[0.0060 – 0.0077]
>5th and≤10th percentile	0.0033*** (0.0004)	[0.0026 – 0.0040]
>10th and≤15th percentile	0.0033*** (0.0005)	[0.0023 – 0.0043]
>15th and<20th percentile	0.0039*** (0.0005)	[0.0028 – 0.0050]
≥ 20th and<25th percentile	0.0023*** (0.0007)	[0.0010 – 0.0036]
≥ 75th and<80th percentile	-0.0008** (0.0003)	[-0.0013 - -0.0003]
≥ 80th and<85th percentile	0.0004 (0.0003)	[-0.0002 - 0.0011]
≥ 85th and<90th percentile	0.0003 (0.0003)	[-0.0002 – 0.0008]
≥ 90th and<95th percentile	0.0005* (0.0002)	[0.0002 – 0.0010]
≥ 95th percentile	0.0051*** (0.0004)	[0.0043 – 0.0060]
Females	-0.4009*** (0.0031)	
Age 70-74	0.4172*** (0.0029)	
Age 75-79	0.9180*** (0.0052)	
Age 80-84	1.508*** (0.0073)	
Age 85-89	2.155*** (0.0093)	
Age ≥ 90	2.928*** (0.0129)	
Solar radiation	-0.0145*** (0.0039)	
Precipitation	-2.532*** (0.5237)	
Relative humidity	0.0007* (0.0004)	
Wind speed	0.0023** (0.0008)	
PM _{2.5}	-0.0001 (0.0002)	
Population density	-0.0023 (0.0032)	
NUTS3	964	
Observations	1,147,392	

Note: Estimates are obtained by estimating Equation (1) considering maximum temperatures. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 6 Temperature and Older Mortality (65+) in Europe – Minimum Temperatures

Variables	Coefficients	CI
≤5th percentile	0.0062*** (0.0003)	[0.0056 – 0.0068]
>5th and≤10th percentile	0.0018*** (0.0004)	[0.0010 – 0.0026]
>10th and≤15th percentile	0.0025*** (0.0004)	[0.0016 – 0.0033]
>15th and<20th percentile	0.0016*** (0.0005)	[0.0007 – 0.0025]
≥ 20th and<25th percentile	0.0012. (0.0006)	[-0.0000 – 0.0024]
≥ 75th and<80th percentile	-0.0017*** (0.0003)	[-0.0022 - -0.0011]
≥ 80th and<85th percentile	-0.0010*** (0.0003)	[-0.0015 - -0.0005]
≥ 85th and<90th percentile	-0.0004. (0.0002)	[-0.0009 – 0.0000]
≥ 90th and<95th percentile	-0.0004. (0.0002)	[-0.0008 – 0.0000]
≥ 95th percentile	0.0046*** (0.0003)	[0.0040 – 0.00]
Females	-0.4009*** (0.0031)	
Age 70-74	0.4172*** (0.0029)	
Age 75-79	0.9180*** (0.0052)	
Age 80-84	1.508*** (0.0073)	
Age 85-89	2.155*** (0.0093)	
Age ≥ 90	2.928*** (0.0129)	
Solar radiation	-0.0348*** (0.0043)	
Precipitation	-1.678** (0.5445)	
Relative humidity	0.0004 (0.0003)	
Wind speed	0.0019** (0.0007)	
PM _{2.5}	-0.0001 (0.0002)	
Population density	-0.0021 (0.0031)	
NUTS3	964	
Observations	1,147,392	

Note: Estimates are obtained by estimating Equation (1) considering minimum temperatures. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 7 Temperature and Older Mortality in Europe (65+) by Sex

Variables	Coefficients	CI
≤5th percentile	0.0059 (0.0003)	[0.0053 – 0.0065]
>5th and≤10th percentile	0.0021 (0.0004)	[0.0013 – 0.0029]
>10th and≤15th percentile	0.0037 (0.0005)	[0.0027 – 0.0046]
>15th and<20th percentile	0.0032 (0.0006)	[0.0020 – 0.0044]
≥ 20th and<25th percentile	0.0025 (0.0006)	[0.0013 – 0.0036]
≥ 75th and<80th percentile	-0.0005. (0.0003)	[-0.0010 - 0.0000]
≥ 80th and<85th percentile	-0.0009 (0.0003)	[-0.0015 - -0.0003]
≥ 85th and<90th percentile	-4.16e-5 (0.0003)	[-0.0006 – 0.0005]
≥ 90th and<95th percentile	0.0006 (0.0003)	[0.0001 – 0.0011]
≥ 95th percentile	0.0045 (0.0003)	[0.0038 – 0.0052]
≤5th percentile * Females	0.0023*** (0.0001)	[0.0080 – 0.0085]
>5th and≤10th percentile * Females	0.0012*** (0.0002)	[0.0028 – 0.0037]
>10th and≤15th percentile * Females	-0.0002 (0.0003)	[0.0029 – 0.0040]
>15th and<20th percentile * Females	0.0006* (0.0003)	[0.0033 – 0.0043]
≥ 20th and<25th percentile * Females	3.89e-5 (0.0003)	[0.0020 – 0.0031]
≥ 75th and<80th percentile * Females	-0.0011*** (0.0002)	[-0.0020 - -0.0011]
≥ 80th and<85th percentile * Females	0.0003 (0.0003)	[-0.0010 - -0.0000]
≥ 85th and<90th percentile * Females	0.0003 (0.0003)	[-0.0002 – 0.0008]
≥ 90th and<95th percentile * Females	2.28e-5 (0.0002)	[0.0002 – 0.0011]
≥ 95th percentile * Females	0.0024*** (0.0002)	[0.0066 – 0.0073]
NUTS3	964	
Observations	1,201,488	

Note: Estimates are obtained by estimating Equation (2) with sex as interaction term. Male is the baseline category. The 95 % confidence interval around each coefficient is calculated by taking the point estimate and adding to or subtracting from it the appropriate margin of error. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 8 Temperature and Older Mortality in Europe (65+) by age

Variables	Coefficients	CI
≤5th percentile	0.0016 (0.0004)	[0.0009 – 0.0023]
≤5th percentile * 70-74	0.0012*** (0.0003)	[0.0023 – 0.0033]
≤5th percentile * 75-79	0.0028*** (0.0003)	[0.0039 – 0.0049]
≤5th percentile * 80-84	0.0051*** (0.0003)	[0.0062 – 0.0072]
≤5th percentile * 85-89	0.0068*** (0.0003)	[0.0079 – 0.0090]
≤5th percentile * 90+	0.0101*** (0.0003)	[0.0110 - 0.0123]
≥ 95th percentile	0.0037 (0.0004)	[0.0030 - 0.0044]
≥ 95th percentile * 70-74	0.0006* (0.0003)	[0.0037 – 0.0048]
≥ 95th percentile * 75-79	0.0010*** (0.0003)	[0.0042 – 0.0053]
≥ 95th percentile * 80-84	0.0016*** (0.0003)	[0.0048 – 0.0059]
≥ 95th percentile * 85-89	0.0023*** (0.0003)	[0.0054 – 0.0067]
≥ 95th percentile * 90+	0.0045*** (0.0004)	[0.0074 – 0.0089]
NUTS3	964	
Observations	1,201,488	

