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Changes in the Frequency and Intensity of Extreme Temperature Events and Human Health Concerns

Scott C. Sheridan[1] **· Michael J. Allen**[2]

Abstract Extreme temperature events (ETEs), both hot and cold, have received much attention in the literature because of their adverse impacts upon society, in particular human health. Under scenarios of climate change, substantial changes in the frequency and intensity of ETEs are projected. Here, we review literature from the last few years that have assessed recent changes and projected future ETEs, along with projected impacts on human health. Regarding the impacts on health, we pay particular attention to the many dimensions of uncertainty in making these assessments.

Keywords Climate change · Extreme temperature events · Heat · Cold · Human health · Acclimatization

Overview of the Extreme Temperature–Health Relationship

It has long been known that extremes of thermal conditions, both hot and cold, are associated with negative health outcomes. A number of heat wave case studies have been examined, such as Chicago in 1995 [e.g., 1, 2], Europe in 2003 [3], Russia in 2010 [4, 5], and England in 2013 [6]. While less studied, the impact of cold spells has also been examined, in Russia [7], Europe [8, 9], and China [10–12]. Additionally, some studies have attributed *changes* in weather conditions to human health outcomes [13–15].

In holistic assessments, plots of mortality against any thermal exposure metric yield what is typically called a J- or U-curve, whereby both extremes typically are associated with increased mortality [16]. Impacts become more extreme as conditions do, although given the large differences in frequency, moderate cold and heat events may outweigh collectively outweigh the burden of extreme events [17]. While broadly similar in terms of the overall shape of the relationship [e.g., 18], the considerable spatial and temporal variability in the temperature–health relationship has driven much research over recent years. Vulnerability has been observed to be temporally variable [e.g., 19–21] and spatially variable [22], with steeper increases commonly observed in places where extreme temperatures are rare [e.g., 23]. There is still a disproportionate number of studies examining the developed world; however, many other areas are receiving increased attention, particularly China [e.g., 24–30] and also India [31, 32], Iran [33], Lebanon [34], and Thailand [35], among more global studies [e.g., 18, 36].

Explored in further depth, the temperature–health relationship becomes quite complex. In the case of health outcomes due to excessive heat, much evidence exists to suggest that negative health outcomes from a variety of causes are exacerbated, with increases in cardiovascular and respiratory deaths [e.g., 26, 29, 37, 38] far exceeding deaths directly due causes such as heat stroke [e.g., 19]. For cold, while there certainly are deaths due to hypothermia [39, 40], most substantially in parts of the developing world [41, 42], in many cases far greater increases in mortality are often seen in respiratory and cardiovascular causes as well [12], although critically, the impacts of cold are often seen with a much greater lag than those of heat [43–45].

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✉ Scott C. Sheridan
ssherid1@kent.edu

[1] Department of Geography, Kent State University, Kent, OH, USA

[2] Department of Political Science and Geography, Old Dominion University, Norfolk, VA, USA

Proper analysis therefore requires the use of some form of time series modeling, not only to account for the lagged influence, but also because of mortality displacement, or harvesting, the phenomenon in which a percentage of all deaths associated with short-term increases in mortality are "brought forward," that is, would have happened soon thereafter anyway [46]. Distributed lag non-linear model (DLNM) time series modeling [47], which accounts for accumulated impacts over a specified time interval after exposure, has become a widely used method over recent years for temperature–health research [e.g., 19, 26, 28, 29, 48–50].

These questions of lag are part of a broader array of confounders in the temperature–health relationship. Assessing the association between impacts from pollution with those from temperature has been studied often but not clearly settled [e.g., 51, 52]; further, the very notion of exposure is difficult to estimate as "individually experienced environments" vary widely across short distances, meaning personal exposure must usually be approximated [e.g., 53]. Thus, the impacts of excessive temperatures can vary widely on all spatial scales, depending upon a host of socioeconomic and physiological factors [54].

Further, morbidity and mortality outcomes often do not show very similar results [e.g., 38]. Far fewer studies have analyzed morbidity relationships [55–60]. Hospital admissions [54, 61, 62], cardiovascular disease [19, 63], respiratory disease [64], and stroke [65] have also been considered.

Given the very likely substantial shifts in climate moving into the future, and the clear connection between excessive temperatures and health, understanding the temperature–health relationship in light of climate change is critical. There has been a substantial increase in studies that have explored this topic in recent years; we summarize some of the most critical research below related to present-day trends as well as projections: first in terms of extreme temperature events (ETEs), and then in projected health impacts.

