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Review article

Accounting for adaptation when projecting climate change impacts on health: A review of temperature-related health impacts

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ABSTRACT

Exposure to high and low ambient temperatures can cause harm to human health. Due to global warming, heat-related health effects are likely to increase substantially in future unless populations adapt to living in a warmer world. Adaptation to temperature may occur through physiological acclimatisation, behavioural mechanisms, and planned adaptation. A fundamental step in informing responses to climate change is understanding how adaptation can be appropriately accounted for when estimating future health burdens. Previous studies modelling adaptation have used a variety of methods, and it is often unclear how underlying assumptions of adaptation are made and if they are based on evidence. Consequently, the most appropriate way to quantitatively model adaptation in projections of health impacts is currently unknown. With increasing interest from decisionmakers around implementation of adaptation strategies, it is important to consider the role of adaptation in anticipating future health burdens of climate change.

To address this, a literature review using systematic scoping methods was conducted to document the quantitative methods employed by studies projecting future temperature-related health impacts under climate change that also consider adaptation. Approaches employed in studies were coded into methodological categories. Categories were discussed and refined between reviewers during synthesis.

Fifty-nine studies were included and grouped into eight methodological categories. Methods of including adaptation in projections have changed over time with more recent studies using a combination of approaches or modelling adaptation based on specific adaptation strategies or socioeconomic conditions. The most common approaches to model adaptation are heat threshold shifts and reductions in the exposure–response slope. Just under 20% of studies were identified as using an intervention-based empirical basis for statistical assumptions.

Including adaptation in projections considerably reduced the projected temperature-mortality burden in the future. Researchers should ensure that all future impact assessments include adaptation uncertainty in projections and assumptions are based on empirical evidence.

1. Background

Ambient temperature-related morbidity and mortality occurs within most populations and is a direct public health risk posed by climate change. Increases in the frequency and intensity of extreme temperature are projected for the future, with average temperatures increasing year on year (Lee and Romero, 2023). Higher temperatures have been associated with increased morbidity and mortality globally, with estimates projecting that by 2099, mortality rates may increase by between 1.8 % and 6.2 % depending on the emissions scenario used for modelling (Bressler et al., 2021). Adaptation to these temperature changes will, therefore, be imperative to minimise health impacts since temperature-related health effects may be largely preventable with appropriate adaptation measures (Boeckmann and Rohn, 2014).

Adaptation to increasing temperatures may occur through different mechanisms, including natural acclimatisation (i.e., physiological adaptation) or through behavioural mechanisms (e.g., clothing choice, staying in the shade, drinking more water). Planned adaptation may also occur through interventions (for example, air-conditioning installation, changes to buildings and infrastructure, and public health measures

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such as heat health warning systems) (Macintyre and Murage, 2023). In addition to targeted interventions, the ability of individuals to prepare for, respond to, and recover from non-optimal temperatures is also influenced by wider socioeconomic factors (e.g., income, social network), hereafter referred to as “socioeconomic adaptive capacity” (Andrijevic et al., 2023). Understanding to what extent adaptation can affect future temperature-related health burdens is crucial for decision makers and communities when implementing adaptation strategies, with modelling studies often providing the evidence base for these decisions.

Projections of temperature-related health effects have been provided by many modelling studies (Gasparrini et al., 2017; Huang et al., 2011; Macintyre and Murage, 2023), however, most either do not include adaptation, or often include adaptation based on arbitrary assumptions, with no empirical basis. It is currently unclear what is the most appropriate way of incorporating adaptation into projections or indeed even if it is possible to determine this, making it difficult to understand and apply in health impact assessments (Gosling et al., 2017).

In this scoping review, we aim to identify, categorise, and describe methods for including adaptation in projections of temperature-related morbidity and mortality, determine the categories of empirical evidence for adaptation assumptions in projections and identify whether methods have changed or developed over time. Where possible, we quantify the impacts of including adaptation in future projected temperature-related health burdens compared to assumptions of no adaptation and identify factors to improve the reporting of modelling adaptation in projections.

2. Methodology

2.1. Data sources and search strategy

Searches were conducted in three scientific databases: Web of Science (Core Collection), PubMed and Scopus. Key search terms were ‘heat’, ‘mortality’, ‘projections’ and ‘climate change’, synonyms of these terms were used to complete this search. Search strategies are in Supplementary tables S1-3. To examine the effectiveness and validity of search terms, several key papers were identified beforehand, and a pilot search was conducted in Web of Science (Core Collection) to determine whether these articles were returned. For the full search, terms were then adapted for each database and restricted to the English language for practicality. All searches were carried out in December 2022 and repeated in June 2023.A snowballing method was used, whereby reference lists of reviews were hand searched for any additional relevant articles. All articles were exported into EndNote for reference management.

2.2. Inclusion criteria and screening

All studies that attempted to quantitatively incorporate adaptation into projections of temperature-related morbidity/mortality are included. Here we consider ‘adaptation’ to include any mechanism by which a population may adjust to temperature changes, including behavioural adaptation, physiological acclimatisation, interventions (such as heat health warning systems), actions that modify indoor heat exposure, actions that modify outdoor heat exposure and wider socioeconomic conditions that may affect a population’s adaptive capacity. Inclusion of only changes in demography or socioeconomic circumstances are not considered as adaptation unless the study clearly identifies that these drive an underlying assumption regarding an adaptive mechanism. We consider studies that included heat, cold or both, with no restriction on population or geographical area.

Articles were excluded if they focused on animal populations, if they did not look at future projections, only investigated exposure without quantifying health outcomes, did not include adaptation in future projections, if they estimated the amount of adaptation required to maintain current mortality levels, were not published in the English language, or if they were a form of review only with no new quantification. Conference abstracts or other non-peer-reviewed articles were also excluded.

Title and abstract screening were carried out by two independent reviewers, with recourse to a third reviewer in the case of disagreement. Full text screening was then carried out in the same manner. Full text screening was carried out in Rayyan, with exclusion reasons recorded for each article.

2.3. Data extraction and quality assessment

A data extraction form was drafted based on the aims of the review and information obtained from the full text screening stage, which was then piloted with two articles to identify areas that may need refinement. The form was then amended, and data extraction carried out by one reviewer, being checked over for consistency by a second reviewer. Any discrepancies were addressed through discussion or by recourse to a third reviewer where necessary.

Data extracted included: general study information, climate model information, population information, methods used to reflect adaptation, results of the study, and any limitations.

Formal quality assessment of the studies was not carried out because of the scoping nature of the review (Tricco et al., 2018) and the main objective of this review was to obtain insights on all methods that have been used to model adaptation. Nevertheless, the limitations of studies were discussed around the method categories. In addition, a category of empirical basis was assigned for each study (Section 2.4).

2.4. Data synthesis

The focus of the review was to identify and categorise the main methodological ways of including adaptation into future health projections. Several categories of methods were identified during the screening process and used to categorise study methodologies during data extraction and synthesis, and an iterative approach to category selection was used as screening proceeded.

The empirical basis of the adaptation assumption was categorised as follows: an empirical category of ‘Empirical Basis of Interventions’ is assigned to mostly intervention-based adaptation methods, i.e., have identified a specific factor to which a reduction in mortality can be attributed. A category of ‘Partial Empirical Basis’ is assigned to methods that make use of empirical findings, e.g., risk functions in others location, period or extrapolated based on the historical trend, but do not identify the specific adaptation factors. Methods that are based on hypothetical assumptions without empirical basis e.g., those that select an arbitrary threshold, are assigned a category of ‘Low empirical Basis’.

Where possible, the impact of including adaptation compared to not including adaptation in health projections was quantified. To demonstrate this using a consistent comparison, results were extracted for each paper under the following criteria:

- The 2050′s and furthest projection period reported
- Climate scenario RCP8.5 (or the closest possible warming scenario to this)
- No population changes (where included, the lowest population-change scenario)
- Highest adaptation scenario/level used

A percentage difference in mortality was then calculated for including adaptation in projections compared to not including adaptation in projections, that is the percentage change in impact of including adaptation was calculated using the projected increase in burden as the baseline, for example an adaptation that offsets the full amount of future increase in heat-related mortality (and so keeps mortality at the same level as present day) would be considered a 100 % change, but would not eliminate future health burden to zero. Due to the heterogeneity of studies and that formal quality assessment was not conducted, this is an initial explorative assessment aimed only to give an indication of the potential differences in the projected temperature-related health burden if adaptation is not considered.

