

# Rising Temperatures, Human Health, and the Role of Adaptation

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**Abstract** There is near consensus in the scientific community that humans will experience higher future temperatures due to the ongoing accumulation of greenhouse gases in the atmosphere. The human response to this climatic change, particularly if accompanied by a surge in extreme heat events, is a key topic being addressed by scientists across many disciplines. In this article, we review recent (2012–2015) research on human health impacts of observed and projected increases in summer temperature. We find that studies based on projected changes in climate indicate substantial increases in heat-related mortality and morbidity in the future, while observational studies based on historical climate and health records show a decrease in negative impacts during recent warming. The discrepancy between the two groups of studies generally involves how well and how quickly humans can adapt to changes in climate via physiological, behavioral, infrastructural, and/or technological adaptation, and how such adaptation is quantified.

**Keywords** Climate change · Adaptation · Heat · Mortality · Morbidity · Health

## Introduction

Over the past four decades, climate change has emerged as the leading environmental issue being confronted by nations across the planet. There is no doubt that human activities are significantly altering atmospheric composition, particularly by increasing the concentration of long-lived greenhouse gases (LLGHGs). The climatic effect of increased concentrations of LLGHGs has been of interest to the scientific community for more than a century, but this issue has drawn global socio-economic attention only in recent decades. One of the most robust predictions given the buildup of greenhouse gases is that global temperatures will increase in the future, and indeed over the past 50 to 100 years, there is overwhelming evidence that the planet has warmed overall. The regional, seasonal, and diurnal character of projected future warming is still a matter of considerable debate, but nearly all scientists agree that future decades will be marked by a warming due to anthropogenic activities [1].

Future warming and other climatic changes could present a range of health consequences [2, 3]. We focus this review on one subset of climate-sensitive health outcomes: those related to high ambient temperature exposure. At the first glance, the relationship between extreme heat and health issues appears straightforward, and yet, the relationship is far more complicated given the ability of humans to adapt to their environs. In discussing this issue, the Intergovernmental Panel on Climate Change (IPCC) provides a definition of adaptation as “the process of adjustment to actual or expected climate and its effects” [4]. It is noteworthy that many of the fastest growing areas of the world are located in hot climates where extreme

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heat events are commonplace [5], clearly illustrating the power of human adaptation to cope with regularly occurring periods of extreme heat.

We examine heat-related morbidity and mortality for several reasons. First, the conceptual pathway linking climate change to heat-health outcomes is direct and obvious: a warmer climate will expose people to higher temperatures assuming no changes in behavior. Second, a wealth of studies exists establishing a positive association between high temperatures and adverse health outcomes. This literature is most well established in developed countries [6–9], but a growing literature documents effects in developing countries as well [10–14]. Furthermore, in some developed countries, extreme heat ranks currently as a leading cause of weather-related deaths [15, 16].

Our focus on heat-health impacts is especially critical due to the high confidence expressed in the literature regarding observed and projected temperature increases. It is “virtually certain” that many places around the world have warmed in recent decades [17–19]. The observed increase in globally averaged twentieth century near-surface temperatures has stimulated substantial research asking relevant societal questions: are summers becoming warmer and increasingly extreme; and is this expected to continue in the future as a result of continued emissions of LLGHGs? There is a scientific agreement in reference to the first part of the preceding question, namely, that summers have been warming and are expected to continue doing so [20–23], and this warming is coincident with increasingly frequent and intense heat waves in many locations [24, 25]. This stems from the increase in mean temperature owing to a shifting summertime probability distribution function. The historical evidence for increasing summertime temperature variability, however, is less clear [26–28]. In addition, assessing the total urban-generated heat impact in combination with warming due to LLGHGs is an important consideration given the rising number of urban dwellers, but is a topic only recently gaining consideration [29–31]. The focus on urban areas is especially germane because of the probable built environment-generated amplification and extension of heat waves and their health impacts [32, 33].

