GeoHealth

REVIEW ARTICLE

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Key Points:

- Distributed lag non-linear models were widely used across various health outcomes and study designs, especially in time series studies
- There were disparities in research focus across different regions with regions like Africa and Oceania being underrepresented
- Access to public health data and standardized definitions for extreme heat remain significant challenges in heat impact studies

Supporting Information:

Supporting Information may be found in the online version of this article.

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Methodological Approaches for Measuring the Association Between Heat Exposure and Health Outcomes: A Comprehensive Global Scoping Review

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Abstract Objective: To synthesize the methodologies of studies that evaluate the impacts of heat exposure on morbidity and mortality. Methods: Embase, MEDLINE, Web of Science, and Scopus were searched from date of inception until 1 March 2023 for English language literature on heat exposure and health outcomes. Records were collated, deduplicated and screened, and full texts were reviewed for inclusion and data abstraction. Eligibility for inclusion was determined as any article with climate-related heat exposure and an associated morbidity/mortality outcome. Results: Of 13,136 records initially identified, 237 articles were selected for analysis. The scope of research represented 43 countries, with most studies conducted in China (62), the USA (44), and Australia (16). Across all studies, there were 141 unique climate data sources, no standard threshold for extreme heat, and 200 unique health outcome data sources. The distributed lag non-linear model (DLNM) was the most common analytic method (48.1% of studies) and had high usage rates in China (68.9%) and the USA (31.8%); Australia frequently used conditional logistic regression (50%). Conditional logistic regression was most prevalent in case-control studies (5 of 8 studies, 62.5%) and in case-crossover studies (29 of 70, 41.4%). DLNMs were most common in time series studies (64 of 111, 57.7%) and ecological studies (13 of 20, 65.0%). Conclusions: This review underscores the heterogeneity of methods in heat impact studies across diverse settings and provides a resource for future researchers. Underrepresentation of certain countries, health outcomes, and limited data access were identified as potential barriers.

Plain Language Summary Climate change and global warming are major threats to public health, leading to increased illness and death worldwide due to rising temperatures. Heatwaves are becoming more frequent and severe, causing various health problems, particularly affecting low-income and minority communities. Studying the link between heat and health requires diverse methods due to regional differences. Different study designs and analytical techniques have been used, but there is no consensus on the best approach. Factors like heat severity, duration, air quality, and humidity must be considered. However, defining extreme heat and determining the best metric for heat exposure remain debated. With climate change worsening, understanding previous research on heat-related health impacts is crucial for future policies and adaptation strategies. This scoping review aims to address gaps in knowledge by examining the range of epidemiological approaches used to study the effects of extreme heat on health outcomes.

1. Introduction

Climate change and global warming are considered the greatest public health threats of the 21st century with significant projected excess morbidity and mortality as temperatures rapidly rise worldwide (Romanello et al., 2022). Extreme heat events are expected to increase in frequency, intensity, and duration, and are known to be independently associated with a myriad of adverse health outcomes (Hess et al., 2023; White-Newsome et al., 2014). The global burden of extreme heat-related disease and mortality is inequitably distributed as low income and minority groups are disproportionately affected (Gronlund, 2014). Numerous studies have characterized the relationship between heat and specific adverse health outcomes; however, their approaches are heterogeneous and vary based on a multitude of factors.

