

Recent Trends in Heat-Related Mortality in the United States: An Update through 2018

SCOTT C. SHERIDAN,^a P. GRADY DIXON,^b ADAM J. KALKSTEIN,^c AND MICHAEL J. ALLEN^d

^a *Department of Geography, Kent State University, Kent, Ohio*

^b *Werth College of Science, Technology, and Mathematics, Fort Hays State University, Hays, Kansas*

^c *Department of Geography and Environmental Engineering, United States Military Academy, West Point, New York*

^d *Department of Political Science and Geography, Old Dominion University, Norfolk, Virginia*

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ABSTRACT: Much research has shown a general decrease in the negative health response to extreme heat events in recent decades. With a society that is growing older, and a climate that is warming, whether this trend can continue is an open question. Using eight additional years of mortality data, we extend our previous research to explore trends in heat-related mortality across the United States. For the period 1975–2018, we examined the mortality associated with extreme-heat-event days across the 107 largest metropolitan areas. Mortality response was assessed over a cumulative 10-day lag period following events that were defined using thresholds of the excess heat factor, using a distributed-lag nonlinear model. We analyzed total mortality and subsets of age and sex. Our results show that in the past decade there is heterogeneity in the trends of heat-related human mortality. The decrease in heat vulnerability continues among those 65 and older across most of the country, which may be associated with improved messaging and increased awareness. These decreases are offset in many locations by an increase in mortality among men 45–64 (+1.3 deaths per year), particularly across parts of the southern and southwestern United States. As heat-warning messaging broadly identifies the elderly as the most vulnerable group, the results here suggest that differences in risk perception may play a role. Further, an increase in the number of heat events over the past decade across the United States may have contributed to the end of a decades-long downward trend in the estimated number of heat-related fatalities.

KEYWORDS: North America; Summer/warm season; Risk assessment

1. Introduction

Globally, heat-related mortality is among the largest direct causes of weather-related mortality (e.g., Green et al. 2019). Adverse health impacts generally occur once exposure exceeds a threshold based on a temperature or human energy-balance metric (Smith et al. 2013). Examples of such metrics include various temperature thresholds, apparent temperature, wet-bulb globe temperature, and the humidity index (Humidex) along with human heat budget models such as the universal thermal climate index, physiological subjective temperature, and physiological equivalent temperature (Blazejczyk et al. 2012). Aside from the direct impacts of hyperthermia, excessive heat can also substantially influence cardiovascular and respiratory system functionality, and thus increases mortality from a number of causes (Gasparrini et al. 2015b; Kalkstein and Davis 1989). While the overall relationship has been well known, greater access to data in recent years has enabled studies of both spatial and temporal trends in heat impacts across regions (e.g., Hondula et al. 2015; Bobb et al. 2014), age, sex, race, and socioeconomic status (e.g., Gronlund et al. 2014).

Recent assessments indicate an overall decrease in heat vulnerability (Sheridan and Allen 2018), especially among the

elderly (Martínez-Solanas and Basagaña 2019; Bobb et al. 2014). Gasparrini et al. (2015a) found a statistically significant decrease in heat-related mortality for a majority of the 272 locations analyzed. Bobb et al. (2014) noted a greater than 60% decrease in heat sensitivity from 1987 to 2005, with trends most notable in the oldest populations. In comparing notable heat events, research suggests that similar events more recently have been less deadly than those prior, such as in France (Rey et al. 2007; Fouillet et al. 2008), Italy (Morabito et al. 2012), and Chicago, Illinois (Palecki et al. 2001). This trend is not universal, however. For instance, while there has been a decline in heat sensitivity in the Netherlands (Folkerts et al. 2020) and a decline in heat-related attributable fraction in Sweden (Åström et al. 2018), another study showed stable vulnerability in Australia, Ireland, and the United Kingdom (Vicedo-Cabrera et al. 2018). Scortichini et al. (2018) note the role of exceptional single heat events in driving the increasing trends. Nevertheless, even where rates have fallen, they are still statistically significantly elevated in many places (e.g., Sheridan and Dixon 2017; Åström et al. 2013), and sometimes an observed increase in the number of hot days offsets somewhat the decreased impact of any single hot day (Matzarakis et al. 2011). Further, this general decline in heat-related mortality has varied somewhat by cause of death and gender with decreasing trends particularly evident among women with circulatory disease mortality and men with respiratory disease mortality (Achebak et al. 2018).

As age has long been identified as a primary determinant of risk (O'Neill et al. 2009), many studies have focused exclusively on older subsets of the population (e.g., Rosenthal et al. 2014). However, other studies have also shown a persistent risk

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Corresponding author: Scott Sheridan, ssherid1@kent.edu