3. Results

A total of 1,321 (+78 from updated searches) records were identified across databases. After duplicates and irrelevant studies were removed, 610 articles (+35 from updated searches) were retained for title and abstract screening. Fifty-nine studies were included in the final review (see Fig. 1 for flow of information through the review).

3.1. Location, focus and climate scenarios

Sixty percent of studies were conducted in Europe and Asia, with no identified studies in Africa. One study was conducted in South America, one in Oceania, twelve in North America and eight included data from multiple regions. Just over 60 % of studies included both adaptation and population changes in their projections. All studies used the health outcome of mortality, thirteen studies used condition-specific mortality (with nine of these only using condition specific and four of these using both all cause and condition specific mortality). Condition-specific mortality included cardiovascular, respiratory, ischemic heart disease, stroke, diabetes mellitus and cerebrovascular disease.

A variety of climate scenarios were used in studies, with most studies using official Inter Governmental Panel on Climate Change (IPCC) scenarios that have developed over time, including the Special Report on Emissions Scenarios (SRES) pathways (IPCC, 2000), the Representative Concentration Pathways (RCPs) (IPCC, 2013), and the more recent Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al., 2017). Most studies use RCPs (56 %) or SRES (25 %) scenarios. Four studies used SSP scenarios, two studies used KNMI (Koninklijk Nederlands Meteorologisch Instituut) climate scenarios (KNMI, 2015), and five studies used other bespoke climate scenarios (See Table 2 for details).

3.2. Methodological categories

Seven main categories of methods for including adaptation into future health projections were identified through the review, with an additional eighth category 'other' (see Table 1), which we describe in more detail below. The effect of the adaptation modelling approach on the pathway between temperature and health risk is illustrated in Fig. 2.

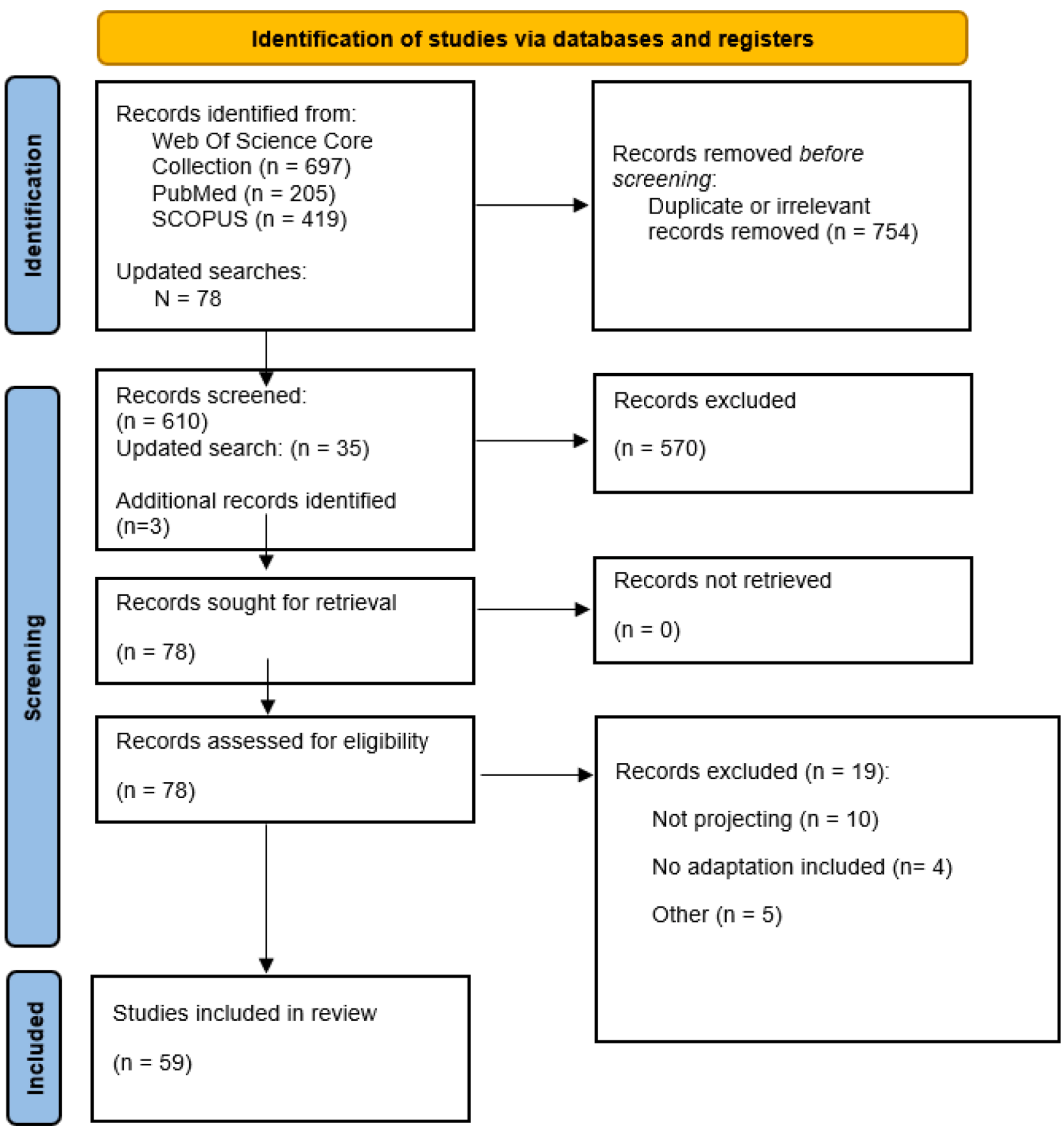

Fig. 1. Flow chart illustrating the flow of articles through the review following PRISMA guidelines (Matthew et al., 2021), from searches through to inclusion.

Table 1
Categories of methods for including adaptation into future health projections.

Category	Brief Description
I. Analogue location	Apply the historical risk function obtained or constructed for locations where their historical climate approximates the projected climate of the location under investigation.
II. Analogue period	Apply the risk function in the same location but in an analogue period which reflect the health effect under the adaptation scenario considered.
III. Shift in threshold or minimum mortality temperature (MMT, see the footnote)	Absolute shift: shifting the threshold temperature or MMT beyond which there is an elevated risk in the health outcomes by an absolute value of temperature. Relative shift: shifting the threshold/MMT relative to the change in the long-term climate under climate change.
IV. Adjustment of the slope or RR	Adjusting the slope of the risk function or RRs by a certain percentage.
V. Change in exposure through the built and natural environments	The effect of the built and natural environments such as land cover, use and buildings on the temperature that people are exposed to.
VI. Change in socioeconomic adaptative capacity	Modification or model the risk function using socioeconomic conditions that affect the adaptive capacity to heat and/cold, such as income and air conditioning prevalence.
VII. Combination of threshold shift (III) and slope/RR adjustment (IV)	Making adjustment on both the threshold/MMT and the slope/RR of the risk function.
VIII. Other	Other approaches cannot be categorised into the above categories.

Threshold shift: The term heat/cold threshold is used when separate shifts in the heat and cold thresholds are made, or only one of the heat and cold burdens are analysed. The shift in the MMT is used when the MMT represents the heat and cold thresholds, and both the heat and cold burdens are analysed.
Relative threshold shift on pace with climate change: an increase in the threshold temperature in line with climate change by applying the same temperature percentile to historical and future temperature distributions under climate change.
Relative threshold shift lagged to climate change: shifting the threshold temperature by a certain percentage of the temperature difference between the threshold temperature calculated by applying the same temperature percentile to the historical and future temperature distributions under climate change. For example, a 50% lagged relative threshold shift is a shift in the threshold temperature by 50% of the temperature shift under the relative threshold shift on pace with climate change scenario.

