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ORIGINAL PAPER

The impact of heat and cold events on direct, indirect, and intangible healthcare costs: a systematic review

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Abstract

Background Numerous studies have examined the effects of extreme temperatures on healthcare costs. However, most lack a detailed presentation of cost-related findings and often exclude cold-related effects. This systematic review provides a comprehensive overview of the economic burden associated with both heat- and cold-related temperature exposure.

Methods Literature published between 2014 and 2024 in English or German was searched in Medline (via PubMed) and the Cochrane Library, supplemented by reference tracking and Internet searches. We included primary studies published in peer-reviewed journals. Two authors independently assessed eligibility and determined a methodological quality score for each included article.

Results In total, 39 studies were included: 18 examined heat-related effects, another 18 analyzed combined heat- and cold-related effects, and 3 focused exclusively on cold-related effects. Furthermore, 18 studies focused on direct costs, 1 on indirect costs, 17 on intangible costs, and 3 on multiple cost types. Retrospective studies reported lower annual direct costs per 100,000 persons (mean €678,585; range €43,428–€2.06 million) than prospective studies (mean €1.13 million; range €14,433–€2.02 million). Indirect costs based on retrospective studies averaged €2,287 annually (range €72.75–€8,603), or 19.7 workdays lost per 100,000 persons. Intangible costs were reported using disability-adjusted life years (DALYs), years of life lost, and value of a statistical life. For example, retrospective evidence showed lower annual DALYs per 1,000 persons (mean 1.12; range 0.02–1.82) compared with prospective studies (mean 2.94; range 0.71–11.48). Methodological quality varied between 50 and 79%.

Conclusion Extreme temperatures were shown to impact healthcare costs, representing a significant economic burden for healthcare systems. However, findings should be interpreted with caution because of the substantial heterogeneity across studies.

Keywords Heat · Cold · Temperature exposure · Direct costs · Indirect costs · Intangible costs

JEL Classification I14

Introduction

In Europe, the effects of climate change have become increasingly evident. In 2024, Europe experienced its warmest year on record, with the second-highest number of heat stress days and tropical nights since systematic records began [1]. At the same time, the number of cold stress days reached an all-time low [1, 2]. According to the World Meteorological Organization (WMO), a heat wave can be defined as a period of pronounced and unusual heat lasting at least two consecutive days [3]. Similarly, a cold wave refers to unusually cold weather accompanied by an abrupt and substantial drop in near-surface air temperatures persisting for at least

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two consecutive days [3]. Despite these definitions, no universally accepted criteria for heat and cold events currently exist. Consequently, definitions vary widely across studies, ranging from percentile-based thresholds (e.g., 90th–97.5th percentile for heat; 2.5th–10th percentile for cold [4–8]) to event-based criteria (e.g., ≥ 3 consecutive days with maximum temperatures > 35 °C [9]) or case identification based on coding [10–12]. Evidence for changes in the frequency and intensity of extreme weather events, particularly heat waves, has continued to accumulate [2]. Heat and cold are a widespread meteorological phenomenon that leads to an increase in many risks, including health risks and increased mortality [3]. Heat events, in particular, have been described as the greatest climate-related risk to human health [13, 14].

In general, exposure to extreme temperatures has been shown to affect morbidity, mortality, hospital admissions, outpatient visits, and emergency department (ED) visits [15–23]. The health impacts of both hot and cold temperatures have been demonstrated across a range of diseases, including cardiovascular and circulatory diseases [22–33], stroke [22, 24–27, 29, 31], myocardial infarction [27, 32], respiratory diseases [22, 23, 25–27, 29–32, 34–37], mental health disorders [23, 38, 39], urological diseases [6, 40–42], renal diseases [23, 34, 38, 40–42], and heat-related illnesses [35, 41, 43]. Beyond this, the increased disease burden associated with heat and cold also translates into higher healthcare costs [4–6, 10]. For example, Romanello et al. [44] reported that heat stress resulted in the loss of 512 billion potential work hours in 2023, equivalent to a potential income loss of $835 billion. They further observed an average annual increase of 23% in economic losses from weather-related extreme events, rising from the period 2010–2014 to 2019–2023, reaching $227 billion—more than the GDP of about 60% of global economies.

In health economic evaluations, healthcare costs are typically categorized as direct, indirect, and intangible [45]. Direct costs reflect the consumption of resources in monetary terms, including medical services, hospital treatments, rehabilitation, and non-healthcare expenses such as transportation and household expenditures [45–47]. Cost-of-illness studies further distinguish between prevalence-based and incidence-based approaches on the one hand and between top-down and bottom-up approaches on the other [45, 46]. The top-down approach starts from highly aggregated macroeconomic data. Here, total costs are subsequently allocated to the individual level by dividing aggregate expenditures by the number of affected individuals. In contrast, the bottom-up approach is conducted at the patient level, where an average patient with a specific disease is defined and individual treatment costs are calculated [45]. Furthermore, a prevalence-based approach estimates the total cost of illness for all existing cases within a given year, thereby capturing the economic burden of a condition over a defined period, typically one year. By contrast, an incidence-based approach estimates the lifetime costs of all newly occurring cases by identifying the number of new cases within a year and applying lifetime cost estimates to these cases [46].

The aim of these studies is to quantify the economic impact of a particular disease or health condition on healthcare systems, thereby supporting health policy, resource allocation, and priority setting [47, 48]. Indirect costs primarily refer to productivity losses due to illness-related work absence, reduced work performance, disability, or premature death [45]. These costs may be borne by the patient, relatives, or others within the patient's environment [49]. The two most common methods for estimating such costs are the human capital and friction cost approaches [45, 46]. The human capital method calculates productivity losses as expected future earnings based on days of incapacity or premature death but has been criticized for overestimating costs by ignoring workforce replacement [45, 47]. By contrast, the friction cost method accounts for replacement time (the friction period) and associated costs, assuming the labor market adapts within a certain timeframe. This approach is considered more realistic, as it better reflects labor market dynamics [45, 50, 51].

Intangible costs are generally not expressed in monetary terms but refer to losses in quality of life (e.g., pain, suffering, stress, physical impairment). The most common measure is the concept of disability-adjusted life years (DALY) calculated as the sum of years of life lost (YLL) due to premature death and years lived with disability (YLD) [45, 47, 49]. YLL captures premature mortality by comparing age at death with a standard life expectancy and may include discounting and age-weighting [52]. YLD, by contrast, is estimated by multiplying disease incidence or prevalence by a disability weight reflecting the loss of healthy life years [53]. By contrast, the value of a statistical life (VSL) expresses intangible costs in monetary terms by dividing the willingness to pay or willingness to accept risks by the change in risk. This method enables the monetary valuation of life-saving measures [54].

Alongside broader research on extreme temperatures, see above [16, 23, 30, 36, 41, 55, 56], literature on the healthcare costs of heat and cold events has grown rapidly in recent years [5, 6, 10, 57–61]. Several primary studies have assessed the economic burden of temperature exposure, focusing either on a single cost type (e.g., direct [4, 5, 10, 11, 62, 63], indirect [6, 9, 10, 62, 64], or intangible costs [7, 61, 65–67]) or on multiple cost types. While this growing body of literature is a welcome development, the evidence remains fragmented. In response, the first systematic reviews have begun to synthesize available findings, though with differing objectives. To the best of our knowledge, no review has yet comprehensively assessed the economic burden of temperature exposure on healthcare costs across all three cost types together. Moreover, evidence on cold-related costs is still limited. For example, Wondmagegn et al. [68] examined only heat-related direct costs, excluding indirect and intangible costs as well as cold-related events. This systematic review therefore aims to address these gaps by evaluating the economic burden of both heat- and cold-related exposure across direct, indirect, and intangible costs.

