AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2018EF001085

Localized Changes in Heat Wave Properties Across the United States

Javad Shafiei Shiva[1], **David G. Chandler**[1], **and Kenneth E. Kunkel**[2]

[1]Department of Civil and Environmental Engineering, Syracuse University, Syracuse, NY, USA, [2]North Carolina Institute for Climate and Satellites, North Carolina State University, Asheville, NC, USA

Key Points:

- This study uses many different definitions for heat wave to make broad comparisons
- Regional differences in heat wave components complicate uniform public health and urban management strategies
- Frequency and intensity of extreme climate-related urban heat wave events are increasing for the various climates of the United States

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

Correspondence to:
J. Shafiei Shiva,
jshafiei@syr.edu

Citation:
Shafiei Shiva, J., Chandler, D. G., & Kunkel, K. E. (2019). Localized changes in heat wave properties across the United States. *Earth's Future*, *7*, 300–319. https://doi.org/10.1029/2018EF001085

Received 30 OCT 2018
Accepted 26 FEB 2019
Accepted article online 1 MAR 2019
Published online 20 MAR 2019

Abstract Heat waves are an important type of extreme climate event and directly result in more than 130 deaths per year across the United States. Heat waves have been described by several attributes and combinations which constitute various event typologies. Attributes of heat waves from 10 cities are analyzed over the period 1950–2016 to understand how these attributes determine variability in local heat waves and how climate change affects heat waves across the United States. This study uses eight definitions to differentiate heat waves and tests for temporal trends in key properties of heat waves over the period 1950–2016. At least five harmful attributes of heat waves have increased simultaneously for Dallas, Miami, New York, Phoenix, and Portland.Miami showed the greatest change in heat wave season length, frequency, and timing over the study period. Surprisingly, the greatest mean heat wave intensities above daily thresholds were for Bismarck, ND (+8.2 °C) and Syracuse, NY (+6.5 °C). Similar results across Baltimore, MD, Colorado Springs, CO, Dallas, TX, Des Moines, IA, Miami, FL, New York, NY, Phoenix, AZ, and Portland, OR, are presented to clarify the many quantitative differences in heat wave attributes and variance in quantification approaches across climates. This work explores the nexus of quantitative description and social construction of heat waves through the lens of the various regional metrics to describe heat waves. Ultimately, this assessment will guide the development of various strategies to help communities understand and prepare for heat resilience based on local heat wave components.

Plain Language Summary Heat waves are a series of consecutive days and nights with very high temperatures. They impact human health and increase water and energy demands, particularly in the urban areas. Heat waves have different lengths, occur in various seasons, and have different ranges between daytime and nighttime temperatures. These variations create numerous types of heat waves. Although heat waves happen more frequently in hot regions, residents of cities in northern climates also experience various types of heat waves. Analysis of differences in heat wave occurrences from 1950 to 2016 in 10 cities with various climates across the United States shows how different types of heat waves are changing across the United States. We found that many descriptive characteristics are increasing in value through time. For example, heat wave duration has increased in Miami, FL. The findings of this study are intended to guide policy makers, urban managers, and first responders to better prepare for future changes in regional heat waves and mitigate negative impacts of heat waves on human health and the environment.

1. Introduction

Heat waves are the most notable cause of weather-related human hospitalization and mortality in the United States and the world and are generally considered as a period of extremely hot weather (Altman et al., 2012; Brooke Anderson & Bell, 2011; Robinson, 2001; Thacker et al., 2008).

The impact of heat waves is often greater in cities, where dense urbanization often replaces vegetated and natural soil surfaces with hardscape, thereby decreasing natural cooling by evapotranspiration (Ramamurthy & Bou-Zeid, 2014; Stone & Rodgers, 2001). Furthermore, the heat capacity of most urban structures alters the surface energy balance (Ramamurthy & Bou-Zeid, 2014) and thereby elevates nighttime temperatures (Stone & Rodgers, 2001). Such additional endogenous heat sources contribute to a phenomenon known as the Urban Heat Island, which further exacerbates local heating and magnifies the frequency and intensity of heat waves in cities (Li & Bou-Zeid, 2013; Oke, 1982). Continued urbanization throughout the United States and increased global warming will likely increase heat wave frequency, duration, and intensity across climates and locally across urban and rural transitions (Habeeb et al., 2015; Rosenzweig & Solecki, 2014; Stone et al., 2010).

Prolonged extreme heat waves in urban areas are closely related to air pollution such as PM2.5 concentrations and especially ground level ozone formation (Camalier et al., 2007; H. Zhang et al., 2017). These two pollutants have been regulated to limit impairment to human respiratory systems, health, and the environment. (Sun et al., 2017; H. Zhang et al., 2017). The compound effect of high ozone concentration during heat waves is greater than the sum of the individual impacts (Schnell & Prather, 2017).

Other impacts of heat waves include serious agricultural and ecological impairments (Peterson et al., 2013). Many plants are sensitive to extended elevated temperatures (Schlenker & Roberts, 2009) and when accompanied by meteorological droughts, heat waves can significantly decrease crop yield (van der Velde et al., 2012). Furthermore, heat waves are associated with decreased forest biomass and ecological biodiversity (Morri et al., 2017; Toomey et al., 2011). Importantly, heat waves stress power grids and water distribution systems due to the extra consumption of power for cooling and drinking water (Hansen et al., 2017; Ramamurthy et al., 2015; Smoyer-Tomic et al., 2003).

Many climate models project that the number of hot days will continue to increase across most parts of the United States as a result of global warming, particularly by the end of this century (Intergovernmental Panel on Climate Change, 2014; Kunkel et al., 2013; Melillo et al., 2014). Although there are uncertainties among climate change models (Clark et al., 2016), the Coupled Model Intercomparison Project Phase 5 projections indicate that the current rare high summer average temperatures will become more frequent during this century (Duffy & Tebaldi, 2012; Kharin et al., 2013). This increase in the higher average summer temperature is expected to be attended by meteorological droughts and will bring concurrent extreme events for the United States, especially for the western and central United States (AghaKouchak et al., 2014; Melillo et al., 2014). These models predict that most of the United States will experience more frequent extremely hot days, with the historical 20-year high-temperature return period decreasing to 2 or 3 years (Diffenbaugh & Ashfaq, 2010; Kharin et al., 2013). Global models indicate that even if all emissions from human activities cease immediately, a minimum increase of 0.27 °C is inevitable (Hawkins & Sutton, 2011; Matthews & Zickfeld, 2012). Accordingly, heat wave intensity and duration are likely to increase in many places, followed by an increase in the ground level ozone concentration (Karl & Trenberth, 2003; Meehl & Tebaldi, 2004; J. Zhang et al., 2018). In the United States, it is expected that extreme heat days will increase throughout the United States and extended summer seasons will exacerbate heat wave frequency, intensity, and duration (Diffenbaugh & Ashfaq, 2010; Kharin et al., 2013).

Despite the long-standing and excessive harmful impacts of heat waves on humankind, there is no single quantitative definition for heat waves (Kuchcik, 2006; Peterson et al., 2013; Robinson, 2001). To our knowledge, the first recorded quantitative heat wave definition was for the 1896 New York City event, which was defined as seven or more consecutive days with an average daily temperature greater than 29 °C (Ellis & Nelson, 1978; Kuchcik, 2006). More recently, National Weather Service (NWS) defined a heat wave in the United States as "a period of at least 48 hours during which neither the overnight low nor the daytime high apparent temperature falls below the NWS heat stress thresholds". The overnight threshold is defined as the greater value of 80 °F (26.7 °C) and 99th quantile of historical minimum apparent temperature, and the daytime threshold is defined as the greater value of 105 °F (40.6 °C) and 99th quantile of historical maximum apparent temperature (Robinson, 2001). The U.S. Environmental Protection Agency defines a heat wave as a period of 4 days with an average temperature greater than a location-specific threshold that is expected to happen every 10 years (Environmental Protection Agency, 2016). Another popular definition for a heat wave in the United States is a period of at least two consecutive days with the regional daily average temperature higher than the 95th percentile (Brooke Anderson & Bell, 2011). Some scholars use the 90th percentile of the historical data distribution for the daily maximum and minimum temperature as the thresholds and identify a heat wave event as at least two consecutive days with both maximum and minimum temperatures above those thresholds (Keellings & Waylen, 2014). Another set of definitions rely on apparent temperature rather than ambient temperature as a metric that incorporates both air temperature and relative humidity. This approach recognizes the importance of limited evaporative cooling on the physical experience of a human body during heat waves (Brooke Anderson & Bell, 2011; Robinson, 2001). Meanwhile, Environment Canada defines a heat wave as a period of at least three consecutive days, with a maximum temperature higher than 32 °C (Smoyer-Tomic et al., 2003). A list of heat wave definitions in different countries is available in the supporting information of this paper.

This inconsistency in recognizing a unique definition for heat wave also extends to international organizations. World Meteorological Organization in cooperation with World Health Organization (WHO) defined the 95th percentile of the historical data distribution for the daily maximum and minimum temperatures as the thresholds to a heat wave and identify a heat wave event as at least two consecutive days with both maximum and minimum temperatures above these thresholds (World Meteorological Organization, 2015). However, WHO regional office for Europe defined a heat wave as a period when maximum apparent temperature and minimum temperature exceed the 90th percentile of the monthly distribution for at least two consecutive days (WHO, 2009). Finally, the Intergovernmental Panel on Climate Change describes a heat wave as a several consecutive days and nights with high temperatures (Trenberth et al., 2007).

Similar to various heat wave definition, there are too many heat wave components and metrics, where some of them are defined for a particular impact group (Perkins & Alexander, 2013). For example, Expert Team for Climate Change Detection Monitoring and Indices recommended 16 indices for extreme temperature studies (Alexander et al., 2006). Most of these indices are based on maximum or minimum daily temperature. In addition, there are metrics that combine two or more of individual measures of heat waves. For example, Frich et al. (2002) described Heat Wave Duration Index, which is the number of five or more consecutive days with maximum daily temperature more than 5 °C above the 1961–1990 daily maximum temperature. Correspondingly, Heat Wave Magnitude Index daily considers heat wave intensity for at least 3-day-long heat wave events (Russo et al., 2015).

Despite this diversity in heat wave metrics, in most studies four main properties are used to describe the impacts of heat waves: (a) frequency, (b) intensity, (c) duration, and (d) timing (Brooke Anderson & Bell, 2011; Karl et al., 2009; Robinson, 2001). These properties vary sufficiently to result in a wide range of heat wave histories and are further complicated by differences in affected populations. This diversity leads to the importance of focused study of local scale heat wave properties (Photiadou et al., 2014). For example, vernal heat waves can come as a shock, and the impact on human health under severe conditions can double the associated mortality rate (Brooke Anderson & Bell, 2011; Smoyer-Tomic et al., 2003). These various properties may be experienced differently by various age, socioeconomic, and health status groups, who may display a range of responses to the same heat wave. Photiadou et al. (2014) proposed that no two heat waves are exactly the same, and no two populations have the same response to an extreme event.

In this study, we examine the historical change of important properties of heat waves, including the number of hot days, frequency, intensity, duration, timing, total length, the first day of heat waves, and longest heat wave event in each year. We selected 10 sites in different climatological situations across the United States and obtained atmospheric data from airport weather stations for the period of 1950 to 2016. We use two main groups of heat wave definitions, those based on maximum and minimum daily ambient temperatures above the certain thresholds and those based on average daily apparent temperature above a defined threshold.

Although previous studies on different properties of heat waves are available (Della-Marta et al., 2007; Furrer et al., 2010; Habeeb et al., 2015; Kuglitsch et al., 2010; Morabito et al., 2017), this research develops two novel analyses: first, eight characteristics of heat waves have been examined simultaneously for the 67 years, and second, two main definitions of heat waves (subdivided by statistical thresholds resulting in eight definitions) generally represent the range of widely used definitions.

The findings of this research are intended to, first, indicate the significant importance of definitions and metrics in the heat wave studies and, second, help policymakers, managers, and first responders understand the changing characteristics of heat waves to best prepare communities for locally extreme heat conditions. This approach particularly supports the United Nations Sendai Framework for Disaster Risk Management that recognizes understanding hazard characteristics from global to regional levels as the first priority in prevention and mitigation of and response to the disasters (United Nations, 2015).