A common approach for performing health impact assessments is to apply a risk function obtained from epidemiological analysis of temperature and health outcomes (or exposure response function, ERF) (Gosling et al., 2017). The ERF characterises the relative risk (RR) of a health outcome with increase in exposure increment, which is often summarised using the slope of the ERF above (or below) a given threshold for attributing effects. This threshold can be defined as the temperature associated with the lowest health risk (i.e. minimum mortality/morbidity temperature, MMT)(Gasparrini et al., 2015; Huber et al., 2022), or a pre-determined temperature threshold (e.g. 95th percentile of location-specific temperature distributions)(Guo et al., 2018). Some studies applied the risk function characterised from one location to another location (Method Category I in Table 1) or different historical periods (category II) to the future to represent adaptation scenarios. In addition, modifications of the historical ERF by changing the slope (i.e., a smaller or larger increase in RR) or threshold (moving the threshold temperature at which health effects are attributed to effects of heat/cold) have also been used to represent a change in response (or 'adaptation') to the exposure (Category III, IV and VII). Socioeconomic variables can also be used explain historical risk functions, and future health risk is estimated using future socioeconomic values to integrate the effect of adaptation (Category VI) (Zhao et al., 2000). In addition to the modification of the risk function, another approach is maintaining the risk function, whereas estimating the health burden by modifying the exposure, e.g., through the built and/or natural environment to represent adaptation (Category V) (Taylor et al., 2021).

Studies were grouped by method and year of publication to determine the inclusion of adaptation in projections over time and whether methods had varied (see Fig. 3). Since 2018, there has been a considerable increase in the number of studies including adaptation in projections, with combination methods becoming more popular in recent years. The most used method is the threshold shift. Seven studies used either multiple or a combination of methods. Figures S1 and S2 in the supplementary information provide a visual breakdown of the year of publication of studies and the proportion of studies using each methodology for further information.

3.2.1. *Analogue location*

The analogue location method (Category I) assumes that people in the location under investigation will acclimatise and adapt to temperatures as people in the analogue (usually hotter) locations have achieved at present. This is based on evidence from epidemiological studies that populations in warmer places tend to be less sensitive (and therefore more adapted) to higher temperatures, and similar findings have been discovered for cold as well, which are likely due to acclimatisation and adaptation (Anderson and Bell, 2009; Curriero et al., 2002; Keating and Donaldson, 1997). Some studies identify analogue locations and directly apply their risk functions to the location of interest to represent adaptation scenario. For example, Knowlton et al. (2007) applied the risk function derived from two US cities, Washington, DC and Atlanta, GA to New York as the adaptation scenario because the present climate of Washington and Atlanta are within 1°F of the projected climate in the New York region in the 2050 s under climate change scenario SRES A2. In another study, Mills et al. (2015) calculated the 1st and 99th percentile of temperature distributions in 33 US cities as the cold and heat thresholds respectively and applied the highest historical threshold temperature among the 33 cities to all cities in 2100 to represent the scenario of adapting to a warming climate. Another study used the analogue location method, however the specific analogue locations were not stated (Li et al., 2018c).

Rather than applying the risk function in analogue locations directly, one study in the US constructed a uniform risk function for different locations using city-specific summer mean temperature as a predictor (Shindell et al., 2020). This uniform risk function is assumed to reflect acclimatisation and adaptation to regional climate and is used to derive the future risk function using the projected climate under adaptation scenario.

3.2.2. *Analogue period*

Instead of using the risk function in analogue locations, another approach to model adaptation is to use the risk function in the same location but in an "analogue period" (Category II). This method assumes that people will most likely respond to heat under climate change conditions as they do today during some special periods when acclimatisation and adaptation may have occurred. Two studies in this review found a lower heat susceptibility in hot summers compared to other summers, which was likely due to short-term acclimatisation to high temperatures (Cheng et al., 2008; Kalkstein and Smoyer, 1993). Therefore, the risk function in hot summers was applied to the future under global warming representing an acclimatised scenario in these two studies. Lay et al. (2021) fitted the risk function separately in four historical periods in the US and found a lower and higher risk in the first and last periods respectively, and hence applied the risk function in these two periods to the future as an approximation of a low and high adaptation scenario respectively.

Like the analogue location method of constructing a uniform risk

Table 2
Summary characteristics of included studies.

Citation	Adaptation Method/s Used (From Table 1 categories)	Climate Scenarios Used[a]	Health Outcome Data[b]	Location
Abadie and Polanco-Martinez (2022)	III	RCPs: 4.5, 8.5	Mortality	Europe
Aboubakri et al. (2020)	III and IV	RCPs: 2.6, 4.5, 8.5	Mortality	Asia
Ballester et al. (2011)	III	SRES A1B	Mortality	Europe
Botzen et al. (2020)	III	KNMI: G, G+, W, W+	Mortality (all cause)	Europe
(Bressler et al., 2021) (Gasparrini et al., 2017)	VI	RCPs: 2.6, 4.5, 6.0, 8.5	Mortality (all cause or non-external cause)	Multi-region
Carleton et al. (2022)	VI	RCPs: 4.5, 8.5	Mortality	Multi-region
Chaston et al. (2022)	V	RCPs: 8.5	Mortality (all cause)	Oceania
Cheng et al. (2008)	II	SRES: A2, B2	Mortality (non-traumatic) ICD-6 (1953–1957): 001–795; ICD-7 (1958–1968): 001–795; ICD-8 (1969–1978): 000–796; ICD-9 (1979–1999): 001–799; ICD-10 (2000): A00–R99	North America
Dessai (2003)	III	SRES: A1, A2, B1, B2	Mortality (all cause)	Europe
Díaz et al. (2019)	III	RCPs: 4.5, 8.5	Mortality (natural cause) ICD-10: A00-R99	Europe
Diniz et al. (2020)	III	RCPs: 4.5, 8.5	Condition Specific Mortality (respiratory and cardiovascular) ICD-10: I00-J99	South America
Dong et al. (2020)	III	RCPs: 4.5, 8.5	Condition Specific Mortality (respiratory) ICD-10 A00-R99	Asia
El-Fadel and Ghanimeh (2013)	III	SRES: A1, A2, B1, B2	Mortality (All-cause)	Asia
Fronzek et al. (2022)	III	RCPs: 4.5, 8.5	Mortality	Europe
Gosling et al. (2009)	III	SRES A2	Mortality (all cause)	Multi-region
Guo et al. (2018)	III	RCPs: 2.6, 4.5, 6.0, 8.5	Mortality (all cause or non-external cause) ICD-9: 0–799; ICD-10: A00–R99	Multi-region
Hales (2014)	III	SRES A1B	Mortality (all cause)	Multi-region
Heutel et al. (2021)	I	RCPs: 8.5	Mortality	North America
Honda et al. (2014)	III	SRES A1B	Mortality (all cause)	Multi-region
Huang et al. (2018)	VII	RCPs: 2.6, 4.5, 8.5	Condition Specific Mortality (Cardiovascular) ICD-10: I00-I99	Asia
Huang et al. (2019)	III	RCPs: 2.6, 4.5, 8.5	Condition Specific Mortality converted to YLL (Ischaemic heart disease) ICD10: I20-I25	Asia
Huber et al. (2022)	III	SSPs: 126, 370	Mortality (Non external cause) ICD-9: 0–799; ICD-10: A00-R99	Europe
Huynen and Martens (2015)	VII	KNMI: G_L, G_H, W_L, W_H	Mortality (all cause and cause specific for cardiovascular and respiratory)	Europe
Hyun et al. (2021)	VIII	RCP 8.5	Mortality	Asia
Jenkins et al. (2014)	III	SRES: B1, A1F1	Mortality	Europe
Kalkstein and Smoyer (1993)	II	NASA Goddard Institute for Space Studies (Doubled CO_2) scenario	Mortality	Multi-region
Knowlton et al. (2007)	I	SRES: A2, B2	Mortality (daily non-accidental) ICD-9 0 to 799.9	North America
Kouis et al. (2021)	III and V	SSPs: 1–2.6, 2–4.5, 3–7.0, 5–8.5	Condition specific mortality (cardio-respiratory mortality)	Europe
Lay et al. (2021)	II	RCP: 8.5	Mortality (all non-accidental)	North America
Lee et al. (2019)	VII	RCPs: 4.5, 8.5	Mortality (all non-accidental) ICD-10:A00-R99	Asia
Li et al. (2016)	VII	RCPs: 4.5, 8.5	Mortality (all non-accidental) ICD-10: A00-R99	Asia
Li et al., (2018a)	VII	RCPs: 2.6, 4.5, 8.5	Mortality converted to YLL(condition specific) ICD 10: I60-I69	Asia
Li et al., (2018b)	VII	RCPs: 2.6, 4.5, 8.5	Mortality converted to YLL (condition specific) ICD-10:I00-I99	Asia

(continued on next page)

Table 2 (*continued*)