Methods

This review was carried out in accordance with the Cochrane Handbook for Systematic Reviews of Interventions [69, 70] and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline [71].

Search strategy

The literature search was performed on May 27, 2024, in Medline (via PubMed) and the Cochrane Library, limited to English- or German-language publications from 2014 to 2024. Search terms were grouped into three categories: (1) temperature exposure, drawing on prior reviews (e.g., [68, 72–76]); (2) health outcomes, also based on earlier reviews (e.g., [68, 72, 76, 77]), including morbidity and mortality to capture studies with costs as secondary outcomes; and (3) economic outcomes, informed by more recent secondary studies (e.g., [68, 72, 78, 79]). An overview of the final search terms is provided in Supplementary Material 1. We also searched the Internet via Google and Google Scholar, contacted experts, and reviewed reference lists to identify additional studies.

Study selection criteria

Two authors independently assessed titles and abstracts using predefined inclusion and exclusion criteria (see below). When a study appeared to meet the criteria, or when a final decision could not be reached, the full text was analyzed. In cases where consensus was not achieved, a third author was consulted.

Inclusion and exclusion criteria

We focused on primary studies published in peer-reviewed journals, with all study types considered potentially relevant. Only studies that evaluated the impact of heat- and/or cold-related events on direct (e.g., [12, 57, 58, 80–86]), indirect (e.g., [6, 10, 62, 64]), or intangible costs (e.g., [7, 21, 61, 67, 87–97]) were included. Cost calculations could be based on actual costs (e.g., [6]) or derived from literature (e.g., [10]). Eligible studies assessed costs either for specific diseases (e.g., [6, 80, 84, 98]) or across all diseases (e.g., [62, 82, 85]*)*. No restrictions were imposed on retrospective and prospective studies based on the methodology used. We excluded comments, guidelines, interviews, lectures, conference papers, and studies where reported costs were unrelated to temperature or lacked connection to healthcare [99, 100]. Research on other climate factors (e.g., air pollution, ozone, forest fires) was excluded [101, 102], as were studies that did not differentiate cost types (i.e., direct, indirect, intangible) [62]).

Study quality assessment

The quality of the selected studies was evaluated using the Consolidated Health Economic Evaluation Reporting Standards 2022 (CHEERS 2022) checklist [103]. This checklist comprises 28 criteria organized into seven categories: Title, Abstract, Introduction, Methods, Results, Discussion, and Other relevant information. Each criterion was rated as "yes" (1), "no" (0), "partially" (0.5), or "not appropriate" (N/A) [104]. Prior to assessment, specific definitions were established for each criterion to guide the scoring process [105, 106]. To determine overall study quality, we calculated both the total score across all 28 criteria and an average score (excluding items rated "N/A"). The quality assessment was conducted independently by two authors, with disagreements resolved by consulting a third investigator.

Description of cost aggregation

Because included studies used different cost calculation approaches, we standardized results—where possible—by calculating annual costs per 100,000 persons. Therefore, all costs were adjusted to 2024 price levels. First, cost values were converted into euros using the average exchange rate of the original year. They were then adjusted using the consumer price indices of the original year and the German consumer price index for 2024.

For direct cost studies, total costs were divided by study duration and population of the respective region (e.g., Sydney, Perth) to determine annual costs, which were then multiplied by 100,000 to calculate annual costs per 100,000 persons if necessary. For example, Tong et al. [107] reported costs attributable to heat over seven year baseline period were estimated to be €212.63 million (AU$252 million) in a population of 4.82 million, corresponding to €630,205 per 100,000 persons per year.

For patient-level comparisons of treatment costs with and without temperature-related impacts, hospitalization and incidence rates were incorporated to derive values per 100,000 persons (e.g., [108–110]). The same procedure was applied to indirect cost studies. For intangible costs, total YLL were divided by study duration and population and then multiplied by 100,000 (e.g., [7, 8, 10]). Where studies reported YLL per death (e.g., [65, 67, 93, 94]) or only percentage changes (e.g., [94, 97]), we calculated the minimum, maximum, and average values. Studies reporting additional temperature-related YLL per day were converted to a rate per 100,000 persons by dividing the YLL per day by the reported population and multiplying by 100,000 [67, 93, 95]. For DALY studies, results were expressed per 1,000 persons due to small numbers [61, 66, 96]. Finally, annual averages were calculated to determine overall economic burden, distinguishing between retrospective and prospective studies due to methodological differences.

Relevant study characteristics

We extracted key characteristics from each study, including whether the focus was on heat or cold, the types of costs analyzed, and whether the study addressed all diseases or specific conditions (e.g., HF). We also recorded study perspective, time frame, cost calculation approach, and statistical methods. Studies were categorized as examining heat (e.g., [10, 62, 84]), cold (e.g., [65]), or both extremes (e.g., [4, 58, 84]). We also analyzed how heat and cold were defined—for example, some studies relied on temperature thresholds (e.g., [6, 9, 10, 12]), while others used diagnostic coding (e.g., [11, 80, 82]).

Results

Search results

In total, 8,898 potentially relevant articles were identified. After removing duplicates and screening titles and abstracts, 433 studies were selected for more detailed review. Additional internet searches yielded ten further articles. Finally, 39 studies met the inclusion criteria and were included in the analysis (Fig. 1).

Categorization, description, and comparison of studies

Overall, 18 studies focused exclusively on direct costs [4, 5, 11, 12, 57–59, 63, 80–86, 98, 107, 108], 1 study on indirect costs [64], and 17 studies on intangible costs [7, 8, 60, 61, 65–67, 87, 89–97] (Table 1). In addition, one study analyzed all three cost types [10], and two studies combined direct and indirect costs [6, 9]. Geographically, most studies were conducted in China [5–8, 61, 64, 65, 67, 87, 89–95, 97], Australia [9, 57, 59, 61, 80, 81, 83, 86, 107], and the United States [11, 12, 60, 98, 108]. Additional studies originated from South Korea [66, 84, 96], Spain [58, 84], Canada [4], Indonesia [63], and France [10] (Supplemental Material 1). In terms of study design, 26 studies applied a retrospective approach [4–6, 9–12, 58, 60, 61, 64, 65, 67, 82, 84, 85, 87, 89–95, 97, 108], 2 used a prospective approach [59, 63], and 11 combined both approaches [7, 8, 57, 66, 80, 81, 83, 86, 96, 98, 107]. Different approaches were used to identify costs attributable to temperature. For instance, some studies identified heat- and cold-related illnesses through diagnostic coding within datasets [10–12], while others linked disease-related data with temperature data [4–6]. Distributed lag non-linear models (DLNMs) were most frequently applied to assess the non-linear effects of temperature on disease outcomes (e.g., incidence). These models allow for the evaluation of complex relationships between environmental factors (e.g., temperature) and health outcomes (e.g., mortality, costs), while also capturing delayed effects and variations across different temperature ranges [111]. The methodological quality assessment using the CHEERS 2022 checklist produced scores ranging from 50 to 79% (see Table 1 for an overview and Supplemental Material 2 for details).

Direct cost studies (n = 21)

In total, 12 studies evaluated the economic burden of heat [6, 9, 10, 12, 59, 63, 81, 84–86, 98, 107], 8 studies examined both heat and cold [4, 11, 57, 58, 80, 82, 83, 108], and 1 study focused on cold-related effects [5] (Supplemental Material 3). Most studies addressed either all diseases [10, 59, 82, 85, 86] or a selection of diseases [57, 81, 83, 107]. Three studies each focused on cardiovascular diseases [4, 98, 108] and respiratory diseases [5, 58, 80] (Supplemental Material 4). Regarding study perspective, 12 studies applied a retrospective approach [4–6, 9–12, 58, 82, 84, 85, 108], 2 applied a prospective perspective [59, 63] and 7 combined both perspectives [57, 80, 81, 83, 86, 98, 107]. Overall, annual direct costs based on retrospective evidence ranged between €43,428 and €2.06 million, with mean costs of €678,585 per 100,000 persons (Fig. 2). In contrast, simulated future-related costs were slightly higher, with average annual direct costs of €1.13 million per 100,000 persons (range: €14,433–€2.02 million). Please see Supplemental Material 5 for a detailed description of each study.

