HHS Public Access
Author manuscript
Environ Int. Author manuscript; available in PMC 2024 November 09.

Published in final edited form as:
Environ Int. 2021 December ; 157: 106834. doi:10.1016/j.envint.2021.106834.

Heat warnings, mortality, and hospital admissions among older adults in the United States

Kate R. Weinberger[a,*], **Xiao Wu**[b], **Shengzhi Sun**[c], **Keith R. Spangler**[c], **Amruta Nori-Sarma**[c], **Joel Schwartz**[b], **Weeberb Requia**[d], **Benjamin M. Sabath**[b], **Danielle Braun**[b,e], **Antonella Zanobetti**[b], **Francesca Dominici**[b], **Gregory A. Wellenius**[c]

[a]School of Population and Public Health, University of British Columbia, 2206 East Mall, Vancouver, British Columbia V6T 1Z3, Canada

[b]Harvard T.H. Chan School of Public Health, 677 Huntington Avenue, Boston, MA 02115, USA

[c]Boston University School of Public Health, 715 Albany Street, Boston, MA 02118, USA

[d]School of Public Policy and Government, Fundação Getúlio Vargas, Brasilia, SGAN (Setor de Grandes Áreas Norte) Quadra 602 – Módulos A, B e C – Asa Norte, Brasilia, DF 70830-051, Brasil

[e]Department of Data Science, Dana-Farber Cancer Institute, 450 Brookline Avenue, Boston, MA 02215, USA

Abstract

Background: Heat warnings are issued in advance of forecast extreme heat events, yet little evidence is available regarding their effectiveness in reducing heat-related illness and death. We estimated the association of heat warnings and advisories (collectively, "alerts") issued by the United States National Weather Service with all-cause mortality and cause-specific hospitalizations among Medicare beneficiaries aged 65 years and older in 2,817 counties, 2006–2016.

Methods: In each county, we compared days with heat alerts to days without heat alerts, matched on daily maximum heat index and month. We used conditional Poisson regression models stratified on county, adjusting for year, day of week, federal holidays, and lagged daily maximum heat index.

Results: We identified a matched non-heat alert day for 92,029 heat alert days in 2,817 counties, or 54.6% of all heat alert days during the study period. Contrary to expectations, heat alerts were not associated with lower risk of mortality (RR: 1.005 [95% CI: 0.997, 1.013]). However, heat

*Corresponding author at: School of Population and Public Health, University of British Columbia, 2206 East Mall, Vancouver, British Columbia, V6T 1Z3, Canada. kate.weinberger@ubc.ca (K.R. Weinberger).

Declaration of Competing Interest
Dr. Wellenius has received consulting fees from the Health Effects Institute (HEI) (Boston, Massachusetts) and recently served as a paid visiting scientist at Google LLC (Mountain View, California). Dr. Dominici is a member of the HEI research committee and has received consulting fees from HEI (Boston, Massachusetts).

Appendix. Supplementary material
Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106834.

alerts were associated with higher risk of hospitalization for fluid and electrolyte disorders (RR: 1.040 [95% CI: 1.015, 1.065]) and heat stroke (RR: 1.094 [95% CI: 1.038, 1.152]). Results were similar in sensitivity analyses additionally adjusting for same-day heat index, ozone, and $PM_{2.5}$.

Conclusions: Our results suggest that heat alerts are not associated with lower risk of mortality but may be associated with higher rates of hospitalization for fluid and electrolyte disorders and heat stroke, potentially suggesting that heat alerts lead more individuals to seek or access care.

Keywords

Extreme heat; Early warning systems; Mortality; Hospitalization; United States; Medicare

1. Introduction

While exposure to high ambient temperature (i.e., "heat") has long been recognized as a threat to health, the burden of illness and death attributable to heat remains high. In the United States (US), recent estimates suggest that heat contributes to thousands of excess deaths annually (Shindell et al., 2020; Weinberger et al., 2020), and the impact of heat on non-fatal health outcomes as measured by hospital admissions or emergency department visits may be even larger (Wellenius et al., 2017). Compounding the problem, the frequency and severity of extreme heat events is expected to increase in future decades due to climate change (IPCC, 2013).

In response to the danger posed by extreme heat events, particularly to vulnerable subgroups of the population such as older adults, many communities have developed early warning systems to reduce heat-related illness and death (Hawkins et al., 2017; Lowe et al., 2011). These systems typically make use of weather forecasts to issue heat alerts to public health and emergency management officials as well as the general public in advance of hot weather (McGregor et al., 2015). Yet despite their key role in the response to heat, there remains a paucity of evidence regarding the effectiveness of heat alerts in reducing adverse health outcomes related to heat at the population scale. A limited number of studies have explored this question with mixed results (Benmarhnia et al., 2016; Benmarhnia et al., 2019; Chau et al., 2009; Heo et al., 2019; Weinberger et al., 2018), but these studies have largely considered only one or a few cities and focused on mortality as a health endpoint. A large-scale, systematic assessment of the benefits of existing heat early warning systems in the US across a range of health outcomes is currently lacking.