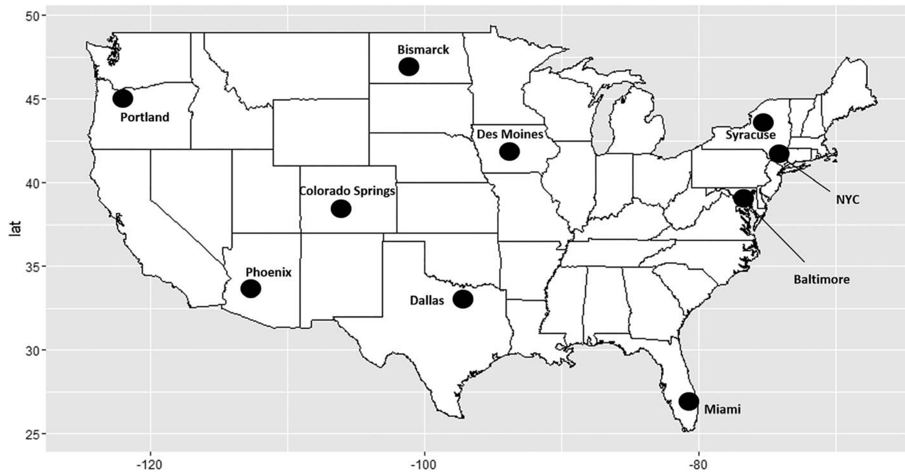

Figure 1. Location of the cities selected for this study.

2. Data and Methods

2.1. Data Sources

This study focuses on 10 cities in the Contiguous United States (CONUS) with different climates. We obtained historical daily and hourly weather data (minimum, maximum, and average temperatures, and average daily humidity) from the National Centers for Environmental Information for 1950–2016. The data are extracted from the airport weather station in each city, because they are reliable and continuous weather data sources and are known to provide a realistic representation of temperature in most cities within the contiguous United States (Davis et al., 2003; Habeeb et al., 2015; Metzger et al., 2010). These cities are Baltimore, MD, Bismarck, ND, Colorado Springs, CO, Dallas, TX, Des Moines, IA, Miami, FL, New York City, NY, Phoenix, AZ, Portland, OR, and Syracuse, NY (Figure 1). Analysis of daily data includes occasional infilling of missing daily data with proxy data derived from the hourly climatological data.

2.2. Heat Wave Definitions

At present, there is no globally accepted definition for the conditions that constitute a heat wave. In fact, debates abound on the parameters that should be included in measuring heat waves (Mcphillips et al., 2018; Robinson, 2001). To address this challenge, we used two main groups of definitions to span the basic range of approaches. The first definition is based on both daily minimum and maximum temperatures: *A heat wave event has at least two consecutive days with minimum and maximum daily temperatures greater than 85th, 90th, 95th, and 99th percentiles of the historical minimum and maximum daily temperatures, respectively*. We referred these subclasses as HW1A, HW1B, HW1C, and HW1D (or mild, moderate, severe, and extreme events). This definition helps to identify the events that are mainly dangerous for elderly and disadvantaged people who need nighttime relief from daytime high temperature; this definition is similar to many previous studies (Keellings & Waylen, 2014; Robinson, 2001; Smith et al., 2013). Furthermore, it helps to capture events that include the effect of high nighttime temperatures, which have greater physiological impacts on vulnerable urban population and the simultaneous maximum daily temperatures that are dangerous for humans (Habeeb et al., 2015; Photiadou et al., 2014).

The second definition includes the apparent temperature to represent the effect of humidity in each location. In this definition, we highlight the importance of the physical experience of the human body during heat waves (Brooke Anderson & Bell, 2011; Robinson, 2001). We also used different values of local historical frequency percentiles as thresholds, to recognize regional acclimatization of the population to the heat waves (Habeeb et al., 2015). The second type of heat wave is defined as follows: *At least four consecutive days with average daily apparent temperature more than 85th, 90th, 95th, and 99th percentiles of the historical average daily apparent temperature*. We denote the second class of heat wave definition as HW2A, HW2B, HW2C, and HW2D (or mild, moderate, severe, and extreme events), similar to those used previously (Brooke Anderson & Bell, 2011; Habeeb et al., 2015; Smith et al., 2013).

Different upper tail percentiles ranging from 85th to 99th of year-round data separate various heat wave strengths (Xu et al., 2016, 2017). This method might decrease the heat wave thresholds in areas with shorter warm season but highlights the possible sensitivity of the area to hot weather by capturing more events as a heat wave, similar to previous studies (Gasparrini & Armstrong, 2011; Habeeb et al., 2015; Ma et al., 2015).

2.3. Methods

For each station, we obtained weather data from the National Centers for Environmental Information from 1950 to 2016. The required data were daily minimum, maximum, and average temperatures and average humidity. When daily data summaries were not available, we calculated daily values from hourly data. We then calculated the apparent temperature for each station based on average daily temperature and average daily humidity.

The heat index is a function of at least temperature, humidity, wind speed, and net radiation (Brooke Anderson et al., 2013; Steadman, 1979). However, limitations in data availability in many locations reduced our analysis to temperature and humidity data for uniform calculation of a heat index across cities (Brooke Anderson et al., 2013). Accordingly, we applied the method that is most commonly used by NWS and described by Robinson (2001). The nonlinear characteristic of this method implies that the use of daily averages to compute apparent temperature will not necessarily produce the same value as averaging apparent temperature from instantaneous (e.g., hourly) observations of temperature and humidity. However, this has inconsequential impacts on the results because we are using percentile thresholds to define heat waves. We develop a set of indices by basing the calculation on the 85th, 90th, 95th, and 99th percentiles of the minimum, maximum, and apparent temperature daily records for each station. This method acknowledges that human perception and tolerance of heat in different climates lead to different responses to the heat waves according to personal history (Habeeb et al., 2015; Kalkstein et al., 2011; Keellings & Waylen, 2014; Robinson, 2001). The associated data set supported the calculation of minimum, average, maximum daily temperatures, average daily apparent temperature, and analysis of the heat wave 's properties in each year for every station over 67 years.

2.4. Heat Waves Metrics

In this study, we measured heat wave properties for seven cases by the definition of HW1 and six cases by the definition of HW2. We also measured the number of hot days, which is common to both definitions of extreme heat event, regardless of whether the days are consecutive within the year. We analyzed these properties over 67 years at 10 locations and aggregated the daily results to the annual level from daily temperature and humidity data. Accordingly, we define heat wave properties as follows:

- Number of hot days (*Days*): A hot day has either both maximum and minimum temperatures higher than thresholds (for the HW1 definition) or a day with the average daily apparent temperature higher than the threshold (for the HW2 definition).
- Frequency of heat wave (*Waves*): Number of independent heat waves in each calendar year.
- Total length of heat waves (*Total*): The cumulative length of all heat waves in each calendar year.
- Longest heat wave event (*Longest*): The longest heat wave event in each calendar year.
- Nighttime heat wave intensity (*Night*): The cumulative value of nighttime temperature above the HW1 minimum temperature threshold during a heat wave. Equation (1) summarizes the definitions of nighttime heat wave intensity for HW1 definition of heat wave.

$$\mathrm{Night}_{\mathrm{HW1}} = \sum_{i=1}^{i=n}\left(T_{\min,\mathrm{day}\ i} - \mathrm{Threshold}_{\min}\right) \tag{1}$$

where $T_{\min,\,\mathrm{day}\,i}$ is the minimum temperature of Day$_i$within a heat wave based on the HW1 definition, Threshold$_{\min}$ is the threshold for minimum temperature of a heat wave based on the HW1 definition, The variable n is total length of days during heat waves based on the HW1 definition. For example, for a HW1 heat wave of two consecutive days, if the minimum and maximum daily temperatures are 25, 28, 35, and 38 °C and at that station the thresholds for a heat wave are 24 and 34 °C respectively, the nighttime heat wave intensity is 5 °C for this event.

- Total heat wave intensity (*Intensity*): The sum of the cumulative value of nighttime temperature above the HW1 minimum temperature threshold and the cumulative value of daytime temperature above the HW1 maximum temperature threshold during a heat wave. For HW2, total heat wave intensity is the cumulative value of daily average apparent temperature above the defined threshold. Equations (2) and (3) summarize the definitions of total heat wave intensity for HW1 and HW2, respectively

$$\text{Intensity}_{\text{HW1}} = \sum_{i=1}^{i=n}\left[\left(T_{\max,\text{day } i} - \text{Threshold}_{\max}\right) + \left(T_{\min,\text{day } i} - \text{Threshold}_{\min}\right)\right] \tag{2}$$

$$\text{Intensity}_{\text{HW2}} = \sum_{j=1}^{j=m}\left(T_{\text{apt,ave,day } j} - \text{Threshold}_{\text{apt,ave}}\right) \tag{3}$$

where $T_{\text{max, day } i}$ is the maximum temperature of Day_i during a heat wave based on the HW1 definition. $T_{\text{min, day } i}$ is the minimum temperature of Day_iwithin a heat wave based on the HW1 definition, $\text{Threshold}_{\text{max}}$ is the threshold for maximum temperature of a heat wave based on the HW1 definition. $\text{Threshold}_{\text{min}}$ is the threshold for minimum temperature of a heat wave based on the HW1 definition. $T_{\text{apt, ave, day } j}$ is the average apparent temperature of Day_j as a part of a heat wave based on the HW2 definition. $\text{Threshold}_{\text{apt, ave}}$ is the threshold for average apparent temperature of a heat wave based on the HW2 definition. The variables n and m are total length of days during heat waves based on the HW1 and HW2 definitions. In addition, we use Intensity per day ($\text{Intensity}_{\text{Day}}$) to present average intensity of heat wave during the event as the following:

$$\text{Intensity}_{\text{Day}} = \frac{\text{Intensity}}{\text{Total}} \tag{4}$$

For example, in a two consecutive days heat wave, if the minimum and maximum daily temperatures are 25, 28, 35, and 38 °C, respectively, and the site thresholds for a heat wave are 24 and 34 °C respectively, the total heat wave intensity is 10 °C and intensity per day is 5 °C. This approach is similar to a method used previously (Habeeb et al., 2015; Morabito et al., 2017).

- First heat wave event (*First*): The number of first day of the first heat wave in a calendar year.
- Heat wave season duration (*Duration*): The period between the first day of the first heat wave and the last day of the last heat wave in each calendar year.

We defined these properties based on four main heat wave components to clarify and cover a few possible interpretations for each component. For example, heat wave intensity is defined both as cumulative value of nighttime temperature above the minimum temperature threshold during a heat wave and cumulative value of daytime maximum temperature above the maximum temperature threshold during a heat wave (Harlan et al., 2006; Laaidi et al., 2011). Accordingly, we defined Night and Intensity to integrate both metrics. Similarly, *Total*, Longest, First, and Duration define four possible comprehensions of “timing” and “duration” as other main components of heat waves.

We argue that studying changes in the heat wave properties using nonarbitrary definitions for multiple properties is crucial to understand heat wave impacts and can reduce uncertainties resulting from various definitions of the heat waves (Kent et al., 2014; Xu et al., 2016, 2017). Two R codes were used to calculate heat wave properties based on both HW1 and HW2 definitions (Shafiei Shiva, 2018a, 2018b). We applied the nonparametric Mann-Kendall test (Kendall, 1948; Mann, 1945) with p values smaller than the 0.05 significance level to detect any trends similar to those used previously (Della-Marta et al., 2007; Donat et al., 2013; Habeeb et al., 2015; Kuglitsch et al., 2010; Smith et al., 2013; Vogel et al., 1997). We considered the result of Mann-Kendall trend analysis for each heat wave property from 1950 to 2016 as either “no significant trend or no trend”, “statistically significant increasing trend or positive trend”, or “statistically significant decreasing trend or negative trend.”

2.5. Simultaneous Trends Visual Presentation (Heat Wave Trend Profile)

We present the temporal trend analysis results by sunburst type charts (also known as a multilevel pie chart, multilayer donut chart, and multilayer ring chart) in section 3.1. These charts simultaneously highlight the changes in the defined properties for each strength of heat waves. Henceforth, we point to these charts as the “heat wave trend profile” or “heat wave profile” in each location. Accordingly, the four concentric rings represent mild, moderate, severe, and extreme heat waves (Figure 2). We identify the properties of each strength of heat wave by a section on the related ring, labeled according to the defined metrics in section 2.4. In these charts, trends in temporal properties over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative) according to Mann-Kendall trend test.

