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Spatiotemporal trends in human vulnerability and adaptation to heat across the United States

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ABSTRACT

Many studies have connected excess heat to increased human mortality, but comparatively few have examined long-term temporal trends in this relationship. This study examined temporal trends in mortality associated with heat waves in 51 metropolitan areas in the United States for the period 1975–2010, using three different definitions of heat wave. Collectively, all three metrics showed a linear decline in human vulnerability to heat over time, while the number of heat events has generally increased. By the final decade of the study period, only six to seven cities were associated with statistically significant increases in mortality during heat waves. This trend, while generally declining, was variable on an individual metropolitan-area level. Contributing factors to this variability include the occurrence of an extreme heat wave affecting the overall relationship in heat wave and human mortality, and the variability in heat events over a given period. The observed broad adaptation in the human population to extreme heat, however, should be viewed in a cautionary sense. Even with decreased rates in overall human vulnerability, a greater number of heat events is expected in the future given anthropogenic climate change. Combined with an increasing population of susceptible individuals as society ages, human vulnerability to heat will remain a critical challenge for the "anthropocene" in the coming decades.

1. Introduction

Humans have modified the thermal landscape on many spatiotemporal levels, and changes in this thermal landscape have in turn had numerous impacts on human health and well-being. One such impact is exposure to extreme temperatures. Ample epidemiological research has examined the association between heat and negative human-health outcomes. These studies have shown that impacts generally occur once a thermal metric exceeds a certain threshold (e.g., Gosling et al., 2009; Kovats and Hajat, 2008; Basu and Samet, 2002). This relationship is widespread, with people in many locations experiencing negative health effects from direct exposure (e.g., heat stroke), as well as indirect effects on cardiovascular and respiratory systems, on the warmest days (e.g., Gasparrini et al., 2015; Kalkstein and Davis, 1989) across different climate types (e.g., Bobb et al., 2014; Curriero et al., 2002) and levels of development (e.g., McMichael et al., 2008). Assessments have broadly aimed to further understand this relationship by examining how human vulnerability to extreme heat is affected by age, sex, race, health, or socioeconomic status (Gronlund et al., 2014; Bouchama et al., 2007), and how this relationship varies on smaller sub-urban scales (e.g., Hondula et al., 2015).

One long-term historical analysis (Carson et al., 2006) covering the 20th century in London showed an overall decreased sensitivity of society to temperature extremes. This decrease was generally attributed to improved health care, better working conditions, residential climate control, as well as greater awareness of the potential dangers of extreme heat, particularly in the developed world. As data sets have become longer and more readily available, temporal trends in heat-related mortality over recent decades have been studied more frequently (e.g., Ng et al., 2016; Gasparrini et al., 2015; Sheridan and Lin, 2014; Bobb et al., 2014; Kyselý and Plavcová, 2012; Matzarakis et al., 2011; Sheridan et al., 2009; Barnett 2007; Davis et al., 2003b). These studies show a generally decreasing vulnerability to heat in the human population, although considerable variability exists in the magnitude of this trend. Further, while health care and awareness have mostly improved over time, assessing their relative roles is difficult, as well as the potential

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role of heat warning systems that have become more commonplace (Boeckmann and Rohn, 2014).

For several reasons, it is difficult to know how human vulnerability to extreme heat is changing at present, and how it will continue to change into the future (Sheridan and Allen, 2015). Heat events have increased in many areas (Perkins et al., 2012; Smith et al., 2013), and will very likely continue to do so with global anthropogenic climate change (e.g., Lau and Nath, 2012). In many cases, local increases in temperature are related to the urban heat island (e.g., Tomlinson et al., 2011; Zhou and Shepherd, 2010). With steadily increasing numbers of urban areas across the globe, exposure of residents to these urban effects will likely grow (McCarthy et al., 2010). Beyond these larger impacts, individual vulnerability to extreme heat is profoundly affected by one's own physical thermoregulation and ability (or inability) to alter ambient conditions. Therefore, factors such as increased use of air conditioning have modulated human vulnerability to heat over time. These factors clearly involve socio-economic, behavioral, and physiological processes that are difficult to disentangle (Boeckmann and Rohn, 2014).

This study assesses trends and variability in human vulnerability to heat across 51 largest metropolitan areas (all cities with population of at least 1 million in 2010; Fig. 1) in the United States from 1975 to 2010. We evaluate the spatiotemporal trends in human vulnerability during long heat events over the full period of record, with one of the longest continuous data sets of daily mortality available. Within this broad goal, we focus on several uncertainties in the current literature base: the pace of temporal trends in heat vulnerability, the impact of the choice of periods of analysis, acclimatization, and the role of the extreme heat wave. Specifically, with our analysis we aim to answer the following questions: how human vulnerability to heat events has changed over time, what factors can be associated with the observed trends in human vulnerability across space and time, and how the trends in human vulnerability guide predictions into the future, given changing human-Earth dynamics.