To address this gap in knowledge, we assessed the association between heat alerts, all-cause mortality, and cause-specific hospital admissions among Medicare beneficiaries aged 65 years and older living in more than 2,800 counties, 2006–2016. In the US, regional offices of the National Weather Service (NWS) issue excessive heat warnings and heat advisories (collectively, "heat alerts") when periods of high heat are forecast. In addition to providing advance warning of dangerous conditions, NWS alerts frequently contain information that can inform individual behavior (e.g., remaining hydrated) and may also trigger additional local risk reduction measures (e.g., the opening of cooling centers) (Hawkins et al., 2017; Sheridan and Kalkstein, 2004). While the criteria vary regionally, in most communities forecast values of the heat index are used to inform decisions about when to issue heat alerts. For example, heat advisories – a type of alert issued for less severe heat events – are typically issued when the daily maximum heat index is forecast to exceed 100°F (37.8 °C) in northern communities and 105°F (40.6 °C) in southern communities (Hawkins et al., 2017). However, due to weather forecast uncertainty and the discretion typically given to forecasters in deciding when to issue heat alerts, in any given location we hypothesize that there will be a set of days within a narrow range of observed heat index, some of which will have alerts and some of which will not. For example, in a location where heat alerts are issued when the heat index is forecast to exceed 100°F, there may be some days with alerts that have observed heat index values slightly below 100°F, and some days without alerts that have observed heat index values slightly above 100°F. Our analysis leverages this data structure in order to test whether on days of similar heat index, heat alerts are associated with changes in the risk of all-cause mortality and cause-specific hospital admissions.

2. Methods

2.1. Study population

We obtained enrollment and inpatient claims data on Medicare beneficiaries aged 65 and older from the Centers for Medicare and Medicaid Services. Medicare is a federal health insurance program that covers the vast majority of older adults in the US; in 2016, approximately 47.8 million of the 49.2 million individuals aged 65 and older in the US were enrolled in Medicare (The Boards of Trustees of the Federal Hospital Insurance and Federal Supplementary Medical Insurance Trust Funds, 2017; Roberts et al., 2016). For each county in the contiguous US for which at least one heat alert was issued between 2006 and 2016, we constructed daily time series of the number of all-cause deaths occurring among all Medicare beneficiaries and the number of cause-specific hospital admissions occurring among fee-for-service (FFS) Medicare beneficiaries. For mortality, we examined only all-cause deaths as we did not have access to information on cause of death. For hospital admissions, we examined seven specific causes chosen because they were associated with extreme heat events in a previous analysis of the Medicare FFS population (Bobb et al., 2014). These seven causes, which are defined by groups of International Classification of Diseases (ICD) principal discharge diagnosis codes identified using the Clinical Classifications Software (CCS) algorithm (Elixhauser and Palmer, 2014; Wasey, 2018), were: septicemia (except in labor) (CCS 2), diabetes mellitus with complications (CCS 50), fluid and electrolyte disorders (CCS 55), peripheral vascular disease (CCS 114), renal failure (acute/unspecified) (CCS 157), urinary tract infections (CCS 159), and heat stroke and other external causes (CCS 244).

2.2. Data sources

2.2.1. Heat alerts—We obtained text files containing records of all non-precipitation alerts issued by the US NWS during the warm months (April to October) of 2006–2016 from the National Oceanic and Atmospheric Administration (NOAA 2016). During this time period, the record for each alert included a header containing information on the type, location, and timing of the alert in a standard format. We used the information in this header to identify the date and location of each heat advisory (issued when a less severe heat event is forecast) and excessive heat warning (issued when a more severe heat event is forecast) issued in the contiguous US. Collectively, we refer to these advisories and warnings as "heat alerts." The geographic unit for which heat alerts are issued is the forecast zone, a unit delineated by the NWS that does not necessarily conform to other commonly used geographic boundaries (i. e., counties) and may change over time. For each county, we identified the forecast zone containing the largest proportion of the 2010 county population using shapefiles of forecast zone boundaries for the study period (US National Weather Service). We then created a daily time series containing a binary variable for heat alert exposure for each county.

2.2.2. Heat index—We obtained gridded (4-km resolution) estimates of daily maximum temperature and vapor-pressure deficit for the contiguous US from the Parameter-elevation Regressions on Independent Slopes Model (Daly et al., 2008; PRISM Climate Group OSU, 2013). From these variables, we generated time series of population-weighted daily maximum heat index for each county (Spangler et al., 2019). This process is further described in the Supplemental Material, Appendix A.

2.2.3. Air pollution—We obtained daily estimated concentrations of fine particulate matter (with an aerodynamic diameter of less than 2.5 μm; $PM_{2.5}$) and ozone for the contiguous US on a 1-km grid (Di et al., 2019; Requia et al., 2020). From these data, we calculated time series of population-weighted concentrations of $PM_{2.5}$ and ozone for each county (see Supplemental Material, Appendix A).

2.3. Statistical analysis

Our approach compares the number of deaths or admissions occurring on days with heat alerts ("heat alert days") to similar days without heat alerts ("non-heat alert days") in the same county. Specifically, for each heat alert day in a given county, we identified a pool of candidate non-heat alert days that: 1) occurred in the same county, 2) occurred in the same month of the year, 3) had an observed daily maximum heat index value within +/− 2°F, and 4) were not within three days of a heat alert day. We then matched each heat alert day to one randomly selected non-heat alert day from within the pool of candidate days, excluding non-heat alert days that were already matched to a different heat alert day (i.e., sampling without replacement).