Much of the key observational and modeling evidence needed to draw a conclusion related to the relationship between heat-related health outcomes and climate change, thus, would seem to be in place: we know that people are sensitive to high temperatures; we know that temperatures have been increasing in many locations; and we have a high degree of confidence that these temperature increases will continue or potentially accelerate. These evidence have led scientists and government agencies to express serious concerns about future heat-related health impacts because of a dangerous confluence of these and other (e.g., population growth, aging) factors [12, 34]. In a 2012 report focusing on the United States Midwest region, the Union of Concerned Scientists advocated

“aggressive action to reduce heat-trapping emissions from the burning of fossil fuels” citing the health risks posed by increasing temperatures [35]. The 2014 United States National Climate Assessment similarly warned of an “increase in heat-related deaths” and draws attention to the projected temperature of the hottest summer days by the late twenty-first century [36]. Finally, the Fifth Assessment Report of the IPCC includes heat waves and heat stress in its assessment of Reasons for Concern regarding human influence on climate, listing a “greater likelihood of injury, disease, and death due to more intense heat waves” as the first example of concerns from the health sector [37].

The next section examines the literature reporting observed changes in heat-related mortality and morbidity based on historical records. Next, studies anticipating future heat-related health impacts based on climate projections are reviewed, followed by a discussion of our current understanding of the pathways by which humans may (or may not) be able to adapt to increasing temperatures. We conclude with our own assessment of the state of the recent literature in providing a basis for assessing mankind’s ability to adapt to increasing temperatures. To highlight the most recent findings on these topics, this review emphasizes articles published in the period 2012–2015. To complete “[Historical Evidence: Trends in Heat-Related Mortality and Morbidity](#)”, “[Considering the Future Health Burden of Heat](#)”, and “[Pathways for Adaptation](#)”, we identified an initial set of articles to include in the review by using the following search terms through Web of Science and Google Scholar search engines restricted to peer-reviewed publications: heat, mortality, trend, health, adaptation, and climate. Many articles that quantified the association between temperature and mortality were excluded because they did not focus on how the relationship has evolved or will evolve over time. We employed a snowballing approach in which articles cited in and/or citing the initially identified set of publications were deemed relevant to the topics of each main section of the manuscript.

## **Historical Evidence: Trends in Heat-Related Mortality and Morbidity**

### **Methods Employed to Understand Trends**

Measurement of the changes in heat-related mortality and morbidity over time requires multidecadal datasets of both health outcomes and meteorological observations. The specific statistical methods applied by researchers vary, but generally involve the calculation of decade-specific relative risks (RR) of heat-related mortality or morbidity on days considered to present elevated danger. A representative study [38] developed a distributed lag non-linear model relating temperature to mortality for each of nine different decades in the

1900s and early 2000s, reporting both the shape of the temperature-mortality relationship and the decade-specific RR of mortality above a threshold temperature. Some studies with an emphasis on evaluating the effectiveness of heat preparedness strategies report only two time points using a similar experimental design—the temperature effect before and after implementation [39]. An alternative approach to this piecewise examination of the temperature-health relationship is to allow for time-varying coefficients for the effect of heat in statistical models [40].

### Observed Changes in Heat-Related Mortality and Morbidity

There is nearly unanimous reporting of declining sensitivity to heat in the literature we reviewed. In many cases, sensitivity to heat has been found to decline by more than 50 % comparing recent decades to those prior. In New York, the RR of mortality above a threshold temperature declined from greater than 1.30 in the earlier twentieth century to 1.26 in the 1970s and 1.09 in the 2000s [38]. Statistically significant differences in late-summer cardiovascular mortality were observed in Seoul, with a nearly two-thirds decline in mortality increases per 1 °C change in temperature (14.8 to 5.7 %). The risk of all non-accidental causes of mortality increased from the 1990s to the 2000s in Seoul, among all age groups and the elderly, however, these differences were not statistically significant [41]. In Stockholm, the RR of mortality on extreme heat days for all age groups was estimated to be between 1.00 and 1.12 for the period 2000–2009 versus an RR at or above 1.15 for several prior decades [42].