Note: Estimates are obtained by estimating Equation (2) with age as interaction term. Age 65-69 is the baseline category. The 95 % confidence interval around each coefficient is calculated by taking the point estimate and adding to or subtracting from it the appropriate margin of error. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 9 Coefficients Temperature and Older Mortality (65+) in Europe - Balanced panel dataset

Variables	Coefficients	CI (95%)
≤5th percentile	0.0066*** (0.0003)	[0.0059 – 0.0072]
>5th and≤10th percentile	0.0029*** (0.0005)	[0.0020 – 0.0038]
>10th and≤15th percentile	0.0039*** (0.0005)	[0.0028 – 0.0049]
>15th and<20th percentile	0.0034*** (0.0008)	[0.0019 – 0.0048]
≥ 20th and<25th percentile	0.0033*** (0.0006)	[0.0020 – 0.0045]
≥ 75th and<80th percentile	-0.0003 (0.0003)	[-0.0008 - 0.0003]
≥ 80th and<85th percentile	-0.0002 (0.0003)	[-0.0008 - 0.0004]
≥ 85th and<90th percentile	0.0000 (0.0003)	[-0.0005 – 0.0007]
≥ 90th and<95th percentile	0.0009** (0.0003)	[0.0003 – 0.0014]
≥ 95th percentile	0.0070*** (0.0004)	[0.0061 – 0.0078]
Females	-0.4271*** (0.0032)	
Age 70-74	0.4118*** (0.0035)	
Age 75-79	0.9043*** (0.0065)	
Age 80-84	1.494*** (0.0092)	
Age 85-89	2.153*** (0.0112)	
Age ≥ 90	2.957*** (0.0142)	
Solar radiation	-0.0316*** (0.0048)	
Precipitation	-2.239*** (0.5678)	
Relative humidity	0.0008* (0.0004)	
Wind speed	0.0039*** (0.0009)	
PM _{2.5}	-0.0001 (0.0002)	
Population density	-0.0013 (0.0021)	
NUTS3	590	
Observations	846,720	

Note: Estimates are obtained by estimating Equation (1) on the values in the NUTS3, month, year and demographic group (age groups and sex) cells. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

Table B.S. 10 Temperature and Older Mortality in Europe (65+) – Balanced panel dataset by Climate regions, Urbanization level, GDP per capita, and PM_{2.5} air pollution

Climate Regions variables	Coefficients	CI
≤5th percentile	0.0077 (0.0004)	[0.0068 – 0.0087]
≤5th percentile * Temperate	-0.0021*** (0.0005)	[0.0047 – 0.0066]
≤5th percentile * Hot	-0.0003 (0.0010)	[0.0055 – 0.0093]
≥ 95th percentile	0.0051 (0.0004)	[0.0041 – 0.0061]
≥ 95th percentile * Temperate	0.0019*** (0.0006)	[0.0059 – 0.0081]
≥ 95th percentile * Hot	0.0047*** (0.0006)	[0.0086 – 0.0111]
Urbanization level variables	Coefficients	
≤5th percentile	0.0065 (0.0006)	[0.0037 – 0.0066]
≤5th percentile * Intermediate	-2.28e-5 (0.0007)	[0.0040 – 0.0075]
≤5th percentile * Rural	0.0004 (0.0007)	[0.0055 – 0.0090]
≥ 95th percentile	0.0076 (0.0006)	[0.0061 – 0.0095]
≥ 95th percentile * Intermediate	-0.0012* (0.0006)	[0.0055 – 0.0087]
≥ 95th percentile * Rural	-0.0011 (0.0006)	[0.0051 – 0.0082]
GDP per capita variables	Coefficients	
≤5th percentile	0.0087 (0.0004)	[0.0079 – 0.0095]
≤5th percentile * Medium	-0.0026*** (0.0005)	[0.0052 – 0.0070]
≤5th percentile * High	-0.0032*** (0.0006)	[0.0042– 0.0067]
≥ 95th percentile	0.0074 (0.0005)	[0.0064 – 0.0083]
≥ 95th percentile * Medium	-0.0010 (0.0005)	[0.0053 – 0.0074]
≥ 95th percentile * High	-0.0004 (0.0006)	[0.0058 – 0.0082]
PM _{2.5} air pollution variables	Coefficients	
≤5th percentile	0.0052 (0.0007)	[0.0037 – 0.0066]
≤5th percentile * Q2	0.0005 (0.0009)	[0.0040 – 0.0075]
≤5th percentile * Q3	0.0021* (0.0009)	[0.0055 – 0.0090]
≤5th percentile * Q4	0.0026** (0.0009)	[0.0061 – 0.0095]
≥ 95th percentile	0.0071 (0.0008)	[0.0055 – 0.0087]
≥ 95th percentile * Q2	-0.0004 (0.0008)	[0.0051 – 0.0082]
≥ 95th percentile * Q3	-0.0010 (0.0008)	[0.0046 – 0.0076]
≥ 95th percentile * Q4	0.0005 (0.0008)	[0.0061 – 0.0092]
NUTS3	590	
Observations	846,720	

Note: Estimates are obtained by estimating Equation (2) with age as interaction term. The baseline categories are respectively: Cool regions, Urban, Low GDP per capita, and Low PM_{2.5} air pollution. The 95 % confidence interval around each coefficient is calculated by taking the point estimate and adding to or subtracting from it the appropriate margin of error. Standard errors clustered at NUTS3 level and reported in parenthesis. *p<0.05; **p<0.01; ***p<0.001.

