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Rising heat wave trends in large US cities

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Abstract Exposures to dangerously high temperatures are a public health threat expected to increase with global climate change. Heat waves exacerbate the risks associated with heat exposure, and urban residents are particularly vulnerable to threats of heat waves due to the urban heat island effect. To understand how heat waves are changing over time, we examine changes in four heat wave characteristics from 1961 to 2010, frequency, duration, intensity, and timing, in 50 large US cities. Our purpose in measuring these trends is to assess the extent to which urban populations are increasingly exposed to heat-related health hazards resulting from changing trends in extreme heat. We find each of these heat wave characteristics to be rising significantly when measured over a five-decade period, with the annual number of heat waves increasing by 0.6 heat waves per decade for the average US city. Additionally, on average, we find the length of heat waves to be increasing by a fifth of a day, the intensity to be increasing 0.1 °C above local thresholds, and the length of the heat wave season (time between first and last heat wave) to be increasing by 6 days per decade. The regions most at risk due to increasing heat wave trends must plan appropriately to manage this growing threat by enhancing emergency preparedness plans and minimizing the urban heat island effect.

Keywords Climate change · Health effects · Heat waves · Extreme heat events

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1 Introduction

Today, extreme heat events are responsible for more annual fatalities in the USA than any other form of extreme weather (CDC 2004; NWS 2011). This is seen most directly when extreme temperatures result in a high number of heat-related illnesses, such as heat exhaustion, heat cramps, and heat stroke, which can lead to death. Temperature extremes are known to exacerbate health conditions already compromised by cardiovascular and respiratory illness, leading to an increase in heat-related mortality (CDC 2006; Wainwright et al. 1999).

On average, yearly estimates of heat-related deaths in the USA range from 170 to 690 per year (CDC 2004, 2006; NWS 2011). In the USA, the Midwest heat waves of 1995 and 1999 claimed more than 1,000 and 300 lives, respectively. More recently, heat waves of unprecedented intensity and duration in Europe have resulted in much greater loss of life, with more than 70,000 fatalities estimated from a 2003 European heat wave and more than 20,000 from a 2010 heat wave in Russia These recent heat waves rank among the most deadly weather-related disasters on record. (Palecki et al. 2001; Revich and Shaposhnikov 2012; Robine et al. 2008).

Heat-related deaths occur when a rapid rise in environmental temperatures outpaces the body's ability to cool itself through increased blood circulation and perspiration. High humidity compounds this effect by reducing the rate at which perspiration evaporates from the skin. The elderly, young, and people with mental disorders or chronic illnesses are some of the most susceptible to heat stress (Bouchama et al. 2007; CDC 2004). Additionally, urban populations are particularly vulnerable to the threats of excessive heat as most cities are home to concentrations of lower-income individuals who often lack access to air-conditioning and adequate healthcare facilities. Urban centers are also more prone to high temperatures due to the well-documented urban heat island (UHI) phenomenon. Climate change and elevated urban temperatures also drive the formation of ground level ozone, which presents additional hazardous respiratory exposures to urban residents (Bell et al. 2007; Stone Jr 2008). As the global population continues to urbanize, the number of vulnerable individuals will continue to increase (IPCC 2012; UN DESA 2008).

Characteristics of heat waves, including duration, timing, and intensity, are known to negatively impact public health by increasing the risk of heat-related mortality. Longer heat waves increase dangerous thermal exposures, particularly in urban areas where elevated minimum temperatures limit individuals' ability to recover overnight (Anderson and Bell 2009; Hajat et al. 2002). Extreme temperatures occurring earlier in the year have been shown to have a greater impact on mortality than temperatures of the same magnitude occurring later in the year (Hajat et al. 2002; Kalkstein and Davis 1989)—an outcome associated with insufficient acclimatization to higher temperatures in the late winter or early spring. Additionally, heat-related mortality increases during heat waves with greater intensities (Anderson and Bell 2009).