Within this dataset of heat alert days and 1:1 matched non-heat alert days (hereafter, "main dataset"), we modeled the association between heat alerts and each health outcome using overdispersed conditional Poisson regression models (Armstrong et al., 2014) implemented in the R package 'gnm' (Turner and Firth, 2020). We included stratum indicators for county; adjusted for year, day of week, and federal holidays with indicator variables; and adjusted for lagged daily maximum heat index (lag days 1 and 2) with linear terms. In the models for hospital admissions, we additionally included an offset term consisting of the natural logarithm of the monthly number of individuals in the FFS population (i.e., excluding individuals who have died or who have Health Maintenance Organization (HMO) plans). In secondary analyses, we included an interaction term for time period (2006–2010 vs. 2011–2016) in order to investigate whether the association between heat alerts and health outcomes varies over time.

We conducted several sensitivity analyses to examine the robustness of results from the main analyses. First, we additionally adjusted models for same-day $PM_{2.5}$, ozone, and maximum heat index to reduce potential residual confounding by these variables. For example, even after matching on heat index, there may still be small differences in heat index on days with versus without heat alerts. Second, as our analyses revealed that heat alerts are sometimes issued on days that are only moderately hot, in sensitivity analysis we restricted our model to include only heat alert days that were at least 100°F and their matched non-heat alert days. Third, we restricted our analysis to days for which excessive heat warnings (the type of alert issued for more extreme heat) were issued, as well as their matched non-heat alert days. Fourth, we assessed whether our results were sensitive to the random component of our matching process (as we randomly selected a non-heat alert day to match on) by generating 10 additional matched datasets, each with a different random seed, and re-rerunning the conditional Poisson regression models on each dataset.

As an additional diagnostic, we used a similar approach to verify that in the set of days and counties included in our analysis, heat index was indeed associated with a higher risk of morbidity and mortality. Specifically, we matched each day in our main dataset (both heat alert and non-heat alert days) to a single day in the same county and month that was at least 5°F cooler. We then constructed overdispersed conditional Poisson regression models for each health outcome, including stratum indicators for county and adjusting for year, day of week, and federal holidays with indicator variables.

All analyses were carried out in R version 3.5.2. ICD processing was carried out using the “ICD” package (Wasey, 2018).

3. Results

Between 2006 and 2016, a total of 168,604 heat alert days were reported in 2,837 counties across the contiguous US. There was a median of 44 (range: 1, 243) heat alert days per county over the 11-year study period, or a median of 4 heat alert days per county per year (range: 0.1, 22.1) (Fig. 1A). We were able to match 92,029 (54.6%) heat alert days in 2,817 counties to a similar day without a heat alert. The median number of successfully matched heat alert days in individual counties was 26 (range: 1, 148), while the median percent of heat alert days with a match in individual counties was 57% (range: 12.5%, 100%) (Fig. 1B). Days with heat alerts for which we were able to identify a match tended to be cooler and more likely to occur in the earlier months of the warm season than days with heat alerts for which we were not able to identify a match (Table 1).

The 2,817 counties included in our analysis contained 94.0% of the total US population in 2010 and 93.7% of the US population age 65 and older. Our main analyses are based on a total of 275,653 deaths. The total number of hospitalizations included in our analyses ranged from 3,780 hospitalizations for heat stroke to 71,460 hospitalizations for septicemia (Table 2).

Contrary to expectation, we did not observe evidence that heat alerts were associated with a lower relative rate of mortality (RR: 1.005 [95% CI: 0.997, 1.013). Similarly, we did not find evidence of an association between heat alerts and admissions for septicemia, diabetes mellitus, peripheral vascular disease, renal failure, or urinary tract infections. However, we did observe that heat alerts were associated with higher rates of hospitalizations for fluid and electrolyte disorders (RR: 1.040 [95% CI: 1.015, 1.065]) and heat stroke (RR: 1.094 [95% CI: 1.038, 1.152]) (Table 2). In these models, the associations between the lagged heat index terms (which we included as covariates) and health outcomes were weak (Supplemental Material, Table 1).

In sensitivity analyses, these results were robust to adjustment for same-day $PM_{2.5}$, ozone, and heat index (Fig. 2). When models were restricted to heat alert days that were 100°F or hotter (n = 62,399 alert days distributed across 2,300 counties), results were somewhat stronger for fluid and electrolyte disorders (RR: 1.055 [95% CI: 1.021, 1.090]), heat stroke (RR: 1.118 [95% CI: 1.043, 1.198]), and renal failure (RR: 1.031 [95% CI: 1.001, 1.062]) (Fig. 2). Results were similar in the sensitivity analysis restricted to heat alert days for which excessive heat warnings were issued (Fig. 2), as well as in analyses run on the 10 additional randomly matched datasets (Supplemental Material, Fig. 1). We did not observe evidence of effect measure modification by time period in any of the models in our main analysis.

