



Thermal indices for assessing the impact of outdoor thermal environments on human health: a systematic review of epidemiological studies

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Abstract

The global rise in temperatures contributes to the increase of climate-sensitive diseases. Despite mitigation efforts, temperatures are projected to keep rising, highlighting the need for integrated methods to assess the impact of thermal environments on human health. This study summarizes the existing evidence on the statistical relationships (associations) between thermal indices and health outcomes. Medline, Scopus, and Web of Science were systematically searched until December, 2023 for studies examining the association between thermal indices and health outcomes in outdoor environments (protocol registration: PROSPERO CRD42023412470). The quality of the included studies was assessed using the United States National Institutes of Health Quality Assessment Tool. The search identified 5038 records, with 310 meeting eligibility criteria and examining 1143 associations. These associations represented 51 countries, primarily in North America ($n=448$, 39.2%) and Europe ($n=399$, 34.9%). Temperate climates ($n=597$, 52.2%) were the most frequently examined. Seventeen indices were identified, with Apparent Temperature being the most common (141 publications, 634 associations). Frequently used indices included also Heat Index, Universal Thermal Climate Index, and Physiologically Equivalent Temperature. About half of the associations focused on mortality and half on morbidity. The most frequently examined associations were for diseases of the circulatory system ($n=304$, 26.6%), all-cause morbidity/mortality ($n=288$, 25.2%), and diseases of the respiratory system ($n=151$, 13.2%). Among associations examining heat-related outcomes ($n=882$), 57.8% ($n=510$) suggested an increased risk of adverse health outcomes as indices increased, while for cold-related outcomes ($n=367$), 44.1% ($n=162$) suggested an increased risk as indices decreased. This systematic review reveals significant associations between thermal indices and health outcomes, indicating that thermal indices could be valuable tools for public health planning. However, the diversity in methodologies across studies highlights the need for standardization in methodology and reporting, including the reporting of non-significant findings.

Keywords Heat stress · Cold stress · Health outcomes · PET · UTCI · Apparent temperature · Heat index · Humidex

Introduction

The climate crisis driven by climate change is accelerating faster than initially expected (IPCC 2023; Hansen et al. 2025). Across the globe, climate-related events are already having severe consequences, leading to widespread damage to both ecosystems and human societies (IPCC 2023; Arnell et al. 2016). Over the past decade, global surface temperatures have risen by approximately 1.1 °C compared to the pre-industrial baseline (1850–1900) (IPCC 2023), with numerous temperature records being broken in the past two years (Daalen et al. 2024; WMO 2024). Climate-sensitive pathogens and disease vectors, such as West Nile

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virus, *Vibrio*, dengue, malaria, and leishmaniasis, are thriving in increasingly favorable conditions, resulting in a rise of water-, food-, and pest-borne diseases (Daalen et al. 2024). Heat-related mortality and morbidity have increased (Daalen et al. 2024). Additionally, the risk of non-communicable diseases might be growing due to reduced physical activity, as extreme heat discourages outdoor activities during the hottest hours of the day (Daalen et al. 2024).

Despite a growing body of policies and mitigation strategies since the release of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2014, continued emissions of greenhouse gases are anticipated to push temperatures even higher (IPCC 2023). Models project an increase of at least 1.5 °C within this century, making it difficult to prevent global warming from surpassing the 2 °C threshold (IPCC 2023). As a result, climate-related health impacts are expected to worsen, potentially affecting billions of people worldwide. This growing threat highlights the urgent need for integrated approaches to assess the relationship between thermal environments and human health.

Thermal indices quantify the thermal effect of meteorological conditions on human health and well-being (Freitas and Grigorieva 2015). Thermal indices integrate multiple variables of the ambient environment such as air temperature, humidity, wind speed, and solar radiation. Some of them also incorporate physiological variables, such as age, sex, height, weight and activity to estimate thermal stress or comfort experienced by the human body in a given outdoor environment (Freitas and Grigorieva 2015). They usually provide an output of a thermal dimension (°C), which reflects a level into a scale of human thermal comfort, sensation, or stress (Freitas and Grigorieva 2015). Thermal indices are used because they offer a more comprehensive measure of thermal stress by considering environmental factors beyond air temperature and, in some cases, physiological responses. They are widely applied in meteorology (Napoli et al. 2021), public health (Romaszko et al. 2022a), occupational safety (Flouris et al. 2018), urban planning (Tseliou et al. 2022), and tourism (Zare et al. 2018) to assess and mitigate the effects of extreme thermal conditions. Thermal indices are employed by international meteorological agencies, including the National Oceanic and Atmospheric Administration in United States (NOAA-National Weather Service 2024), the Bureau of Meteorology in Australia (Bureau of Meteorology Australian Government (BOM) 2010), and the Hong Kong Observatory (Hong Kong Observatory 2022) in People's Republic of China among others. They serve as valuable tools for assessing how weather conditions affect human thermal comfort, predicting heat- or cold-related health risks, and guiding public health interventions (Napoli et al. 2021; Potchter et al. 2022, 2018).

The literature includes a wide variety of thermal indices, developed using diverse theoretical approaches, integrating different sets of variables, applied in different climates (i.e., warm or cold climates) or thermal conditions (i.e., extremes, non-extremes), and producing diverse outputs such as thermal sensation, comfort levels, or stress. Simple thermal indices—including Apparent Temperature (AT), Heat Index (HI), Humidex (HU), Wet-Bulb Globe Temperature (WBGT), and Wind Chill Temperature (WCT)—are estimated by simple equations using only basic meteorological variables (i.e., air temperature, humidity and wind speed). These indices are commonly used by international meteorological agencies (NOAA-National Weather Service 2024; Bureau of Meteorology Australian Government (BOM) 2010; Government of Canada 2024) due to their reliance on easily accessible data and calculation, which avoid the need for radiation flux estimates. However, thermo-physiological indices, such as the Physiologically Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI), are considered more appropriate for the comprehensive assessment of thermal environments as they account for radiation fluxes and are based on heat balance models of the human body. PET and UTCI already have a wide range of applications including their use in the weather forecasting procedure (Napoli et al. 2021; Potchter et al. 2022).

The aim of this paper is to summarize the existing evidence on the statistical relationship, (i.e., association) between thermal indices and human health. This will help identify the most commonly used indices, thereby contributing to the standardization of information and facilitating easier comparison of results. Moreover, this review aims to popularize the use of thermal indices among medical scientists, public health professionals, epidemiologists, and policymakers. It will also examine which diseases have been studied in relation to thermal indices, aiming to consolidate this information and highlight gaps in the application of thermal indices in medical and public health research.

Materials and methods

Search strategy and selection criteria

We conducted a systematic review to examine the association between the thermal indices and health outcomes. We searched Medline (via PubMed), Scopus, and Science Citation Index Expanded, Social Sciences Citation Index and Emerging Sources Citation Index (via Web of Science) from inception to December 31 st, 2023. The search algorithm included the words “heat”, “warm”, “cold”, “cool”, “thermal environment” and “thermal condition” which encompass concepts such as heat waves, cold spells, and extreme

warm/cool/thermal conditions. Additionally, the search included the terms “weather”, “climate”, “thermal index” and “biometeorological index”, “equivalent temperature”, “universal thermal climate index”, “predicted mean vote”, “wind chill”, “heat index”, “apparent temperature”, “humidity”, “effective temperature”, “perceived temperature”, “mortality”, “death”, “morbidity”, “hospital, emergency”, “health”, “exposure”, “exhaustion”, “illness”, “disease”. Boolean operators (AND, OR) were used to combine these terms appropriately. The search terms were chosen based on their relevance to the core concepts of thermal environments and health, as well as their ability to capture a broader range of related topics. We also included specific biometeorological indices (e.g., predicted mean vote, perceived temperature, wind chill) guided by their widespread use in existing literature, and health outcomes (e.g., exhaustion) to ensure that relevant studies were not overlooked. The full search strategy can be found in the supplement (Online Resource 1– [Search strategy](#)).

The inclusion criteria required studies published in English, concentrating on human subjects. There were not any restrictions related to the publication status of the studies; however, publications such as books, letters, and commentary were not assessed due to their potential inability to provide adequate data for inclusion in our study. Publications focusing on indoor thermal environments were excluded as well as those focusing on injuries. Additionally, studies focusing on physiological responses were omitted, as they did not address medical conditions.

Title, abstract, and full text screening was performed in duplicate by two authors (KP, LL) in Rayyan software (Ouzzani et al. 2016) after having removed the duplicates in the Mendeley reference management software (version 1.19.8, 2008–2020 Mendeley Ltd). Disagreements among reviewers during the screening process were resolved through discussion. If consensus could not be reached, a third team member (AF) was consulted to make the final decision. Consensus was defined as an agreement among reviewers regarding the inclusion or exclusion of a study. The reference lists of the identified articles were screened for additional eligible publications. For articles where the full text could not be retrieved, we contacted their authors, primarily through ResearchGate, to obtain the necessary information.

This systematic review follows a standardized methodology based on a predefined protocol (PROSPERO CRD42023412470). The findings are presented in accordance to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Online Resource 1– [PRISMA Checklist](#)) (Page et al. 2020).

Data extraction and analysis

Data extraction was performed by 3 authors (KP, AF, LL) using a predefined extraction form in Excel. The extracted information from each eligible publication included first author’s last name, year and journal of publication, examined thermal indices and health outcomes, characteristics of the study populations (e.g., country, city, age), type of meteorological data (e.g., data from stations, gridded data, in-situ measurements) and health data sources (e.g., hospital admissions, emergency visits, ambulance calls, statistical services), type of indices’ measures used in the analysis (e.g., daily/weekly/monthly average, median, maximum, or minimum values), analysis method (e.g., correlation, linear, logistic, negative binomial regression), effect estimate (descriptive assessment, correlation coefficient, odds ratio, relative risk), and whether potential confounders were examined in the analysis (adjusted, not adjusted). The climate of the studied areas was obtained using Koppen classification (Kottek et al. 2006). The health outcomes were classified according to the International Statistical Classification of Diseases and Related Health Problems 11 th Revision (ICD-11). Thermal conditions examined in the included publications were classified as warm and cool based on the seasons they focused on.

The analysis was conducted using a standard software package (Stata, version. 18; StataCorp). A two-sample test of proportions (prtest) was used to compare proportions across different categories, such as mortality versus morbidity, to assess whether the observed differences in the effects of thermal indices on health outcomes were statistically significant.

Quality was assessed using the United States National Institutes of Health (NIH) Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies (NIH 2021). The NIH tool critically appraises the quality of studies using 14 items and focusing on key methodological issues for studies’ internal validity. The NIH tool provides a structured and transparent approach for evaluating study quality, minimizing bias, and improving the reliability of synthesized evidence.

Results

Studies and associations

The search algorithm across the PubMed, Scopus, and Web of Science databases, identified 6825 records (Fig. 1). Four additional records were found through review articles and reference lists. After removing duplicates, 5038 unique records remained and were screened based on their title and

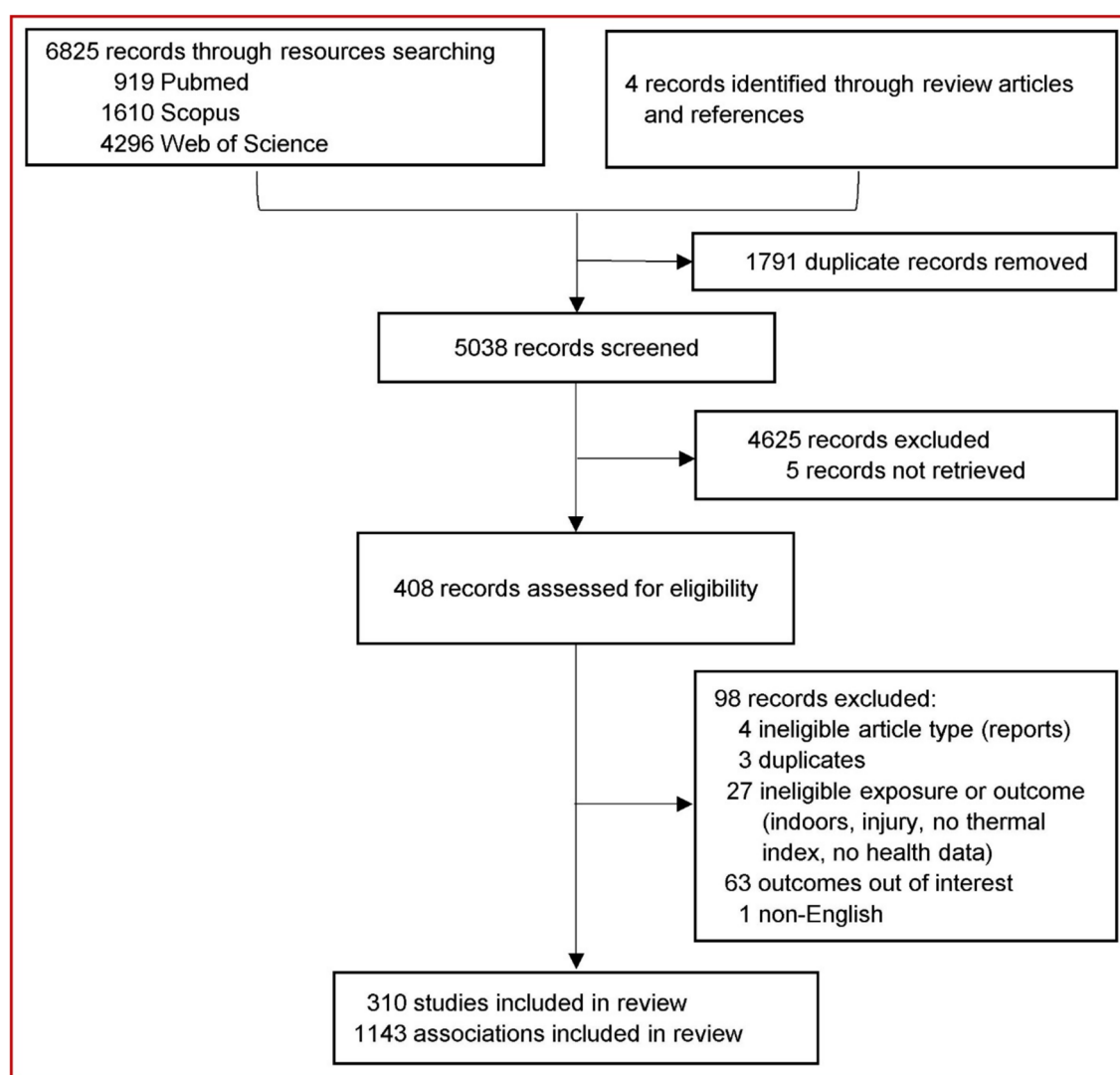


Fig. 1 Study selection

abstract. Of these, 408 met the inclusion criteria and underwent full-text screening. Ultimately, after full-text screening, 310 (O'Neill et al. 2005, 2003; de Donato et al. 2008; Morabito et al. 2012, 2014, 2005; Lee et al. 2016; Choi et al. 2017; Smoyer et al. 2000; Smoyer 1980; Hattis et al. 2012; Xu et al. 2013, 2023; Ostro et al. 2009, 2010; Alessandrini et al. 2011; Basu and Malig 2011; Ragettli et al. 2017; Royé et al. 2020; Davis et al. 2020; Henderson et al. 2013; Chung et al. 2009; Lin et al. 2012, 2013, 2016a, 2009, 2016b; Wichmann 2017; Stanojevic et al. 2014; Analitis et al. 2008; Saha et al. 2014; Bell et al. 2008; Stafoggia et al. 2006, 2009, 2008; Basu et al. 2008, 2015, 2012, 2018a, 2017, 2010, 2018b, 2016; Zanobetti and Schwartz 2008; Baccini et al. 2008; Madrigano et al. 2013; Michelozzi et al. 2006, 2005, 2009; Wiru et al. 2020; Hondula et al. 2012; Schifano et al. 2012, 2009, 2013, 2016; Almeida et al. 2010; D'Ippoliti et al. 2010; Leone et al. 2013; Astrom et al. 2015; Chen et al.