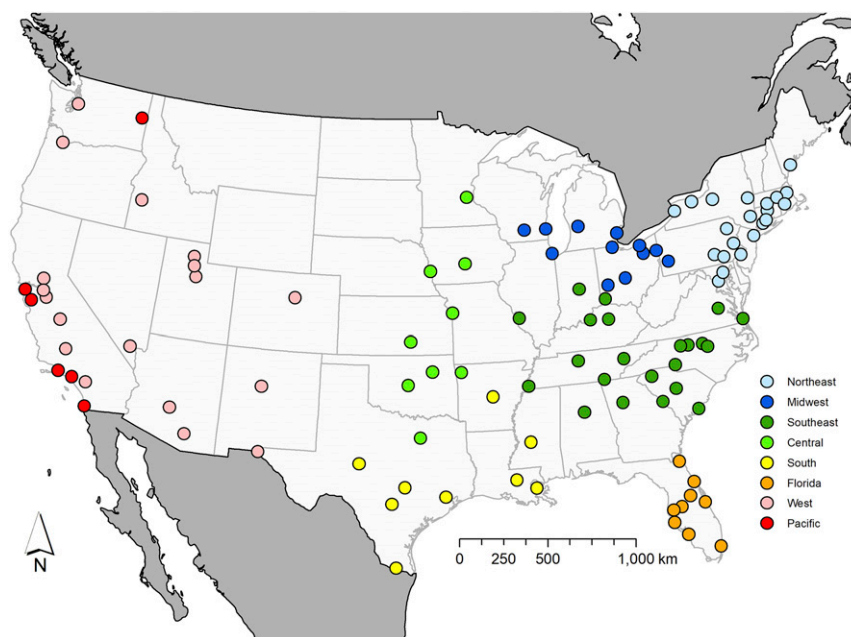


FIG. 1. A map of the metropolitan areas and their region. Note that Honolulu, Hawaii, is not in any region aside from the overall national assessment.

among younger groups. This risk is particularly notable with occupational hazards (e.g., [Gubernot et al. 2015](#)) and can be a particularly acute issue where there are large populations of outdoor laborers, such as in Qatar ([Pradhan et al. 2019](#)). Beyond occupational exposure itself, [Isaksen et al. \(2016\)](#) showed an increase in diabetes deaths during hot weather for the 45–64 age group citing the role of underlying health conditions as a major contributing factor. This finding is consistent with [Díaz et al. \(2006\)](#), who showed an increased mortality during heat events among males 45–64 in Madrid, Spain, and [Nitschke et al. \(2011\)](#), who noted a larger increase in ambulance calls among those under 65 in a 2009 Adelaide, Australia, heat event.

In assessing the socioeconomic, behavioral, and physiological factors that affect thermal vulnerability, the precise roles of human adaptation, improved healthcare, and overall heat awareness is difficult to discern. Nevertheless, with more frequent and intense heat events likely to continue as a result of anthropogenic climate change, and an aging population around the world, collective human vulnerability to heat will likely continue to grow ([Huber et al. 2017](#); [Sanderson et al. 2017](#); [Broadbent et al. 2020](#)). Further, shifts in the climate will likely highlight disparities in impacts and responses across the globe due to inequalities in health system capacities and wealth ([Chambers 2020](#)).

[Sheridan and Dixon \(2017\)](#) explored the general trends in heat-related mortality in the United States for the years 1975–2010. In this research, we extend that work in several new directions. First, we are able to add 8 years of analysis due to the procurement of additional data, and our study period now comprises 1975–2018. Second, we have expanded our study geographically to all metropolitan areas of 500 000 persons or

more, of which there are 107 in the United States. And finally, we have added further subdivisions of mortality by age and sex to assess temporal trends separately for these groups.

2. Research framework, data, and methods

a. Mortality data

In this research, we use mortality data for the period 1975–2018, acquired from the National Center for Health Statistics for the United States. Deaths are binned to daily all-cause totals at metropolitan-area level, using the spatial definitions of all Metropolitan Statistical Areas with populations of at least 500 000 as they were defined by the U.S. Census Bureau at the end of 2018, the end date of our mortality data ([Fig. 1](#)). Note that around one-third of metropolitan areas analyzed in [Sheridan and Dixon \(2017\)](#) had minor adjustments to their spatial extents in the 2010s, and thus some minor differences in mortality totals occur. We use all-cause mortality totals for two reasons. First, while exposure to heat is also a substantial burden on the health care system ([Wondmagegn et al. 2019](#)), there are no morbidity datasets that are as systematic, long term, and spatially consistent as the nationwide mortality data. Second, analyzing only directly identified heat-related mortality [International Classification of Diseases (ICD)-10 code X30] significantly underestimates overall mortality increases during hot weather ([Dixon et al. 2005](#)).

While there are many ways to subdivide data, we have chosen for this analysis to use age and sex only, to account for population aging over the period of the study and to evaluate the differences between males and females. In particular, we examine total mortality for five groups: all ages, males 65 and

older, females 65 and older, males 45–64, and females 45–64. As our preliminary analysis showed very little association between mortality and extreme weather for those under age 45, and in particular because of the very low sample sizes, we decided to exclude those subdivisions from the analysis.

All days in which mortality was at least 4 standard deviations above the expected value (calculated using the splines discussed in section 2c) were examined for singular, non-heat-related events. A total of 47 days were removed from analysis as a result (18 days related to airplane crashes; 6 days each to tornadoes and fires; 3 days each to terrorism and mass shootings; 2 days each to building collapses, bus crashes, and earthquakes; and 1 day each to mudslide, bridge collapse, flood, explosion, and mass suicide). Further, because of data incompleteness, June–October 1990 were eliminated for all locations in Texas (Austin, Dallas, El Paso, Houston, McAllen, San Angelo, and San Antonio), and all of 2008 was omitted for Atlanta and Augusta, Georgia, due to county coding irregularities in Georgia for that year.

b. Heat-wave data

To define thermal exposure, we used the Steadman (1984) apparent temperature (AT) variable, which was calculated from hourly temperature, dewpoint, and wind speed data obtained from the National Centers for Environmental Information (NCEI; formerly the National Climatic Data Center). A representative airport was chosen for each metropolitan area (Table S1 in the online supplemental material). One of the most common metrics for identifying heat exposure (Anderson et al. 2013), the Steadman AT accounts for humidity, allowing a comparison across the diverse climate zones of the United States. We use a daily mean AT, calculated from the 24 hourly values to represent overall thermal exposure. As data are quality controlled by NCEI, no further processing of data was done, except to classify as “missing” any AT observation for which one or more of the individual variables used in its calculation was missing. Gaps of 1 or 2 h within a day were filled in by interpolation; any further missing meteorological data resulted in the daily mean AT being classified as “missing,” and thus omitted from analysis. Across all cities, 0.75% of days were classified as having missing AT data.

