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Temperature-Related Mortality in Countries with Cold Climates: a Mapping Review

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Abstract

Background. Climate change is accelerating heatwave frequency in cold-climate regions, yet cold exposure remains the dominant driver of temperature-related mortality. This shift creates uncertainty regarding future health burdens, compounded by the historic lack of preparedness for extreme heat by local population. To clarify these competing risks, we conducted a systematic mapping review of temperature-related mortality across cold-climate countries.

Method. To synthesize heat and cold effects and identify research gaps, we evaluated temperature-mortality associations in cold-climate countries (1990–2026). We searched Scopus, Web of Science, and PubMed, identifying 9,135 articles; supplementary searching added 1,693.

Results. After screening, 117 studies met inclusion criteria, predominantly from Canada (n=41) and Sweden (n=39). Of these, 83 assessed full temperature–mortality exposure–response relationships, 42 assessed extreme temperature events, and 8 examined both approaches. Cardiovascular and respiratory diseases dominated cause-specific analyses. Across the mapped literature, cold-related cardiovascular risks were frequently reported as greater than heat-related risks, while evidence for respiratory mortality was heterogeneous and often limited by small numbers of deaths.

Discussion. Key gaps included: (1) geographic bias toward milder regions, underrepresenting polar and continental areas; (2) methodological inconsistencies in extreme event definitions and lag specifications; and (3) limited non-cardiorespiratory cause-specific evidence. This review identifies critical methodological and geographic gaps, establishing a foundation for future quantitative assessments of temperature-mortality associations in cold-climate populations.

Keywords: cold-climate regions, environmental epidemiology, extreme temperature events systematic mapping review, temperature-related mortality

1. Introduction

Climate change is affecting populations worldwide, but its impacts are not evenly distributed across regions. High-latitude areas are experiencing particularly rapid warming, with temperatures in polar and subpolar regions increasing up to four times faster than the global average [1–3]. Recent projections from the Intergovernmental Panel on Climate Change [4] indicate that this amplified warming at higher latitudes is likely to persist throughout the twenty-first century, with significant direct and indirect consequences for human health and mortality.

Climate change impacts in high-latitude areas are diverse, including permafrost degradation, increased forest and peat fire activity, and shifts in the distribution of infectious disease vectors [5,6]. Rising temperatures are also expected to alter patterns of temperature-related mortality by increasing exposure to heat while reducing exposure to cold [7,8]. However, the net health consequences remain uncertain, as populations living in cold-climate regions may respond differently to climatic changes because of their distinctive climatic conditions, pronounced seasonality, and long-standing adaptation to cold environments.

A growing body of epidemiological research has examined the relationship between temperature and mortality, demonstrating that both heat and cold influence mortality risks. Despite ongoing climate warming, cold-related mortality remains an important component of the overall temperature-attributable burden and often exceeds heat-related mortality in many populations [9,10]. However, studies from different climatic settings suggest that populations are generally most vulnerable to temperatures outside their historical range of experience, reflecting adaptation to prevailing climatic conditions [11,12]. For example, heat-related mortality risks tend to be steeper in regions where populations are less accustomed to high temperatures [13], This raises important questions about whether populations in cold-climate regions, including Arctic and sub-Arctic areas, may face disproportionate risks from increasing heat exposure despite lower average temperatures. Conversely, current evidence does not indicate that cold exposure will substantially decline or that population resilience to cold in these regions will significantly increase [14]. The balance between these competing processes remains poorly understood.

Beyond understanding overall mortality patterns, it is also important to examine how temperature affects specific causes of death, particularly cardiovascular and respiratory diseases, which have consistently been identified as the causes of death most strongly associated with non-optimal temperatures [15]. Temperature-related mortality is highly heterogeneous across disease categories because heat and cold affect physiological systems through different biological pathways. Cold exposure has been associated with increased risks of cardiovascular and respiratory mortality through mechanisms including vasoconstriction, elevated blood pressure, thrombosis, and impaired respiratory function, whereas heat exposure can increase mortality through dehydration, cardiovascular strain, and exacerbation of chronic respiratory diseases [10,15,16]. Understanding these cause-specific patterns is particularly important in cold-climate regions, where prolonged cold exposure, population ageing, and emerging heat extremes may alter the distribution of mortality across diseases.

As the literature on temperature-related health impacts continues to expand, an increasing number of review studies have synthesized evidence on the relationship between temperature and mortality [17–22]. However, important gaps remain. Existing reviews typically adopted either a global perspective or focus on individual countries, as in Russia [23] or Canada [24], with limited attention to cold-climate regions as a group. . While, studies of cold-climate settings are often too broad or too narrow in scope. Some address the general health impacts of climate change across

cold-climate countries, covering multiple outcomes such as infectious disease range shifts alongside temperature effects [25,26]. Others focus on specific hazards [27], outcomes [28], or population groups, such as Indigenous communities. Consequently, evidence on geographic variation, cause-specific mortality, and vulnerability across population subgroups has not been comprehensively compared, leaving a need for an up-to-date synthesis of temperature-related mortality across diverse cold-climate settings. To address these gaps, we conducted a multi-country mapping review of the evidence on temperature-related mortality in cold-climate countries, balancing epidemiological specificity with broad geographic coverage. This mapping review aims to characterize the extent, distribution, and nature of the available evidence while identifying key research gaps. Furthermore, this review provides an updated synthesis of temperature-related mortality research across cold-climate regions published between 1990 and mid-2026, incorporates evidence published in all languages, and examines both all-cause and cause-specific mortality outcomes.

Specifically, this review addresses the following research questions:

- RQ1: What evidence exists on the relationship between non-optimal temperatures and mortality and what is specifically emphasized in these studies?
- RQ2: How do extreme temperature events (heat waves and cold waves) impact mortality risk, and what critical aspects are highlighted in the literature?
- RQ3: Which methodological approaches are most commonly used to quantify the impacts of ambient temperature and extreme temperature events on mortality, and what are their specific considerations in cold climate context?
- RQ4: What are the cause-specific patterns of temperature-related mortality in countries with cold climates?
- RQ5: How does demographic heterogeneity modify temperature-related mortality in countries with cold climates?

By systematically mapping the available evidence, this review identifies major knowledge gaps and research priorities, thereby supporting future epidemiological research and informing more robust assumptions for climate-sensitive population and mortality projections in cold-climate regions.

2. Cold-climate regions: geographic, climatic, and population characteristics

To interpret temperature-related mortality in cold-climate regions, it is not sufficient to consider exposure alone; the broader climatic, infrastructural, and social context must also be taken into account, as this background is essential for situating these regions within the wider literature and framing the key thematic and structural gaps that this review addresses.

2.1 Definition and geographic distribution of cold-climate regions

There is no universally accepted definition of regions with cold climates. To delineate the geographic scope of this review, we focus on territories characterized by two groups of Köppen-Geiger climate types [29]. First, we include continental climates with short, cool summers (Dfc, Dfd, Dwc, Dwd, Dsc, Dsd), defined by mean temperatures of the coldest month below 0°C and only a few months exceeding 10°C. Second, we include polar climates (ET and EF), where tundra climates (ET) have mean temperatures of the warmest month between 0 and 10°C and ice-cap climates (EF) remain below 0°C throughout the year. With the exception of high-altitude regions,

these cold climates are largely concentrated at latitudes above approximately 50-60°N, although substantial climatic variability persists within them [29].

Population distribution across cold-climate regions is extremely uneven. Vast subarctic and Arctic areas are sparsely populated and consist mainly of small settlements, Indigenous communities with livelihoods tied to traditional activities, and specialized industrial towns focused on resource extraction. As a result, there are few large cities in the coldest parts of these regions, and empirical data from individual locations are limited. This uneven population distribution presents challenges for assessing temperature-related mortality and underscores the importance of adopting a broad and inclusive approach to evidence synthesis.

To operationalize this definition, we restrict our analysis to countries and territories that contain substantial areas of these cold climate types, as specified in the Methods section. This country-level focus facilitates a transparent and reproducible study selection process, given differing delineations and gradual shifts of climatic boundaries under ongoing climate change. At the same time, it allows us to supplement evidence from sparsely populated areas with the coldest climates by including populations that share broadly comparable climatic and socio-economic contexts.

2.2 Temperature and extreme temperature events

Although cold-climate regions are generally characterized by long winters and low annual temperatures, considerable variation exists in the intensity and duration of cold exposure across the study area. Coastal areas influenced by the Atlantic Ocean, such as much of Iceland and Norway, often have winter mean temperatures close to 0°C even at very high latitudes, whereas continental areas of northern Eurasia and North America regularly experience winter temperatures below -20°C. In some inland locations, particularly in eastern Siberia, temperatures may fall below -50°C, making them among the coldest inhabited places on Earth. However, absolute air temperature alone does not fully capture cold-related thermal stress, which is also shaped by wind, humidity, and other meteorological factors, a consideration that has motivated alternative thermal-stress indicators and adjustment approaches in the temperature-mortality literature.