The UHI effect amplifies the impact of heat waves on human health by increasing both afternoon and nighttime temperatures. (Basara et al. 2010; Tan et al. 2010). Elevated urban temperatures during heat waves have been shown to increase the heat-related mortality rate in cities, as much as four times more, than in surrounding rural areas (Conti et al. 2005; Tan et al. 2010). The UHI effect occurs when urban temperatures exceed temperatures in the surrounding rural area. Heat island formation results from changes in natural land cover associated with urbanization as well as from the release of waste heat from urban activities, such as the operation of vehicles and air-conditioning systems. Urban land cover changes

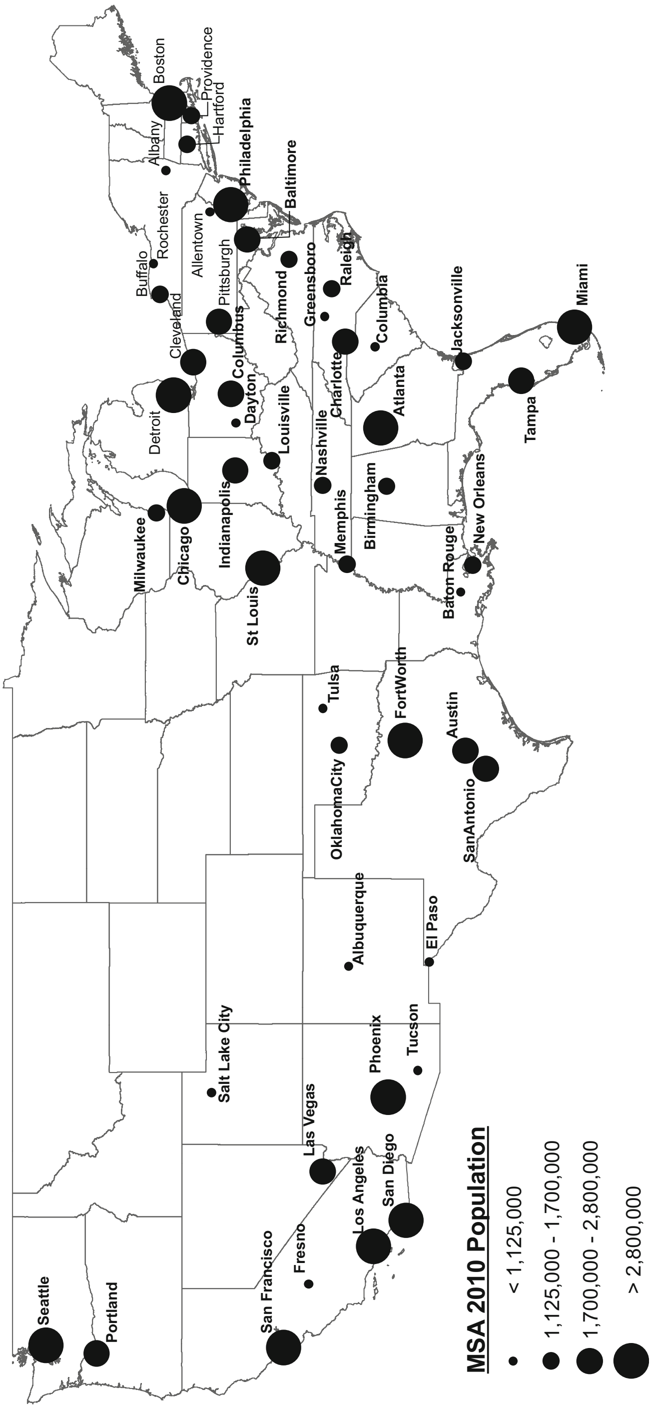

Fig. 1 Fifty US cities with population size

include a reduction in vegetative cover and local soil moisture, as well as a resurfacing of natural land covers with the impervious materials of roads, buildings, and parking lots. These land surface changes tend to enhance the absorption and storage of solar radiation and reduce evaporative cooling. In addition, the morphology of downtown districts serves to further trap and absorb reflected and emitted radiation resulting in elevated temperatures (Oke 1987).

In this study we examine the changing characteristics of heat waves in 50 large US cities using historical meteorological data over a five-decade period (1961–2010). While previous studies have examined different measures of changing heat wave activity (Della-Marta et al. 2007; Gaffen and Ross 1998; Kuglitsch et al. 2010; Smoyer-Tomic et al. 2003), this study is the first to concurrently examine the frequency, duration, intensity, and timing of heat waves—components of heat wave activity associated with elevated heat-related mortality. Additionally, this study is the first to investigate changes in the length of the heat wave season over time, which may be exposing vulnerable populations to extreme heat both earlier and later in the calendar year. We focus exclusively on large cities in response to recent work finding the UHI to be the dominant driver of warming trends in large US cities (Stone et al. 2012). Evidence of consistent patterns in the frequency, duration, intensity and/or timing of heat waves may inform the revision of emergency preparedness plans to better respond to an increase in the number of heat waves occurring both earlier and later in the year, for a more prolonged duration, and of a greater intensity than previously experienced.

