A spatially informed demographic assessment of extreme-heat mortality in the United States, 1979-2011.

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Over the past three decades, extreme heat waves have been among the most deadly weather-related events in the United States [1, 2]. Globally, the past three years (2015-2017) are the hottest on record, and the academic literature as well as mainstream scientific outlets overwhelmingly suggest that the frequency and intensity of extreme-heat events will continue increasing over the course of this century [3-5]. Without adequate adaptation measures, this is likely to lead to an even greater increase in mortality [6-8]. The risk of heat-related mortality is a directly related to the level of vulnerability present in any population. Vulnerability itself is a function of *exposure* to extreme heat and the *sensitivity* of individuals and sub-populations to the adverse effects of heat due to age, income, social isolation, and other demographic and socio-economic factors [9-11]. *Coping capacity* (reacting to and reducing adverse effects) and *adaptive capacity* (anticipating and preparing for risk) counter specific threats to populations [9]. These four aspects of risk and vulnerability vary spatially and temporally [9]. Exposure is a function of the dominant local climate regime, which determines the degree to which a population is exposed and conditioned to extreme heat. Sensitivity and coping capacity change with demographic and socio-economic trends, while adaptive capacity may change in response to extreme events (e.g., a high-mortality heatwave) or longer-term prospects (such as the effects of climate change).

An unfortunate characteristic of any research targeting heat-related mortality is surprising difficulty determining exactly what qualifies as a heat-related mortality event. While certain acute ailments such as heat stroke are fairly straightforward, heat often becomes deadly as it exacerbates existing ailments in its victims, such as heart disease or respiratory illness. Further confounding accurate counts is the temporal lag often present between extreme heat events and heat-related deaths. As such, there is some skepticism among researchers regarding existing mortality records that explicitly consider natural heat as a primary or contributing cause. Instead, most researchers tend to use all-cause mortality data, opting to identify irregular deviation from historical means that appear with and following known extreme heat events. Little is known regarding how well the all-cause approach correlates with, or deviates from, methods based on counts of documented heat-related deaths, particularly over space and time. Despite this relatively glaring issue, much is known about the impact of heat on the US population, as well as how this relationship has evolved over time.

The spatial heterogeneity of heat-related mortality in the United States has been known since the early 20th century when several studies noted mortality differences among cities [12]. Since then, heat-related mortality has been studied at various spatial and temporal scales, often with the goal of describing how different factors mitigate or exacerbate the effects of extreme heat. These studies generally find adverse effects for increased exposure (using various measures of heat, lag times, and the inclusion of air pollutants) and for populations in cooler parts of the country who are presumably not acclimatized to high heat [13, 14]. Infants, the elderly, those of low socio-economic status, people living alone, and people with pre-existing medical conditions are consistently shown to be particularly vulnerable, while findings regarding race and gender are more mixed [13, 14]. Several studies find access to air conditioning, transportation, and green spaces protective against heat-related mortality [13]. Local governance and response to heat-events also has had an important role [15].

Much of our collective knowledge informing which of these factors are most important is drawn from many studies of particular localities across the US. For example, a study in Philadelphia County over 26 years found spatial variability in heat-related mortality with significantly higher mortality in areas where there were higher surface temperatures, more high-density residential and mixed-use zones, more recreationally zoned areas, and a higher percentage of poor and elderly residents [16]. A state-wide study in Massachusetts over 19 years found 5.11 excess deaths on days exceeding the 85th percentile of apparent temperature with relative size of the African American and elderly positively associated with increased mortality, but no significant results for increased urbanization [17]. Adaptive capacities also have spatial variation; heat events may have less effect in the South, presumably due to acclimatization of those populations to extreme heat [18]. Changes over time are also significant. Barreca *et al.* [19] found a 70% decline in heat-related mortality from 1900 to 2004, almost all of which they attribute to increasing ownership of air conditioning after 1960.