Finally, we verified that heat index was associated with higher risk of morbidity and mortality on the days and counties included our study (Table 3). Specifically, we successfully matched 183,831 (99.9%) of the 184,058 days in the main dataset (including 91,912 heat alert days and 91,900 non-heat alert days) to days in the same county and month that were at least 5°F cooler. The average value of daily maximum heat index on successfully matched days from the main dataset was 100.8°F, compared to 88.3°F among the matched cooler days. We observed a positive association between heat index and all-cause mortality (RR: 1.011 [95% CI: 1.005, 1.016]), as well as with each category of cause-specific admissions except for diabetes mellitus and peripheral vascular disease.

4. Discussion

In the US, heat alerts are issued by the NWS in advance of periods of forecast high heat, but the effectiveness of these alerts in reducing morbidity and mortality remains largely unknown. In this study covering most counties in the contiguous US, we did not find evidence that heat alerts are associated with lower rates of all-cause mortality among Medicare beneficiaries age 65 and older between 2006 and 2016. These results were robust to sensitivity analyses including additional adjustment for same-day concentrations of air pollutants. Additionally, we confirmed the presence of an association between heat index and mortality in the specific population, locations, time period, and days included in our analyses.

Our results add to an emerging body of evidence regarding the effectiveness of heat alerts in reducing mortality. A few prior studies have reported a reduction in heat-related mortality following the implementation of heat early warning systems (Hess et al., 2018; Martínez-Solanas and Basagaña, 2019; Nitschke et al., 2016; Palecki et al., 2001; Donato et al., 2018). For example, a study of 23 Italian cities provided evidence of decreasing relative and absolute risks of mortality in the years following the implementation of a national heat plan, which included a warning system (D'Ippoliti et al., 2010). However, these analyses rely on pre/post contrasts and may thus be confounded by other factors that change over time, such as awareness of heat-health risks, adoption of other risk reduction measures (e.g., air conditioning), and shifting population demographics. A smaller set of studies, including the present study, have avoided this form of confounding by instead comparing days with and without heat alerts at comparable levels of heat while accounting for other factors that vary over time; with mixed results. While we did not find evidence of an association between heat alerts and all-cause mortality (RR: 1.005, 95% CI: 0.997, 1.013) in this study, other studies have documented small decreases in the risk of all-cause mortality in Philadelphia (Ebi et al., 2004) and Montreal (Benmarhnia et al., 2016), and of mortality due to ischemic heart disease and stroke in Hong Kong (Chau et al., 2009). In contrast, a study conducted in seven Korean cities did not find evidence that heat alerts were associated with lower all-cause mortality, although there was some evidence of decreased cause-specific mortality among subgroups defined by employment status, marital status, and education (Heo et al., 2019). Similarly, in a previous study we did not find evidence of an association between heat alerts and mortality across 20 US cities between 2001 and 2006, but we did observe an association between heat alerts and a lower risk of mortality in Philadelphia (Weinberger et al., 2018). We posit that factors contributing to these diverging results could include differences in study design, location, time period, and age groups examined.

To date, few studies have examined the impact of heat alerts on non-fatal outcomes such as hospital admissions, although limited evidence from specific cities suggests a reduction in measures of morbidity (Benmarhnia et al., 2019; Toloo et al., 2013). In the present study we found that heat alerts were associated with a higher risk of hospital admissions for multiple specific causes. In particular, we found that heat alerts were associated with a relative risk of 1.040 (95% CI: 1.015, 1.065) for fluid and electrolyte disorders, and of 1.094 (95% CI: 1.038, 1.152) for a group of causes including heat stroke and other external disorders. In contrast, we did not find evidence of an association between heat alerts and hospital admissions due to renal failure, urinary tract infections, septicemia, diabetes and peripheral vascular disease. For diabetes and peripheral vascular disease, these results could be due to a lack of a primary association with heat index on the days included in our study (Table 3).

In Fig. 3, we present a causal diagram illustrating potential pathways by which heat alerts may alter the impact of heat on hospitalizations and deaths. As noted above, heat alerts typically include messaging about heat risks and information about how to minimize exposures and/or recognize the symptoms of heat-related illness. Based on the hypothetical framework presented in Fig. 3, our results suggest that heat alerts are not leading to a net reduction in heat exposure in this population (e. g., through behavior leading to reduced exposure such as the use of air conditioning); if so, we would expect to have found that heat alerts were associated with decreases in both hospitalizations and deaths. Instead, the finding that heat alerts were associated with higher rates of hospitalization for heat-related illnesses suggests that heat alerts may be effective in helping some older adults more readily recognize the symptoms associated with extreme heat and thus seek appropriate medical attention. The further observation that heat alerts are not associated with a lower rate of all-cause mortality could suggest that heat alerts may not be reaching (or may not be affecting the behaviors of) those older adults most susceptible to heat-related deaths. That said, an alternative explanation for this null finding is that the impact of heat alerts on health-protective behaviors is not confined only to days with alerts, but rather confer a more general awareness of the health risks posed by heat that protects populations even on moderately hot days without alerts. All of these interpretations of our results are admittedly speculative; additional research is needed to confirm or refute these hypotheses. Additionally, it is possible that heat alerts may be associated with lower risk of mortality from some specific causes; however, we were not able to evaluate associations with cause-specific mortality in our study.