2 Data and methods

For this study, we constructed a database of 50 major US metropolitan statistical areas (MSAs) with 50 years (1961–2010) of historical daily temperature data. The 50 MSAs are the largest US MSAs for which daily temperature data are available during the study period. To be considered for inclusion in the study, cities also had to have at least 590 valid months of data out of the total 600 months. Of the 50 largest MSAs, the following did not meet the criteria for inclusion in our study: New York City, Houston, Minneapolis, Sacramento, Kansas City, and Omaha. Population data for the 50 MSAs in the study are presented in Fig. 1.

2.1 Defining heat waves

At present, there is no standard definition of heat waves (Koppe et al. 2004; Robinson 2001). Heat wave definitions vary depending on the length of consecutive days, the type of temperature metrics employed (minimum, average, maximum), the thresholds used to determine an extreme temperature, and whether humidity is taken into account.

In this study, we utilize minimum apparent temperature to classify heat waves, a metric which accounts for both temperature and humidity. As established in previous work, the physiological impacts of high nighttime temperatures have been found to be greater than the physiological impacts associated with high daytime temperatures (Kalkstein and Davis 1989; Tan et al. 2010). While the elevation of both daytime and nighttime temperatures stresses cardiovascular and respiratory systems, the persistence of heat exposure throughout the night appears to most impact human susceptibility to extreme heat. This association was clearly confirmed during the European heat wave of 2003—the deadliest heat wave event on record—wherein nighttime minimum temperatures were most strongly predictive of human mortality (Laaidi et al. 2012). We adopt a measure of minimum apparent temperature to capture the well-established association between both heat and humidity with heat-related illness (Kalkstein and Davis 1989; Koppe et al. 2004).

This work is further distinguished from previous heat wave studies through its focus on heat wave trends in the largest urbanized areas of the USA. As demonstrated in previous work, large urbanized areas have been found to be amplifying global-scale warming trends due to the urban heat island effect (Stone Jr 2007; Stone et al. 2012; Zhou et al. 2004)—a trend consistent with other work finding minimum temperatures to be rising more rapidly in cities than maximum temperatures (Hale et al. 2006; Kalnay et al. 2006; Zhou et al. 2004). If the urban heat island effect is enhancing the rate at which cities are warming, most directly in the form of elevated nighttime temperatures, then urban populations may be particularly susceptible to heat wave trends amplified by the urban environment itself. We focus on trends in minimum apparent temperatures in cities to most directly capture the influence of human-enhanced climate change on health in the most heavily populated regions of the USA.

2.2 Data

For each city in the study, we identify heat wave events with data obtained from the National Climate Data Center (NCDC), a division of the US National Oceanic and Atmospheric Administration. The NCDC extends a dataset originally developed by Gaffen and Ross (1998) through which apparent temperature, combining both temperature and humidity, is measured for 187 US cities and compared to regional long-term distributions to identify anomalous heat events. The following equation is used by NCDC to derive apparent temperature:

$$A = -1.3 + 0.92T + 2.2e,$$

where A is the apparent temperature (°C), T is ambient air temperature (°C) and e is water vapor pressure (kPa), and indicator of humidity (Steadman 1984).

An index of regionalized heat stress provides the basis for identifying days with an elevated risk of heat-related health effects among a regional population. The NCDC heat index classifies an extreme heat event (EHE) as any day in which the minimum, maximum, or average apparent temperature exceeds the 85th percentile of the base period (1961–1990) for each first-order meteorological station in the database. Found in previous work to be associated with heat-related health effects, the 85th percentile threshold captures variable regional population acclimatization to heat and humidity (Gaffen and Ross 1998; Kalkstein and Davis 1989). This approach recognizes that human health responses to extreme heat vary across different climatic regions (Curriero et al. 2002; Gaffen and Ross 1998; Kalkstein and Davis 1989; Kalkstein and Greene 1997). By using local heat index thresholds to define EHEs, we are controlling for differences in climatic variability between our cities (CCSP 2008).

Based on the NCDC heat stress index data, we define a heat wave event as any minimum apparent temperature exceedance of the local 85th percentile threshold that occurs for two or more consecutive days. We compute the frequency, duration, intensity, and timing of all such heat wave events across the 50 MSAs in our study during the period of 1961–2010.