Projected Trends in Extreme Temperature Events

A variety of metrics, including temperature thresholds [49, 52, 66, 67], synoptic patterns [68, 69], and indices [70–74], have been used to define ETEs. Despite the variability in methodology, studies generally indicate recent increases in heat wave frequency, duration, and strength [75–77]. In examining various definitions of Australian heat waves, Perkins and Alexander [78] concluded that the intensity of heat waves was increasing. The same study showed spatial variability in regards to heat wave changes with regional differences existing across Australia. Perkins et al. [79] found that non-summer heat events were responsible for the changes in duration, intensity, and frequency in annual heat event trends in some locations. In Moscow, Rahmstorg and Coumou [80] estimated that the local warming trend was responsible for fivefold increase in record heat events. Allen et al. [81] found urbanization to be a major factor with increasing temperature extremes in Toronto. Based on 1979–2011, significant increases in the number of heat waves per year were shown for the USA, with the greatest trends in the Southeast and Great Plains [82].

Unlike heat, studies have generally shown decreases in the frequency of cold spells [83–87]. In China, Wang et al. [88] showed a decreasing trend of cold days and nights from 1960 to 2010 while warm days and nights increased. Kruger and Sekele [89] and El Kenawy et al. [90] investigated patterns of extreme temperature events in Spain and South Africa, respectively. In both cases, the frequency and intensity of heat extremes increased while cold extremes decreased. Liu et al. [91] showed a decrease in cold surges in Inner Mongolia. However, spatial variability has been found in some areas, for example, in Southeast China, Ou et al. [68] found slight increases in cold surges since the early 1980s. Since 2000, Peterson et al. [84] showed the fewest cold waves in the USA compared to previous decades. This is consistent with other studies which indicate changing air mass characteristics [92, 93]. Using satellite imagery, Cavanaugh et al. [94] linked expanding mangrove forests to a decline in severe cold events in Florida. Despite the overall observed changes, spatial and temporal variability has been noted [88, 95–97].

Studies have noted an ocean–atmosphere relationship [98–103] and urbanization [104, 105] both playing a role in the observed and projected changes to ETEs. For example, Fontaine et al. [106] analyzed larger scale synoptic patterns associated with heat wave episodes suggesting that longer duration of heat waves and shorter intervals between consecutive events were linked to the occurrence of negative North Atlantic Oscillation (NAO) patterns. Similarly, persistent NAO patterns have been shown to explain cold anomalies [107]. Sillmann and Croci-Maspoli [108] showed that cold winter ETEs are influenced by atmospheric blocking patterns and large-scale changes in these patterns will modify the frequency and spatial distribution of cold events. Rustinucci [109] also draws attention to the importance local forcing mechanisms like land use changes in evaluating and projecting changes in ETEs. Evaluating global extremes, Song et al. [110] found annual mean increases of 2.7 and 6.4 heat waves and cold spells each decade since the 1980s. However, despite the increase in land and sea surface temperatures, cold spells did not decrease globally.

In addition to evaluating the historical changes in ETEs, climate projections evaluate the ways that ETEs will occur in the future. Projections result from specific demographic and economic change, land use change, technological advances, and energy consumption. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) indicates an increase in global surface temperature of 0.85

(0.65 to 1.06) °C since 1880 [83]. The largest changes have taken place in high latitude locations [99, 111, 112]. These changes will continue to impact ETEs as climate projections indicate an increase of 0.6 to 7.8 °C by the end of the twenty-first century [113]. As the report states, “It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration” [113]. Through the twenty-first century, climate models indicate some regions that will experience an increase in heat wave frequency, duration, and strength [114, 115]. Warm nights will increase at a greater rate than warm days [116]. Research indicates that much of the future changes will be a result of an increase of seasonal mean temperature [117]. In addition to a warmer climate, small shifts in the temperature distribution can lead to significant changes in tropical locations where ecosystems are not accustomed to temperature variations [116]. Therefore, changes in the mean and distribution are both relevant in terms of future ETEs.

Using the Coupled Model Intercomparison Project (CMIP5) RCP2.6 scenario, Wuebbles et al. [118] projected increases in the number of days on which the temperature exceeds the mean annual maximum temperature of the 1986–2005 period. By the end of the twenty-first century, these daily temperatures will be between four and ten times more frequent. Using the higher RCP8.5 scenario, these extremes are projected to occur every year across the CONUS. Sheridan et al. [119, 120] showed significant increases in heat events in the next century in California, where offensive weather types doubled in frequency, and the likelihood of long-lasting heat events of at least 2 weeks increased tenfold along the coastline. With decreased cloudiness and rainfall, Lelieveld et al. [121] used a regional climate model Providing Regional Climates for Impact Studies (PRECIS) and found increasing episodes of heat irrespective of emission scenario. They study also highlighted the role of air pollution in metropolitan areas and the relationship to ETEs. In addition to increases in temperature, studies suggest increasing heat stress being amplified by soil moisture–temperature feedbacks which impact local humidity characteristics [122, 123]. Despite warming, Kodra et al. [124] showed that while frequency of cold events may decline, intensity and duration may persistent throughout the twenty-first century. However, whether these changes are a result of mean temperature or temperature distribution remains unclear [125, 117].