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The spatiotemporal association between heat exposure and health outcomes is complex in that the assessment of heat impact on human health can vary greatly depending on the definition of extreme heat exposure and the classification of disease. As such, quantifying this association requires a methodological approach that can accommodate diverse explanatory variables at multiple timepoints (Anderson & Bell, 2011; Curriero et al., 2002). Cohort, case-control, and case-crossover study designs have been utilized in previous extreme heat literature, in addition to many others (Hollander et al., 2021; Lawrence et al., 2021; Sun et al., 2021). Analytical methods such as distributed lag non-linear models (DLNM), conditional logistic regression, and time series models have all been applied for assessing the risk or odds of various heat-related health outcomes as they relate to extreme heat exposure, though there is no consensus on which is most effective (Chen et al., 2017; Gasparrini et al., 2010; Van den Wyngaert et al., 2021). Prior studies have shown that the severity and duration of heat must both be taken into account while modeling health outcomes, in addition to other climate indicators, like air quality and humidity (Anderson & Bell, 2011; Arsad et al., 2022). While many definitions of heatwaves have been developed, there is no standardized threshold for what constitutes a heatwave, especially in relation to particular health events (Pascal et al., 2021; Tong et al., 2015). At an even more foundational level, there is continued debate on the best metric to characterize heat exposure (e.g., air temperature, heat index, Wet Bulb Globe Temperature (WBGT)) (Baldwin et al., 2023; Spangler et al., 2022). The heterogeneity of the methodological approaches for studying the association between heat and health reflects the diversity of geographic and cultural contexts from which they originate.

As the projected impacts from anthropogenic climate change worsen, it is imperative to understand the previous research on extreme heat morbidity and mortality that may inform future inquiries into mitigation policy thresholds and adaptation design. While some earlier reviews have reported study designs and analytical approaches for modeling heat exposure for specific adverse health events (Benmarhnia et al., 2015; Syed et al., 2022), none have described the extent of epidemiological methodologies employed for all types of heat impact studies. Such examples could help identify potentially relevant geographic, academic, or cultural similarities and differences within this topic. This scoping review seeks to close this gap by detailing the scope of epidemiological approaches adopted across the entire body of published English language literature for quantifying the impact of extreme heat exposure on all morbidity and mortality endpoints.

2. Methods

This review is reported in adherence to the PRISMA extension for scoping reviews (PRISMA-ScR) and followed the guidance and standards set in the literature (Colquhoun et al., 2014; Munn et al., 2018; Peters et al., 2015; Tricco et al., 2018). Our protocol was also drafted using items 1 and 3–13 of the PRISMA-ScR and was not registered or published. A medical librarian conducted searches in Embase (Elsevier), MEDLINE (Ovid), Web of Science (Clarivate), and Scopus (Elsevier) from date of inception until the date of the search, 1 March 2023. Keywords and subject headings were used to locate English language literature on heat vulnerability, statistical modeling, and adverse health events. Full search strategies are available in Table S1 in Supporting Information S1. After collation and deduplication in Endnote, records were uploaded to Rayyan (Ouzzani et al., 2016) for title and abstract screening.

Studies that met the inclusion criteria reported a direct measurement of ambient heat exposure, a direct measurement of any morbidity and/or mortality outcome, and an analytical method that measured the association between the two. No specific populations were excluded, and pediatric, maternal, military, prisoner, and all other adult studies were included. Studies were excluded if they failed to have direct heat or health measurements, such as systematic and scoping reviews and meta-analyses. Abstracts were screened twice with scoring from both a primary and secondary reader using an "Include," "Maybe," or "Exclude" designation. Abstracts with reader agreement for Include/Exclude were respectively assigned, and "Maybe" cases were re-reviewed by two separate readers with only Include/Exclude options. For instances where there was not agreement, the corresponding author made the final decision.

Following abstract screening, full texts were retrieved for the included studies and reviewed using the inclusion criteria. Full texts were read by two readers and classified as "Include" or "Exclude"; agreements were triaged respectively and disagreements were decided by a third author. Data from eligible studies were charted using a

