

Estimating the number of excess deaths attributable to heat in 297 United States counties

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Background: There is a well-established relationship between high ambient temperature and risk of death. However, the number of deaths attributable to heat each year in the United States remains incompletely quantified.

Methods: We replicated the approach from a large, international study to estimate temperature-mortality associations in 297 United States counties and additionally calculated the number of deaths attributable to heat, a quantity of likely interest to policymakers and the public.

Results: Across 297 counties representing 61.9% of the United States population in 2000, we estimate that an average of 5,608 (95% empirical confidence interval = 4,748, 6,291) deaths were attributable to heat annually, 1997–2006.

Conclusions: Our results suggest that the number of deaths related to heat in the United States is substantially larger than previously reported.

Key Words: Extreme heat; Temperature; Mortality; United States

Introduction

Exposure to high ambient temperature (i.e., “heat”) is recognized as a significant threat to public health associated with substantial excess morbidity and mortality.¹ Studies quantifying the association between temperature and adverse health outcomes increasingly report attributable as well as relative measures of excess risk. Several recent studies have reported the proportion or percent of deaths attributable to heat—a measure of attributable risk referred to as the “attributable fraction”²—on a national³ or international⁴ scale. For example, Gasparrini et al⁴ estimated the fraction of deaths attributable to both hot and

cold temperatures in each of nearly 400 communities located in 13 countries, including 135 communities in the United States.

Although the attributable fraction is a useful measure of excess risk, the absolute *number* of excess deaths attributable to heat (i.e., the “attributable number”) may be of greater utility to public health practitioners, policymakers, and community members. Furthermore, there are surprisingly few estimates of the number of people who die due to heat on a national scale in the United States. Thus, to provide an estimate of the magnitude of the impact of heat on health in the United States, we replicated the analysis performed by Gasparrini et al⁴ in a larger number of United States communities and additionally calculated the attributable number. Specifically, we combined daily temperature estimates from a high-resolution, gridded meteorological dataset with county-level mortality data to estimate the number of deaths attributable to heat in 297 populous counties representing nearly 62% of the United States population, 1997–2006.

Methods

We obtained individual-level data on all deaths (excluding those from external causes) in counties in the contiguous United States with a population > 100,000 from the National Center for Health Statistics (eTable 1; <http://links.lww.com/EE/A85>). We constructed time series of the daily number of deaths occurring in each of the 297 counties for which we had continuous mortality data for the study period of 1997 to 2006, the most recent decade for which these data were publicly available. We obtained gridded estimates of daily mean ambient temperature at a spatial resolution of 4 by 4 km for the contiguous United States from the Parameter-elevation Relationships on Independent Slopes Model (PRISM)⁵ and calculated population-weighted

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SDC Supplemental digital content is available through direct URL citations in the HTML and PDF versions of this article (www.enviroepidem.com).

This work was supported by grants F32-ES027742 and R01-ES029950 from the National Institute of Environmental Health Sciences (NIEHS), National Institutes of Health (NIH). The contents of this report are solely the responsibility of the authors and do not necessarily represent the official views of the sponsoring organizations.

The computing code and exposure data required to replicate this analysis can be obtained by contacting the corresponding author. The mortality data can be obtained by making a data request to the US National Center for Health Statistics.

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Environmental Epidemiology (2020) 4:e096

Received: 31 October 2019; Accepted 30 March 2020

Published online 23 April 2020

DOI: 10.1097/EE9.000000000000096

What this study adds

There is substantial evidence that high ambient temperature is a threat to human health. However, there are surprisingly few estimates of the number of people who die from heat each year in the United States. In this study, we applied well-established regression methods to estimate the number of excess deaths attributable to heat in each of 297 populous United States counties. Using these methods, we found that annual number of deaths attributable to heat was larger than previous estimates produced by searching death records for cases coded as being due to heat.

daily values of mean temperature for each study county as previously described.⁶ As PRISM estimates are available on a grid throughout the contiguous United States, we were able to construct time series of daily temperature even for counties without a nearby first-order weather station, which are typically located at commercial airports. We obtained estimates of county population size in the year 2000 from the United States Census.⁷