2017; Gronlund et al. 2014, 2020; Ghirardi et al. 2015; Kim et al. 2006, 2018, 2020, 2016; Harlan et al. 2014; Davis and Novicoff 2018; Analitis et al. 2018; Cao et al. 2021; Lee et al. 2021; Yong et al. 2023; Ngarambe et al. 2022; Pantavou et al. 2008, 2011, 2016, 2021; Green et al. 2010; Lim et al. 2022a, 2022b, 2015, 2017, 2021; Meng et al. 2023; Zhan et al. 2023, 2022; Gao et al. 2022; Basu and Ostro 2008; Heidari et al. 2016; Min et al. 2019; Jin et al. 2023; Ohno et al. 1970; Ohno 1970; Roye et al. 2019; Shartova et al. 2018; Zutphen et al. 2012; Wichmann et al. 2011a, 2011b, 2012; Urban and Kyselý 2014; Grjibovski et al. 2012a; Grjibovski et al. 2012b, 2013, 2021; Zhai et al. 2022a, 2023a, 2022b, 2023b; Psistaki et al. 2023; Santurtun et al. 2020; Avalos et al. 2017; Li et al. 2021; Mbanu et al. 2007; Nguyen et al. 2015; Moghadamnia et al. 2018a; Halonen et al. 2011; Zhang et al. 2016, 2023, 2020, 2022, 2017; Moghadamnia et al. 2018b; Shrikhande et al. 2023; Liu et al. 2018a,

2018b, 2021; Telesca et al. 2023; Buehler et al. 2023; Roye et al. 2018; Nick et al. 2022; Zhou et al. 2022, 2023; Krstić and Krstić 2011; Sun et al. 2023; Benmarhnia et al. 2015; Cushing et al. 2022; Veron et al. 2021; Vicedo-Cabrera et al. 2014; Requía et al. 2022; Mohammadi et al. 2019; Porter et al. 1999; Soim et al. 2018, 2017; Hartz et al. 2013, 2012; Ng et al. 2014; Sen and Nag 2019; Milsten et al. 2003; Vassil et al. 2020; Milani et al. 2022; Aguglia et al. 2021; Rammah et al. 2019; Lu et al. 2023; Leung et al. 2008, 2021; Aboubakri et al. 2020; Mohammadi and Karimi 2018; Goncalves et al. 2007; Emelina et al. 2015; Costa et al. 2021; Wenfang et al. 2020; de Sousa Zanotti Stagliorio Coêlho et al. 2010; Gunasekara et al. 2023; Yip et al. 2008; Chien et al. 2016; Perron et al. 2005; Vaidyanathan et al. 2019; Matte et al. 2016; Spangler et al. 2023a; Zottarelli et al. 2021; Rathi and Sodani 2021; Kivimäki et al. 2050; Khatana et al. 2022a, 2022b; Skarha et al. 2022; Monteiro et al. 2013; Weinberger et al. 2021; Burkart et al. 2011, 2013, 2016, 2014; Wellenius et al. 2017; Rosenthal et al. 2014; Sung et al. 2013; Metzger et al. 2010; Levy et al. 2015; Desai et al. 2015; Fritze 2020; Rathi et al. 2017, 2021; Saddique et al. 2021; Williams et al. 2020; Boeke et al. 2010; Deng et al. 2022; Gao et al. 2020; Hahn et al. 2023; Brunetti et al. 2014; Kysely and Huth 2004; Huang et al. 2021; Yin and Wang 2018; Hamilton et al. 2021; Ross et al. 2018; Chu et al. 2022; Tam et al. 2008; Jiao et al. 2023; Son et al. 2019; Carlson et al. 2021; Kranc et al. 2021; Bandala et al. 2019; Shire et al. 2020; Saha et al. 2015; Lewandowski et al. 2022; Na et al. 2013; DeMartini et al. 2014; Grundstein et al. 2012; Bethancourt et al. 2021; Bai et al. 2014; Erickson et al. 2019; Moore et al. 2017; Cloud et al. 2023; Savitz and Hu 2021; Theoharatos et al. 2010; Isaksen et al. 2016, 2015; DeVine et al. 2017; Rainham and Smoyer-Tomic 2003; Conti et al. 2007, 2005; Kegel et al. 2021; Calkins et al. 2016; Ho et al. 2017; Arnold et al. 2022; Zhao et al. 2023; Pan et al. 2019; Bassil et al. 2011; Mastrangelo et al. 2007; Infusino et al. 2021; Thach et al. 2015; Schroeder et al. 2023; Thorsson et al. 2021; Laschewski and Jendritzky 2002; Muthers et al. 2010a, 2010b; Zaninovic et al. 2014; Urban et al. 2019; Matzarakis et al. 2011; Nastos and Matzarakis 2012, 2006, 2008; Dastoorpoor et al. 2022a, 2022b; Zaninovic and Matzarakis 2014; Zemtsov et al. 2020; Sharafkhani et al. 2018; Shiue et al. 2015, 2016a, 2016b, 2016c; Ferrari et al. 2015; Vasconcelos et al. 2013; Roshan et al. 2022a; Roshan et al. 2022b; Caglak 2022; Caglak and Matzarakis 2023; Borsi et al. 2021; Silva and Ribeiro 2012; Dastoorpoor et al. 2021; Pantavou et al. 2020; Kienbacher et al. 2021; Koppe et al. 2011; Schlegel et al. 2020; Garin and Bejaran 2003; Błażejczyk et al. 2018; Błażejczyk et al. 2022; Chau et al. 2022; Urban et al. 2021; Ghada et al. 2021a, 2021b; Romaszko et al. 2017, 2019; Lokys et al. 2018; Romaszko et al. 2022b; Jingsi et al. 2023; Ma et al. 2018; Skutecki et al. 2019; Kuchcik 2021; Lindner-Cendrowska and Bröde 2021; Romaszko-Wojtowicz et al. 2020; Kruger and Nedel 2023; Fallah Ghalhari et al. 2016; Nyadanu et al. 2022a; Nyadanu et al. 2023a, 2023b, 2022b; Cymes et al. 2021; Krzyzewska et al. 2017; Khodadadi et al. 2022; Bonell et al. 2022; Sombatsawat et al. 2023; Pradhan et al. 2019; Meshi et al. 2018; Lewandowski and Shaman 2022; Morris et al. 2019; Wallace et al. 2005; Carder et al. 2005; Oh et al. 2021; Gill et al. 1988; Eng and Mercer 2000; Ohlson et al. 1991) records met the inclusion criteria and were included in this systematic review (Table 1). The included articles examined 1143 associations (Online Resource 2–Table S1) between thermal indices and health outcomes. The earliest publication dates back to 1969 followed by nine studies published until 2002, while the number of relevant publications increased significantly thereafter (Online Resource 1–Figure S1). The articles were distributed across 120 journals with 41.9% ($n = 130$) being published in journals focusing on environmental sciences, climate and meteorology, 26.8% ($n = 83$) in journals of epidemiology and public health, and 19% ($n = 59$) in journals focusing on medical sciences (Online Resource 1–Figure S2).

Fifty-one countries across six continents- Asia, Africa, North America, South America, Europe, and Oceania- were represented in the associations. About 96% of the associations were reported in studies conducted in North America ($n = 448$, 39.2%), Europe ($n = 399$, 34.9%), and Asia ($n = 251$, 22%) (Online Resource 1–Figure S3). The countries with the highest representation (Online Resource 1–Table S1) were the United States ($n = 430$, 37.6%), Italy ($n = 80$, 7%), and the People's Republic of China ($n = 69$, 6%). Climates considered in the associations were primarily temperate ($n = 595$, 52.1%) while continental ($n = 238$, 21%), arid ($n = 89$, 7.8%), and tropical climates ($n = 47$, 4.1%) were also examined (Online Resource 1–Figure S4).

The associations were examined across a variety of thermal conditions and seasons. Among the 1143 associations analyzed, 43.8% ($n = 501$) considered both cool and warm thermal conditions, while 47.9% ($n = 547$) focused exclusively on warm thermal conditions and 8.3% ($n = 95$) associations examined only cool thermal conditions (Fig. 2). Since some studies assessed both cool and warm thermal conditions for the same health outcome, the total number of associations for heat- and cold-related effects combined ($n = 1249$) exceeds the overall number of associations ($n = 1143$). Annual thermal conditions were addressed in 42.3% ($n = 484$) of the associations. Additionally, 16.4% ($n = 188$) focused on a single season—winter, spring, summer, or autumn—while 30.7% ($n = 351$) analyzed summer along with a transitional season, such as spring or autumn. Furthermore, 31% ($n = 354$) of the associations specifically

Table 1 Thermal indices identified in this systematic review and characteristics of included studies

Index	Country	Climate	Health outcome
ASV	Greece	Temperate	22 Injury, poisoning or certain other consequences of external causes (Pantavou et al. 2016, 2011)
AT	Argentina, Australia, Brazil, Canada, Chile, Czech Republic, Denmark, Finland, France, Ger- many, Ghana, Greece, Hungary, India, Iran, Ireland, Israel, Italy, Japan, Kazakhstan, Malaysia, Mexico, People's Republic of China, Portu- gal, Republic of China (Taiwan), Republic of Korea, Rus- sia, Serbia, Slovenia, South Africa, Spain, Sweden, Switzerland, Thailand, Tunis, Turkey, United States, United Kingdom	Arid, Con- tinental, Temperate, Tropical	All causes (O'Neill et al. 2005, 2003; de Donato et al. 2008; Morabito et al. 2012, 2014; Lee et al. 2016; Choi et al. 2017; Smoyer et al. 2000; Smoyer 1980; Hattis et al. 2012; Xu et al. 2013; Ostro et al. 2009; Alessandrini et al. 2011; Basu and Malig 2011; Ragetti et al. 2017; Royé et al. 2020; Davis et al. 2020; Henderson et al. 2013; Chung et al. 2009; Lin et al. 2012, 2013; Wichmann 2017; Stanojevic et al. 2014; Analitis et al. 2008; Saha et al. 2014; Bell et al. 2008; Stafoggia et al. 2006, 2009, 2008; Basu et al. 2008, 2015; Zanobetti and Schwartz 2008; Baccini et al. 2008; Madrigano et al. 2013; Michelozzi et al. 2006, 2005; Wiru et al. 2020; Hondula et al. 2012; Schifano et al. 2012, 2009; Almeida et al. 2010; D'Ippoliti et al. 2010; Leone et al. 2013; Astrom et al. 2015; Chen et al. 2017; Gronlund et al. 2014; Ghirardi et al. 2015; Kim et al. 2006; Harlan et al. 2014; Davis and Novicoff 2018; Analitis et al. 2018; Cao et al. 2021; Lee et al. 2021; Yong et al. 2023; Ngarambe et al. 2022) 01 Certain infectious or parasitic diseases (Chen et al. 2017; Green et al. 2010; Lim et al. 2022a, 2022b; Meng et al. 2023; Zhan et al. 2023; Lin et al. 2016a; Ostro et al. 2010; Basu et al. 2012; Gao et al. 2022) 05 Endocrine, nutritional or metabolic diseases (Chen et al. 2017; Harlan et al. 2014; Green et al. 2010; Ostro et al. 2010; Basu et al. 2012; Lim et al. 2015; Basu and Ostro 2008; Heidari et al. 2016) 06 Mental, behavioural or neurodevelopmental disorders (Basu et al. 2018a; Min et al. 2019; Jin et al. 2023) 08 Diseases of the nervous system (Analitis et al. 2008; D'Ippoliti et al. 2010; Chen et al. 2017; Green et al. 2010; Ostro et al. 2010; Basu et al. 2012; Basu and Ostro 2008; Michelozzi et al. 2009; Ohno et al. 1970; Ohno 1970; Zhan et al. 2022; Royé et al. 2019; Shartova et al. 2018; Zutphen et al. 2012; Wichmann et al. 2011a, 2011b; Urban and Kysely 2014; Grjibovski et al. 2012a; Grjibovski et al. 2012b) 11 Diseases of the circulatory system (Alessandrini et al. 2011; Basu and Malig 2011; Royé et al. 2020; Chung et al. 2009; Analitis et al. 2008; Baccini et al. 2008; Madrigano et al. 2013; Stafoggia et al. 2009; Basu et al. 2015, 2012, 2017; Almeida et al. 2010; D'Ippoliti et al. 2010; Chen et al. 2017; Gronlund et al. 2014; Harlan et al. 2014; Green et al. 2010; Ostro et al. 2010; Basu and Ostro 2008; Michelozzi et al. 2009; Zhan et al. 2022; Shartova et al. 2018; Zutphen et al. 2012; Wichmann et al. 2011a, 2011b, 2012; Urban and Kysely 2014; Grjibovski et al. 2012a; Grjibovski et al. 2012b; Zhai et al. 2022a, 2023a, 2022b, 2023b; Psistaki et al. 2023; Morabito et al. 2005; Santurtun et al. 2020; Li et al. 2021; Mbanu et al. 2007; Nguyen et al. 2015; Lin et al. 2009, 2016b; Moghadamnia et al. 2018a; Halonen et al. 2011; Zhang et al. 2016; Xu et al. 2023; Moghadamnia et al. 2018b; Shrikhande et al. 2023; Liu et al. 2018a; Telesca et al. 2023; Buehler et al. 2023) 12 Diseases of the respiratory system (Alessandrini et al. 2011; Basu and Malig 2011; Chung et al. 2009; Analitis et al. 2008; Baccini et al. 2008; Stafoggia et al. 2009; Basu et al. 2015, 2012; Almeida et al. 2010; D'Ippoliti et al. 2010; Chen et al. 2017; Gronlund et al. 2014; Harlan et al. 2014; Green et al. 2010; Ostro et al. 2010; Basu and Ostro 2008; Michelozzi et al. 2009; Wichmann et al. 2011a, 2011b; Lin et al. 2009; Royé et al. 2018; Zhang et al. 2023, 2020; Liu et al. 2021; Zhou et al. 2022; Grjibovski et al. 2021) 11 and 12 Diseases of the circulatory and Diseases of the respiratory system (Krstić and Krstić 2011) 14 Diseases of the skin (Sun et al. 2023) 16 Diseases of the genitourinary system (Chen et al. 2017; Gronlund et al. 2014; Harlan et al. 2014; Green et al. 2010; Ostro et al. 2010; Basu et al. 2012; Lim et al. 2015) 18 Pregnancy, childbirth or the puerperium (Avalos et al. 2017; Benmarhnia et al. 2015; Basu et al. 2010; Cushing et al. 2022) 19 Certain conditions originating in the perinatal period (Basu et al. 2015, 2018b; Veron et al. 2021; Schifano et al. 2013, 2016; Viccino-Cabrera et al. 2014; Requía et al. 2022; Gronlund et al. 2020; Mohammadi et al. 2019; Porter et al. 1999) 20 Developmental anomalies (Basu et al. 2015; Zutphen et al. 2012; Soim et al. 2018, 2017) 21 Symptoms, signs or clinical findings, not elsewhere classified (Basu et al. 2015; Zutphen et al. 2012) 22 Injury, poisoning or certain other consequences of external causes (Harlan et al. 2014; Green et al. 2010; Ostro et al. 2010; Basu et al. 2012; Hartz et al. 2013; Ng et al. 2014; Sen and Nag 2019; Milsten et al. 2003; Vassil et al. 2020; Milani et al. 2022) 23 External causes of morbidity or mortality (Basu et al. 2018a; Aguglia et al. 2021; Grjibovski et al. 2013) 24 Factors influencing health status or contact with health services (Rammah et al. 2019; Basu et al. 2016) Other (non-categorized in one code) (Lu et al. 2023; Zhang et al. 2022)
DI	Greece, Republic of China (Taiwan)	Temperate	All causes (Lin et al. 2013) 22 Injury, poisoning or certain other consequences of external causes (Pantavou et al. 2011)

Table 1 (continued)

Index	Country	Climate	Health outcome
ET	Brazil, Greece, Iran, People's Republic of China, Repub- lic of China (Taiwan), Russia, Spain, Sri Lanka	Arid, Con- tinental, Temperate, Tropical	All causes (Lin et al. 2013; Leung et al. 2008; Aboubakri et al. 2020) 11 Diseases of the circulatory system (Psistaki et al. 2023; Santurtun et al. 2020; Mohammadi and Karimi 2018; Goncalves et al. 2007; Emelina et al. 2015; Costa et al. 2021) 12 Diseases of the respiratory system (Nick et al. 2022; Wenfang et al. 2020; de Sousa Zanotti Stagliorio Coêlho et al. 2010) 16 Diseases of the genitourinary system (Gunasekara et al. 2023)
HI	Bangladesh, Czech Repub- lic, Finland, Germany, India, Israel, Italy, Paki- stan, People's Republic of China, Portu- gal, Republic of China (Tai- wan), Repub- lic of Korea, Sri Lanka, United States, Vietnam	Arid, Con- tinental, Temperate, Tropical	All causes (Lin et al. 2012; Yip et al. 2008; Chien et al. 2016; Perron et al. 2005; Vaidyanathan et al. 2019; Matte et al. 2016; Spangler et al. 2023a; Liu et al. 2018b; Zottarelli et al. 2021; Rathi and Sodani 2021; Kivimäki et al. 2050; Khatana et al. 2022a; Skarha et al. 2022; Monteiro et al. 2013; Weinberger et al. 2021; Burkart et al. 2011; Wellenius et al. 2017; Rosenthal et al. 2014; Sung et al. 2013; Metzger et al. 2010; Levy et al. 2015; Desai et al. 2015; Fritze 2020; Rathi et al. 2017, 2021) 01 Certain infectious or parasitic diseases (Saddique et al. 2021; Williams et al. 2020) 02 Neoplasms (Kivimäki et al. 2050; Williams et al. 2020) 05 Endocrine, nutritional or metabolic diseases (Vaidyanathan et al. 2019; Liu et al. 2018b; Weinberger et al. 2021; Williams et al. 2020; Boeke et al. 2010) 06 Mental, behavioural or neurodevelopmental disorders (Williams et al. 2020; Deng et al. 2022; Gao et al. 2020) 08 Diseases of the nervous system (Williams et al. 2020; Hahn et al. 2023) 11 Diseases of the circulatory system (Vaidyanathan et al. 2019; Liu et al. 2018b; Kivimäki et al. 2050; Monteiro et al. 2013; Weinberger et al. 2021; Burkart et al. 2011; Wellenius et al. 2017; Williams et al. 2020; Hahn et al. 2023; Brunetti et al. 2014; Khatana et al. 2022b; Kysely and Huth 2004; Huang et al. 2021; Yin and Wang 2018) 12 Diseases of the respiratory system (Vaidyanathan et al. 2019; Liu et al. 2018b; Monteiro et al. 2013; Williams et al. 2020; Hahn et al. 2023) 16 Diseases of the genitourinary system (Gunasekara et al. 2023; Vaidyanathan et al. 2019; Liu et al. 2018b; Weinberger et al. 2021; Hamilton et al. 2021; Ross et al. 2018; Chu et al. 2022) 18 Pregnancy, childbirth or the puerperium (Tam et al. 2008) 19 Certain conditions originating in the perinatal period (Jiao et al. 2023; Son et al. 2019; Carlson et al. 2021) 20 Developmental anomalies (Williams et al. 2020) 21 Symptoms, signs or clinical findings, not elsewhere classified (Kranc et al. 2021) 22 Injury, poisoning or certain other consequences of external causes (Sen and Nag 2019; Weinberger et al. 2021; Wellenius et al. 2017; Hahn et al. 2023; Bandala et al. 2019; Shire et al. 2020; Saha et al. 2015; Lewandowski et al. 2022; Na et al. 2013; DeMartini et al. 2014; Grundstein et al. 2012; Bethancourt et al. 2021; Bai et al. 2014; Erickson et al. 2019; Hartz et al. 2012; Moore et al. 2017) 23 External causes of morbidity or mortality (Kivimäki et al. 2050; Williams et al. 2020; Cloud et al. 2023) 24 Factors influencing health status or contact with health services (Savitz and Hu 2021) Other (non-categorized in one code) (Spangler et al. 2023a; Kivimäki et al. 2050; Weinberger et al. 2021; Williams et al. 2020; Gao et al. 2020)
HL	Greece	Temperate	22 Injury, poisoning or certain other consequences of external causes (Pantavou et al. 2011; Theoharatos et al. 2010)