Much research has shown that absolute thresholds for heat waves are not appropriate, since it has long been understood that thresholds for health impacts from heat will vary with generally higher thresholds observed in warmer locations (e.g., Hajat and Kosatky 2010; Guo et al. 2014). Thus, to standardize assessment, daily mean ATs were converted to percentile values relative to the climatological normal period of 1981–2010. While different threshold percentiles have been used, the 95th percentile as a baseline AT is common in previous research. Across the cities studied here, the 95th percentile of daily mean AT ranges from 16.8°C in San Francisco, California, to 36.2°C in Phoenix, Arizona.

There is some evidence that heat waves in the early summer have a disproportionately large human impact compared to those later in the season (Anderson and Bell 2011; Ng et al. 2014; Allen and Sheridan 2018), with one suggested reason

being a lack of acclimatization. Building upon the AT, as with our previous work (Sheridan and Dixon 2017; Sheridan et al. 2019), we base our heat event definition on the *excess heat factor* (EHF) in Nairn and Fawcett (2015), which effectively favors extended hot weather preceded by relatively cooler conditions. Specifically, the excess heat factor is defined as the exceedance of the three-day mean (from day −2 to day 0) AT above the 95th percentile of AT, multiplied by the difference between the three-day mean AT and the mean of the 30 days prior (from day −32 to day −3). A day is defined as an extreme-heat-event (EHE) day if the EHF exceeds the 85th percentile of all positive EHF values for a location over the climatological period (Nairn and Fawcett 2015). We initially also assessed different thresholds of EHF values; with higher thresholds, there was a greater relative risk overall, but the results were much less spatiotemporally stable, due to their infrequent occurrence.

c. Assessment of the impacts of heat on mortality

To assess spatiotemporal trends of heat-related mortality across the United States, we first calculated relative risks of mortality on EHE days for

- each of the 107 metropolitan areas;
- five mortality all-cause totals: all age, males over 65, females over 65, males 45–64, and females 45–64; and
- each of 36 rolling 9-yr periods (1975–83, 1976–84, ..., 2010–18).

We also initially examined three additional subsets of mortality (males 5–44, females 5–44, and children 0–4), but those results are not presented as overall death rates are very low and there are no clear patterns observable due to low statistical power. Relative risks were calculated by a distributed-lag nonlinear model (dlm), which evaluates the cumulative impact of heat on mortality, using the *dlm* package in R (Gasparrini et al. 2010). This model is based on a cross-basis function that is derived from two separate functions: the exposure response, and the lag response. The exposure-response association was modeled through a binary indicator of EHE or non-EHE on each day. The lag-response effects of heat were modeled to fit a natural cubic B-spline with 4 degrees of freedom (df) over a 10-day lagged period following exposure. The specific quasi-Poisson regression model used here is as follows: $\log(\text{mortality}) = \text{intercept} + \text{EHE} + \text{ns}(\text{time})$, where mortality is the daily mortality total, $\text{ns}(\text{time})$ is a natural spline fit to the period with 9 df yr^{-1} , similar to our previous work (Sheridan and Dixon 2017), and EHE is a binary variable with values of 1 for an occurrence of an EHE day and 0 for all other days.

Relative risks (RR) were thus calculated to assess the relative change in mortality on EHE days with the reference case being non-EHE days. As there is a lagged impact of heat on mortality, with the possibility of negative impacts lasting more than one day, followed by a trough of mortality due to short-term displacement (Hajat et al. 2005), the model examined the cumulative impact of heat over a 10-day period. As with our previous work, we performed sensitivity analyses on modifying the length of the lag period and changing the number of degrees of freedom (up to 20 days and 6 df), with negligible