Hospitalization

The impact of both heat and cold on hospitalization costs was analyzed in 13 studies, all of which applied a retrospective approach [4–6, 10–12, 80, 81, 83–85, 107, 108]; 4 of

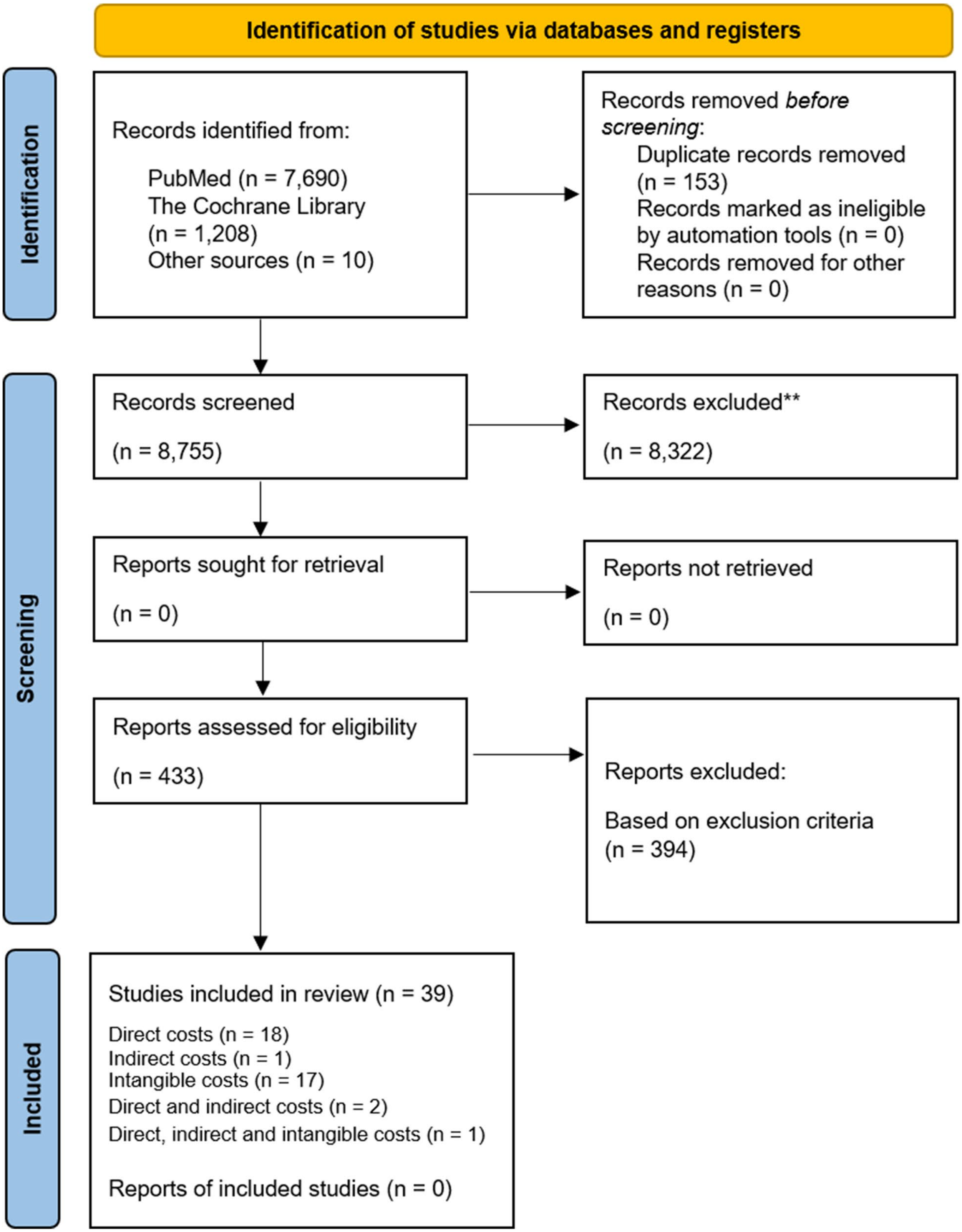


Fig. 1 Overview of the results from the systematic search procedure according to the PRISMA 2020 flow diagram. From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. https://doi.org/10.1136/bmj.n71

Table 1 Overview of the studies included ($n = 39$)

Nr	Author, Year	Country, City	Temperature		Types of Costs			Perspective		Quality Score
			Heat	Cold	Direct	Indirect	Intangible	Retrospective	Prospective	
1	Antwi-Amoabeng et al. [108]	USA, nationwide	X	X	X			X		50%
2	Bai et al. [4]	Canada, Ontario	X	X	X			X		68%
3	Feng et al. [5]	China, Shanxi		X	X			X		70%
4	Friedman et al. [11]	USA, Illinois	X	X	X			X		54%
5	Fritz et al. [63]	Indonesia, nationwide	X		X				X	68%
6	Park et al. [84]	South Korea, nationwide	X		X			X		70%
7	Royé et al. [58]	Spain, five cities	X	X	X			X		71%
8	Schmeltz et al. [12]	USA, nationwide	X		X			X		55%
9	Tong et al. [80]	Australia, Sydney, Perth	X	X	X			X	X	77%
10	Wang et al. [82]	China, 17 cities	X	X	X			X		71%
11	Wondmagegn et al. [83]	Australia, Adelaide	X	X	X			X	X	64%
12	Wondmagegn et al. [57]	Australia, Adelaide	X	X	X			X	X	75%
13	Roldán et al. [85]	Spain, Zaragoza	X		X			X		50%
14	Lay et al. [98]	USA, 136 areas	X		X			X	X	61%
15	Tong et al. [107]	Australia, Sydney	X		X			X	X	73%
16	Tong et al. [81]	Australia, Perth	X		X			X	X	79%
17	Campbell et al. [59]	Australia, Tasmania	X		X				X	55%
18	Toloo et al. [86]	Australia, Brisbane	X		X			X	X	63%
19	Ma et al. [64]	China, Guangzhou	X			X		X		53%
20	Cheng et al. [65]	China, Hong Kong		X			X	X		74%
21	Chu et al. [60]	USA, nationwide	X				X	X		70%
22	Chung et al. [66]	South Korea, nationwide	X				X	X	X	68%
23	Jiao et al. [67]	China, Wuhan	X				X	X		66%
24	Li et al. [7]	China, Tianjin	X	X			X	X	X	72%
25	Li et al. [8]	China, Tianjin	X	X			X	X	X	68%
26	Liu et al. [87]	China, 364 locations	X	X			X	X		70%
27	Luan et al. [89]	China, 31 cities	X	X			X	X		68%
28	Lv et al. [90]	China, Hunan	X	X			X	X		78%
29	Lv et al. [91]	China, Central China	X	X			X	X		78%
30	Sun et al. [92]	China, 280 counties		X			X	X		68%
31	Varghese et al. [61]	Australia, nationwide	X				X	X		62%
32	Wang et al. [93]	China, Yuxi	X	X			X	X		78%
33	Xu et al. [94]	China, Weifang	X	X			X	X		76%
34	Yang et al. [95]	China, Guangzhou	X	X			X	X		70%
35	Yoon et al. [96]	Sout Korea, nationwide	X				X	X	X	60%
36	Zhang et al. [97]	China, Hubei	X	X			X	X		70%
37	Huang et al. [6]	China, nationwide	X		X	X		X		73%
38	Xiang et al. [9]	Australia, Adelaide	X		X	X		X		61%
39	Adélaïde et al. [10]	France, nationwide	X		X	X	X	X		79%

