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Scott C. Sheridan

Michael J. Allen
Old Dominion University, mallen@odu.edu

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TOPICAL REVIEW

Temporal trends in human vulnerability to excessive heat

Scott C Sheridan[1,3] and Michael J Allen[2]

1 Department of Geography, Kent State University, Kent, OH, United States of America
2 Department of Political Science and Geography, Old Dominion University, Norfolk, VA, United States of America
3 Author to whom any correspondence should be addressed.

E-mail: ssherid1@kent.edu

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Abstract

Over recent decades, studies have examined various morbidity and mortality outcomes associated with heat exposure. This review explores the collective knowledge of the temporal trends of heat on human health, with regard to the hypothesis that humans are less vulnerable to heat events presently than in the past. Using Web of Science and Scopus, the authors identified all peer-reviewed articles that contained keywords on human impact (e.g. mortality, morbidity) and meteorological component (e.g. heat, heatwave). After sorting, a total of 71 articles, both case studies and epidemiological studies, contained explicit assessments of temporal trends in human vulnerability, and thus were used in this review. Most of the studies utilized mortality data, focused on the developed world, and showed a general decrease in heat sensitivity. Factors such as the implementation of a heat warning system, increased awareness, and improved quality of life were cited as contributing factors that led to the decreased impact of heat. Despite the overall recent decreases in heat vulnerability, spatial variability was shown, and differences with respect to health outcomes were also discussed. Several papers noted increases in heat's impact on human health, particularly when unprecedented conditions occurred. Further, many populations, from outdoor workers to rural residents, in addition to the populations in much of the developing world, have been significantly underrepresented in research to date, and temporal changes in their vulnerability should be assessed in future studies. Moreover, continued monitoring and improvement of heat intervention is needed; with projected changes in the frequency, duration, and intensity of heat events combined with shifts in demographics, heat will remain a major public health issue moving forward.

Introduction

Excessive heat events are the largest direct cause of increased weather-related mortality in the developed world, and one of the largest in the developing world (Lee 2014). Over recent decades, the relationship between extreme high temperatures and negative human health outcomes has been studied in hundreds, if not thousands, of published articles (Sheridan and Allen 2015). Collectively, these studies have shown that there is a near universal increase in human mortality and morbidity when a thermal metric exceeds a locally-relevant threshold, with many studies typically focused on a thermal metric exceeding the 95th percentile of the local distribution (Gosling *et al* 2009). As greater volumes of health data have become available, more refined research has shown increases in human mortality and morbidity across multiple causes (e.g. respiratory, cardiovascular) beyond direct heat stroke (Gronlund *et al* 2014), across different levels of development (e.g. Gasparrini *et al* 2015, McMichael *et al* 2008), and climate (e.g. Bobb *et al* 2014, Curriero *et al* 2002). Finer resolution data has led to numerous studies focusing on neighborhood-level data to further understand spatiotemporal variability in human vulnerability, focusing on issues of age, race, sex, and health and socioeconomic status (e.g. Hondula *et al* 2015, Uejio *et al* 2011).

Our understanding of the impacts of heat on health has a sense of urgency in order to prepare for adaptation in the future. Climate change is extremely likely to increase the number and duration of large-scale heat events (Lau and Nath 2012), and this has already been observed in many places (Hartmann *et al* 2013, Smith *et al* 2013). At the same time, demographic changes affecting nearly the entire planet will result in a much older population collectively, with very large increases in the number of people over age 65 (Åström *et al* 2011), which has been shown to be the most vulnerable population subgroup.

Research has helped to inform adaptation efforts on multiple fronts. Short-term responses, typically in the form of heat-health warning systems, aim to provide cooler locations to vulnerable people, and greater awareness and vigilance overall, and have generally been shown to be effective (Toloo *et al* 2013). Long-term responses include rethinking urban planning, and modifying city infrastructure to mitigate excess urban heat island impacts (Harlan and Ruddell 2011).

The vast majority of heat-impact research has tended to view heat vulnerability as temporally static; that is, the heat-health relationships are implicitly assumed to not change over the entire period of study since multiple years are aggregated for analysis. Yet conventional wisdom assumes that we are collectively less vulnerable to extreme temperatures, particularly in the developed world in locations where air-conditioning usage has increased as an adaptation mechanism (O'Neill 2003). Marmor (1975) is the first study known to comment on decreasing human vulnerability to heat, examining New York City, and Davis *et al* (2002) is the earliest multi-city systematic assessment of temporal changes.

In the past decade and a half, an increasing, but still relatively low, number of studies have examined temporal (interannual) trends and variability of human vulnerability to heat. We know of only one review article (Arbuthnott *et al* 2016) that has attempted to evaluate these results holistically, using relatively strict thresholds for inclusion, and a second (Hondula *et al* 2015) that synthesizes several studies within the context of how trends may be used for future projections. While comprehensively assessing the collective heat impacts across studies is valuable for the reasons cited above, it is difficult, given that there is no standard for what a heat event is (Robinson 2001), and that the studies comprise different temporal periods that will feature different levels of adaptation.