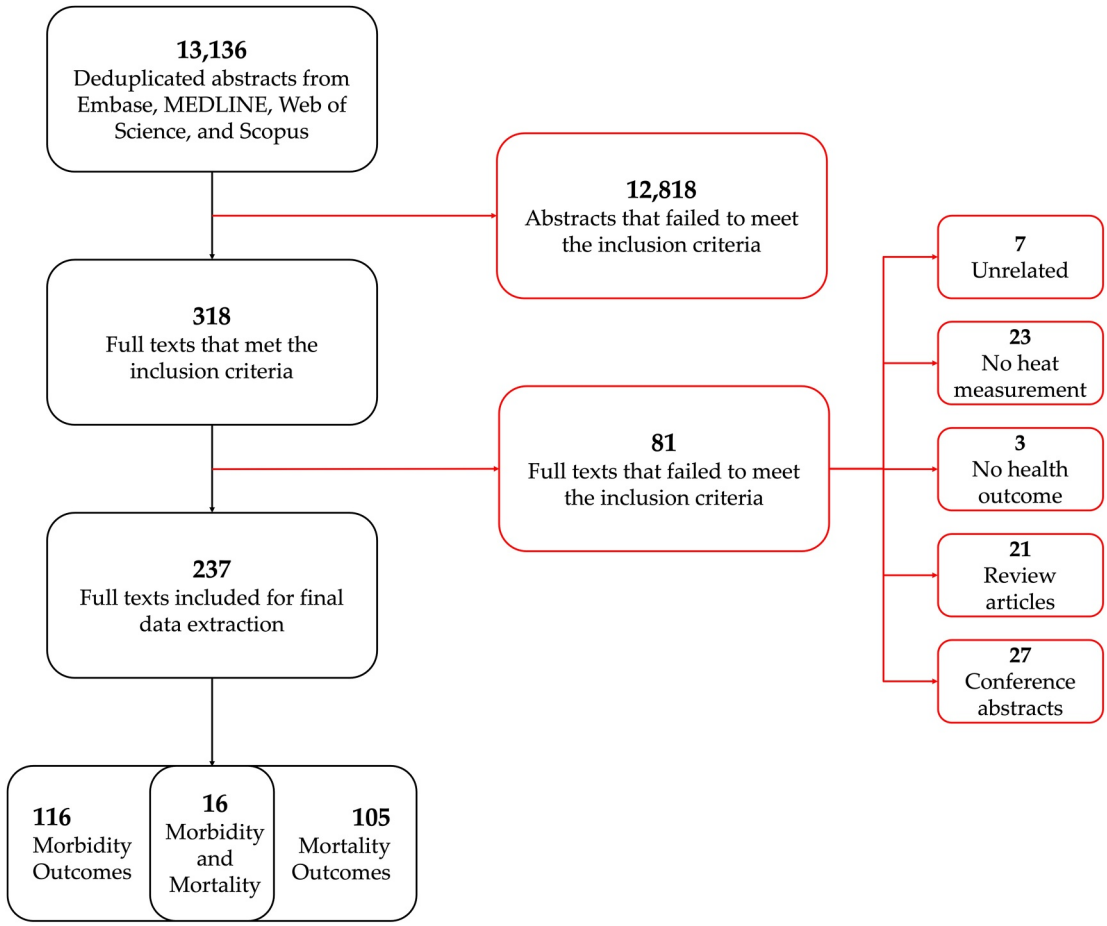

Figure 1. Flow chart of abstract and full text inclusion/exclusion.

standardized data abstraction tool designed for this study to abstract information on study characteristics pertaining to study methodology, heat definitions, and primary outcomes. Two reviewers independently charted data from each eligible article with disagreements iteratively discussed or final adjudication being provided by a third reviewer. Full text data extraction included the variables: journal information, publication year, country of study, duration of study, sample population, sample size, heat measurement method, heat measurement source, extreme heat definition, health outcome, health outcome source, analytic method, statistical value, significant findings, and key findings, among others. Study data were primarily reported using the classifications as specified by the authors within each text. If study design was not specified, it was inferred based on previously published epidemiological study design definitions (Belbasis & Bellou, 2018; Munnangi & Boktor, 2024).

3. Results

A total of 237 articles met the inclusion criteria and were eligible for data extraction (Figure 1). Nearly 80% of all included studies were published since 2015 with the majority of study data collection occurring between 2000 and 2009 (Table 1). The scope of the research represented 43 countries, with most studies conducted in China (62), the USA (44), and Australia (16). The global distribution of studies can be found in Figure S1 in Supporting Information S1. The studies collectively utilized 116 unique definitions of extreme heat, the most common of which was a percentile of daily mean temperature (T_{mean}) in °C for a certain duration, which was generally reported as 2 to 4 consecutive days for heatwave studies. Percentile thresholds ranged from 90th to 99th for classifying extreme heat. Studies included other temperature metrics such as daily maximum temperature (T_{max}), minimum temperature (T_{min}), apparent temperature (T_{app}), WBGT, with few studies opting for hourly, weekly, or monthly temperature measurement intervals.