these also included a prospective component [80, 81, 83, 107]. Based on retrospective evidence, average annual hospitalization costs ranged between €9,804 and €1.61 million, with mean costs of €462,489 per 100,000 persons (Fig. 2) [4, 6, 10–12, 80, 81, 83–85, 107, 108]. Bai et al. [4] reported an annual medical cost burden of €276,684 per 100,000 persons due to both low and high temperatures for coronary heart disease and stroke. Huang et al. [6] estimated annual heat-related treatment costs of €24,553 per 100,000 persons for urinary tract diseases. Similarly, Park et al. [84] found an increase in annual medical costs of €340,094 per 100,000 persons for mental disorders and €178,917 for intellectual disability. In the United States, temperature-related illness in patients with atrial fibrillation was associated with higher treatment costs (€10,329 vs. €8,818), resulting in €168,887 per 100,000 persons per year [108]. By contrast, heat-related illness in general was linked to lower hospitalization costs (€8,721 vs. €12,141), as shorter lengths of stay during

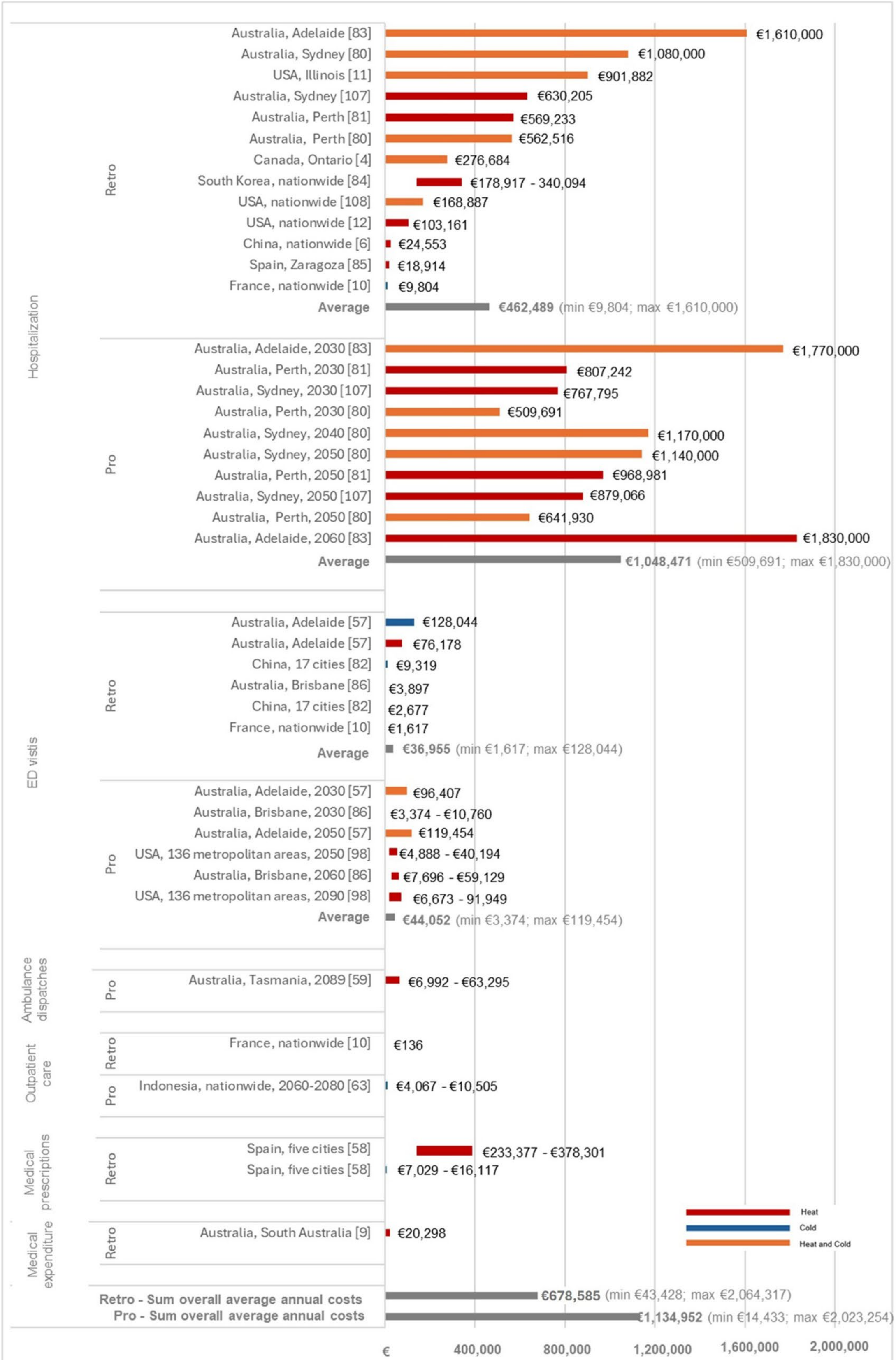


Fig. 2 Retrospective and prospective direct costs per 100,000 persons per year ($n=21$ studies)

heatwaves reduced total treatment costs [12]. Feng et al. [5] reported that cold spells increased hospitalization expenses for respiratory diseases to €849.84 per 100,000 persons. Tong et al. [80, 81, 107] showed that annual heat-related hospital costs for selected diseases amounted to €630,205 per 100,000 persons in Sydney [107] and €569,233 per 100,000 persons in Perth [81]. In Sydney, annual hospital costs for respiratory diseases reached €1.08 million, compared with €562,516 in Perth [80]. Friedman et al. [11] reported annual cumulative hospital costs of €901,882 per 100,000 persons, while Wondmagegn et al. [83] estimated temperature-related hospitalization costs of €1.61 million per 100,000 persons for a selection of diseases. Finally, Roldán et al. [85] identified 107 heat-related deaths over a 5-year period, with associated annual hospital costs of €18,914 per 100,000 persons.

As shown in Fig. 2, average annual hospitalization costs based on future-related simulations ranged between €509,691 and €1.83 million, with mean costs of €1.05 million per 100,000 persons [80, 81, 83, 107]. For example, under different climate change scenarios, annual heat-attributable hospitalization costs for a selection of diseases were projected to reach €807,242 per 100,000 persons in Perth and €764,795 in Sydney by 2030 [81, 107]. By 2050, these estimates rose to €968,981 per 100,000 persons in Perth and €879,066 in Sydney [81, 107]. Similarly, Wondmagegn et al. [83], using climate change scenarios, estimated annual hospitalization costs of €1.77 million per 100,000 persons for the 2040 s and €1.83 million for the 2060s. Tong et al. [80] projected increases in annual future costs for respiratory diseases in Sydney from €1.08 million per 100,000 persons in the 2010 s to more than €1.17 million in the 2030 s and approximately €1.14 million in the 2050s. In Perth, annual costs initially declined from €562,516 per 100,000 persons in the 2010 s to €509,691 in the 2030 s, but then increased again to about €641,930 in the 2050s.