2. Research framework, data, and methods

2.1. Data on human mortality from heat events

While morbidity outcomes, such as ambulance calls or hospitalizations, are increasingly studied (e.g., Fuhrmann et al., 2016; Schmeltz et al., 2015; Saha et al., 2015; Bassil et al., 2010), the majority of heat-related health assessments have involved data on human mortality (Kovats and Hajat, 2008). These data are readily available, and they present an accessible metric to denote the long-term vulnerability of the human population to extreme heat. The relationship between heat and health is typically assessed via mortality data from all causes or critical subsets such as cardiovascular disease, (Kovats and Hajat, 2008), since analyzing only deaths that are officially described as heat-related (ICD10: $\times 30$) significantly underestimate heat's true toll (e.g., Dixon et al., 2005).

Nevertheless, these broad aggregations create uncertainty based on how 'expected' mortality is determined. With the well-established seasonal cycle in overall mortality (i.e., the winter peak), for example, subtracting the seasonal cycle leaves ambiguity in understanding the specific impact of early-season heat waves. These heat waves occurring early in the warm season may have greater impacts on people than events later in the year (e.g., Nairn and Fawcett, 2014; Barnett et al., 2012; Sheridan et al., 2009). Rocklöv et al. (2009) suggested that seasonal acclimatization may explain

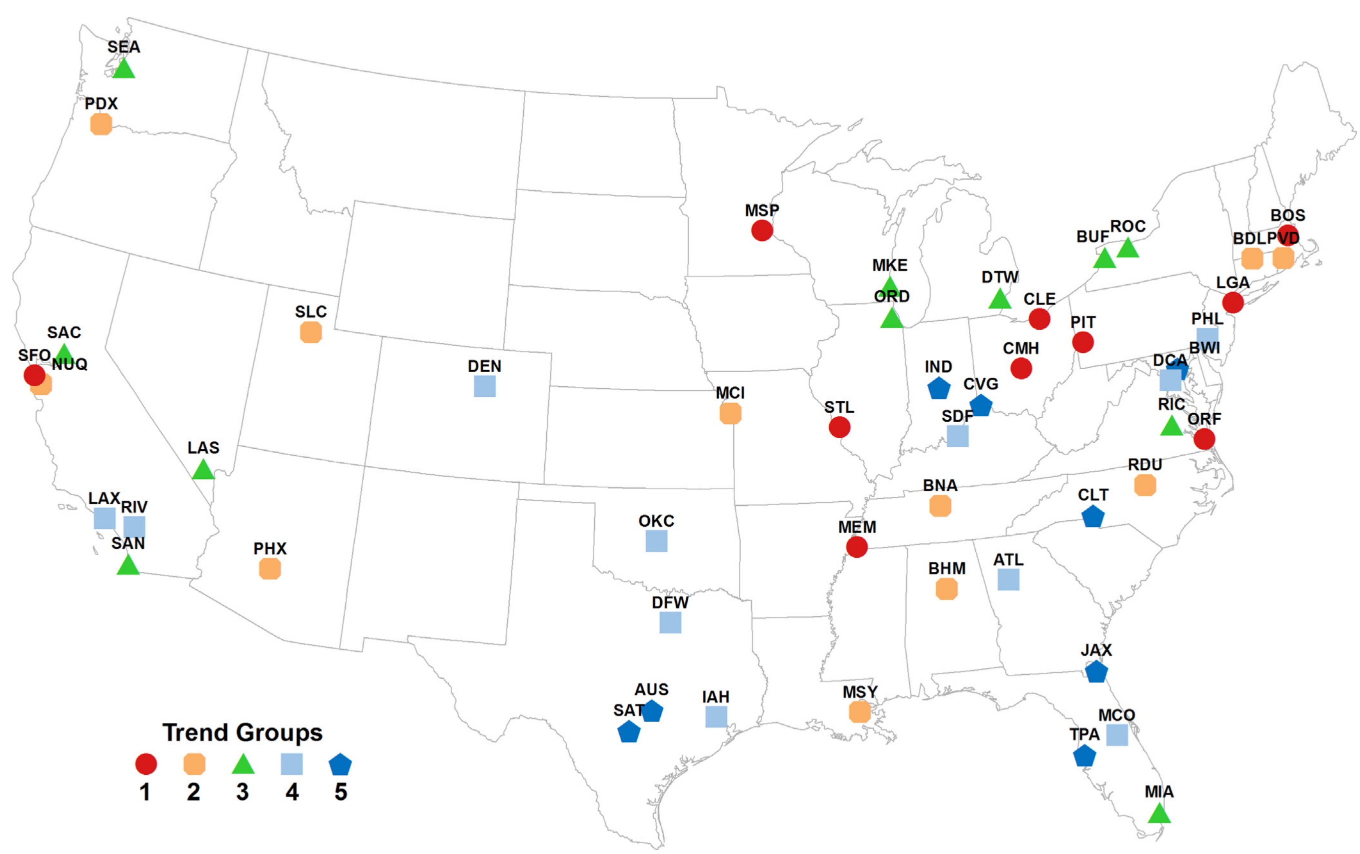

Fig. 1. Map of the 51 metropolitan areas in this research, and their temporal trend groupings discussed in Section 3.2. See Table 1 for the names of cities denoted by abbreviations.

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