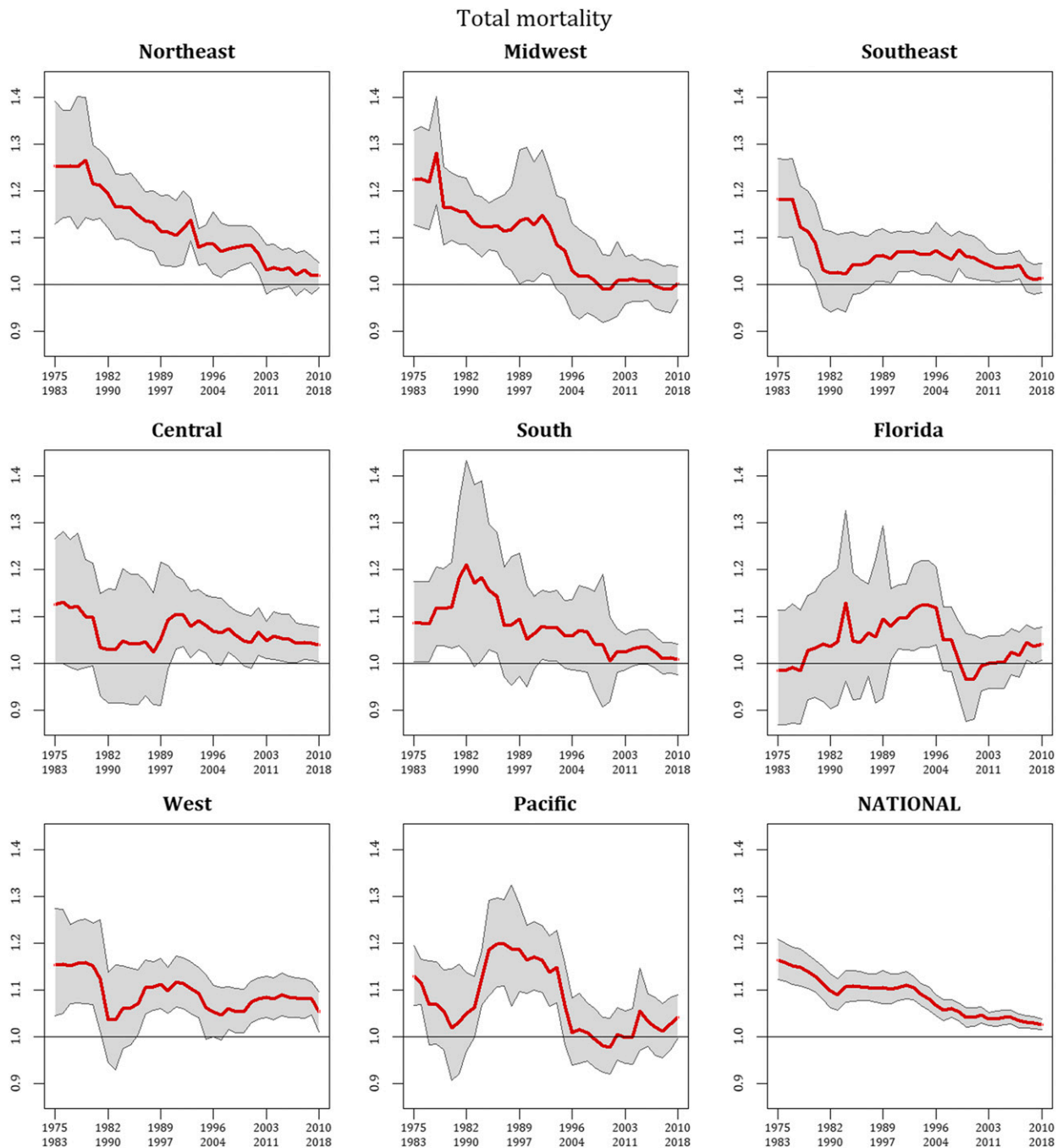


FIG. 2. Relative risk by region for total mortality on EHE days as compared with non-EHE days, divided into rolling 9-yr intervals. The red line represents the point estimate, and gray shading represents the 95% confidence interval.

impact on the results. We chose a 9-yr period as this was the ideal length identified in [Sheridan and Dixon \(2017\)](#); we did also consider periods shorter than 9 years, although this tended to result in less stable results due to small sample sizes.

To improve the robustness of the analyses, we then clustered all metropolitan areas (other than Honolulu, Hawaii) into one of eight regions ([Fig. 1](#)). Rather than an a priori grouping of metropolitan areas, we wanted to aggregate by similar climate

region. We selected the temporal variability of EHE days as the input variable for clustering, as this would allow us to group metropolitan areas based on common heat event experience (e.g., southern United States in 2011, much of the midwestern and eastern United States in 1988 and 1995, and the Pacific in 2014). Several different methods of clustering were considered. A hierarchical cluster analysis (using Ward's minimum variance) identified 8 as an ideal number, and this was confirmed

through visual inspection of the resultant clusters shown in Fig. 1. We then calculated pooled relative risks at the regional level via meta-analysis, using a random-effects model fitted through restricted maximum likelihood, using the *mixmeta* package in R (Gasparrini et al. 2020).

To translate the spatiotemporal trends by age group, we also calculated attributable number (AN) and attributable fraction (AF) based on the relative risk, using the methods defined in Gasparrini and Leone (2014). AN effectively estimates total anomalous mortality associated with EHE days, and AF estimates the percentage of total deaths that may be attributed to EHE, both accounting for the 10-day cumulative impact. Point estimates were calculated for each year for each metropolitan area to highlight the interannual variability in heat events observed.

3. Results

a. Changes in relative risk over space and time

Our results reinforce some key points from previous research. Specifically, vulnerability to heat has generally been decreasing across the United States for the past couple decades and that decrease is starting to stall (Sheridan and Dixon 2017). This change in trend seems to be due, at least in part, to increased frequency and intensity of events affecting an aging population. When including data through 2018, the overall vulnerability at the national level has leveled off (Fig. 2) after consistently decreasing over 1975–2007, with a relatively stable RR of approximately 1.05 over more recent years. Unsurprisingly, that is not true for all demographic groups and regions, with some that show increases (Fig. 2 and Figs. S1–S4 in the online supplemental material).

When comparing the different demographic groups at the national level, the most substantive changes observed have been the continuous decrease in vulnerability among females 65 and older; over the full period of the dataset, this subset of population has gone from the most vulnerable [1975–84 RR of 1.24; confidence interval (CI) from 1.18 to 1.31] to one of the least (2010–18 RR of 1.0; CI from 0.98 to 1.04). There have been decreases in vulnerability among men 65 and older as well, although the decrease is less steep for men, and the overall risk at the end of the period is still statistically significant.

In contrast, there has been much less marked change in those 45–64 years of age. For middle-aged women, the relative risk has decreased slightly, but at the national level the relative risk for this group has not been significant in decades. For men aged 45–64, there is no evidence of a reduced risk in heat vulnerability since 1975. Running 9-yr national relative risks vary from 1.08 to 1.13, but the variability is distributed throughout the period, and the statistical significance has been maintained over time.