ED visits

The impact of heat and cold on ED visits was analyzed in six studies across four countries. Three studies applied a retrospective approach [10, 57, 82, 86], two applied a prospective approach [80, 86, 98], and one combined both approaches [86]. Based on retrospective evidence, average annual costs ranged between €1,617 and €128,044, with mean costs of €36,955 per 100,000 persons. By contrast, simulation studies projected somewhat higher average annual costs, with mean values of €1.05 million per 100,000 persons (range: €509,691–€1.83 million) (Fig. 2) [10, 57, 82, 86]. For example, Adélaïde et al. [10] found that ED visits during heatwaves not followed by hospitalization resulted in annual costs of €1,617 per 100,000 persons. Wang et al. [82] estimated increased annual national ED costs of €9,319 per 100,000 persons for heat-related effects and €2,677 per 100,000 persons for cold-related effects. Wondmagegn et al. [57] identified heat-attributable ED visits with associated annual costs of €76,178 per 100,000 persons, whereas cold-related visits showed no significant attributable costs. Future projections indicated that annual ED costs could range from €3,374 to €96,407 per 100,000 persons in the 2030 s, €4,888 to €119,454 in the 2050 s and 2060 s, and €6,673 to €91,949 in the 2090 s [57, 86, 98]. In the 2030 s, average annual costs were estimated at €36,847 per 100,000 persons, rising to €46,272 in the 2050 s [57]. Lay et al. [98] projected hyperthermia-related ED costs between €4,888 and €40,194 per 100,000 persons by 2050, increasing further to €6,673–€91,949 by 2090. Toloo et al. [86] reported heat-related ED costs of €3,897 per 100,000 persons in 2010, with projections ranging from €3,374 to €10,760 in 2030, and from €7,696 to €59,129 by 2060 [86].

Medical prescriptions

The effect of temperature on medical prescriptions for respiratory diseases was evaluated in one retrospective study conducted by Royé et al. [58]. The authors reported larger cost impacts for heat-related effects, with annual values ranging between €233,377 and €378,301 per 100,000 persons, compared to cold-related effects, which ranged between €7,029 and €16,117 per 100,000 persons.

Medical expenditure

Xiang et al. [9], using a retrospective approach, analyzed compensation claims per worker to assess the effect of occupational heat-related illnesses on total medical treatment costs. They estimated annual costs of €20,298 per 100,000 persons.

Outpatient care

Two studies examined the impact of heat on outpatient care costs, including outpatient clinic visits [10] and primary healthcare [63] (Fig. 2). Adélaïde et al. [10] conducted a retrospective analysis in France (2015–2019) and found that outpatient clinic visits not followed by hospitalization amounted to €136 per 100,000 persons per year. Fritz et al. [63], in a prospective study, projected that for non-communicable diseases the Indonesian health system could face between 1 and 2.80 million additional primary care visits annually, corresponding to an extra financial burden of €4,067–€10,505 per 100,000 persons per year.

Ambulance dispatches

Campbell et al. [59], using a prospective simulation analysis, estimated that in Australia, annual additional ambulance costs due to heat between 2010 and 2089 would range from €6,992 to €63,295 per 100,000 persons (Fig. 2).

Indirect cost studies (n = 4)

Overall, four studies [6, 9, 10, 64] analyzed the impact of heat on indirect costs using retrospective approaches (Supplemental Material 3). Two studies focused on production losses [6, 10], one on workdays lost [9], and one on insurance payouts [64] (Supplemental Material 6). By disease category, one study examined the effects of temperature extremes on work-related injuries [64], one on urinary diseases [6], and two on heat-related illness [9, 10]. On average, indirect costs attributable to extreme temperature events amounted to €2,287 annually per 100,000 persons (min €73; max €8,603), or 19.7 workdays lost per 100,000 persons [6, 9, 10, 64] (Fig. 3).

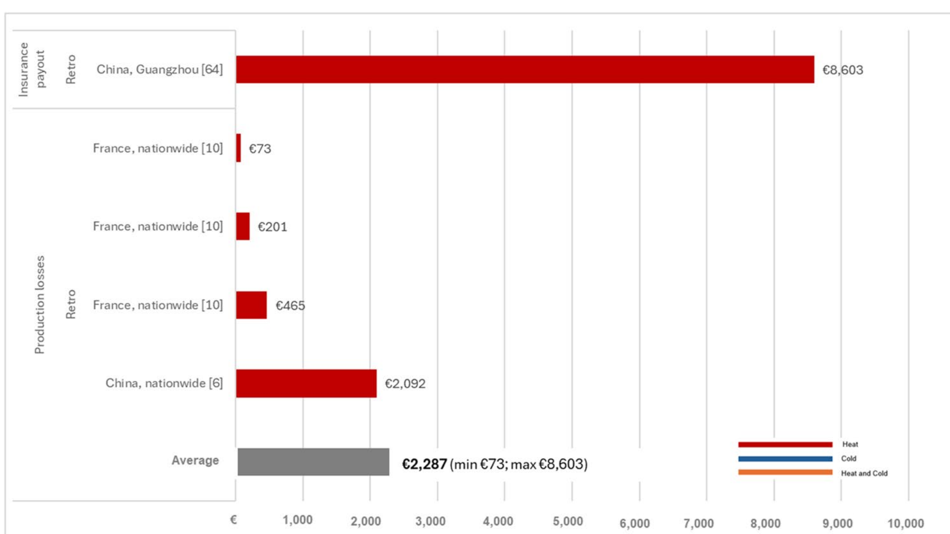
All four studies reported increases in heat-related indirect costs, with two specifically analyzing production losses. For instance, Huang et al. [6] calculated production losses due to hospitalizations for urinary diseases in China, estimating annual indirect costs of €2,092 per 100,000 persons attributable to heatwaves. Adélaïde et al. [10] estimated an annual economic burden from production loss of €73 per 100,000 persons due to outpatient clinic visits, rising to €465 per 100,000 persons for hospitalizations. In addition, Ma et al. [64] reported an indirect economic burden of €8,603 per 100,000 persons per year in the form of insurance payouts linked to heat exposure. Xiang et al. [9] identified an annual heat-attributable loss of 19.7 workdays per 100,000 persons.

Intangible cost studies (n = 18)

In total, 6 studies examined the effects of heat [10, 60, 61, 66, 67, 96], 10 assessed both heat and cold [7, 8, 87, 89–91, 93–95, 97], and 2 focused on cold-related economic effects [65, 92] (Supplemental Material 3). The diseases and outcomes investigated included respiratory diseases [60, 65, 67, 87, 89, 90, 92–95, 97], cardiovascular diseases [7, 65–67, 87, 90, 91, 93–97], non-accidental diseases [8, 67, 90, 92–95, 112], cerebrovascular diseases [66, 87, 96], circulatory diseases [92], occupational injuries [61], heat-related illness [10] and all diseases combined [10, 66]. Most studies focused on YLL (n = 14) [7, 8, 10, 60, 65, 67, 87, 89–91, 93–95, 97], while a small number assessed DALYs (n = 3) [61, 66, 96] or VSL (n = 1) [92] (Supplemental Material 7). Fourteen studies employed a retrospective approach [10, 60, 61, 65, 67, 87, 89–95, 97], while four combined both retrospective and prospective approaches [7, 8, 66, 96].

Retrospective evidence on intangible costs indicated that DALYs ranged between 0.02 and 1.82 per 1,000 persons annually, with a mean of 1.12 DALYs (mean 1.12 DALYs) per 1,000 persons per year [61, 66, 96] (Fig. 4). Prospective studies reported slightly higher values, with a mean of 2.94 DALYs per 1,000 persons per year (min 0.71; max 11.48) (see also Supplemental Material 8 for a more detailed description). For YLL, results were presented in several ways: ranging from 31.10 to 2,056.75 YLL (mean 915.86) per 100,000 persons annually; from 0.02 to 1.89 YLL (mean 1.01) per death; from 0.02 to 1.65 YLL (mean 0.37) per 100,000 persons per day; or as the average attributable risk of temperature exposure, with a mean of 7.03% (min 0.02%; max 28.98%) [7, 8, 10, 60, 65, 67, 87, 90, 91, 93–95, 97]. Projections showed that annual YLL per 100,000 persons could increase to 677 by 2055 and 742 by 2090 [8].