Citation	Adaptation Method/s Used (From Table 1 categories)	Climate Scenarios Used[a]	Health Outcome Data[b]	Location
Li et al., (2018c)	I	RCPs: 2.6, 4.5, 8.5	Mortality (all cause)	Asia
Liu et al. (2019)	VII	RCPs: 2.6, 4.5, 8.5	Mortality converted to YLL ICD 10: A00-R99	Asia
Liu et al. (2023)	III	SSPs: 2–4.5, 5–8.5	Mortality (all cause) ICD 10: A00-Z99	Asia
Martens (1998)	VII	Warming of 1.2 degrees	Mortality (all cause and condition specific cardiovascular and respiratory)	Multi-region
Martinez et al., (2018a)	III	RCP 8.5	Mortality (all cause) ICD-10: A00-R99	Europe
Martinez et al., (2018b)	III	RCP 8.5	Mortality (all cause) ICD-10: A00-R99	Europe
Marvuglia et al. (2020)	V	RCP 8.5	Mortality	Europe
Mills et al. (2015)	I and III	REF and POL3.7	Mortality	North America
Muthers et al. (2010)	II and IV	SRES: A1B, B1	Mortality	Europe
Ostro et al. (2011)	VI	SRES: A2, B1	Mortality (all non-accidental, cardiovascular, respiratory) ICD-10 codes A through U ICD-10 code I ICD-10 code J Morbidity (respiratory and cardiovascular hospitalisations) ICD-9 390–459 ICD-9 460–519	North America
Petkova et al. (2017)	IV	RCPs: 4.5, 8.5	Mortality (all cause)	North America
Rai et al. (2022)	IV and VI	SSPs: 1–2.6, 3–7.0	Mortality (all non-accidental and condition specific cardiovascular)	Europe
Rodrigues (2023)	III	RCP 8.5	Mortality (All cause and condition specific) Diabetes mellitus (ICD-9: 250; ICD-10: E10-E14) Ischemic heart disease (ICD-9: 410–414; ICD-10: I20-I25) , Cerebrovascular disease (ICD-9:430–438; ICD-10: I60-I69) Respiratory disease (ICD-9: 460–519; ICD-10: J00-J99)	Europe
Rohat et al. (2019)	V and VI	RCPs: 4.5, 8.5	Mortality (all non-accidental)	North America
Sheridan et al. (2012)	VIII	SRES: A1F1, A2, B2	Mortality (all cause)	North America
Shindell et al. (2020)	I and III	RCPs: 2.6, 4.5, 8.5	Mortality (all cause)	North America
Stone et al. (2014)	V	RCP 4.5	Mortality (all cause and all non-accidental)	North America
Taylor et al. (2018)	V	SRES A1B	Mortality (all cause)	Europe
Taylor et al. (2021)	V	Medium and High emissions	Mortality	Europe
Trajer et al. (2022)	V	RCPs: 2.6, 4.5, 6.0, 8.5	Mortality (all non-accidental)	Europe
Wang et al. (2018)	II	RCPs: 2.6, 4.5, 6.0, 8.5	Mortality (all non-accidental)	North America
Wang et al. (2019)	VI	Warming of 1.5° and 2°	Mortality (all non-accidental, cardiovascular and respiratory) ICD-10: A00-R99 I00–I99 J00–J99	Asia
Wang et al. (2022)	VII	RCPs: 2.6, 4.5, 6.0, 8.5	Mortality (all non-accidental)	Asia
Watkiss and Hunt (2012)	III	SRES: A2, B2	Mortality (all cause)	Europe
Zacharias et al. (2015)	III	SRES A1B	Condition specific mortality (ischemic heart disease) ICD10: I20–I25	Europe
Zhang et al. (2018)	III	RCPs: 2.6, 4.5, 8.5	Condition specific mortality (cardiovascular) ICD10: I00-I99	Asia

a) SRES = Special Report on Emissions Scenarios pathways (IPCC, 2000). RCPs = Representative Concentration Pathways (RCPs) (IPCC, 2013). SSPs = Shared Socioeconomic Pathway (SSP) scenarios (Riahi et al., 2017). KNMI (Koninklijk Nederlands Meteorologisch Instituut (KNMI, 2015). YLL = Years of Life Lost.
b) Cause-specificity is included as reported in the original study, therefore where 'Mortality' alone is referred to, no further classification has been reported in the selected study. ICD = International Classification of Diseases.

function using data from multiple locations, a uniform risk function can also be constructed using data in different time to reflect temporal acclimatisation/adaptation. For example, Wang et al. (2018) used an interaction term of the occurrence of heatwave and mean summer temperature in individual summers between 1962 and 2006 to predict the mortality risk during heatwaves in the US to represent the risk under the adaptation scenario of seasonal heat acclimatisation.

3.2.3. *Shift in threshold or MMT*

The most used method to integrate adaptation to the projection of temperature-related health burdens is by shifting the threshold temperature. Some of the studies assumed an increase in the heat threshold by a fixed value. For example, an increase of 1 °C in the heat threshold every 3 decades was assumed by Dessai (2003) and Watkiss and Hunt (2012), a 0.25 °C increase in threshold every 2 decades was used in Wang et al. (2022) and an increase of 1–4 °C was used for future periods in various studies (El-Fadel and Ghanimeh, 2013; Gosling et al., 2009; Jenkins et al., 2014).

Another method of modelling acclimatisation and adaptation in a warming climate is a shift of the threshold temperature proportional to the projected change in long-term average temperature (Ballester et al., 2011; Huang et al., 2018; Huynen and Martens 2015). This method is

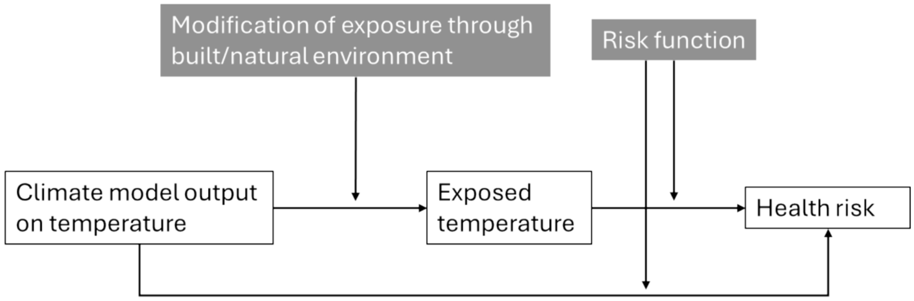

Fig. 2. The effect of the adaptation modelling approach (grey square) on the pathway between temperature and health risks.