Notable strengths of this study include the use of a matched approach that controls for many potential confounders by design, the inclusion of data on both deaths and cause-specific hospitalizations, and the use of a very large national dataset. The size of our analysis represents an important advance in this area of research, allowing us to examine the average impacts of heat alerts across the country and providing greater statistical power to detect associations compared to previous studies. However, we were not able to quantify the extent to which there may be heterogeneity in associations across different counties in our study area. Several previous studies provide evidence that heat alerts may be effective in reducing mortality and morbidity in specific locations where heat alerts trigger local risk reduction measures such as opening air-conditioned shelters and conducting outreach to vulnerable populations (Benmarhnia et al., 2019; Ebi et al., 2004). For example, in New York City, which has a heat action plan where NWS heat alerts trigger such measures, the implementation of a lower heat alert threshold in 2008 was associated with a reduction in hospital admissions for heat-related illnesses among Medicare beneficiaries aged 65 years and older (Benmarhnia et al., 2019). These results, which diverge from what we observed on a larger spatial scale, suggest there is value in future studies elucidating whether modifiable local factors contribute to making a heat alert more or less effective.

The results from our analysis should be considered in the context of several limitations. First, we were not able to match all heat alert days, especially those days with the highest observed heat index values which are more likely to be under an excessive heat warning (versus a heat advisory). Thus, our results may not be generalizable to the hottest days in a given location. In other words, it is possible that impacts of heat alerts issued on the very hottest days are different from what we report here. Nonetheless, our results are relevant to discussions with National Weather Service offices as to whether the criteria for issuing heat alerts should be lowered so that heat alerts are issued more often (Wellenius et al., 2017; Benmarhnia et al., 2019). Second, there may be exposure misclassification in the heat alert variable, particularly in counties spanning multiple NWS forecast zones. However, adjacent forecast zones tend to have similar exposure histories when the responsibility for issuing alerts lies with the same local forecast office. Third, we are unable to distinguish between “true” heat alerts and heat alerts that were subsequently cancelled due to a changing forecast, potentially resulting in an attenuation of associations. Fourth, even in this analysis encompassing the large majority of US counties, we may be underpowered to detect very small associations. Finally, we are not able to exclude the possibility of residual confounding of the observed associations by heat. However, results from our main models in which days were matched on a narrow range of same-day heat index (i.e., within 2°F) were similar to those from a sensitivity analysis in which we additionally adjusted for same-day heat index as a continuous variable. Furthermore, associations between the lagged heat index terms included as covariates in our model and each health outcome were weak.

In summary, in this study of older adults covering nearly all of the contiguous US and including multiple health outcomes, we did not find evidence that heat alerts are associated with a lower risk of mortality, but did find evidence that the risk of hospital admissions for several heat-related conditions is elevated on heat alert days. These results suggest that heat alerts may be effective in helping this population access needed medical care on dangerously hot days. Additional research confirming this finding and clarifying the underlying mechanism(s) could further inform the public health response to extreme heat.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Funding

This study was funded by the US National Institutes of Health (grants R01ES029950, F32ES027742, R01ES026217, R01MD012769, R01ES028033, and 1R01AG066793-01R01), the US Environmental Protection Agency (grant 83587201-0); the Wellcome Trust (grant 216033-Z-19-Z); and the Harvard University Climate Change Solutions Fund.

Data Sharing

The exposure data required to replicate the results reported in this manuscript can be obtained by contacting the corresponding author. The core R code is provided in the Supplemental Material, Appendix B. The mortality and hospital admissions data are not publicly available but can be obtained through the Centers for Medicare and Medicaid Services.

Abbreviations:

US	United States
NWS	National Weather Service
FFS	fee-for-service
ICD	International Classification of Diseases
CCS	Clinical Classifications Software

References

Armstrong BG, Gasparrini A, Tobias A, 2014. Conditional Poisson models: a flexible alternative to conditional logistic case cross-over analysis. BMC Med. Res. Method 14, 122.

Benmarhnia T, Bailey Z, Kaiser D, Auger N, King N, Kaufman JS, 2016. A difference-in-differences approach to assess the effect of a heat action plan on heat-related mortality, and differences in effectiveness according to sex, age, and socioeconomic status (Montreal, Quebec). Environ. Health Perspect 124 (11), 1694–1699. [PubMed: 27203433]

Benmarhnia T, Schwarz L, Nori-Sarma A, Bell ML, 2019. Quantifying the impact of changing the threshold of New York City heat emergency plan in reducing heat-related illness. Environ. Res. Lett 14 (114006).

Bobb JF, Obermeyer Z, Wang Y, Dominici F, 2014. Cause-specific risk of hospital admission related to extreme heat in older adults. JAMA 312 (24), 2659–2667. [PubMed: 25536257]

Chau PH, Chan KC, Woo J, 2009. Hot weather warning might help to reduce elderly mortality in Hong Kong. Int. J. Biometeorol 53, 461. [PubMed: 19462184]

Daly C, Halbleib M, Smith JI, Gibson WP, Doggett MK, Taylor GH, et al. , 2008. Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. Int. J. Climatol 28, 2031–2064.