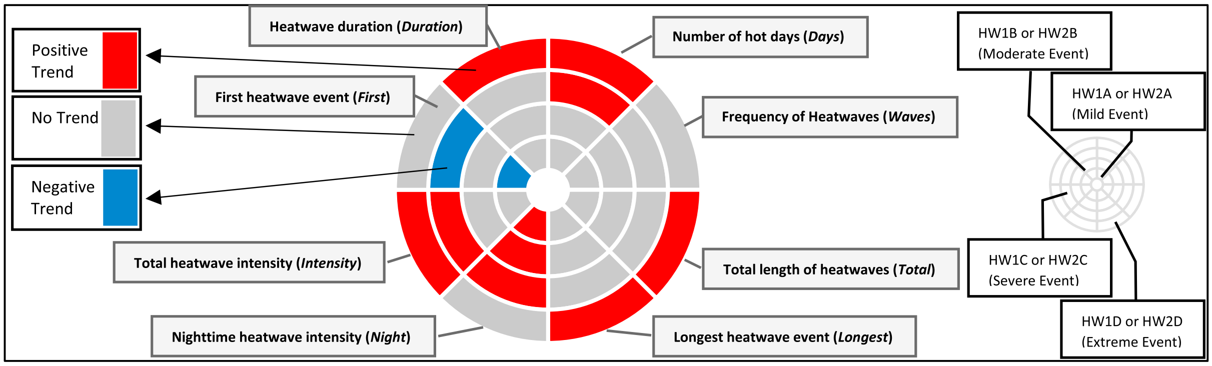

Figure 2. Legend and explanation of visualization approach for multiple heatwave properties, intensities, and trends (heat wave profile). Each of the eight segments (seven segments in HW2) corresponds to a heat wave property. Within the segments, the smallest to largest rings represent increasing intensities, from mild to extreme, with the color in each ring indicating the temporal trend for each heatwave property. This figure applies to both HW1 and HW2 definitions and properties.

3. Results

The presented heat wave trend analyses depend strongly on the selected definitions and metrics. These trends vary locally, and no two locations showed a similar heat wave trend profile over the study period. We found that although heat wave properties commonly change simultaneously across analyses, the changes are not necessarily similar in magnitude, direction, or metric. To provide clarity in the outcomes of analysis, we present the study results in two sections. Section 3.1 shows results of trend analysis for heat wave properties based on the HW1 and HW2 definitions. This approach highlights the importance of the chosen definition on the outcome of the heat wave trend analysis. Section 3.2 shows the decadal averages of four important heat wave properties including first heat wave event (First), heat wave season duration (Duration), frequency of heat wave (Waves), and total heat wave intensity (Intensity, in terms of $\text{Intensity}_{\text{Day}}$) for the 10 communities.

3.1. HW1 and HW2 Temporal Trends

The HW1 and HW2 groups include four different heat wave strengths (mild, moderate, severe, and extreme). We further define eight HW1 and seven HW2 properties of heat waves, including number of hot days (*Days*), frequency of heat waves (Waves), cumulative length of heat waves (*Total*), longest heat wave event (Longest), total heat wave intensity (Intensity), first heat wave event (First), heat wave season duration (Duration), and nighttime heat wave intensity (Night, only for HW1). In this section, we present the results of trend analysis for these heat wave properties over the period 1950–2016. Figures 3–7 illustrate simultaneous trends for heat wave properties of each of four strengths of HW1 and HW2 heat waves in the 10 study cities. We present the results in five groups of cites with similar increases in heat wave properties for both HW1 and HW2 definitions. Accordingly, a positive significant trend (based on Mann-Kendall test and $p < 0.05$) represents increasing harmful impact of heat waves, except for the first heat wave event (First). Alternatively, a negative trend on the first heat wave event indicates an earlier incidence of heat waves, which is more harmful than a later onset.

Phoenix and Portland show increasing trends for most heat wave properties for the HW1 definitions. In both cities, the trend in first heat wave event (First) for mild heat waves show decreasing trends, indicating earlier onset of the first heat wave event of the year. Conversely, severe and extreme heat waves show an increasing temporal trend, which indicates a delay in the onset of the hot season. Although incorporating the impact of humidity by changing the definition set from HW1 to HW2 does not change the Phoenix heat wave profile notably, humidity matters for Portland, especially for First, which changes to "no trend."

Dallas and Miami are the two most southern sites in this study. Dallas shows increasing trends in strength of heat waves and hot days for both HW1 and HW2 definitions for all heat wave properties. Only extreme heat waves tend to start later, but same onset of other heat waves accompanied with extended heat wave duration shows longer hot seasons for Dallas (Figure 4). Although Miami is also hot, the heat wave profile for extreme events differs substantially between the HW1 and HW2 definitions. The trend direction of heat wave

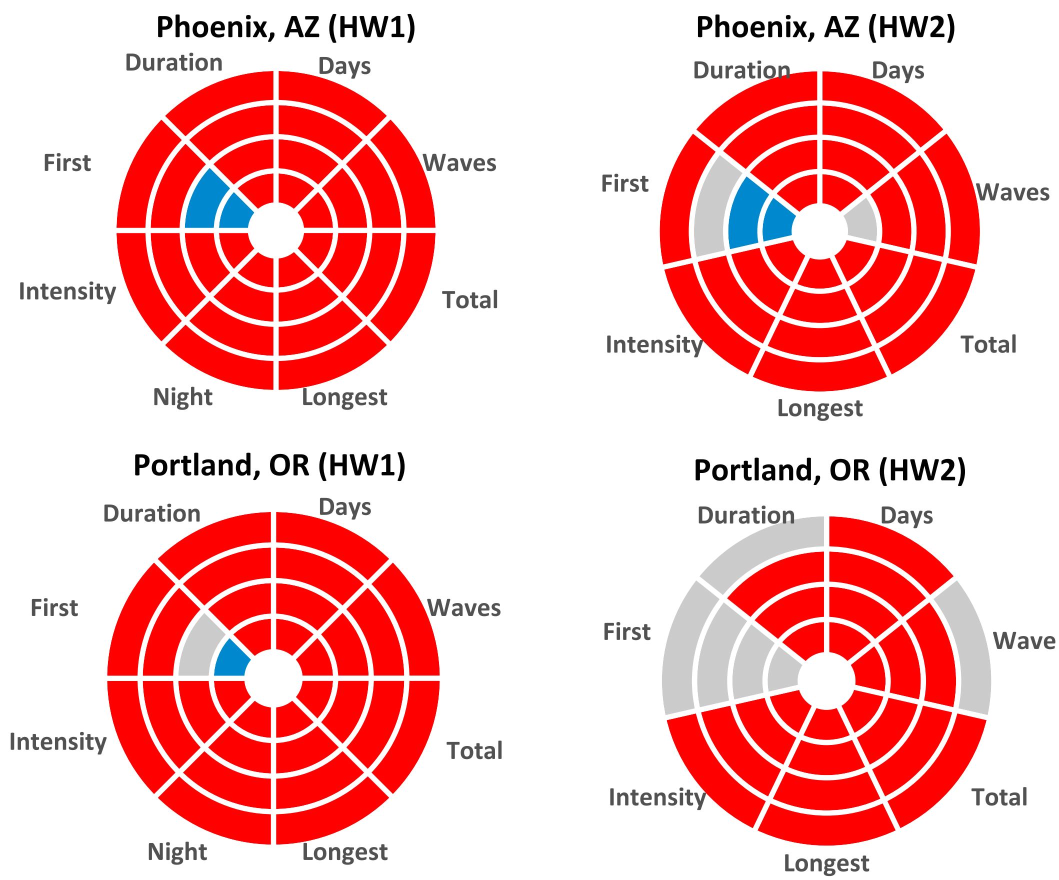

Figure 3. Mann-Kendall trend test results for eight HW1 heat wave properties and seven HW2 heat wave properties for Phoenix and Portland. Trends over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative).

frequency (Waves), total length of heat waves (*Total*), longest heat wave event (Longest), first heat wave event (First), and heat wave season duration (Duration) change from no trend (HW1) to positive trend (HW2) for extreme events. This difference highlights the importance of considering humidity in heat wave definitions for temperate and humid continental climates. It is notable that the extended heat wave season in Miami shows a large increase in mild to extreme heat waves (Figure 4).

The impact of humidity exacerbates heat waves in New York City and has no significant influence in the Mid-Atlantic coast (Baltimore). Figure 5 shows how quantification of heat wave events using apparent temperature (HW2) instead of ambient temperature (HW1) highlights differences in trend direction of event properties in New York City. In this regard, we found that heat wave frequency (Waves), total length of heat waves (*Total*), longest heat wave event (Longest), total heat wave intensity (Intensity), first heat wave event (First), and heat wave season duration (Duration) change from no trend to positive trend between HW1and HW2. This difference in definitions is especially important for understanding changes in heat wave frequency for these cities. In Baltimore the warm oceanic climate limits the difference in properties between HW1 and HW2 heat waves, which results in similar trend directions there. Indeed, we found no change in the heat wave frequency over the study period of 1950–2016 according to eight definitions of heat waves in Baltimore.

The remaining sites share a northern continental climate. Colorado Springs, Syracuse, Bismarck, and Des Moines have the most frequent increases in heat wave properties (Figures 6 and 7). The trend in number of hot days (*Days*) is positive for all sites, yet only Bismarck and Des Moines show an increase in heat wave frequency (Waves). Surprisingly, the only change in heat wave timing among these sites was later onset for severe heat waves (HW2C) in Colorado Springs. Generally, the total length of heat waves increased based on

10.1029/2018EF001085

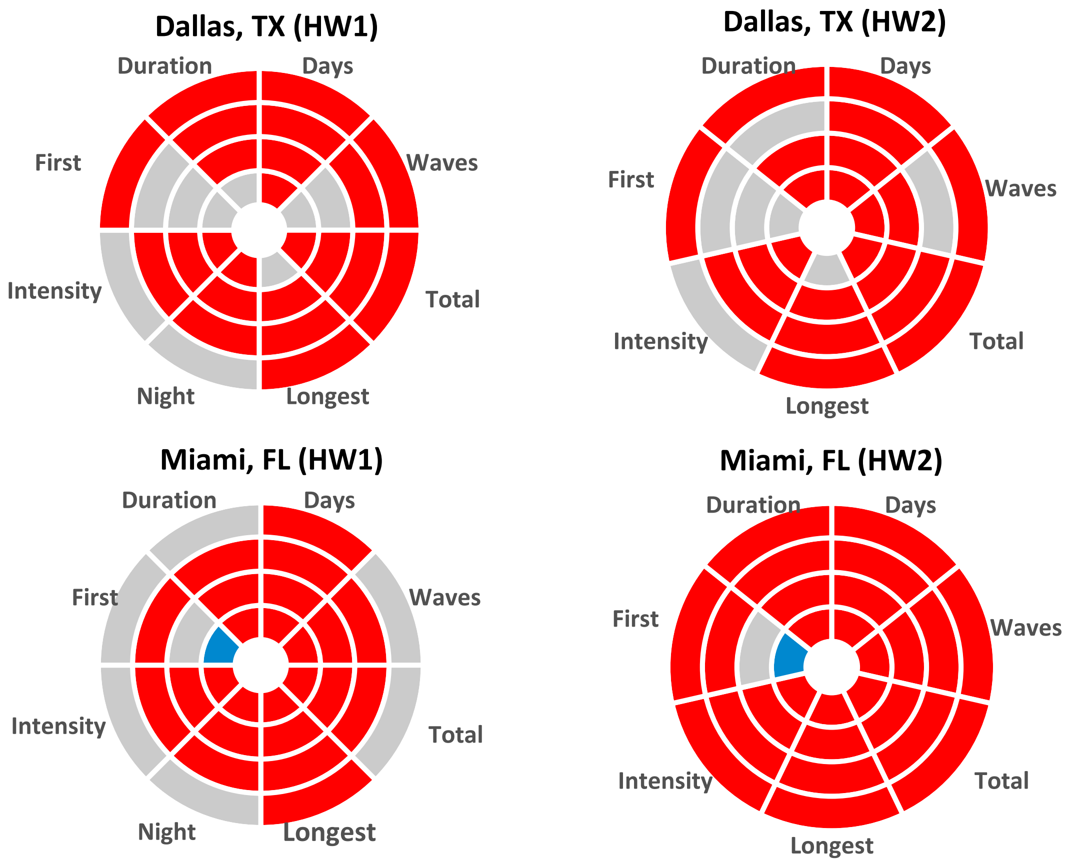

Figure 4. Mann-Kendall trend test results for eight HW1 heat wave properties and seven HW2 heat wave properties for Dallas and Miami. Trends over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative).

at least one definition for these cities. Accordingly, extended heat wave events during the same heat wave season (Duration) are detected for these sites. Nighttime heat wave intensity (Night) shows a positive trend across these sites, and total heat wave intensity (Intensity) has increasing trend in Colorado Springs and Syracuse. We found that humidity in Colorado Springs and Syracuse exacerbates heat wave occurrence and intensity more than in Bismarck and Des Moines. Finally, incorporating the impact of humidity in heat wave analysis results in the greatest increase in severe and extreme heat wave properties.