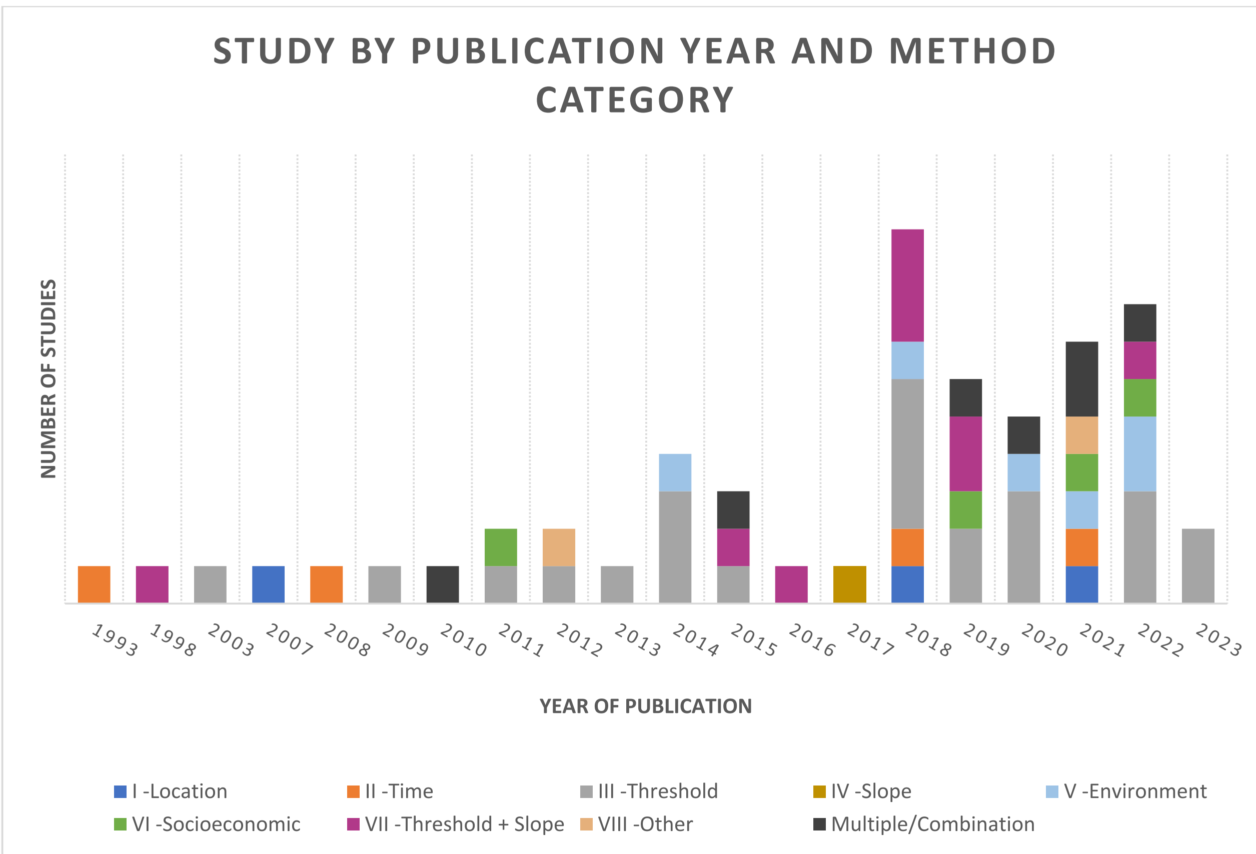

Fig. 3. Use of statistical method for incorporating adaptation across time. Studies are grouped by year and methodological category. Methodological categories correspond to those in Table 1.

based on previous findings of a positive correlation between the MMT and annual average temperature. For example, the MMT was found to increase by 0.73 °C per 1 °C rise in mean summer temperature (MST) over time, and by 0.84 °C per 1 °C rise in MST across cities in Spain (Huber et al., 2022).

Some papers used a relative threshold approach, which assumed the percentile to which the heat/cold threshold corresponds remains constant over time, with further assumptions of "full-pace" (see footnote of Table 1) adaptation (Díaz et al., 2019; Diniz et al., 2020; Guo et al., 2018; Liu et al., 2023; Shindell et al., 2020) and "lagged" adaptation (Abadie and Polanco-Martinez, 2022; Hales, 2014; Honda et al., 2014; Zacharias et al., 2015; Zhang et al., 2018). Shifting the threshold temperature by annual average temperature change focuses on the adaptation to the long-term change in the average climate while the relative threshold approach considers the change in climate variability (Shindell et al., 2020).

3.2.4. *Adjustment of the slope or RR*

The slope of the risk function or RRs can be used to represent people's susceptibility to ambient temperatures, and their changes have been used to reflect effects adaptation. A range of up to a 50 % reduction in the heat slope has been applied in the studies reviewed (Aboubakri et al., 2020; Huynen and Martens 2015; Li et al., 2018a; Li et al., 2018b; Li et al., 2016; Martens, 1998).

Some studies shifted the slope or RRs by extrapolating their historical trend. Muthers et al. (2010) explored the historical trend in heat susceptibility in Vienna, Austria between 1970 and 2007. When a significant historical trend was observed, the trend was extrapolated linearly into the future. If there was no significant historical trend, the susceptibility at the end of the historical period was applied to the future. Petkova et al. (2017) found a decreasing trend in the temperature-specific RRs in New York in the 1900 s-2000 s, which was extrapolated to the end of the 21st century while assuming a further 20 % and

80 % reduction in the RRs in 2100 compared to the 2000 s to represent two adaptation scenarios. Similarly, Lee et al. (2019) estimated temperature-specific RRs in 1991–2000 and 2006–2015, and the trend therein was extrapolated into the future up to 2100 using a sigmoid function assuming an 80 %, 50 % and 20 % reduction in temperature-specific RRs in 2100 compared to 1991–2015 to represent three adaptation scenarios.

3.2.5. *Change in exposure through the built and natural environments*

The modification of land surface type, albedo, vegetative cover or building conditions on the reduction of heat exposure has been utilised as the mechanisms of adaptation in various studies. These studies usually construct the adaptation scenario of a 30 %-100 % utilisation of a modification measure (e.g. green roof, shutter, insulation) and the associated temperature-related mortality (Marvuglia et al., 2020; Stone et al., 2014; Taylor et al., 2018). Some studies do not assume the specific climate mitigation measures in the future, while assuming the elimination of the UHI effect as a whole (Chaston et al., 2022).

Instead of making arbitrary assumption of the changes in the natural and built environments, a study applied the current building retrofit rate including demolition and insulation to the future to estimate the future building conditions and the associated temperature exposure and mortality burden (Taylor et al., 2021). To integrate the effect of different probable changes in land use due to different socioeconomic trajectories, the SSPs were used by a study to project the fraction of main urban land use types in Great Houston, US, which were downscaled from and hence in line with global population and land use projections under the SSPs (Rohat et al., 2019).

3.2.6. *Change in socioeconomic adaptative capacity*

Socioeconomic factors can have a strong effect on the adaptive capacities to ambient temperature (Section 1). The effect of socioeconomic factors on the susceptibility to ambient temperature can be assessed as by including it as a predictor in the risk function using historical data, then the future risk function is determined based on assumptions or projections on the values of the socioeconomic factors (Bressler et al., 2021; Carleton et al., 2022; Huber et al., 2022; Shindell et al., 2020; Wang et al., 2018). Recently, the SSP framework has been increasingly utilised to explore plausible future values of socioeconomic variables (Bressler et al., 2021; Carleton et al., 2022; Kouis et al., 2021; Rai et al., 2022; Rohat et al., 2019).

GDP and income per capita were most widely used as an indicator of socioeconomic adaptive capacity to ambient temperatures (Bressler et al., 2021; Carleton et al., 2022; Wang et al., 2019). The prevalence of using air conditioning (AC) was also used as a predictor in the heat risk function or the MMT (Kouis et al., 2021; Ostro et al., 2011). Key socioeconomic factors investigated in the studies included in this review include population ageing, AC prevalence, social isolation, ethnicity and poverty, which were identified as strong predictors of summer mortality in Greater Houston, US (Rohat et al., 2019).

3.2.7. *Combination of threshold shift and slope/RR adjustment*

This method employs a shift in the threshold and an adjustment of the slope/RR at the same time (individual adjustment methods are explained in Section 3.2.3 and 3.2.4). A schematic illustration of the effect of threshold shift, slope adjustment and a combination of these methods on the exposure–response relationship between high temperature and relative risk of mortality is shown in Fig. 4. For example, Huynen et al. (2015) constructed adaptation scenarios of a shift in the threshold proportional to the projected global warming level, a 10 % decrease in the heat slope, as well as a combination of these two adjustments. Similarly, Lee et al (2019) used three different threshold shifts (1 °C, 2 °C and 3 °C increase) and three different slope reductions (10 %, 20 % and 30 %) in combination to provide nine combination