Despite these generally cold conditions, extreme heat also occurs across parts of the study region. In some southern and continental areas of Canada and Russia, particularly in cold semi-arid and arid regions, populations experience exceptionally large seasonal temperature ranges, with winter temperatures frequently falling well below 0°C and summer maxima occasionally exceeding 40°C. Similarly, the extremely continental climates in the Asian part of Russia combine prolonged winters, often below -30°C, with summer temperatures exceeding 30°C. Across much of the remaining region, however, extreme heat is relatively uncommon and typically occurs during occasional heatwave events, such as those observed in western Russia in 2010 and western Canada in 2021 [30]. By contrast, many subarctic and Arctic coastal areas have historically experienced little or no extreme heat and therefore have had limited prior exposure and adaptation to high temperatures. Together, these climatic contrasts highlight the diversity of temperature environments encompassed within cold-climate regions and provide important context for interpreting patterns of temperature-related mortality.

2.3 Population adaptation and built environment

Because populations in cold climates experience prolonged exposure to temperatures that would be considered extreme in milder regions, the contribution of non-extreme cold to mortality may be even more pronounced than elsewhere [15]. Such prolonged and severe cold exposure has driven extensive infrastructural and behavioral adaptations across cold-climate regions. Centralized district heating systems, which distribute heat and hot water from a central source to multiple buildings, are widespread in many countries, while detached homes typically rely on individual heating systems [31]. Behavioral adaptations are also well established and include the use of layered clothing, well-insulated dwellings, and reduced outdoor activity during the winter months [32]. Together, such measures can be associated with reduced cold-related risks at comparable temperatures [14].

In contrast, adaptation to extreme heat remains much less advanced. For example, air-conditioning prevalence in Russia was minimal prior to the 2010 heatwave [33], and in Canada only around 60% of households have access to air conditioning [34]. These contrasting patterns of adaptation suggest that, although populations in cold-climate regions may be relatively well protected against cold-related health risks, they may remain disproportionately vulnerable to unexpected or unusually intense heat events, particularly as heatwave frequency and intensity increase under climate change. Nevertheless, it remains uncertain to what extent cold-related mortality can be mitigated or prevented, and how strongly heat-related risks vary across cold-climate regions.

These uncertainties directly motivate the present review. The following section describes the data sources and methods used to address them.

3. Data and Methods

Our primary objective was to investigate temperature-related mortality in countries characterized by cold climates, based on the evidence from the academic literature. To achieve this, we conducted a systematic search of three electronic databases: Scopus, Web of Science, and PubMed, using a multi-stage screening process to identify relevant studies. Our focus was restricted to natural, non-communicable deaths, therefore excluding external causes and infectious diseases, given their distinct temperature-related mortality patterns in this climatic context. We concentrated specifically on two types of studies: those addressing extreme weather events and those investigating the full spectrum of temperature exposures. Geographically, our study is restricted by countries and territories encompassing substantial areas under Subarctic and Arctic climates, as defined by Köppen-Geiger climate zones, the most widely used classification system for global climates [29][1]. These include Finland, Iceland, Norway, Sweden, Canada, Russia, and parts of the United States and Denmark, such as Alaska and Greenland.

3.1. Search strategy and selection of studies

To identify epidemiologic studies examining the direct effects of temperature on human mortality in countries with cold climates, we performed a systematic mapping review following the Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR)

[1] For cold and polar regions, relevant Köppen-Geiger climate types are the following: Dfc: Continental climate, no dry season, cold summer; Dwc: Continental climate, dry winter, cold summer: Continental climate, dry winter, cold summer; Dsc: Continental climate, dry summer, cold summer; Dfd: Continental climate, no dry season, very cold winter; Dwd: Continental climate, dry winter, very cold winter; Dsd: Continental climate, dry summer, very cold winter; ET: Tundra climate; EF: Ice cap climate

guidelines [35]. We searched three electronic databases, namely Scopus, Web of Science and PubMed. In each database we constructed the search query using the following expression:

("temperature*" OR "climat*" OR "heat*" OR “hot*" OR "thermal stress" OR “cold*") AND ("mortal*" OR "death*" OR "life expectancy" OR “years of life lost” OR “yll” OR "attributable fraction" OR "relative risk" OR “mmt”) AND ("Alaska" OR "Greenland" OR "Norway" OR "Finland" OR "Sweden" OR "Canada" OR "Russia" OR "Iceland" OR "Subarctic" OR "Arctic" OR "Polar" OR "Subpolar") AND (NOT animal*) AND (NOT plant*)

The initial search was conducted on 5 July 2024 and restricted to studies published between 1 January 1990 and 31 December 2023. To add more recent literature published after the initial search, an updated search was performed on 16 June 2026, applying an identical search strategy, restricted to publications dated between 1 January 2024 and 16 June 2026. Both iterations followed the same principles and procedures described below.

We restricted the scope of our study to the entire territories of Canada, Russia, Finland, Norway, Sweden, Iceland, and selected regions of Denmark (Greenland) and the United States (Alaska). Inclusion criteria were strictly limited to studies investigating the general population (or specific age groups within the general population), residing in these areas. To ensure our findings reflect community-wide impacts, we explicitly excluded studies focused on restricted population subgroups, such as specific occupational cohorts, clinical subpopulations, or individuals selected based on pre-existing medical conditions. Outcomes assessed were limited to the direct effects of non-optimal temperatures on mortality from natural non-communicable causes.These causes were defined as all deaths excluding infectious and parasitic diseases (ICD-10 codes A00–B99) and external causes (V00–Y99). However, studies reporting only all-cause or non-accidental mortality were also included. Infant mortality (P00-P96), sudden infant death syndrome (R95) and stillbirths (P95) were considered in the analysis as well.

Eligible studies were original research articles reporting direct quantitative estimates of the association between non-optimal temperatures or individual extreme temperature events and mortality risk, commonly expressed as relative risk (RR), odds ratio (OR), or percentage increase in mortality. Derived parameters, such as attributable fraction (AF), minimum mortality temperature (MMT), or years of life lost (YLL), were also included. Other original quantitative estimates, including regression and correlation coefficients, were considered relevant for inclusion. For studies presenting projections of temperature-related mortality, baseline estimates derived from observed data were extracted whenever possible. Studies primarily focused on other topics, such as air pollution, were also eligible if they considered temperature and provided original numerical estimates for temperature effects. Detailed inclusion and exclusion criteria, structured according to the PECOS framework, are provided in Supplementary Table S1.

To enhance the comprehensiveness of our systematic review, we supplemented database searches with backward citation tracking. We examined the reference lists of articles identified through citation databases. This process was facilitated by the Citationchaser web application (https://estech.shinyapps.io/citationchaser/), which automatically retrieves cited references from each article’s bibliography. Citationchaser utilizes The Lens.org bibliographic database aggregator, which compiles content from multiple sources, including Microsoft Academic Graph, CrossRef, CORE, PubMed, and PubMed Central [36]. Given that some included studies originated from specific research projects using shared databases (e.g. Multi-Country Multi-City), we also evaluated other publications from these projects for potential inclusion if they reported relevant

findings for the locations of interest. Additionally, experts recommended a small number of further papers, which were included only if they met the predefined eligibility criteria.

3.2. Screening

For each database, we adjusted the search query to follow database-specific syntax, while keeping the list of keywords consistent. After the searches, duplicate records were removed based on the article title and DOI.

The initial screening of titles and abstracts was conducted using ASReview, an open-source software tool that facilitates systematic reviews by ranking records based on machine-learning algorithms [37]. For each article, both the title and abstract were evaluated within ASReview for potential relevance to the review's inclusion criteria.

At the second screening stage, each paper identified as potentially relevant underwent full-text review to determine whether it met the inclusion criteria. Both SK and MM conducted all stages of the selection process independently, and in cases of disagreement a third reviewer was consulted to reach a final decision.

3.3. Data extraction and analysis

From the studies identified through the two-stage review process, we conducted full-text readings to extract all relevant information. Initially, we developed a standardized data extraction form that captured article metadata, study characteristics, and numerical results. This form was piloted on a subset of ten papers and subsequently refined to reflect the specific characteristics of the studies. Data extraction was then performed for all included papers. Some studies were excluded at this stage due to the absence of extractable relevant results despite meeting the inclusion criteria, for example, when a paper presented findings based entirely on data already reported in another included study.

The data extraction form included fields for bibliographic characteristics (such as authors, journal, year, and DOI), as well as information on the spatial and temporal scope of each study (including study duration and locations or cities covered). The form also documented study design, classifying included studies as time-series, case-crossover, or case-time-series designs.

Because two distinct research types were present, studies addressing extreme weather events and studies examining temperature-related mortality in general, the form was subdivided accordingly. For studies on extreme weather events, we extracted details on event criteria, the number of identified events, and the principles used to construct baseline mortality levels. For temperature-related mortality studies, we obtained model specifications, including the exposure–response function, the treatment of temporal trends and lag effects, and the inclusion of additional control variables and effects.

Furthermore, we collected detailed information on the type of variable used to assess exposure and the corresponding data sources. The same level of detail was applied to outcomes: we documented the causes of death considered in each study, the data sources for mortality, and the specific indicators used to quantify temperature effects. Additionally, we recorded the format in which results were presented (e.g. graphical or tabular) and the availability of confidence intervals or similar measures of statistical uncertainty. When studies compared mortality across

different groups, such as age, sex, other demographic characteristics, socioeconomic status (income, education, occupation), or geographic context (e.g. geographic or climate zones), we noted these comparisons and assessed whether the relevant data could be extracted.

4. Results

A total of 6,676 articles were retrieved from three electronic databases: 3,352 from Scopus, 2,280 from Web of Science, and 1,044 from PubMed. The search expression was slightly modified to align with the query syntax of each database, while the list of key terms remained consistent. After removing duplicates, 2,617 records remained for title and abstract screening, which was conducted using ASReview [37]. This screening process resulted in 114 studies selected for full-text assessment, of which 65 met all inclusion criteria and were retained for the mapping review.