B.3. Additional figures

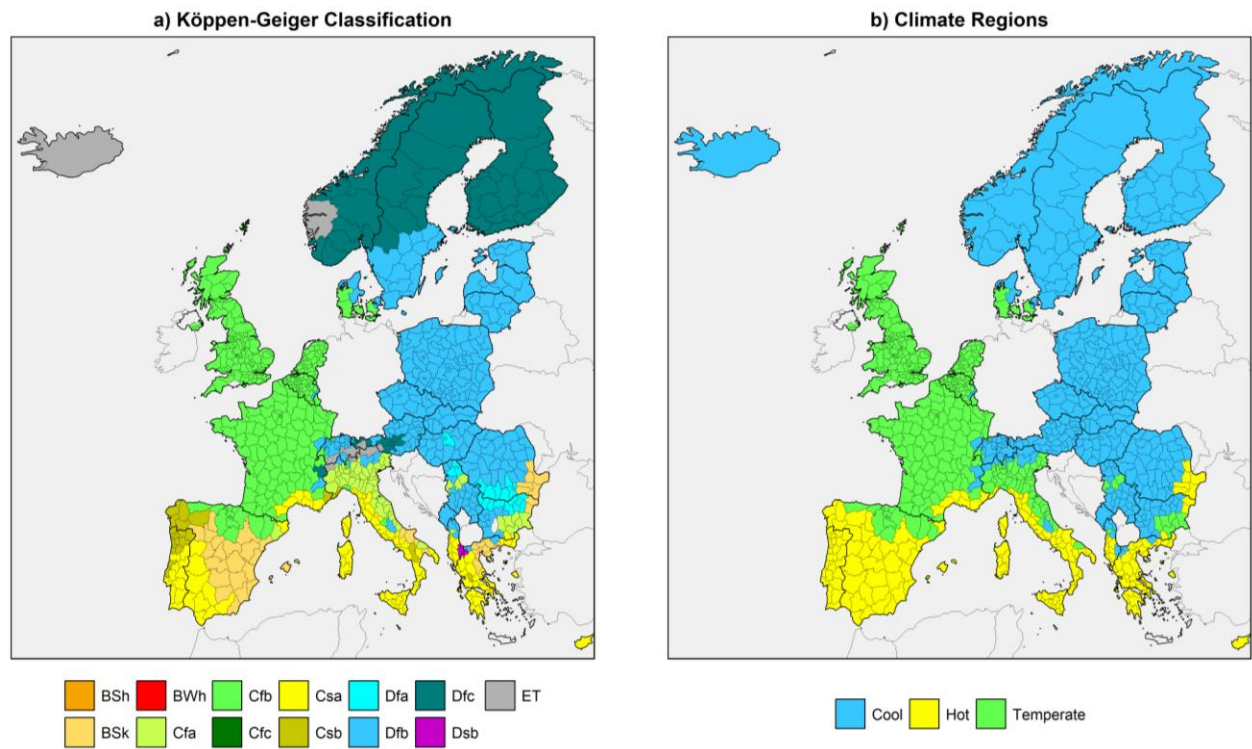


Figure B.S. 1 Classification of regions in Europe in different climate zones based on the Köppen-Geiger classification

Note: Panel a) shows the Köppen-Geiger climate classification based on Beck et al. (2018). Panel b) shows the classifications of regions in three climate zones with a hot (Bwh, Bwk, Bsh, Bsk, Csa, Csb), temperate (Cfa, Cfb, Cfc) or cool (Dsa, Dsb, Dsc, Dfa, Dfb, Dfc, eT, eF) climate.

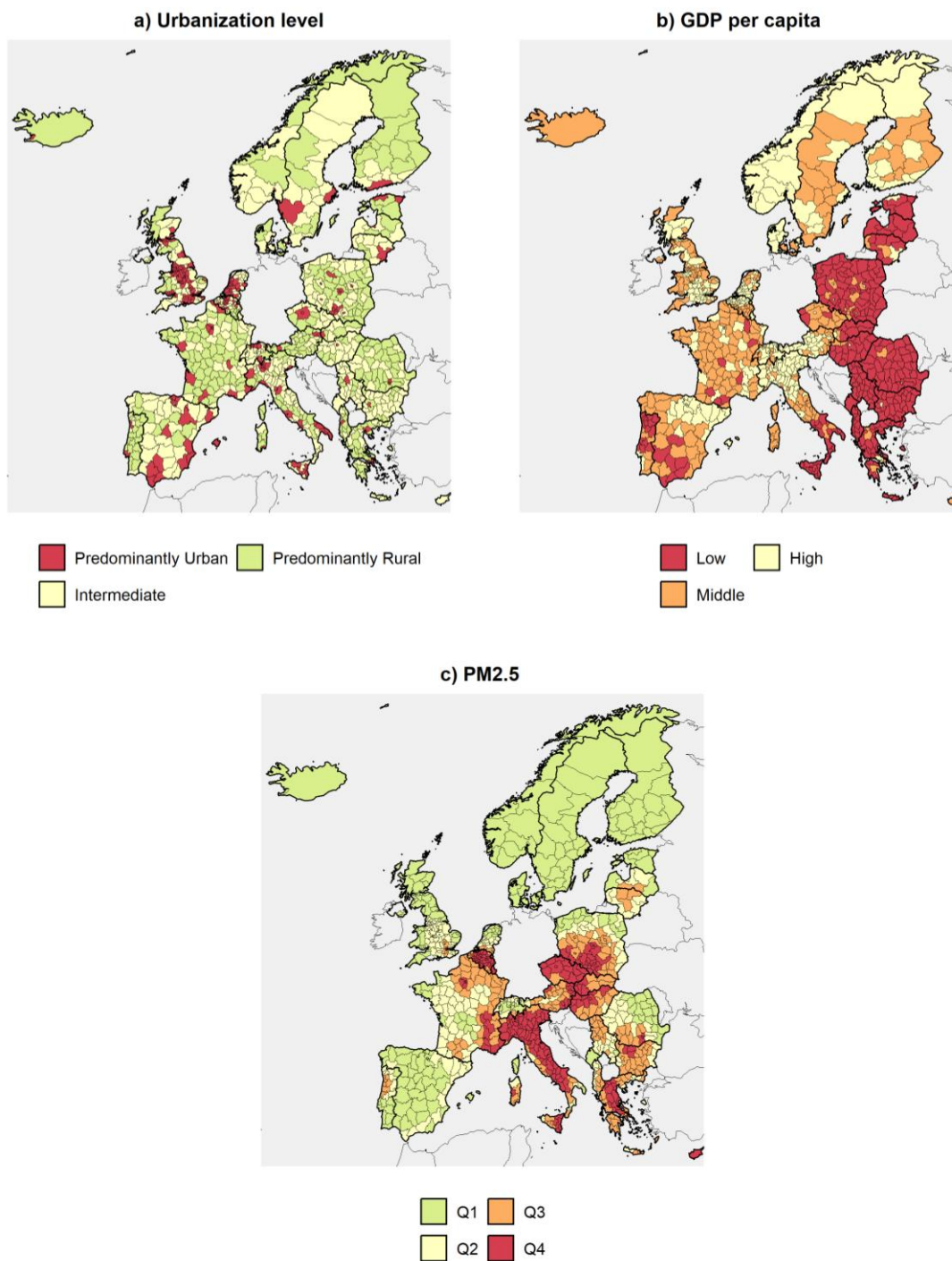


Figure B.S. 2 Classification of regions in Europe by Urbanization, GDP per capita, and PM_{2.5} pollution level