One very open question is how much humans acclimatize to the weather, that is, if temperatures get warmer, how well do we adjust to those warmer temperatures? What role do factors such as increased awareness and improved health care play? There are many studies projecting future heat impacts on human health, including a number of review articles (e.g. Huang *et al* 2011). These projections of future human vulnerability must address the issue of acclimatization, though there is no clear standard for how to do this (Kinney *et al* 2008).

We thus conduct this review to assess the collective knowledge of temporal trends in the impact of heat on human health. We cast a broad net and include any articles that have assessed interannual changes in human health outcomes. Specifically, this analysis includes two broad themes of heat literature:

1. **Case studies of extreme heat events and their impact on mortality and morbidity over time.** These studies generally analyze multiple discrete heat events (typically two or more of similar magnitude and location), to assess how human health response has changed. Frequently, these papers also discuss potential causal mechanisms for temporal shifts.
2. **Epidemiological studies that examine the overall mortality and morbidity relationship to high temperatures and how these have changed over time.** This broad category of studies apply a general threshold system for identifying oppressive weather. Some of these papers examine one location, while others examine hundreds systematically (e.g. Gasparrini *et al* 2015).

These themes are not entirely independent, as there is ample evidence for an 'added heat wave effect' (e.g. Rocklöv *et al* 2012), and many papers examine this effect within the context of the overall heat-mortality relationship. Further, the mortality and morbidity responses must be considered separately, and geographic differences are discussed to the extent that there is sufficient evidence to do so. We then close with a discussion on implications for future studies.

Table 1. Search words used in Scopus and Web of Science.

Heat OR Heat Wave OR Extreme Heat
AND
Morbidity OR Mortality OR Hospitalization OR Emergency

Methods

This review examines all assessments of interannual trends in human vulnerability to excessively hot conditions. As such, the initial evaluation was performed to identify all peer-reviewed articles that contained keywords on both the meteorological component and the human impact component (table 1). We did not set publication date restrictions. The initial query was completed in Web of Science, in which more than 8000 articles were identified. After an initial scan, it was clear that many articles were examining non-human impacts (e.g. forests, corals, animals), and so a series of terms that incorporated these keywords were used to exclude manuscripts.

Following this refinement, the Web of Science query resulted in 2808 articles. To filter these results further, we applied three criteria for further consideration:

1. The study must have used actual human health outcome data as part of its assessment.

2. The study must analyze interannual trends, differences, and/or variability in heat vulnerability. Studies that solely examine within-season variability (e.g. early-season vs. late-season heat events, impact of previous winter mortality on summer vulnerability) are excluded.
3. The study must make its assessments based on 'apples-to-apples' comparisons. That is, any trends or differences observed must be contextualized against similar events over time. Thus, a study may examine interannual variability of overall heat vulnerability, or it may examine changes in the toll of heat events over time. We thus exclude studies that examine the relative impact of a heat wave in one year to a baseline level of summer mortality, since the level of exposure is clearly different.

Examining the titles of the manuscripts within Web of Science (with each author taking one half of the time period), we were able to reduce the number of articles from 2808 to 571. Reading the abstracts reduced the number of relevant papers to 87, to which four were added from the authors' previous database on heat-related health outcome papers. Of these 91, upon examining the full manuscript, 57 were ultimately chosen for inclusion.

We then performed the same search in Scopus, with each author switching his respective time period of focus to assure redundancy. The Scopus search returned 2 179 articles, from which 312 were chosen based on titles, and 83 based on abstracts. Duplicates were removed from those selected from the Web of Science search, and upon examining those that remained, an additional 12 articles were identified. Two additional articles were published over the course of our work, resulting ultimately in 71 (57 + 12 + 2) articles being included in the analysis.

Results

Overview of the approaches used

An overview of the manuscripts (table 2) reveals the varied ways in which this topic has been approached across the 71 articles (table 3). The locations of analysis reveal a bias that echoes that of the overall heat-related literature, with a preponderance of studies that assess temporal shifts in heat-related mortality in North America and Europe, with no studies using data from outside of these two regions, Australia, and East Asia, likely reflecting the difficulty in securing long-term, often sensitive data sets. Complicating the fact that the definition of heat will vary from one research project to another is that 41 of the 71 papers evaluate trends at one single spatial unit, ranging from the city to country, along with one paper assessing all US Military bases globally (Carter *et al* 2005). This leaves only 30 papers for which spatial variability in temporal changes in heat vulnerability can be explicitly defined,

Table 2. Overview of article scope.

Nations Studied	n
USA	27
Japan	7
Spain	6
UK	6
South Korea	6
France	5
Italy	4
Sweden	4
Australia	3
Austria	3
China	3
Finland	3
Canada	2
Czech Republic	3
Germany	1
Greece	1
Hungary	1
Ireland	1
Netherlands	1
Switzerland	1
Taiwan	1
Spatial Scope	n
Single City or Metropolitan Area	25
Single Region or Country in Aggregate	14
Comparison of multiple regions, metropolitan areas, or cities	29
Comparison between adjacent rural and urban areas	2
Other aggregation (all US Military bases)	1
Event Scope	n
Multiple heat events	16
Trends in general vulnerability	55
Periods	29
Periods Defined	10
Trends	16

although in only 12 of them do the studies span multiple countries or climate zones, and only two explicitly segregate rural areas in their study design.