National-scale studies have examined the USA, Czech Republic, Italy, and Australia. The number of deaths attributed to heat across 105 cities in the USA declined by nearly 63 % between 1987 and 2005 [40]. In the Czech Republic, the mortality impact of heat wave days was found to be declining significantly at a rate of 0.44 % per year from 1986–2009, corresponding to an overall reduction in sensitivity of around 10 % [43]. The heat-related death rate in recent decades in Australia has been approximately two-thirds less than that observed in the late nineteenth and early twentieth century [15]. In a study of 16 cities in Italy, the effect among the elderly of 9–12 °C increases in temperature above city-specific baselines declined from 36.8 % in the period 1998–2002 to 13.3 % in the period 2006–2010 following the implementation of a heat response plan [39].

Reasons offered for the drivers of these declines include increasing availability of air conditioning, the introduction of heat warning systems, coordination of networks of cooling centers, increased healthcare expenditures, and broad-scale epidemiologic transition including life expectancy increases related to reduced sensitivity to infectious diseases [38, 39, 41, 42]. Formal statistical evaluation of associations between

these adaptation mechanisms is largely absent from the recent literature, with a notable exception found by Bobb et al. [40] who reported that in cities with larger increases in air conditioning prevalence in the USA, there was no statistically significant evidence pointing to greater reductions in heat-related mortality.

### Historical Evidence: Climate Change Impacts

The above studies do not specifically examine the impact of climate change on heat-related mortality per se. Our review of the literature revealed only one study aimed at this issue, which investigated the heat mortality response in Stockholm during two periods: 1900–1929 and 1980–2009. The authors concluded that heat-related mortality from 1980–2009 was double the effect that would have been observed in the absence of climate change due to the temperature distribution shifting toward a warmer climate between the two periods [44]. In response to this study, others suggested a contradiction [45] to results previously reported for Stockholm [42], noting significant adaptation over a longer time span. If the present-day population had the same sensitivity to heat as that of the early twentieth century, the weather observed during the period 1980–2009 would have resulted in more than four times the number of observed deaths (2993 versus 689). The response [45] further noted that the number of deaths avoided by adaptation (2304) is significantly larger than the number of deaths attributed to climate change (288).

This exchange [44, 45] raises critical concerns about the relative importance of intentional versus unintentional adaptation. Unintentional adaptation to extreme weather events relate to an overall increase in population resilience, whereby health and socioeconomic development may indeed be key drivers of declining sensitivity to heat even though these processes are not directly instituted in response to climate change [43, 45]. On the other hand, there is a wide suite of adaptation measures implemented in specific response to the threat of extreme heat, where climate change is a potential trigger of such measures. There is limited evidence of direct consideration of the extent to which these intentional and unintentional adaptations contribute to changing sensitivity to heat over time, and parsing out their relative effect is a key challenge. If changing climate is itself a modifier of the relationship between temperature and mortality (e.g., increasing heat wave frequency or severity leads to increasing public awareness and preventative measures), a quantitative approach for disentangling these effects has yet to be established.

### Considering the Future Health Burden of Heat

A complimentary body of literature examines changes in heat-related mortality and morbidity moving from present to future.

The majority of these studies are designed around historical health and meteorological data in conjunction with projections of a future climate obtained from global-, regional-, or urban-scale models. The basic framework is to derive a temperature-mortality (or morbidity) relationship based on the historical observations. Then, the historical meteorology is replaced with projections for the future, and a new impact assessment is performed. More comprehensive studies include a range of climate models, greenhouse gas and urbanization forcing scenarios, and anticipated changes in the demographic composition, size, and geography of the population.

Based on fundamental physiological principles [4, 46], we can assume that people will acclimatize to new temperatures at varying rates (and to a certain extent). However, many studies produce heat-related mortality projections in the absence of physiological (or other forms of) adaptation (e.g., [47–51]), and are discussed in detail in “[Results From Projections Without Adaptation](#)”. A subset of projection-oriented studies explicitly strives to account for potential adaptation in calculating future impacts (e.g., [52–55]) as discussed in “[Projections of Heat-Health Impacts With Adaptation](#)”. Quantification of uncertainty in such projections is a considerable challenge, as nearly all steps in making such a calculation introduce some range of confidence. These ranges, when compounded, can become quite large, yet are critical to understand and report as they provide a more comprehensive assessment of plausible outcomes [56].