In regards to future changes in ETEs, models indicate strong consensus [116, 126]. However, Clark et al. [127] notes the uncertainty associated with internal variability and model scenarios. Orlowsky and Seneviratne [126] highlight the importance of drought and dryness in future scenarios. Future land use changes [100, 103, 109] and large-scale atmospheric patterns [108, 128] are also important factors that will influence future ETEs.

Projected Changes in Health Impacts

With very long-term records [e.g., 129], a decreased sensitivity to both extremes, cold and hot, particularly across the developed world, is apparent. While difficult to thoroughly assess, more recent changes in the heat–mortality relationship are thought to be at least somewhat due to increased awareness and heat warning systems [20, 130] or broader adaptation [131].

Over the last several years, there has been a sharp increase in the number of research articles projecting changes in human health impacts from extreme temperature events [e.g., 132, 133]. As with retrospective research, most research focuses on projections of changes in either mortality or mortality rates. Recent papers predict broad increases in heat-related mortality [e.g., 119, 134–142]. Some recent papers have compared heat-related mortality projections to those of cold-related mortality, with mixed results in terms of how the two compare in the future [e.g., 34, 143, 144].

All assessments of future extreme temperature-related impacts need to account for several important issues. While the impacts on heat on human mortality are undisputed, projecting these into the future is complicated. First, there are the uncertainties intrinsic to all climate change-related studies, including scenario-related uncertainty [e.g., 136] as well as differences among models [e.g., 141]; Gosling et al. [145] showed considerable uncertainty depending upon climate model physics. Much of the broad ranges observed exist based on the fact that temperature-related mortality estimates are based on the steep slopes at the uppermost end of the distribution of temperature and that small differences in projections of or changes in this tail can have excessive influence on final mortality tolls. Inter-research differences can also be attributed to differences in how heat and cold events are defined [e.g., 70, 71, 146].

Beyond these concerns, there are several other critical factors that affect temperature-related mortality impacts. With substantial age-related differences in vulnerability, demographic changes, particularly in the rapidly aging developed world, may lead to a greater increase in numbers of lives affected than that associated with changes in climate [119]; uncertainty in terms of population projections will also affect results. Further, assessing the dose–response relationship in the future involves numerous assumptions. As noted above, the relationship between temperature and mortality has changed over time in many places [20], generally decreasing. Assumptions are made as to how this may or may not change in the future. Acclimatization may well reduce vulnerability [e.g., 137], as can more proactive measures such as increased awareness through warning systems or urban design to reduce heat island impacts, countering broader scale temperature increases and thus mitigating some mortality increases [134]. However, any assessment of heat vulnerability must also address some other key aspects, such as the non-linearity of the temperature–mortality relationship and how to account for lagged effects and mortality displacement [147, 148], and also the potential for unprecedented events whose impacts may be impossible to ascertain in advance [149].

In broader context, research also has assessed whether the health "savings" from reduced cold-related mortality may offset, or even exceed, increases in heat-related mortality. As noted in section I, heat-related mortality and cold-related mortality require different fundamental assumptions when they are analyzed and so are difficult to assess and compare. It is thus unsurprising that some studies suggest that cold-related mortality reductions will offset increases in heat-related mortality [e.g., 34, 144], while others do not [e.g., 143, 150]. Some of this may be the ambiguity of the question; Hajat et al. [144] reported projected increases in heat-related mortality in the UK of 257 % by the 2050s, compared with a 2 % reduction in cold-related mortality, yet cold still remains by far the greater burden, in part due to aging. This noted, one big uncertainty of comparison studies of this sort is the difference between season-related mortality (that is, that mortality rates nearly universally are higher in winter than summer) compared to temperature-related mortality. Some research has suggested that warmer winters will decrease mortality [151], while other work has suggested that climate change may not theoretically change winter mortality in a warmer world, as season may be the more critical factor [152], and given that warmer climates tend to have steeper mortality slopes on the cold side, a warmer climate may yield similar numbers of deaths, only on fewer days [23].

How these projections may affect policy is also a subject of research. While heat response plans, improved health care, and awareness have likely worked well in reducing mortality [130], particularly in the developed world, intervention plans could be developed further, to provide more fully access to shelters and more adaptive social service agencies to address these future challenges [153]. With improved technology and data, data on critical factors, including physical ones such as the urban heat island, social ones such as crime, poverty, social isolation, and behavioral ones such as use of air conditioning or cooled public spaces, can collectively be analyzed to more precisely target vulnerable populations [54]. With the projected mean aging of the world's population, particularly in the developed world, accommodating the substantial increase in absolute numbers of elderly may prove the most significant challenge; other socioeconomic changes, such as increased obesity rates, may play pivotal roles as well [154].

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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