In terms of how heat itself was evaluated, 16 primarily focus on comparing the health impacts of two or more heat waves within the same location, 11 of which analyzed only two events; six of these 11 directly or indirectly cite the development of heat warning systems as an aspect of the differences observed.

The remaining 55 papers focus upon changes in the overall statistical relationships between high temperature and health outcome; more than half of these subdivide available data into general periods (typically decades) to foster comparison, while eight have divided their data into subsets based on a singular event (implementation of a watch warning system, unprecedented heat event, or in the case of Japan, electricity rationing following the 2011 tsunami); 17 papers examined generalized trends, either calculating a linear or non-linear slope, or evaluating interannual variability through other means. The papers have a median of 29 years' worth of data, ranging from five to 151 and an interquartile range of 18–38 years.

The overarching majority of papers utilize some broad aggregation of daily mortality totals; depending on the study this may include all-cause mortality, all non-accidental mortality, or mortality within certain broad subsets (e.g. cardiovascular, respiratory). Only five papers exclusively examine direct heat-related

Table 3. A list of the 70 articles included in the study and brief description of the key results.

Article	Summary
Akihiko *et al* (2014)	Heatstroke mortality in Japan has increased significantly since 1994.
Åström *et al* (2013a)	In Stockholm, Sweden, the relative risk of heat-related mortality has remained stable from 1980–2009.
Åström *et al* (2013b)	While heat events have increased iin the last two decades, their impact on mortality in Stockholm, Sweden over the 20th century.
Åström *et al* (2016)	The effect of temperature on mortality decreased over time in Sweden (1800–1950).
Barnett (2007)	From 1987–2000, elderly heat-related cardiovascular deaths declined markedly in the US, with greater decreases in historically more vulnerable areas.
Barreca *et al* (2016)	In the US, the impact of hot days on mortality impact has declined by almost 70% over the 20th century.
Benmarhnia *et al* (2016)	Heat action plans contributed to reduced mortality on hot days in Montreal, Canada after implementation in 2004.
Bobb *et al* (2014)	Across 105 US cities, the number of deaths attributed heat decreased from 1987–2005.
Carson *et al* (2006)	Despite an aging population, there was a significant reduction in temperature-related deaths in London, UK over the 20th century.
Carter *et al* (2005)	On US military bases, there has been a decrease in heat exhaustion cases but a five fold increase in heat stroke hospitalization rates between 1980 and 2002.
Christidis *et al* (2010)	A small, positive trend in heat-related mortality is observed after 1976 in England and Wales, due to more events despite a weaker response.
Chung *et al* (2017)	Heat-related mortality rates decreased in northeast Asia from 1972–2009.
Coates *et al* (2014)	Overall decrease in heat deaths attributed to extreme heat events in Australia from 1844–2010.
Davis *et al* (2002)	In three northern US cities, decreases in heat-related mortality rate are observed between 1964 and 1994, with no heat-mortality associations in southern US cities.
Davis *et al* (2003a)	Mortality rates were lower in the 1980s and 1990s than in 1960s and 1970s for majority of US cities.
Davis *et al* (2003b)	Systematic desensitization of US metro populations to high heat and humidity from 1964–1998.
Davis *et al* (2004)	Long term decline in mortality rates associated with heat are observed in the US, with some seasonal and regional differences.
de'Donato *et al* (2015)	From 1996–2010, a reduction in heat risk for most European cities studied, but an increased risk in Helsinki, Finland.
De Castro *et al* (2011)	For Galicia, Spain, mortality associated with 1990 heat wave was higher than 2003 event despite the latter event being more extreme.
Donaldson *et al* (2003)	Since 1971, annual heat-related mortality fell in North Carolina (USA), southern Finland, and southeastern England.
Ebi *et al* (2004)	Reduced mortality after heat warning system implemented in Philadelphia in 1996.
Ekamper *et al* (2009)	Reduced effect of heat from after 1930 in the Netherlands, attributed to changes in nutrition, clothing, and education.
Fechter-Leggett *et al* (2016)	Emergency department visits for heat stress decreased over time, with significant interannual variability.
Fouillet *et al* (2008)	Decreased excess mortality observed when comparing the 2006 heat event to the 1975–2003 baseline heat-mortality relationship in France.
Gabriel and Endlicher (2011)	In Germany, heat-related mortality was much higher in the 1994 heat event than the 2006 event.
Gasparrini *et al* (2015)	Mortality risk associated with high temperatures was lower in 2006 than 1993 in the US, Japan, and Spain, with a nonsignificant decrease in Canada.
Guo *et al* (2012)	There was a decline in the main effect of high temperature related deaths from 1987–2000 in all regions in the US.
Green *et al* (2016)	Despite sustained 2013 heatwave in England, mortality was less than expected.
Ha and Kim (2013)	In Seoul, Korea, temperature-related mortality declined over a 17 year time period, most strongly for cardiovascular deaths.
Heo *et al* (2016)	Increasing rate heat-related mortality was observed in the hottest cities in Korea during 2008–2012 compared to 1996–200, with decreases elsewhere.
Johnson *et al* (2016)	More heat-related deaths have been documented in Oklahoma, USA in recent years.
Kalkstein *et al* (2011)	Declines in heat-related mortality in 35 of 39 US metropolitan areas from 1975–2004.
Kim *et al* (2015)	Decreasing overall effect of heat in Japan though variability by cause; while risk of cardiovascular death increased over time, respiratory mortality decreased.
Kim *et al* (2017)	Despite reduction in electricity consumption following the earthquake, decreases in all-cause heat-related mortality were still found for Japan.
Kyselý and Kříž (2008)	Mortality response in 2003 heat event in the Czech Republic was less previous events in the 1990s.
Kyselý and Plavcová (2012)	In Czech Republic, declining trends in mortality impacts from 1986–2009 were observed.
Lee *et al* (2016)	Impact of heat on mortality in Seoul, Korea decreased from 1991–2012, but no change was observed in Busan, Korea.
Li *et al* (2017)	Heat-effect has increased with higher respiratory-related deaths in the most recent time period om Ningbo, China.
Linares *et al* (2015)	In Spain, a significant decrease in heat-related mortality was observed in some locations while others did not show any change.
Marmor (1975)	Excess mortality during first summer heatwave may have decreased in New York City but no trend is observed for later season events, using 1949–1971 data.
Matzarakis *et al* (2011)	In Vienna, a decrease in sensitivity to heat stress is observed from 1970–2007, particularly for moderate heat stress.
Michelozzi *et al* (2006)	A reduction in heat-related mortality was observed between 2003 and 2004 in four Italian cities.
Mirabelli and Richardson (2005)	A general decline in heat-related fatalities was observed in North Carolina, USA between 1977 and 2001.
Miron *et al* (2008)	Reduced comfort temperatures were observed in Spain, leading to an increased effect of heat on mortality over the 1975–2003 period.