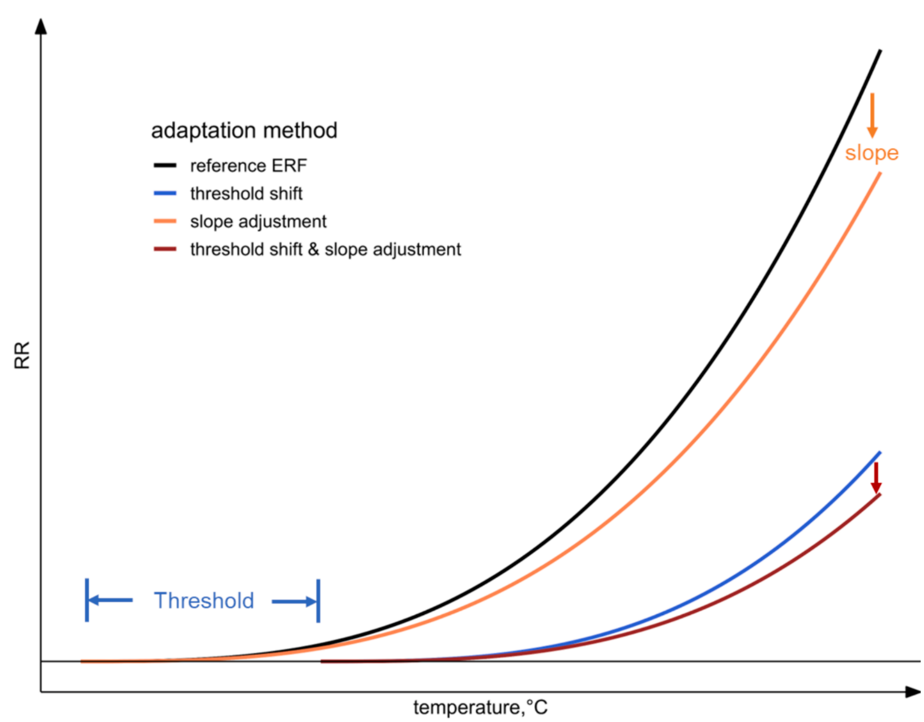

Fig. 4. Schematic illustration of threshold shift, slope adjustment and a combination of these approaches. RR = relative risk. The threshold shift method moves the curve further to the right of the graph representing an increase in the temperature at which we begin to see higher risk of heat-related mortality (from blue/orange curve to blue/red curve). The slope adjustment method moves the curve further towards the bottom of the graph and demonstrates an alteration in the rate at which increasing temperature affects the risk of mortality above the defined threshold (from black/blue curve to orange/red curve). A combination approach shows an increase in the temperature at which we begin to see higher risk of heat-related mortality alongside a reduction in the rate at which increasing temperature affects risk of mortality above that threshold (from black to red curve). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenarios. Fig. 4 shows that the threshold shift method moves the temperature-mortality curve to the right representing an increase in the temperature at which we begin to see higher risk of heat-related mortality (from blue/orange curve to blue/red curve). The slope adjustment method moves the curve further towards the bottom and demonstrates an alteration in the rate at which increasing temperature affects the risk of mortality above the defined threshold (from black/blue curve to orange/red curve). A combination approach shows an increase in the temperature at which we begin to see higher risk of heat-related mortality alongside a reduction in the rate at which increasing temperature affects risk of mortality above that threshold (from black to red curve).

3.2.8. Other

In one study, acclimatisation was modelled by estimating excess deaths during heatwaves but neglecting all heat-related mortality that occurred in the first 3 days of a given heat episode (Sheridan et al., 2012). This method assumes that people gain short-term acclimatisation after being exposed to high temperatures. However, the lower mortality risk in the days after the initial three days of a heatwave may not only be due to acclimatisation but could be a combination of short-term acclimatisation and mortality displacement.

Another study designed adaptation strategies considering a series of interventions including urban greening, cooling centre, road sprinkle and heat warning in terms of their adaptation effect, maximum units each intervention can be implemented and the cost Future heat-related mortalities are projected under scenarios of adaptation target and budget level (Hyun et al., 2021).

3.3. Empirical basis

To determine the level of empirical evidence used for adaptation assumptions in projections, papers were categorised into three groups (see section 2.4 for further description of each category). Twenty-four studies were categorised as ‘Low Empirical Basis’, 25 studies as ‘Partial Empirical Basis’ and 10 studies as ‘Empirical Basis of Interventions’. Less than 20 % of studies were categorised as having an intervention-based empirical basis for adaptation assumptions.

3.4. Impacts of including adaptation in projections

Where possible, the percentage change in mortality/morbidity between including and not including adaptation in projections was calculated for extracted results. This was carried out to give an indication of the potential differences in the projected temperature-related health burden, however, did not include all climate, adaptation or population scenarios presented across the studies (See section 2.4 for the results extraction criteria and Table S4 for a summary table of extracted results).

Fig. 5 (and Fig. S3a-c) shows the percentage change in mortality between including vs not including adaptation for the furthest projection period reported (for all studies this was between the years of 2050 to 2100). Most studies report a considerable reduction in future temperature-related mortality (particularly for heat-related mortality) when including adaptation compared to not. One study (Rohat et al., 2019) reported elevated heat-mortality burden which is likely due to the adaptation result that has been extracted. The result extracted from this study was one which modelled mortality along with changes in land use/urbanisation under SSP scenarios, which includes narratives around the contribution of land use to Urban heat island (UHI) effects.

For those studies reporting on cold-related mortality, most studies report an increase in cold-related deaths, which is likely due to the adaptation methods being employed (threshold shift). This threshold shift method assumes that the threshold temperature increases for heat, but as a result, also increases for cold, meaning that the population may lose adaptation or acclimatisation to cold in the future, further discussed in Section 4.

There is no indication that the methodological category has an impact on the mortality reductions reported (Fig. 6 and Fig. S4a-c). There is large variation in the adaptation effect within each empirical basis category (Fig. 7) meaning it is difficult to determine whether the empirical basis category affects the mortality reductions reported. Though a formal regression is perhaps not appropriate based on the empirical basis categorisation developed here, there appears to be a larger overall estimated effect of adaptation from studies applying methods that are based on arbitrary assumptions, though other specification such as climate scenario, demographic change and location of

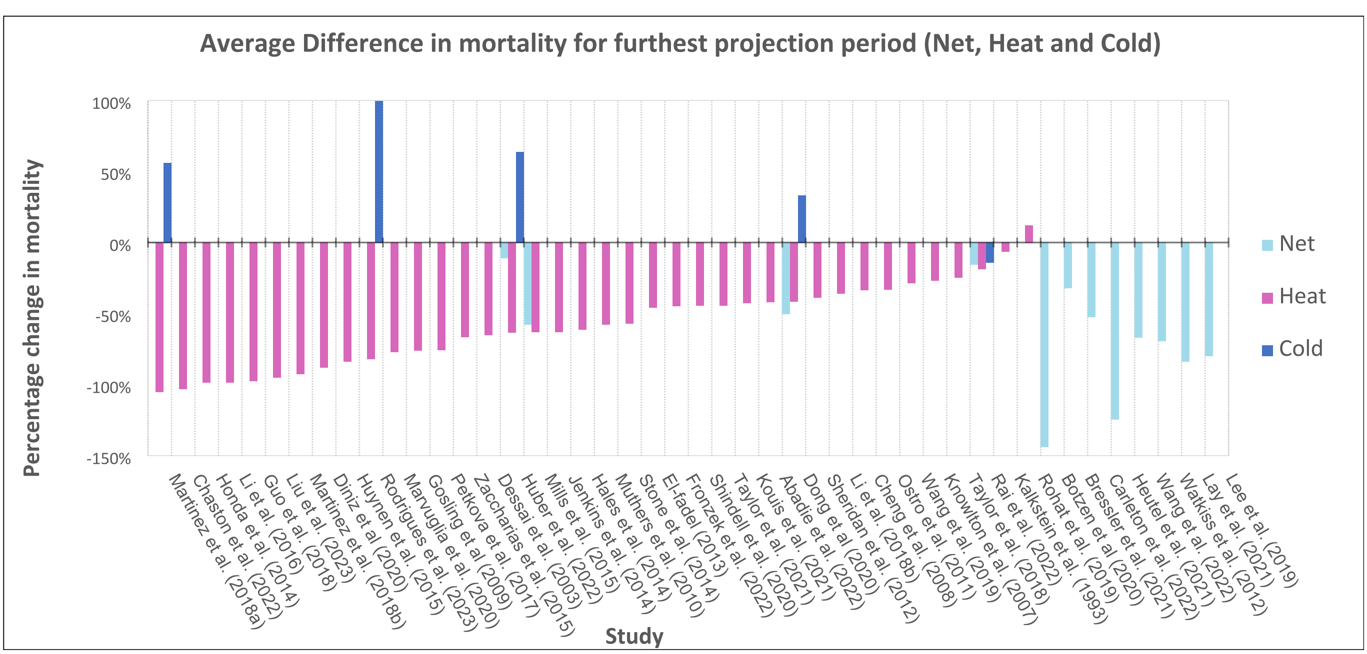

Fig. 5. The average percentage change in net, heat and cold related mortality when including adaptation in future projections compared to not including adaptation, ordered by impact on heat-related mortality. The furthest projection period was selected for this plot. Where an average in the data was not available, the midpoint of a range was calculated. Outliers were removed from the plot (those either above + 150 % or below −150 %).