Table 1 (continued)

Index	Country	Climate	Health outcome
HU	Canada, India, Italy, People's Republic of China, Republic of China (Taiwan), Russia, Sri Lanka, United States	Continental Temperate Tropical	All causes (Lin et al. 2012; Isaksen et al. 2016, 2015; DeVine et al. 2017; Rainham and Smoyer-Tomic 2003; Conti et al. 2007, 2005; Kegel et al. 2021; Calkins et al. 2016; Ho et al. 2017; Arnold et al. 2022) 01 Certain infectious or parasitic diseases (Zhang et al. 2017) 04 Diseases of the immune system (Calkins et al. 2016) 05 Endocrine, nutritional or metabolic diseases (Isaksen et al. 2016, 2015; Calkins et al. 2016; Arnold et al. 2022) 06 Mental, behavioural or neurodevelopmental disorders (Isaksen et al. 2016, 2015; Calkins et al. 2016; Arnold et al. 2022; Zhou et al. 2023) 08 Diseases of the nervous system (Shartova et al. 2018; Isaksen et al. 2016, 2015; Calkins et al. 2016; Arnold et al. 2022) 09 Diseases of the visual system (Zhao et al. 2023) 11 Diseases of the circulatory system (Shartova et al. 2018; Isaksen et al. 2016, 2015; Calkins et al. 2016; Arnold et al. 2022) 12 Diseases of the respiratory system (Isaksen et al. 2016, 2015; Calkins et al. 2016; Arnold et al. 2022; Pan et al. 2019) 16 Diseases of the genitourinary system (Gunasekara et al. 2023; Isaksen et al. 2016, 2015; Arnold et al. 2022) 22 Injury, poisoning or certain other consequences of external causes (Sen and Nag 2019; Isaksen et al. 2016, 2015; Calkins et al. 2016; Bassil et al. 2011) 23 External causes of morbidity or mortality (Isaksen et al. 2016) Other (non-categorized in one code) (Calkins et al. 2016; Mastrangelo et al. 2007; Infusino et al. 2021)
PET	Austria, Bangladesh, Brazil, Croatia, Czech Republic, Germany, Greece, Iran, People's Republic of China, Portugal, Republic of Cyprus, Republic of Korea, Russia, Sweden, Turkey, United States	Arid, Continental, Temperate, Tropical	All causes (Aboubakri et al. 2020; Burkart et al. 2011; Thach et al. 2015; Schroeder et al. 2023; Thorsson et al. 2021; Laschewski and Jendritzky 2002; Pantavou et al. 2021; Muthers et al. 2010a, 2010b; Urban et al. 2019; Matzarakis et al. 2011; Nastos and Matzarakis 2012; Dastoorpoor et al. 2022a; Zaninovic and Matzarakis 2014; Zemtsov et al. 2020; Sharafkhani et al. 2018) 02 Neoplasms (Shiue et al. 2015) 08 Diseases of the nervous system (Shartova et al. 2018; Urban and Kyselý 2014; Dastoorpoor et al. 2022a, 2022b; Ferrari et al. 2015; Lim et al. 2017) 11 Diseases of the circulatory system (Shartova et al. 2018; Urban and Kyselý 2014; Mohammadi and Karimi 2018; Costa et al. 2021; Burkart et al. 2011; Thach et al. 2015; Dastoorpoor et al. 2022a, 2022b; Sharafkhani et al. 2018; Shiue et al. 2016a, 2016b, 2016c; Vasconcelos et al. 2013; Roshan et al. 2022a; Roshan et al. 2022b; Caglak 2022) 12 Diseases of the respiratory system (Thach et al. 2015; Dastoorpoor et al. 2022a; Sharafkhani et al. 2018; Caglak and Matzarakis 2023; Nastos and Matzarakis 2006; Borsi et al. 2021) 11 and 12 Diseases of the circulatory and Diseases of the respiratory system (Muthers et al. 2010a; Silva and Ribeiro 2012) 18 Pregnancy, childbirth or the puerperium (Dastoorpoor et al. 2021) 19 Certain conditions originating in the perinatal period (Dastoorpoor et al. 2021) 21 Symptoms, signs or clinical findings, not elsewhere classified (Thorsson et al. 2021; Nastos and Matzarakis 2008) 22 Injury, poisoning or certain other consequences of external causes (Hartz et al. 2013; Pantavou et al. 2020) 24 Factors influencing health status or contact with health services (Dastoorpoor et al. 2021) Other (non-categorized in one code) (Schroeder et al. 2023)
PMV	Brazil, Greece, Iran	Arid, Temperate	All causes (Aboubakri et al. 2020) 11 Diseases of the circulatory system (Mohammadi and Karimi 2018; Costa et al. 2021; Roshan et al. 2022b) 11 and 12 Diseases of the circulatory and Diseases of the respiratory system (Pantavou et al. 2008) 12 Diseases of the respiratory system (Nastos and Matzarakis 2006)
PT	Austria, Germany, Iran, People's Republic of China	Arid, Continental, Temperate	11 Diseases of the circulatory system (Roshan et al. 2022b; Kienbacher et al. 2021; Koppe et al. 2011; Schlegel et al. 2020) 11 and 12 Diseases of the circulatory and Diseases of the respiratory system (Leung et al. 2021)
RSI	Argentina	Temperate	All causes (Garin and Bejaran 2003)
SET	Brazil, Greece, Iran	Arid, Temperate	All causes (Aboubakri et al. 2020) 11 Diseases of the circulatory system (Costa et al. 2021) 12 Diseases of the respiratory system (Nastos and Matzarakis 2006)
Tek	Iran	Temperate	11 Diseases of the circulatory system (Mohammadi and Karimi 2018)
TS	Greece	Temperate	22 Injury, poisoning or certain other consequences of external causes (Pantavou et al. 2011)

Table 1 (continued)

Index	Country	Climate	Health outcome
UTCI	Australia, Bangladesh, Brazil, Czech Republic, Germany, Ghana, Greece, India, Iran, Italy, People's Republic of China, Poland, Portugal, Republic of Cyprus, Spain, Sweden, The Cambodia, United States	Arid, Continental, Temperate, Tropical	All causes (Morabito et al. 2014; Aboubakri et al. 2020; Spangler et al. 2023a; Burkart et al. 2011, 2013, 2016, 2014; Thorsson et al. 2021; Pantavou et al. 2021; Urban et al. 2019; Nastos and Matzarakis 2012; Błażejczyk et al. 2018; Błażejczyk et al. 2022; Chau et al. 2022; Urban et al. 2021; Ghada et al. 2021a, 2021b; Romaszko et al. 2017; Lokys et al. 2018)
			01 Certain infectious or parasitic diseases (Burkart et al. 2014)
			05 Endocrine, nutritional or metabolic diseases (Romaszko et al. 2022a)
			08 Diseases of the nervous system (Urban and Kyselý 2014; Jingsi et al. 2023; Ma et al. 2018)
			11 Diseases of the circulatory system (Urban and Kyselý 2014; Santurtun et al. 2020; Burkart et al. 2011, 2014; Jingsi et al. 2023; Skutecki et al. 2019)
			11 and 12 Diseases of the circulatory and Diseases of the respiratory system (Kuchcik 2021)
			12 Diseases of the respiratory system (Romaszko et al. 2019; Lindner-Cendrowska and Bröde 2021; Romaszko-Wojtowicz et al. 2020; Kruger and Nedel 2023; Fallah Ghalhari et al. 2016)
			19 Certain conditions originating in the perinatal period (Nyadanu et al. 2022a; Nyadanu et al. 2023a)
			21 Symptoms, signs or clinical findings, not elsewhere classified (Thorsson et al. 2021; Cymes et al. 2021)
			22 Injury, poisoning or certain other consequences of external causes (Pantavou et al. 2016; Hartz et al. 2013; Sen and Nag 2019; Krzyzewska et al. 2017)
			23 External causes of morbidity or mortality (Ghada et al. 2021b)
			24 Factors influencing health status or contact with health services (Nyadanu et al. 2023b, 2022b)
			Other (non-categorized in one code) (Spangler et al. 2023a; Khodadadi et al. 2022; Bonell et al. 2022)
WBGT	Australia, Czech Republic, India, Qatar, Republic of China (Taiwan), Sri Lanka, Sweden, Tanzania, Thailand, The Cambodia, United States	Arid, Continental, Temperate, Tropical	All causes (Lin et al. 2012; Spangler et al. 2023a; Schroeder et al. 2023; Thorsson et al. 2021; Urban et al. 2019)
			05 Endocrine, nutritional or metabolic diseases (Sombatsawat et al. 2023)
			11 Diseases of the circulatory system (Pradhan et al. 2019; Meshi et al. 2018)
			12 Diseases of the respiratory system (Sombatsawat et al. 2023)
			16 Diseases of the genitourinary system (Gunasekara et al. 2023)
			21 Symptoms, signs or clinical findings, not elsewhere classified (Thorsson et al. 2021; Sombatsawat et al. 2023; Meshi et al. 2018)
			22 Injury, poisoning or certain other consequences of external causes (Sen and Nag 2019; Vassil et al. 2020; Lewandowski et al. 2022; Grundstein et al. 2012; Erickson et al. 2019; Sombatsawat et al. 2023; Meshi et al. 2018; Lewandowski and Shaman 2022; Morris et al. 2019; Wallace et al. 2005)
			Other (non-categorized in one code) (Spangler et al. 2023a; Schroeder et al. 2023; Bonell et al. 2022)
WCT	Brazil, Germany, Ireland, Norway, People's Republic of China, Republic of Korea, Russia, Sweden, United Kingdom	Continental, Temperate	All causes (Fritze 2022; Carder et al. 2005; Kim et al. 2018)
			01 Certain infectious or parasitic diseases (Oh et al. 2021; Kim et al. 2020; Lim et al. 2021)
			06 Mental, behavioural or neurodevelopmental disorders (Gao et al. 2020)
			08 Diseases of the nervous system (Gill et al. 1988; Kim et al. 2016; Eng and Mercer 2000)
			11 Diseases of the circulatory system (Emelina et al. 2015; Carder et al. 2005; Eng and Mercer 2000; Ohlson et al. 1991)
			12 Diseases of the respiratory system (Nick et al. 2022)
			22 Injury, poisoning or certain other consequences of external causes (Kim et al. 2018)
			Other (non-categorized in one code) (Gao et al. 2020)

Abbreviations: *ASV* Actual Sensation Vote; *AT* Apparent Temperature; *DI* Discomfort Index; *ET* Effective Temperature; *HI* Heat Index; *HL* Heat Load; *HU* Humidex; *PET* Physiologically Equivalent Temperature; *PMV* Predicted Mean Vote; *PT* Perceived Temperature; *RSI* Relative Strain Index; *SET* Standard Effective Temperature; *Tek* Equivalent Temperature; *TS* Thermal Sensation; *UTCI* Universal Thermal Climate Index; *WBGT* Wet-Bulb Globe Temperature; *WCT* Wind Chill Temperature

examined extreme thermal conditions, such as heatwaves or cold spells.

Thermal indices

A total of seventeen indices were used in the publications included in this systematic review (Fig. 2). Of these, 32 publications (10.3%) used more than one index. The most frequently used index was AT, which appeared in 631 associations (55.2%), followed by HI in 128 (11.2%), PET in 86 (7.5%), and UTCI in 76 associations publications (6.7%) (Online Resource 1—Figure S5).

The indices were estimated using diverse meteorological data sources and type of indices' measures. In most associations, the indices were estimated using weather stations within the network of official meteorological services or institutions ($n = 552$, 48.3%). In several associations, the calculation of the indices relied on data derived from airport stations ($n = 221$, 19.3%) and some on a combination of surface and airport stations ($n = 141$, 12.3%). In other associations the indices were derived from gridded meteorological data ($n = 121$, 10.6%), in-situ measurements, data found on websites (i.e., www.weather.org, www.accuweather.com), satellite data, and kriging interpolation ($n = 63$, 5.5%). The

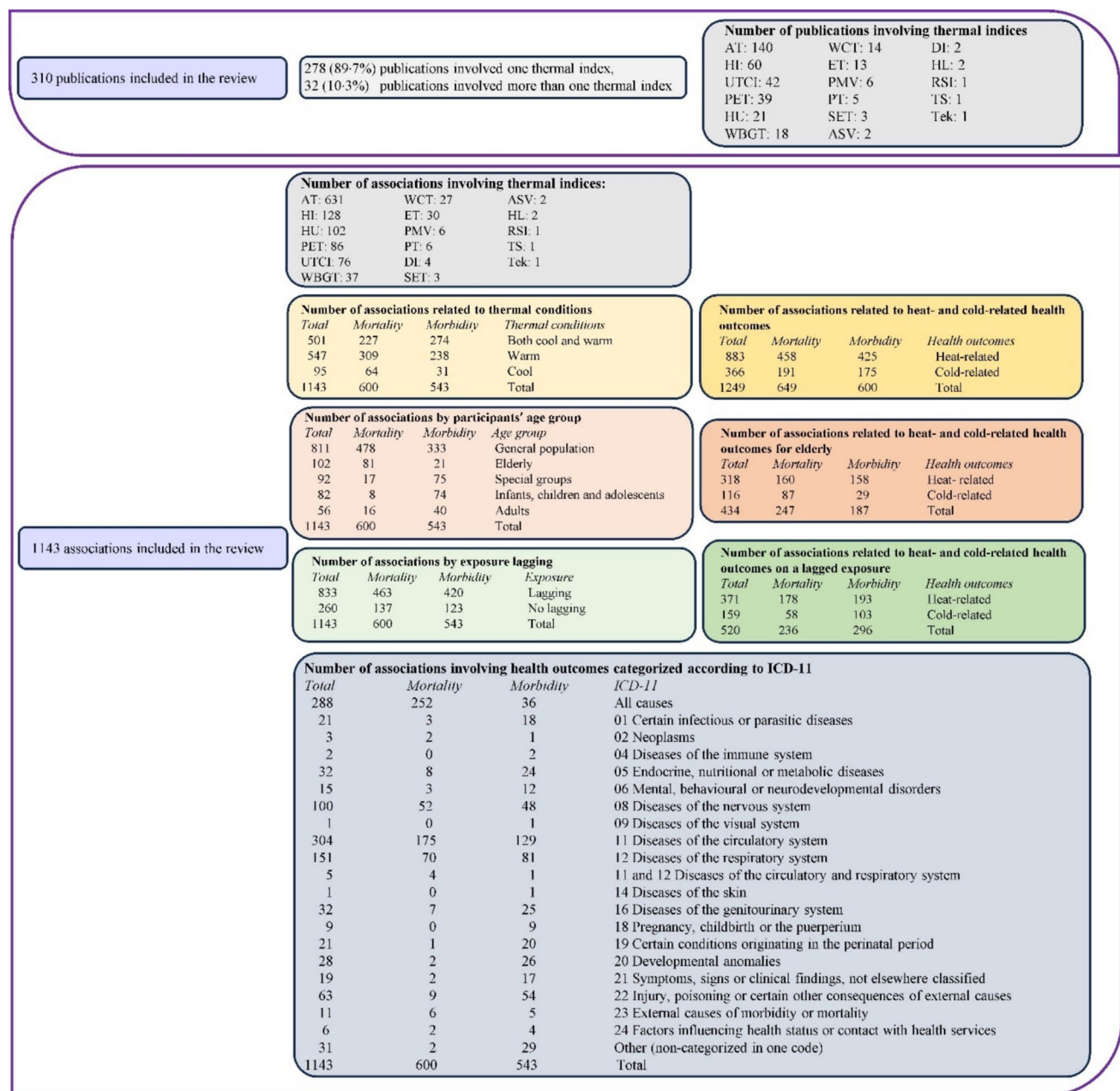


Fig. 2 Distribution of publications and associations examining the association between thermal indices and health outcomes. Abbreviations: ASV, Actual Sensation Vote; AT, Apparent Temperature; DI, Discomfort Index; ET, Effective Temperature; HI, Heat Index; HL, Heat Load; HU, Humidex; ICD-11, International Statistical Classification of Diseases and Related Health Problems 11 th Revision; PET,

Physiologically Equivalent Temperature; PMV, Predicted Mean Vote; PT, Perceived Temperature; RSI, Relative Strain Index; SET, Standard Effective Temperature; Tek, Equivalent Temperature; TS, Thermal Sensation; UTCI, Universal Thermal Climate Index WBGT, Wet-Bulb Globe Temperature; WCT, Wind Chill Temperature

diversity of indices calculation was also evident in the type of indices' measure. Most associations ($n = 607$, 53.1%) between indices and health outcomes were estimated using indices' daily, weekly, and monthly measures of central tendency such as the mean or median value of the indices. Associations based on extreme values, such as maximum or minimum value, were included in 428 (37.5%) associations.

Additionally, 50 associations (4.4%) used both measures of central tendency and extreme values.