Backward citation tracking conducted with Citationchaser yielded an additional 1,281 records. Following title and abstract screening, 16 articles obtained via this method were included in the review. Additionally, 12 relevant articles were identified from studies conducted under projects using shared databases (e.g. Multi-Country Multi-City), and 6 further articles were recommended by experts based on their knowledge of publication activity in this field.

Afterwards an additional search was performed on 16 June 2026 with the same criteria but publication dates from 1 January 2024 to 16 June 2026. This updated search resulted in another 660 records from Scopus, 384 from Web of Science, and 1,415 from PubMed, resulting in 2,046 records after deduplication. Of these, 70 were selected at the title and abstract screening stage, and 16 were included following full-text assessment. From the 565 records identified through citation tracking from there papers, a further 3 articles were included. In total, this updated search contributed 19 additional articles (Supplementary Figure S1).

In total, 117 articles were included in the final review synthesis: 83 studies (70.9%) examined exposure-response relationships across the full spectrum of temperatures, and 42 studies (35.9%) focused on extreme temperature events, with 8 studies (6.8%) contributing to both categories (Figure 1).

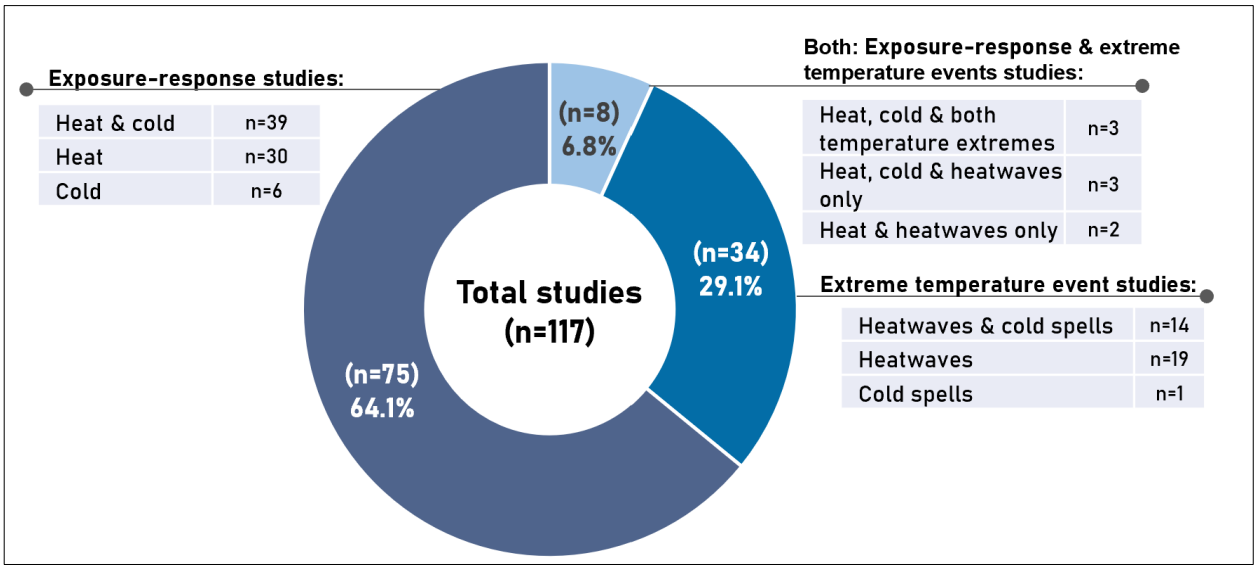


Figure 1. Type of included studies according to climate exposure category

4.1 Temporal trends and geographical distribution of the included studies

The review included studies published between 1990 and June 2026. Publication activity increased progressively over time. Only 3 studies (2.6%) were published during 1990–1999, increasing to 15 (12.8%) during 2000–2009. The number of publications then rose sharply, with 55 studies (47.0%) published during 2010–2019 and a further 44 (37.6%) published between 2020 and June 2026 (Figure 2).

Such a rapid increase likely reflects several complementary trends. First, growing public and scientific concern about climate change, heightened following events such as the 2010 Russian heatwave, the 2021 Canadian heatwave, and the recurrent European heatwaves from 2022 onward, has drawn substantial attention to temperature-related health impacts [38]. Second, the establishment of large research projects, such as the Multi-Country Multi-City (MCC) Collaborative Research Network, has facilitated the integration of evidence across multiple locations to assess global and regional risks, with cold-climate countries becoming represented within them [39]. Third, improved data availability, including high-quality, openly accessible climate reanalysis products and mortality datasets, along with their linkage to individual- and small-area-level data, has enabled more geographically granular temperature-mortality analyses.

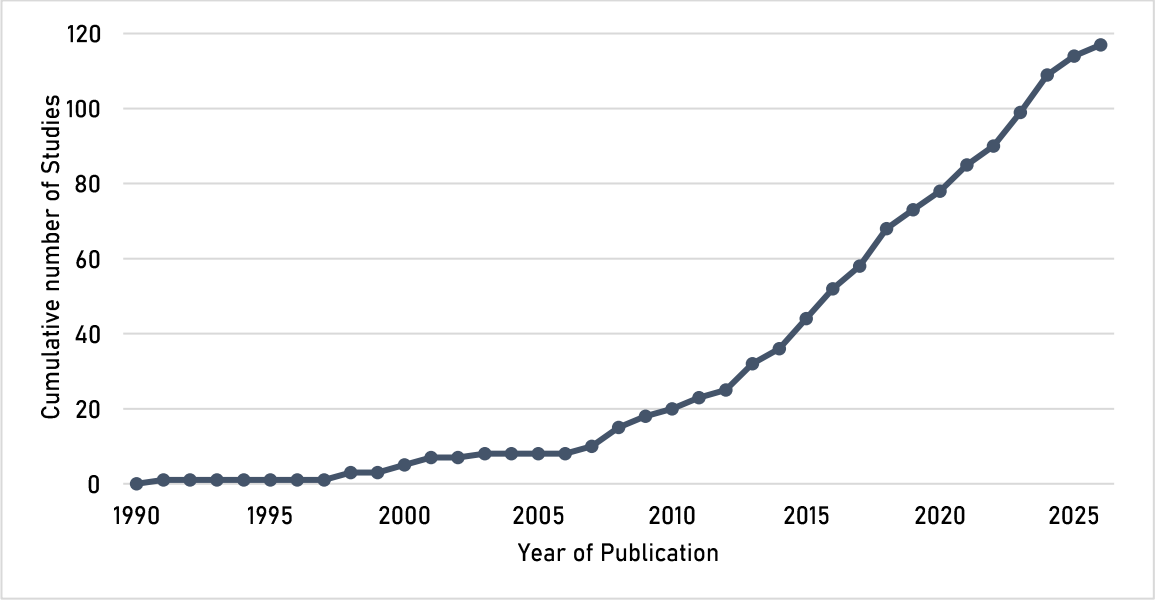


Figure 2. Cumulative number of studies by the year of publication from those included in the final review synthesis

The geographical distribution of the evidence base was uneven. Canada was represented in 41 included studies, followed by Sweden (39 studies), Russia (30), Finland (26), Norway (15), Alaska, United States (7), and Iceland (3). These counts include both national-level studies and multi-location studies that generated estimates for subnational units. Therefore, this country-level distribution should be interpreted as the number of included studies providing extractable evidence for at least one location within the respective country or territory.

This distinction matters because some studies were based on comprehensive analysis of all the subnational units, such as Norwegian municipalities [40] or Canadian census divisions [41], while others were focused only on specific cities or regions within a country. Among studies not providing comprehensive subnational coverage, 368 individual study locations were identified across cities, metropolitan areas, and administrative units. Where studies reported estimates at the level of higher-level administrative units rather than named cities, the principal city or administrative center was used as the geographic reference for mapping and grouping purposes.

The most frequently represented locations were Stockholm, Sweden (27 studies), Montréal, Canada (26), and Vancouver, Canada (24). Among other national capitals, Oslo, Norway was represented in 10 studies and Moscow, Russia in 6. In addition, Anchorage, Alaska was represented in 7 studies. No studies specifically addressed Reykjavik, although evidence was available for Iceland as a whole.

Most evidence was derived from urban areas or major population centers, which may present different exposure profiles, specifically due to more pronounced urban heat island effects in cold settings [42]. Accordingly, 6 studies examined difference in temperature-related mortality associated with urban-rural gradient: 4 reported stronger heat-related risks in urban areas, and 2 found no statistically significant differences.

In terms of Köppen–Geiger climate zones, most study locations were classified as Dfb (warm-summer humid continental), with 70 studies included locations within this zone. Other continental climates were also well-represented, including Dfa (35 studies) and Dfc (33). Temperate climates were covered less frequently: Cfa (3), Cfb (28), and Csb (18), corresponding to studies conducted in the extreme southwestern parts of Canada, Sweden, and Russia. Arid climates, specifically cold steppe and cold desert zones, were represented by BSk (5) and BWk (3), mostly located in Russia. As the second letter of the Köppen–Geiger codes describes precipitation regimes, and the principal exposure of interest here is temperature (defined by the third letter), zones sharing the same precipitation patterns are hereafter referred to jointly (e.g., temperate hot-summer climates: Csa, Cwa, and Cfa with dry summer, dry winter and no dry season, respectively, are considered together as Csa/Cwa/Cfa).