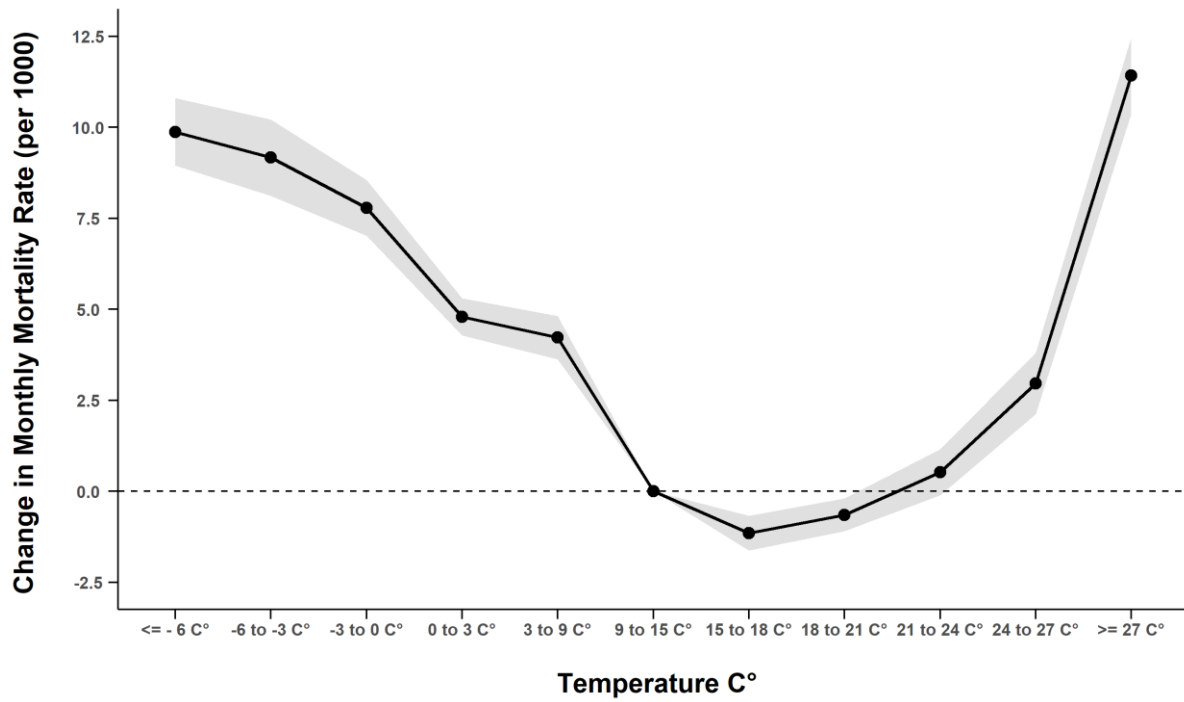


Figure B.S. 3 Extreme temperature and mortality in Europe (65+) – Absolute Temperature

Note: The figure shows estimates are obtained by estimating Equation (1) with Absolute Temperature. Standard errors clustered at the NUTS3 level. 95% Confidence intervals.

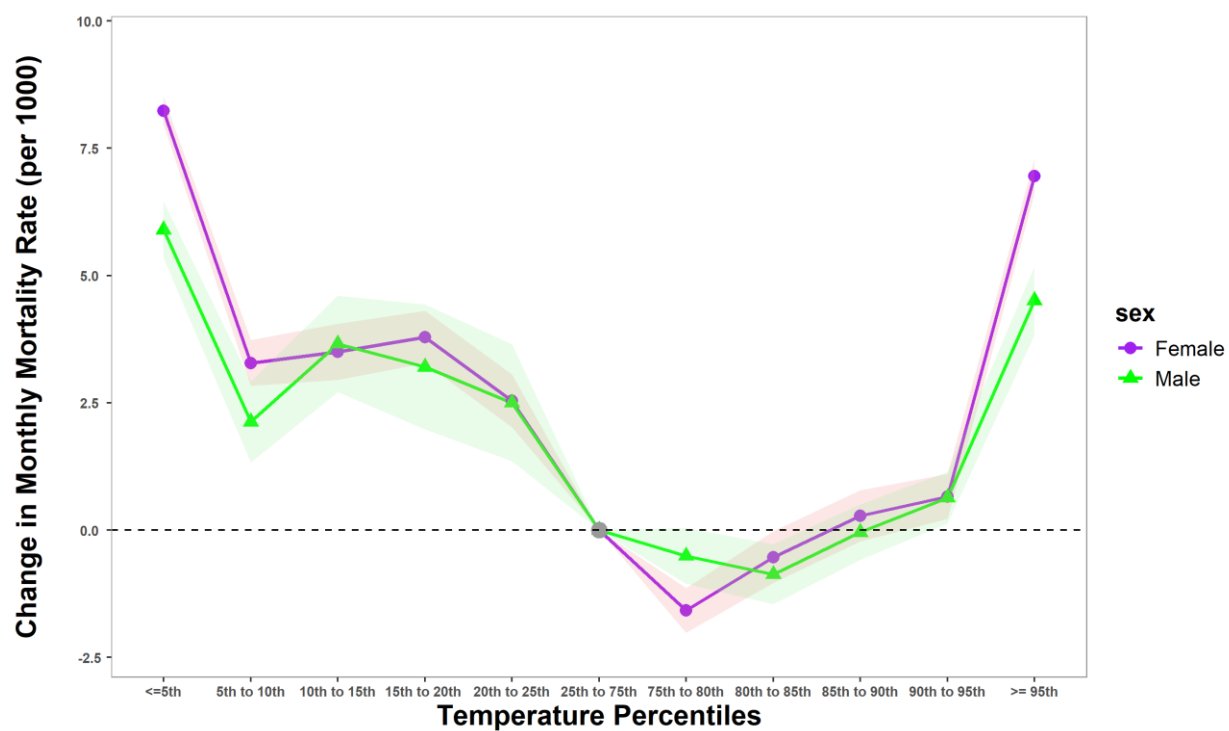


Figure B.S. 4 Extreme temperature and mortality in Europe (65+) by sex

Note: The figure shows estimates are obtained by estimating Equation (2) with sex as interaction value. Standard errors clustered at the NUTS3 level. 95% Confidence intervals.