While these studies address fundamental questions about the risk of heat-related mortality in particular U.S. cities or states, there remain important gaps in our knowledge of how heat-related mortality varies over space across the whole country. In other words, our spatial knowledge of the impacts of extreme heat, including important variation in the mortality response *and* the factors contributing to vulnerability/mortality is somewhat incomplete. Additionally, the manner in which the mortality response is empirically derived leaves questions regarding the interpretation of results. The current state-of-the-art considers *excess* mortality over the area in question during and following a known extreme heat event, where excess is defined as the number of deaths above the periodic average. Such estimates, while certainly inclusive of heat-related deaths, likely over-estimate the actual impact of extreme events. Alternatively, the Center for Disease Control (CDC) reports deaths, at the county-level, in which natural-heat is determined to be a primary or contributing cause. Many experts believe these data underestimate the true extent of heat-related mortality given the mechanisms through which heat often works to cause death (e.g., temporal lag, exacerbating existing health issues). Additionally, county coroners, the source of the CDC data, may not apply consistent standards in determining whether heat was a contributing factor.

In this study, we examine historical patterns of exposure to extreme heat, and heat-related mortality at the county-level in the continental United States, paying particular attention to geographic variation in the mortality response to exposure. We apply two methods of deriving the mortality response, by month and year, to heat extremes; (1) the excess mortality approach using all-cause mortality data from the CDC, and (2) deaths coded as heat-related from the same data set. Furthermore, we consider the contribution of key demographic and socio-economic factors in driving heat-related mortality. We address the following specific research questions: (1) how has heat-related mortality varied geographically and on aggregate over the past 33 years, (2) how does this distribution vary in intensity and over space as a function of the choice of method for deriving the mortality response, (3) how does the mortality response to extreme heat exposure vary geographically, (4) what additional factors contribute to heat-related mortality at the national and local level, and (5) how does the definition of extreme heat impact results? Understanding the relationship between exposure and mortality at alternative spatial scales, as well as the relative importance of potential risk factors associated with heat-related mortality, is crucial to implementing effective mitigation and adaptation strategies. Furthermore, the baseline, spatially explicit relationships established here are potentially useful to future predictions of exposure and mortality under alternative population and climate change scenarios, identified as a key research goal in the recently completed third National Climate Assessment [20].

Data and Methods

In this work we seek to improve our geographic understanding of the mortality response to extreme heat, the factors contributing to that response, and the implications of selecting alternative methods to define heat-related mortality and extreme heat on outcomes. We combine historic temperature data with records of heat-related mortality, all-cause mortality data, population counts, and general characteristics of the population that serve as proxies for the sensitivity and adaptive/coping capacity components of vulnerability. We recognize that a fuller set of individual, household and institutional factors may also contribute extreme-heat mortality, but consideration of those is constrained either by lack of data at the temporal and spatial scale of this analysis or our modeling choices.

To assess to the drivers of heat-related mortality and the geographic variation in their importance we employ two different statistical techniques: a spatial autoregressive model applied at the national-level and geographically weighted regression (a local version of a spatial regression which produces parameter estimates for each unit of analysis). The primary unit of analysis is the county, and we consider the time period 1979-2011 (all data were adjusted to use the 2011 county boundaries).

Preliminary Results

To date, we have begun the comparison of the all-cause mortality approach and the natural heat mortality counts from the CDC. Figure 1 below illustrates the average monthly crude death rate (Fig 1a) and average monthly extreme heat deaths (Fig 1b) against the monthly values for 1995 in Cook County, Illinois, which encompasses most of Chicago. The 1995 Chicago heat-wave is perhaps the most well-studied extreme heat event in recent US history, and by both metrics a significant departure from average is observed in July, albeit much greater in the count data (Fig 1b).