Table 3. *Countined.*

Article	Summary
Miron *et al* (2015)	In central Spain, heat-related respiratory mortality did not decrease while circulatory cases declined from 1975–2008.
Morabito *et al* (2012)	A decrease of the impact of excessive heat effect on mortality was observed in Italy after a warning system was implemented after the 2003 heat event.
Muthers *et al* (2010a)	Projected changes in heat vulnerability were assessed using temporal shifts observed in Vienna, Austria from 1970–2007.
Muthers *et al* (2010b)	Sensitivity to heat stress has decreased in Vienna, Austria from 1970–2007.
Ng *et al* (2016)	In Japan, excess mortality attributable to heat has decreased from 1972–2010, with stronger decreases in more prosperous prefectures.
Nitschke *et al* (2011)	During the 2009 heat wave in Adelaide, Australia, direct heat-related hospital admissions increased up to 14 fold compared to the 2008 heat events.
Nordio *et al* (2015)	Each 50% increase in air conditioning prevalence was associated with a 1.37% decrease in the impact of heat on mortality in the US.
Onozuka and Hagihara (2015)	There was a gradual declining trend in the relative risk of heat-related mortality in Japan from 1973–2012.
Onozuka and Hagihara (2017)	No temporal variation in the effect of extremely high temperature on out-of-hospital-cardiac incidences in Japan from 2005–2014.
Palecki *et al* (2001)	Comparing 1995 and 1999 heat waves in Chicago, USA, the death toll was approximately one-fourth for the 1999 event.
Pascal *et al* (2012)	Mortality in France was less in 2006 heat event than 2003 heat event.
Pascal *et al* (2013)	Heatwave related mortality in Ireland declined from 1981–2006.
Petkova *et al* (2014)	The excess mortality in New York, USA, with high temperatures between 1900 and 1948 was substantially reduced between 1973 and 2006.
Ragettli *et al* (2017)	Following 2003, a reduction in the effect of high temperatures on mortality was found in Switzerland, though it is not statistically significant.
Rey *et al* (2007)	Excess mortality was substantially lower than expected during 2006 heat wave in France, after the implementation of public health surveillance.
Ruuhela *et al* (2017)	In Finland, the sensitivity to heat stress has decreased from 1972–2014.
Schifano *et al* (2012)	A significant decrease in heat-related mortality in those 65 and older in Italy is observed in 2006–2010 following implementation of a national prevention plan.
Sheridan and Dixon (2017)	A general decline in heat-related mortality in the US from the 1970s to 1990s, after which the decline seems to have abated.
Sheridan and Lin (2014)	Decreased risk in relative risk associated with heat-related mortality, with an increase in heat-related hospitalizations in New York City, USA.
Sheridan *et al* (2009)	Recent decades showed a clear decrease in human vulnerability to heat events across the largest metropolitan areas in the US.
Smoyer (1998)	The heat wave of 1980 had higher associated mortality than that of 1995 in St. Louis, USA.
Tan *et al* (2007)	In Shanghai, China, elevated mortality was much more pronounced during the 1998 heat event than the 2003 event.
Todd and Valleron (2015)	In central France, the ratio of mortality attributed to high temperatures declined significantly from 1968–2009.
Urban *et al* (2017)	The summer of 2015 was as pronounced as the summer of 1994 in terms of heat related mortality.
Wang *et al* (2016)	In the US, heat stroke hospitalizations have decreased substantially between 1999 and 2010.
Weisskopf *et al* (2002)	In Milwaukee, USA, heat related deaths and EMS runs show reductions in 1999 heat event compared to 1995 event.
Yang *et al* (2015)	No clear decline in heat effects in Shanghai, China from 1981–2012.