Health outcomes

Nearly half of the associations focused on mortality ($n = 600$, 52.5%), while the other half examined morbidity (n

=543, 47.5%; p -value =0.0914; Fig. 2). The associations mainly concerned the general population (n =811, 71%; Fig. 2). Secondly, mortality was studied specifically among the elderly (n =81, 13.5% of 600), while morbidity was examined particularly among special population groups (n =75, 13.9% of 543) including outdoor workers (n =30, 5.5% of 543), women (n =23, 4.2% of 543), and athletes (n =15, 2.8% of 543) as well as among infants, children and adolescents (n =74, 13.6% of 543). Nevertheless, subgroup analysis for the elderly populations was often provided in the studies.

Mortality data were primarily retrieved from national statistical services (n =367, 61.2% of 600), health centers including centers for catastrophic injuries or for disease control and prevention (n =93, 15.5% of 600), and hospitals (n =75, 12.5% of 600). Morbidity data were obtained from hospitals based on hospital admissions (189, 34.8% of 543) and emergency department visits (n =115, 21.2% of 543), as well as emergency calls to services such as ambulance (n =69, 12.7% of 543).

Eighteen categories of specific-cause mortality or morbidity were examined according to the ICD-11 (Fig. 2). The most frequently examined associations were for diseases of the circulatory system (n =304, 26.6%), followed by all-cause morbidity or mortality (n =288, 25.2%), diseases of the respiratory system (n =151, 13.2%), and diseases of the nervous system (n =100, 8.8%). Among circulatory system diseases, cardiovascular diseases accounted for the majority (n =164, 53.9% of 304), with coronary heart disease comprising a significant portion (n =82, 27.6% of 304). For respiratory system diseases, nearly all cases were classified as overall respiratory diseases (n =150, 99.3% of 151), while cerebrovascular diseases dominated the nervous system category (n =84, 84% of 100).

The high percentage of associations examining all-cause health outcomes is largely due to those focusing on mortality which primarily concentrated on all-cause health outcomes. The associations focusing on morbidity examined a broader range of ICD-11 categories than those focusing on mortality (18 versus 14). Among mortality associations, 42% (of 600, n = 252) addressed all-cause mortality, with additional focus on diseases of the circulatory system (n =175, 29.2% of 600) and respiratory system (n =70, 11.7 of 600%). Conversely, associations focusing on morbidity addressed most frequently diseases of the circulatory (n =129, 23.8% of 543) and respiratory system (n =81, 14.9% of 543) (Fig. 2).

Methods of statistical analysis used in primary studies

The publications included in this systematic review examined the association of thermal indices with health-related

outcomes using various statistical methods. Poisson regression or Poisson-family models were used in 508 associations (44.4%). Logistic regression was applied in 238 associations (20.8%), while negative binomial regression was used in 12 associations (1.1%). Linear regression was employed in 50 associations (4.4%). Correlations and tests for comparison of means were conducted in 82 associations (7.2%). Other statistical methods, such as Cox regression models, partial least squares regression, cubic regression, and survival analysis, were used in 222 associations (19.4%). In some cases, the association of thermal indices with health-related outcomes was presented descriptively in Figs. (29 studies, 2.5%).

Effect estimates such as odds ratios, hazard ratios, incidence rate ratios, and relative risk were provided in 53.2% (n =608) of the associations. Nearly 62% of the associations were adjusted for confounding variables including day of week and holidays, air quality, and participants' sociodemographic characteristics. Exposure lagging was examined in most of the associations (n =883, 77.3%), both for mortality (n =465, 77.2%) and morbidity (n =420, 77.3%); however, the health outcomes of these associations were reported in 371 of them.

Outcome of associations

Among the 883 associations focusing on heat-related health outcomes (Fig. 3a), 57.8% (n =510) indicated an increased risk of adverse health outcomes as thermal indices increased, while 39.3% (n =347) were non-significant. The increased risk was more pronounced for mortality (71.6% of 458, n = 328) than for morbidity (42.8% of 425, n = 182). This difference was particularly striking for circulatory system diseases, where 77% (n =107 of 139) of mortality-related analyses showed increased risk, compared to only 28.9% (n =22 of 85) for morbidity (p -value <0.001). A similar pattern was observed for respiratory system diseases, where an increased risk was reported in 55.1% (n =27 of 49) for mortality-focused analysis versus 23.4% (n =15 of 64) for morbidity (p -value <0.001). However, the trend was reversed for all-cause morbidity, which had a higher percentage than mortality. In this case, 86.7% (n =26 of 30) of morbidity-related analyses showed an increased risk, compared to 79.7% (n =157 of 198) for mortality (p -value <0.001).

A similar pattern was found for lagged exposure and elderly populations. Among the 371 associations with lagged exposure outcomes (Fig. 3b), 47.7% (n =177 of 371) suggested an increased risk of adverse health outcomes as indices increased and 50.4% (n =187 of 371) were non-significant. Mortality showed a higher risk (59%, n =105 of 178) than morbidity (37.3%, n =72 of 193; p -value <0.001), particularly for circulatory system diseases

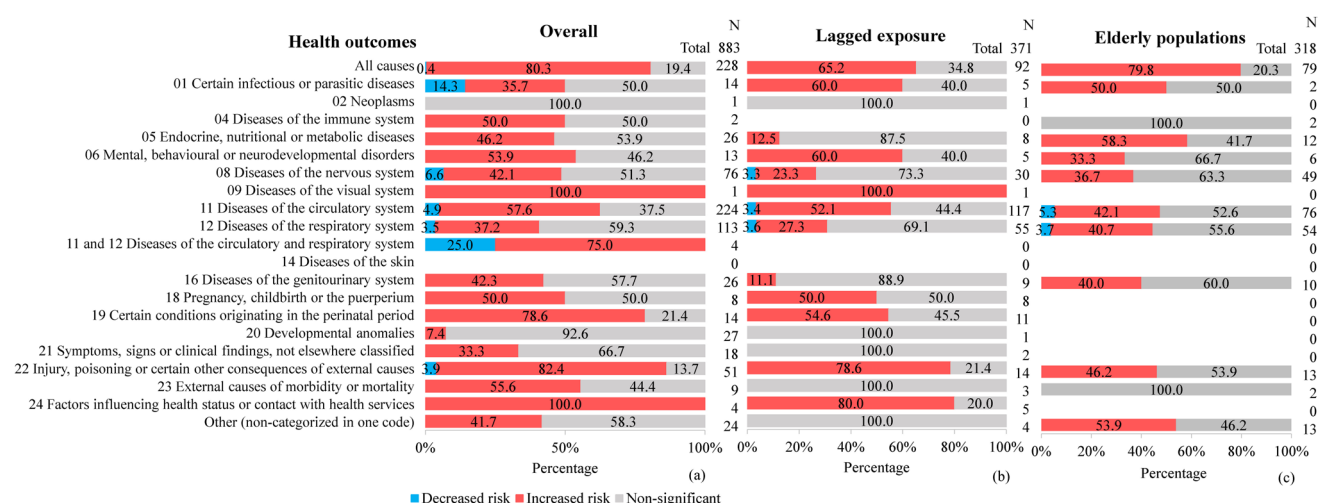


Fig. 3 Percentage of associations for heat-related health outcomes, categorized by ICD-11 (11th revision of the International Classification of Diseases). Results are shown for (a) overall population, (b) lagged exposure effects, and (c) elderly populations

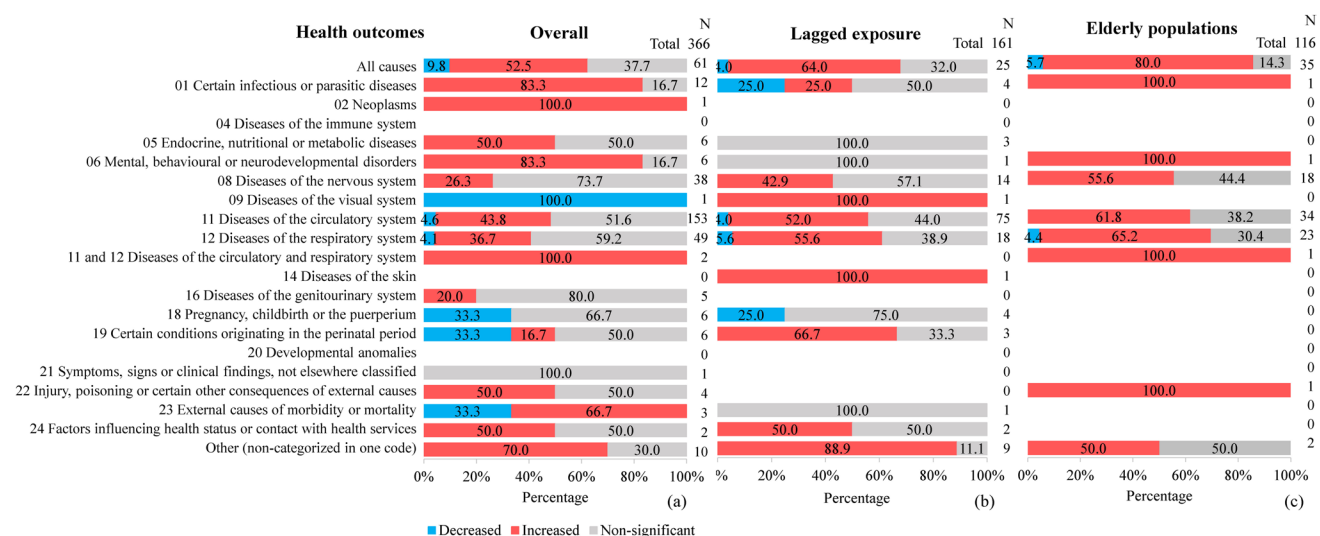


Fig. 4 Percentage of associations for cold-related health outcomes, categorized by ICD-11 (11th revision of the International Classification of Diseases). Results are shown for (a) overall population, (b) lagged exposure effects, and (c) elderly populations

(mortality 70.2%, $n = 40$ of 57 versus morbidity 35%, $n = 21$ of 60; p -value = 0.001). Of the 318 associations related to elderly outcomes (Fig. 3c), 50.9% ($n = 162$ of 318) showed an increased risk of adverse health outcomes as indices increased while 47.2% ($n = 150$ of 318) were non-significant. Again, mortality exceeded morbidity (71.9%, $n = 115$ of 160 versus 29.8%, $n = 47$ of 158; p -value < 0.001), especially for diseases of the circulatory system (mortality 72.2%, $n = 26$ of 36 versus morbidity 15%, $n = 6$ of 40; p -value < 0.001) and for diseases of the respiratory system (mortality 63.2%, $n = 12$ of 19 versus morbidity 28.6%, $n = 10$ of 35; p -value = 0.0135).

For cold-related health risks ($n = 366$; Fig. 4a), 44.1% ($n = 162$ of 366) associations suggested an increased risk of adverse health outcomes as indices decreased, while 49.9%

($n = 183$ of 366) were non-significant. The risk increase was similar between mortality (46.1%, $n = 88$ of 191) and morbidity (42.3%, $n = 74$ of 175). Considering the lagged exposure, among 161 associations (Fig. 4b), 52.8% ($n = 85$ of 161) indicated an increased risk of adverse health outcomes as indices decreased and 42.1% ($n = 69$ of 161) were non-significant. Mortality (77.6%, $n = 45$ of 58) was notably higher than morbidity (38.8%, $n = 40$ of 103; p -value < 0.001), with circulatory system diseases showing the strongest effect (mortality 87.5%, $n = 28$ of 32; morbidity 25.6%, $n = 11$; p -value = 0.001). Of the 116 elderly-related associations (Fig. 4c), 68.1% ($n = 79$ of 116) suggested increased risk as indices decreased, with 29.3% ($n = 34$ of 116) being non-significant. Mortality and morbidity percentages of associations suggesting an increased risk were

statistically similar (mortality 72.4%, $n = 63$ of 87; morbidity 55.2%, $n = 16$ of 29; $p\text{-value} = 0.0852$).

Quality assessment

The methodological quality of the 310 publications included in our systematic review, as assessed using the NIH Quality Assessment Tool, varied widely (Online Resource 2 – Table S2). The median score was 12, with an interquartile range of 11 to 13. Common limitations included the lack of sample size justification, power analysis, or of reporting variance and effect estimates ($n = 241$, 77.7%), as well as the failure to measure and statistically adjust for key potential confounding variables that could influence the relationship between exposure and outcome ($n = 123$, 39.7%).

Discussion

This systematic review, the first of its kind, summarizes the evidence on the relationship between thermal indices and health outcomes. It provides a structured overview of how different thermal indices have been used in health research, identifies gaps in the literature, and highlights methodological challenges. The findings demonstrate a growing scientific interest over time in using thermal indices to quantify the effects of thermal environments on human health. However, the distribution of research across continents and climate zones is uneven. Studies from the United States and temperate climates dominate the literature, while there is relatively less research in tropical regions, despite the high population density in both tropical and temperate zones (Klinger and Ryan 2022).

Most of the studies included in this systematic review focused on heat-related health risks, likely driven by concerns over climate change and rising global temperatures. However, there is some evidence that cold temperatures are linked to higher mortality rates compared to heat. For instance, Gasparrini et al. (Gasparrini et al. 2015) and Chigozie et al. (Chigozie et al. 2022) found that cold-related mortality, especially among older adults and those with cardiovascular conditions, surpasses the mortality associated with heat. The multi-country study by Gasparrini et al. (Gasparrini et al. 2015) further highlighted that most temperature-related deaths occur during moderately cold days, with a particularly strong trend observed in Mediterranean countries.

In terms of the indices used, this systematic review found that the AT is the most frequently employed index, in contrast to earlier reviews that documented the widespread use of the thermo-physiological indices PET, Predicted Mean Vote, UTCI, and Standard Effective Temperature for

assessing outdoor thermal perception (Potchter et al. 2018). This discrepancy could be explained by the high number of studies conducted in the United States (where AT and HI are commonly used by the National Weather Service), as well as the simplicity of their calculation. Nonetheless, despite being more recent, the thermo-physiological indices PET and UTCI were also frequently employed, following AT and HI in terms of frequency of use. PET and UTCI are considered more suitable for human biometeorological evaluations as they account for the energy exchange between the environment and the human body (Matzarakis 2021). Notably, UTCI has been recently incorporated into forecasting procedures at several weather institutes and at the European Centre for Medium-Range Forecasts (Napoli et al. 2021).

This systematic review also found that both mortality and morbidity were equally represented in the associations examined. The most examined outcomes were all-cause morbidity or mortality and all-cause circulatory and respiratory diseases, followed by cerebrovascular diseases and coronary heart diseases. However, other health conditions were underrepresented. Additionally, there was a notable lack of research on thermal indices and vector-borne diseases, which are expected to spread more due to climate change. Most studies indicated an increased risk of heat-related health outcomes as indices rose in warm thermal conditions or fell in cold ones, although the patterns for mortality and morbidity varied. Mortality risk was significantly higher for circulatory and respiratory diseases while morbidity showed a higher percentage for all-cause outcomes.

There was significant heterogeneity in methods to analyze the association between thermal indices and health outcomes. Different metric measures, such as mean, maximum, or minimum values of the indices, raise concerns about potential inconsistencies in calculating effect sizes. While some suggest that these variations exhibit similar predictive abilities, allowing for the combination of studies with different metrics (Bhaskaran et al. 2009), other studies indicate that maximum and mean values are associated with higher relative risks of morbidity and mortality compared to minimum values of the same indices (Spangler et al. 2023b). Furthermore, extreme thermal conditions seem to have a greater impact on health outcomes compared to non-extreme conditions (Heo and Bell 2019). While daily data are typically used, some studies have suggested that weekly data can reasonably estimate short-term exposure–response relationships, while bi-weekly or monthly data are more suited for long-term exposure assessment (Ebi 2024; Ballester et al. 2024).

Many studies employed inadequate or overly simplistic statistical approaches, often failing to adjust for confounders. Additionally, frequently statistically significant results and effect sizes were reported, while non-significant

findings were often omitted. In some cases, the lag period of the effect was extended until statistical significance was achieved. This selective reporting likely introduces bias and compromises the validity of any meta-analysis conducted on the available data.

This systematic review represents the most comprehensive review to date on the associations of thermal indices with population health. It provides insights that support the use of thermal indices as a more integrated approach to accurately estimating the thermal environment for heat-related prevention recommendations and guidance, both at an individual level and for public health initiatives. However, this study has certain limitations. The search query may not have included all possible search terms for existing thermal indices in the literature. The selected terms focused on indices commonly used in biometeorological studies and weather services. Nonetheless, given the broad scope of our search-incorporating general thermal and health-related terms, it likely captured studies relevant to these indices despite their omission as specific search terms. Significant differences in terms of thermal indices, health outcomes, study designs, or inconsistent and incomplete reporting made it inappropriate to quantitatively synthesize the data in a meta-analysis. This highlights the need for standardization in methodology and reporting. Key recommendations that would enhance comparisons of results across different regions, climates, and studies include:

- Use of standardized thermal indices: thermal indices such as UTCI and PET apply across all climates and thermal conditions (i.e., warm, cool).
- Preference for thermo-physiological indices: thermo-physiological indices are better suited for human biometeorological evaluations, as they account for the complex interactions between the human body and the environment (Matzarakis 2024). These indices should be prioritized for studies examining the effects of thermal environments on human health.
- Robust statistical methods: it is essential to use advanced and robust statistical methods that account for confounding factors and provide reliable effect sizes. These methods include multi-variable regression models (e.g., Poisson, negative binomial), as well as time-series analysis techniques.
- Systematic and detailed reporting of sample size and characteristics: reporting sample sizes and participant characteristics (e.g., age, gender, health status) allows for more precise comparisons across studies.
- Standardized reporting of health outcomes: health outcomes should be systematically categorized and reported using internationally recognized classifications (e.g., ICD codes); furthermore, the methods used for measuring health outcomes (e.g., hospital admissions, mortality records) should be reported.
- Comprehensive presentation of results: effect sizes should be systematically reported for all associations, including non-significant results, and standardized metrics, such as mean, median, maximum and minimum values of thermal indices, should be consistently used for comparisons. This approach can enhance the accuracy of findings and reduce the risk of selective reporting bias.