We began by applying an analytic approach described in a previous large, multicountry analysis⁴ to estimate the fraction of deaths attributable to heat in each of our 297 study counties. This approach consists of three stages. In the first stage, we used distributed lag nonlinear models⁸ with a quasi-Poisson distribution to estimate the cumulative association between daily mean temperature and mortality counts in each county over 21 days of lag, making identical choices with respect to confounder control and the form of the temperature and lag functions as in previous work.⁴ Specifically, we modeled the temperature variable with a quadratic B-spline with three internal knots at the 10th, 75th, and 90th percentiles of the county-specific temperature distribution, and the lag function with a natural cubic B-spline with three internal knots at equally spaced values on the log scale (i.e., at values of approximately 1, 3, and 8). We controlled for seasonal and long-term time trends using a natural cubic spline with 8 degrees of freedom per year. We additionally controlled for day of week and federal holidays. In the second stage, we fit a multivariate meta-analytic model of the 297 county-specific associations, including the mean and range of each county's temperature distribution over the study period as predictors. From this model, we extracted the best linear unbiased prediction (BLUP) of the temperature-mortality association for each county, centering the spline of temperature at the county-specific minimum mortality temperature (i.e., the temperature at which mortality risk is lowest). In the third and final stage, we applied the approach proposed by Gasparrini and Leone² to calculate the fraction of deaths attributable to heat from each county's BLUP and observed temperature distribution. For each county, we defined heat as all temperatures greater than the county-specific minimum mortality temperature.

The analysis described above is a replication of previous work by Gasparrini et al.,⁴ applied to a larger number of locations in the United States in a different set of years. We then extended this analysis by additionally calculating the absolute number of excess deaths attributable to heat in each county, using the method proposed by Gasparrini and Leone.² We additionally calculated the fraction and number of deaths attributable to extreme versus moderate heat in each county, where extreme heat is defined as all temperatures greater than the 97.5th percentile of the county-specific observed temperature distribution and moderate heat is defined as temperatures above the county-specific minimum mortality temperature but below the 97.5th percentile of the county-specific temperature distribution.

We present the both the fraction and number of deaths attributable to heat and their 95% empirical confidence intervals (eCI) aggregated across all 297 counties, as well as grouped into seven geographic regions as defined in the 4th National Climate Assessment.⁹ To facilitate comparisons across locations with differing population sizes, we also present the annual attributable number per million people in each county and among counties aggregated by region, calculated using county population sizes from the 2000 Census. All analyses were conducted in R version 3.3.3 using the packages 'dlnm'⁸ and 'mvmeta'.¹⁰

Results

We estimated the fraction and number of deaths attributable to heat in 297 counties across 44 United States states and the District of Columbia. In the year 2000, our study area encompassed approximately 174 million individuals or 61.9% of the United States population. The proportion of the population

captured by the study counties varied across regions (Table 1). For example, study counties in the Northern Great Plains and the Southwest represented 13.0% and 83.5% of the total population of their respective regions.

A total of 12,882,584 deaths occurred in the study counties between 1997 and 2006. During this time period, we estimate that 0.44% (95% eCI = 0.37, 0.49) of deaths occurring in the 297 counties were attributable to heat. This attributable fraction corresponds to an attributable number of 5,608 (95% eCI = 4,748, 6,291) excess deaths due to heat on average each year. Out of the total number of heat-related deaths, we estimate that an average of 3,309 (95% eCI = 2,615, 3,918) were attributable to moderate heat and an average of 2,299 (95% eCI = 2,062, 2,463) were attributable to extreme heat each year.

When expressed as a rate relative to a constant population, we estimate an annual average of 32.2 (95% eCI = 27.3, 36.1) deaths attributable to heat per million individuals across the study counties. Considered at the regional level, this rate ranged from 12.6 (95% eCI = 1.3, 23.6) excess deaths per year per million in the Southern Great Plains to 48.5 (95% eCI = 40.9, 55.1) excess deaths per year per million people in the Northeast (Table). The annual number of excess deaths attributable to heat per million individuals also varied substantially across counties (Figure).

Discussion

In this study representing more than three-fifths of the United States population, we estimated that 0.44% of deaths (95% eCI = 0.37, 0.49) were attributable to heat between 1997 and 2006. Our estimate of the attributable fraction is similar to that of Gasparrini et al.,⁴ who using identical methods estimated that 0.35% of deaths (95% eCI = 0.30, 0.39) were attributable to heat in 135 United States communities between 1985 and 2006. In addition to the inclusion of a different set of study locations and years, another key difference between these two analyses is that we used population-weighted temperature estimates derived from a gridded climate dataset, whereas Gasparrini et al.⁴ based their analysis on temperature observations taken at weather stations.