Fig. 3 Retrospective indirect costs per 100,000 persons per year (n = 4 studies)



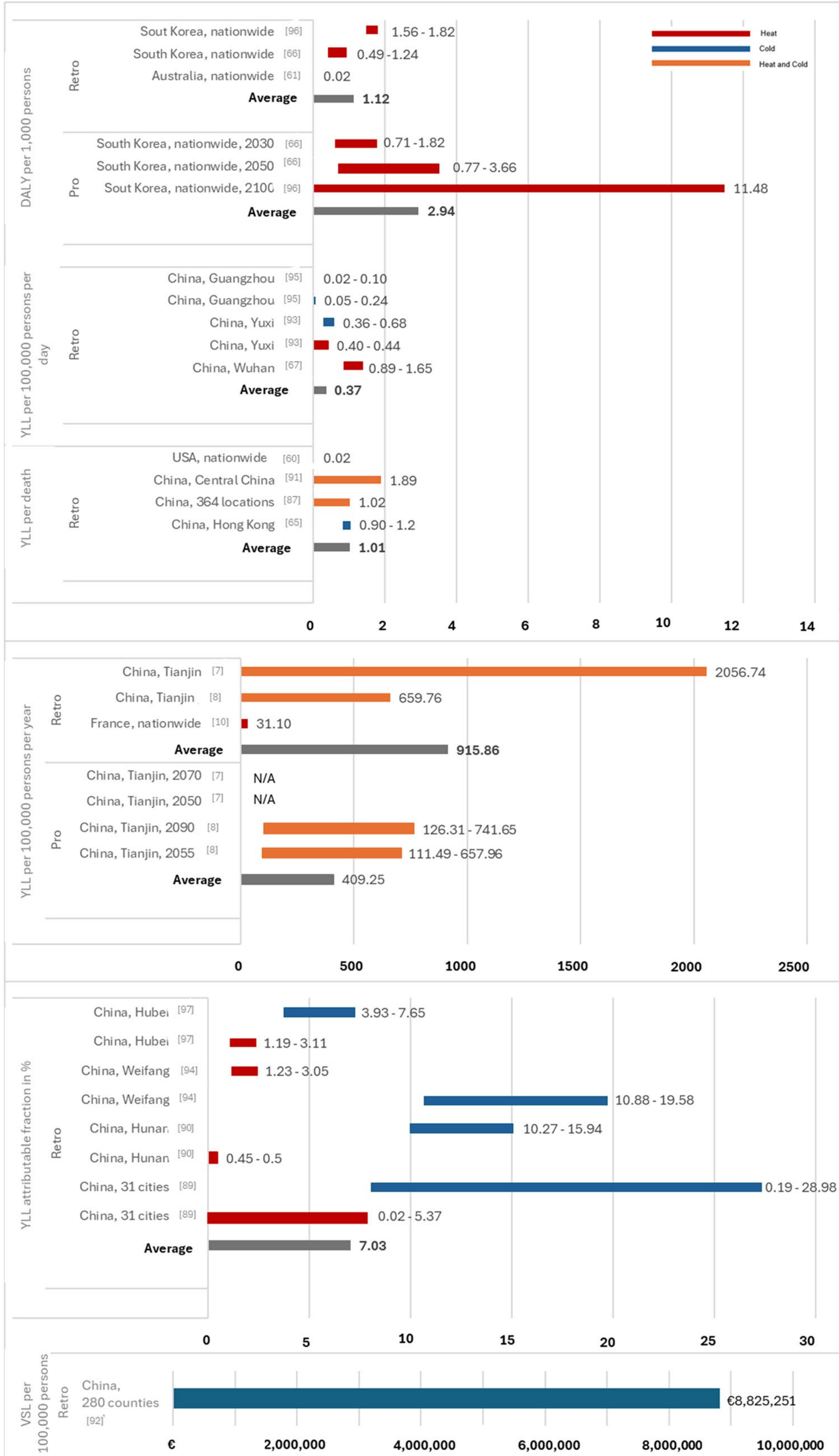


Fig. 4 Retrospective and prospective intangible costs per year ($n=18$ studies)

Finally, one study estimated the annual VSL attributed to cold-related effects at €8.83 million per 100,000 persons [92].

Disability-adjusted life year (DALY)

Overall, three studies [61, 66, 96] from two countries estimated intangible costs by calculating DALYs. One study employed a retrospective approach [61], while two studies combined both retrospective and prospective approaches [66, 96]. Reported annual DALYs ranged from 0.02 to 1.82 per 1,000 persons, with a mean of 1.12 DALYs. Varghese et al. [52] reported that, over a 6-year study period, 967 occupational injury-related DALYs were attributable to heat. This accounted for 2.3% of all occupational injury-related DALYs and corresponded to 0.02 DALYs per 1,000 persons per year. In South Korea, Yoon et al. [96] found that heatwave-induced hypertensive disease caused 1.82 DALYs per 1,000 persons, while ischemic heart disease and cerebrovascular disease each accounted for 1.56 DALYs per 1,000 persons. Chung et al. [66] reported annual DALYs of 0.49 per 1,000 persons for all-cause deaths, and 1.24 DALYs per 1,000 persons for cardiovascular and cerebrovascular diseases. Future projections indicated further increases. According to Yoon et al. [96], DALYs could rise to 11.48 per 1,000 persons by 2100. Similarly, Chung et al. [66] predicted 0.71 DALYs per 1,000 persons per year for all-cause deaths and 1.63–1.82 DALYs for cardiovascular and cerebrovascular diseases in 2030, increasing to 0.77–1.72 DALYs and 1.76–3.66 DALYs per 1,000 persons per year, respectively, by 2050.

Years of life lost (YLL)

Fourteen studies investigated YLL: 12 employed a retrospective approach [7, 8, 10, 60, 65, 67, 87, 89–91, 93–95, 97], and 2 combined both retrospective and prospective approaches [7, 8]. Annual effects of heat and cold on YLL were reported as from 31.10 to 2,056.74 YLL per 100,000 persons per year (mean 915.86) [7, 8, 10], 0.02 to 1.89 YLL per death (mean 1.01) [60, 65, 87, 91], 0.02 to 1.65 YLL per 100,000 persons per day (mean 0.37) [67, 93, 95], and as attributable risks of 0.02 to 28.98% (mean 7.03%) (min 0.02%; max 28.98%) [89, 90, 94, 97]. Disease-specific analyses showed that during COVID-19, high temperatures were linked to 0.02 YLL per death [60]. For COPD, attributable fractions were higher for cold (8.19–28.98%) than for heat (0.02–5.73%) [89]. Lv et al. [90] and Xu et al. [94] found cold increased YLL from cardiovascular deaths by 15.94% and 19.58% and from non-accidental deaths by 10.27% and 10.88%, compared with smaller heat effects (≤1.71%). Zhang et al. [97] reported similar patterns: non-accidental mortality increased by 1.91% (heat) vs. 5.09% (cold), and cardiovascular mortality by 2.70% vs. 7.65%. In China, the effects of extreme temperatures on mortality and YLL were described by Cheng et al. [65], Jiao et al. [67], Liu et al. [87], Lv et al. [91], Wang et al. [93], and Yang et al. [95]. For example, Liu et al. [87] attributed an average of 1.02 YLL per death to temperature exposure, with cold accounting for 0.98 YLL per death and heat for 0.04 YLL per death. Furthermore, Lv et al. [91] reported an average YLL attributable to heat and cold of 1.89 years per death. For cardiovascular mortality, cold effects were reported as 0.90 YLL per death [65], 0.36 YLL per 100,000 persons per day [93], and 0.10 YLL per 100,000 persons per day [95]. Heat effects on cardiovascular deaths per 100,000 persons per day ranged from 0.04 YLL [95] to 0.40 YLL [93], up to 0.89 YLL [67]. For non-accidental deaths, cold effects ranged from 0.24 YLL [95] to 0.68 YLL [93] per 100,000 persons per day, while heat effects ranged from 0.10 YLL [95] to 1.65 YLL [67] per 100,000 persons per day. For respiratory diseases, cold effects were 1.20 YLL per death [65] and 0.05 YLL per 100,000 persons per day [95], whereas heat effects were 0.02 YLL per 100,000 persons per day [95]. Regarding overall diseases, Adélaïde et al. [10] reported 31.10 YLL per 100,000 persons per year. Li et al. [8] reported temperature-attributable YLL of 659.76 per 100,000 persons for non-accidental diseases in 2008, and annual temperature-related cardiovascular deaths of 2,056.74 YLL per 100,000 persons [7].