While there is an overall flattening in trends nationally over the last decade, regionally, there are notable trends in opposite directions. Vulnerability in the Northeast, Midwest, Southeast, Central, South, and West has been steady or showing consistent, but insignificant, decreases since 2010. Florida has seen a

TABLE 1. Point estimates of national excess heat-related mortality by year, for all ages and examined subgroups [female (F); male (M)]. Linear trend in deaths per year is also shown.

	All ages	F 45–64	M 45–64	F 65+	M 65+
1975	1219	91	124	626	350
1976	87	7	10	46	13
1977	2181	170	317	1086	533
1978	755	24	97	369	192
1979	368	9	35	225	50
1980	2250	242	283	1048	451
1981	983	60	102	538	249
1982	435	30	35	241	130
1983	1148	42	97	612	320
1984	1070	42	87	573	314
1985	50	–5	16	44	–31
1986	509	23	16	291	134
1987	815	40	95	404	193
1988	2687	125	243	1430	706
1989	494	37	29	248	144
1990	302	–22	19	149	95
1991	1005	63	110	464	290
1992	446	16	21	198	154
1993	1570	81	194	637	513
1994	1047	76	91	438	372
1995	2800	174	380	1106	866
1996	348	14	44	125	132
1997	378	11	55	143	143
1998	908	39	131	329	278
1999	1699	90	173	738	566
2000	223	15	32	82	48
2001	844	44	144	354	255
2002	925	48	134	302	366
2003	188	–46	93	40	31
2004	20	–35	–3	5	25
2005	601	40	130	221	182
2006	970	19	314	306	263
2007	518	34	102	224	73
2008	261	–2	47	98	87
2009	312	16	49	84	112
2010	1071	87	169	426	254
2011	914	49	209	268	243
2012	701	10	269	132	193
2013	587	–29	250	124	167
2014	161	8	5	67	63
2015	348	46	26	118	52
2016	731	62	149	207	198
2017	807	108	161	238	155
2018	600	26	276	164	77
Trend	–13.5	–1.1	+1.3	–10.8	–3.5

somewhat consistent, significant increase in vulnerability, and the Pacific region is marked by year-to-year variability but an overall slight positive trend in the last decade.

Examining the population subsets, results for the Midwest suggest a possible change in trend, from decreasing to slightly increasing, for women 45 and older, although men 45–64 in the Central region have seen steadily decreasing vulnerability in recent years. However, neither of those two signals are statistically significant. More noteworthy are the significant trends in Florida and the Pacific, which are opposite (i.e., increasing

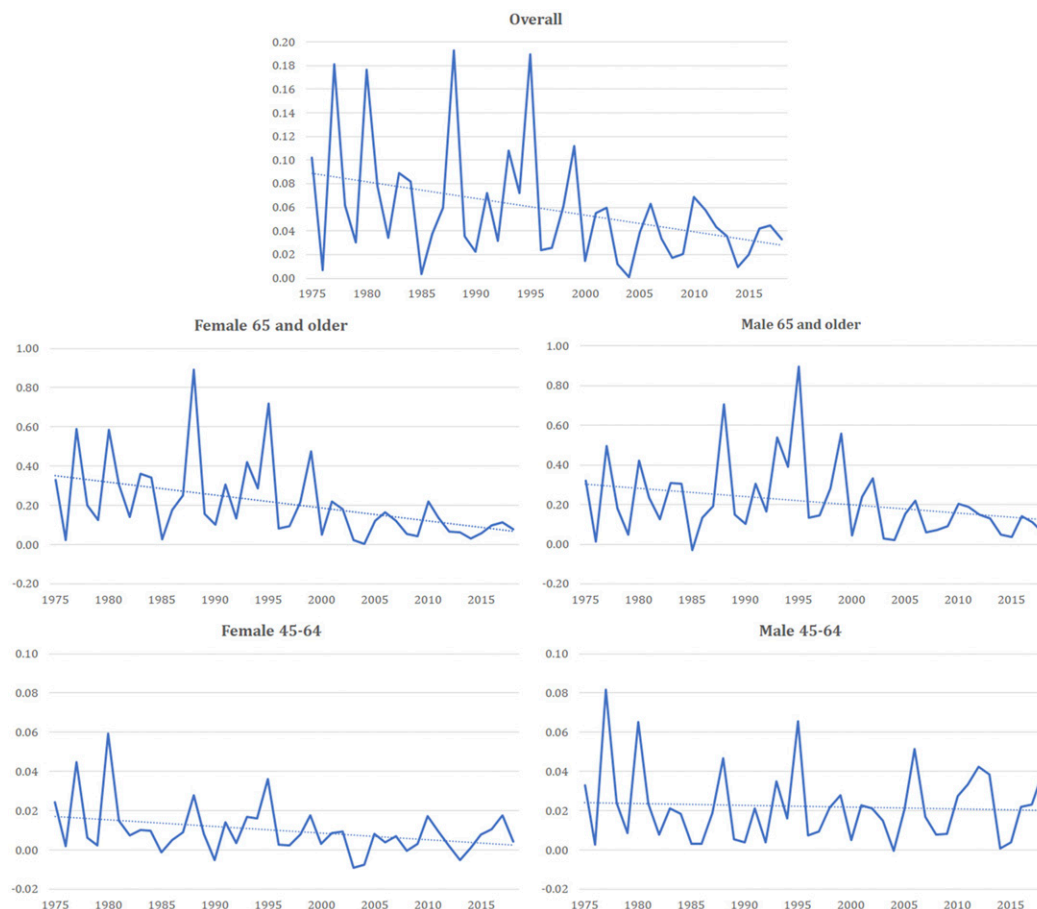


FIG. 3. Point estimates of national attributable fraction by year for all ages and examined subgroups. This subset of total deaths is composed of the percentage that can be attributed to excess heat. Linear trend is also shown. Note that the y axis has different scales for the age groups, to enhance comparisons over time.