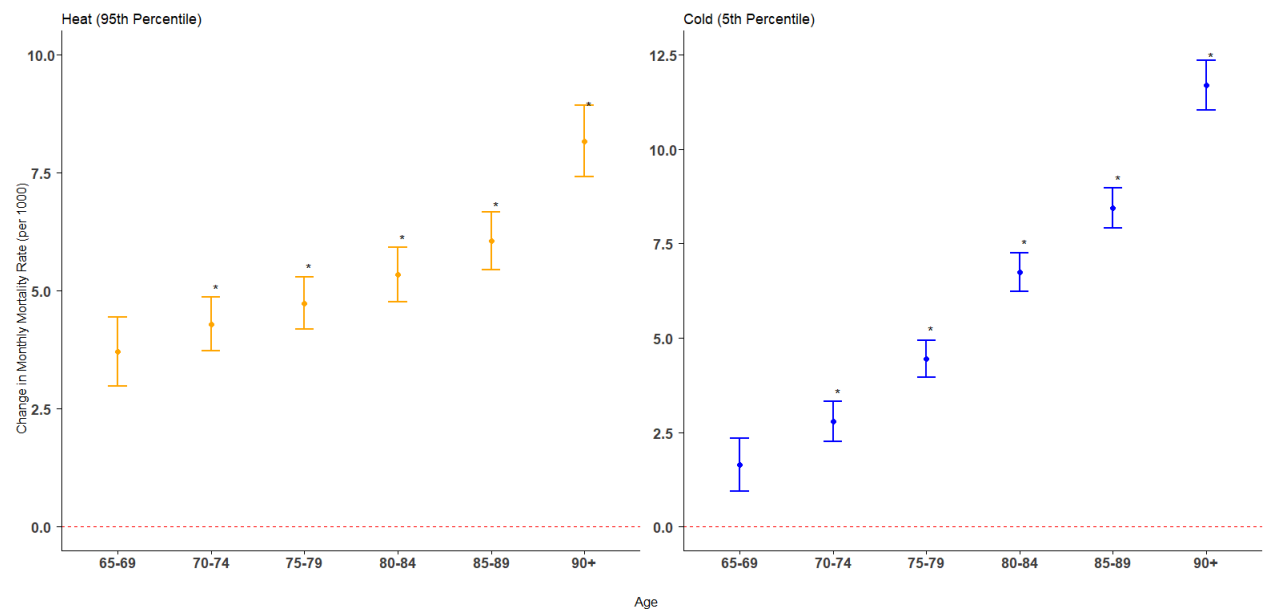


Figure B.S. 5 Extreme temperature and mortality in Europe (65+) by age

Note: The figure shows estimates are obtained by estimating Equation (2) with age as interaction value. Standard errors clustered at the NUTS3 level. 95% Confidence intervals.

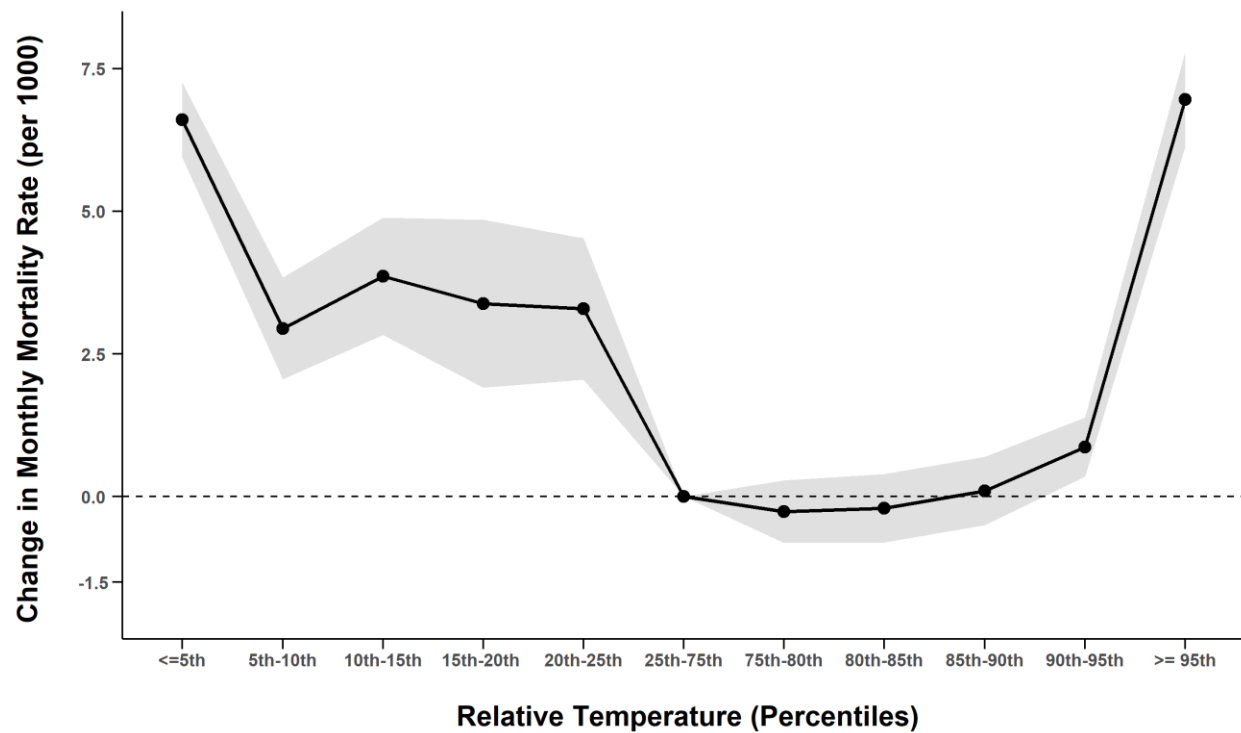


Figure B.S. 6 Extreme temperature and mortality in Europe (65+) – Balanced panel dataset

Note: The figure shows estimates are obtained by estimating Equation (1) with Absolute Temperature. Standard errors clustered at the NUTS3 level. 95% Confidence intervals.