Conclusions

Thermal indices, which consider multiple meteorological factors, offer a valuable tool for public health planning and are especially relevant in the context of climate change. These indices are well-established methods for assessing thermal environment and its effects on human health, and can serve as effective operational tools for developing public health protection policies. Summarizing the existing evidence on thermal indices is expected to raise awareness among public health professionals and policymakers, promoting their wider application in public health initiatives.

This systematic review reveals significant associations between thermal indices and health outcomes, highlighting the broad and multidimensional impact of thermal environment on human health. However, the diversity in methodologies and reporting across the literature complicates direct comparisons and limits the ability to synthesize data effectively. This problem emphasizes the need for standardization in future research, particularly in how thermal indices, health outcomes, and their associations are measured and reported. Moreover, expanding the range of health outcomes studied, especially across different climates, is essential in order to fully understand the relationship between thermal stress and health. This broader approach will help establish associations and provide a more comprehensive picture of how climate impacts health across various geographic regions.

As climate change continues, integrated approaches that monitor the relationship between thermal conditions and health outcomes, including the use of thermal indices, are essential for developing, implementing, and evaluating effective health policies.

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Data availability Most of the data and the list of all meta-analyses not selected for data extraction are provided in the supplemental material.

Declarations

Competing interest All authors declare no competing interests.

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References

- Aoubakri O, Khanjani N, Jahani Y, Bakhtiari B (2020) Thermal comfort and mortality in a dry region of Iran, Kerman; a 12-year time series analysis. *Theor Appl Climatol* 139:403–413
- Aguglia A, Giacomini G, Montagna E et al (2021) Meteorological variables and suicidal behavior: air pollution and apparent temperature are associated with high-lethality suicide attempts and male gender. *Front Psychiatry* 12. <https://doi.org/10.3389/fpsy.2021.653390>
- Alessandrini E, Zauli Sajani S, Scotto F, Miglio R, Marchesi S, Lauriola P (2011) Emergency ambulance dispatches and apparent temperature: a time series analysis in Emilia-Romagna. *Italy Environ Res* 111:1192–1200
- Almeida SP, Casimiro E, Calheiros J (2010) Effects of apparent temperature on daily mortality in Lisbon and Oporto. *Portugal Environ Health* 9:12
- Analitis A, Katsouyanni K, Biggeri A et al (2008) Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. *Am J Epidemiol* 168:1397–1408
- Analitis A, De' Donato F, Scortichini M et al (2018) Synergistic Effects of Ambient Temperature and Air Pollution on Health in Europe: Results from the PHASE Project. *Int J Environ Res Public Health* 15. <https://doi.org/10.3390/ijerph15091856>
- Arnell NW, Brown S, Gosling SN et al (2016) Global-scale climate impact functions: the relationship between climate forcing and impact. *Clim Change* 134:475–487
- Arnold L, Scheuerell MD, Isaksen TB (2022) Mortality associated with extreme heat in Washington state: the historical and projected public health burden. *Atmosphere* 13. <https://doi.org/10.3390/atm13091392>
- Astrom DO, Schifano P, Asta F et al (2015) The effect of heat waves on mortality in susceptible groups: a cohort study of a Mediterranean and a northern European City. *Environ Heal* 14:30
- Avalos LA, Chen H, Li D-K, Basu R (2017) The impact of high apparent temperature on spontaneous preterm delivery: a case-cross-over study. *Environ Health* 16:5
- Baccini M, Biggeri A, Accetta G et al (2008) Heat effects on mortality in 15 European cities. *Epidemiology* 19:711–719
- Bai L, Ding G, Gu S et al (2014) The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013. *Environ Res* 132:212–219
- Ballester J, van Daalen KR, Chen ZY et al (2024) The effect of temporal data aggregation to assess the impact of changing temperatures in Europe: an epidemiological modelling study. *Lancet Reg Heal Eur* 36:100779
- Bandala ER, Kebede K, Jonsson N et al (2019) Extreme heat and mortality rates in Las Vegas, Nevada: inter-annual variations and thresholds. *Int J Environ Sci Technol* 16:7175–7186
- Bassil KL, Cole DC, Moineddin R et al (2011) The relationship between temperature and ambulance response calls for heat-related illness in Toronto, Ontario, 2005. *J Epidemiol Community Health* 65:829–831
- Basu R, Malig B (2011) High ambient temperature and mortality in California: exploring the roles of age, disease, and mortality displacement. *Environ Res* 111:1286–1292
- Basu R, Ostro BD (2008) A multicounty analysis identifying the populations vulnerable to mortality associated with high ambient temperature in California. *Am J Epidemiol* 168:632–637
- Basu R, Feng W-Y, Ostro BD (2008) Characterizing temperature and mortality in nine California counties. *Epidemiology* 19:138–145
- Basu R, Malig B, Ostro B (2010) High ambient temperature and the risk of preterm delivery. *Am J Epidemiol* 172:1108–1117
- Basu R, Pearson D, Malig B, Broadwin R, Green R (2012) The effect of high ambient temperature on emergency room visits. *Epidemiology* 23:813–820
- Basu R, Pearson D, Sie L, Broadwin R (2015) A case-crossover study of temperature and infant mortality in California. *Paediatr Perinat Epidemiol* 29:407–415
- Basu R, Sarovar V, Malig BJ (2016) Association between high ambient temperature and risk of stillbirth in California. *Am J Epidemiol* 183:894–901
- Basu R, May WuX, Malig BJ et al (2017) Estimating the associations of apparent temperature and inflammatory, hemostatic, and lipid markers in a cohort of midlife women. *Environ Res* 152:322–327
- Basu R, Gavin L, Pearson D, Ebisu K, Malig B (2018a) Examining the association between apparent temperature and mental health-related emergency room visits in California. *Am J Epidemiol* 187:726–735
- Basu R, Rau R, Pearson D, Malig B (2018b) Temperature and term low birth weight in California. *Am J Epidemiol* 187:2306–2314
- Bell ML, O'Neill MS, Ranjit N, Borja-Aburto VH, Cifuentes LA, Gouveia NC (2008) Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City. *Mexico Int J Epidemiol* 37:796–804
- Benmarhnia T, Auger N, Stanislas V, Lo E, Kaufman JS (2015) The relationship between apparent temperature and daily number of live births in Montreal. *Matern Child Health J* 19:2548–2551
- Bethancourt HJ, Swanson ZS, Nzunza R et al (2021) Hydration in relation to water insecurity, heat index, and lactation status in two small-scale populations in hot-humid and hot-arid environments. *Am J Hum Biol off J Hum Biol Counc* 33:e23447
- Bhaskaran K, Hajat S, Haines A, Herrett E, Wilkinson P, Smeeth L (2009) Effects of ambient temperature on the incidence of myocardial infarction. *Heart* 95:1760–1769

- Błażejczyk A, Błażejczyk K, Baranowski JJ et al (2018) Heat stress mortality and desired adaptation responses of healthcare system in Poland. *Int J Biometeorol* 62:307–318
- Błażejczyk K, Twardoszy R, Walach P et al (2022) Heat strain and mortality effects of prolonged central European heat wave—an example of June 2019 in Poland. *Int J Biometeorol* 66:149–161
- Boeke PS, House HR, Graber MA (2010) Injury incidence and predictors on a multiday recreational bicycle tour: the register's annual great bike ride across Iowa, 2004 to 2008. *Wilderness Environ Med* 21:202–207
- Bonell A, Sonko B, Badjie J et al (2022) Environmental heat stress on maternal physiology and fetal blood flow in pregnant subsistence farmers in The Gambia, west Africa: an observational cohort study. *Lancet Planet Heal* 6:e968–e976
- Borsi SH, Khodadadi N, Khanjani N, Dastoorpoor M (2021) Physiological equivalent temperature (PET) index and respiratory hospital admissions in Ahvaz, southwest of Iran. *Environ Sci Pollut Res Int* 28:51888–51896
- Brunetti ND, Amoroso D, De Gennaro L et al (2014) Hot spot: impact of July 2011 heat wave in southern Italy (Apulia) on cardiovascular disease assessed by emergency medical service and telemedicine support. *Telemed J e-Health off J Am Telemed Assoc* 20:272–281
- Buehler JL, Shrikhande S, Kapwata T et al (2023) The association between apparent temperature and hospital admissions for cardiovascular disease in Limpopo Province, South Africa. *Int J Environ Res Public Health* 20. <https://doi.org/10.3390/ijerph2010116>
- Bureau of Meteorology Australian Government (BOM) (2010) Thermal comfort observations. http://www.bom.gov.au/info/thermal_stress/. Accessed 14 Mar 2025
- Burkart K, Schneider A, Breitner S, Khan MH, Krämer A, Endlicher W (2011) The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. *Environ Pollut* 159:2035–2043
- Burkart K, Canário P, Breitner S et al (2013) Interactive short-term effects of equivalent temperature and air pollution on human mortality in Berlin and Lisbon. *Environ Pollut* 183:54–63
- Burkart K, Breitner S, Schneider A, Khan MMH, Krämer A, Endlicher W (2014) An analysis of heat effects in different subpopulations of Bangladesh. *Int J Biometeorol* 58:227–237
- Burkart K, Meier F, Schneider A et al (2016) Modification of heat-related mortality in an elderly urban population by vegetation (Urban Green) and proximity to water (Urban Blue): evidence from Lisbon. *Portugal Environ Health Perspect* 124:927–934
- Caglak S (2022) Evaluation of the effects of thermal comfort conditions on cardiovascular diseases in Amasya City, Turkey. *J Public Health* <https://doi.org/10.1007/s10389-022-01773-5>
- Caglak S, Matzarakis A (2023) Evaluation of the relationship between thermal comfort conditions and respiratory diseases in Amasya City, Turkey. *Z Gesundh Wiss* 1–11
- Calkins MM, Isaksen TB, Stubbs BA, Yost MG, Fenske RA (2016) Impacts of extreme heat on emergency medical service calls in King County, Washington, 2007–2012: relative risk and time series analyses of basic and advanced life support. *Environ Health* 15:13
- Cao R, Wang Y, Huang J et al (2021) The mortality effect of apparent temperature: A multi-city study in Asia. *Int J Environ Res Public Health* 18. <https://doi.org/10.3390/ijerph18094675>
- Carder M, McNamee R, Beverland I et al (2005) The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland. *Occup Environ Med* 62:702–710
- Carlson JM, Zanutti A, Ettinger de Cuba S et al (2023) Critical windows of susceptibility for the effects of prenatal exposure to heat and heat variability on gestational growth. *Environ Res* 216:114607
- Chau PH, Lau KK-L, Qian XX, Luo H, Woo J (2022) Visits to the accident and emergency department in hot season of a city with subtropical climate: association with heat stress and related meteorological variables. *Int J Biometeorol* 66:1955–71
- Chen T, Sarnat SE, Grundstein AJ, Winquist A, Chang HH (2017) Time-series analysis of heat waves and emergency department visits in Atlanta, 1993 to 2012. *Environ Health Perspect* 125:57009
- Chien L-C, Guo Y, Zhang K (2016) Spatiotemporal analysis of heat and heat wave effects on elderly mortality in Texas, 2006–2011. *Sci Total Environ* 562:845–851
- Chigozie N, Enembe OO, Samuel OD, Isaac E (2022) A systematic review and meta-analysis on the relationships between extreme ambient temperature and all-cause mortality risk: a time series approach. *Int J Environ Clim Chang* 12:3479–3493
- Choi G, Bae H-J, Lim Y-H (2017) Estimation of abnormal temperature effects on elderly mortality in South Korea using the temperature deviation index. *Int J Biometeorol* 61:1291–1298
- Chu L, Phung D, Crowley S, Dubrow R (2022) Relationships between short-term ambient temperature exposure and kidney disease hospitalizations in the warm season in Vietnam: A case-crossover study. *Environ Res* 209:112776
- Chung J-Y, Honda Y, Hong Y-C, Pan X-C, Guo Y-L, Kim H (2009) Ambient temperature and mortality: an international study in four capital cities of East Asia. *Sci Total Environ* 408:390–396
- Cloud D, Williams B, Haardörfer R, Brinkley-Rubinstein L, Cooper H (2023) Extreme heat and suicide watch incidents among incarcerated men. *JAMA Netw Open* 6:e2328380
- Conti S, Meli P, Minelli G et al (2005) Epidemiologic Study of Mortality during summer 2003 in Italy. *Env Res* 98:390–399
- Conti S, Masocco M, Meli P et al (2007) General and specific mortality among the elderly during the 2003 heat wave in Genoa (Italy). *Environ Res* 103:267–274
- Costa IT, Wollmann CA, Gobo JPA, Ikefuti PV, Shooshtarian S, Matzarakis A (2021) Extreme weather conditions and cardiovascular hospitalizations in Southern Brazil. *Sustainability* 13. <https://doi.org/10.3390/su132112194>
- Cushing L, Morello-Frosch R, Hubbard A (2022) Extreme heat and its association with social disparities in the risk of spontaneous preterm birth. *Paediatr Perinat Epidemiol* 36:13–22
- Cymes I, Jalali R, Glińska-Lewczuk K, Dragańska E, Giergiele-wicz-Januszko B, Romaszko J (2021) The association between the biometeorological indicators and emergency interventions due to fainting: A retrospective cohort study. *Sci Total Environ* 770:145376
- D'Ippoliti D, Michelozzi P, Marino C et al (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environ Health* 9:37
- Dastoorpoor M, Khodadadi N, Masoumi K et al (2022a) Physiological equivalent temperature (PET) and non-accidental, cardiovascular and respiratory disease mortality in Ahvaz. *Iran Environ Geochem Health* 44:2767–2782
- Dastoorpoor M, Khodadadi N, Khanjani N, Borsi SH (2022b) Physiological equivalent temperature (PET) index and cardiovascular hospital admissions in Ahvaz, southwest of Iran. *Arch Environ Occup Health* 77:653–661
- Dastoorpoor M, Khanjani N, Khodadadi N (2021) Association between physiological equivalent temperature (PET) with adverse pregnancy outcomes in Ahvaz, southwest of Iran. *BMC Pregnancy Childbirth* 21. <https://doi.org/10.1186/s12884-021-03876-5>
- Davis RE, Markle ES, Windoloski S et al (2020) A comparison of the effect of weather and climate on emergency department visitation in Roanoke and Charlottesville. *Virginia Environ Res* 191:110065
- Davis RE, Novicoff WM (2018) The impact of heat waves on emergency department admissions in Charlottesville, Virginia, U.S.A.