Furthermore, Li et al. carried out future projections and reported that heat- and cold-related YLL from non-accidental diseases are expected to increase by between 112 and 657 YLL per 100,000 persons in 2050, and between 126 and 742 YLL per 100,000 persons in 2090 [8]. For cardiovascular disease, annual heat-related YLL are expected to increase by 91.3% to 164.9% in 2050 and by 87.8% to 297.7% in 2070 [7].

Value of a statistical life (VSL)

Sun et al. [92] focused on VSL in a retrospective study and reported 57,783 deaths from non-accidental mortality, 29,827 deaths from circulatory mortality, and 10,922 deaths from respiratory mortality attributable to cold-related effects over a 7-year period in China. The authors further calculated the corresponding annual VSL, estimated at €8.83 million per 100,000 persons.

Discussion

This systematic review explored the economic burden of both heat- and cold-related effects by distinguishing between direct, indirect, and intangible costs. In doing so, it contributes to the literature by assessing temperature-related healthcare costs across all three cost categories. Importantly, the review also evaluates the impact of cold-related temperature events in addition to heat, whereas much of the existing research has focused primarily on heat. Based on our findings, several conclusions can be drawn.

First, we included 39 studies in our systematic review, thereby exceeding the number considered in comparable previous reviews. For example, Wondmagegn et al. [68] incorporated 10 studies on direct costs in their 2018 review of healthcare costs related to extreme heat exposure, whereas we identified 12 studies focusing exclusively on the effects of heat on direct costs. Similar to our review, Wondmagegn et al. [68] examined costs associated with hospitalizations, ED visits, outpatient care, and ambulance transport. However, because our review also covered cold-related effects, we were able to add additional cost categories such as medical expenditure and medical prescriptions. The review by Schmitt et al. [113], published in 2016, is also relevant for comparison. Unlike our study, it examined weather-related extreme events more broadly—including flooding, hurricanes, and pollution peaks—and identified heat-related indirect costs in three studies, although one of these primarily addressed pollution. By contrast, our review identified four studies on heat-related production losses, insurance payouts, and workdays lost. Another pertinent review was conducted by Cheng et al. [114] in 2019, focusing on intangible costs. The authors examined 22 studies assessing DALYs, YLL, and YLD in the context of heat and cold. Our review identified a comparable number of 18 studies addressing intangible costs.

Second, most studies focus on specific cost categories (i.e., direct, indirect, or intangible) when evaluating the economic burden of temperature-related effects. Of the 39 studies included, 36 examined only one cost category. Direct and intangible costs were almost equally represented (18 and 17 studies, respectively), whereas just one study analyzed indirect costs. Notably, only one study analyzed temperature-related effects across all three cost categories simultaneously. The evidence also shows an imbalance in research focus: 18 studies examined heat, another 18 considered both heat and cold, and only 3 focused exclusively on cold. This indicates substantial research gaps, particularly regarding indirect costs, DALYs, and direct costs beyond hospitalization. In line with Schmitt et al. [113], who noted that climate change research often emphasizes infrastructure over human health, we found no study addressing cold-related effects on indirect costs, nor any on rehabilitation or broader healthcare expenditures related to heat or cold. The concentration of previous research on heat-related evaluations of direct and intangible costs is consistent with prior reviews. For example, Wondmagegn et al. [68] examined heat-related effects on direct costs, while Schmitt et al. [113] examined only heat-related indirect costs, and Cheng et al. [114] remains the only review to assess both heat- and cold-related impacts on intangible costs.

Third, most studies were conducted in China ($n = 17$) [5–8, 61, 64, 65, 67, 87, 89–95, 97], Australia ($n = 9$) [9, 57, 59, 61, 80, 81, 83, 86, 107], and the United States ($n = 5$) [11, 12, 60, 98, 108], with additional studies from South Korea ($n = 3$) [66, 84, 96], Spain ($n = 2$) [58, 84], and single studies from Canada [4], Indonesia [63], and France [10]. This distribution is consistent with previous reviews that also pointed to marked geographical gaps. Schmitt et al. [113] noted the absence of studies from Africa, Latin and Central America, and the Middle East, while Wondmagegn et al. [68] emphasized the underrepresentation of regions most at risk. In line with this, our review shows that—with the exception of Fritz et al. [63]—all studies were conducted in industrialized countries. Meanwhile, several European studies demonstrate effects of heat and cold on mortality and morbidity, including research from Sweden [55, 115], Germany [16, 116], Finland [23, 56, 117], the Czech Republic [118–120], Greece [121–123], and Norway [124]. Yet, despite this evidence, cost analyses remain scarce in Europe.

Fourth, the average direct annual costs attributable to temperature amounted to €678,585 per 100,000 persons across the various cost areas and diseases. These estimates ranged from €136 per 100,000 persons for outpatient visits in France [10] to €1.61 million per 100,000 persons for hospitalizations in Adelaide, Australia [83]. The wide variation reflects differences in cost types, disease focus, study setting, methodology, and whether heat- or cold-related effects were examined. For hospitalization costs alone, estimates ranged from €9,804 to €1.61 million per 100,000 persons [83]; the former included only heat-related illness, while the latter covered a broader range. Most direct cost studies concentrated on a single cost area, typically hospitalization [4, 5, 12, 80, 81, 83, 84, 107, 108]; whereas only Adélaïde et al. [10] and Friedman et al. [11] examined multiple cost areas. However, no study provided a comprehensive analysis covering all direct healthcare costs (hospitalizations, ED visits, medical prescriptions, outpatient care, and ambulance services) attributable to heat or cold exposure. Direct costs play a key role in health economic analyses [47], partly because they are easier to measure given better data availability. Evidence further suggests that heat is more frequently associated with additional costs than cold. For example. For example, Friedman et al. [11] reported nearly €918.09 million in spending on all temperature-related injuries, comprising €763.56 million for 23,834 cold injury cases and €154.56 million for 24,233 heat injury cases. Finally, whether heat or cold has the stronger impact on direct costs cannot be conclusively determined. The only identified review focused exclusively on heat-related effects [68], and to our knowledge, no review has yet examined the economic burden of cold-related effects.

Fifth, the average annual indirect costs due to heat-related effects ranged from €73 for outpatient clinic visits to €465 for visits followed by hospitalization per 100,000 persons, depending on the source of costs [10]. Yearly insurance payouts attributable to heat exposure were estimated at €8,603 per 100,000 persons, alongside 19.7 workdays lost [9, 64]. We could not determine whether heat or cold has a stronger impact, as no study on the indirect economic burden of cold-related effects was identified. Moreover, because Schmitt et al. [113] focused on environmental events more broadly, their findings on indirect costs are only partly comparable. Our findings align with Borg et al. [62], who estimated €2.6 million annually in insurance payouts for heat-related occupational illnesses and injuries. By 2030, projected costs of extreme heatwaves are expected to reach €468.48–506.30 million, depending on the climate scenario [62]. Similarly, Hübler et al. [125], in a 2008 study on rising temperatures in Germany, projected reduced work performance leading to productivity losses equivalent to 0.1% to 0.5% of GDP by 2100. Overall, only four studies examined indirect costs in detail. As Adélaïde et al. [10] noted, analyzing indirect costs is considerably more challenging than direct costs, since it requires information on employment status that is often unavailable. This uncertainty makes accurate assessment difficult. For instance, Adélaïde et al. [10] assumed one lost workday per ED visit and 13.4 days per hospitalization due to missing data. Huang et al. [6] also highlighted the lack of occupational data as a reason for underestimation, while Xiang et al. [9] further noted that the true burden of occupational heat-related illnesses is likely underestimated, since many cases go unreported.