2.2.1 *Data: historic airport temperatures*

Due to the need for long-term time-series temperature data, the NCDC heat stress index is constructed from meteorological stations situated at airports, which are often the only long-term, quality-controlled sources of temperature data available in metropolitan regions and are therefore commonly used to represent urban climate trends (Davis et al. 2003; Hayhoe et al. 2010; Rosenzweig et al. 2005; Stone Jr 2007; Zhou and Shepherd 2010). While no monitor location can fully represent the heterogeneity of a region's urban landscape, we believe the physical context of most airport locations is indicative of the changing land cover conditions of large metropolitan regions as a whole over the last half century, with decentralizing land use patterns typically enveloping these locations in suburban land development. Additionally, the meteorological observations used to derive the apparent temperature in our analysis have not been corrected for urbanization effects. While many regional and global climate studies use datasets that are corrected for standard inhomogeneities, including urbanization, the NCDC TD3280 dataset was specifically selected for this study due to the fact that no attempt has been made to statistically remove the effects of urbanization. As such, it provides an ideal dataset for capturing the effects of urban land cover change on regional temperature trends over time.

To assess how well the airport stations in our study represent climatic conditions in the central business district, we measured the temperature differences between airport and downtown stations using the Daily Surface Weather and Climatological Summaries (DAYMET) dataset for the period of 1980–2012. The DAYMET dataset provides gridded, interpolated estimates of temperature across the USA at a 1 km $\times$ 1 km resolution. We compared DAYMET temperatures between airport and downtown zones in each of our 50 cities, while adjusting for elevation differences between the stations. We found a non-statistically significant mean difference in average warm season (May–September) minimum temperatures of -0.01 °C, with 29 airport stations registering a cooler average temperature than the local central business district (CBD) and 21 airports registering a warmer average temperature. Based on this analysis, we conclude that our airport stations, on average, provide a reasonable proxy for temperature trends in the most centralized zones of large US cities.

2.3 Heat wave metrics

Four distinct characteristics of heat waves are measured over the 50-year study period: frequency, duration, intensity, and timing. Each characteristic was aggregated to the annual level from daily temperature data. Heat wave frequency is the number of heat wave events that occur in each year for each MSA. Heat wave duration is the total number of consecutive days that comprise a heat wave event and is averaged annually for each MSA. Heat wave intensity is the difference between the temperature of an average heat wave day and the local EHE temperature threshold. For example, Fresno has a local EHE temperature threshold of 22.2 °C. If Fresno experiences a heat wave with an average minimum apparent temperature of 25 °C, it therefore has a heat wave intensity of 2.8 °C.

Heat wave timing examines changes in the heat wave season. Specifically, we investigate changes in the length of the heat wave season and explore if heat waves are occurring earlier or later in the year. To calculate the length of the heat wave season in a particular year, we counted the number of days that elapsed from the start of the first heat wave to the end of the last heat wave. For each year and city, we measured the number of days that elapsed from January 1 until the start of the first heat wave and from January 1 until the end of the last heat wave in order to distinguish whether the heat wave season is starting earlier, lasting longer or both.

For this study, we analyzed the trends in these four heat wave characteristics at both the MSA and national levels. Where trends were analyzed at the national level, the heat wave characteristics were averaged across all 50 cities. National trends were analyzed using repeated measure ANOVAs to test for differences between decadal averages, and with ordinary least squares (OLS) regression to assess 50-year trends. At the MSA level, we calculated a 10-year moving average in order to smooth short-term fluctuations in the data. We then used OLS regression to assess the statistical significance of a linear trend. Finally, to facilitate comparison with previous work, the annual linear trends from the OLS regression were aggregated to the decadal level.

3 Results

The frequency, duration, timing, and intensity of heat waves across all cities exhibited a statistically significant ($p < 0.001$) positive trend over the 50-year period. In the average US city, the annual number of heat waves was found to increase by 0.6 additional heat waves per decade (0.6 HW ± 0.14/decade), heat wave duration extends a fifth of a day per decade (±0.06/decade), and heat wave intensity increases by 0.1 °C above local thresholds per decade (±0.04). We also find the heat wave season to increase by 6 days per decade (±1.6). On average, the heat wave season starts 3.5 (±1.3) days earlier and lasts an additional 2.3 (±1.2) days longer in each decade.

Figure 2 illustrates the decadal average for each heat wave characteristic when averaged across all 50 cities. All of the heat wave characteristics are increasing throughout this period with the exception of heat wave duration, which decreases during the last decade of the analysis.