No study locations were identified within the ET (tundra) or EF (ice cap) zones, nor within the Dsd/Dwd/Dfd continental climates characterized by very cold winters (below -38°C). These zones cover substantial land areas but are extremely sparsely populated, which limits the availability of mortality data of sufficient statistical power for statistical analysis. For example, city with coldest winters included in the sample, Yakutsk, was classified as Dfc, situated just at the boundary with the Dfd zone (Figure 3, Table 1).

Figure 3. Total number of studies by geographic locations from studies included in the review

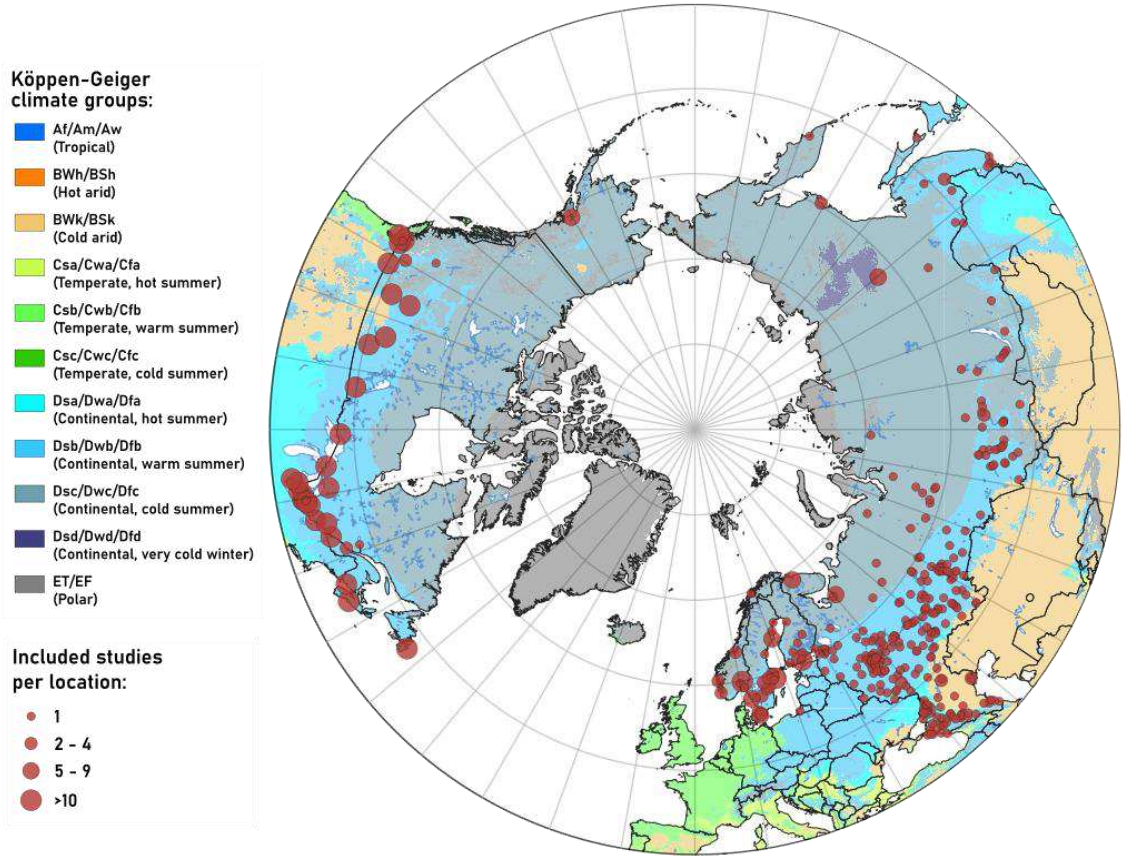


Table 1. Number of studies included by study location within aggregated Köppen–Geiger climate groups.

Köppen–Geiger codes	Climate group	Criteria	No. of included studies
Af/Am/Aw	Tropical	Mean temperature of every month ≥18°C	0
BWh/BSh	Hot arid	Precipitation below aridity threshold, mean annual temperature ≥18°C	0
BWk/BSk	Cold arid	Precipitation below aridity threshold, mean annual temperature <18°C	5
Csa/Cwa/Cfa	Temperate, hot summer	Coldest month >0°C, hottest month ≥22°C	3
Csb/Cwb/Cfb	Temperate, warm summer	Coldest month >0°C, hottest month <22°C, ≥4 months >10°C	28
Csc/Cwc/Cfc	Temperate, cold summer	Coldest month >0°C, only 1-3 months >10°C	0
Dsa/Dwa/Dfa	Continental, hot summer	Coldest month ≤0°C, hottest month ≥22°C	35
Dsb/Dwb/Dfb	Continental, warm summer	Coldest month ≤0°C, hottest month <22°C, ≥4 months >10°C	72
Dsc/Dwc/Dfc	Continental, cold summer	Coldest month ≤0°C, only 1-3 months >10°C	33
Dsd/Dwd/Dfd	Continental, very cold winter	Coldest month <-38°C, hottest month <22°C, only 1–3 months >10°C	0

ET/EF	Polar	Warmest month <10°C	0

4.2. Summary of studies examining exposure-response relationships

This section synthesizes the evidence relevant to the research questions outlined earlier, beginning with the relationship between non-optimal temperatures and mortality ***(RQ1*: What evidence exists on the relationship between non-optimal temperatures and mortality, and what is specifically emphasized in these studies?)**. A total of 83 studies (70.9% of 117 studies) included in the mapping review were identified as focusing, either primarily or partially, on the construction of exposure–response relationships between temperature and mortality. These investigations assessed the impact of non-optimal temperatures over extended periods, rather than being limited to discrete extreme temperature events.

Among these, 32 studies (38.5%) focused on the association between high temperatures and mortality risk, predominantly restricting their analyses to the warm season (typically the 3 to 5 warmest months). In contrast, only 6 studies (7.2%) examined cold-related mortality exclusively during the cold season. More than half of the studies (44; 53.0%) assessed temperature–mortality associations across the full temperature spectrum, capturing both heat and cold effects across all seasons.

Results from the full-spectrum studies showed considerable variability. In 19 studies (43.2%), cold-related mortality risks were clearly demonstrated to be stronger than heat-related risks [9,43,44]. Here, 'risk' refers to point estimates such as relative risk (RR), odds ratio (OR), or the relative steepness of heat- versus cold-related exposure–response slopes, extracted wherever these were reported. Conversely, 8 studies (18.2%) reported the opposite pattern, with heat posing the greater risk [33,45,46]. The remaining 17 studies (38.6%) reported a lack of statistical significance, mixed results across subgroups that were difficult to interpret, or minimal, inconclusive differences between heat- and cold-related effects.

Cold-climate countries show higher relative risks of death from short-term cold exposure than from heat exposure, compared with their southern counterparts, at both global [15] and European [9] scales. However, when cumulative impacts are considered (e.g., risk magnitude combined with the duration of exposure) cold-related mortality dominates globally, not only in cold-climate settings, reflecting the far greater frequency of cold exposure worldwide [10]. Furthermore, these cold-related attributable fractions were shown to remain higher in cold-climate countries than in warmer countries when comparable methodology is applied [9,41,44]. These findings indicate that cold has been the dominant contributor to temperature-related mortality in cold-climate countries to date. However, projections diverge regarding whether this pattern will persist: Vázquez Fernández et al. [47] project that in Oslo the decrease in cold-related impacts will not be sufficient to offset the projected increase in heat-related impacts, whereas Revich et al. [48] reported the opposite pattern in the Russian Arctic.

4.3. Summary of studies examining extreme temperature events

This section examines studies evaluating mortality risks associated with short-term extreme temperature events, including heatwaves and cold waves, to address ***RQ2: How do extreme temperature events (heat waves and cold waves) impact mortality risk, and what critical aspects are highlighted in the literature?*** The findings below focus on mortality responses to acute

extreme temperature events, which capture short-term temperature anomalies distinct from broader continuous temperature–mortality relationships.

Across the evidence base, 42 studies (35.9% of 117 studies included in mapping review) specifically investigated the effects of extreme temperature events risks of deaths and excess mortality. Several of these studies additionally explored the relationship between non-optimal temperatures and mortality, however, the findings presented here are restricted to outcomes relevant to extreme weather events. Heatwaves received substantially greater attention: 24 (57.1% of studies investigating extreme weather events) examined heatwaves alone, while only 1 study (2.4%) focused exclusively on cold waves. 17 studies (40.5%) analyzed both heat waves and cold waves.

Among the studies analyzing both types of events, 8 (47.1%) reported stronger mortality effects linked to cold waves. All of these studies examined Russian cities in subarctic or severely continental climates, including Yakutsk, Arkhangelsk, and Murmansk [49–51]. In contrast, 5 studies (29.4%) identified stronger heatwave-related mortality effects, primarily in locations with higher summer temperatures, such as Krasnoyarsk [52] and Khabarovsk [53]. This pattern is further illustrated by two studies from southern European Russia that, together, cover both hazard types under identical methodology, dataset, and spatial and temporal scope: one on heatwave-related mortality [54] and the other on cold-wave-related mortality [51]. Comparing their reported effects indicates higher heatwave-related than cold-wave-related risks in this area. These findings suggest a possible north–south gradient in the relative dominance of cold- versus heat-related mortality risk, though this remains based on limited evidence from Russia alone.