Table 1
Study Attributes Across All Full Text Articles That Met Inclusion Criteria

		N (%)
Journal articles		237
Publication date	1995–2000	4 (1.7)
	2000–2005	1 (0.4)
	2005–2010	9 (3.8)
	2010–2015	34 (14.3)
	2015–2020	95 (39.8)
	2020-present	95 (40.1)
Study design	Case-control	8 (3.4)
	Case-crossover	70 (29.5)
	Cohort	21 (8.9)
	Cross-sectional	1 (0.4)
	Ecological	20 (8.4)
	Other	4 (1.7)
	Serial cross-sectional	2 (0.8)
	Time series	111 (46.8)
Primary analytic method	Distributed lag non-linear model	114 (48.1)
	Generalized linear model	34 (14.3)
	Conditional logistic regression	41 (17.3)
	Generalized additive model	12 (4.6)
	Cox proportional hazard	8 (3.4)
	Generalized estimating equations	2 (0.8)
	Other	27 (11.4)
Data collection start	1880–1889	1 (0.4)
	1970–1979	9 (3.8)
	1980–1989	19 (8.1)
	1990–1999	69 (29.2)
	2000–2009	96 (40.7)
	2010–2019	43 (17.9)
Primary outcome	CVD	61 (25.7)
	Diabetes	5 (2.1)
	Hospitalizations	25 (10.5)
	Infectious disease	13 (5.5)
	Maternal	23 (9.7)
	Mortality	65 (27.4)
	Neurological	20 (8.4)
	Renal	11 (4.6)
	Respiratory	14 (5.9)
Analysis period	0–5 years	60 (25.4)
	5–10 years	76 (32.2)
	10–15 years	46 (19.5)
	15–20 years	29 (12.3)
	20–30 years	14 (5.9)
	30+ years	11 (4.7)
Study duration (years, mean (SD))		10.56 (9.22)

Most studies measured heat exposure on a daily interval, and nearly all studies used daily count data for the health outcome response. Studies assessing health outcome count data in regression models mainly used Poisson or quasi-Poisson distributions. Researchers studied daily mortality (all-cause and cause-specific) most frequently, with 65 total studies, followed by cardiovascular disease (CVD) at 61, and general hospitalizations (all-cause and cause specific) at 25. Studies most frequently utilized the DLNM as the analytic method overall (48.1% of studies). Researchers most commonly used conditional logistic regression in case-control studies (5 of 8 studies, 62.5%) and in case-crossover studies (29 of 70, 41.4%). Researchers most commonly used the DLNM for ecological studies (13 of 20, 60.0%) and time series analyses (64 of 111, 57.7%). Of the three countries most represented, China and the USA most frequently utilized DLNMs (68.9% and 31.8%, respectively), with Australia mainly using conditional logistic regression (50%). Among countries with more than 1 study, China, Taiwan, and Iran used the DLNM the most frequently for all study designs. Australia was the only country to favor the conditional logistic regression for all respective study designs, while all other countries had heterogeneity in their most frequently used method and design (Figure 2).

When assessing study designs and methods for different health outcomes, there were few differences seen by health outcome type. However, case-control and case-crossover studies frequently used conditional logistic regression irrespective of health outcome, and DLNM was the most frequent for all other designs (Figure 3). Four maternal child health studies used Cox proportional hazard models, which can be attributed to measuring the impact of heat on time-to-event outcomes like pre-term birth, gestational age, or low birthweight.