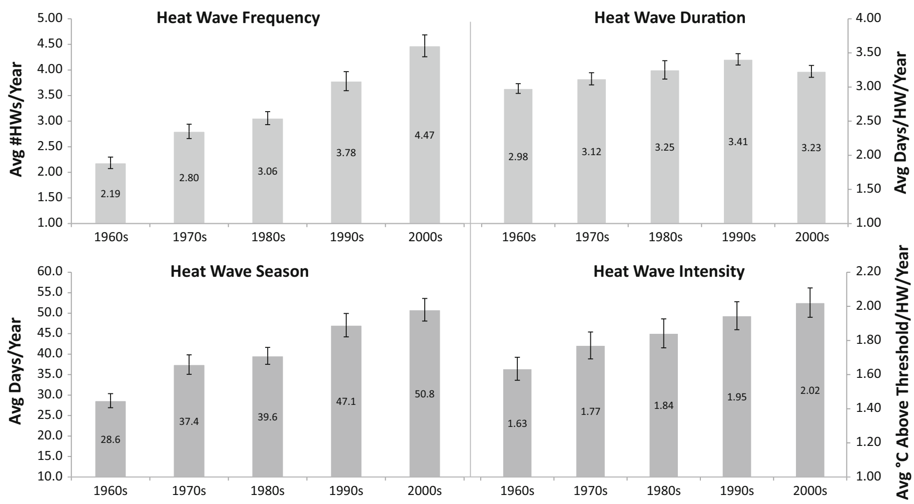

Fig. 2 Decadal average for each heat wave characteristic across all 50 cities

To confirm the statistical significance of these trends, we conducted repeated measure ANOVAs and employed post hoc pairwise comparisons using Bonferroni correction. We found statistically significant differences between the first and last decades in the analysis (1960s and 2000s) for all four heat wave characteristics. Of the four characteristics, heat wave frequency was found to be increasing most consistently during this period, with a significant increase between each decade except from the 1970s to 1980s.