mortality events, and seven examine heat-related morbidity (either hospitalizations or ambulance call-outs). The papers also vary considerably, including estimating direct absolute differences in mortality, rates of mortality that account for demographic changes, or relative-risks with regard to temperature values. Roughly half of the papers (33) consider either lagged influence of weather on health; these range from assessing cumulative impacts via models such as the distributed lag nonlinear model (DLNM, Gasparrini *et al* 2010) to simply lagging the mortality response; most lags were one week or less, though several papers extended the impacts out to up to 30 days.

Overall, a decrease in vulnerability

Seven papers (Åström *et al* 2013a, Carson *et al* 2006, Coates *et al* 2014, Åström *et al* 2016, Barreca *et al* 2016, Ekamper *et al* 2009, Petkova *et al* 2014) assessed trends in heat-related mortality over a period dating back to at least 1900. Given the coarser resolution of mortality data (generally weekly or monthly aggregates), the changes in the relationship over time are studied in a more general fashion, but all seven studies show a clear decrease in human mortality to all temperature extremes; including overall heat-associated mortality rates decreasing 70% in the US (Barreca *et al* 2016) and 85% in Australia (Coates *et al* 2014). In these papers, broad changes in the seasonality in mortality are observed, as they span vast changes in societal lifestyle, education, housing, and wealth.

Far more studies avail of shorter periods of study, generally from the 1960s to the present. The overwhelming majority of the research studies (56 out of 64) have concluded that the relative impact of heat events on human health has declined in recent decades. This is true for both heatwave-to-heatwave comparisons as well as long-term epidemiological studies. While most studies conclude that heat-related mortality has decreased, most still show a statistically significant increase in mortality during periods of hot weather;

further, most studies have not directly compared the statistical significance of the change in vulnerability over time and thus the results are difficult to assess. In other studies where differences have been tested for significance, changes can be ambiguous. For instance, in Gasparrini *et al* (2015), at 90 percent (245/272) of the locations studied the point estimate for relative risk (RR) of human mortality at the highest observed temperature is lower in 2006 than in 1993; however, when aggregated to the national level, in only three of the six countries which were studied was the decrease in RR statistically significant.

Several factors must be considered to contextualize these results. First, many of the longer-term studies evaluate heat vulnerability in terms of relative risks to exposure, with few papers actually exploring the overall total change in heat burden, in which changes in the frequency of heat events and as well as human vulnerability are assessed. For example, in Christidis *et al* (2010), a decrease in relative vulnerability to hot conditions is offset by an increasing number of heat events, resulting in an overall insignificant (but upward) trend in total mortality. This result is echoed in two studies that have examined totals of direct heat-related deaths and found an increase over time (Akihiko *et al* 2014, Johnson *et al* 2016), and several studies that have found increases in specific types of mortality (e.g. cardiovascular in Kim *et al* (2015)), and Li *et al* (2017) who found a substantial increase in years of life lost due to heat in Ningbo, China, in the two years following a major heat event. In other cases, where ambiguous results have emerged, these have been related to unprecedented conditions, such as de'Donato *et al* (2015), in which observed increases in vulnerability in Helsinki may be associated with increased maximum temperatures; and Nitschke *et al* (2011) who in studying the 2009 heat event in Adelaide, Australia notes its lack of similar events. Miron *et al* (2008) note an increased vulnerability to heat that they associated with a lowering of the temperature at which heat impacts begin at their sites in Spain, which they suggest is associated with an increased elderly population.

The impact of the heat wave

Of the studies that have examined heat wave-to-heat wave variability in human impacts, only in the Nitschke *et al* (2011) study are heat impacts greater with the later event, though this is framed in the context that the later (2009) event was unprecedented for Adelaide, Australia. For the summer of 2015 in the Czech Republic, heat related mortality was similar to that of 1994, despite a baseline decline in heat vulnerability (Urban *et al* 2017). For the remaining studies, all show general declines; for instance, Palecki *et al* (2001) and Weisskopf *et al* (2002) show mortality in the midwestern USA in a 1999 heat wave was far lower than that of the 1995 'Chicago Heat Wave'; Smoyer (1998) shows in St. Louis, USA the 1995 heat event was less impactful than a 1980 event; and Tan *et al* (2007) show similar decreases between heat events in 1998 and 2003 in Shanghai, China.