3.2. Decadal Analysis of Heat Wave Properties

Figures 8–11 show the average decadal values of four important heat wave properties in 10 communities for mild and severe strength of heat waves and based on both HW1 and HW2 definitions. These properties include first heat wave event (First), heat wave season duration (Duration), frequency of heat waves (Waves), and total heat wave intensity (Intensity) as $Intensity_{Day}$. This approach supports quantitative visualization of heat waves spatial differences and temporal changes across sites.

The first heat wave can be the most harmful heat wave event of the year without an appropriate heat mitigation plan. Thus, Figure 8 presents the decadal average values of first heat wave event for both mild and severe events as defined by HW1 and HW2 for the 10 cities from the 1950s to 2010s. This figure shows that mild and severe HW1 and HW2 heat waves advanced by 35, 29, 48, and 37 days, respectively, in Miami. Similarly, First has changed by 24, 17, 8, and 19 days for Phoenix. In Portland, where heat waves are moderated by the Pacific Ocean, we found that severe heat waves based on the HW2 definition have advanced by a month (August 11 to July 10) over the study period. Despite these shifts in heat waves onset, we found no trend in average decadal values of first heat wave event in Bismarck, Des Moines, and Syracuse (Figure 8).

10.1029/2018EF001085

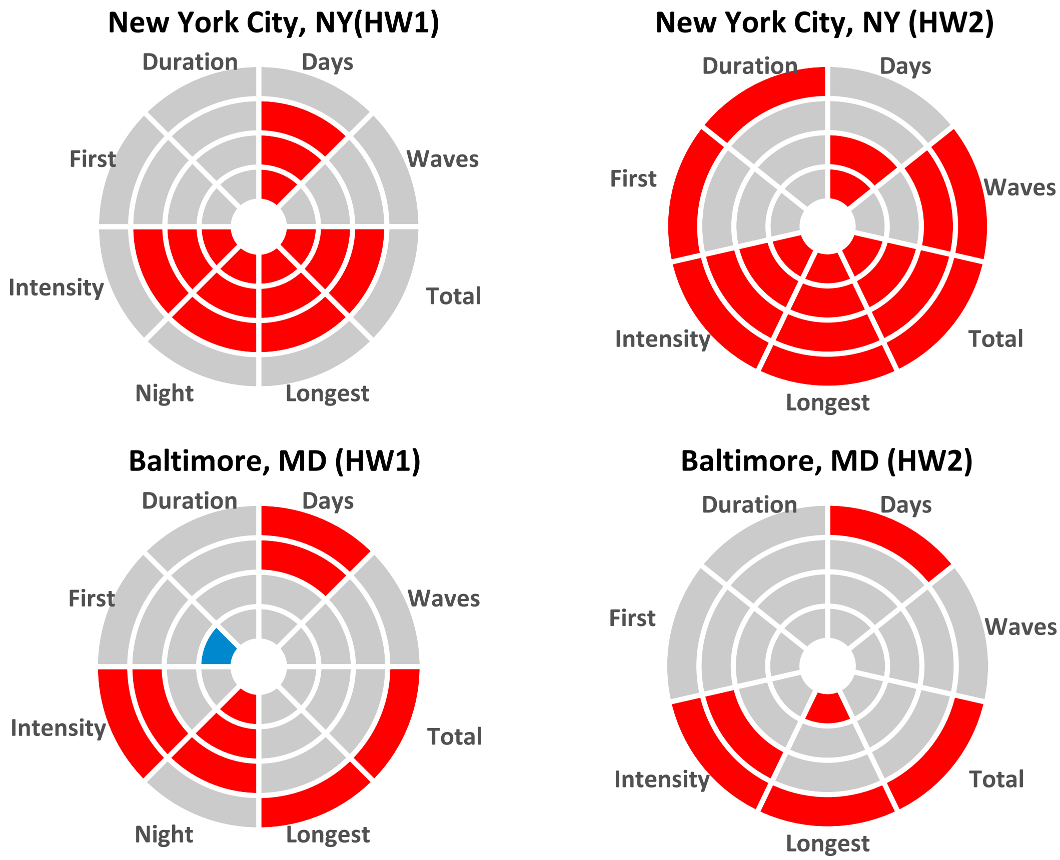

Figure 5. Mann-Kendall trend test results for eight HW1 heat wave properties and seven HW2 heat wave properties for New York City and Baltimore. Trends over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative).

Similar analysis of the decadal average change in Duration in Phoenix, Portland, Dallas, Miami, Bismarck, and Des Moines highlights many positive trends from the 1950s to 2010s. Importantly, Duration for HW1 in Miami has increased from 84 to 115 days for mild heat waves and from 3 to 53 days for severe heat waves. Similarly, Duration for HW2 has increased by 71 days for mild heat waves and 46 days for severe heat waves. In Phoenix, Duration for HW1 mild and severe heat waves has increased from 42 to 95 days and from 2 to 57 days, respectively, over the same period. The HW2 mild and severe Durations have increased from 53 and 14 to 79 and 49 days, respectively, during the same time (Figure 9). We found no significant decadal trend in heat wave season change for Baltimore, Bismarck, Colorado Springs, Des Moines, New York City, and Syracuse.

Within the heat wave season, the frequency and intensity of heat waves are two important components for adaption and mitigation planners. Figure 10 shows decadal average values for Waves based on HW1, HW2 (mild events), HW1, and HW2 (severe events) definitions. As shown in Figure 10, the greatest increase in Waves is for Miami, based on HW1 (mild). There, the frequency increased from 3.6 to 12.9 events per year. In addition, we found increases in Waves of 3.9, 6, and 2.5 events per year for Miami for HW1 (severe) and HW2 (mild and severe) definitions of heat wave.

As expected, following Miami, the greatest increase in Waves based on HW1A and HW1B definitions are found for Phoenix and Portland, equal to 5.6, 5.3, 3.8, and 3.5 more events per year over the study period. However, we found no significant trend for Waves in Baltimore, Colorado Springs, and Syracuse. Interestingly, in Syracuse, maximum Waves based on HW1A, HW1C, HW2A, and HW2C definitions are 10.7, 3.4, 6.1, and 2.3, respectively, and is found for the 2010s.

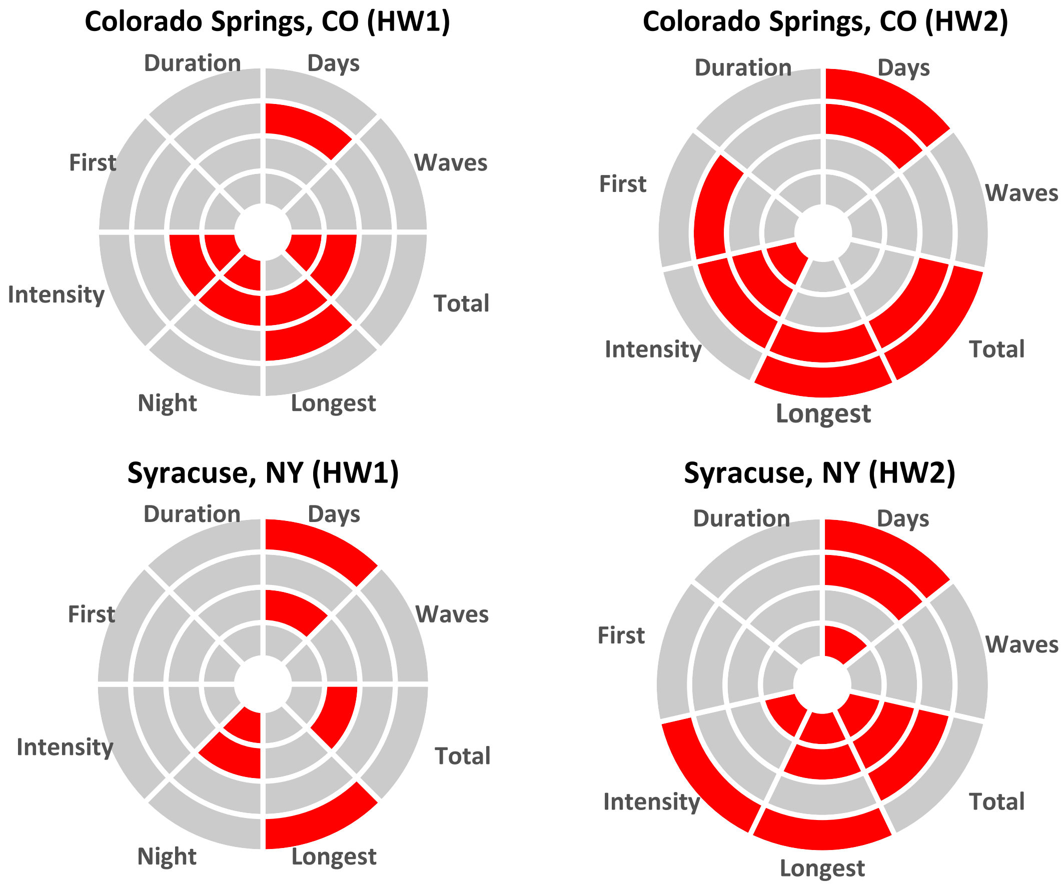

Figure 6. Mann-Kendall trend test results for eight HW1 heat wave properties and seven HW2 heat wave properties for Colorado Springs and Syracuse. Trends over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative).

Finally, we present Intensity, which many researchers identify as the main criteria for determining harmful impacts of a heat wave on human health (Xu et al., 2017). Analysis of the decadal average values for $\text{Intensity}_{\text{Day}}$ shows a positive trend for HW1A (mild heat wave) for Phoenix and Portland (Figure 11). Surprisingly, the least $\text{Intensity}_{\text{Day}}$ was for Miami. Conversely, Bismarck and Syracuse show the greatest $\text{Intensity}_{\text{Day}}$ during the 1950s to 2010s. During this time, these locations have experienced average temperatures of 8.2 and 6.5 °C above daily threshold(s) during heat wave events.

4. Discussion

Similar to many recent studies, we found that most harmful properties of heat waves show an increase over time across the United States (Altman et al., 2012; Habeeb et al., 2015; Keellings & Waylen, 2014; Mishra et al., 2015; Smith et al., 2013). However, the range of these trends depends on the heat wave definitions and selected properties. In addition, this study reinforces the importance of locality in the analysis of heat waves. In particular, we found that two cities in one state (Syracuse and New York City) have completely different heat wave trend profiles. Similar to recent studies, we found significant increasing trends ($p < 0.05$) in excessive heat event (EHE) days, frequency, intensity, and heat wave season duration for mild to extreme heat wave ranges in five locations including Dallas, Miami, New York City, Phoenix, and Portland (Kovats & Hajat, 2008; Sheridan et al., 2009). These properties are directly connected to human health and water and energy consumption (Brooke Anderson et al., 2013; Brooke Anderson & Bell, 2011).