vulnerability) of the other regions. Florida's trend is not seen among women, so it is being driven by men 45 and older, with the disappearance of a protective effect ($RR < 1.0$) from heat events earlier in the period of study. Both men and women 45 and older show generally increased risk during the last decade in the Pacific region.

b. Attributable number and fraction

Point estimates for the annual totals of heat-related mortality based on our methods are presented in Table 1; with the corresponding attributable fractions in Fig. 3. Across most demographic groups, the trend in AN, or excess deaths associated with EHE days (using the cumulative 10-day lag), is downward, particularly for males and females over 65, at -3.5 and -10.8 deaths per year, respectively. There is great variability from year to year: summers that were hot across broad areas of the United States stand out (e.g., 1980, 1988, 1995, 2010, and 2017; Fig. 4), as do anomalously cool summers (e.g., 1985, 2004, 2014). Despite having the largest reduction in overall vulnerability, because of having the highest overall death rate, females 65 and older still are highly represented in annual totals. More interesting is the lack of decrease among

males 45–64: while the trend in AF is insignificantly downward (-0.01% per year), the AN is increasing ($+1.3$ deaths per year). Some of the years with the largest death totals have occurred in the last 15 years, and in 4 years (2006, 2012, 2013, and 2018) the estimated mortality from this age group was larger than any other subset analyzed.

In examining subsets of mortality for males 45–64 at a finer spatial scale, it is clear that the generalizations seen at the regional level are not reflected in all cities that make up each region. Indeed, any spatial pattern is difficult to discern (Fig. 5; Tables S1–S3 in the online supplemental material), although the pattern for males 45–64 is generally similar to that of total attributable number summed across all age groups (Fig. 6) because of the substantive role males 45–64 play in overall mortality over the last decade. While AN is generally still highest during 2010–18 across many of the urbanized centers of the Northeast and Midwest, there are also very high values across a number of cities in the West and South regions. A number of these cities are large, such as Phoenix (mean AN of 20.4 deaths per year among males 45–64; $AF = 0.52\%$ of all deaths of males 45–64) and Las Vegas, Nevada (14.0; 0.58%), both of which trail only New York in absolute numbers.

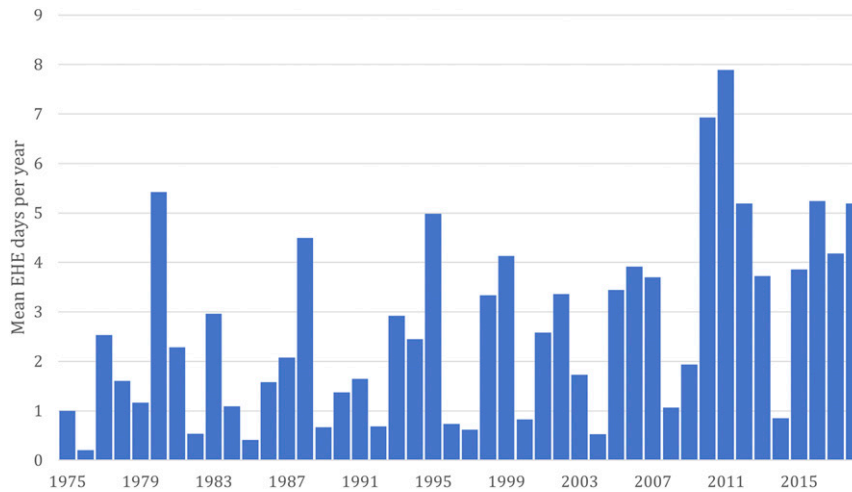


FIG. 4. Mean number of EHE days per year across all cities studied.

Complementing these cities are a number of smaller locations where the highest AF are found, including Bakersfield, California (AF = 1.13%; AN = 9.5); Provo, Utah (0.81%, 1.6); Wichita, Kansas (0.75%, 5.7); and McAllen, Texas (0.67%, 3.5).

4. Discussion and conclusions

The results in our analyses indicate both spatial heterogeneity and demographic differences with respect to changes in heat vulnerability in the United States. Previous decades indicate significant declines in vulnerability, similar to the overall literature in U.S. cities (e.g., [Gasparrini et al. 2015a](#); [Bobb et al. 2014](#)) likely due to a combination of factors including the development of heat watch-warning systems, increased air-conditioning prevalence, and heightened education and awareness ([Barreca et al. 2016](#)). However, in more recent years, this trend has stagnated or even reversed in some locations and for some populations. While the most substantive increase being among the oldest subsets of the population is similar to what [Bobb et al. \(2014\)](#) uncovered using data through 2005, it appears that the trend in decreasing elderly mortality is being offset by increasing mortality among middle-aged males. As heat-warning messaging broadly identifies the elderly as the most vulnerable group ([Grothmann et al. 2017](#)), the results here suggest that differences in risk perception may play a role ([Howe et al. 2019](#)).

Spatially, many of the cities in which trends are reversing, with increased vulnerability, are across the southern and western United States, including Southern California, which [Bobb et al. \(2014\)](#) identified as the only region not showing decreasing trends in their study. In these regions, the proportion of immigrant labor is greatest ([Bureau of Labor Statistics 2020](#)). Further, nearly all of the cities with the highest rates of vulnerability for middle-aged men have relatively high percentages of low-skill immigrants ([Hall et al. 2011](#)), have higher-than-average estimates of undocumented migrants ([Pew Research Center 2019](#)), and the western locations have larger and increasing homeless populations

([National Alliance to End Homelessness 2020](#); [Putnam et al. 2018](#)). As research has identified linguistic minorities, laborers ([Montz et al. 2011](#)), and the homeless ([Gronlund et al. 2018](#)) to be particularly vulnerable during heat events further attention to this recent increase is warranted. Improving risk communication, particularly for non-native-English speakers, could aid in reducing heat vulnerability within these demographic groups.