3.1. Heat Measurement Data Sources

There were 141 unique climate data sources utilized across all included heat impact studies with variability based on study setting. The most common data source for heat measurement was the China Meteorological Data Sharing Service System from the China Meteorological Administration (34 studies), followed by the Australian Bureau of Meteorology (12 studies), and the US National Climatic Data Center (11 studies). Nearly all studies used local climate data sources which were specific to the respective study setting, with few choosing global climate data sets which only included the European Center for Medium Range Weather Forecasts (ECMWF) ERA-5 (9 studies), Weather Underground (2 studies), and the World Bank Climate Change Data Portal (1 study). Studies from Ghana, Brazil, China, Spain, and Australia all used the ERA-5 data set. While many studies used sensor measurements from weather stations or airports, recent studies from the US and Europe utilized regional hindcast and reanalysis products that resolve temperature and heat metrics at a high spatial resolution, such as gridMET, HadUK, Daymet, and PRISM.

3.2. Health Outcome Data Sources

Studies reported 200 different health outcome data sources, with many being regionally specific and from local databases. Queensland Health from Australia was the most used health data source overall (nine studies), with no other source being used more than 5 times in this review. Despite having the

Table 1
Continued

		N (%)
Continent	Africa	3 (1.3)
	Americas	63 (26.8)
	Asia	113 (48.1)
	Europe	40 (17.0)
	Oceania	16 (6.8)

Note. CVD: Cardiovascular disease, SD: Standard Deviation.

most studies total, the most frequent data source for studies from China was the China Center for Disease Control, which was used 5 times, while other studies primarily relied on local and regional hospital records. International Classification of Disease (ICD)-9 and ICD-10 diagnosis codes for various outcomes were utilized at least 61 times. Specific sources for particular outcomes and countries can be found in Table S2 in Supporting Information S1.

4. Discussion

This scoping review of peer-reviewed English literature helps to broaden the understanding of the scope of methodologies and data sources that have previously been applied in heat impact studies in diverse geographical settings for a variety of health outcomes. Whereas previous scoping or systematic reviews have focused on specific health events, no studies have synthesized the scope of heat impact literature as well as the data sources and analytic techniques used within it (Cheng et al., 2019; Liu et al., 2021; Syed et al., 2022). Our study found that the DLNM was the most commonly used analytic framework irrespective of health outcome type, especially in conjunction with the time series study design. We identified a spectrum of extreme heat thresholds in the literature that were not standardized for health event or study setting. We also found that 44.7% of English language literature on the topic originated from either China or the USA, with 1.3% of studies coming from Africa, 16.9% from Europe, and 6.8% from Oceania.

Other reviews have reported the methodological approaches that are typically used in heat impact studies, and some systematic reviews have reported the statistical values in meta-analyses for morbidity and mortality (Kovats & Hajat, 2008; Liu et al., 2022; Syed et al., 2022; Xu et al., 2016). These reviews identified case-crossover, time series, and cohort study designs to be some of the most common, along with Poisson