- Int J Environ Res Public Health 15. <https://doi.org/10.3390/ijerph15071436>
- de Freitas CR, Grigorieva EA (2015) A comprehensive catalogue and classification of human thermal climate indices. *Int J Biometeorol* 59:109–120
- de Garin A, Bejaran R (2003) Mortality rate and relative strain index in Buenos Aires city. *Int J Biometeorol* 48:31–36
- de Donato FK, Stafoggia M, Rognoni M et al (2008) Airport and city-centre temperatures in the evaluation of the association between heat and mortality. *Int J Biometeorol* 52:301–10
- de Sousa Zanotti Stagliorio Coêlho M, Luiz Teixeira Gonçalves F, de Dias R, de Oliveira Latorre M (2010) Statistical analysis aiming at predicting respiratory tract disease hospital admissions from environmental variables in the city of São Paulo. *J Environ Public Health* 2010:209270
- DeMartini JK, Casa DJ, Belval LN et al (2014) Environmental conditions and the occurrence of exertional heat illnesses and exertional heat stroke at the falmouth road race. *J Athl Train* 49:478–485
- Deng X, Brotzge J, Tracy M et al (2022) Identifying joint impacts of sun radiation, temperature, humidity, and rain duration on triggering mental disorders using a high-resolution weather monitoring system. *Environ Int* 167:107411
- Desai VK, Wagle S, Rath SK, Patel U, Desai HS, Khatri K (2015) Effect of ambient heat on all-cause mortality in the coastal city of Surat, India. *Curr Sci* 109:1680–1686
- De Vine AC, Vu PT, Yost MG, Seto EYW, Busch Isaksen TM (2017) A geographical analysis of emergency medical service calls and extreme heat in King County, WA, USA (2007–2012). *Int J Environ Res Public Health* 14. <https://doi.org/10.3390/ijerph14080937>
- Di Napoli C, Messeri A, Novák M et al (2021) The universal thermal climate index as an operational forecasting tool of human biometeorological conditions in Europe. In: Krüger EL, (ed). *Applications of the universal thermal climate index UTCI in biometeorology*. Biometeorology (vol 4). Springer
- Ebi KL (2024) Weekly temperature data are sufficient to estimate exposure-response relationships: a boon for health adaptation in low-resource settings. *Lancet Reg Heal Eur* 36:100811
- Emelina SV, Rubinshtein KG, Gur'yanov VV, Perevedentsev YP, Ivanov AV, (2015) Effects of short-term weather changes in Naberezhnye Chelny city on people suffering from ischemic heart disease. *Russ Meteorol Hydrol* 40:838–43
- Eng H, Mercer JB (2000) The relationship between mortality caused by cardiovascular diseases and two climatic factors in densely populated areas in Norway and Ireland. *J Cardiovasc Risk* 7:369–375
- Erickson EA, Engel LS, Christenbury K, Weems L, Schwartz EG, Rusiecki JA (2019) Environmental heat exposure and heat-related symptoms in united states coast guard deepwater horizon disaster responders. *Disaster Med Public Health Prep* 13:561–569
- Fallah Ghalhari G, Mayvaneh F, Ghalhari GF, Mayvaneh F (2016) Effect of air temperature and universal thermal climate index on respiratory diseases mortality in Mashhad. *Iran Arch Iran Med* 19:618–624
- Ferrari J, Shiue I, Seyfang L, Matzarakis A, Lang W (2015) Weather as physiologically equivalent was not associated with ischemic stroke onsets in Vienna, 2004–2010. *Environ Sci Pollut Res Int* 22:8756–8762
- Flouris A, Dinas P, Ioannou L et al (2018) Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Heal* 2:e521–e531
- Fritze T (2020) The effect of heat and cold waves on the mortality of persons with Dementia in Germany. *Sustainability* 12. <https://doi.org/10.3390/su12093664>
- Gao W, Tu R, Li H, Fang Y, Que Q (2020) In the subtropical monsoon climate high-Density City, what features of the neighborhood environment matter most for public health?. *Int J Environ Res Public Health* 17. <https://doi.org/10.3390/ijerph17249566>
- Gao C, Wang Y, Hu Z, Jiao H, Wang L (2022) Study on the Associations between Meteorological Factors and the Incidence of Pulmonary Tuberculosis in Xinjiang, China. *Atmosphere* 13. <https://doi.org/10.3390/atmos13040533>
- Gasparrini A, Guo Y, Hashizume M et al (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 386:369–375
- Ghada W, Estrella N, Pfoerringer D et al (2021a) Effects of weather, air pollution and Oktoberfest on ambulance-transported emergency department admissions in Munich. Germany *Sci Total Env* 755:143772
- Ghada W, Estrella N, Ankerst DP, Menzel A (2021b) Universal thermal climate index associations with mortality, hospital admissions, and road accidents in Bavaria. *PLoS ONE* 16:e0259086
- Ghirardi L, Bisoffi G, Mirandola R, Ricci G, Baccini M (2015) The impact of heat on an emergency department in Italy: attributable visits among children, adults, and the elderly during the warm season. *PLoS ONE* 10:e0141054
- Gill JS, Davies P, Gill SK, Bevers DG (1988) Wind-chill and the seasonal variation of cerebrovascular disease. *J Clin Epidemiol* 41:225–230
- Goncalves FLT, Braun S, Dias PLS et al (2007) Influences of the weather and air pollutants on cardiovascular disease in the metropolitan area of Sao Paulo. *Environ Res* 104:275–281
- Government of Canada (2024) Wind chill and humidex calculators - environment Canada
- Green RS, Basu R, Malig B, Broadwin R, Kim JJ, Ostro B (2010) The effect of temperature on hospital admissions in nine California counties. *Int J Public Health* 55:113–121
- Gribovski AM, Nurgaliyeva N, Kosbayeva A, Menne B (2012a) No association between temperature and deaths from cardiovascular and cerebrovascular diseases during the cold season in Astana, Kazakhstan--the second coldest capital in the world. *Int J Circumpolar Health* 71. <https://doi.org/10.3402/ijch.v71i0.19769>
- Gribovski AM, Nurgaliyeva N, Kosbayeva A, Sharbakov A, Seysembekov T, Menne B (2012b) Effect of high temperatures on daily counts of mortality from diseases of circulatory system in Astana. *Kazakhstan Med* 48:640–646
- Gribovski AM, Kozhakhmetova G, Kosbayeva A, Menne B (2013) Associations between air temperature and daily suicide counts in Astana. *Kazakhstan Med* 49:379–385
- Gribovski AM, Adilbekova B, Omralina E et al (2021) Effects of air temperature on the number of ambulance calls for asthma during cold season in Nur-Sultan- the second coldest capital in the world. *Int J Circumpolar Health* 80:1978228
- Gronlund CJ, Zanobetti A, Schwartz JD, Wellenius GA, O'Neill MS (2014) Heat, heat waves, and hospital admissions among the elderly in the United States, 1992–2006. *Environ Health Perspect* 122:1187–1192
- Gronlund CJ, Yang AJ, Conlon KC et al (2020) Time series analysis of total and direct associations between high temperatures and preterm births in Detroit. *Michigan BMJ Open* 10:e032476
- Grundstein AJ, Ramseyer C, Zhao F et al (2012) A retrospective analysis of American football hyperthermia deaths in the United States. *Int J Biometeorol* 56:11–20
- Gunasekara TDKSC, De Silva PMCS, Chandana EPS et al (2023) Environmental heat exposure and implications on renal health of pediatric communities in the dry climatic zone of Sri Lanka: An approach with urinary biomarkers. *Environ Res* 222:115399
- Hahn MB, Kuiper G, Magzamen S (2023) Association of temperature thresholds with heat illness-- and cardiorespiratory-related emergency visits during summer months in Alaska. *Environ Health Perspect* 131:57009

- Halonen JJ, Zanobetti A, Sparrow D, Vokonas PS, Schwartz J (2011) Relationship between outdoor temperature and blood pressure. *Occup Environ Med* 68:296–301
- Hamilton SA, Jarhyan P, Fecht D et al (2021) Environmental risk factors for reduced kidney function due to undetermined cause in India: An environmental epidemiologic analysis. *Environ Epidemiol* 5:E170
- Hansen JE, Kharecha P, Sato M et al (2025) Global warming has accelerated: are the United Nations and the public well-informed? *Environ Sci Policy Sustain Dev* 67(1):6–44. <https://doi.org/10.1080/00139157.2025.2434494>
- Harlan SL, Chowell G, Yang S et al (2014) Heat-related deaths in hot cities: estimates of human tolerance to high temperature thresholds. *Int J Environ Res Public Health* 11:3304–3326
- Hartz DA, Golden JS, Sister C, Chuang W-C, Brazel AJ (2012) Climate and heat-related emergencies in Chicago, Illinois (2003–2006). *Int J Biometeorol* 56:71–83
- Hartz DA, Brazel AJ, Golden JS (2013) A comparative climate analysis of heat-related emergency 911 dispatches: Chicago, Illinois and Phoenix, Arizona USA 2003 to 2006. *Int J Biometeorol* 57:669–678
- Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33:45–52
- Heidari L, Winquist A, Klein M, O'Lenick C, Grundstein A, Ebelt Sarnat S (2016) Susceptibility to heat-related fluid and electrolyte imbalance emergency department visits in Atlanta, Georgia, USA. *Int J Environ Res Public Health* 13. <https://doi.org/10.3390/ijerph13100982>
- Henderson SB, Wan V, Kosatsky T (2013) Differences in heat-related mortality across four ecological regions with diverse urban, rural, and remote populations in British Columbia. *Canada Health Place* 23:48–53
- Heo S, Bell ML (2019) Heat waves in South Korea: differences of heat wave characteristics by thermal indices. *J Expo Sci Environ Epidemiol* 29:790–805
- Ho HC, Knudby A, Walker BB, Henderson SB (2017) Delineation of spatial variability in the temperature-mortality relationship on extremely hot days in greater Vancouver. *Canada Environ Health Perspect* 125:66–75
- Hondula DM, Davis RE, Leisten MJ, Saha MV, Veazey LM, Wegner CR (2012) Fine-scale spatial variability of heat-related mortality in Philadelphia County, USA, from 1983–2008: a case-series analysis. *Environ Health* 11:16
- Hong Kong Observatory (2022) Hong Kong heat index. https://www.hko.gov.hk/en/wxinfo/ts/display_element_hkhi.htm. Accessed 14 Mar 2025
- Huang H-C, Suen P-C, Liu J-S, Chen CC-H, Liu Y-B, Chen C-C (2021) Effects of apparent temperature on the incidence of ventricular tachyarrhythmias in patients with an implantable cardioverter–defibrillator: differential association between patients with and without electrical storm. *Front Med* 7. <https://doi.org/10.3389/fmed.2020.624343>
- Infusino E, Caloiero T, Fusto F, Calderaro G, Brutto A, Tagarelli G (2021) Characterization of the 2017 summer heat waves and their effects on the population of an area of Southern Italy. *Int J Environ Res Public Health* 18. <https://doi.org/10.3390/ijerph18030970>
- IPCC (2023) Sections. In: Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change [Core Writing Team, Lee H, Romero J (eds.)]. Geneva, Switzerland. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- Isaksen TB, Yost MG, Hom EK, Ren Y, Lyons H, Fenske RA (2015) Increased hospital admissions associated with extreme-heat exposure in King County, Washington, 1990–2010. *Rev Environ Health* 30:51–64
- Isaksen TB, Fenske RA, Hom EK, Ren Y, Lyons H, Yost MG (2016) Increased mortality associated with extreme-heat exposure in King County, Washington, 1980–2010. *Int J Biometeorol* 60:85–98
- Jiao A, Sun Y, Sacks DA et al (2023) The role of extreme heat exposure on premature rupture of membranes in Southern California: A study from a large pregnancy cohort. *Environ Int* 173:107824
- Jin J, Xu Z, Cao R et al (2023) Long-term apparent temperature, extreme temperature exposure, and depressive symptoms: a longitudinal study in China. *Int J Environ Res Public Health* 20. <https://doi.org/10.3390/ijerph20043229>
- Jingesi M, Lan S, Hu J et al (2023) Association between thermal stress and cardiovascular mortality in the subtropics. *Int J Biometeorol* 67:2093–2106
- Kegel F, Luo OD, Richer S (2021) The impact of extreme heat events on emergency departments in Canadian hospitals. *Wilderness Environ Med* 32:433–440
- Khatana SAM, Werner RM, Groeneveld PW (2022a) Association of extreme heat with all-cause mortality in the contiguous US, 2008–2017. *JAMA Netw Open* 5:e2212957
- Khatana SAM, Werner RM, Groeneveld PW (2022b) Association of extreme heat and cardiovascular mortality in the United States: a county-level longitudinal analysis from 2008 to 2017. *Circulation* 146:249–261
- Khodadadi N, Dastoorpoor M, Khanjani N, Ghasemi A (2022) Universal thermal climate index (UTCI) and adverse pregnancy outcomes in Ahvaz. *Iran Reprod Health* 19:33
- Kienbacher CL, Kaltenberger R, Schreiber W et al (2021) Extreme weather conditions as a gender-specific risk factor for acute myocardial infarction. *Am J Emerg Med* 43:50–53
- Kim H, Ha J-S, Park J (2006) High temperature, heat index, and mortality in 6 major cities in South Korea. *Arch Environ Occup Health* 61:265–270
- Kim J, Yoon K, Choi JC, Kim H, Song J-K (2016) The association between wind-related variables and stroke symptom onset: A case-crossover study on Jeju Island. *Environ Res* 150:97–105
- Kim TH, Lee SC, Seo JS et al (2018) Characteristics and outcomes of patients with cold-related local injuries and accidental hypothermia from emergency department-based surveillance network in northern region of South Korea. *Hong Kong J Emerg Med* 25:130–136
- Kim JM, Jeon JS, Kim JK (2020) Climate and human coronaviruses 229E and human coronaviruses OC43 infections: respiratory viral infections prevalence in hospitalized children in Cheonan. *Korea J Microbiol Biotechnol* 30:1495–1499
- Kivimäki M, Batty GD, Pentti J et al (2023) Climate change, summer temperature, and heat-related mortality in Finland: multicohort study with projections for a sustainable vs. fossil-fueled future to 2050. *Environ Health Perspect* 131:127020
- Klinger BA, Ryan SJ (2022) Population distribution within the human climate niche. *PLOS Clim* 1:e0000086
- Koppe C, Ghafoor J, Springer S et al (2011) The influence of meteorological parameters on the occurrence of hypertensive urgency and emergency. *Meteorol Zeitschrift* 20:509–516
- Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. *Meteorol Zeitschrift* 15:259–263
- Kranc H, Novack V, Shtein A, Sherman R, Novack L (2021) Extreme temperature and out-of-hospital-cardiac-arrest. Nationwide study in a hot climate country. *Environ Health* 20:38
- Krstić G, Krstić G (2011) Apparent temperature and air pollution vs. elderly population mortality in Metro Vancouver. *PLoS One* 6:e25101

- Kruger ELL, Nedel AS (2023) Investigating the relationship between climate and hospital admissions for respiratory diseases before and during the COVID-19 pandemic in Brazil. *Sustainability* 15. <https://doi.org/10.3390/su15010288>
- Krzyewska A, Dobek M, Domzal-Drzewicka R, Rzaca M (2017) Emergency interventions due to weather-related hypothermia. *Weather* 72:8–12
- Kuchcik M (2021) Mortality and thermal environment (UTCI) in Poland-long-term, multi-city study. *Int J Biometeorol* 65:1529–1541
- Kysely J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and 'traditional' approaches. *Clim Res* 25:265–274
- Laschewski G, Jendritzky G (2002) Effects of the thermal environment on human health: An investigation of 30 years of daily mortality data from SW Germany. *Clim Res* 21:91–103
- Lee WK, Lee HA, Lim YH, Park H (2016) Added effect of heat wave on mortality in Seoul, Korea. *Int J Biometeorol* 60:719–726
- Lee JY, Rössli M, Ragetti MS (2021) Estimation of heat-attributable mortality using the cross-validated best temperature metric in Switzerland and south Korea. *Int J Environ Res Public Health* 18. <https://doi.org/10.3390/ijerph18126413>
- Leone M, D'Ippoliti D, De Sario M et al (2013) A time series study on the effects of heat on mortality and evaluation of heterogeneity into European and Eastern-Southern Mediterranean cities: results of EU CIRCE project. *Environ Health* 12:55
- Leung YK, Yip KM, Yeung KH (2008) Relationship between thermal index and mortality in Hong Kong. *Meteorol Appl* 15:399–409
- Leung SY, Lau SYF, Kwok KL, Mohammad KN, Chan PKS, Chong KC (2021) Short-term association among meteorological variation, outdoor air pollution and acute bronchiolitis in children in a subtropical setting. *Thorax* 76:360–369
- Levy M, Broccoli M, Cole G, Jenkins JL, Klein EY (2015) An analysis of the relationship between the heat index and arrivals in the emergency department. *PLoS Curr* 7. <https://doi.org/10.1371/currents.dis.64546103ed4fa0bc7c5b779dd16f5358>
- Lewandowski S, Shaman J (2022) Correction to: Heat stress morbidity among US military personnel: daily exposure and lagged response (1998–2019). *Int J Biometeorol* 66:1209–1217
- Lewandowski SA, Kioumourtoglou M-A, Shaman JL (2022) Heat stress illness outcomes and annual indices of outdoor heat at U.S. Army installations. *PLoS One* 17:e0263803
- Li N, Ma J, Liu F et al (2021) Associations of apparent temperature with acute cardiac events and subtypes of acute coronary syndromes in Beijing, China. *Sci Rep* 11:15229
- Lim Y-H, Park M-S, Kim Y, Kim H, Hong Y-C (2015) Effects of cold and hot temperature on dehydration: a mechanism of cardiovascular burden. *Int J Biometeorol* 59:1035–1043
- Lim J-S, Kwon H-M, Kim S-E, Lee Y-S, Lee Y-S, Yoon B-W (2017) Effects of temperature and pressure on acute stroke incidence assessed using a Korean nationwide insurance database. *J Stroke* 19:295–303
- Lim DK, Jung BK, Kim JK (2021) Climate factors and their effects on the prevalence of rhinovirus infection in Cheonan, Korea. *Microbiol Biotechnol Lett* 49:425–431
- Lim DK, Jeon J-S, Jang TS, Kim JK (2022a) Association between climatic factors and respiratory syncytial virus detection rates in Cheonan. *Korea Environ Sci Pollut Res Int* 29:13315–13322
- Lim DK, Kim JW, Kim JK (2022b) Effects of climatic factors on the prevalence of influenza virus infection in Cheonan. *Korea Environ Sci Pollut Res Int* 29:59052–59059
- Lin S, Luo M, Walker RJ, Liu X, Hwang S-A, Chinery R (2009) Extreme high temperatures and hospital admissions for respiratory and cardiovascular diseases. *Epidemiology* 20:738–746
- Lin Y-K, Chang C-K, Li M-H, Wu Y-C, Wang Y-C (2012) High-temperature indices associated with mortality and outpatient visits: characterizing the association with elevated temperature. *Sci Total Environ* 427–428:41–49
- Lin Y-K, Wang Y-C, Lin P-L, Li M-H, Ho T-J (2013) Relationships between cold-temperature indices and all causes and cardiopulmonary morbidity and mortality in a subtropical island. *Sci Total Environ* 461–462:627–635
- Lin S, Sun M, Fitzgerald E, Hwang S-A (2016a) Did summer weather factors affect gastrointestinal infection hospitalizations in New York State? *Sci Total Environ* 550:38–44
- Lin S, Soim A, Gleason KA, Hwang S-A (2016b) Association between low temperature during winter season and hospitalizations for ischemic heart diseases in New York State. *J Environ Health* 78:66–74
- Lindner-Cendrowska K, Bröde P (2021) Impact of biometeorological conditions and air pollution on influenza-like illnesses incidence in Warsaw. *Int J Biometeorol* 65:929–944
- Liu X, Kong D, Fu J et al (2018a) Association between extreme temperature and acute myocardial infarction hospital admissions in Beijing, China: 2013–2016. *PLoS ONE* 13:e0204706
- Liu Y, Hoppe BO, Convertino M (2018b) Threshold evaluation of emergency risk communication for health risks related to hazardous ambient temperature. *Risk Anal* 38:2208–2221
- Liu X, He Y, Tang C et al (2021) Association between cold spells and childhood asthma in Hefei, an analysis based on different definitions and characteristics. *Environ Res* 195:110738
- Lokys HL, Junk J, Krein A (2018) Short-term effects of air quality and thermal stress on non-accidental morbidity—a multivariate meta-analysis comparing indices to single measures. *Int J Biometeorol* 62:17–27
- Lu S, Liu X, Niu Y et al (2023) Short-term effect of apparent temperature on daily hospitalizations for osteoporotic fractures in Beijing, China: A retrospective observational study. *Sci Total Environ* 874:162583
- Ma P, Zhou J, Wang S et al (2018) Differences of hemorrhagic and ischemic strokes in age spectra and responses to climatic thermal conditions. *Sci Total Environ* 644:1573–1579
- Madrigano J, Mittleman MA, Baccarelli A et al (2013) Temperature, myocardial infarction, and mortality: effect modification by individual- and area-level characteristics. *Epidemiology* 24:439–446
- Mastrangelo G, Fedeli U, Visentin C, Milan G, Fadda E, Spolaore P (2007) Pattern and determinants of hospitalization during heat waves: an ecologic study. *BMC Public Health* 7:200
- Matte TD, Lane K, Ito K (2016) Excess Mortality Attributable to Extreme Heat in New York City, 1997–2013. *Heal Secur* 14:64–70
- Matzarakis A (2021) Curiosities about thermal indices estimation and application. *Atmosphere (Basel)* 12:1–7
- Matzarakis A (2024) Comments on the quantification of thermal comfort and heat stress with thermal indices. *Atmosphere (Basel)* 15:963
- Matzarakis A, Muthers S, Koch E (2011) Human biometeorological evaluation of heat-related mortality in Vienna. *Theor Appl Climatol* 105:1–10
- Mbanu I, Wellenius GA, Mittleman MA, Peeples L, Stallings LA, Kales SN (2007) Seasonality and coronary heart disease deaths in United States firefighters. *Chronobiol Int* 24:715–726
- Meng L, Zhou C, Xu Y et al (2023) The lagged effect and attributable risk of apparent temperature on hand, foot, and mouth disease in Changsha, China: a distributed lag non-linear model. *Environ Sci Pollut Res Int* 30:11504–11515
- Meshi EB, Kishinhi SS, Mamuya SH, Rusibamayila MG (2018) Thermal exposure and heat illness symptoms among workers in Mara gold mine. *Tanzania Ann Glob Heal* 84:360–368
- Metzger KB, Ito K, Matte TD (2010) Summer heat and mortality in New York City: how hot is too hot? *Environ Health Perspect* 118:80–86