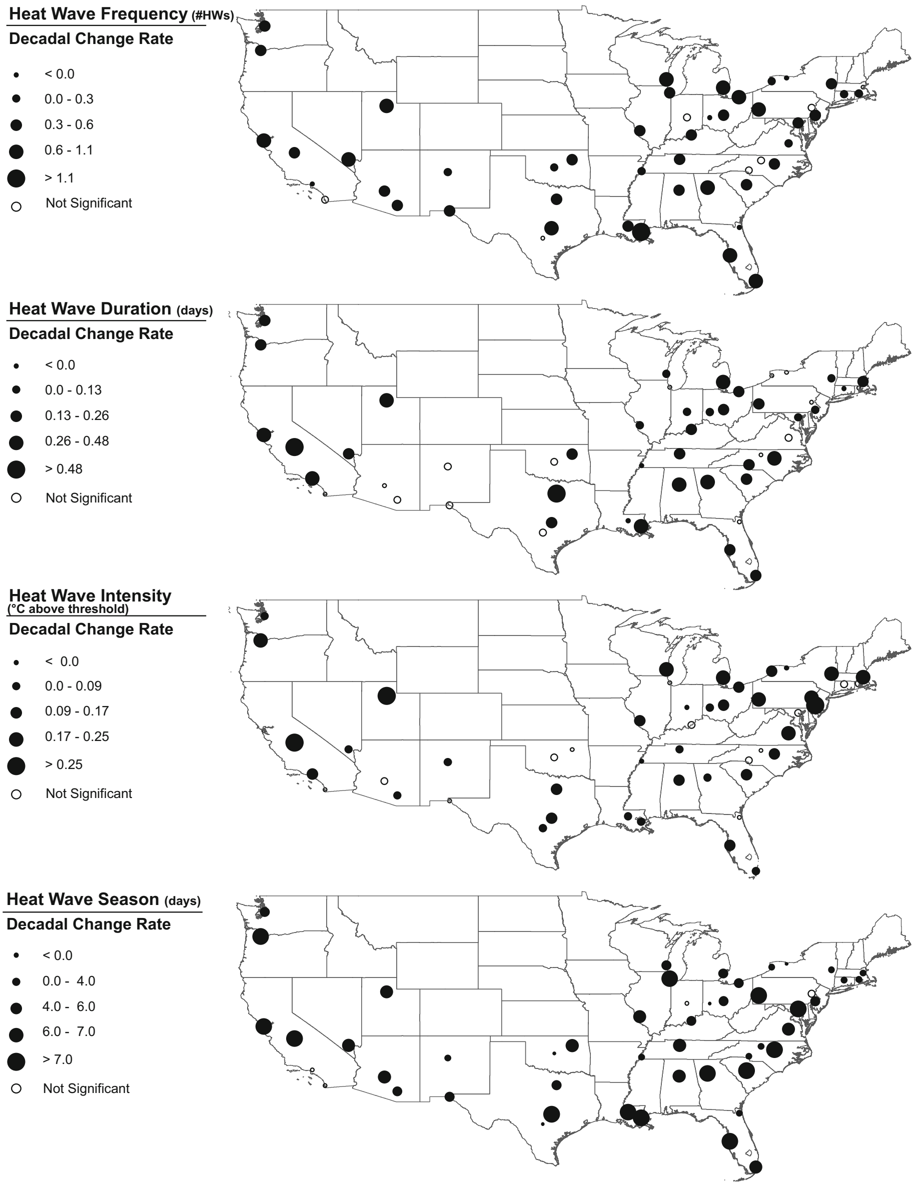

Fig. 3 This map shows the individual change rates for each city. The *closed circles* indicate a significant trend

The magnitude of change for three of the four characteristics was found to be rising by more than 5 % per decade. Of the four characteristics, the frequency of heat waves in large US cities was found to be increasing by the greatest magnitude, with an average increase per decade of 20 %. Heat wave season and intensity were also found to exhibit a relatively large positive trend over time. Length of the heat wave season was found to be increasing 16 % per decade on average and heat wave intensity had an average increase in minimum apparent temperatures above regional thresholds of 6 % per decade, or an average 24 % increase in heat wave intensity over the 50-year study period. The average magnitude change in the duration of heat waves was found to be smaller than trends in the other characteristics, increasing by only 2 % per decade. The smaller magnitude of this trend results, in part, from the shift from a positive to a negative trend in the last decade of the analysis.

Figure 3 presents trends for the 50 individual MSAs in our study. For each of the four heat wave characteristics, trends are categorized by the magnitude of their decadal change rates, as denoted by the graduated symbol sizes. Heat wave characteristics for which a trend was not found to be statistically significant are denoted with an open circle. Overall, we find a significant trend for each of the heat wave characteristics in at least 70 % of the MSAs in the study. The individual MSA change rates for each heat wave characteristic can be found in Online Resource 1. In the following section, we assess population susceptibility to these changing heat wave dynamics based on concurrent rising trends among multiple heat wave characteristics in specific metropolitan regions.

4 Discussion

From our analysis, we find a statistically significant increase in the frequency, duration, intensity, and length of the heat wave season across large US cities. By analyzing heat waves in large US cities, we are capturing the changes in heat wave trends caused from both global- and local-scale drivers, such as increases in global greenhouse gas concentrations as well as local changes from the urban environment.

Our heat wave results are consistent with other recent work finding trends in minimum temperatures, apparent temperatures, and the duration of the frost-free season to be increasing in recent decades across the USA due to global-scale drivers. (CCSP 2008; Cooter and LeDuc 1995; DeGaetano 1996; Easterling 2002; Gaffen and Ross 1998; IPCC 2012). Global climate change is already increasing the number and duration of heat waves in areas that are already experiencing EHEs (Meehl and Tebaldi 2004). These trends are likely to not only continue but increase over time. Global climate models found in the southwest, southeast and Midwest regions of the USA are likely to experience increases in heat waves, with some cities experiencing a 25 % increase in heat wave frequency (Meehl and Tebaldi 2004; Tebaldi et al. 2006). Studies examining the relationship between global climate change and mortality have found "business as usual" emissions scenarios to result in a doubling of heat-related deaths by the end of the century in the USA, with some estimates as high as 2,200 heat-related deaths occurring annually by 2,100 (Greene et al. 2011; Peng et al. 2011).

An association between land cover change and rising temperatures established in numerous recent studies (Fall et al. 2010; Hale et al. 2006; Kalnay and Cai 2003) is supportive of the hypothesis that increasing trends in EHEs are influenced by both global- and local-scale phenomena. In concert with global-scale climate change, recent work suggests that local-scale phenomena, such as the urban heat island effect, are contributing to rising EHEs and therefore may also be contributing to rising heat wave frequency. In an analysis of warming trends across a set of large US cities similar to those examined in this study, Stone et al. (2012) found the UHI effect to be the dominant driver of warming trends at the urban scale over the past half century. Related to this finding, an association was found between rates of regional deforestation and an increasing frequency of EHEs, suggesting a potential linkage between local land development patterns and heat wave activity (Stone et al. 2010). In accounting for both global climate change and urban heat island effects, McCarthy et al. (2010) project that the number of extremely hot nights will increase by as much as 50 % by 2050 in large cities globally. These cities are projected to have a much greater increase in hot nights than projected for their surrounding rural areas, illustrating the susceptibility of urban populations to extreme heat due to the urban heat island effect.