The remaining 4 studies (23.5%) produced inconclusive results. For instance, Rocklöv et al. [55] reported heterogeneous effects of heatwaves and cold waves across population subgroups likely due to the limited sample size. Another study found that relative risks varied across different time periods, with the dominant hazard depending on the occurrence and intensity of extreme temperature events in each period [56].

4.4. Summary of methodological approaches

This section summarizes the methodological approaches adopted across studies assessing both temperature–mortality relationships and extreme temperature events, addressing ***RQ3: Which methodological approaches are most commonly used to quantify the impacts of ambient temperature and extreme temperature events on mortality, and what are their specific considerations in cold-climate contexts?*** Particular attention is given to study design, statistical modeling choices, lag structures used to capture delayed temperature effects, and the definition of temperature exposure metrics (Figure 4).

Overview of study designs and statistical methods applied

Among the 83 studies quantifying the effects of temperatures, 67 (80.7%) employed a time-series analysis or similar approaches. Time-series analysis evaluates associations between temperature and mortality by modeling temporally aggregated mortality counts as a function of ambient temperature while controlling for temporal trends and potential confounders [57]. The majority of time-series studies used quasi-Poisson regression models to estimate associations between temperature and daily mortality counts. Quasi-Poisson regression is the standard

approach in temperature-mortality research because it accounts for overdispersion, which is common for daily mortality counts where the variance exceeds the mean.

15 studies (18.1%) used case-crossover design. The case-crossover design estimates temperature-mortality association by comparing exposures on case days when deaths occurred with exposures on control days for the same group of individuals. Control days are selected from the same time stratum (e.g., same month and year) and matched on day of the week to control for temporal trend, while differing in temperature exposure. Case-crossover analysis is usually conducted using conditional logistic regression, which produces odds ratios as measures of risk associated with short-term temperature exposures. By comparing individuals with themselves at different times, the case-crossover design automatically controls for individual-level factors that remain constant over the study period. Although these two designs differ in the level of analysis and strategies to address confounding, they generally produce equivalent effect estimates under most circumstances [58,59].

One study employed the case-time series design [40] that combines the self-matched approach of case-crossover design with the temporal structure and modeling flexibility of time-series regression [60]. This is a relatively novel approach, with only a recently emerging body of evidence. It was applied here specifically because municipal-level analysis involves small daily death counts per unit, which established time-series or case-crossover approaches may fail to model reliably.

Similarly, within the 42 studies examining extreme temperature events and mortality, 35 studies (83.3%) employed time-series designs, while 7 studies (16.7%) investigated the impact of heatwaves and cold waves on mortality using a case-crossover design. A further methodological complication arises from the fact that many studies assessed control periods without adequately adjusting for key covariates (e.g., day of the week, month), instead comparing mortality during extreme events with mortality in adjacent time periods (Figure 4, Panel A). This is a particularly important issue, as earlier studies lacked consistent methodological conventions for calculating the long-term mortality baseline against which extreme weather-related risks are modeled. First, it reduces comparability between older and more recent evidence. Second, it may leave earlier results more susceptible to residual confounding. Some pre-2010 studies calculated the baseline as a simple average, which may not fully capture long-term mortality trends or seasonal patterns. Approaches in most recent studies, following Bhaskaran et al. [57], typically use smoothed functions or multilevel interaction models with adjustments for long-term trends and seasonal or environmental confounders.

The most common and well-established statistical technique, typically applied to establish the relationship between temperature and mortality, was the distributed lag non-linear model (DLNM). Most often, both the exposure–response and lag–response dimensions are modelled using splines to capture their non-parametric associations with mortality risk, jointly forming the full exposure-lag-response surface [61]. However, this was not always the case for the lag dimension: some studies instead used stratified lags, for example in the weekly analyses of Ballester et al. [62], Gallo et al. [63], and Beck et al. [64]. Among studies aimed specifically at establishing the temperature–mortality relationship (rather than extreme events alone), 56 (67.5% of 83) used DLNM approaches. Other methods included linear, piecewise linear, and polynomial functions, as well as one-dimensional splines. These alternative approaches generally did not

model lagged effects explicitly, instead sometimes applying a simple moving average over several days (Figure 4, Panel B).

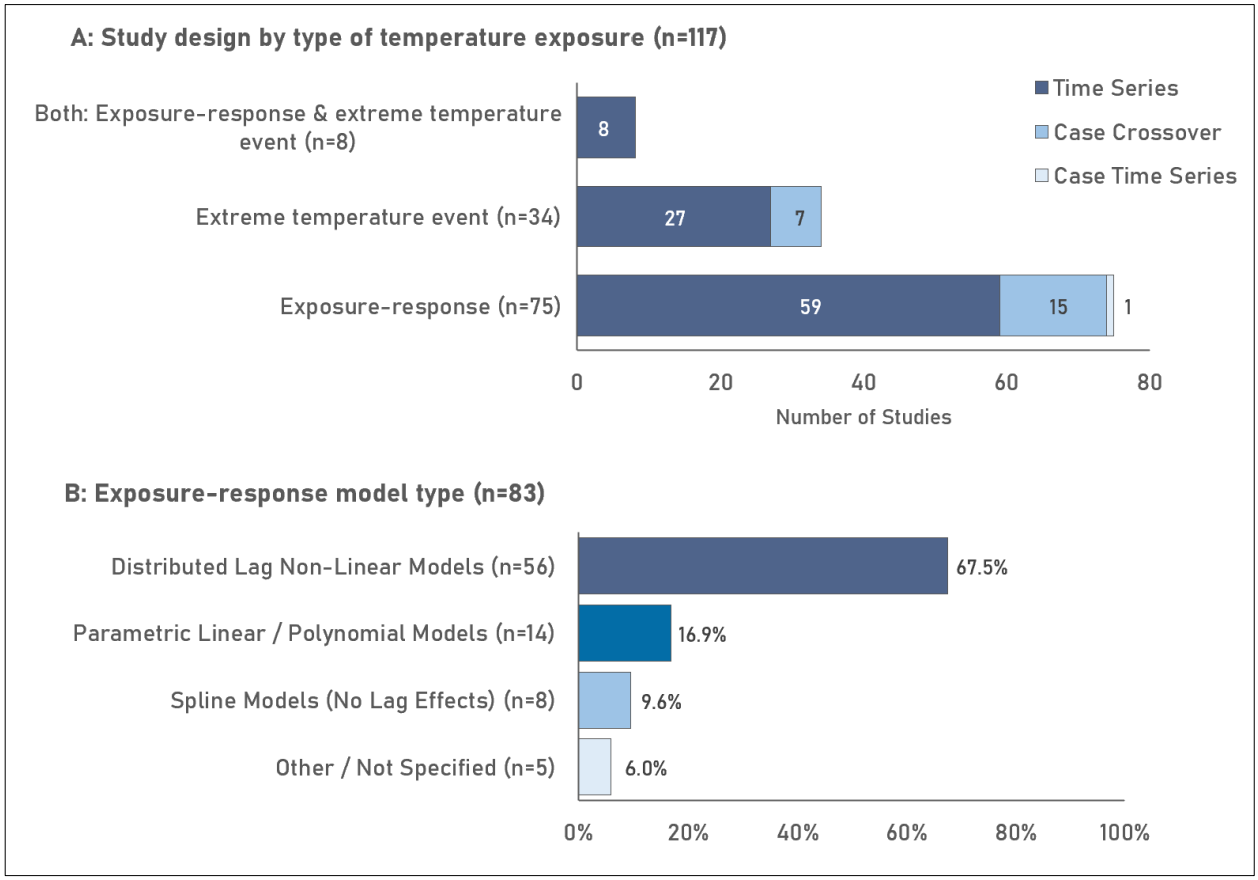


Figure 4. Study designs and statistical methods applied. Panel A shows the distribution of study designs by type of temperature exposure; Panel B shows types of exposure-response model using in exposure-response studies.

Overview of lag structure characteristics

Most studies accounted for lagged effects, reflecting established knowledge of their existence and available methods for addressing them. As noted above, most DLNM-based studies modeled the lag dimension using splines, with stratified weekly or daily [65] lags used less commonly. Outside the DLNM framework, lagged effects were typically addressed using simple moving averages. For example, Rai et al. [66] modeled interaction effects between temperature and air pollution using a tensor product. Because adding further lagged dimensions would have been computationally expensive and statistically infeasible, they instead used 2-day moving averages of temperature and air pollution to approximate short-term lagged effects.

In general, studies focusing on heat-related mortality adopted relatively short lag structures, typically ranging from 1 to 3 days. For instance, among studies that evaluated exposure–response relationships and focused specifically on heat, 79.3% (of studies where only one lag definition was used and lags were clearly specified) used a lag duration of less than 14 days. For studies covering the full temperature spectrum, this figure was only 23.4% (Table 2). This reflects the adjustment of methodological choices, such as lag duration, to the specific research objectives.