Several studies have focused on the 2003 European Heat Wave, and all point to general decreases in impacts over time. In some areas that were more marginally affected, mortality was observed to be lesser than in previous events (e.g. De Castro *et al* 2011, in Spain, Pascal *et al* 2013, in Ireland, and Kyselý and Kříž 2008, in the Czech Republic). In core areas, where mortality was much more substantial in 2003, Fouillet *et al* (2008) compared the event in France to a 2006 event, and estimates that approximately 4400 fewer deaths were observed in 2006 than would have been the case if the impacts were similar to 2003; similarly, Green *et al* (2016) shows mortality in the UK in a 2013 event was only one fifth as strong as 2003.

Spatial variability in trends

Historical heat-mortality research has frequently noted that some places are more vulnerable than others, and several papers have examined the spatial variability in temporal changes in vulnerability, with mixed results. Several studies that have examined multiple cities across diverse climates have shown the biggest decreases in heat mortality across the regions that were traditionally more vulnerable (e.g. Donaldson *et al* 2003, Barnett 2007, Sheridan and Dixon 2017, Bobb *et al* 2014, Davis *et al* 2002, 2003a, 2003b, 2004, Sheridan *et al* 2009), such as the northeastern, midwestern, and northwestern US. In these cooler climates, higher mortality risk was found for at the beginning of the period, suggesting hotter climates had already adapted to some extent. In contrast, other studies that assess spatial variability see no clear connection between why certain places have greater reductions than others (Miron *et al* 2008, Linares *et al* 2015, Michelozzi *et al* 2006, Guo *et al* 2012, Wang *et al* 2016, Kalkstein *et al* 2011, Schifano *et al* 2012), or no clear variability (Onozuka and Hagihara 2017). In South Korea, Lee *et al* (2016) showed heterogeneity in the temperature-mortality relationships when comparing inland and coastal locations. Ragettli *et al* (2017) show a greater decrease in heat vulnerability in the warmer cities in Switzerland, to which they attribute greater emphasis on heat awareness. de'Donato *et al* (2015) similarly see a greater decrease in warmer locales, in Europe, with increases in vulnerability in cooler cities, including Helsinki, by virtue of heat events exceeding historical norms. Converse to expectations, Kim *et al* (2017) show a greater decrease in heat vulnerability in Japanese prefectures where electricity consumption decreased the most following the 2011 Fukushima disaster.

In some cases, economic development is cited in heat vulnerability decreases; Ng *et al* (2016) showed statistically the relationship between improvement in wealth and decrease in mortality; while Chung *et al* (2017) show an earlier decrease in vulnerability in Japan than Korea or Taiwan, which is connected into different timing of development.

Possibly due to data limitations, very few studies examine rural communities explicitly. In Ireland, Pascal *et al* (2013) noted a greater decline in heat vulnerability in rural areas; while in urban Berlin and rural Brandenburg, Germany, Gabriel and Endlicher (2011) found excess mortality during two heatwaves to be higher in urban regions overall, with no clear difference in trend. Todd and Valleron (2015), in examining all of France, found a evidence of acclimatization in rural areas as well as urban areas over time, though these were not specifically partitioned.

Causes of mortality and morbidity

The majority of the studies considered mortality health outcomes, likely due to the availability of health data; for the sake of statistical power, most of these studies made their primary outcome all-cause total mortality, in some cases excluding accidents. Of the very long-term studies, differential changes in vulnerability broadly reflect larger societal changes; e.g. in Australia, with decreases in outdoor labor the male heat mortality rate has fallen faster than the female rate (Coates *et al* 2014), and in the greater decreases that are seen with children mortality rates, with other studies showing slower decreases in the elderly mortality rate (Åström *et al* 2013b) or even a noticeable uptick (Ekamper *et al* 2009) indicative of changes in overall age structure. In studies confined to more recent decades, decreases in vulnerability have been most substantial in the oldest age groups (Ruuhela *et al* 2017, Sheridan and Dixon 2017, Bobb *et al* 2014, de'Donato *et al* 2015), although in others there was no consistent age-related differentiation (Onozuka and Hagihara 2015, Ha and Kim 2013).

In terms of causes, when split, some studies see relatively similar declines in respiratory and cardiovascular deaths (e.g. Bobb *et al* 2014, Li *et al* 2017, Ng *et al* 2016); in others the results are more diverse, such as in de'Donato *et al* (2015) where the relative changes between respiratory and cardiovascular vary across the 9 European cities studied, Kyselý and Plavcová (2012) where cardiovascular mortality shows a steeper drop, in Miron *et al* (2015) where cardiovascular mortality decreases but respiratory does not, Ha and Kim (2013) which shows a similar drop in cardiovascular mortality but actually shows an increase in non-accidental mortality due to heat over time, or Yang *et al* (2015) which found no long-term trend associated with cardiovascular-heat effects.

In studies that have examined differences between the sexes, generally results are comparable, although in some cases (e.g. Muthers *et al* 2010a, Kyselý and Plavcová 2012) females show a greater decrease in heat vulnerability over time, though coming from a higher baseline. In Vienna, Matzarakis *et al* (2011) showed a slightly higher sensitivity to heat stress for women, but this finding was contingent upon the thermal variable used to assess sensitivity.