### Results From Projections Without Adaptation

Nearly all researchers projecting heat-health impacts for the future (without accounting for adaptation) have concluded that heat-related deaths or illnesses will increase. In some cases, the projected increases are staggeringly large, spanning multiple orders of magnitude. Heat-related mortality projections for the 2080s for three cities in the northeastern USA, for example, indicate sixfold to ninefold increases under a higher emission scenario (RCP 8.5) [47]. Similarly, heat-related mortality rates were projected to increase by factors of more than five in a suite of Canadian cities for the period 2071–2090 [48]. Other studies have reported substantial increases in heat-health impacts for heat-related deaths in Italy [49], New York City [57], the United Kingdom [50], the eastern USA [51], and Washington State (USA) [58], ischemic heart disease mortality in Germany [59], multiple causes of hospital admission in Milwaukee, USA [60], and respiratory-related hospital admissions in Southern Europe [61]. Logically, projected increases in heat-health outcomes are greater under higher emission scenarios when compared to lower emission scenarios [e.g., 57]. A study of 12 cities in the USA concluded that 22,000 heat-related deaths would be avoided by the end of the century under a lower emission scenario compared with a higher emission scenario [62].

### Projections of Heat-Health Impacts With Adaptation

Recognizing the importance of considering non-stationarity in the temperature-health relationship [63], a number of methodological approaches to incorporate adaptation into calculations of future health impacts associated with temperature changes have been introduced, as described in Table 1.

Accounting for potential adaptation in projecting future heat-related health impacts has had a large impact on the quantitative burden reported in several recent studies. In a study of London, accounting for adaptation using the fixed value approach decreased projected future deaths by more than 55 % [52]. Similar results were reported in a study of future impacts in Beirut, Lebanon [71]. A study using a combination of the fixed value and analog city approaches led to the conclusion that even in the presence of adaptation measures, climate mitigation policy would still have a beneficial impact in terms of reducing heat-related (and overall temperature-related) mortality, although the benefits of the mitigation policy were smaller than they would have been in the absence of adaptation [65]. Studies from the USA using methods discounting early heat wave mortality and modeling urban climate changes also report that projections of future heat-related impacts could be scaled back by, in some cases, 40 % or more [30, 53, 72].

### Pathways for Adaptation

The main types of climate change adaptation related to heat include physiological adaptation (or acclimatization), behavioral, infrastructure, and technological adaptation. Individuals and defined groups within society demonstrate a range of adaptive capacities (a measure of ability to adjust to the potential impacts of climate change [73]), which are based on location, and physical or social vulnerabilities. However, little to no quantitative information concerning the role of adaptation in mitigating the effects of extreme temperatures on health exists, largely due to few real-world datasets on adaptation behaviors [74]. Further, most studies in public health do not directly measure and analyze adaptive behaviors in response to temperature extremes, although some do consider adaptation as a residual explanation for observed changes in mortality over time [74].

Physiological adaptation refers to acclimatization and is broadly defined by the IPCC as a change in functional or morphological traits occurring once or repeatedly (e.g., seasonally), where through short-term acclimatization, the individual maintains performance across a range of environmental conditions [4]. Specific to heat, acclimatization is a relatively quick (days to weeks) and automatic change in human physiology (e.g., increased tolerance to extreme heat through increased blood flow to the periphery, lower resting core temperature, and more efficient sweating) [75, 76]. Limits to

**Table 1** Approaches employed in the literature to incorporate various forms of adaptation into calculations of future heat-related mortality