Table 2. Methodological characteristics of lag structures and temperature exposure metrics in the included studies (N=117)

Characteristics	Number of studies (%)	Exposure-response studies			Extreme temperature event studies		
		Heat	Cold	Both	Heat waves	Cold spell	Both
Lag structure	**117 (100%)**	32	6	45	**24**	**1**	**17**
1 day	9 (8%)	8	0	0	1	0	0
2 - 6 days	16 (14%)	7	0	3	4	0	2
7 - 13 days	15 (13%)	8	0	6	3	0	1
14 - 20 days	9 (8%)	2	1	4	2	0	0
21 - 28 days	24 (21%)	3	1	20	1	0	0
> 28 days	7 (6%)	1	1	5	0	0	0
Multiple or variable lags	14 (12%)	1	2	3	1	1	7
No lag/ not reported/ irrelevant	23 (20%)	2	1	4	12	0	7
Temperature exposure metrics	**117 (100%)**	**32**	**6**	**45**	**24**	**1**	**17**
Apparent temperature	6 (5%)	3	1	1	1	0	0
Daily max temperatures	10 (9%)	2	0	3	5	0	0
Daily mean temperatures	82 (70%)	24	4	36	12	1	13
Heat Index	1 (1%)	0	0	0	1	0	0
Humidex	1 (1%)	1	0	0	0	0	0
Multiple	17 (15%)	2	1	5	5	0	4

Note that one study may explore both exposure-response relationship and extreme weather event-attributable mortality

Descriptive characteristics of temperature exposure metrics

Across the studies included in this review, a range of temperature-based exposure metrics was employed (Table 2). Daily mean temperature was the most commonly used indicator, applied in 82 studies (70.1%), largely due to its broad availability and its capacity to reflect overall thermal conditions. Additionally, 10 studies (8.5%) utilized daily maximum temperature, as it may more accurately capture peak thermal stress, particularly during heatwaves. However, temperature alone is often considered insufficient to represent thermal stress, because other factors such as humidity, wind, and solar radiation also substantially influence perceived thermal conditions. To address this limitation, various biometeorological indices have been developed.

For example, apparent temperature (AT), which estimates are based on temperature, humidity, and wind speed, was used in 6 studies (5.1%), including 4 conducted within the Assessment and Prevention of Acute Health Effects of Weather Conditions in Europe (PHEWE) project [16]. In addition, 17 studies (14.5%) employed multiple metrics of thermal stress, with some specifically focusing on the comparison of their performance and predictive value. However, the results of these comparisons were inconsistent. Ruuhela et al. [46] reported that the Physiological Equivalent Temperature (PET) provided more reliable results than temperature alone, while Shartova et al. [67] found that the Universal Thermal Climate Index (UTCI) outperformed other metrics. However, Lo et al. [68] recommended selecting the exposure metric based on its performance in the specific study context, suggesting that no single index is

universally optimal; for example, AT performed best in Canada, Finland, and Sweden, while average temperature was preferable in Norway.

When examining exposure metrics for extreme weather events, variability in event definitions emerges as a significant methodological challenge. The most common approach identifies heatwaves or cold waves as sequences of consecutive days on which temperatures exceed (for heat) or fall below (for cold) a specified percentile of the local temperature distribution. Percentile thresholds vary widely across studies, typically ranging from the 90th to 98th percentile for heatwaves and from the 2nd to 3rd percentile for cold waves, reflecting attempts to align definitions with local climatic conditions. The 97th percentile (or 3rd percentile for cold waves) was the most commonly used threshold, applied in 15 studies (35.7%), followed by the 98th/2nd percentile in 7 studies (16.7%) and the 95th percentile in 3 studies (7.1%). Additionally, 2 studies (4.8%) defined heatwaves based on the 90th percentile of summer temperature distributions. In several studies (6 studies, 14.3%), absolute thresholds (predefined temperature values) were adopted. For example, Smoyer et al. [69] identified heatwave days using Heat Index values exceeding 32°C. Furthermore, 9 studies (21.4%) defined temperature waves without providing numerical or statistical basis for chosen thresholds. Some studies, such as Guo et al. [70], employed multiple definitions to compare their performance and determine the most appropriate approach. Their findings demonstrated that heatwaves defined by higher temperature thresholds were associated with higher death risks [71], differences in definitions based on duration remained less certain.

Duration criteria also varied, with events typically required to persist for at least 2 to 5 consecutive days. However, studies comparing the effects of short (<8 days) and long (≥8 days) temperature waves often failed to detect statistically significant differences in their health impacts, likely due to limited statistical power [51,54].

Overall, there is no universally accepted definition of a “hot” or “cold” day, nor a standardized classification of “heat wave” or “cold wave,” either in scientific research or policy frameworks [72]. This lack of standardization complicates comparisons across studies and highlights the need for more harmonized methodological approaches.

Table 3 Definitions and threshold criteria used for studies of extreme temperature events (N=40)

Criteria	Number of studies	%
90th percentile of summer distribution	2	4.8%
95th percentile	3	7.1%
97th percentile (heat) / 3rd percentile (cold)	15	35.7%
98th percentile (heat) / 2nd percentile (cold)	7	16.7%
Absolute thresholds (Specified level of temperature)	6	14.3%
No explicit criteria specified	9	21.4%

* Note: Some studies also considered duration (number of consecutive days) in definition of temperature waves, but these criteria are not presented in this table

4.5. Overview of mortality differences by causes of deaths

This section maps the cause-specific patterns of temperature-related mortality in cold-climate countries, addressing RQ4 ***(RQ4: What are the cause-specific patterns of temperature-related mortality in countries with cold climates?).***

Summary of cause-specific mortality patterns

A wide range of health outcomes was investigated across the included studies, reflecting the diverse physiological pathways through which non-optimal temperatures can influence mortality. All-cause mortality estimates were provided in 57 studies (48.7%), while 47 studies (40.2%) focused on natural or non-accidental mortality, as defined by ICD-10 codes A00–R99 (Table 4).

The most frequently investigated causes of death were diseases of the respiratory system (ICD-10 codes J00–J99) and the circulatory system (I00–I99), represented in 35 (29.9%) and 27 (23.1%) studies, respectively. These categories are widely recognized as most susceptible to direct temperature effects [10], which explains their predominance in the literature. Within them, ischemic heart disease (I20–I25) and cerebrovascular diseases (I60–I69) were the most commonly investigated specific outcomes, both appearing in 25 (21.4%) studies. Fewer studies addressed chronic lower respiratory disease, including chronic obstructive pulmonary disease (COPD; J40–J47; 4 studies, 3.4%) and diabetes mellitus (E10–E14; 2 studies, 1.7%). Research on infant and maternal health was limited but notable, with neonatal outcomes explored in a small subset of studies, including stillbirths (P95): 3 studies (2.6%), and sudden infant death syndrome (R95): 1 study (0.9%).

Among less-studied causes, multiple patterns emerged. For mental and nervous system disorders, evidence was heterogeneous. Kollanus and Lanki [73] reported heat-related risks for mental and nervous system disorders that were among the highest of all causes examined in Finland, while Wen et al. [41] found higher relative risks for cold than for heat in Canada. This divergence likely reflects both the small number of deaths and inconsistencies in how these outcomes were coded and reported across countries and in time. Evidence for renal and digestive diseases was heterogeneous: Nafstad et al. [74] reported digestive causes (ICD-9: 520-572) as largely temperature-insensitive, while Revich et al. [54] found renal (ICD-10 N00-N99) heat-related mortality risk to be the second-highest among the causes examined. For neoplasms, evidence was similarly mixed: several significant associations were reported, though generally modest in magnitude [41].

Overall, these findings show that temperature-related mortality research in cold-climate regions has largely concentrated on all-cause and natural mortality, with cause-specific analyses focused mainly on cardiovascular and respiratory diseases, and comparatively limited attention given to other diagnostic categories.

Table 4 The distribution of causes of death investigated across included studies.

Cause of death	ICD-10	Number of studies	%
All-cause	**A00-Z99**	**57**	**48.7%**
All natural/non-accidental	**A00-R99**	**47**	**40.2%**
Diseases of circulatory system	**I00-I99**	**27**	**23.1%**
Ischemic heart disease	I20-I25	25	21.4%
Cerebrovascular	I60-I69	25	21.4%
Diseases of respiratory system	**J00-J99**	**35**	**29.9%**
Chronic lower respiratory diseases	J40-J47	4	3.4%
Diseases of digestive system / gastrointestinal	**K00-K99**	**4**	**3.4%**
Diseases of genitourinary system / renal	**N00-N99**	**4**	**3.4%**
Diabetes	E10-E14	2	1.7%
Mental and behavioural disorders	**F00-F99**	**5**	**4.3%**
Diseases of the nervous system	**G00-G99**	**5**	**4.3%**
Neoplasms	**C00-C99**	**7**	**6.0%**
Stillbirth	**P95**	**3**	**2.6%**
Sudden infant death syndrome	**R95**	**1**	**0.9%**

*Note: Some studies also considered multiple causes of death.

Beyond documenting which causes have been studied, it is also possible to assess, within studies reporting both hazards, which temperature extreme poses the greater mortality risk for each cause (Table 5). Among such studies that examine all-cause or natural-cause mortality, most reported statistically significant associations with both heat and cold, with cold exposure more frequently associated with stronger effects (28 of 53 studies, 52.8%).