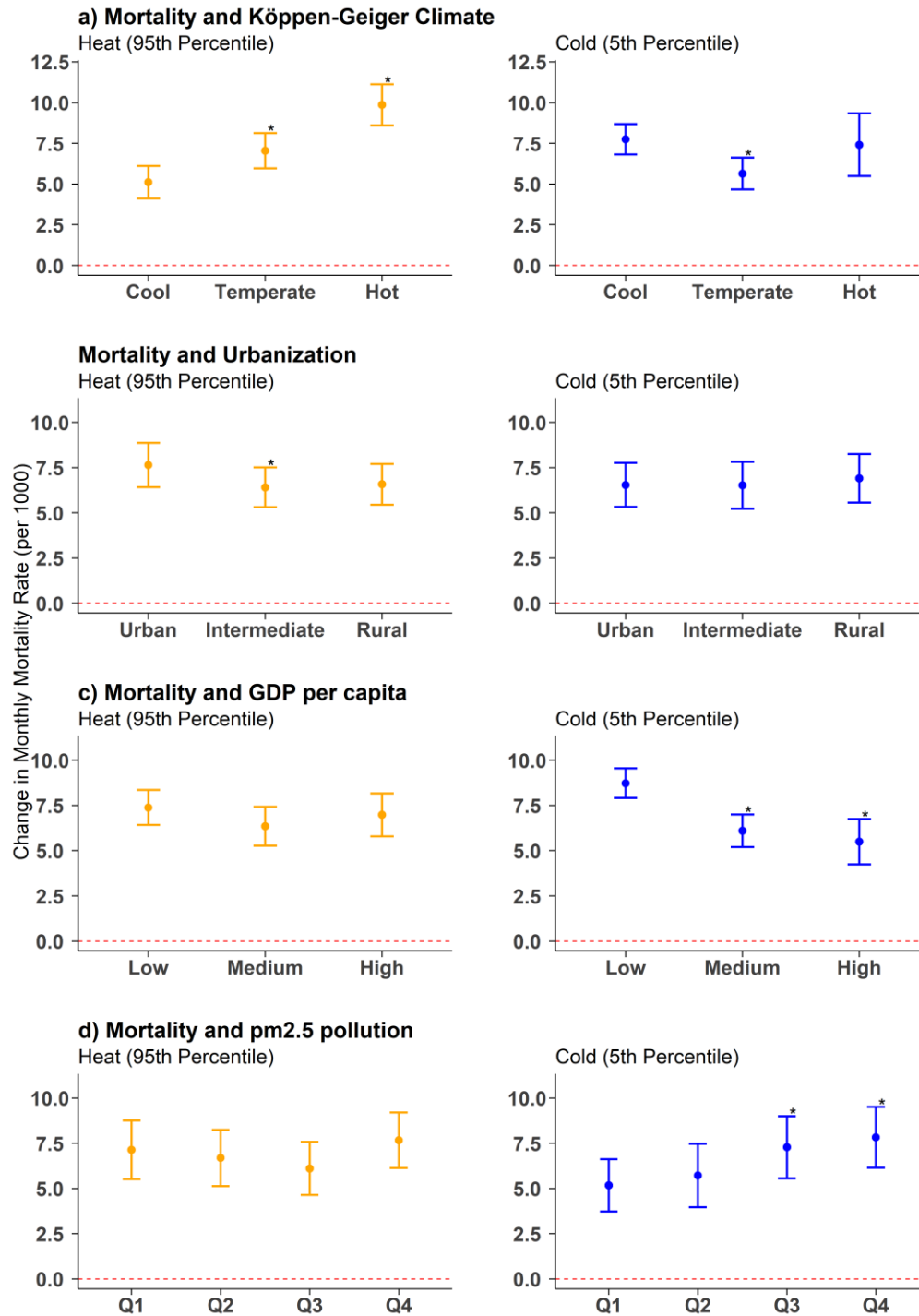


Figure B.S. 7 Extreme temperatures and mortality in Europe (population aged 65+) by climate region (a), urbanization (b), GDP per capita (c), and $PM_{2.5}$ ($\mu g/m^3$) air pollution (d) – Balanced panel dataset

Note: The figure shows estimates obtained by estimating equation (2) with respective interactions with climate regions (reference category: cool), urbanization patterns (reference category: urban), GDP per capita levels (reference category: low), and $PM_{2.5}$ pollution levels (reference category: low). Q1, Q2, Q3, Q4 refers to quartile categorization, from lower to higher level of $PM_{2.5}$ air pollution. Standard errors are clustered at the NUTS3 level. 95% confidence intervals. * Denotes the category as having a statistically significant ($p < 0.05$) difference relative to the baseline category.

Appendix C: Supplemental Information

C.1. Additional Descriptive Tables and Figures

Table C.S 1 provides descriptive statistics of the variables used in our analysis. On average in each NUTS2 region, there are about 33833 people aged 65 or older. The total deaths per each NUTS2 region are on average 101, with a standard deviation of above 174. The number of days falling in the $\leq 6^{\circ}\text{C}$ temperature range per each NUTS2 region per month is on average 0.34 [0; 30], while the number of days falling in the ≥ 27 is on average 0.32 [0; 31].

Table C.S 1 Descriptive statistics of the monthly observations for European NUTS2 regions

Variables	Mean	SD	Min	Max
<i>Mortality and population</i>				
Population exposures 65+	33833	34158	175	314778
Total deaths	101	174	0	8149
<i>Temperature</i>				
$\leq -6^{\circ}\text{C}$	0.34	1.9	0	30
$> -6^{\circ} \leq -3^{\circ}\text{C}$	0.43	1.6	0	17
$> -3^{\circ} \leq 0^{\circ}\text{C}$	1.1	2.8	0	23
$> 0^{\circ} < 3^{\circ}\text{C}$	2.3	4.1	0	23
$\geq 3^{\circ} < 9^{\circ}\text{C}$	3.5	4.9	0	27
$\geq 15^{\circ} < 18^{\circ}\text{C}$	4	5.5	0	31
$\geq 18^{\circ} < 21^{\circ}\text{C}$	3	4.8	0	28
$\geq 21^{\circ} < 24^{\circ}\text{C}$	2	4.2	0	29
$\geq 24^{\circ} < 27^{\circ}\text{C}$	1.1	3.4	0	29
$\geq 27^{\circ}\text{C}$	0.32	1.8	0	31
<i>Control variables</i>				
Solar radiation	2	1.5	0	17
Relative humidity	76	8.7	29	93
Wind speed	2.9	0.91	0.77	8.8
Precipitation	136	80	0	546
<i>Observations</i>				
N. NUTS2	244			
N. NUTS2 – years	194,730			

Notes: SD refers to the standard deviation. For temperature ranges, we report average values (number of days in range) for our month-year-NUTS2 cells. Source: Eurostat and Copernicus Climate Data Store.

Figure C.S.1 presents the results of our model based on Equation (1), illustrating the relationship between temperature extremes and mortality. The pattern follows an inverse J-shaped curve, with higher monthly mortality rates observed at colder extremes compared to hotter temperature ranges. Specifically, an additional day in the coldest temperature range ($\leq -6^{\circ}\text{C}$) increases the monthly mortality rate by 7‰, whereas an additional day in the hottest temperature range ($\geq 27^{\circ}\text{C}$) raises it by 4.4‰. The full set of estimated coefficients for temperature-related deaths during the historical period (2014–2022) is provided in Table C.S.2.