We found that heat wave seasons started earlier for Baltimore, Miami, Phoenix, and Portland, based on at least one of the presented heat wave definitions. This is similar to findings of Habeeb et al. (2015) for

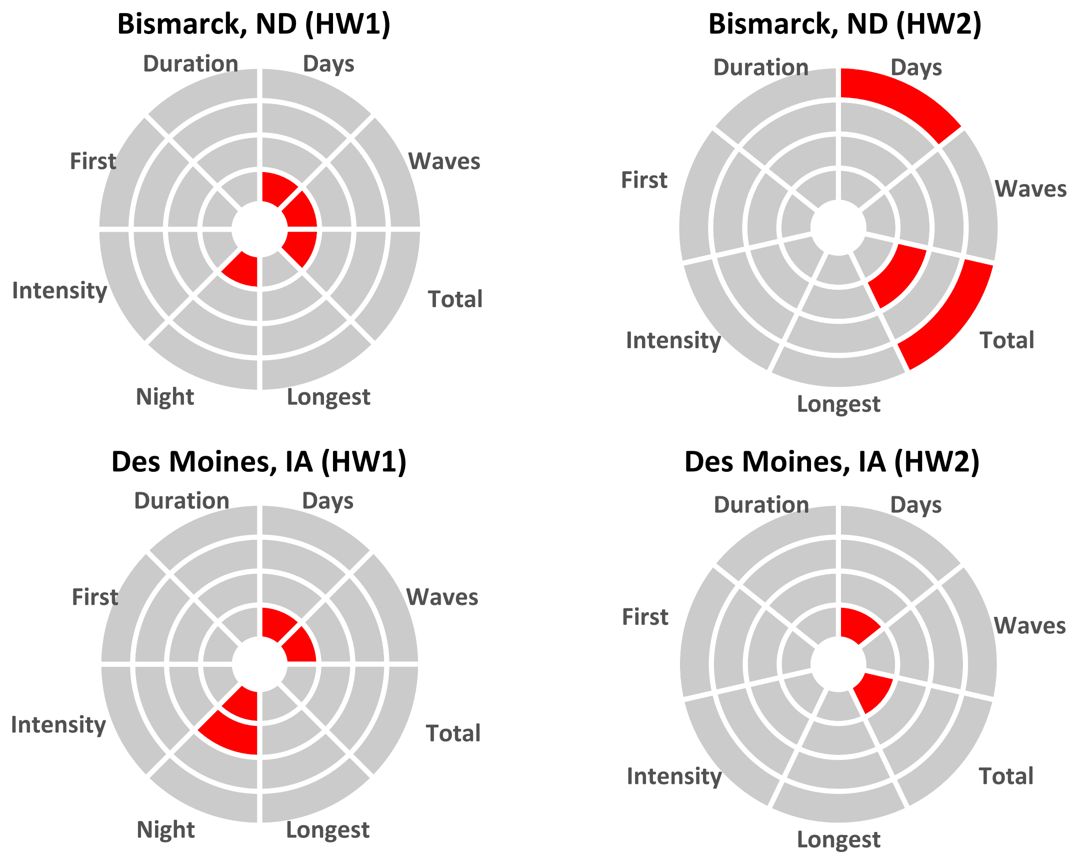

Figure 7. Mann-Kendall trend test results for eight HW1 heat wave properties and seven HW2 heat wave properties for Bismarck and Des Moines. Trends over the period of analysis (1950–2016) are indicated as red (positive), gray (no trend), and blue (negative).

Miami and Portland; however, the magnitude and direction of change were inconsistent among the eight heat wave definitions in this study. Hence, we emphasize the importance of understanding how various heat wave definitions can result in different calculated trajectories of change. As an alternative to single metric definitions, we found that simultaneous evaluation of heat wave properties provides the opportunity to understand the compound impact of these properties. For example, in Syracuse despite no change in heat wave frequency, nighttime heat wave intensity has increased, and extreme heat waves are longer than in the past. Differently, in Phoenix, mild heat waves happen earlier, and extreme events occur later than in the past.

An examination of possible causes of the observed heat wave spatial and temporal trends is not the focus of this study. A number of meteorological conditions can contribute to heat wave occurrence in the United States, including horizontal advection of hot air masses, large-scale sinking motion (subsidence) associated with pressure ridges in the middle and upper troposphere, and forced subsidence of air masses over mountain barriers. Atmospheric subsidence associated with pressure ridges causes clear skies and light winds that contribute to the intensity of heat waves (Meehl & Tebaldi, 2004). Local land surface conditions and remote teleconnections can affect the likelihood and intensity of heat waves. Recent studies provide evidence that land-ocean-atmosphere interactions during recent global warming and human activities are the drivers for recent decade heat wave formation and their spatial-temporal variations (Fall et al., 2010; Lyon & Barnston, 2017; Mechoso et al., 2014). Wu et al. (2012) found that heat waves during 1958–2010 in North America are connected with the sea surface temperature anomalies and the change of phase in ENSO. Lee et al. (2016) found that deficit in soil moisture is an important driver for increasing heat wave frequency during 1979–2010 in the South Central United States. Conversely, under nondeficit soil moisture conditions,

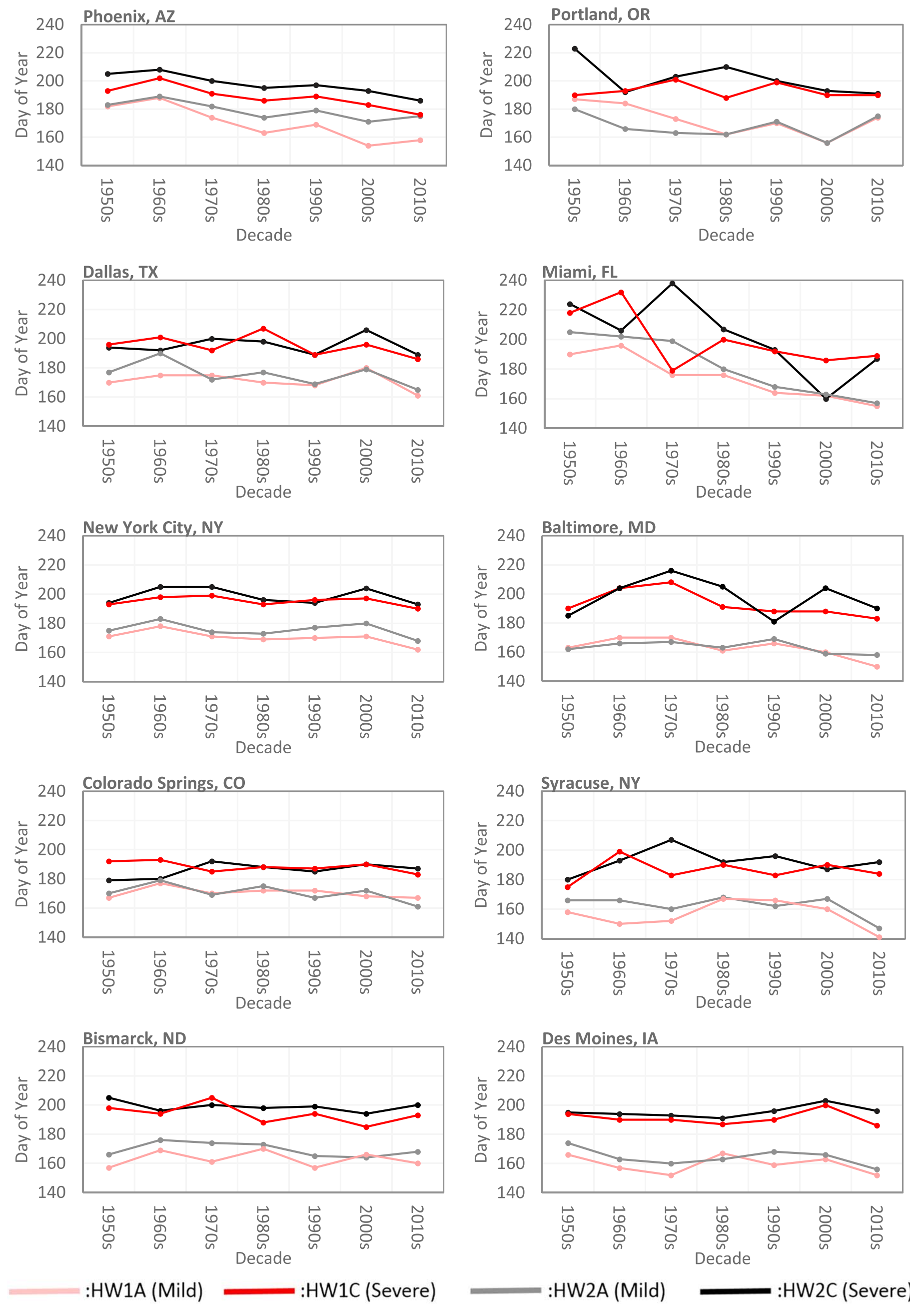

Figure 8. First heat wave event (*First*) based on HW1A, HW1C, HW2A, and HW2C.

local evaporation increased near-surface atmospheric water vapor content and resulted in extremely high apparent temperature during the 1995 heat wave in the northern Midwest (Kunkel et al., 1996). Atmospheric blocking is known as a driver for drought and heat waves in the United States with recent research showing its importance in the Southeastern United States, including Miami, FL (Dong et al., 2018). These complex atmospheric interactions act differently for the regional heat wave events, supporting the importance of local heat wave attribution studies.

Impact of urbanization on local climate in terms of temperature increase, particularly during nights and consequently increasing the intensity of heat waves, is well documented (Ghobadi et al., 2018; Li & Bou-Zeid, 2013; Oke, 1982). The populations of Phoenix and Dallas have increased from about 107,000 to 1,600,000 and 434,000 to 1,200,000, respectively, during 1950 to 2010 (“U.S. Census Bureau,” n.d.). We hypothesize

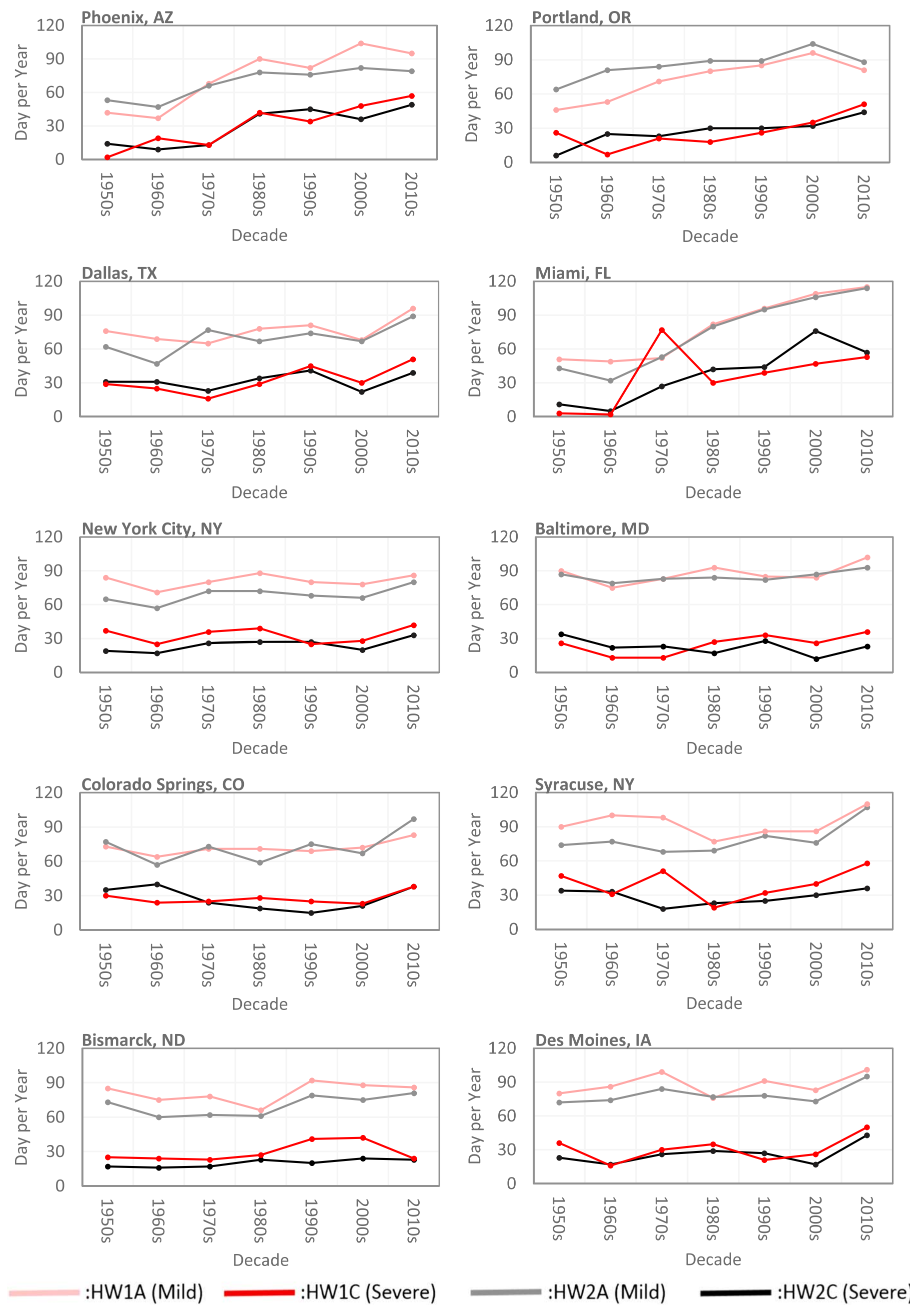

Figure 9. Heat wave season duration (*Duration*) based on HW1A, HW1C, HW2A, and HW2C.

that such tremendous population growth has created significant change in urban climate and causes or intensifies heat waves. Further investigation is required to distinguish the impact of different heat waves physical drivers in any location and for various events.