- Michelozzi P, de Donato F, Bisanti L et al (2005) The impact of the summer 2003 heat waves on mortality in four Italian cities. *Euro Surveill* 10:161–165
- Michelozzi P, De Sario M, Accetta G et al (2006) Temperature and summer mortality: geographical and temporal variations in four Italian cities. *J Epidemiol Community Health* 60:417–423
- Michelozzi P, Accetta G, De Sario M et al (2009) High temperature and hospitalizations for cardiovascular and respiratory c. *Am J Respir Crit Care Med* 179:383–389
- Milani GP, Lo Leggio A, Castellazzi ML, Agostoni C, Bianchetti MG, Carugno M (2022) Outdoor temperature and circulating sodium in children with acute gastroenteritis. *Pediatr Res* 92:1270–1273
- Milsten AM, Seaman KG, Liu P, Bissell RA, Maguire BJ (2003) Variables influencing medical usage rates, injury patterns, and levels of care for mass gatherings. *Prehosp Disaster Med* 18:334–346
- Min M, Shi T, Ye P et al (2019) Effect of apparent temperature on daily emergency admissions for mental and behavioral disorders in Yancheng, China: a time-series study. *Environ Heal A Glob Access Sci Source* 18. <https://doi.org/10.1186/s12940-019-0543-x>
- Moghadamnia MT, Ardalan A, Mesdaghinia A, Naddafi K, Yekaninejad MS (2018a) Association between apparent temperature and acute coronary syndrome admission in Rasht, Iran. *Heart Asia* 10. <https://doi.org/10.1136/heartasia-2018-011068>
- Moghadamnia MT, Ardalan A, Mesdaghinia A, Naddafi K, Yekaninejad MS (2018b) The effects of apparent temperature on cardiovascular mortality using a distributed lag nonlinear model analysis: 2005 to 2014. *Asia-Pacific J Public Heal* 30:361–368
- Mohammadi B, Karimi S (2018) The relationship between thermal sensation and the rate of hospital admissions for cardiovascular disease in Kermanshah. *Iran Theor Appl Climatol* 134:1101–1114
- Mohammadi D, Naghshineh E, Sarsangi A, Zare Sakhvidi MJ (2019) Environmental extreme temperature and daily preterm birth in Sabzevar, Iran: a time-series analysis. *Environ Health Prev Med* 24:5
- Monteiro A, Carvalho V, Oliveira T, Sousa C (2013) Excess mortality and morbidity during the July 2006 heat wave in Porto. *Portugal Int J Biometeorol* 57:155–167
- Moore BF, Brooke Anderson G, Johnson MG, Brown S, Bradley KK, Magzamen S (2017) Case-crossover analysis of heat-coded deaths and vulnerable subpopulations: Oklahoma, 1990–2011. *Int J Biometeorol* 61:1973–1981
- Morabito M, Modesti PA, Cecchi L et al (2005) Relationships between weather and myocardial infarction: a biometeorological approach. *Int J Cardiol* 105:288–293
- Morabito M, Profili F, Crisci A, Francesconi P, Gensini GF, Orlanini S (2012) Heat-related mortality in the Florentine area (Italy) before and after the exceptional 2003 heat wave in Europe: an improved public health response? *Int J Biometeorol* 56:801–810
- Morabito M, Crisci A, Messeri A et al (2014) Environmental temperature and thermal indices: what is the most effective predictor of heat-related mortality in different geographical contexts? *Sci World J* 2014:961750
- Morris CE, Gonzales RG, Hodgson MJ, Tustin AW (2019) Actual and simulated weather data to evaluate wet bulb globe temperature and heat index as alerts for occupational heat-related illness. *J Occup Environ Hyg* 16:54–65
- Muthers S, Matzarakis A, Koch E (2010a) Climate change and mortality in Vienna—a human biometeorological analysis based on regional climate modeling. *Int J Environ Res Public Health* 7:2965–2977
- Muthers S, Matzarakis A, Koch E (2010b) Summer climate and mortality in Vienna - a human-biometeorological approach of heat-related mortality during the heat waves in 2003. *Wien Klin Wochenschr* 122:525–531
- Na W, Jang J-Y, Lee KE et al (2013) The effects of temperature on heat-related illness according to the characteristics of patients during the summer of 2012 in the Republic of Korea. *J Prev Med Public Health* 46:19–27
- Nastos PT, Matzarakis A (2006) Weather impacts on respiratory infections in Athens. Greece *Int J Biometeorol* 50:358–369
- Nastos PT, Matzarakis A (2008) Human-biometeorological effects on sleep disturbances in Athens, Greece: a preliminary evaluation. *Indoor Built Environ* 17:535–542
- Nastos PT, Matzarakis A (2012) The effect of air temperature and human thermal indices on mortality in Athens. Greece *Theor Appl Climatol* 108:591–599
- Ng CFS, Ueda K, Ono M, Nitta H, Takami A (2014) Characterizing the effect of summer temperature on heatstroke-related emergency ambulance dispatches in the Kanto area of Japan. *Int J Biometeorol* 58:941–948
- Ngarambe J, Santamouris M, Yun GY (2022) The impact of urban warming on the mortality of vulnerable populations in Seoul. *Sustainability* 14. <https://doi.org/10.3390/su142013452>
- Nguyen JL, Link MS, Luttmann-Gibson H et al (2015) Drier air, lower temperatures, and triggering of paroxysmal atrial fibrillation. *Epidemiology* 26:374–380
- Nick LM, Nedel AS, Alonso MF, Marques JQ, de Freitas RA (2022) Relationship between meteorological variables and pneumonia in children in the Metropolitan Region of Porto Alegre. Brazil *Int J Biometeorol* 66:2301–2308
- NIH (2021) Study quality assessment tools. Quality assessment tool for observational cohort and cross-sectional studies. <https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools>. Accessed 20 Mar 2025
- NOAA-National Weather Service (2024) Heat index forecasts. <https://www.weather.gov/bgm/heat>. Accessed 14 Mar 2025
- Nyadanu SD, Tessema GA, Mullins B, Pereira G (2022b) Maternal acute thermophysiological stress and stillbirth in Western Australia, 2000–2015: A space-time-stratified case-crossover analysis. *Sci Total Environ* 836:155750
- Nyadanu S, Tessema G, Mullins B, Chai K, Yitshak-Sade M, Pereira G (2023a) Critical windows of maternal exposure to biothermal stress and birth weight for gestational age in Western Australia. *Env Heal Perspect* 131:127017
- Nyadanu SD, Tessema GA, Mullins B, Kumi-Boateng B, Ofosu AA, Pereira G (2023b) Prenatal exposure to long-term heat stress and stillbirth in Ghana: A within-space time-series analysis. *Environ Res* 222:115385
- Nyadanu SD, Tessema GA, Mullins B, Pereira G (2022a) Prenatal acute thermophysiological stress and spontaneous preterm birth in Western Australia, 2000–2015: a space-time-stratified case-crossover analysis. *Int J Hyg Environ Health* 245. <https://doi.org/10.1016/j.ijheh.2022.114029>
- O'Neill MS, Zanobetti A, Schwartz J (2003) Modifiers of the temperature and mortality association in seven US cities. *Am J Epidemiol* 157:1074–1082
- O'Neill MS, Hajat S, Zanobetti A, Ramirez-Aguilar M, Schwartz J (2005) Impact of control for air pollution and respiratory epidemics on the estimated associations of temperature and daily mortality. *Int J Biometeorol* 50:121–129
- Oh EJ, Jeon J-S, Kim JK (2021) Effects of climatic factors and particulate matter on Rotavirus infections in Cheonan, Korea, in 2010–2019. *Environ Sci Pollut Res Int* 28:44332–44338
- Ohlson CG, Bodin L, Bryngelsson IL, Helsing M, Malmberg L (1991) Winter weather conditions and myocardial infarctions. *Scand J Soc Med* 19:20–25
- Ohno Y (1970) Biometeorologic studies on cerebrovascular diseases: II. Seasonal observation on effects of meteorologic factors on the death from cerebrovascular accident. *JPN Circ J* 33:1299–308

- Ohno Y, Horibe H, Hayakawa N, Aoki N, Okada H (1970) Biometeorologic studies on cerebrovascular diseases (IV) evaluation of meteorologic factors, their changes or combinations on the occurrence of cerebrovascular accident. *JPN Circ J* 34:69–75
- Ostro BD, Roth LA, Green RS, Basu R (2009) Estimating the mortality effect of the July 2006 California heat wave. *Environ Res* 109:614–619
- Ostro B, Rauch S, Green R, Malig B, Basu R (2010) The effects of temperature and use of air conditioning on hospitalizations. *Am J Epidemiol* 172:1053–1061
- Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A (2016) Rayyan—a web and mobile app for systematic reviews. *Syst Rev* 5:210
- Page MJ, McKenzie JE, Bossuyt PM, The PRISMA et al (2020) statement: an updated guideline for reporting systematic reviews. *BMJ* 2021:372. <https://doi.org/10.1136/BMJ.N71>
- Pan R, Gao J, Wang X et al (2019) Impacts of exposure to humidity on the risk of childhood asthma hospitalizations in Hefei, China: Effect modification by gender and age. *Sci Total Environ* 691:296–305
- Pantavou K, Theoharatos G, Nikolopoulos G, Katavoutas G, Asimakopoulos D (2008) Evaluation of thermal discomfort in Athens territory and its effect on the daily number of recorded patients at hospitals' emergency rooms. *Int J Biometeorol* 52:773–778
- Pantavou K, Theoharatos G, Mavarakis A, Santamouris M (2011) Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens. *Build Environ* 46:339–344
- Pantavou KG, Lykoudis SP, Nikolopoulos GK (2016) Milder form of heat-related symptoms and thermal sensation: a study in a Mediterranean climate. *Int J Biometeorol* 60:917–929
- Pantavou K, Giallourous G, Lykoudis S et al (2020) Impact of heat exposure on health during a warm period in Cyprus. *Euro-Mediterranean J Environ Integr* 5. <https://doi.org/10.1007/s41207-020-00164-0>
- Pantavou K, Giallourous G, Philippopoulos K et al (2021) Thermal conditions and hospital admissions: analysis of longitudinal data from Cyprus (2009–2018). *Int J Environ Res Public Health* 18:13361
- Perron AD, Brady WJ, Custalow CB, Johnson DM (2005) Association of heat index and patient volume at a mass gathering event. *Pre-hospital Emerg Care* 9:49–52
- Porter KR, Thomas SD, Whitman S (1999) The relation of gestation length to short-term heat stress. *Am J Public Health* 89:1090–1092
- Potchter O, Cohen P, Lin TP, Matzarakis A (2018) Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. *Sci Total Environ* 631–632:390–406
- Potchter O, Cohen P, Lin TP, Matzarakis A (2022) A systematic review advocating a framework and benchmarks for assessing outdoor human thermal perception. *Sci Total Environ* 833:155128
- Pradhan B, Kjellstrom T, Atar D et al (2019) Heat stress impacts on cardiac mortality in Nepali migrant workers in Qatar. *Cardiology* 143:37–48
- Psistaki K, Dokas IM, Paschalidou AK (2023) Analysis of the heat- and cold-related cardiovascular mortality in an urban mediterranean environment through various thermal indices. *Environ Res* 216:114831
- Ragetti MS, Vicedo-Cabrera AM, Schindler C, Röösli M (2017) Exploring the association between heat and mortality in Switzerland between 1995 and 2013. *Environ Res* 158:703–709
- Rainham DGC, Smoyer-Tomic KE (2003) The role of air pollution in the relationship between a heat stress index and human mortality in Toronto. *Environ Res* 93:9–19
- Rammah A, Whitworth KW, Han I, Chan W, Hess JW, Symanski E (2019) Temperature, placental abruption and stillbirth. *Environ Int* 131:105067
- Rathi SK, Sodani PR (2021) Summer temperature and all-cause mortality from 2006 to 2015 for Hyderabad. *India Afr Health Sci* 21:1474–1481
- Rathi SK, Desai VK, Jariwala P, Desai H, Naik A, Joseph A (2017) Summer temperature and spatial variability of all-cause mortality in Surat city, India. *Indian J Commun Med* 42:111–115
- Rathi SK, Sodani PR, Joshi S (2021) Summer temperature and all-cause mortality from 2006 to 2015 for smart City Jaipur India. *J Health Manag* 23:294–301
- Requia WJ, Koutrakis P, Papatheodorou S (2022) The association of maternal exposure to ambient temperature with low birth weight in term pregnancies varies by location: In Brazil, positive associations may occur only in the Amazon region. *Environ Res* 214:113923
- Romaszko J, Cymes I, Dragańska E, Kuchta R, Glińska-Lewczuk K (2017) Mortality among the homeless: causes and meteorological relationships. *PLoS ONE* 12:e0189938
- Romaszko J, Skutecki R, Bocheński M et al (2019) Applicability of the universal thermal climate index for predicting the outbreaks of respiratory tract infections: a mathematical modeling approach. *Int J Biometeorol* 63:1231–1241
- Romaszko J, Dragańska E, Jalali R, Cymes I, Glińska-Lewczuk K (2022a) Universal Climate Thermal Index as a prognostic tool in medical science in the context of climate change: A systematic review. *Sci Total Environ* 828:154492
- Romaszko J, Dragańska E, Cymes I, Drozdowski M, Gromadziński L, Glińska-Lewczuk K (2022b) Are the levels of uric acid associated with biometeorological conditions?. *Sci Total Environ* 819. <https://doi.org/10.1016/j.scitotenv.2021.152020>
- Romaszko-Wojtowicz A, Cymes I, Dragańska E, Doboszyńska A, Romaszko J, Glińska-Lewczuk K (2020) Relationship between biometeorological factors and the number of hospitalizations due to asthma. *Sci Rep* 10:9593
- Rosenthal JK, Kinney PL, Metzger KB, Klein Rosenthal J, Kinney PL, Metzger KB (2014) Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Heal Place* 30:45–60
- Roshan G, Ghanghermeh A, Mohammadnejad V, Fdez-Arroyabe P, Santurtun A (2022a) Predicting climate change impact on hospitalizations of cardiovascular patients in Tabriz. *URBAN Clim* 44. <https://doi.org/10.1016/j.uclim.2022.101184>
- Roshan G, Halabian A, Moghbel M (2022b) The relationship between thermal sensation and cardiovascular patients' admission rates in Tabriz. *Iran J Therm Biol* 110:103379
- Ross ME, Vicedo-Cabrera AM, Kopp RE et al (2018) Assessment of the combination of temperature and relative humidity on kidney stone presentations. *Environ Res* 162:97–105
- Roye D, Figueiras A, Taracido M, Royé D, Figueiras A, Taracido M (2018) Short-term effects of heat and cold on respiratory drug use. A time-series epidemiological study in A Coruna, Spain. *Pharmacoepidemiol Drug Saf* 27:638–44
- Roye D, Zarrabeitia MTMT, Riancho J et al (2019) A time series analysis of the relationship between apparent temperature, air pollutants and ischemic stroke in Madrid. *Spain Environ Res* 173:349–358
- Royé D, Codesido R, Tobías A, Taracido M (2020) Heat wave intensity and daily mortality in four of the largest cities of Spain. *Environ Res* 182:109027
- Saddique A, Adnan S, Bokhari H et al (2021) Prevalence and Associated Risk Factor of COVID-19 and Impacts of Meteorological and Social Variables on Its Propagation in Punjab. *Pakistan EARTH Syst Environ* 5:785–798
- Saha MV, Davis RE, Hondula DM (2014) Mortality displacement as a function of heat event strength in 7 us cities. *Am J Epidemiol* 179:467–474
- Saha S, Brock JW, Vaidyanathan A, Easterling DR, Lubert G (2015) Spatial variation in hyperthermia emergency department visits