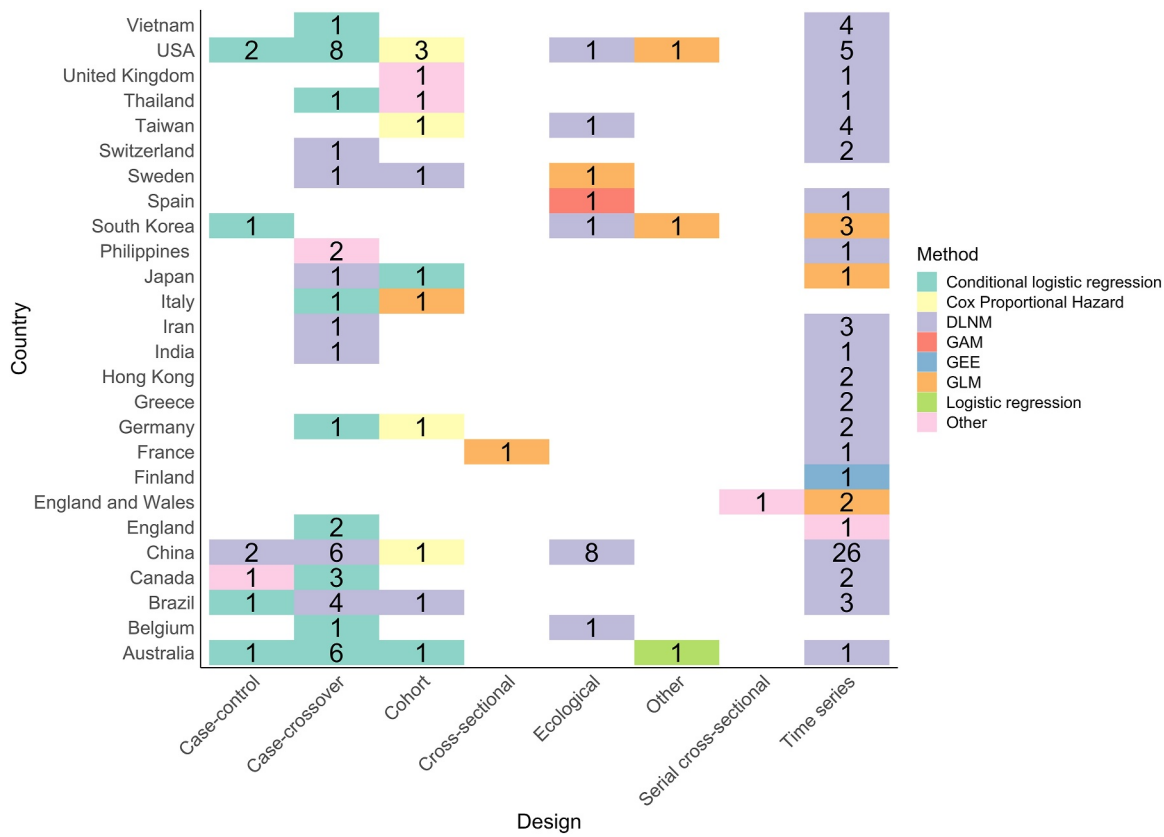

Figure 2. Tile plot of most utilized statistical method by study design for each country with >1 study. The value in each tile refers to the number of times used. DLNM: distributed lag non-linear model, GAM: generalized additive model, GEE: generalized estimating equations, GLM: generalized linear model.