In the United States, air-conditioning prevalence reached 87% with most newer homes having central air conditioning ([U.S. Energy Information Administration 2015](#)). This same study noted 46% of people turn on the unit only as needed, suggesting additional factors such as affordability may also play a role ([Miller et al. 2017](#)), particularly during times of economic hardship ([Tirado and Jiménez Meneses 2016](#)). While air conditioning may be an effective strategy to reduce exposure—[Nordio et al. \(2015\)](#) note a 1.37% decrease in heat-related mortality for 50% increase in air conditioning prevalence—its utility is dependent on the electric grid ([Lubega and Stillwell 2018](#)). Further, overnight temperatures are increasing faster than daytime ([Davy et al. 2017](#)) and [Spangler and Wellenius \(2020\)](#) show that areas with lower socioeconomic status are warming at faster rates in the United States. Future research should explore how the trends observed in this research are apparent across race/ethnicity and socioeconomic status, as improving the social capacity of individuals and at-risk communities can reduce extreme heat vulnerability ([Harlan et al. 2019](#)).

The recent increase in vulnerability in the Pacific Region was identified previously by [Reid et al. \(2009\)](#), and to a lesser extent by [Bobb et al. \(2014\)](#), but our results show greater increases associated with females 65 years of age and older (Fig. S1 in the online supplemental material). Similarly, the lack of declining heat vulnerability in Florida raises important questions about regional demographics. One reason for the persistent heat risk there may be attributed to the seasonal migration of northern populations to more temperate climates. [Smith and House \(2006\)](#) estimated that 800 000 “snowbirds” relocate temporarily to Florida each

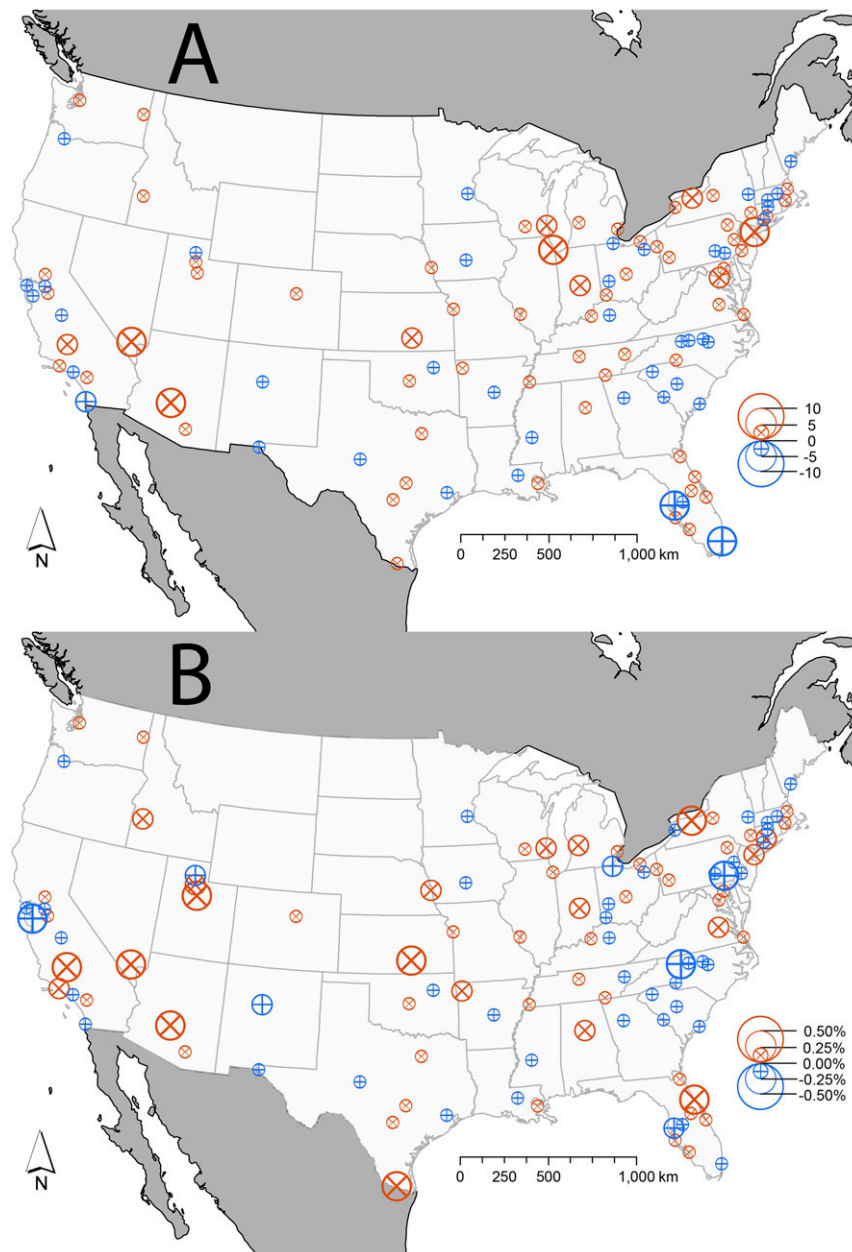


FIG. 5. (a) Attributable number of excess deaths on EHE days (mean deaths per year for males 45–64) and (b) attributable fraction of total deaths per year by city for males 45–64 during the period 2010–18.

year. These findings suggest that the changing trends are not the result of a singular issue, and in this research no analyses were done statistically comparing these socioeconomic differences to spatial variability in the trends. Likewise, a number of other shorter-term anomalies in the trends can be seen, and continued attention to the geographic and demographic heterogeneity in heat-related health outcomes is warranted.