- among those with employerbased insurance in the United States - a case-crossover analysis. *Environ Heal A Glob Access Sci Source* 14. <https://doi.org/10.1186/s12940-015-0005-z>
- Santurtun A, Almendra R, Fdez-Arroyabe P et al (2020) Predictive value of three thermal comfort indices in low temperatures on cardiovascular morbidity in the Iberian peninsula. *Sci Total Environ* 729:138969
- Savitz DA, Hu H (2021) Ambient heat and stillbirth in Northern and Central Florida. *Environ Res* 199:111262
- Schifano P, Cappai G, De Sario M et al (2009) Susceptibility to heat wave-related mortality: a follow-up study of a cohort of elderly in Rome. *Environ Health* 8:50
- Schifano P, Leone M, De Sario M et al (2012) Changes in the effects of heat on mortality among the elderly from 1998–2010: results from a multicenter time series study in Italy. *Environ Health* 11:58
- Schifano P, Lallo A, Asta F, De Sario M, Davoli M, Michelozzi P (2013) Effect of ambient temperature and air pollutants on the risk of preterm birth, Rome 2001–2010. *Environ Int* 61:77–87
- Schifano P, Asta F, Dadvand P, Davoli M, Basagana X, Michelozzi P (2016) Heat and air pollution exposure as triggers of delivery: A survival analysis of population-based pregnancy cohorts in Rome and Barcelona. *Environ Int* 88:153–159
- Schlegel I, Muthers S, Muecke H-G, Matzarakis A (2020) Comparison of respiratory and ischemic heart mortalities and their relationship to the thermal environment. *Atmosphere* 11. <https://doi.org/10.3390/atmos11080826>
- Schroeder AN, Suriano ZJ, Kliethermes SA, Asplund CA, Roberts WO (2023) Using wet bulb globe temperature and physiological equivalent temperature as predicative models of medical stress in a marathon: analysis of 30 years of data from the twin cities marathon. *Clin J Sport Med off J Can Acad Sport Med* 33:45–51
- Sen J, Nag PK (2019) Human susceptibility to outdoor hot environment. *Sci Total Environ* 649:866–875
- Sharafkhani R, Khanjani N, Bakhtiari B, Jahani Y, Sadegh TJ (2018) Physiological equivalent temperature index and mortality in Tabriz (The northwest of Iran). *J Therm Biol* 71:195–201
- Shartova N, Shaposhnikov D, Konstantinov P, Revich B (2018) Cardiovascular mortality during heat waves in temperate climate: an association with bioclimatic indices. *Int J Environ Health Res* 28:522–534
- Shire J, Vaidyanathan A, Lackovic M, Bunn T (2020) Association between work-related hyperthermia emergency department visits and ambient heat in five Southeastern States, 2010–2012-a case-crossover study. *Geohealth* 4. <https://doi.org/10.1029/2019GH000241>
- Shiue I, Perkins DR, Bearman N (2015) Inverted U-shape relationships of the weather as biometeorological and hospital admissions due to carcinoma in situ and benign neoplasm in Germany in 2009–2011. *Environ Sci Pollut Res Int* 22:9378–9399
- Shiue I, Perkins DR, Bearman N (2016a) Hospital admissions of hypertension, angina, myocardial infarction and ischemic heart disease peaked at physiologically equivalent temperature 0 degrees C in Germany in 2009–2011. *Environ Sci Pollut Res* 23:298–306
- Shiue I, Perkins DR, Bearman N (2016b) Relationships of physiologically equivalent temperature and hospital admissions due to I30–I51 other forms of heart disease in Germany in 2009–2011. *Environ Sci Pollut Res Int* 23:6343–6352
- Shiue I, Perkins DR, Bearman N (2016c) Hospital admissions due to diseases of arteries and veins peaked at physiological equivalent temperature-10 to 10 A degrees C in Germany in 2009–2011. *Environ Sci Pollut Res* 23:6159–6167
- Shrikhande SS, Pedder H, Rösli M et al (2023) Non-optimal apparent temperature and cardiovascular mortality: the association in Puducherry, India between 2011 and 2020. *BMC Public Health* 23:291
- Silva EN, Ribeiro H (2012) Impact of urban atmospheric environment on hospital admissions in the elderly. *Rev Saude Publica* 46:694–701
- Skarha J, Dominick A, Spangler K et al (2022) Provision of air conditioning and heat-related mortality in Texas prisons. *JAMA Netw Open* 5:e2239849
- Skutecki R, Jalali R, Dragańska E, Cymes I, Romaszko J, Glińska-Lewczuk K (2019) UTCI as a bio-meteorological tool in the assessment of cold-induced stress as a risk factor for hypertension. *Sci Total Environ* 688:970–975
- Smoyer KE (1998) A comparative analysis of heat waves and associated mortality in St. Louis, Missouri - 1980 and 1995. *Int J Biometeorol* 42:44–50
- Smoyer KE, Rainham DG, Hewko JN (2000) Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. *Int J Biometeorol* 44:190–197
- Soim A, Lin S, Sheridan SC et al (2017) Population-based case-control study of the association between weather-related extreme heat events and neural tube defects. *Birth Defects Res* 109:1482–1493
- Soim A, Sheridan SC, Hwang S-A et al (2018) A population-based case-control study of the association between weather-related extreme heat events and orofacial clefts. *Birth Defects Res* 110:1468–1477
- Sombatsawat E, Luangwilai T, Kaewchandee C, Robson MG, Siriwong W (2023) Impact of environmental heat exposure on the health status in farmworkers, Nakhon Ratchasima. *Thailand Rocznik Hig* 74:103–111
- Son J-Y, Lee J-T, Lane KJ, Bell ML (2019) Impacts of high temperature on adverse birth outcomes in Seoul, Korea: disparities by individual- and community-level characteristics. *Environ Res* 168:460–466
- Spangler K, Adams Q, Hu J et al (2023a) Does choice of outdoor heat metric affect heat-related epidemiologic analyses in the US Medicare population? *Env Epidemiol* 7:e261
- Spangler KR, Adams QH, Hu JK et al (2023b) Does choice of outdoor heat metric affect heat-related epidemiologic analyses in the US Medicare population? *Environ Epidemiol* 7:e261
- Stafoggia M, Forastiere F, Agostini D et al (2006) Vulnerability to heat-related mortality: a multicity, population-based, case-crossover analysis. *Epidemiology* 17:315–323
- Stafoggia M, Forastiere F, Agostini D et al (2008) Factors affecting in-hospital heat-related mortality: a multi-city case-crossover analysis. *J Epidemiol Community Health* 62:209–215
- Stafoggia M, Forastiere F, Michelozzi P, Perucci CA (2009) Summer temperature-related mortality: effect modification by previous winter mortality. *Epidemiology* 20:575–583
- Stanojevic G, Stojilkovic J, Spalevic A, Kokotovic V (2014) The impact of heat waves on daily mortality in Belgrade (Serbia) during summer. *Environ Hazards-Hum Pol Dimens* 13:329–342
- Sun H, Wang X, Zhang X, Wang L, Zou Y, Hu H (2023) The association between apparent temperature and psoriasis outpatient visits: a time-series study in Hefei, China. *Environ Res Commun* 5. <https://doi.org/10.1088/2515-7620/acc013>
- Sung T-I, Wu P-C, Lung S-C, Lin C-Y, Chen M-J, Su H-J (2013) Relationship between heat index and mortality of 6 major cities in Taiwan. *Sci Total Environ* 442:275–281
- Tam WH, Sahota DS, Lau TK, Li CY, Fung TY (2008) Seasonal variation in pre-eclampsia rate and its association with the ambient temperature and humidity in early pregnancy. *Gynecol Obstet Invest* 66:22–26
- Telesca V, Castronuovo G, Favia G, Marranchelli C, Pizzulli VA, Ragosta M (2023) Effects of meteorological factors on hospital admissions for cardiovascular diseases in the City of Bari, Southern Italy. *Healthcare* 11. <https://doi.org/10.3390/healthcare11050690>

- Thach T-Q, Zheng Q, Lai P-C et al (2015) Assessing spatial associations between thermal stress and mortality in Hong Kong: a small-area ecological study. *Sci Total Environ* 502:666–672
- Theoharatos G, Pantavou K, Mavarakis A et al (2010) Heat waves observed in 2007 in Athens, Greece: synoptic conditions, bioclimatological assessment, air quality levels and health effects. *Environ Res* 110:152–161
- Thorsson S, Rayner D, Palm G et al (2021) Is physiological equivalent temperature (PET) a superior screening tool for heat stress risk than Wet-Bulb Globe Temperature (WBGT) index? Eight years of data from the Gothenburg half marathon. *Br J Sports Med* 55:825–830
- Tseliou A, Koletsis I, Pantavou K (2022) Evaluating the effects of different mitigation strategies on the warm thermal environment of an urban square in Athens. *Greece Urban Clim* 44:101217
- Urban A, Kysely J (2014) Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *Int J Environ Res Public Health* 11:952–967
- Urban A, Hondula DM, Hanzlikova H, Kysely J (2019) The predictability of heat-related mortality in Prague, Czech Republic, during summer 2015a comparison of selected thermal indices. *Int J Biometeorol* 63:535–548
- Urban A, Di Napoli C, Cloke HL et al (2021) Evaluation of the ERA5 reanalysis-based universal thermal climate index on mortality data in Europe. *Environ Res* 198. <https://doi.org/10.1016/j.envr.2021.111227>
- Vaidyanathan A, Saha S, Vicedo-Cabrera AM et al (2019) Assessment of extreme heat and hospitalizations to inform early warning systems. *Proc Natl Acad Sci U S A* 116:5420–5427
- van Daalen KR, Carvalho BM, Gonzalez-Reviriego N et al (2024) The 2024 Europe report of the Lancet Countdown on health and climate change: unprecedented warming demands unprecedented action. *Countdown Lancet Public Heal* 9:495–522
- van Zutphen AR, Lin S, Fletcher BA, Hwang S-A (2012) A population-based case-control study of extreme summer temperature and birth defects. *Environ Health Perspect* 120:1443–1449
- Vasconcelos J, Freire E, Almendra R, Silva GL, Santana P (2013) The impact of winter cold weather on acute myocardial infarctions in Portugal. *Environ Pollut* 183:14–18
- Vassil JC, Winn L, Heslop DJ (2020) The sun herald sydney City-2-Surf Fun Run - historical injury patterns and factors influencing injury type and frequency. *Prehosp Disaster Med* 35:189–196
- Veron GL, Tissera AD, Bello R et al (2021) Association between meteorological variables and semen quality: a retrospective study. *Int J Biometeorol* 65:1399–1414
- Vicedo-Cabrera AM, Iñiguez C, Barona C, Ballester F (2014) Exposure to elevated temperatures and risk of preterm birth in Valencia, Spain *Environ Res* 134:210–217
- Wallace RF, Kriebel D, Punnett L et al (2005) The effects of continuous hot weather training on risk of exertional heat illness. *Med Sci Sports Exerc* 37:84–90
- Weinberger KR, Wu X, Sun S et al (2021) Heat warnings, mortality, and hospital admissions among older adults in the United States. *Environ Int* 157:106834
- Wellenius GA, Eliot MN, Bush KF et al (2017) Heat-related morbidity and mortality in New England: Evidence for local policy. *Environ Res* 156:845–853
- Wenfang G, Yi L, Wang P, Wang B, Li M (2020) Assessing the effects of meteorological factors on daily children's respiratory disease hospitalizations: a retrospective study. *Heliyon* 6. <https://doi.org/10.1016/j.heliyon.2020.e04657>
- Wichmann J (2017) Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006–2010. *Sci Total Environ* 587–588:266–272
- Wichmann J, Andersen Z, Ketzel M, Ellermann T, Loft S (2011a) Apparent temperature and cause-specific emergency hospital admissions in Greater Copenhagen. *Denmark Plos One* 6:e22904
- Wichmann J, Andersen ZJ, Ketzel M, Ellermann T, Loft S (2011b) Apparent temperature and cause-specific mortality in Copenhagen, Denmark: a case-crossover analysis. *Int J Environ Res Public Health* 8:3712–3727
- Wichmann J, Ketzel M, Ellermann T, Loft S (2012) Apparent temperature and acute myocardial infarction hospital admissions in Copenhagen, Denmark: a case-crossover study. *Environ Health* 11:19
- Williams AA, Allen JG, Catalano PJ, Spengler JD (2020) The role of individual and small-area social and environmental factors on heat vulnerability to mortality within and outside of the home in Boston, MA. *Climate* 8. <https://doi.org/10.3390/cli8020029>
- Wiru K, Oppong FB, Agyei O et al (2020) The influence of apparent temperature on mortality in the kintampo health and demographic surveillance area in the middle belt of Ghana: a retrospective time-series analysis. *J Environ Public Health* 2020:5980313
- WMO (2024) July sets new temperature records. <https://wmo.int/media/news/july-sets-new-temperature-records>. Accessed 20 Mar 2025
- Xu W, Thach T-Q, Chau Y-K et al (2013) Thermal stress associated mortality risk and effect modification by sex and obesity in an elderly cohort of Chinese in Hong Kong. *Environ Pollut* 178:288–293
- Xu R, Huang S, Shi C et al (2023) Extreme temperature events, fine particulate matter, and myocardial infarction mortality. *Circulation* 148:312–323
- Yin Q, Wang J (2018) A better indicator to measure the effects of meteorological factors on cardiovascular mortality: heat index. *Environ Sci Pollut Res Int* 25:22842–22849
- Yip FY, Flanders WD, Wolkin A et al (2008) The impact of excess heat events in Maricopa County, Arizona: 2000–2005. *Int J Biometeorol* 52:765–772
- Yong KH, Teo YN, Azadbakht M, Phung H, Chu C (2023) The scorching truth: investigating the impact of heatwaves on Selangor's elderly hospitalisations. *Int J Environ Res Public Heal* 20:5910
- Zaninovic K, Matzarakis A (2014) Impact of heat waves on mortality in Croatia. *Int J Biometeorol* 58:1135–1145
- Zaninovic K, Matzarakis A, Zaninović K, Matzarakis A (2014) Impact of heat waves on mortality in Croatia. *Int J Biometeorol* 58:1135–1145
- Zanobetti A, Schwartz J (2008) Temperature and mortality in nine US cities. *Epidemiology* 19:563–570
- Zare S, Hasheminezhad N, Sarebanzadeh K, Zolala F, Hemmatjo R, Hassanvand D (2018) Assessing thermal comfort in tourist attractions through objective and subjective procedures based on ISO 7730 standard: a field study. *Urban Clim* 26:1–9
- Zemtsov S, Shartova N, Varentsov M et al (2020) Intraurban social risk and mortality patterns during extreme heat events: A case study of Moscow, 2010–2017. *Health Place* 66:102429
- Zhai G, Qi J, Zhang X, Zhou W, Wang J (2022a) A comparison of the effect of diurnal temperature range and apparent temperature on cardiovascular disease among farmers in Qingyang, Northwest China. *Environ Sci Pollut Res Int* 29:28946–28956
- Zhai G, Tian Y, Zhang K, Qi J, Chai G (2022b) The effect of apparent temperature on hospital admissions for cardiovascular diseases in rural areas of Pingliang, China. *Ann Agric Environ Med* 29:281–286
- Zhai G, Gao Z, Zhou W (2023a) Effects of apparent temperature on cardiovascular disease admissions in rural areas of Linxia Hui Autonomous Prefecture. *Sci Rep* 13:14971
- Zhai G, Wang Y, Zhang K, Tian Y (2023b) Association between apparent temperature and hypertension hospital admissions: a

- case study in rural areas in western China. *Ann Agric Env Med* 30:490–497
- Zhan Z-Y, Zhong X, Yang J et al (2022) Effect of apparent temperature on hospitalization from a spectrum of cardiovascular diseases in rural residents in Fujian. *China Environ Pollut* 303:119101
- Zhan Z, Fang H, Xu X, Hu Z (2023) Interactions of particulate matter with temperature, heat index and relative humidity on pediatric hand, foot, and mouth disease in a subtropical city. *Env Pollut* 336:122385
- Zhang K, Arauz RF, Chen T-H, Cooper SP (2016) Heat effects among migrant and seasonal farmworkers: a case study in Colorado. *Occup Environ Med* 73:324–328
- Zhang W, Du Z, Huang S et al (2017) The association between human perceived heat and early-stage syphilis and its variance: Results from a case-report system. *Sci Total Environ* 593–594:773–778
- Zhang Y, Liu X, Kong D et al (2020) Effects of ambient temperature on acute exacerbations of chronic obstructive pulmonary disease: results from a time-series analysis of 143318 hospitalizations. *Int J Chron Obstruct Pulmon Dis* 15:213–223
- Zhang F, Zhang X, Zhou G et al (2022) Is cold apparent temperature associated with the hospitalizations for osteoporotic fractures in the central areas of Wuhan? A Time-Series Study *Front Public Heal* 10:835286
- Zhang J, Bai S, Lin S et al (2023) Maternal apparent temperature during pregnancy on the risk of offspring asthma and wheezing: effect, critical window, and modifiers. *Environ Sci Pollut Res Int* 30:62924–62937
- Zhao H, Yang Y, Feng C et al (2023) Nonlinear effects of humidex on risk of outpatient visit for allergic conjunctivitis among children and adolescents in Shanghai, China: A time series analysis. *J Glob Heal* 3:04132
- Zhou Y, Pan J, Xu R et al (2022) Asthma mortality attributable to ambient temperatures: A case-crossover study in China. *Environ Res* 214:114116
- Zhou Y, Ji A, Tang E et al (2023) The role of extreme high humidex in depression in chongqing, China: a time series-analysis. *Environ Res* 222:115400
- Zottarelli LK, Sharif HO, Xu X, Sunil TS (2021) Effects of social vulnerability and heat index on emergency medical service incidents in San Antonio, Texas, in 2018. *J Epidemiol Community Health* 75:271–276

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