To facilitate the communication of research on heat and health to a more general audience, we additionally calculated the number of deaths attributable to heat across our study area. Across the 297 counties included in our study, we estimate that between 1997 and 2006, approximately 5,600 deaths per year were attributable to heat. We further found that a substantial number of deaths occurred at only moderately hot temperatures, consistent with prior work.⁴

Our estimate of the number of deaths attributable to heat each year in the United States is substantially larger than previous estimates for similar periods of time. For example, in a study consisting of the entire United States population, the United States Centers for Disease Control and Prevention (CDC) estimated that an average of 658 people died due to heat each year between 1999 and 2009.¹¹ The large difference between this estimate and our results is likely due to the application of different methods to calculate excess deaths attributable to heat. In the CDC study, heat-related deaths were identified by abstracting information from death records. Specifically, deaths were considered as being attributable to heat if the death record included an International Classification of Diseases code related to heat. Other studies based on searching for specific documented causes of death have yielded similar estimates of 618¹² and 666¹³ deaths per year. However, owing to the absence of standardized criteria for identifying and recording a death as attributable to heat and the difficulty of identifying cases where heat contributed to death from another cause (e.g., cardiovascular disease), analyses based on cause of death may substantially underestimate the total burden of heat-related mortality.¹² In contrast, we used a regression-based method to statistically relate temperature estimates to mortality rates in a large number of communities, allowing for a more comprehensive assessment of the

Table 1. Estimated annual number of excess deaths attributable to heat and 95% eCI, overall and for each of seven United States regions

Region	No. counties (n)	No. deaths ^a (n)	Population ^b (n)	Percent of total population included ^{b,c} (%)	Fraction of deaths attributable to heat (95% eCI) (%)	No. deaths attributable to heat (95% eCI) (n/year)	No. deaths attributable to heat per million people (95% eCI) (n/year/million)
Midwest	69	2,635,999	33,658,082	57.4	0.35 (0.25, 0.45)	923 (645, 1,184)	27.4 (19.2, 35.2)
Northeast	79	3,816,007	47,443,384	76.5	0.60 (0.51, 0.69)	2,302 (1,942, 2,616)	48.5 (40.9, 55.1)
Northern Great Plains	2	40,070	586,738	13.0	0.37 (-0.29, 1.00)	15 (-11, 40)	25.3 (-20, 68)
Northwest	10	387,531	5,755,694	54.2	0.42 (0.18, 0.63)	162 (70, 244)	28.1 (12.2, 42.4)
Southeast	79	2,518,230	30,764,422	45.6	0.32 (0.20, 0.44)	813 (493, 1,100)	26.4 (16.0, 35.8)
Southern Great Plains	20	913,740	14,838,842	55.0	0.20 (0.02, 0.38)	186 (19, 351)	12.6 (1.3, 23.6)
Southwest	38	2,571,007	41,187,851	83.5	0.47 (0.25, 0.67)	1,206 (650, 1,715)	29.3 (15.8, 41.6)
Total	297	12,882,584	174,235,013	61.9	0.44 (0.37, 0.49)	5,608 (4,748, 6,291)	32.2 (27.3, 36.1)

Heat is defined for each county as all temperatures greater than the county-specific minimum mortality temperature

^a1997–2006.

^bData from the 2000 United States Census.

^cPopulation of included counties in each region relative to the total population of all counties in each region.

impact of heat on population health by estimating the number of excess deaths attributable to heat regardless of the assigned cause of death. Although other studies using regression-based methods to estimate the number of excess deaths attributable to heat in the United States have focused on a smaller number of communities, their results similarly suggest that the number of heat-related deaths is substantial. For example, Kalkstein et al¹⁴ estimated that an average of approximately 1,300 deaths were attributable to extreme heat events each summer between 1975 and 2004 across 40 large United States cities.

We further observed that the number of excess deaths per million people attributable to heat varied substantially by region

and by county, suggesting heterogeneity in the health impacts of heat across the country. Factors contributing to differences in rates across counties could include demographic characteristics, underlying health status, the prevalence of heat adaptation strategies such as air conditioning, and the shape of the local temperature distribution. For example, age structure may be an important driver of difference in rates across counties, as older adults are thought to be particularly susceptible to heat.¹⁵

Our study has a number of potential limitations. First, although this study encompassed a majority of the United States population during the study period, we were not able to estimate the number of heat-related deaths in less populated counties as mortality data