Type of adaptation method	Explanation/reasoning and examples	References
1. Fixed value approach (shifted dose-response relationship)	<ul style="list-style-type: none"> <li>• Also referred to as the “delta method”</li> <li>• Adjusts the heat-mortality relationship (including the slope and/or threshold) by a fixed value based on temperature predictions from climate change scenarios</li> </ul>	[52, 64, 71]
2. Analog city approach	<ul style="list-style-type: none"> <li>• Assumes that if a city’s climate changes in the future to that of a warmer city, then its heat-mortality relationship in the future will be similar to that of the warmer city’s</li> <li>• Method has been criticized by some as it assumes stationarity of temperature-mortality relationships by using past ones to represent future ones</li> <li>• One could assume that in the future, Philadelphia’s (Pennsylvania, US) population will have the same dose-response relationship as that of the population of a warmer city like Charlotte (North Carolina, US).</li> </ul>	[54, 55, 65, 66] [67]
3. Analog years approach	<ul style="list-style-type: none"> <li>• A way of approximating response in a warmer world by assuming that future acclimatization is based on the dose-response temperature-mortality relationship only in the hottest summers or years in the past record</li> </ul>	[68–70]
4. Remove early heat wave mortality	<ul style="list-style-type: none"> <li>• Essentially neglects early heat wave mortality by removing the deaths projected to occur in the first few days of extreme heat events from the total projected impact</li> <li>• Implicitly assumes that the population would suffer only under the cumulative effects</li> <li>• Aims to capture the potential for short-term adaptation but maintains population sensitivity to particularly severe and prolonged events</li> </ul>	[53]
5. Altered urban climate	<ul style="list-style-type: none"> <li>• Predicts that the expected change in urban climate associated with adaptation-oriented technologies results in measurable temperature decreases in urban areas</li> <li>• Examples include physical alterations to the urban landscape, such as the introduction of white and/or reflective roofs to reduce air temperature</li> <li>• Impact of these strategies on heat-health outcomes is measured by considering resulting changes analogously to considering different global climate scenarios</li> <li>• No change in the temperature-mortality relationship is assumed or implied</li> </ul>	[30]

short- and long-term physiological adaptation and human capacity to adapt are presently unknown [77], and major sources of uncertainty exist in understanding how much acclimatization may mitigate the effects of heat on human health [53, 78].

Human and societal adaptive capacity, defined as “the ability to adjust potential damage, to take advantage of opportunities, or to respond to consequences” [79] is based on a set of actions that are taken in order to reduce heat-health impacts [74]. The IPCC defines three types of adaptation: anticipatory, planned, and autonomous [77]. These are discussed in the context of behavioral, infrastructure, and technological adaptations in the following texts. These three adaptation types are made up of both “household” (individual) and “community” level adaptation measures as identified by Deschenes [74] and referred to in the following paragraphs at both short- and long-time scales.

Behavioral adaptation is based on a set of actions that households (individuals), communities, and populations can take to adjust to change. These include change in structure of activity (i.e., time allocation responses to extreme temperatures), and geographic mobility. Both are types of anticipatory adaptation, which is an “action that avoids or reduces a climate-change impact” [4]. Few studies find credible opportunities to combine long-term large-scale empirical data on adaptive behaviors with health outcomes [74]; however, some have recently addressed this issue [40, 79] by examining the protective effectiveness of air conditioning (AC) against heat-related mortality. AC is a commonly utilized and cited

behavioral adaptation [80–82]. In one study, increasing use of residential AC alone explained almost 90 % of the decline in heat-related mortality on hot (>32.2 °C) days from 1960 to 2004 [79]. However, contrary conclusions have also been suggested [40].

Infrastructure adaptation aims to reduce the risks to physical and organizational structures that are major societal investments [83], including healthcare systems, roads, and communication systems. This is a planned, or “human-assisted” adaptation, which is proactive and can either adjust the broader system or transform it, with the intent of increasing the capacity of a system (such as community or population) to function at a future temperature [4]. However, a review of 30 articles on “planned adaptation” specific to heat reported inconclusive evidence on the effect, despite the majority of studies reporting mortality/morbidity reductions over time [84].