Epidemiological studies in the aftermath of heat wave events find heat-related illnesses to increase in response to the combination of two or more characteristics of heat wave activity. For example, heat wave events characterized by both high intensity and prolonged duration pose a greater threat to urban populations than high-intensity events of short duration (Anderson and Bell 2011). Likewise, the occurrence of a high-intensity event early in the year poses a greater threat to human health than a similar event occurring later in the warm season, due to variable acclimatization to high temperatures by season (Hajat et al. 2002). In light of these associations, our study supports a classification of heat wave risk by metropolitan region responsive to the number and magnitude of the rate of change in heat wave characteristics over time.

Of the 50 MSAs in our study, 40 had significant and increasing trends in at least two heat wave characteristics. Twenty-six of these MSAs exhibit heat wave trends that are increasing at a faster rate than the national average for at least two heat wave characteristics. Figure 4 presents metropolitan regions of the USA where two or more heat wave characteristics are increasing faster than the national average over the study period of 1961 to 2010.

Examining the regional distribution of these MSAs, we found that 50 % (10/20), 61 % (11/18), and 42 % (5/12) of the MSAs in the northeast, south, and west regions of the USA,

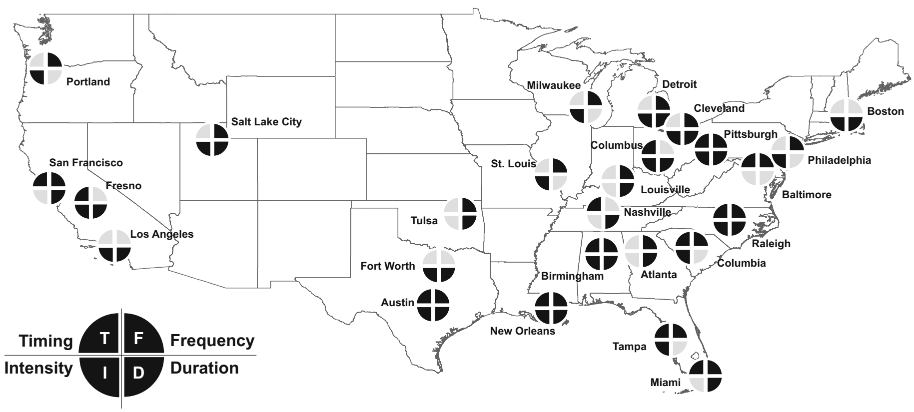

Fig. 4 This map shows the cities that have at least two heat wave characteristics with significant trends above the national average. The sections of the pie represent heat wave characteristics (*upper left,* timing; *upper right,* frequency; *lower left,* intensity; *lower right,* duration)

respectively, are exhibiting these trends. Five metro areas, including Austin, Birmingham, New Orleans, Pittsburgh, and Raleigh, have increasing trends exceeding the national average for all four heat wave characteristics.

Of the 26 MSAs whose heat wave trends are increasing faster than the national average, New Orleans, Dallas-Fort Worth, Fresno and San Francisco experienced the largest change in one of the four heat wave characteristics. In terms of heat wave frequency, New Orleans added 1.6 additional heat waves per decade (±0.3) on average—an addition of approximately 8 heat waves over the entire study period. Dallas-Fort Worth experienced the greatest change in heat wave duration, increasing the length of its average heat wave by 0.7 days per decade (±0.15), with heat waves on average 3.5 days longer in the 2000s as compared to 1960s. Fresno experienced the greatest change in heat wave intensity by increasing 0.35 °C per decade (±0.14) above the local minimum heat index threshold of 22.2 °C. San Francisco exhibited the largest shift in heat wave timing, with heat waves occurring 12 days earlier per decade (±3.3). For example, San Francisco's heat waves on average did not begin until late July in the 1960s, and by the 2000s, they are starting 1.5 months earlier in the beginning of June.

5 Recommendations and conclusions

The regions most at risk due to increasing heat wave trends must plan appropriately to manage this growing threat. A lack of planning for heat wave activity has resulted in disastrous effects in the past. For example, prior to the deadly European heat wave of 2003, only two cities in Europe had heat wave emergency response plans. This lack of planning contributed to the high number of heat-related deaths that resulted from this catastrophic event (Koppe et al. 2004). Europe is not alone in lacking adequate heat-related planning. Unfortunately, many US cities are without heat response plans or heat-focused components in emergency response plans (Bernard and McGeehin 2004). Even when cities do have plans, they are seldom based in health departments (Sheridan 2007). Research shows that cities can better manage the outcome of heat waves and lower heat-related mortality, by preparing emergency response plans (Palecki et al. 2001). According to the IPCC (IPCC 2012), risk management strategies should include attempts to both reduce exposure and vulnerability while increasing resilience to changing levels of risk. Both emergency response plans and urban heat island mitigation strategies can be implemented in cities to address these challenges.