Despite the relatively small number of studies on the impact of various coupled components of heat waves on human health (Brooke Anderson & Bell, 2011; O'Neill et al., 2009), we found no other study that compared the compound impact of heat wave properties. For example, there is no comparison between health-related impacts of an earlier mild heat wave versus a later extreme heat wave. This challenge is essential, especially since the magnitude and direction of coupled heat wave components may change in opposite directions and confound analysis. Accordingly, it is important to investigate the expanding resilience plans in the urban areas that could alleviate the increasing harmful impacts of heat waves concurrently (O'Neill et al., 2009). Hence, similar to recent efforts, we resonate the importance of the study of "heat wave

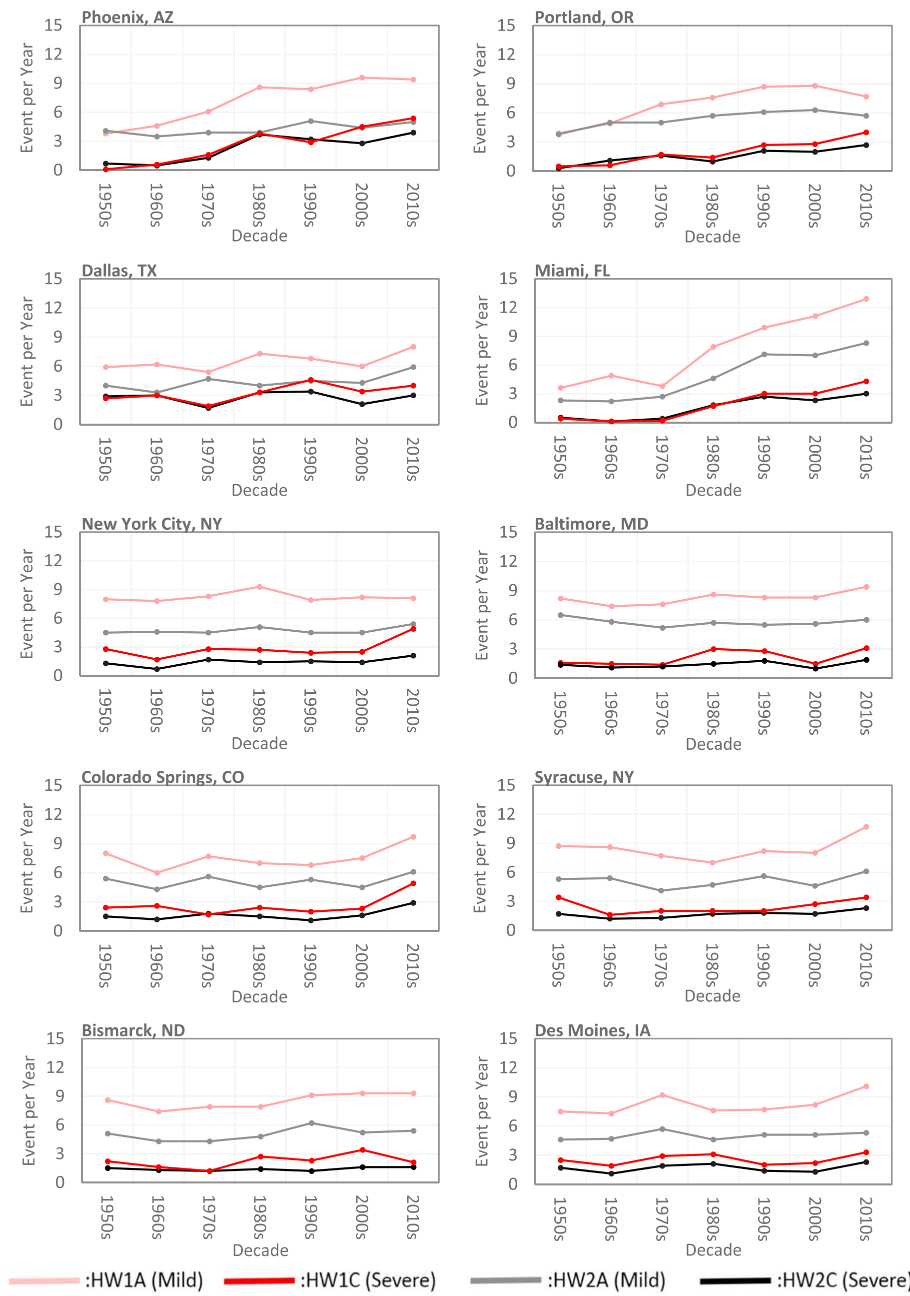

Figure 10. Frequency of heat waves (*Waves*) based on HW1A, HW1C, HW2A, and HW2C.

definition impact" on extreme events studies (Xu et al., 2016). This will become more significant in dealing with the public perception of heat waves and consequently will alter the resilience of a community to the future harmful heat waves (Chen et al., 2015; Kent et al., 2014; Mcphillips et al., 2018).

We support the utility of heat wave study over the CONUS as a national challenge rather than a local problem. The results of this study showed that there are many harmful components of heat waves that indicate increasing trends over the last seven decades across the United States. In this regard, cities in moist midlatitude climates with cold winters may lack appropriate acclimatization to heat waves which may increase the vulnerability of the local population (Rocklov et al., 2012). Similar studies in Scandinavia indicated the deadly impacts of heat waves, which led to calls for a heat wave Early Warning system (Åström et al., 2015; Rocklov et al., 2012).

10.1029/2018EF001085

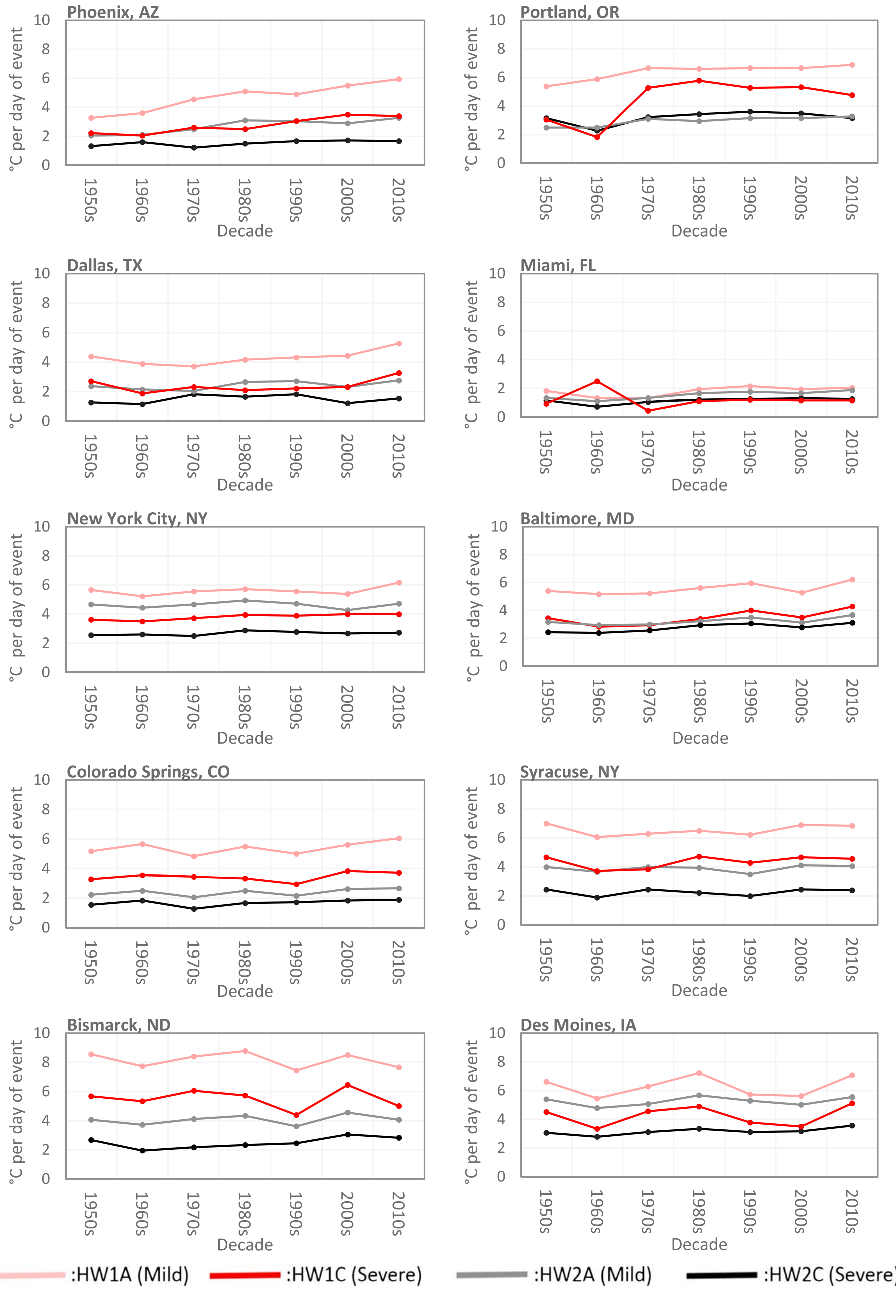

Figure 11. Intensity of heat waves ($Intensity_{Day}$) based on HW1A, HW1C, HW2A, and HW2C.

5. Conclusions and Recommendations

Heat waves are inevitable extreme climate events and appropriate planning in terms of adaption, and mitigation is required to minimize the risks. In this regard, it is essential to understand interactions among harmful components of heat waves. In this study, we explored long-term trends (1950–2016) of heat wave using eight definitions for 10 U.S. cities with different climate and geographic settings. In addition, we highlighted the significant role of definitions and metrics on heat wave studies to show the temporal and spatial extension of heat waves. We expect that use of this method elsewhere will generate unique heat wave profiles for each location. This highlights the importance of focusing on local extreme climate events rather than regional conclusions. In addition, we think that the suggested method in this study helps communities to understand various aspects of heat waves by comparing different locations and heat wave strengths side by side. Similar to other studies, we believe that global warming and increasing urbanization will result in more harmful heat waves across the United States (Habeeb et al., 2015; Li & Bou-Zeid, 2014; Zhao et al., 2017). Particularly, we think that further urbanization will increase some heat wave components more than others, such as nighttime heat wave intensity from urban heat island effect. Accordingly, we suggest further investigation on the future changes of heat wave components in a local scale.