Di Q, Amini H, Shi L, Kloog I, Silvern R, Kelly J, et al. An ensemble-based model of PM (2.5) concentration across the contiguous United States with high spatiotemporal resolution. Environment international. 2019;130:104909. [PubMed: 31272018]

D'Ippoliti D, Michelozzi P, Marino C, de'Donato F, Menne B, Katsouyanni K, et al. The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environmental health : a global access science source. 2010;9:37. [PubMed: 20637065]

de'Donato F, Scortichini M, De Sario M, de Martino A, Michelozzi P. Temporal variation in the effect of heat and the role of the Italian heat prevention plan. Public Health. 2018;161:154–62. [PubMed: 29751981]

Ebi KL, Teisberg TJ, Kalkstein LS, Robinson L, Weiher RF, 2004. Heat watch/warning systems save lives: estimate costs and benefits for Philadelphia 1996–98. Bull. Amer. Meteor. Soc 85, 1067–1073.

Elixhauser A CS, Palmer L Clinical Classifications Software for ICD-9-CM. Rockville, MD: Agency for Healthcare Research and Quality; 2014. https://www.hcup-us.ahrq.gov/toolssoftware/ccs/ccs.jsp#overview.

Hawkins MD, Brown V, Ferrell J, 2017. Assessment of NOAA National Weather Service Methods to Warn for Extreme Heat Events. Weather Clim. Soc 9, 5–13.

Heo S, Nori-Sarma A, Lee K, Benmarhnia T, Dominici F, Bell ML. The Use of a Quasi-Experimental Study on the Mortality Effect of a Heat Wave Warning System in Korea. International journal of environmental research and public health. 2019;16(12).

Hess JJ, Lm S, Knowlton K, Saha S, Dutta P, Ganguly P, et al. , 2018. Building Resilience to Climate Change: Pilot Evaluation of the Impact of India's First Heat Action Plan on All-Cause Mortality. J. Environ. Public Health 2018, 7973519. [PubMed: 30515228]

IPCC (Intergovernmental Panel on Climate Change). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, et al., editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.

Lowe D, Ebi KL, Forsberg B, 2011. Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. Int. J. Environ. Res. Public Health 8 (12), 4623–4648. [PubMed: 22408593]

Martínez-Solanas È, Basagaña X, 2019. Temporal changes in temperature-related mortality in Spain and effect of the implementation of a Heat Health Prevention Plan. Environ. Res 169, 102–113. [PubMed: 30447497]

McGregor G, Bessemoulin P, Ebi K, Menne B. Heat waves and health: guidance on warning system development. 2015. https://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf.

Nitschke M, Tucker G, Hansen A, Williams S, Zhang Y, Bi P, 2016. Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. BMJ open. 6, e012125.

Palecki MA, Changnon SA, Kunkel KE, 2001. The nature and impacts of the July 1999 heat wave in the Midwestern United States: learning from the lesson 1995. Bull. Amer. Meteor. Soc 82 (7), 1353–1367.

PRISM Climate Group OSU. Descriptions of PRISM Spatial Climate Datasets for the Conterminous United States 2013 [updated August 2016. Available from: https://prism.oregonstate.edu/documents/PRISM_datasets.pdf.

Requia WJ, Di Q, Silvern R, Kelly JT, Koutrakis P, Mickley LJ, et al. , 2020. An ensemble learning approach for estimating high spatiotemporal resolution of ground-level ozone in the contiguous United States. Environ. Sci. Technol 54 (18), 11037–11047. [PubMed: 32808786]

Roberts AW, Ogunwole SU, Blakeslee L, Rabe MA. The Population 65 Years and Older in the United States: 2016 (American Community Survey Reports) 2018 [Available from: https://www.census.gov/content/dam/Census/library/publications/2018/acs/ACS-38.pdf.

Sheridan SC, Kalkstein LS, 2004. Progress in heat watch-warning system technology. Bull Amer Meteor Soc. 85 (12), 1931–1941.

Shindell D, Zhang Y, Scott M, Ru M, Stark K, Ebi KL. The Effects of Heat Exposure on Human Mortality Throughout the United States. Geohealth. 2020;4(4): e2019GH000234.

Spangler KR, Weinberger KR, Wellenius GA, 2019. Suitability of gridded climate datasets for use in environmental epidemiology. J. Expo. Sci. Environ. Epidemiol 29, 777–789. [PubMed: 30538298]

The Boards of Trustees of the Federal Hospital Insurance and Federal Supplementary Medical Insurance Trust Funds. 2017 Annual Report of the Boards of Trustees of the Federal Hospital Insurance and Federal Supplementary Medical Insurance Trust Funds 2017 [Available from: https://www.cms.gov/Research-Statistics-Data-and-Systems/Statistics-Trends-and-Reports/ReportsTrustFunds/Downloads/TR2017.pdf.

Toloo G, FitzGerald G, Aitken P, Verrall K, Tong S, 2013. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. Int. J. Public Health 58 (5), 667–681. [PubMed: 23564031]

Turner H, Firth D. Generalized nonlinear models in R: An overview of the gnm package. R package version 1.1-1. 2020. https://cran.r-project.org/web/packages/gnm/index.html.

US National Weather Service. NWS Public Forecast Zones [Available from: https://www.weather.gov/gis/PublicZones.

Wasey JO. ICD: Tools for Working with ICD-9 and ICD-10 Codes, and Finding Comorbidities. 2018. https://cran.r-project.org/web/packages/icd/index.html.