Of the studies included in our review, only three (Onozuka and Hagihara 2017, Fechter-Leggett *et al* 2016, Wang *et al* 2016) explicitly analyzed morbidity, and four others (Weisskopf *et al* 2002, Carter *et al* 2005, Nitschke *et al* 2011, Sheridan and Lin 2014) considered both mortality and morbidity outcomes. Morbidity data included out-of-hospital cardiac arrests (Onozuka and Hagihara 2017), heat stroke hospitalizations (Wang *et al* 2016, Carter *et al* 2005), EMS runs (Weisskopf *et al* 2002), heat stroke illness (Fechter-Leggett *et al* 2016). Some studies found reductions in heat-related morbidity outcomes (Fechter-Leggett *et al* 2016, Weisskopf *et al* 2002), but others showed increasing trends with regard to heat stroke hospitalizations (Wang *et al* 2016) and ambulance call outs (Nitschke *et al* 2011). In Japan, Onozuka and Hagihara (2017) found no temporal variation in out-of-hospital cardiac arrests. Carter *et al* (2005) found reductions in heat exhaustion cases but a five-hold increase in heat stroke hospitalizations on US military bases. Sheridan and Lin (2014) show a general decrease in heat-related mortality over time in New York City concomitant with an increase in heat-related hospital admissions.

Despite the overall decrease in heat-related impacts, health risks clearly vary across different illness types and demographic confounders. Physiological mechanisms associated with heat-health relationships may help explain some of these differences, and the impact of short-term mortality displacement or harvesting also plays a role in some of the heat-heath relationships (Sheridan and Lin 2014). Such differences reflect the geographical variability in heat-related health outcomes as well as the complex interaction of non-climate factors including air quality, pre-existing health status, and socio-economic status.

Possible mechanisms for temporal changes

Various technological, infrastructural, and societal mechanisms help explain the general decrease in heat-related impacts (Davis *et al* 2004, Davis *et al* 2002). For instance, Nordio *et al* (2015) showed a lower risk of death associated with the increased use of air conditioning. Each 50% increase in air conditioning prevalence lead to a 1.37% decrease in heat effect on mortality. Other studies however, indicated no significant relationship between health outcome and air conditioning (Heo *et al* 2016, Ng *et al* 2016, Bobb *et al* 2014). While air conditioning offers a mitigation opportunity, Smoyer (1998) notes that the cost can serve as an obstacle in reducing adverse heat-health outcomes. The most vulnerable—the poor or those living on fixed incomes—may not be able to afford to operationalize the air conditioning.

The occurrence of extreme heat events is often a spur for implementation of mitigation plans, and where heat mortality has decreased over time, this is often cited as a contributing factor to reduced heat sensitivity (Tan *et al* 2007, Benmarhnia *et al* 2016, Pascal *et al* 2012, Rey *et al* 2007, Schifano *et al* 2012, de'Donato *et al* 2015), although it can be difficult to make specific attribution given the myriad confounding variables (Toloo *et al* 2013). In response to the extreme heat in France in 2003, extra vigilance was prospectively connected to an overall decline in the total mortality rate (Toulemon and Barbieri 2008, Rey *et al* 2007). Several studies have confirmed a decrease in heat-related mortality in Italy following implementation of a heat warning system after 2003 (Michelozzi *et al* 2006, Morabito *et al* 2012, Schifano *et al* 2012), similar to Ebi *et al* (2004) for Philadelphia, USA. Linares *et al* (2015), however, note that the decrease in mortality in Spain following implementation of a heat warning system in 2004 was inconclusive and varied spatially. Miron *et al* (2008) draws attention to the need to monitor and review such systems. With increasing elderly populations and in the context of a changing climate, such interventions must account for changing demographics (Hess and Ebi 2016).

Many studies have suggested the decreased heat vulnerability is a function of broader societal changes, such as increased improved living standards (e.g. Tan *et al* 2007, Åström *et al* 2013a), healthcare resources and improved economic status (e.g. Kyselý and Kříž 2008, Ng *et al* 2016), long-term adaptation (e.g. Muthers *et al* 2010b), and general overall awareness (e.g. Ekamper *et al* 2009, Gabriel and Endlicher 2011). However, despite the recent declines in heat sensitivity, many of the analyzed studies note a stabilization in recent years (e.g. Miron *et al* 2008, Sheridan *et al* 2009, Åström *et al* 2013b), and thus within the context of the reasons for the decline, questions are raised as to the ultimate level of plausible acclimatization.

Moving forward

The tally of publications included in this review shows a sharp increase over recent years, from between two and three publications per year between 2002–2010, to nine in 2015 and 12 in 2016. This increased interest in studying trends in heat vulnerability is likely to continue in the years to come, particularly as lengthier data sets become available. Moving forward, we identify three general areas in which further research is needed.