For specific causes of death, more distinct patterns emerged. Among the 14 studies that aimed to evaluate exposure–response relationships for cardiovascular disease mortality (I00–I99), 10 (71.4%) reported higher mortality risks associated with cold than with heat [43,75,76], although heterogeneity was observed across specific cardiovascular outcomes. Evidence was most consistent for ischemic heart disease (IHD; I20–I25), with 11 of 13 studies (84.6%) identifying cold exposure as the predominant contributor to temperature-related mortality [51,77,78]. For cerebrovascular diseases (I60–I69), associations were observed for both temperature extremes. Specifically, 7 of 13 studies (53.8%) reported stronger cold-related risks [43,50], 4 of 13 studies (30.8%) observed greater heat-related effects [79]. This suggests that IHD mortality is particularly sensitive to cold, whereas cerebrovascular disease mortality is sensitive to both heat and cold, with effects varying across populations. A study focused specifically on cerebrovascular temperature-related mortality [80] found higher cold- than heat-related risks for both ischemic and hemorrhagic stroke overall. However, in locations with colder winters, risk of ischemic stroke was elevated during both heat and cold extremes, indicating that local climatic conditions can modify the exposure–response relationship in ways that increase overall vulnerability in cold-climate countries.

Although point estimates of relative risks associated with heat and cold, respiratory heat-related respiratory mortality were generally higher, results were less consistent across studies due to limited statistical power from low daily counts of respiratory deaths, particularly in smaller cities [50]. Of 18 studies, 8 (44.4%) reported stronger heat-related associations [74,75,81], whereas 7 (38.8%) provided non-significant estimates or insufficient data for both heat and cold effects, largely due to wide confidence intervals, and therefore did not demonstrate clear differences between heat and cold effects [51,52]. Direct comparison of heat- and cold-related

estimates for the remaining causes discussed above (e.g., renal, digestive, mental and behavioural, and nervous system diseases) was not feasible due to an insufficient number of studies. This unevenness in cause-specific evidence represents a notable gap in the literature, both globally and particularly within the narrower geographic scope of cold-climate regions.

Table 5. Evidence of temperature-related mortality by cause of death: number and proportion of studies demonstrating significant effects.

Cause	ICD-10	*N*	Heat effect	Cold effect	No differences/ Insufficient data
All-cause/all natural/non-accidental	**A00-Z99**	53	11 (20.8%)	28 (52.8%)	14 (26.4%)
Diseases of circulatory system	**I00-I99**	14	3 (21.4%)	10 (71.4%)	1 (7.1%)
Ischemic heart disease	I20-I25	13	1 (7.7%)	11 (84.6%)	1 (7.7%)
Cerebrovascular	I60-I69	13	4 (30.8%)	7 (53.8%)	2 (15.4%)
Diseases of respiratory system	**J00-J99**	18	8 (44.4%)	3 (16.6%)	7 (38.8%)
Chronic lower respiratory diseases	J40-J47	1	1 (100.0%)	0 (0.0%)	0 (0.0%)

*Note: focusing only studies that assessed full temperature spectrum capturing both heat and cold effects across all seasons; *N* is total number of studies.

4.6. Overview of mortality differences by demographic groups

This section examines the extent to which demographic characteristics influence vulnerability to temperature-related mortality ***(RQ5: How does demographic heterogeneity modify temperature-related mortality in countries with cold climates?).*** Across the reviewed studies, factors such as age and sex were frequently explored to identify groups with heightened sensitivity to heat, cold, or temperature variability. Evidence on the modifying role of socioeconomic factors remained limited and less consistent.

Summary of age and sex-specific mortality patterns

Temperature-related health risks are unevenly distributed across demographic groups. Among the included studies, 61 (52.1% of all studies in the review) investigated associations between temperature exposure and mortality across different age groups to identify populations at higher risk. Older adults (aged 65 years and older) generally experienced substantially higher risks and were the main contributors to excess mortality associated with non-optimal temperatures. Nevertheless, certain specific causes and conditions may disproportionately affect working-age individuals.

The vast majority of these studies reported significantly higher temperature-related mortality risks for adults aged 65 and older than for both the younger (30–64) age group [50,55,76] and the overall population [79,82]. In a large multicity assessment covering Europe, cold-related mortality showed a more pronounced age gradient, while heat-related risks were comparatively homogeneous across age groups [9]. However, exceptions also exist, with some studies reporting higher cold-related mortality among younger individuals [75], particularly for specific causes of death such as cardiovascular and respiratory diseases [83]. This pattern may reflect greater outdoor and occupational cold exposure among working-age males [84]. Furthermore, many studies conducting age-specific analyses were characterized by small

numbers of deaths in younger age groups, resulting in limited statistical power to detect age differences [56].

A subset of studies focused on younger age groups: infant mortality (1 study), neonatal mortality (5 studies), and stillbirths (3 studies). These studies primarily analyzed historical populations (19th to mid-20th century) using parish registers, as infant and neonatal mortality rates during those periods were sufficient for epidemiological analysis [85–87] . Most reported increased mortality associated with both non-optimal heat and cold exposures [88]. However, direct comparisons with risks in the general population were not possible, as these studies typically examined mortality exclusively within younger groups. Nevertheless, they provide important insights into temperature-related mortality among infants and other very young age groups in historical cold-climate contexts.

Temperature-related mortality was also evaluated by sex in 30 studies (25.6% of all studies in the review). Most of these (56.7%, 17 studies) reported no significant or consistent sex differences, while others lacked sufficient detail to evaluate sex-specific effect modification. However, 8 studies (26.7% of studies with sufficient sex-specific results) reported clearly higher risks for females [40,41], particularly among older age groups and during periods of extreme heat [44]. In contrast, 5 studies (16.7%) found higher risks for males [89]. Of these, 3 studies focused on neonatal mortality and stillbirths [86,88], where observed differences are likely attributable to physiological rather than behavioral or occupational factors. Underlying mechanisms for observed sex differences were rarely explored in the reviewed literature. Higher heat-related mortality among older females has been linked to a greater probability of living alone [90,91]. Conversely, increased male susceptibility has been associated with greater occupational exposure, especially among working-age males [84]. Nonetheless, evidence remains limited and inconsistent across different populations and outcomes.

Evidence regarding other sociodemographic and healthcare factors is even more scarce. For instance, 4 studies (3.4%) compared temperature-related mortality by place of death, specifically distinguishing between deaths occurring at home and in hospitals. All reported higher mortality risks among hospitalized patients during heatwaves compared to those dying at home [91]. Some studies attributed this pattern to the low prevalence of air conditioning in hospitals, as observed in Finland [91] and Canada [92], and the subsequent inability to maintain adequate indoor thermal conditions for patients during heatwaves.

Additionally, 6 (5.1%) studies investigated the relationship between pre-existing conditions and temperature-related mortality. Individuals with chronic diseases and disabilities generally exhibited higher mortality risks during periods of extreme heat [93,94]. Notably, one of the largest increases in risk was observed among individuals with mental disorders [55,94].

However, the variables used to investigate socioeconomic heterogeneity were inconsistently defined, precluding robust cross-study synthesis. A few studies assessed individual-level factors, such as education and employment status [95]. More frequently, studies relied on regional or community-level indicators, such as income, poverty, and age composition [96], as well as material deprivation [90] and housing prices as a proxy for area-level socioeconomic status [92]. This heterogeneity in how socioeconomic indicators are defined across studies constrains the current evidence base and complicates cross-study comparability.

5. Discussion

This systematic review identified substantial evidence on both exposure-response relationships and extreme temperature events across regions with cold climates. Numerous studies documented the predominance of cold-related mortality risks, for both non-optimal temperatures and extreme temperature events. Furthermore, substantial heterogeneity in methodological approaches and effect modifiers complicated cross-study synthesis.

Geographic bias

The included studies revealed substantial geographic and climatic heterogeneity in temperature-related mortality patterns. This heterogeneity is also evident at the local scale, where increased heat-related mortality has been identified in major population centers due to urban heat island effects, while in winter these effects may be protective due to higher temperatures in the city, a phenomenon particularly pronounced in cold climates [42]. Location-level analyses from multicenter studies, where available, revealed marked differences in heat- versus cold-related mortality magnitude and temperature thresholds across geographic regions. In cold arid cities, such as Astrakhan and Volgograd (Köppen-Geiger classifications BWk and BSk, respectively), heatwaves posed substantially higher mortality risks than cold waves [97]. In contrast, subarctic cities with minimal heat exposure experienced negligible heat-related risks [49]. This demonstrates that cold-climate countries face a dual challenge: managing persistently high cold-attributable mortality while simultaneously addressing emerging heat-related risks.

For instance, Köppen-Geiger classifications, relying on long-term averages of temperature and precipitation, fail to capture synoptic atmospheric circulation patterns, such as winter anticyclonic activity [98]. These circulation parameters can significantly alter the duration, severity, and frequency of temperature waves. For example, at comparable latitudes cold waves were associated with substantially lower mortality risks in regions with stronger maritime air mass influence, suggesting moderating effects that reduce cold exposure. In contrast, more continental cities experience longer and more frequent temperature extremes (both heat and cold waves) [49,50].

Moreover, geographic representation in the included studies is substantially biased toward the milder regions within the countries of interest (moderate climates and continental climates with warm summers), where most of the population is concentrated. Consequently, sparsely populated extreme northern territories are largely uncovered by empirical studies. This reflects both a lack of research focus on these areas and the absence of sufficiently large population centers to obtain robust mortality estimates. This geographic data gap is particularly critical, as these extreme northern territories are often home to Indigenous populations with distinct socioeconomic and health profiles and settlement patterns that warrant targeted epidemiological attention.

Studies on circumpolar cities predominantly cover Russia, with a substantial geographic expansion provided by Timonin et al. [44]. However, no studies were identified for locations in continental climates with very cold winters (Dwd, Dsd, and Dfd) or polar climates (ET and EF). While Wen et al. [41] included some Canadian census divisions located in polar areas, no specific results were reported for these subregions. Addressing this data gap in the Arctic will require the broader adoption of novel epidemiological approaches, such as case time series designs, which

are better suited to handle the low statistical power typical in sparsely populated areas with small death counts [40,60].