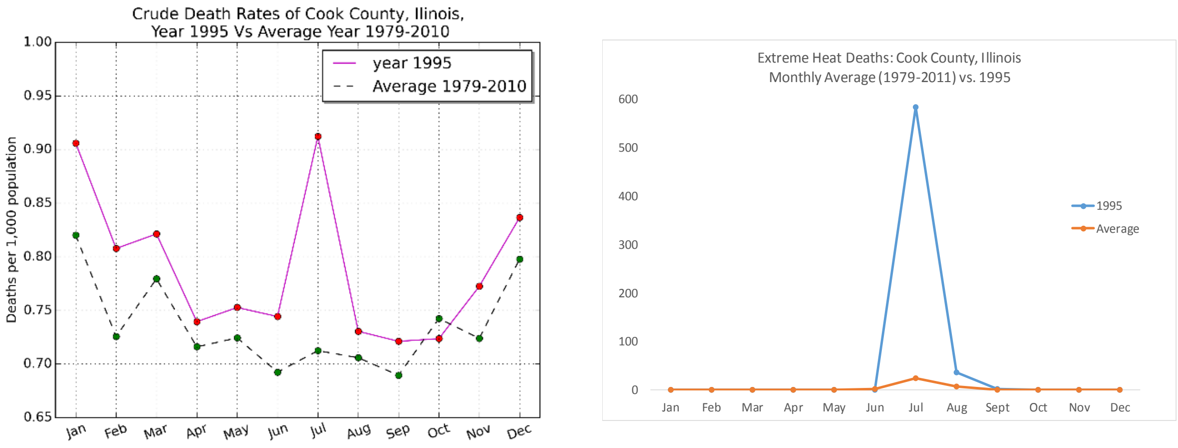

Figure 1. Average (a) monthly crude death rate against observed 1995 monthly crude death rate and (b) average monthly heat-related deaths against observed 1995 monthly heat-related deaths in Cook County, Illinois. Averages are for the period 1979-2011.

We have also completed a good portion of our analysis using the CDC extreme heat mortality count data. Figure 2 depicts extreme heat deaths by county over the study period (Fig 2a), spatial clustering (from the spatial autoregressive analysis; Fig2b), and the correlation between heat-related mortality and the dominant driver in the autoregressive model; the spatial lag variable (Fig 2c).

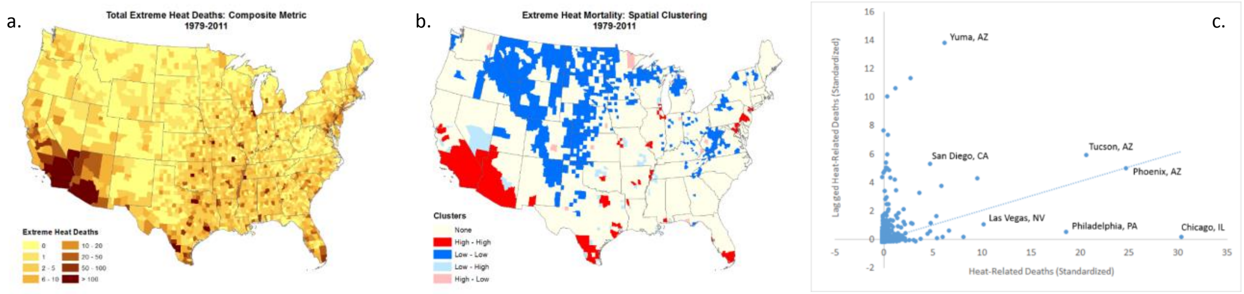

Figure 2. Geographic distribution of (a) heat-related mortality,(b) spatial clustering, and (c) scatterplot of the correlation between local heat-related mortality and the spatial lag variable.

Finally, Figure 3 depicts the average annual number of extreme days over the study period, average annual exposure (population * extreme heat days) at the county-level, and the mortality response to exposure (deaths/exposure) to days with a heat index over 95°F.

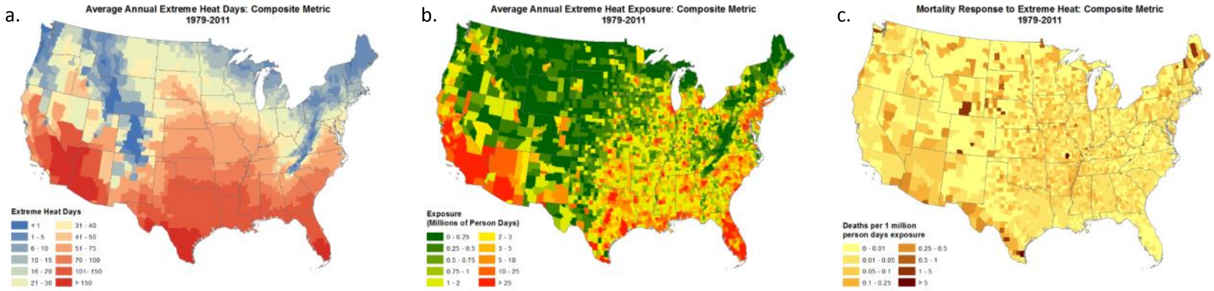

Figure 3. Geographic distribution of (a) average annual number of extreme heat days, (b) average annual exposure, and (c) mortality response, composite metric: 1979-2011.

While beyond the scope of this paper, we hope to use the results of this work (mortality response) in follow-up research projecting extreme heat mortality at the county-level under different climate, population, and adaptation scenarios.

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