First, research must greatly expand the geographic scales of analysis of trends in heat vulnerability. Based on this review, very little is still known about trends in rural heat-health relationships, even though in some studies that have examined direct heat-related mortality (e.g. Mirabelli and Richardson 2005) a majority of deaths occurred among farm laborers. Broadly, such findings draw attention to the occupational risks associated with heat, and opportunities to address such how these risks have changed over time (Xiang *et al* 2014, Kjellstrom *et al* 2016). In one of the few rural studies in Ireland, Pascal *et al* (2013) noted *the coarse geographical scale used to perform* analysis, and highlighted the need to improve geographical resolution in further health-environmental exposure studies. Even within the city, vulnerability varies widely across all spatial scales. New techniques are being used to assess variability in vulnerability based on socio-economic and environmental factors (Reid *et al* 2012) to explore intra-urban variability (Hondula *et al* 2015, Uejio *et al* 2011), and highlight the importance of individual exposure (Kuras *et al* 2017). Including these aspects in temporal analyses will help clarify the causes of the trends observed.

Second, significant opportunity also exists in the developing world, for which very few studies have been undertaken. Heat wave case studies (e.g. Azhar *et al* 2014, in India) or longitudinal studies (e.g. Omonijo *et al* 2013, in Nigeria) have shown that the population is vulnerable to extreme temperature events. However, the collective body of heat literature, with its focus on the developed world, largely frames adaptation in terms of accessibility to air conditioning and the health-care changes that have taken place over recent decades. In many developing nations, in contrast, these factors are less critical in understanding temporal changes to date, whereas the very rapid urbanization taking place may be a more critical factor. In these rapidly urbanizing countries, urban heat island impacts (Wong *et al* 2013) may most substantially compound the impacts of climate change, making the understanding of heat impacts on populations in these regions even more critical to understand.

Third, projections of heat-related mortality in the decades ahead must account more thoroughly for the temporal changes that have been observed to date. Studies of future heat vulnerability have grown more robust over years in accounting for inherent uncertainties in the climate system and human behavior on the global scale, incorporating multiple GCMs, climate-change scenarios, and other model uncertainties (Gosling *et al* 2012). However, accounting for future acclimatization to extreme heat in climate-change scenarios has been a challenge researchers have grappled with for years (Kinney *et al* 2008), and Hondula *et al* (2015) note that there is a vast discrepancy in terms of the studies that simulate human vulnerability in the future, and those that have analyzed recent human vulnerability trends to date. In our review, there is only one paper (Muthers *et al* 2010a) in which historical trends are explicitly derived for use in simulating acclimatization in the decades to come. Beyond this, few other studies focused on climate-change and future projection of heat-related mortality directly utilize by trends established in the literature included in this review (e.g. Petkova *et al* 2017, which is based on trends first shown in Petkova *et al* 2014). Instead, most papers that incorporate acclimatization into projections typically either base acclimatization on methods such as analog cities (translating the present heat-health statistical relationship from a warmer city to a city whose climate will resemble the warmer city in the future) or a fixed-value 'delta' approach, whereby a certain temperature value of acclimatization is stipulated (Hondula *et al* 2015, Kinney *et al* 2008). All of these methods contain inherent assumptions about human adaptive capacity, but do not directly assess or partition the potential changes associated with behavioral adaptation, physiological adaptation or changes in infrastructure and access to care. Many of these different aspects of adaptive capacity can be further refined through additional studies as noted above, to better inform future simulations of human vulnerability.

Understanding these changes in vulnerability over time will be most critical to relate to the projected changes in the frequency, duration, and intensity of extreme temperatures (Hess and Ebi 2016, Hajat *et al* 2006). As noted by Kalkstein *et al* (2011), the magnitude of future events is as important to consider as the frequency. Differential impacts exist with respect to the duration, intensity, and seasonal timing of extreme temperature events. For example, Davis *et al* (2016) showed variability in the temperature-mortality relationship based upon the observation time and type of thermal metric used.

Further, as populations age, the potential for increased vulnerability also exists. Muthers at al (2010a) showed that heat-related mortality could increase up to 129% without adaptation. Taking into account demographic changes, other studies show similar potential for future heat effects (Sheridan *et al* 2012, Hajat *et al* 2014). In addition to the uncertainities associated with Representative Concentration Pathways, a continued assessment of existing mitigation techniques is needed to take into account changing demographic, physiological, and environmental characteristics (Miron *et al* 2008, Hess and Ebi 2016).

Despite the overall decreases in heat sensitivity seen collectively in the literature reviewed, a number of questions remain with future acclimatization and vulnerability, particularly in the context of a changing climate. Longer, more sustained heat events are likely, but beyond the climate itself, given projected changes in population, urbanization, and demography, heat will continue to be a substantial public health issue in the decades to come in both the developed and developing worlds. Facilitating adaptive capacity will require integrating disciplinary approaches, scales, and sectors to bridge the gaps between the social and physical sciences. Reducing thermal vulnerability through education and improved infrastructure is part of the solution, but research questions remain as relates to human adaptation and themal inequality. Preparing for future heat-related impacts hinges on interdisciplinary collaboration, parternships, and continued emphasis on both climate and non-climate factors.

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ORCID iDs

Scott C Sheridan https://orcid.org/0000-0002-6928-6524

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