Regardless, few cities in the United States have a heat wave emergency response plan (Bernard & McGeehin, 2004). Those cities usually suffer from on time actions (Bernard & McGeehin, 2004). In this regard, Smoyer (1998) indicated that despite the increasing number of air-conditioned homes and public awareness, some locations still remain at risk to heat waves. Whereas centralized cooling centers (i.e., libraries, federal buildings) are one potentially acceptable adaption strategy, poor access for seniors during heat waves can limit the efficacy of this solution (Naughton et al., 2002). To compound this problem, the over 65 population in the United States has increased from 9.8% to 13.1% from 1970 to 2010, and this senior population is expected to be more than 89 million (20%) of the population by 2050 (Jacobsen et al., 2011). Accordingly, specific focus on this vulnerable group of people in urban areas is imperative. Hence, it is suggested that risk management strategy planners in the urban areas for heat waves should consider the local heat wave characteristics, available resource, and residents' demographic, before planning for future adaption and mitigation strategies (Bernard & McGeehin, 2004; Habeeb et al., 2015; Kleerekoper et al., 2012).

Acknowledgments
Supporting data including annual heat wave components in each city based on both HW1 and HW2 definitions and a summary table of different heat wave definitions can be found with the online version of this article. R codes developed for heat wave components analysis are available in an online and open access data repository (Shafiei Shiva, 2018a, 2018b). The authors would like to thank two anonymous reviewers and the Editor Dr. Michael Ellis, for their comprehensive review, constructive comments, and suggestions that improved the clarity of the paper. Financial support for this work was provided via the Urban Resilience to Extremes Sustainability Research Network under National Science Foundation grant AGS-1444755.

References

AghaKouchak, A., Cheng, L., Mazdiyasni, O., & Farahmand, A. (2014). Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters*, *41*, 8847–8852. https://doi.org/10.1002/2014GL062308

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., et al. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research*, *111*, D05109. https://doi.org/10.1029/2005JD006290

Altman, P., Lashof, D., Knowlton, K., Chen, E., Johnson, L., & Kalkstein, L. (2012). *Killer summer heat: Projected death toll from rising temperatures in America due to climate change*. New York, NY, USA: Natural Resources Defense Council. https://doi.org/IB12-05C

Åström, C., Ebi, K. L., Langner, J., & Forsberg, B. (2015). Developing a heatwave early warning system for sweden: Evaluating sensitivity of different epidemiological modeling approaches to forecast temperatures. *International Journal of Environmental Research and Public Health*, *12*(1), 254–267. https://doi.org/10.3390/ijerph120100254

Bernard, S. M., & McGeehin, M. A. (2004). Municipal heat wave response plans. *American Journal of Public Health*, *94*(9), 1520–1522. https://doi.org/10.2105/AJPH.94.9.1520

Brooke Anderson, G., & Bell, M. L. (2011). Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. *Environmental Health Perspectives*, *119*(2), 210–218. https://doi.org/10.1289/ehp.1002313

Brooke Anderson, G., Bell, M. L., & Peng, R. D. (2013). Methods to calculate the heat index as an exposure metric in environmental health research. *Environmental Health Perspectives*, *121*(10), 1111–1119. https://doi.org/10.1289/ehp.1206273

Camalier, L., Cox, W., & Dolwick, P. (2007). The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. *Atmospheric Environment*, *41*(33), 7127–7137. https://doi.org/10.1016/j.atmosenv.2007.04.061

Chen, K., Bi, J., Chen, J., Chen, X., Huang, L., & Zhou, L. (2015). Influence of heat wave definitions to the added effect of heat waves on daily mortality in Nanjing, China. *Science of the Total Environment*, *506–507*, 18–25. https://doi.org/10.1016/j.scitotenv.2014.10.092

Clark, M. P., Wilby, R. L., Gutmann, E. D., Vano, J. A., Gangopadhyay, S., Wood, A. W., et al. (2016). Characterizing uncertainty of the hydrologic impacts of climate change. *Current Climate Change Reports*, *2*(2), 55–64. https://doi.org/10.1007/s40641-016-0034-x

Davis, R. E., Knappenberger, P. C., Michaels, P. J., & Novicoff, W. M. (2003). Changing heat-related mortality in the United States. *Environmental Health Perspectives*, *111*(14), 1712–1718. https://doi.org/10.1289/ehp.6336

Della-Marta, P. M., Haylock, M. R., Luterbacher, J., & Wanner, H. (2007). Doubled length of western European summer heat waves since 1880. *Journal of Geophysical Research*, *112*, D15103. https://doi.org/10.1029/2007JD008510

Diffenbaugh, N. S., & Ashfaq, M. (2010). Intensification of hot extremes in the United States. *Geophysical Research Letters*, *37*, L15701. https://doi.org/10.1029/2010GL043888

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., et al. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, *118*, 2098–2118. https://doi.org/10.1002/jgrd.50150

Dong, L., Mitra, C., Greer, S., & Burt, E. (2018). The dynamical linkage of atmospheric blocking to drought, heatwave and Urban Heat Island in Southeastern US: A multi-scale case study. *Atmosphere*, *9*(1), 33. https://doi.org/10.3390/atmos9010033

Duffy, P. B., & Tebaldi, C. (2012). Increasing prevalence of extreme summer temperatures in the U.S. *Climatic Change*, *111*(2), 487–495. https://doi.org/10.1007/s10584-012-0396-6

Ellis, F. P., & Nelson, F. (1978). Mortality in the elderly in a heat wave in New York City, August 1975. *Environmental Research*, *15*(3), 504–512. https://doi.org/10.1016/0013-9351(78)90129-9

Environmental Protection Agency (2016). Climate change indicators in the United States: High and low temperatures. Retrieved from https://www.epa.gov/sites/production/files/2016-08/documents/print_high-low-temps-2016.pdf

Fall, S., Niyogi, D., Gluhovsky, A., Pielke, R. A., Kalnay, E., & Rochon, G. (2010). Impacts of land use land cover on temperature trends over the continental United States: Assessment using the North American Regional Reanalysis. *International Journal of Climatology*, *30*(13), 1980–1993. https://doi.org/10.1002/joc.1996

Frich, P., Alexander, L. V., Della-Marta, P. M., Gleason, B., Haylock, M., Klein Tank, A. M. G., & Peterson, T. (2002). Observed coherent changes in climatic extremes during the second half of the twentieth century. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, *19*, 193–212. https://doi.org/10.3354/cr019193

Furrer, E. M., Katz, R. W., Walter, M. D., & Furrer, R. (2010). Statistical modeling of hot spells and heat waves. *Climate Research*, *43*(3), 191–205. https://doi.org/10.3354/cr00924

Gasparrini, A., & Armstrong, B. (2011). The impact of heat waves on mortality. *Epidemiology*, *22*(1), 68–73. https://doi.org/10.1097/EDE.0b013e3181fdcd99

Ghobadi, A., Khosravi, M., & Tavousi, T. (2018). Surveying of heat waves impact on the Urban Heat Islands: Case study, the Karaj City in Iran. *Urban Climate*, *24*, 600–615. https://doi.org/10.1016/j.uclim.2017.12.004

Habeeb, D., Vargo, J., & Stone, B. (2015). Rising heat wave trends in large US cities. *Natural Hazards*, *76*(3), 1651–1665. https://doi.org/10.1007/s11069-014-1563-z

Hansen, C., McDonald, S., Nabors, A., & Shafiei Shiva, J. (2017). Using the National Water Model Forecasts to Plan for and Manage Ecological Flow and Low-Flow during Drought. In J. M. Johnson et al. (Eds.), *National Water Centers Innovators Program Summer Institute Report 2017* (pp. 66–74). https://doi.org/10.4211/technical.20171009

Harlan, S. L., Brazel, A. J., Prashad, L., Stefanov, W. L., & Larsen, L. (2006). Neighborhood microclimates and vulnerability to heat stress. *Social Science and Medicine*, *63*(11), 2847–2863. https://doi.org/10.1016/j.socscimed.2006.07.030

Hawkins, E., & Sutton, R. (2011). The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, *37*(1), 407–418. https://doi.org/10.1007/s00382-010-0810-6

Intergovernmental Panel on Climate Change (2014). In T. F. Stocker, D. Qin, G. Plattner, M. Tigno, S. K. Allen, J. Boschung, et al. (Eds.), *Climate change 2014 synthesis report summary for policymakers*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/CBO9781107415324

Jacobsen, L. A., Kent, M., Lee, M., & Mather, M. (2011). America's aging population. In *Population bulletin* (Vol. 66, pp. 1–16). Washington, DC: Population Reference Bureau.

Kalkstein, L. S., Greene, S., Mills, D. M., & Samenow, J. (2011). An evaluation of the progress in reducing heat-related human mortality in major U.S. cities. *Natural Hazards*, *56*(1), 113–129. https://doi.org/10.1007/s11069-010-9552-3

Karl, T. R., Melillo, J. M., & Peterson, T. C. (Eds.). (2009). *Global climate change impacts in the United States*. New York, USA: Cambridge University Press.

Karl, T. R., & Trenberth, K. E. (2003). Modern global climate change. *Science*, *302*, 1719–1724.

Keellings, D., & Waylen, P. (2014). Increased risk of heat waves in Florida: Characterizing changes in bivariate heat wave risk using extreme value analysis. *Applied Geography*, *46*, 90–97. https://doi.org/10.1016/j.apgeog.2013.11.008

Kendall, M. G. (1948). *Rank correlation methods*. Oxford, England: Griffin.

Kent, S. T., McClure, L. A., Zaitchik, B. F., Smith, T. T., & Gohlke, J. M. (2014). Heat waves and health outcomes in Alabama (USA): The importance of heat wave definition. *Environmental Health Perspectives*, *122*(2), 151–158. https://doi.org/10.1289/ehp.1307262

Kharin, V. V., Zwiers, F. W., Zhang, X., & Wehner, M. (2013). Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climatic Change*, *119*(2), 345–357. https://doi.org/10.1007/s10584-013-0705-8

Kleerekoper, L., Van Esch, M., & Salcedo, T. B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*, *64*, 30–38. https://doi.org/10.1016/j.resconrec.2011.06.004

Kovats, R. S., & Hajat, S. (2008). Heat stress and public health: A critical review. *Annual Review of Public Health*, *29*, 41–55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843

Kuchcik, M. (2006). Defining heat waves—Different approaches. *Geographica Polonica*, *79*(2), 48–64.

Kuglitsch, F. G., Toreti, A., Xoplaki, E., Della-Marta, P. M., Zerefos, C. S., Trke, M., & Luterbacher, J. (2010). Heat wave changes in the eastern mediterranean since 1960. *Geophysical Research Letters*, *37*, L04802. https://doi.org/10.1029/2009GL041841

Kunkel, K. E., Changnon, S. A., Reinke, B. C., & Arritt, R. W. (1996). The July 1995 heat wave in the midwest: A climatic perspective and critical weather factors. *Bulletin of the American Meteorological Society*. https://doi.org/10.1175/1520-0477(1996)077<1507:TJHWIT>2.0.CO;2

Kunkel, K. E., Stevens, L. E., Stevens, S. E., Sun, L., Janssen, E., Wuebbles, D., et al. (2013). Regional climate trends and scenarios for the U. S. national climate assessment. Part 1. Climate of the northeast U.S.