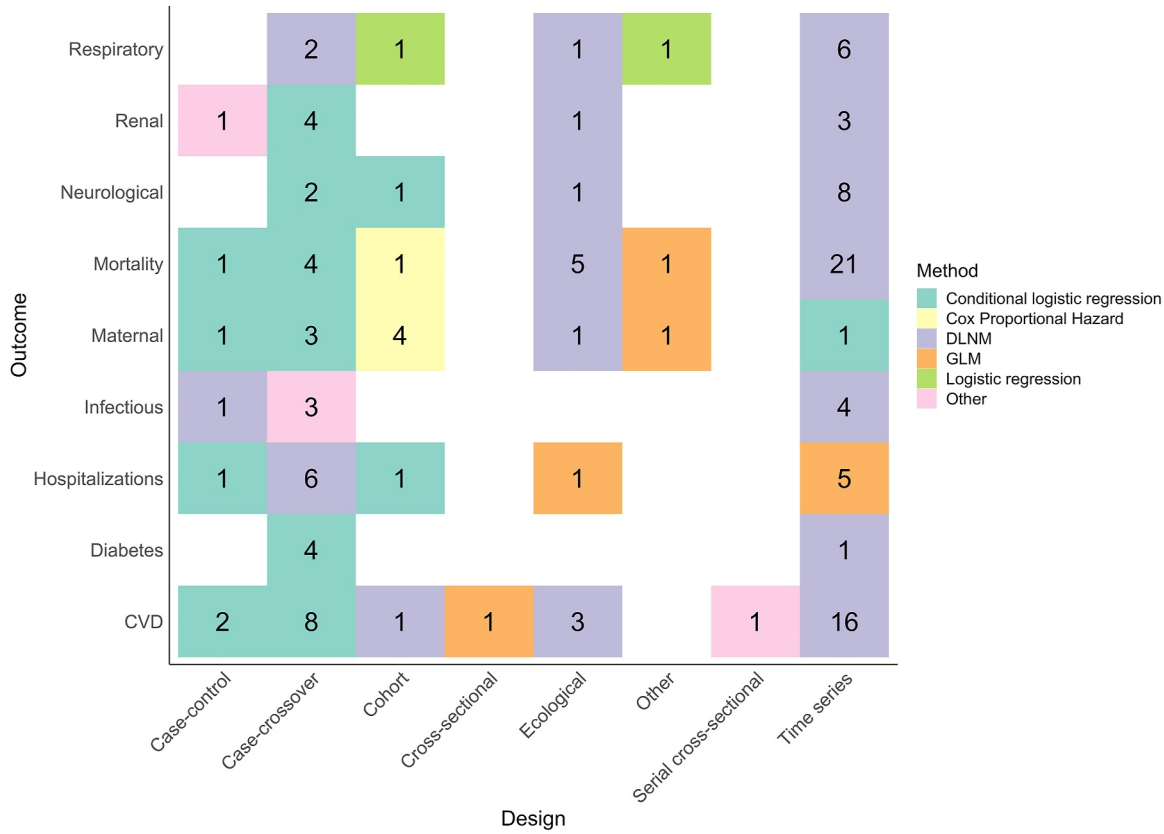

Figure 3. Tile plot of most utilized statistical method by study design for each specific primary health outcome. The value in each tile refers to the number of times used. CVD: cardiovascular disease, DLNM: distributed lag non-linear model, GLM: generalized linear model.

distribution regressions, general linear models, and survival analysis as some of the most common analytic methods. However, their findings are solely focused on a particular outcome of interest rather than the scope of methodological approaches across all health outcomes. Our study found that the DLNM was the most common framework for heat impact studies (48.1% of studies). The DLNM methodology was first proposed by Gasparrini et al. (2010) and has since become one of the most common analytic methods for heat impact studies (Gasparrini et al., 2010). While the DLNM model framework can effectively capture the nonlinear relationship between heat and health, it also has limitations in its statistical assumptions as well as the nonconformity of statistical models that are used in conjunction. Our study found that the DLNM was able to be incorporated into nearly every study design and for every type of health outcome, though it was most frequently used in mortality time series studies. We also found that there was a disparity in DLNM usage by country, as study settings in China used DLNM with a greater frequency than all other countries, while Australia predominantly used conditional logistic regression.

Some studies have characterized the scope of factors influencing the impact of extreme heat on health, which include comorbidities and ecological elements (Ebi et al., 2021). The primary outcomes that were determined relevant in these articles include CVD, respiratory disease, genitourinary disease, diabetes, gestational problems, mental health disorders, and medication use, among many others. Our review included studies from all of these outcome categories, while also identifying a small number of studies that evaluated niche health events less commonly associated with heat, such as tuberculosis, suicide, and meningitis (Jusot et al., 2017; Luan et al., 2019; Zheng et al., 2023). These infrequent events were reported in studies from countries such as Niger and the Philippines, which potentially demonstrates the divergence of research focus for various countries as they study the effects of climate change. Countries in the Americas and Europe have a large burden of chronic disease due to CVD, obesity, and kidney disease, hence the potential focus on the effects of heat on these outcomes. Meanwhile, countries in Africa and Southeast Asia have higher rates of certain infectious diseases like tuberculosis than Europe or North America (MacNeil et al., 2020). There is a global epidemiologic shift of disease patterns that is

partially spurred by climate change and extreme heat events (Atiim & Elliott, 2016). Based on our findings, many important health outcomes are understudied in heat impact English language literature because they are atypical events for the predominant study settings.