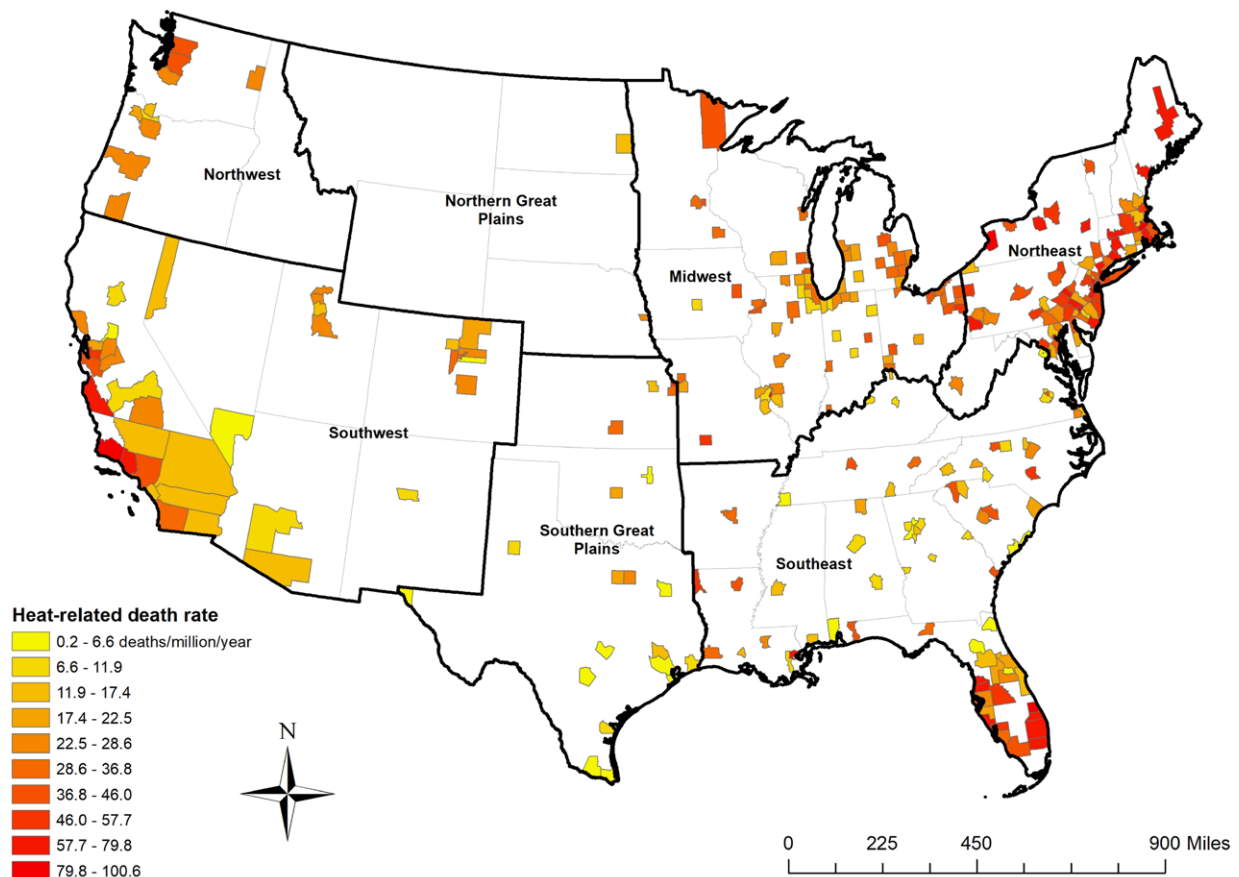


Figure. Estimated annual number of excess deaths attributable to heat per million people in each of 297 populous United States counties, 1997–2006. Heat is defined for each county as all temperatures greater than the county-specific minimum mortality temperature. Heat-related death rates are grouped into deciles. Heat-related death rates are not age-standardized. No study counties were located in Alaska or Hawaii.

for these counties were unavailable. Our results based on more populous counties may or may not be generalizable to people living in less populous counties. Second, our results may not be generalizable to more recent years given evidence of adaptation to heat observed in the United States in recent decades.¹⁶ Third, although previous research⁴ suggests that our results are likely robust to modeling choices such as the specification of the non-linear temperature and lag functions, it is possible that alternative modeling approaches would yield somewhat different estimates. Fourth, we did not have information on deaths resulting from external causes, potentially leading to an underestimate of the burden of heat on health. Finally, we acknowledge that the number of excess deaths is a useful but incomplete marker of the public health impact of heat. Further studies are needed to quantify the years of life lost and excess morbidity attributable to heat.

On the other hand, a key strength of this study is the use of population-weighted temperature estimates for each county, potentially improving exposure assessment in locations where weather station data do not fully capture the exposure of the population of interest and allowing us to quantify the relationship between heat and mortality in communities located far from a weather station.¹⁷ Other strengths include wide geographic coverage throughout the contiguous United States, the application of regression methods to broadly quantify excess deaths attributable to heat regardless of assigned cause of death, and the use of flexible and well-established statistical models to account for the lagged and nonlinear relationship between temperature and mortality.

In summary, our results suggest that the number of heat-related deaths that occur each year in the United States is substantially larger than has been previously reported. This finding highlights the continued importance of interventions to protect public health during hot weather, particularly in light of projected increases in temperature in future decades resulting from continued climate change.⁹

Conflict of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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