For local heat response efforts to be effective, communities must understand the disparities in vulnerability among their residents. During the Chicago heat wave of 1999, the identification of vulnerable people coupled with targeted door-to-door outreach increased the city's resilience to extreme heat and lowered mortality (Palecki et al. 2001). Age is one of the clearest risk factors for extreme heat vulnerability (Kovats and Hajat 2008). The elderly experience a disproportionate health burden from heat stress, due to reduced thermoregulatory function (Flynn et al. 2005). Changing demography in the USA is adding to the threat of extreme heat in cities, as the US population is increasingly made up of individuals over the age of 65. The concurrent trends of increasing heat waves and USA's aging population present more of a public health threat than either would alone. Lower-income residents are also more vulnerable to extreme heat. Low-income residents may be more likely to live in a more heat prone urban environment (i.e. one with limited vegetation and high density), as well as be unwilling to run their air conditions during heat waves because of the high cost associated with summer electricity bills (Sheridan 2007).

Heat response plans must also focus on enhancing infrastructure resilience. Regions should proactively plan to prevent infrastructure failure during more intense heat waves as well as support the creation of additional infrastructure, such as public air-conditioned spaces, necessary to provide relief from future heat waves (Miller et al. 2009; Oven et al. 2012). During extreme heat events, increases in demand to a city's infrastructure such as power, water supply, and health services can overly tax these infrastructures. Air-conditioning is one of the most effective cooling strategies during heat waves, and there is a strong correlation between increases in extreme heat and peak demand for electricity. Older power transmission lines are less effective at supplying power during extreme heat and run the risk of catching on fire (Altalo and Hale 2004), and many regions have experienced blackouts during these critical times. Outdated systems can subject populations to unnecessary heat exposures and can put larger numbers of people at risk for adverse health outcomes.

Nationally, the percentage of the population over the age of 65 increased more than three points between the 1970 and 2010 US Census (9.8 to 13.1 %). In our 50 MSA sample, increases in the number of individuals over age 65 mirrors the US trend closely. By 2050, at least one-fifth of the USA will be older than 65 increasing in number fourfold (to 80 million) since 1970 (Jacobsen et al. 2011). The urban/rural distribution of this population is highly variable by social and economic status, with more wealthy retirees expected to seek out non-urban residences in older age (Jacobsen et al. 2011). The combination of old age, urban living, and low adaptive capacity makes this group exceptionally vulnerable to extreme heat. Attention should be paid to the patterns of urban elderly as climate change continues. Detailed and frequent censuses of urban elderly, as well as call lists and scheduled volunteer visits during heat waves, can be important strategies for reducing this growing public health threat (Naughton et al. 2002).

Public health response planning must also be broadened to mitigate the potential local drivers of enhanced heat wave activity, as recent work suggests heat wave trends are being amplified by the urban heat island effect. To counteract these trends, a handful of large US cities, including Los Angeles and New York, have undertaken campaigns to plant one million new trees through their metropolitan areas. For regions with sufficient annual precipitation, tree planting and other vegetative strategies, such as the installation of green roofs, have been found to be the single most effective approach to moderating the urban heat island effect, reducing the heat island effect in some modeling studies by more than 50 % (Lynn et al. 2009; Rosenzweig et al. 2006; Zhou and Shepherd 2010). Cool roofing and paving strategies, when implemented citywide, have also been shown through modeling studies to significantly lower air temperatures (Akbari et al. 2009; Oleson et al. 2010). An expansion of heat management planning to address these built environment influences on heat wave activity enables municipal governments to work actively in advance of a heat wave to lessen its impact on human health and critical infrastructure.

In this paper, we tracked four heat wave characteristics (frequency, duration, intensity and timing) over five decades for 50 large metropolitan areas in the USA. We found that trends in these heat characteristics show an increase in the frequency, duration, and intensity of heat waves, as well as an expansion of the heat wave season, with heat waves occurring both earlier and ending later in the year. These characteristics of heat waves are associated with negative public health effects including increased illness and death. We recommend that cities actively take steps, such as enhancing emergency preparedness plans and minimizing the urban heat island effect, to mitigate the impacts of future heat waves.

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