Sustainability initiatives address planned adaptation for the long-term in both households and communities [74], where urban redesign guidelines and cooling strategies [29, 31, 72, 85–89], preparedness efforts (education, cooling centers [90]), and interventions to decrease the temperatures in aged buildings (e.g., reducing solar gains, insulation and ventilation [91]) are long-term adaptations that reduce individuals’ heat exposure. Few studies listed assess potential empirical relationships with health outcomes [30, 72]. Heat-health risks for individuals are ultimately determined by the full suite of variables included in the human energy budget [89], but we observed that most literature focuses exclusively on temperature

or a temperature-humidity index. A wide range of indices are available for considering all meteorological variables relevant to the human thermal experience that relate to landscape design [92–94], yet little evidence exists that a combination of variables is a better predictor of population-level response than temperature alone [95–97].

The last type of adaptation to heat is technological adaptation, which refers specifically to retrofitting and replacement of existing technologies to adjust to change. Technological adaptation can be anticipatory, planned, or autonomous, and applied at both the household and community levels. Autonomous refers to “incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced” [4]. One example of technological adaptation is the use of heat warning systems [96, 98–100], yet challenges remain when designing these systems [96–98] and effectively issuing warnings [7, 101]. The improvements in efficiency of air conditioning systems is both a planned and anticipatory technological adaptation, where the reduction of electricity usage at minimal costs to households and increased efficiency [102] and the reduction of heat output into the urban fabric [103], are hypothesized to reduce heat-related risks.

## Discussion and Conclusions

The ability of humans to adapt to climate change, and more specifically cope with the health hazards associated with exposure to high temperatures, will almost certainly be a topic that receives continuing attention in the years ahead. Although heat-related morbidity and mortality are small subsets of the total range of possible health impacts associated with climate change, the literature reviewed herein suggests that it is one in need of more investigation. Few connections between climate change and health could be conceptually clearer, and yet there is a considerable contrast in the literature between observational studies that report decreasing heat-related health impacts over time and projection-based studies that report significant anticipated increases in the future (see Table 2). Resolving this discrepancy—to build confidence in the sign of the trend in heat-health impacts moving forward, let alone the magnitude—is challenging. Studies attempting to account for adaptation in projections of future heat-related health impacts have generally reported that adaptation efforts can partially offset expected impacts associated with climate change.

Researchers tackling this area of investigation in the future years have an even wider range of topical, methodological, and geographical approaches and contexts for pursuing such work beyond what we have reviewed herein. First, we note that much of the information on the relationship between temperature and mortality and how it has evolved over time is derived from temperate climates in developed countries. Yet,

the majority of the global population growth and urbanization expected in the coming decades will occur in developing countries and hot climates. Even in locations that have been examined in this context, there are additional dimensions to the heat-health relationship that are, for the most part, yet to be incorporated in research considering temporal changes in sensitivity to heat. For example, a growing number of studies document significant intra-city spatial variability in heat-related health impacts [104–108], and focusing on the city-scale response may miss opportunities to understand more specifically where and why adaptation has occurred or may occur in the future. Similarly, heat-health impacts differ across a range of health outcomes (e.g., cardiovascular mortality, mortality or morbidity related to direct heat exposure) and sub-populations (e.g., age groups, socioeconomic classes), contrasts masked by unstratified analysis for aggregate populations [7, 12, 109]. Examining trends in multiple health outcomes simultaneously is a particularly appealing study design to understand potential adaptation; reductions in heat-related mortality and concurrent increases in hospital admissions for heat-related causes in New York City were suggested as evidence of increased awareness of the hazards of heat [110]. Study designs that include different response functions for various age groups and account for age group-specific population trends are also more useful than examining aggregated populations, because age is an important risk factor for heat, and large changes in the age structure of the population are expected in the coming decades [e.g., 53]. Accounting for possible mortality displacement [49, 111] in assessing historical and future impacts has also been largely neglected to date as most literature focuses on outcomes observed in the immediate aftermath of a heat event.