Weinberger KR, Zanobetti A, Schwartz J, Wellenius GA, 2018. Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. Environ. Int 116, 30–38. [PubMed: 29649774]

Weinberger KR, Harris D, Spangler KR, Zanobetti A, Wellenius GA, 2020. Estimating the number of excess deaths attributable to heat in 297 United States counties. Environ. Epidemiol 4 (3), e096. [PubMed: 32613153]

Wellenius GA, Eliot MN, Bush KF, Holt D, Lincoln RA, Smith AE, et al. , 2017. Heat-related morbidity and mortality in New England: evidence for local policy. Environ. Res 156, 845–853. [PubMed: 28499499]

Author Manuscript
Author Manuscript
Author Manuscript

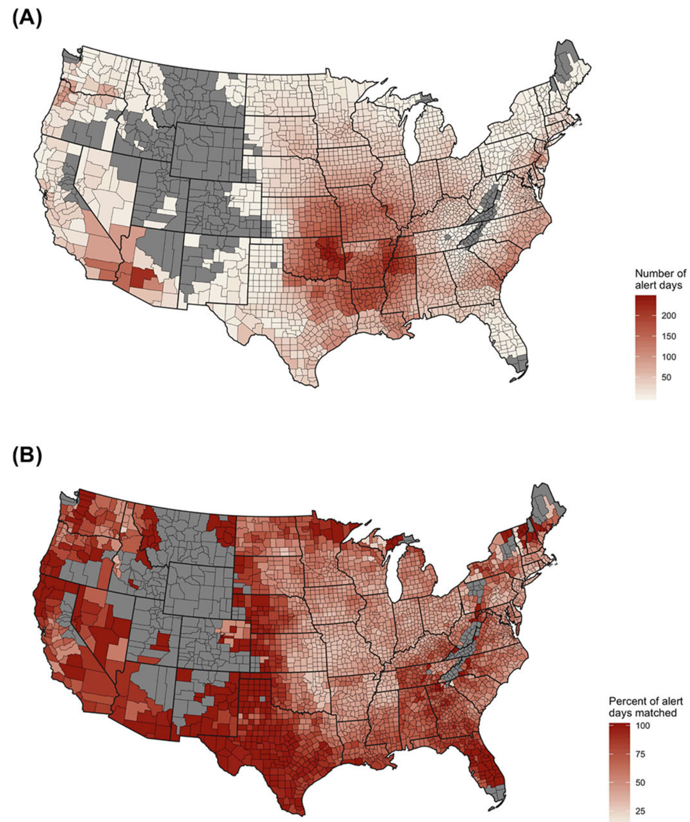

Fig. 1.

Maps of (A) the total number of heat alert days in the contiguous US, 2006–2016, and (B) the percent of heat alert days for which we were able to identify a matched non-heat alert day. Gray shading indicates a value of 0.

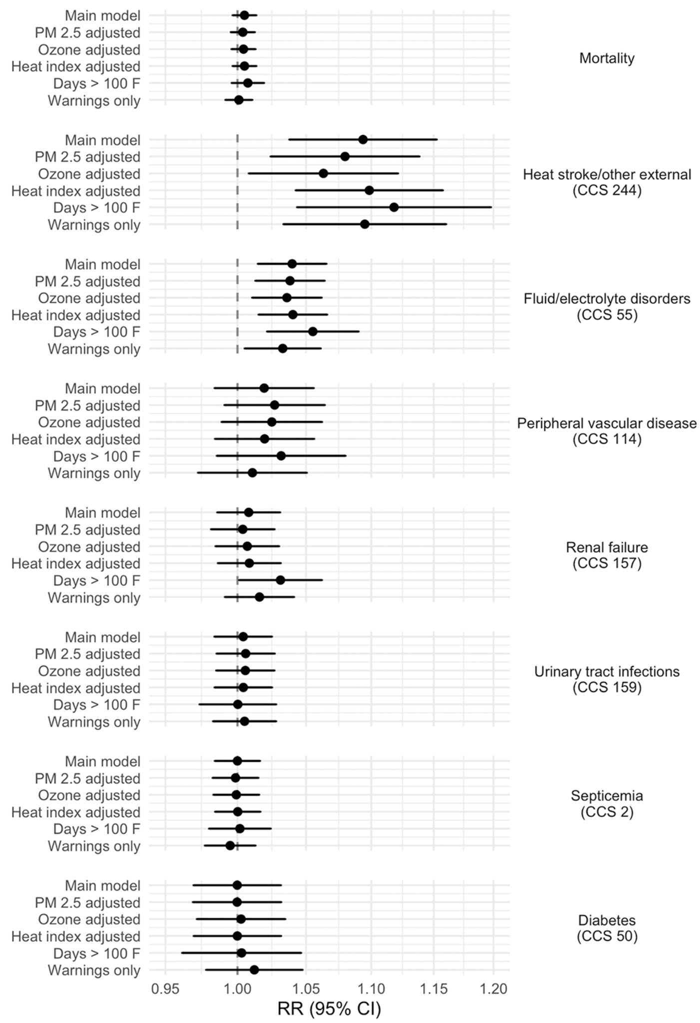

Fig. 2.

Sensitivity analyses of the association between heat alerts and health outcomes among Medicare beneficiaries aged 65 and older, 2006–2016. Results are shown for the main model; the main model additionally adjusted for same day $PM_{2.5}$, ozone, and heat index; the main model restricted to heat alert days with a maximum heat index of at least 100°F; and the main model restricted to days with excessive heat warnings only.