As noted above, there is no single standard definition for a heat event, and there have been a number of studies that have

compared the efficacy of different metrics for evaluating heat-related mortality (e.g., Hajat and Kosatky 2010; Armstrong et al. 2019), as well as different thresholds (e.g., Royé et al. 2020). We have chosen the excess heat factor, as it has been shown to be an optimal predictor of heat-related mortality (Nairn and Fawcett 2015; Nairn et al. 2018; Urban et al. 2019); and specifically based on apparent temperature, because it performed well in our previous work (Sheridan and Dixon 2017), and would allow the most direct comparison. There is considerable value in assessing different heat exposure metrics

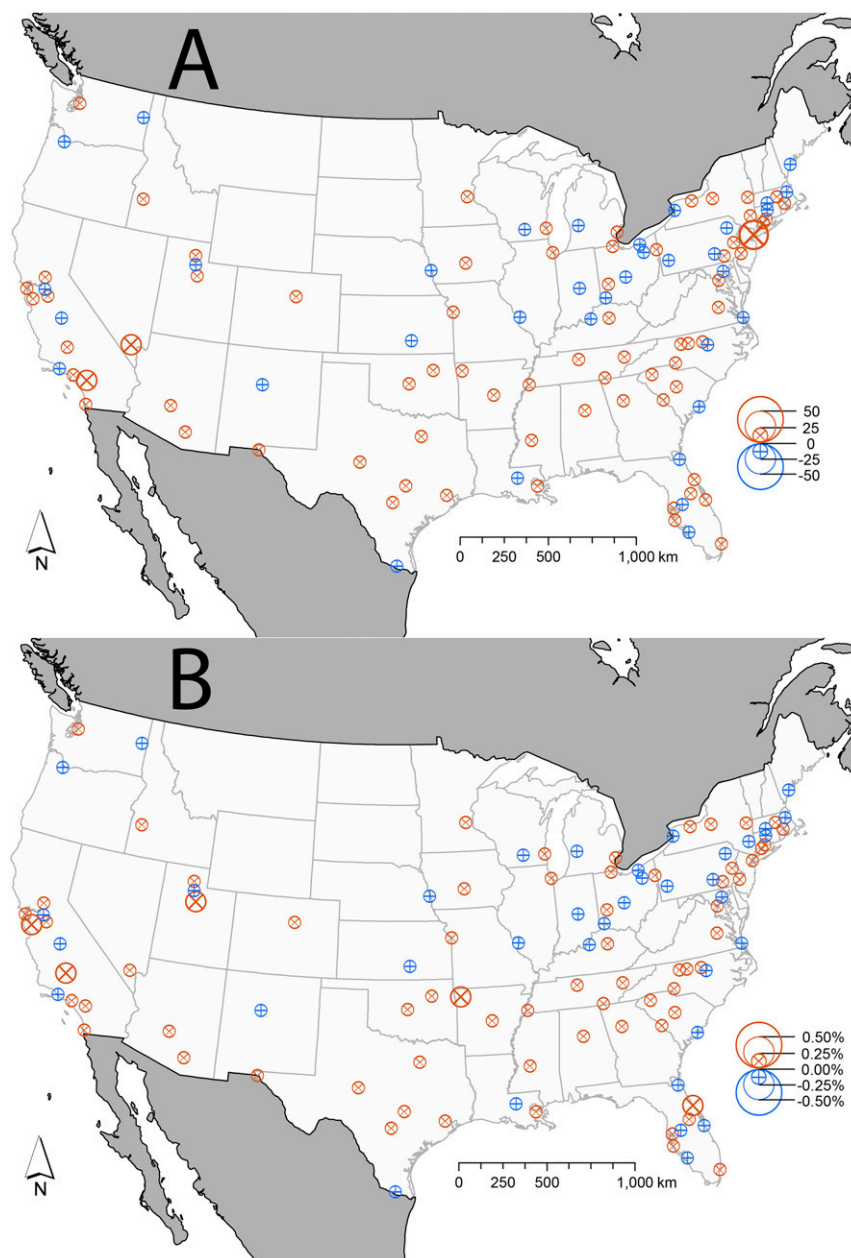


FIG. 6. As in Fig. 5, but including all age groups and sex

and thresholds, and further assessments of the trends observed using different metrics are recommended.

With projected increases in extreme temperature events, unraveling the interconnected dimensions of heat-related vulnerability is difficult to discern yet essential to minimizing the impact of heat on human health (Sheridan and Allen 2015; Boeckmann and Rohn 2014). Using our definition of EHE days, it is clear that there has been an increase in events during the 2010s (Fig. 4). Thus, even where the response to an individual hot day may be weaker than previously, it is still undetermined how an increased prevalence of hot days may affect human health. Moreover, our results have shown that significant

mortality can still be identified in hot summers. This agrees with the increases in mortality seen in other places during recent hot summers (e.g., 2015 in central Europe; Muthers et al. 2017; Urban et al. 2017). Given the prospects of a warmer world in decades to come, heat-related mortality is likely to continue to be a substantial public health issue.

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Data availability statement. Meteorological data are freely available from National Centers for Environmental Information.

Because of the agreement by which the authors procured the mortality data, it is not publicly available for dissemination.

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