Underrepresentation of cold-related mortality studies

Despite numerous studies reporting elevated cold-related mortality risks, the literature remains disproportionately focused on heat-related analyses. This imbalance persists despite cold currently dominating the temperature-related mortality burden, a pattern projected to continue even under future climate change scenarios [99].

The focus on heatwaves likely reflects their acute and highly visible mortality spikes. In contrast, the effects of cold exposure are more prolonged, less noticeable, and epidemiologically more complex to attribute due to delayed lag structures and confounding by seasonal, non-temperature-related factors (such as respiratory infections) [7,14]. Addressing this knowledge gap requires detailed research on cold-related mortality in cold-climate zones. For instance, there is a critical need to identify specific effect modifiers of cold-related mortality and to evaluate the effectiveness of household-level interventions, given that adaptations to cold remain poorly understood [100].

Methodological inconsistency

A fundamental challenge in synthesizing temperature-mortality evidence is the methodological variability in analytical approaches used to evaluate temperature impacts. Before the widespread adoption of the DLNM framework, analytical approaches differed significantly. While DLNMs subsequently became the standard, specific model parameterizations and the covariates included continued to vary across studies depending on research objectives and data availability. This heterogeneity limits the synthesis of evidence into composite exposure-response curves across geographic regions.

Furthermore, studies evaluating mortality risks during extreme temperature events lacked standardized definitions for heat or cold waves, often relying on official national metrics and post hoc criteria. Specifically, definitions varied widely in their temperature thresholds and minimum duration criteria; the latter is known to significantly modify mortality risk [70,101]. An additional issue is the reliance on relative percentile thresholds. Within cold climates, extreme cold defined by a specific percentile may represent vastly different absolute temperatures (e.g., in Vancouver, extreme cold thresholds are close to 0°C, while in Yakutsk, Russia, it may be below -40°C), leading to different magnitudes of physiological thermal stress that are not directly comparable across climates. These methodological differences complicate the direct pooling of risk estimates and limits quantitative synthesis across cold-climate regions.

Cause-specific heterogeneity and unresolved vulnerability patterns

Different causes of death showed varying sensitivity to temperature exposure, as observed in our systematic mapping review. The two most frequently studied causes, which also represent the greatest temperature-related burden, were cardiovascular and respiratory diseases; within the cardiovascular category, ischemic heart disease (IHD) and cerebrovascular diseases were most prominent. Evidence from our review suggests that cold-related relative risks are higher for cardiovascular mortality, while global meta-analytic evidence suggests higher risks for respiratory than for cardiovascular diseases, although with high uncertainty [20]. For heat-related mortality, respiratory risks were consistently higher, aligning with global meta-analyses [102]. Within

cardiovascular mortality, cold-related risks were generally higher for IHD than for cerebrovascular diseases [103]. However, for heat-related risks, many studies in our review reported higher stroke risks, a pattern not confirmed by multicountry studies [43] or meta-analyses [102].

Long-term cold exposure induces physiological adaptations such as increased brown adipose tissue activity, a metabolic response that is particularly pronounced among northern inhabitants. While long-term adaptation is presumed to be protective against cold stress [104], it has also been associated with adverse effects, including elevated blood pressure in colder regions [105] and higher cholesterol levels. This is particularly relevant given evidence of distinct health profiles between Indigenous and migrant populations [106], although this pattern is not consistently confirmed [107] and is likely further shaped by behavioral and dietary factors. This highlights the following issue: despite physiological evidence of heightened vulnerability, temperature-related mortality among northern populations does not appear to differ materially from global patterns, leaving the relationship between long-term adaptation and short-term exposure poorly understood.

Although other diseases, such as renal and neurological, contribute less to overall temperature-related mortality burden, several studies reported substantially elevated relative risks during extreme heat [33,54,73]. Proposed mechanisms for this heightened vulnerability include an impaired ability to self-protect during extreme temperatures due to cognitive or behavioral impairments [91]. However, non-cardiorespiratory causes remain substantially under-investigated in cold-climate contexts, representing an important knowledge gap.

Sociodemographic differentials

Among sociodemographic variables, age showed the most consistent association with temperature-related mortality, with substantially higher risks in older adults, although notable exceptions were documented among working-age populations in selected studies. A subset of studies examined historical infant and child mortality using parish registers, representing a distinct methodological tradition with limited direct comparability to contemporary research. While these studies provide valuable historical evidence on temperature-related mortality among the youngest age groups, their findings are not fully generalizable to modern populations. Sex-specific patterns remained inconsistent across studies, with most reporting no significant differences.

However, other sociodemographic factors, such as education, occupation, and income, were addressed in only a few studies each [55,71,90,108], making cross-study comparison impossible. Furthermore, despite the risk of ecological fallacy, these factors were frequently assessed using aggregated community- or region-level data. While area-level metrics effectively capture contextual determinants, such as infrastructural development and policy capabilities, individual-level data are better equipped to identify specific vulnerabilities, though they remain largely inaccessible due to privacy and data linkage constraints [95]. Moreover, adaptive mechanisms specific to cold exposure, such as layered clothing, behavioral adjustments, and household heating, were insufficiently characterized in contemporary research, despite being emphasized in earlier studies [109,110]. Specifically, regarding housing conditions as a modifier of cold risk, a recent review [111] noted a distinct lack of studies establishing this association. These evidence gaps are particularly crucial for cold-climate countries, where cold-related

mortality remains the dominant temperature-related burden. Consequently, the mechanistic pathways and sociodemographic vulnerabilities modifying cold risk remain largely unquantified, limiting the development of targeted public health interventions.

While our study identified substantial literature on the subject, several limitations of our review design, which may affect the results and their interpretation should be noted. First, the geographic scope does not comprehensively represent all areas with cold climates and was defined somewhat arbitrarily. We applied no strict climatic criteria, selecting studies conducted entirely or partially in countries encompassing the Arctic zone. Consequently, not all study locations were characterized by severely cold climates. Conversely, cities with relatively cold conditions in countries not included in our review, such as the Baltic States or northern China, were omitted. Nevertheless, this approach ensured clarity of scope and allowed us to obtain sufficient evidence for analysis.

Second, our inclusion criteria may be considered too restrictive for a systematic mapping review, as we limited our scope to peer-reviewed, full-length academic publications, excluding reports and gray literature. Non-included sources were partially reviewed via citation tracking and supplementary literature searches; most of these duplicated studies already captured in our analysis, although we cannot confirm that some relevant studies were mistakenly omitted.

Third, although we applied no language restrictions, and the review included several studies published in Finnish, Swedish (translated via Google Translate), and Russian, potential bias may arise from one author's fluency in Russian and familiarity with the Russian context. However, comprehensive investigation of publications by frequently included Finnish and Swedish authors revealed no additional relevant papers published in their national languages that were excluded from our analysis.

Despite these limitations, our systematic mapping provides a comprehensive overview of direct temperature impacts on mortality in countries with cold climates, and identifies key research gaps, while also establishing a foundation for more detailed quantitative assessments.

6. Conclusion

This systematic mapping review synthesized evidence on temperature-related mortality in cold-climate countries published between 1990 and 2026, The evidence base is substantial but uneven. Studies are concentrated in a few countries, notably Canada and Sweden, and in the milder parts of the cold-climate zone. Across the mapped studies, cold was more often reported as the dominant contributor to temperature-related mortality. Heat-related risks, however, were frequently pronounced in locations with warmer summers and during exceptional heatwaves.

The review also identified gaps across geographic, methodological, cause-specific, and demographic domains. Geographically, most evidence comes from milder cold-climate zones (Dfa Köppen classifications), with polar regions (ET, EF) entirely unrepresented. This geographic bias substantially limits applicability of our results to sparsely populated and circumpolar populations, for which temperature-mortality evidence is virtually non-existent, preventing evidence-based policy development in these regions.

Methodologically, substantial heterogeneity in exposure-response modelling specifications and extreme temperature event definitions prevented quantitative meta-analysis and synthesis of

comparable evidence across populations. Cause-specific research focused almost exclusively on cardiovascular and respiratory diseases, with limited evidence for other temperature-articulable causes, constraining comprehensive understanding of temperature-related mortality.

Age was the most consistently reported modifier across studies, with older adults demonstrating elevated temperature-related mortality risks. In contrast, sex-specific patterns and socioeconomic modifications remained poorly understood and less frequently studied. This presents a research gap given that socioeconomic factors (housing quality, household heating, occupational exposure) may substantially modify cold-related mortality.

Future investigations should prioritize: (1) standardized definitions of temperature waves and exposure-response modelling approaches relevant for regional climate contexts and aligned with best practices; (2) more detailed cause-specific and sociodemographic investigations, particularly for socioeconomic gradients; and (3) systematic investigation of Arctic and circumpolar populations, using novel methods for small-area estimations.

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Data Availability Statement

The detailed data extraction forms and assessment tables of the included studies are available from the corresponding author upon reasonable request.

Author Contributions

SK and MM contributed to the conceptualization, study design, methodology development, literature searches, two-stage screening, data visualization, and writing of the original draft. RM contributed to the conceptualization, provided validation by resolving disagreements during the screening and selection process, and critically reviewed and updated the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no competing interests.

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