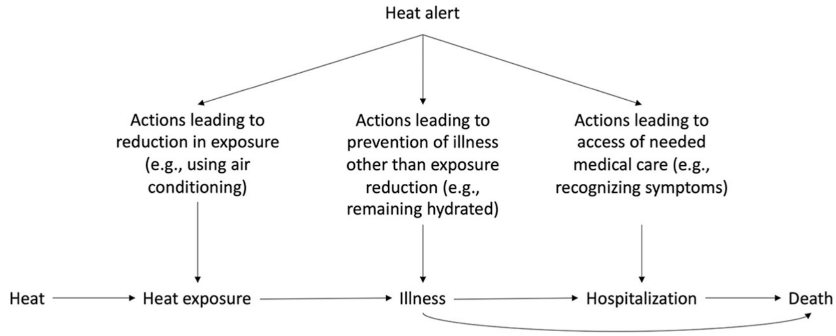

Fig. 3.

Causal diagram of hypothesized impacts of heat on hospitalizations and deaths and the potential mitigating influences of heat alerts. In this diagram, the term “illness” refers to pathophysiologic changes that may or may not be symptomatic. For simplicity, we elect not to explicitly show forecast heat, which is a determinant of heat alerts and could potentially affect individual behaviors independent of heat alerts.

Table 1

Characteristics of matched heat alert days, matched non-heat alert days, and unmatched heat alert days in the counties[1] in the contiguous United States that experienced at least one alert, 2006–2016.

	Heat alert days, matched[2] (n = 92,029)	Non-heat alert days, matched[2] (n = 92,029)	Heat alert days, unmatched (n = 76,575)
Daily maximum heat index (°F)			
Mean (SD)	101.2 (5.0)	100.4 (4.9)	106.0 (3.9)
5th percentile	92.5	92.0	99.8
95th percentile	107.4	106.7	112.2
Year [n (%)]			
2006–2010	34,528 (37.5%)	45,218 (49.1%)	31,724 (41.4%)
2011–2016	57,501 (62.5%)	46,811 (50.9%)	44,851 (58.6%)
Month [n (%)]			
April-June	16,368 (17.8%)	16,368 (17.8%)	7,871 (10.3%)
July-October	75,661 (82.2%)	75,661 (82.2%)	68,704 (89.7%)
Day of week [n (%)]			
Weekday	66,228 (72.0%)	67,060 (72.9%)	55,666 (72.7%)
Weekend	25,801 (28.0%)	24,969 (27.1%)	20,909 (27.3%)
Federal holiday [n (%)]	1158 (1.3%)	1127 (1.2%)	815 (1.1%)

[1] 2,837 counties experienced at least one heat alert, 2006–2016. We were able to match at least one heat alert day to a non-heat alert day in 2,817 of those 2,837 counties.

[2] Matched on daily maximum heat index (+/− 2 degrees F), county, and month.

Table 2

Association between heat alerts and health outcomes among Medicare beneficiaries aged 65 years and older in 2,817 US counties, 2006–2016.

Outcome	**Total number of deaths or admissions (n)**		**RR (95% CI)**
	Heat alert days	**Matched non-heat alert days**	
Deaths[1]	138,356	137,297	1.005 (0.997, 1.013)
Admissions[2]			
Heat stroke and other external causes (CCS 244)	2,052	1,728	1.094 (1.038, 1.152)
Fluid and electrolyte disorders (CCS 55)	14,717	14,097	1.040 (1.015, 1.065)
Peripheral vascular disease (CCS 114)	6,103	6,316	1.019 (0.984, 1.056)
Renal failure (acute/unspecified) (CCS 157)	18,145	17,463	1.008 (0.986, 1.031)
Urinary tract infections (CCS 159)	21,096	20,578	1.004 (0.984, 1.025)
Septicemia (except in labor) (CCS 2)	36,039	35,421	1.000 (0.984, 1.016)
Diabetes mellitus with complications (CCS 50)	7,804	7,894	1.000 (0.969, 1.031)

[1]Among all Medicare beneficiaries aged >= 65 years.

[2]Among fee-for-service Medicare beneficiaries aged >= 65 years.

Table 3

Association between heat and health outcomes among Medicare beneficiaries aged 65 years and older, comparing days in the main analysis (matched heat alert and non-heat alert days) to days at least 5°F cooler in the same county and month.

Outcome	RR (95% CI)
Deaths[1]	1.011 (1.005, 1.016)
Admissions[2]	
Heat stroke and other external causes (CCS 244)	1.446 (1.388, 1.505)
Fluid and electrolyte disorders (CCS 55)	1.081 (1.063, 1.099)
Peripheral vascular disease (CCS 114)	0.997 (0.973, 1.021)
Renal failure (acute/unspecified) (CCS 157)	1.079 (1.063, 1.096)
Urinary tract infections (CCS 159)	1.034 (1.020, 1.048)
Septicemia (except in labor) (CCS 2)	1.016 (1.006, 1.027)
Diabetes mellitus with complications (CCS 50)	1.007 (0.986, 1.028)

[1]Among all Medicare beneficiaries aged >= 65 years.

[2]Among fee-for-service Medicare beneficiaries aged >= 65 years.