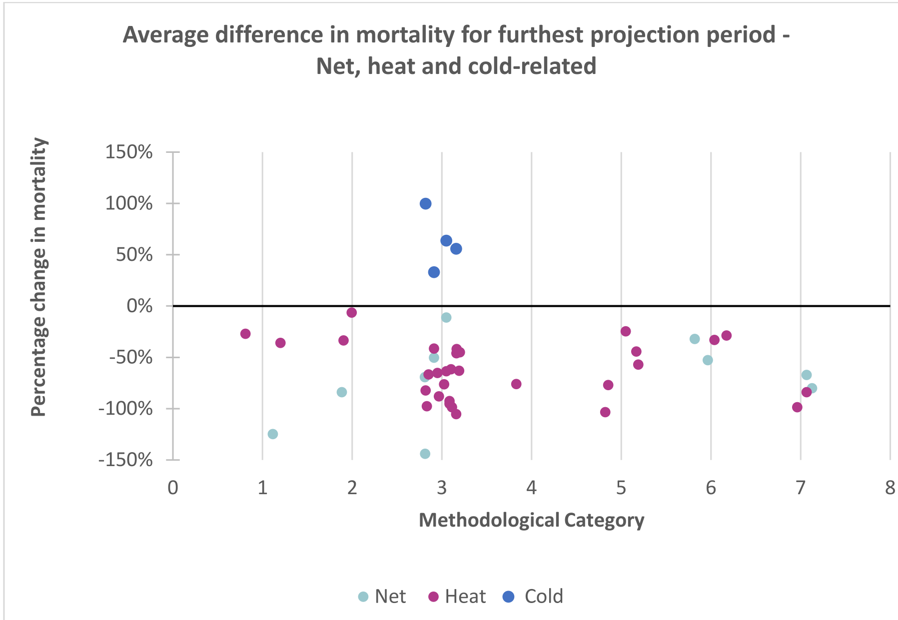

Fig. 6. The average percentage change in mortality when statistically including compared to not including adaptation in future projections, grouped by methodological category. The furthest projection period was selected for this plot. Where an average in the data was not available, the midpoint of a range was calculated. Studies that used multiple methods were excluded from the plot, along with outliers (any numbers that were above + 150 % or below −150 %).

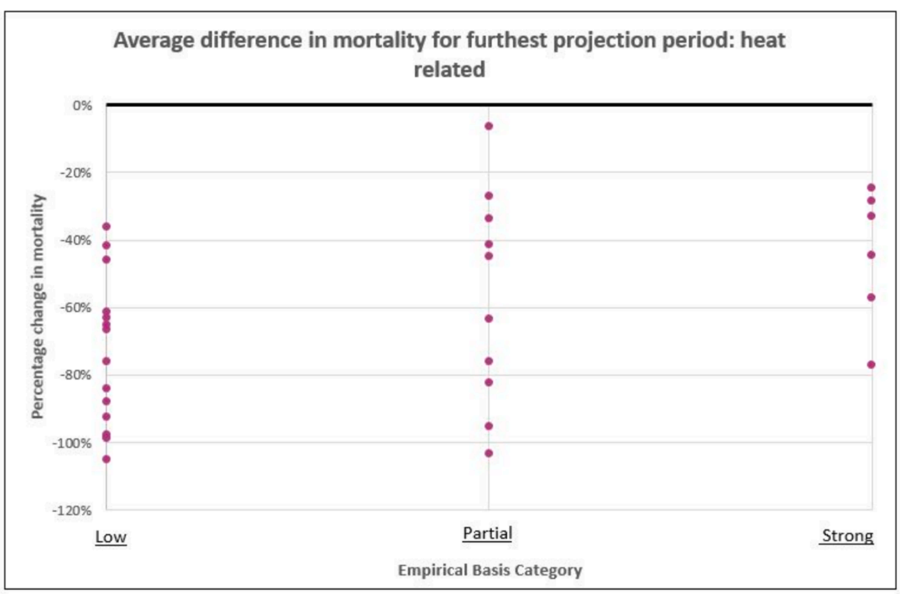

Fig. 7. The average percentage change in heat-related mortality when statistically including compared to not including adaptation in future projections, grouped by empirical basis category. Heat-related results were chosen for plotting due to this category having the largest number of data points. Categories correspond to those described in section 2.4: Low = Low Empirical Basis, Partial = Partial Empirical Basis, Strong = Empirical basis of Interventions.

interest also play a role in the size of the overall effect.

4. Discussion

4.1. Main findings

This review identified 59 studies that modelled adaptation in mortality projections. Seven main categories of methods were identified, with two studies assigned to an eighth category ‘other’. We found that methods of including adaptation do appear to have changed over time, with more recent studies using multiple methods or scenarios in combination, such as socioeconomic pathways. The difference in the temperature burden between including and excluding adaptation can be considerable, in one case as much as −144 %, demonstrating that studies that do not include adaptation could be significantly overestimating future mortality burdens. However, most approaches to model adaptation are not based on strong empirical assumptions, with less than 20 % categorised as having robustly justified or intervention-based assumptions. The large variation in impacts demonstrates that mortality projections are highly sensitive to the adaptation approaches used, even within the same method category, and careful consideration should be given to the specifications chosen to model adaptation.

The findings of this review are consistent with previous literature on this topic with there being no consistently applied methodology for including adaptation in projections (Gosling et al., 2017; Huang et al., 2011; Macintyre and Murage, 2023). Although methods have changed slightly over time, it is surprising to see that there are still only a small number of studies that base assumptions on evidence. This could, in part, be due to a lack of evidence on the efficacy of existing adaptation measures and, therefore, improved evaluation of already implemented interventions will be crucial to increase the evidence base for adaptation potential in future projections.

4.2. Strengths and limitations of methods of including adaptation

The analogue location and time approaches make use of existing exposure–response relationships in other locations or periods that may be considered analogous to what may be expected at the target location in a future warming scenario, and hence are supported by empirical evidence to some extent. An advantage of this approach is that it has implicit assumptions of adaptation, without the need to identify what these adaptation factors may be. However, a major limitation is that different locations have varying demographic, socioeconomic and natural and built environmental profiles that affect vulnerability to temperatures, and hence risk functions may not be comparable. This limitation also applies to studies applying historical trends in threshold temperatures or slope/RRs (Category III and IV) in other locations to the target location. Therefore, it is crucial to be transparent about the choice of analogue locations, and studies should carefully select appropriate locations and clarify their suitability in being the analogue location in terms of climate, socioeconomic and other characteristics.

The analogue time method overcomes some of the limitations of the analogue location since socioeconomic profiles are likely to change only slowly over time in any single location. However, there is still uncertainty in the extent to which historical findings are applicable to future changes in heat susceptibility. This uncertainty may stem from changes in the *rates* of warming that may result from different climate sensitivities (Tebaldi et al., 2021), or changes related to factors that may influence heat risk. For instance, population demographic projections are often based on assumptions of future fertility, mortality and migration based on observed long-term trends, but it is unclear how international migration, or changes since the start of the COVID-19 pandemic will translate into abrupt changes to demographic trends (ONS, 2022). Similarly, there may be behavioural or infrastructure changes such as widespread adoption of air conditioning that may result in a potential step-change in heat risk that is challenging to predict (Petkova et al., 2014; Petkova et al., 2017). The studies extrapolating historical trends in threshold temperatures, slope/RRs or building retrofit rates as empirical evidence have similar limitations too.

Some limitations of the threshold shift method are that there is a lack of evidence and consensus regarding the amount of temperature shift in the threshold and this threshold will vary regionally (Gasparrini et al., 2022; Nordio et al., 2015). It is also unknown to what extent the threshold will shift in accordance to changes in the temperature distribution or its long-term average under climate change. A key consideration is that there may be an upper limit in the threshold temperature and the increase in the heat threshold may slow down over time due to physiological and social limits to adaptation (Smith et al., 2014), which have generally not been explored in the studies included in this review.

Previous research predominantly assumed an increase in heat adaptation in the future. The impact of a reduction or fluctuation in heat adaptation on heat-related health burdens has seldom been considered. For example, there is expected to be increasing nationalism and growing international tensions accompanied by a decrease in social support, education, health and public infrastructures in the future under SSP3 (O'Neill et al., 2017). Under SSP4, higher inequality is assumed, with deteriorating social cohesion and health services for most of the public (O'Neill et al., 2017). It has been shown that factors such as recession periods and austerity measures can lead to reduced health services and therefore declines in population health (Doetsch et al., 2023). These scenarios, therefore, suggest future adaptation could be more challenging than for present-day, with adaptive capacities potentially increasing or decreasing based on a variety of socioeconomic factors (Carleton et al., 2022; Wan et al., 2022; Wan et al., 2024). Therefore, it is imperative to conduct research that considers the projected heat-related health burdens in the face of climate change, considering both a potential enhancement and decline in adaptive capacity to heat.