Sixth, the average annual intangible costs from temperature-related impacts showed that DALYs ranged between 0.02 and 1.82 per 1,000 persons per year [61, 66, 96], while YLL ranged from 31.10 to 2,056.75 per 100,000 persons per year or from 0.02 to 1.89 YLL per death. The studies on DALYs focused exclusively on heat, consistent with Schmitt et al. [113], leaving the effects of cold on DALYs unexplored. Overall, more studies reported YLL ($n=14$) than DALYs ($n=3$). Chung et al. [66] noted that only few studies estimated DALYs from heatwaves. Varghese et al. [61] argued that YLL are easier to calculate because deaths are usually well documented, whereas YLD require detailed data on disease progression and disability weights, which are often lacking. Similarly, Yoon et al. [96] similarly emphasized that DALY estimates rely on international datasets and modeling assumptions, limiting accuracy. Consequently, DALYs are harder to estimate and less reliable, explaining the research focus on YLL. In line with this, no study examined temperature-related effects on YLD, further indicating the need for research in this area. Finally, studies on intangible costs tend to show larger effects of cold. For example, Yang et al. [95], Wang et al. [93], and Xu et al. [94] all reported greater cold-related than heat-related effects; this pattern is also confirmed by Cheng et al. [114]. By contrast, Li et al. [7] projected that heat-related YLL will rise sharply in coming decades, while YLL linked to cold are likely to decline.

Seventh, we observed different methodological approaches across the studies. Some direct cost analyses used a bottom-up approach, estimating individual-level costs and aggregating them across cases [5, 6, 9, 11, 59, 80, 82–84, 98, 108]. Other studies applied a top-down approach, using literature-based average cost values. For instance, Bai et al. [4] used average circulatory disease costs of $11,260 in Canada, while Roldán et al. [85] calculated €3,987.90 per death. Both methods have strengths and limitations: top-down is more efficient but depends on the availability and quality of published data [45], whereas bottom-up offers greater detail and validity but is more resource-intensive and less comparable across studies [45]. Different strategies were also applied to link extreme temperatures with healthcare costs. Some studies identified temperature-related illnesses via coding in datasets [10–12], while in others, disease data were linked with temperature data [4–6]. Furthermore, DLNMs were most frequently applied [6, 7, 63, 64, 80, 83, 84, 93, 95] to capture non-linear exposure–response relationships, delayed effects, and impacts across temperature ranges [111]. In most cases, DLNMs and the determination of attributable risk followed the methodology described by Gasparrini et al. [111, 126–132]. Some studies further combined DLNMs with quasi-Poisson regression [4, 6, 58], generalized additive models [5, 82, 92, 94], or general linear models [57, 81, 97, 107, 133], while others used only quasi-Poisson regression [10], generalized additive models [98], or general linear models [86]. Cheng et al. [114] cautioned that linear models fail to capture non-linear exposure–response patterns. Finally, Schmeltz et al. [12] noted that diagnostic accuracy depends on coding, with administrative data generally less reliable than clinical data and heat- and cold-related illnesses often underreported.

Finally, in line with Wondmagegn et al. [68], we distinguished between retrospective and prospective approaches. Of the 39 included studies, 26 employed a retrospective design, 2 were prospective, and 11 combined both. This dominance of retrospective evidence is consistent with

Wondmagegn et al. [68]. Across cost categories, retrospective approaches clearly dominate. In direct cost studies, however, the share of prospective approaches was higher, with 9 of 21 studies including cost projections. By contrast, only 3 of 18 intangible cost studies applied prospective designs, and all 4 indirect cost studies were conducted retrospectively. According to Toloo et al. [86], prospective evidence is limited due to unavailable or insufficient forecasting data. Li et al. [8] also noted that simulations based on older data may underestimate results, particularly given societal aging and demographic change. Retrospective designs, by contrast, rely on existing health, climate, and population data, making them less complex, more time-efficient, and easier to validate against historical events [66]. Our review highlights that direct costs for hospitalizations (€462,489 vs. €1.05 million) and ED visits (€36,955 vs. €91,949) were approximately twice as high in prospective studies as in retrospective studies. This underscores the likelihood of substantial future cost increases and the growing burden on healthcare systems. Rising temperatures, population growth, demographic aging, and the increasing frequency of extreme temperature events are expected to further amplify these costs [57, 98, 107].

As with any study, several limitations must be acknowledged. First, heterogeneity in methodological quality and study characteristics made cross-study comparisons difficult and weakened the strength of conclusions. We observed variation in approaches and in the cost categories analyzed: while most studies focused on single categories (e.g., hospitalizations, ED visits, medical expenditure), fewer adopted a broader perspective. Second, a longer search period and the inclusion of additional databases might have yielded more relevant studies. The uneven global distribution of evidence also limits generalizability, as most studies were conducted in industrialized countries with varying healthcare systems. We sought to enhance comparability by converting costs using annual exchange rates, adjusting for inflation to 2024, and standardizing results per 100,000 persons, though this inevitably introduces some distortion. Third, a key limitation—also highlighted by Cheng et al. [114], Schmitt et al. [113] and Wondmagegn et al. [68]— is the lack of a standardized definition of heat and cold. This resulted in substantial variation in thresholds, ranging from percentile-based cut-offs (e.g., 90th–97.5th percentile for heat; 2.5th–10th percentile for cold [4–8]) to event-based criteria (e.g., ≥ 3 consecutive days with maximum temperature > 35 °C [9]) or case identification via coding [10–12]. Such heterogeneity inevitably affects study outcomes and limits comparability. Finally, by restricting inclusion to peer-reviewed literature, other potentially relevant work may have been missed. It should also be noted that the literature review was conducted in mid-2024 and further articles may have been published since then.

Conclusion

In sum, this systematic review synthesizes evidence from 39 primary studies on the economic burden of heat- and cold-related effects, distinguishing between direct, indirect, and intangible costs. The evidence base was larger for direct and intangible costs than for indirect costs, and heat-related analyses predominated. Overall, both heat and cold affect all three cost categories and impose a significant economic burden on healthcare systems. Simulations indicate that extreme temperature events will continue to drive additional costs, underscoring the need for political action to ensure healthcare systems can absorb these future burdens. Future research should prioritize standardizing methodologies and definitions of heat and cold to improve comparability, and expand study settings to underrepresented regions in order to better capture the global economic burden of temperature-related events. Political action appears necessary to ensure that healthcare systems can absorb additional costs in the future, particularly in light of the increasing frequency of extreme climate events. To address this challenge, it is essential to systematically investigate all three cost categories and their relationship with temperature extremes. Such evidence would enable more targeted and informed policy responses at both national and international levels.

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Author contributions All authors contributed to the study conception. VS and ME developed the study design, VS, ME and ML analyzed the literature and conducted the quality scoring of the included studies. The first draft of the manuscript was written by VS and ME and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability Data available on request from the corresponding author (martin.emmert@uni-bayreuth.de).

Declarations

Ethics approval Ethics approval for this study was obtained from the University of Bayreuth (24–027).

Conflict of interest The authors declare that they have no competing interests.

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