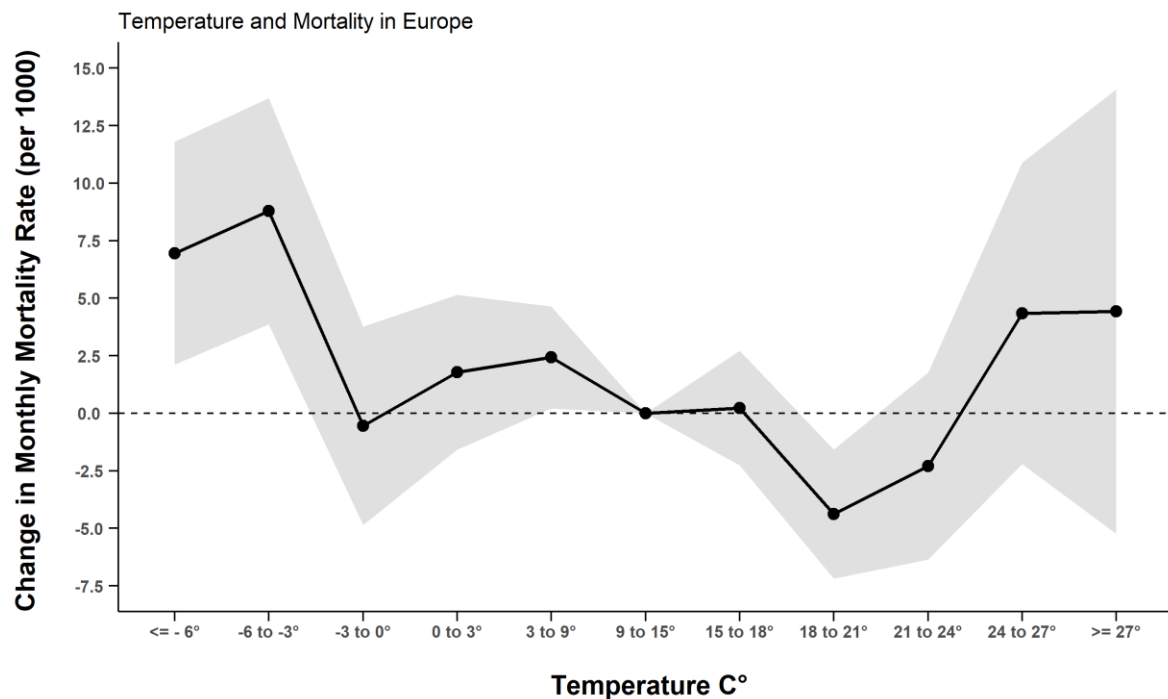


Figure C.S. 1 Extreme temperatures and mortality in Europe from 2014 to 2022 (population aged 65+)

In Figure C.S.1, we observe a higher peak at extremely cold temperature ranges, confirming results consistent with the literature, which indicates cold temperatures as more detrimental to older people compared to hot temperatures (Massetot et al. 2023; Zhao et al. 2021). However, we denote a quite high variability in hotter extremes $[-5.23; 14.07]$, especially when compared to the cold temperature variability range $[2.12; 11.79]$. This great variation in the change monthly mortality rate considering the confidential interval could be due to several factors. The most

discussed in literature are related to regional climatic differences, and various levels of physical and technological adaptation across regions. Indeed, in some areas, particularly in Southern Europe, summer temperatures exceeding 27°C are common, whereas in other regions, such as Northern Europe, such high temperatures are rare or absent (Copernicus et al. 2022; Fiala et al. 2011). In other words, while certain locations - such as Spain, Portugal, and Greece - frequently experience extreme temperatures, exceeding 30°C, others - such as Sweden and Finland - may rarely encounter such conditions, as they fall outside the typical range.

Table C.S 2 Coefficients Historical Temperature and Older Mortality (65+) in Europe

Variables	Coefficients
≤ - 6° C	0.0070** (0.0025)
> -6° ≤ -3°C	0.0088*** (0.0025)
> -3° ≤ 0°C	-0.0005 (0.0022)
> 0° < 3°C	0.0018 (0.0017)
≥ 3° < 9°C	0.0024* (0.0011)
≥ 9° < 15°C	0.0000 (0.0000)
≥ 15° < 18°C	0.0002 (0.0013)
≥ 18° < 21°C	-0.0044** (0.0014)
≥ 21° < 24°C	-0.0023 (0.0021)
≥ 24° < 27°C	0.0043 (0.0033)
≥ 27°C	0.0044 (0.0049)
Males	0.3895*** (0.0050)
Age 70-74	0.4195*** (0.0062)
Age 75-79	0.9105*** (0.0113)
Age 80-84	1.515*** (0.0154)
Age 85+	2.503*** (0.0224)
Solar radiation	0.0088. (0.0051)
Precipitation	-0.0005 (0.0005)
Relative humidity	-0.0037 (0.0025)
Wind speed	-0.0807*** (0.0243)
NUTS2	244
Observations	194,730

Note: Estimates are obtained by estimating Equation (1) on the values in the NUTS2, month, year and demographic group (age groups and sex) cells. Standard errors clustered at NUTS2 level and reported in parenthesis. * p<0.05. The reference bins, respectively, correspond to the following Fahrenheit temperatures: ≤ 21.2°F, 21.2 to 26.6°F, 26.6 to 32°F, 32 to 37.4°F, 37.4 to 48.2°F, 48.2 to 59°F (reference bin), 59 to 64.4°F, 64.4 to 69.8°F, 69.8 to 75.2°F, 75.2 to 80.6°F, and ≥ 80.6°F.