Contrary to the assumption of an increase in heat acclimatisation in previous studies, a loss in adaptation to cold weather has been assumed by many studies. These studies assume the threshold temperature for both cold and heat shifts according to the temperature distribution or average temperature under climate change, and hence the population's current cold acclimatisation and adaptation ability deteriorates as temperature increases. Modelling adaptation using this method results in an increase in the cold threshold and the associated cold burden (Ballester et al., 2011; Díaz et al., 2019; Huang et al., 2018; Huang et al., 2019; Huynen and Martens 2015; Li et al., 2018a; Li et al., 2018b; Wang et al., 2022; Zhang et al., 2018).

Some other studies instead assume an increase in both heat and cold adaptation in the future, assuming a positive scenario where the adaptive capacity to both heat and cold improves (Aboubakri et al., 2020; Wang et al., 2022; Watkiss and Hunt, 2012). There were also two studies that integrated an increase in the cold threshold and a decrease in the cold slope, leading to opposing impacts on the cold burden (Lee et al., 2019; Wang et al., 2022). However, there is no consistent evidence of either adaptation or maladaptation to cold as heat adaptation increases, and it is uncertain how adaptive capacity to cold will develop in the future under climate change scenarios, with very few of the studies in this review including adaptation to cold simultaneously in projections. Therefore, sensitivity of projections to different possibilities of an increase, decrease and no change in adaptive capacities would be instructive.

In this review, studies that identified individual interventions or factors of adaptation reflect the greater evidence-base for these studies compared to making arbitrary assumptions or applying analogue risk functions. However, it is challenging to identify the specific socioeconomic factors that affect adaptive capacity to ambient temperature due to various restrictions such as limited individual data, the low variation of the value of certain socioeconomic factors, and the synergistic effects of multiple correlated variables (Lay et al., 2021). In addition, using only individual socioeconomic factors can not reflect the many contextual drivers of adaptive capacity, and future distributions of these factors may also be difficult to predict. Using an index that reflects the composite effect of various individual and contextual factors on adaptive capacity is a useful approach requiring further research.

The main advantages and disadvantages of each adaptation modelling method are summarised in Table 3. We also give suggestions for key considerations to improve reporting of the methodology. Due to practicality issues, data limitations and varying study objectives, we acknowledge that different studies may prefer to adopt different methods to model adaptation and hence this review does not suggest a single "best practice" method. We therefore encourage future studies to carefully implement and report their methodology to improve transparency and interpretability.

4.3. Study limitations

There are several limitations to this review. Firstly, although comprehensive searches were carried out for peer-reviewed literature, grey literature was not included, meaning some studies or data may have been missed. The literature search was updated in June 2023, and hence literature published after the search was not included in this review. Secondly, studies were only included if they explicitly mentioned the modelling of adaptation (defined above) and excluded if they did not link their methodologies with adaptation. This means that some papers may have unintentionally modelled adaptation (for example, through

Table 3
Summary of advantages, disadvantages, and main considerations to improve reporting the methodology of each adaptation modelling category.

Adaptation modelling category	Advantage	Disadvantage	Reporting Improvements
I. Analogue location	Incorporates partial empirical evidence of potential heat/cold effects as in other more adapted/acclimatised locations without the need to identify what these adaptation factors are	The risk functions in the target location and analogue cities may not be comparable.	Be transparent about the choice of analogue locations. Carefully select appropriate locations and clarify their suitability in being the analogue location.
II. Analogue period	Incorporates empirical evidence of potential heat/cold effects as in certain historical periods without the need to identify what these adaptation factors are.	The risk functions in historical periods may not reflect future risks.	Clarify the rationale of the selected analogue periods.
III. Threshold Shift IV. Adjustment of the slope or RR	Can be easily incorporated with no additional requirement of data compared to projecting health risks assuming no adaptation.	A lack of evidence and consensus regarding the amount of temperature shift in the threshold or the change in the slope. There may be an upper limit in the threshold temperature.	Ensure changes to threshold or adjustment of the slope are suitably explained and justified, based on empirical evidence where possible
V. Change in exposure through the built and natural environments	Individual interventions are identified providing more robust evidence for assumptions	Assumes the historical effect of the intervention remains the same in the future.	Justify the selected future value of the intervention measure. Projections under various probable socioeconomic trajectories might be helpful in exploring uncertainties.
VI. Change in socioeconomic adaptative capacity	Individual interventions are identified providing more robust evidence for assumptions.	Assumes the historical effect of the intervention remains the same in the future. Data heavy—It is challenging to identify the specific socioeconomic factors.	Justify the selected socioeconomic factors and their future values. Projections under various probable socioeconomic trajectories might be helpful in exploring uncertainties.
VII. Combination of threshold shift (III) and slope/RR adjustment (IV)	Same as III and IV.		

SSPs) but, as it was not explicitly identified as such, were excluded from the review. Thirdly, studies were categorised based on their empirical evidence assumptions. This categorisation has an element of subjectivity within it, also being dependent on how authors had reported their adaptation assumptions. Nevertheless, this system provides an overview of the different categories of underlying evidence. Lastly, during the analysis of the impacts of including adaptation vs. not including adaptation, results were only extracted for one climate scenario, adaptation scenario and population scenario but most studies reported many different combinations of these, meaning these results provide only an indication as to the difference in mortality when including adaptation in projections and may not represent the true effect of varying model assumptions.

4.4. Implications for future research

All studies in this review investigated the effects of adaptation on mortality, however, none investigated potential impacts on morbidity outcomes, even though these were included in our search strategy. It is known that temperature can have an impact on many diseases and health outcomes, with exposure to extreme temperatures associated with increased hospital admissions, particularly for cardiovascular, respiratory, and renal illness (Gronlund et al., 2018; Weinberger et al., 2018; Ye et al., 2012). Adaptation to temperature could therefore have an impact on morbidity and future studies should also focus on quantifying potential changes in morbidity due to temperature adaptation, however factors such as future changes in health care systems and delivery add further uncertainties in adaptation potential.

Currently, studies that do not include adaptation may be considerably overestimating the numbers of future deaths attributable to temperature. On the contrary, studies that do model adaptation but without empirical basis may underestimate temperature-related health burdens. The best empirical evidence may derive from epidemiologic assessments applying a consistent methodology in multiple settings, where variation in heat risk observed across settings can then be attributed to specific area-level factors (e.g. prevalence of air-conditioning) in a *meta*-regression analysis (Curriero et al., 2002). Similar to Kinney et al. (2008), we recommend that studies use multiple adaptation approaches to capture a range of future health impacts under adaptation scenarios, in the same way that estimates are ordinarily provided under different climate change scenarios. Future studies should also look to explore potential limits to adaptation within their modelling.

It is recommended that future impact assessments should consider adaptation uncertainty to realistically inform policy actions, and that the inclusion of adaptation should be based on empirical evidence wherever possible. Given future uncertainties, some degree of assumptions are inevitable when making projections, however, we recommend that all papers clearly clarify any assumptions or scenarios made, the empirical evidence these are based on, as well as potential limitations of adaptation methods and assumptions to aid useful interpretation and policy relevance of findings.

5. Conclusion

This review aimed to synthesise the literature and categorise the main methodologies used for including adaptation in future projections of temperature-related health burdens under climate change scenarios. Seven main categories of methods were identified. Although a wider range of methods have been utilised more recently, there is still no best practice approach for statistically including adaptation in projections. Many methods use arbitrary assumptions with no empirical basis, and it is important for future research to base assumptions on evidence where available.

This review provides an overview of the methods that can be used to quantitatively incorporate adaptation into future projections of health burden and demonstrates the importance of including adaptation uncertainty in projections.

CRediT authorship contribution statement

Rhiannon Cordiner: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Conceptualization. **Kai Wan:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Shakoor Hajat:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Helen L Macintyre:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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The views expressed are those of the author(s) and not necessarily those of the NIHR, UK Health Security Agency, London School of Hygiene and Tropical Medicine, University College London, the Met Office or the Department of Health and Social Care.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108761.

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