Further consideration of our ability to adapt to rising temperatures raises additional questions about indirect climate-sensitive health effects and tradeoffs with other health outcomes that are outside the focus of this review but merit acknowledgment in light of their importance for the development of effective policy, practice, and research. For example, even if humans become fully adapted to high temperatures in terms of direct exposure and health impacts, it is possible that their health may still be negatively affected by rising temperatures as a result of poorer air quality. Projections of future air quality resulting from climate change are difficult to calculate in the face of anticipated technological improvements and emission control policies, and thus the isolated net effect of climate change on air quality, particularly for pollutants beyond ozone (at any spatial scale), is highly uncertain and has high regional variability [112, 113]. Separately, a number of researchers have investigated the potential “savings” of decreased cold-related morbidity and mortality, and reached differing conclusions regarding whether or not fewer cold-related illnesses or deaths in the future would offset any increases associated with heat [48, 51, 57, 114]. Regardless of

**Table 2** A list of recent (2012–2014) studies examining historical trends and/or future projections of heat-related health impacts

Citation number	Authors	Year published	Study location	Sample of study results
Observed changes in heat-related mortality and morbidity (“Observed Changes in Heat-Related Mortality and Morbidity”)				
15	Coates et al.	2014	Australia	Two-thirds decline in heat-related death rate between late nineteenth and late twentieth century
38	Petkova et al.	2014	New York City, USA	Decrease in relative risk of mortality from above 1.30 in early 1900s to 1.09 in 2000s
39	Schifano et al.	2012	Italy	Relative risk of mortality among elderly from large temperature increases declined from 36.8 % in 1998–2002 to 13.3 % in 2006–2010.
40	Bobb et al.	2014	USA	Decrease in heat-attributable deaths of 63 % between 1987 and 2005
41	Ha and Kim	2013	Seoul, South Korea	Increase in all-cause heat-related mortality per degree above threshold from 4.73 in 1990s to 6.05 in 2000s (not statistically significant)
42	Åström et al.	2013	Stockholm, Sweden	Decrease in relative risk of mortality from above 1.15 before 2000 to 1.00–1.12 in period 2000–2009
43	Kyselý and Plavcová	2012	Czech Republic	Decrease in heat-related mortality of 10 % between 1986 and 2009
Projections of heat-related mortality and morbidity without adaptation (“Results From Projections Without Adaptation”)				
47	Petkova et al.	2013	Northeastern USA	Increase in heat-related mortality to six to nine times present rates in 2080s using RCP 8.5.
48	Martin et al.	2012	Canada	Increase in heat-related mortality to at least four times present rates in many cities by 2071–2090 using A2 scenario
49	Morabito et al.	2012	Central Italy	Increase in percent change in mortality per degree above threshold temperature from 6.5 to 9.0 % by 2040 in coastal plain cities
50	Hajat et al.	2014	United Kingdom	Mean estimate of heat-related mortality increase by approximately 66, 257, and 535 % in 2020s, 2050s, and 2080s, respectively, from the baseline of around 2000 deaths (2000–2009)
51	Wu et al.	2014	Eastern USA	Mean absolute excess deaths per year due to heat-related mortality of 2397 (range 200–7,807) integrated over RCP 4.5 and RCP 8.5 scenarios
57	Li et al.	2013	Manhattan, USA	Increases from 1980 baseline in heat-related mortality of approximately 22.2, 49.4, and 91 % in 2020s, 2050s, and 2080s, respectively, using the A2 scenario
58	Isaksen et al.	2014	Washington State, USA	Increase in heat-related mortality of 4–22.3 times present rates by 2045 among elderly
59	Zacharias et al.	2014	Germany	Significant increase in ischemic heart disease deaths attributable to heat wave of 1.9-fold (685 deaths per year) in 2021–2050, and 5.1-fold (1801 deaths per year) in 2069–2098 compared to baseline years of 2000–2010
60	Li et al.	2012	Milwaukee, USA	Future projection (2059–2075) of higher temperatures on hospital admissions for five causes of admission and three age groups indicate large but not statistically significant increase in admissions
61	Åström et al.	2013	Europe	Number of heat-related respiratory hospital admissions projected to be 26,000 annually for 2021–2050 compared with 11,000 in the reference period of 1981–2010
62	Petkova et al.	2014	USA	Projections of 200,000 heat-related deaths between 1970 and 2099 for A2 scenario; 22,553 deaths greater than for B1 scenario
Projections of heat-related mortality and morbidity with adaptation (“Projections of Heat-Health Impacts With Adaptation”)				
30	Hondula et al.	2014	Maricopa County, USA	Projected increase in heat-related deaths reduced by nearly two-thirds for the period 2045–2055 with land cover modifications
52	Jenkins et al.	2014	London, England	Fixed value approach decreases projected future heat-related deaths by 55 %
53	Sheridan et al.	2012	California, USA	Projected increases in heat-related mortality decreased by 37–56 % for the 2090s after early heat wave mortality removed
71	El-Fadel et al.	2013	Beirut, Lebanon	Projected increase in mortality resulting from increasing temperatures lowered from 8.4 to 2.8 % for the year 2095 with change in threshold temperature
72	Stone et al.	2014	USA	Modifications to vegetative and surface cover offset increases in heat-related mortality by 40–99 % in 2050 across three cities