While the majority of the studies in our review focused on health endpoints that are normally attributed to heat effects like CVD and mortality, the minority of studies evaluating the lesser-studied health outcomes highlights the deductive nature of the field currently. Of 195 total countries in the world, 43 (22.1%) were represented in the scope of this review. Only 3 (1.3%) studies were from Africa; they originated from Ghana, Senegal, and Niger and the health outcomes of interest were stillbirths, all cause morbidity/mortality, and meningitis. No other studies evaluated the association between heat and meningitis morbidity, and two others in relative geographic proximity (Tehran and Western Australia) evaluated stillbirths. Birth complications and infectious disease outbreaks are more common in Africa relative to continents like North America and Europe, yet these outcomes are not studied in English language heat impact literature at the same rate as chronic conditions affecting populations with more developed public health infrastructure (Mboussou et al., 2019; Onambele et al., 2022). There may be a lack of public health data access in parts of the world with less developed public health surveillance and infrastructure. Our review found that access to health outcome data sources could be a major limiter to heat impact studies, as public health data sources in our review were regionally specific. Another possible explanation may be that small case numbers in limited data sets hinder analysis into less common health events. Our review demonstrates that case-control studies, which are a preferred study design for instances where the outcome is rare, are feasible in heat impact studies, though their efficacy should be confirmed in a systematic review.

Another finding from our review was the assortment of heat measurement sources and extreme heat definitions. It is well-documented in the literature that the lack of a standard definition for heatwaves is a challenge for heat impact studies (Pascal et al., 2021; Tong et al., 2015). The advent of advanced spatially-continuous climate reanalysis data, such as the European Center for Medium-Range Weather Forecasts (ECWMF) ERA-5 data set, provide investigators in any country with an accurate estimate of heat at a moderately high spatial resolution (31 km^2) (Buizza et al., 2005). ERA-5, in addition to other higher resolution local data sets, can provide granular estimates of heat exposure, thus improving the accuracy of heat impact studies. This suggests that researchers with access to health data can perform heat exposure and impact studies in any study setting, which could improve the representation of atypical health outcome studies in underserved parts of the world. Furthermore, studies in this review typically did not incorporate additional ecological elements in their models for associating heat with health risks, which indicates a gap in the literature that would benefit from further study.

There are a few limitations of this review due to its comprehensive nature. Though this scoping review followed PRISMA standards, it is likely that studies were unintentionally excluded through the search terms or review process. To our knowledge, there are no previously published or validated search term methodologies for this type of review, which perhaps can be attributed to a lack of consensus or standardized process for the query. However, this scoping review is the largest of its kind and we anticipate that the studies included accurately describe the extent of the relevant English language literature. Given the scope and size of the review, nine separate reviewers collaborated for abstract screening and full text review. While each reviewer was trained the same and used the same standards and data extraction sheet, there may have been variability in reporting style and language. Likewise, while bias was minimized during the abstract and text inclusion/exclusion process, final arbitration of disagreements for screenings following initial and secondary reviews was likely subjective and a known limitation while adhering to PRISMA-ScR guidelines.

Our study provides what we believe to be the most comprehensive overview of methodological approaches utilized in heat impact studies, which can serve as a resource for future researchers who aim to evaluate the effects of heat on health outcomes. This review focuses on studies with a measurement of association between heat exposure and health outcomes while also providing an in-depth summary of the types of methodological approaches deployed, which can help advance multidisciplinary research efforts and ultimately influence policies to mitigate the effects of climate change. Future studies could investigate the role of further climate variables such as air quality, humidity, and compound heat events, in addition to identifying the future morbidity and mortality impacts of extreme heat. The primary barrier to heat impact studies is data access, as public health data can be limited and climate data can be comparatively low resolution. Future heat impact studies should seek to harness robust public health data sets geocoded to high-resolution climate data as they are available. The creation and expansion of access to high-resolution climatological data which pertain to all continents and regions of the world

would help to facilitate research in this domain as well as potentially improve equitability through environmental justice. As the health impacts of anthropogenic climate change become more pronounced, it is essential for medical and public health investigators to be equipped with knowledge of past successes and effective tools for future actions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The full text PDFs that were retrieved following title and abstract screening cannot be shared directly due to publication copyright and licensing agreements, however the article metadata for all 318 texts and search terms are available at Graffy (2024).

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