C.2. Details on Countries involved

Table C.S 3 List of the European Countries per NUTS2 involved in the study

Country	NUTS2 (Regions)	Coverage period
Austria	Burgenland(AT11), Niederösterreich(AT12), Wien(AT13), Kärnten(AT21), Steiermark(AT22), Oberösterreich(AT31), Salzburg(AT32), Tirol(AT33), Vorarlberg(AT34)	2014-2022
Belgium	Région de Bruxelles-Capitale/ Brussels Hoofdstedelijk Gewest(BE10), Prov. Antwerpen(BE21), Prov. Limburg (BE)(BE22), Prov. Oost-Vlaanderen(BE23), Prov. Vlaams-Brabant(BE24), Prov. West-Vlaanderen(BE25), Prov. Brabant Wallon(BE31), Prov. Hainaut(BE32), Prov. Liège(BE33), Prov. Luxembourg (BE)(BE34), Prov. Namur(BE35)	2014-2022
Bulgaria	Severozapaden(BG31), Severen tsentralen(BG32), Severoiztochen(BG33), Yugoiztochen(BG34), Yugozapaden(BG41), Yuzhen tsentralen(BG42)	2014-2022
Switzerland	Région lémanique(CH01), Espace Mittelland(CH02), Nordwestschweiz(CH03), Zürich(CH04), Ostschweiz(CH05), Zentralschweiz(CH06), Ticino(CH07)	2014-2022
Cyprus	Kýpros(CY000)	2014-2020
Czechia	Praha(CZ01), Střední Čechy(CZ02), Jihozápad(CZ03), Severozápad(CZ04), Severovýchod(CZ05), Jihovýchod(CZ06), Střední Morava(CZ07), Moravskoslezsko(CZ08)	2014-2020; 2022
Denmark	Hovedstaden(DK01), Sjælland(DK02), Syddanmark(DK03), Midtjylland(DK04), Nordjylland(DK05)	2014-2022
Estonia	Eesti(EE00)	2014; 2016-2022
Greece	Attiki(EL30), Voreio Aigaio(EL41), Anatoliki Makedonia, Thraki(EL51), Kentriki Makedonia(EL52), Dytiki Makedonia(EL53), Ipeiros(EL54), Thessalia(EL61), Ionia Nisia(EL62), Dytiki Elláda(EL63), Sterea Elláda(EL64), Peloponnisos(EL65)	2014-2022
Spain	Galicia(ES11), Principado de Asturias(ES12), Cantabria(ES13), País Vasco(ES21), Comunidad Foral de Navarra(ES22), La Rioja(ES23), Aragón(ES24), Comunidad de Madrid(ES30), Castilla y León(ES41), Castilla-La Mancha(ES42), Extremadura(ES43), Cataluña(ES51), Comunitat Valenciana(ES52), Illes Balears(ES53), Andalucía(ES61), Región de Murcia(ES62), Ciudad de Ceuta(ES63), Ciudad de Melilla(ES64), Canarias(ES70)	2014-2022
Finland	Länsi-Suomi(FI19), Helsinki-Uusimaa(FI1B), Etelä-Suomi(FI1C), Pohjois- ja Itä-Suomi(FI1D), Åland(FI20)	2014-2022
France	Ile-de-France(FR10), Centre — Val de Loire(FRB0), Bourgogne(FRC1), Franche-Comté(FRC2), Basse-Normandie(FRD1), Haute-Normandie(FRD2), Nord-Pas de Calais(FRE1), Picardie(FRE2), Alsace(FRF1), Champagne-Ardenne(FRF2), Lorraine(FRF3), Pays de la Loire(FRG0), Bretagne(FRH0), Aquitaine(FRI1), Limousin(FRI2), Poitou-Charentes(FRI3), Languedoc-Roussillon(FRJ1), Midi-Pyrénées(FRJ2), Auvergne(FRK1), Rhône-Alpes(FRK2), Provence-Alpes-Côte d’Azur(FRL0), Corse(FRM0)	2014-2022

Country	NUTS2 (Regions)	Coverage period
Hungary	Budapest(HU11), Pest(HU12), Közép-Dunántúl(HU21), Nyugat-Dunántúl(HU22), Dél-Dunántúl(HU23), Észak-Magyarország(HU31), Észak-Alföld(HU32), Dél-Alföld(HU33)	2014-2022
Island	Ísland(IS00)	2014-2022
Italy	Piemonte(ITC1), Valle d'Aosta/Vallée d'Aoste(ITC2), Liguria(ITC3), Lombardia(ITC4), Abruzzo(ITF1), Molise(ITF2), Campania(ITF3), Puglia(ITF4), Basilicata(ITF5), Calabria(ITF6), Sicilia(ITG1), Sardegna(ITG2), Provincia Autonoma di Bolzano/Bozen(ITH1), Provincia Autonoma di Trento(ITH2), Veneto(ITH3), Friuli-Venezia Giulia(ITH4), Emilia-Romagna(ITH5), Toscana(ITI1), Umbria(ITI2), Marche(ITI3), Lazio(ITI4)	2014-2018; 2020-2022
Liechtenstein	Liechtenstein(LI00)	2014-2022
Lituania	Sostinės regionas(LT01), Vidurio ir vakarų Lietuvos regionas(LT02)	2014-2022
Luxembourg	Luxembourg(LU00)	2014-2016; 2018-2022
Latvia	Latvija(LV00)	2014-2022
Montenegro	Crna Gora(ME00)	2014-2022
Malta	Malta(MT00)	2014-2015; 2017-2022
Netherland	Groningen(NL11), Friesland (NL)(NL12), Drenthe(NL13), Overijssel(NL21), Gelderland(NL22), Flevoland(NL23), Utrecht(NL31), Noord-Holland(NL32), Zuid-Holland(NL33), Zeeland(NL34), Noord-Brabant(NL41), Limburg (NL)(NL42)	2014-2022
Norway	Innlandet(NO02), Trøndelag(NO06), Nord-Norge(NO07), Oslo og Viken(NO08), Agder og Sør-Østlandet(NO09), Vestlandet(NO0A)	2014-2022
Poland	Małopolskie(PL21), Śląskie(PL22), Wielkopolskie(PL41), Zachodniopomorskie(PL42), Lubuskie(PL43), Dolnośląskie(PL51), Opolskie(PL52), Kujawsko-pomorskie(PL61), Warmińsko-mazurskie(PL62), Pomorskie(PL63), Łódzkie(PL71), Świętokrzyskie(PL72), Lubelskie(PL81), Podkarpackie(PL82), Podlaskie(PL84), Warszawski stołeczny(PL91), Mazowiecki regionalny(PL92)	2014-2020
Portugal	Norte(PT11), Algarve(PT15), Centro (PT)(PT16), Área Metropolitana de Lisboa(PT17), Alentejo(PT18), Região Autónoma da Madeira(PT30)	2014-2022
Romania	Nord-Vest(RO11), Centru(RO12), Nord-Est(RO21), Sud-Est(RO22), Sud-Muntenia(RO31), București-Ilfov(RO32), Sud-Vest Oltenia(RO41), Vest(RO42)	2014-2019
Sweden	Stockholm(SE11), Östra Mellansverige(SE12), Småland med öarna(SE21), Sydsverige(SE22), Västsverige(SE23), Norra Mellansverige(SE31), Mellersta Norrland(SE32), Övre Norrland(SE33)	2014-2022
Slovakia	Bratislavský kraj(SK01), Západné Slovensko(SK02), Stredné Slovensko(SK03), Východné Slovensko(SK04)	2014-2022

The NUTS2 subdivision refers to the current period 2021 – 2024 (more details can be reached here: <https://ec.europa.eu/eurostat/web/nuts/history/>).