The sample results were selected to be representative of manuscript findings but are not necessarily comprehensive summations of the reviewed studies

the outcome of the debate around these potential indirect consequences of climate change, we argue that understanding if and how people are able to adapt to heat is an important pursuit. Even if climate change ultimately leads to fewer deaths associated with extreme temperatures (both high and low), there is an opportunity to facilitate even greater reductions in adverse health impacts that bear a large cost for health infrastructure [114, 115].

Significant scientific questions of relevance for heat-health adaptation also exist with respect to an important aspect of global-scale climate change: is a change in mean temperature to be accompanied by a change in variance? In the case of heat, this would be a concern as heat wave frequency and intensity could increase beyond what would be expected simply as a result of overall warming. The scientific community is divided on this matter to date, with one camp suggesting an observed increase in variance and pointing towards similar impacts in the future [20–23] and the opposing camp suggesting such conclusions are incorrect [26], and instead, are artifacts of inappropriate calculations of higher order moments [27, 28]. Disproportionate societal impacts due to extremes [116] require an improved understanding of historical changes to serve as a baseline for the provision of projected alteration in future climate variability. That contemporary modeling systems have important deficiencies in their ability to appropriately simulate historical climate variability [117] points to key physical processes that require further refinement (e.g., land-atmosphere coupling, cloud treatment).

What is most clear from our review is that the evidence and research methods to determine conclusively whether and to what extent heat-related morbidity and mortality will be impacted by climate change are largely absent. The literature related to this topic appearing in journals with an epidemiological, biometeorological, and/or climatological emphasis almost exclusively considers statistical associations and trends. Our understanding of the causal mechanisms of both heat exposure and adaptation, in any of its many forms, is lacking. With few exceptions [80, 118], we have little evidence of the actual heat exposure of individuals when high temperature events occur, the activities and behaviors undertaken by individuals at risk, the extent to which those actions lessen exposure, and the likelihood that such options will remain available in the future [74]. Systematic and coordinated evaluation of climate-health intervention strategies, like that proposed by the Building Resilience Against Climate Effects framework of the United States Centers for Disease Control and Prevention [119], will be instrumental in closing this large knowledge gap.

The historical evidence concerning heat-related mortality and morbidity relating human capacity to adapt to climate change is encouraging, as the public health burden associated with heat has declined in many locales experiencing warming over the same period. Yet health practitioners, researchers,

and policymakers should not take this evidence as a guarantee that there is little concern for the future. Some adaptation measures may be decreasingly effective as physiological and technological limits are approached. Other adaptation measures require sustained effort and coordination to be, or become, effective. We conclude that climate change need not be the sole motivating factor for evaluating heat-health impacts over time and the effectiveness of different adaptation strategies: heat continues to exert a preventable public health burden in cities across the globe. By directing our research efforts to best understand how reduction in heat mortality and morbidity can be achieved, we have the opportunity to improve societal welfare and eliminate unnecessary health consequences of extreme weather—even in a hotter future.

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