Laaidi, K., Zeghnoun, A., Dousset, B., Bretin, P., Vandentorren, S., Giraudet, E., & Beaudeau, P. (2011). The impact of heat islands on mortality in Paris during the August 2003 heat wave. *Environmental Health Perspectives*, *120*(2), 254–259. https://doi.org/10.1289/ehp.1103532

Lee, E., Bieda, R., Shanmugasundaram, J., & Richter, H. (2016). Land surface and atmospheric conditions associated with heat waves over the Chickasaw Nation in the South Central United States. *Journal of Geophysical Research: Atmospheres*, *121*, 6285–6298. https://doi.org/:10.1002/2015JD024659

Li, D., & Bou-Zeid, E. (2013). Synergistic interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts. *Journal of Applied Meteorology and Climatology*, *52*(9), 2051–2064. https://doi.org/10.1175/JAMC-D-13-02.1

Li, D., & Bou-Zeid, E. (2014). Quality and sensitivity of high-resolution numerical simulation of urban heat islands. *Environmental Research Letters*, *9*, 055002. https://doi.org/10.1088/1748-9326/9/5/055002

Lyon, B., & Barnston, A. G. (2017). Diverse characteristics of U.S. summer heat waves. *Journal of Climate*, *30*(19), 7827–7845. https://doi.org/10.1175/JCLI-D-17-0098.1

Ma, W., Zeng, W., Zhou, M., Wang, L., Rutherford, S., Lin, H., et al. (2015). The short-term effect of heat waves on mortality and its modifiers in China: An analysis from 66 communities. *Environment International*, *75*, 103–109. https://doi.org/10.1016/j.envint.2014.11.004

Mann, H. B. (1945). Nonparametric Tests Against Trend. *Econometrica*, *13*(3), 245. https://doi.org/10.2307/1907187

Matthews, H. D., & Zickfeld, K. (2012). Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, *2*(5), 338–341. https://doi.org/10.1038/nclimate1424

Mcphillips, L. E., Chang, H., Chester, M. V., Depietri, Y., Friedman, E., Grimm, N. B., et al. (2018). Defining extreme events: A cross-disciplinary review. *Earth's Future*, *6*, 441–455. https://doi.org/10.1002/2017EF000686

Mechoso, C. R., Wood, R., Weller, R., Bretherton, C. S., Clarke, A. D., Coe, H., et al. (2014). Ocean-cloud-atmosphere-land interactions in the Southeastern Pacific. *Bulletin of the American Meteorological Society*, *95*(3), 357–375. https://doi.org/10.1175/BAMS-D-11-00246.1

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, *305*(5686), 994–997. https://doi.org/10.1126/science.1098704

Melillo, J. M., Terese, R., & Yohe, G. W. (2014). Climate change impacts in the United States: The third national climate assessment. U.S. global change research program. https://doi.org/10.7930/j0z31WJ2

Metzger, K. B., Ito, K., & Matte, T. D. (2010). Summer heat and mortality in New York City: How hot is too hot? *Environmental Health Perspectives*, *118*(1), 80–86. https://doi.org/10.1289/ehp.0900906

Mishra, V., Ganguly, A. R., Nijssen, B., & Lettenmaier, D. P. (2015). Changes in observed climate extremes in global urban areas. *Environmental Research Letters*, *10*(2), 024005. https://doi.org/10.1088/1748-9326/10/2/024005

Morabito, M., Crisci, A., Messeri, A., Messeri, G., Betti, G., Orlandini, S., et al. (2017). Increasing heatwave hazards in the southeastern European Union capitals. *Atmosphere*, *8*(12). https://doi.org/10.3390/atmos8070115

Morri, C., Bianchi, C. N., Di Camillo, C. G., Ducarme, F., Allison, W. R., & Bavestrello, G. (2017). Global climate change and regional biotic responses: Two hydrozoan tales. *Marine Biology Research*, *13*(5), 573–586. https://doi.org/10.1080/17451000.2017.1283419

Naughton, M. P., Henderson, A., Mirabelli, M. C., Kaiser, R., Wilhelm, J. L., Kieszak, S. M., et al. (2002). Heat-related mortality during a 1999 heat wave in Chicago. *American Journal of Preventive Medicine*, *22*(4), 221–227. https://doi.org/10.1016/S0749-3797(02)00421-X

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*(455), 1–24. https://doi.org/10.1002/qj.49710845502

O'Neill, M. S., Carter, R., Kish, J. K., Gronlund, C. J., White-Newsome, J. L., Manarolla, X., et al. (2009). Preventing heat-related morbidity and mortality: New approaches in a changing climate. *Maturitas*, *64*(2), 98–103. https://doi.org/10.1016/j.maturitas.2009.08.005

Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. *Journal of Climate*, *26*(13), 4500–4517. https://doi.org/10.1175/JCLI-D-12-00383.1

Peterson, T. C., Heim, R. R., Hirsch, R., Kaiser, D. P., Brooks, H., Diffenbaugh, N. S., et al. (2013). Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. *Bulletin of the American Meteorological Society*, *94*(6), 821–834. https://doi.org/10.1175/BAMS-D-12-00066.1

Photiadou, C., Jones, M. R., Keellings, D., & Dewes, C. F. (2014). Modeling European hot spells using extreme value analysis. *Climate Research*, *58*(3), 193–207. https://doi.org/10.3354/cr01191

Ramamurthy, P., & Bou-Zeid, E. (2014). Contribution of impervious surfaces to urban evaporation. *Water Resources Research*, *50*, 2889–2902. https://doi.org/10.1002/2013WR013909

Ramamurthy, P., Li, D., & Bou-Zeid, E. (2015). High-resolution simulation of heatwave events in New York City. *Theoretical and Applied Climatology*, 1–14. https://doi.org/10.1007/s00704-015-1703-8

Robinson, P. J. (2001). On the definition of a heat wave. *Journal of Applied Meteorology*, *40*(4), 762–775. https://doi.org/10.1175/1520-0450(2001)

Rocklov, J., Barnett, A. G., & Woodward, A. (2012). On the estimation of heat-intensity and heat-duration effects in time series models of temperature-related mortality in Stockholm, Sweden. *Environmental Health*, *11*(1), 1–12. https://doi.org/10.1186/1476-069X-11-23

Rosenzweig, C., & Solecki, W. (2014). Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change*, *28*, 395–408. https://doi.org/10.1016/j.gloenvcha.2014.05.003

Russo, S., Sillmann, J., & Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, *10*(12), 124003. https://doi.org/10.1088/1748-9326/10/12/124003

Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, *106*(37), 15,594–15,598. https://doi.org/10.1073/pnas.0906865106

Schnell, J. L., & Prather, M. J. (2017). Co-occurrence of extremes in surface ozone, particulate matter, and temperature over eastern North America. *Proceedings of the National Academy of Sciences*, *114*(11), 2854–2859. https://doi.org/10.1073/pnas.1614453114

Shafiei Shiva, J. (2018a). R Code for calculating heatwave properties using ambient temperature (v1.0). https://doi.org/10.5281/ZENODO.1314762

Shafiei Shiva, J. (2018b). R Code for calculating heatwave properties using apparent temperature (v1.0). https://doi.org/10.5281/ZENODO.1317555

Sheridan, S. C., Kalkstein, A. J., & Kalkstein, L. S. (2009). Trends in heat-related mortality in the United States, 1975–2004. *Natural Hazards*, *50*(1), 145–160. https://doi.org/10.1007/s11069-008-9327-2

Smith, T. T., Zaitchik, B. F., & Gohlke, J. M. (2013). Heat waves in the United States: Definitions, patterns and trends. *Climatic Change*, *118*(3–4), 811–825. https://doi.org/10.1007/s10584-012-0659-2

Smoyer, K. E. (1998). A comparative analysis of heat waves and associated mortality in St. Louis, Missouri—1980 and 1995. *International Journal of Biometeorology*, *42*(1), 44–50. https://doi.org/10.1007/s004840050082

Smoyer-Tomic, K. E., Kuhn, R., & Hudson, A. (2003). Heat wave hazards: An overview of heat wave impacts in Canada. *Natural Hazards*, *28*(2001), 465–486. https://doi.org/10.1023/A:1022946528157

Steadman, R. G. (1979). The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *Journal of Applied Meteorology*. https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: Are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives*, *118*(10), 1425–1428. https://doi.org/10.1289/ehp.0901879

Stone, B. Jr., & Rodgers, M. O. (2001). Urban form and thermal efficiency: How the design of cities influences the Urban Heat Island effect. *Journal of the American Planning Association*, *67*(2), 186–198. https://doi.org/10.1080/01944360108976228

Sun, W., Hess, P., & Liu, C. (2017). The impact of meteorological persistence on the distribution and extremes of ozone. *Geophysical Research Letters*, *44*, 1545–1553. https://doi.org/10.1002/2016GL071731

Thacker, M. T. F., Lee, R., Sabogal, R. I., & Henderson, A. (2008). Overview of deaths associated with natural events, United States, 1979–2004. *Disasters*, 303–316. https://doi.org/10.1111/j.1467-7717.2008.01041.x

Toomey, M., Roberts, D. A., Still, C., Goulden, M. L., & McFadden, J. P. (2011). Remotely sensed heat anomalies linked with Amazonian forest biomass declines. *Geophysical Research Letters*, *38*, L19704. https://doi.org/10.1029/2011GL049041

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., et al. (2007). Observations: Surface and atmospheric climate change. In S. Solomon et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change* (pp. 286–295). Cambridge, United Kingdom and New York, NY: Cambridge University Press.

United Nations (2015). Sendai framework for disaster risk reduction 2015–2030. United Nations office for disaster risk reduction (UNISDR).

U.S. Census Bureau. (n.d.). Retrieved February 1, 2019, from https://www.census.gov/prod/www/decennial.html

10.1029/2018EF001085

van der Velde, M., Tubiello, F. N., Vrieling, A., & Bouraoui, F. (2012). Impacts of extreme weather on wheat and maize in France: Evaluating regional crop simulations against observed data. *Climatic Change*, *113*(3–4), 751–765. https://doi.org/10.1007/s10584-011-0368-2
Vogel, R. M., Bell, C. J., & Fennessey, N. M. (1997). Climate,streamflow and water supply in the northeastern United States. *Journal of Hydrology*, *198*, 42–68.
World Health Organization (2009). *Improving public health responses to extreme weather/heat-waves: EuroHEAT*. In B. Menne & F. Matthies (Eds.). Copenhagen, Denmark: WHO Regional Office for Europe. Retrieved from http://www.euro.who.int/__data/assets/pdf_file/0010/95914/E92474.pdf
World Meteorological Organization (2015). *Heatwaves and health: Guidance on warning-system development*. In G. R. McGregor, P. Bessemoulin, K. Ebi, & B. Menne (Eds.). Geneva, Switzerland. Retrieved from http://www.who.int/globalchange/publications/WMO_WHO_Heat_Health_Guidance_2015.pdf
Wu, Z., Lin, H., Li, J., Jiang, Z., & Ma, T. (2012). Heat wave frequency variability over North America: Two distinct leading modes. *Journal of Geophysical Research*, *117*, D02102. https://doi.org/10.1029/2011JD016908
Xu, Z., Crooks, J. L., Black, D., Hu, W., & Tong, S. (2017). Heatwave and infants' hospital admissions under different heatwave definitions. *Environmental Pollution*, *229*, 525–530. https://doi.org/10.1016/j.envpol.2017.06.030
Xu, Z., FitzGerald, G., Guo, Y., Jalaludin, B., & Tong, S. (2016). Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environment International*, *89–90*, 193–203. https://doi.org/10.1016/j.envint.2016.02.007
Zhang, H., Wang, Y., Park, T. W., & Deng, Y. (2017). Quantifying the relationship between extreme air pollution events and extreme weather events. *Atmospheric Research*, *188*, 64–79. https://doi.org/10.1016/j.atmosres.2016.11.010
Zhang, J., Gao, Y., Luo, K., Leung, L. R., Zhang, Y., Wang, K., & Fan, J. (2018). Impacts of compound extreme weather events on ozone in the present and future. *Atmospheric Chemistry and Physics*, 1–17. https://doi.org/10.5194/acp-18-9861-2018
Zhao, L., Oppenheimer, M., Zhu, Q., Baldwin, J. W., Ebi, K. L., Bou-Zeid, E., et al. (2017). Interactions between urban heat islands and heat waves. *Environmental Research Letters*, *13*(3). https://doi.org/10.1088/1748-9326/aa9f73

References From the Supporting Information

Batté, L., Ardilouze, C., & Déqué, M. (2018). Forecasting West African heat waves at subseasonal and seasonal time scales. *Monthly Weather Review*, *146*(3), 889–907. https://doi.org/10.1175/MWR-D-17-0211.1
Ceccherini, G., Russo, S., Ameztoy, I., Francesco Marchese, A., & Carmona-Moreno, C. (2017). Heat waves in Africa 1981–2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, *17*(1), 115–125. https://doi.org/10.5194/nhess-17-115-2017
Ceccherini, G., Russo, S., Ameztoy, I., Patricia Romero, C., & Carmona-Moreno, C. (2016). Magnitude and frequency of heat and cold waves in recent decades: The case of South America. *Natural Hazards and Earth System Sciences*, *16*(3), 821–831. https://doi.org/10.5194/nhess-16-821-2016
Huynen, M. M. T. E., Martens, P., Schram, D., Weijenberg, M. P., & Kunst, A. E. (2001). The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environmental Health Perspectives*, *109*(5), 463–470. https://doi.org/10.1289/ehp.01109463
Indian National Disaster Management Authority. (2016). Guidelines for preparation of action plan—Prevention and management of heat-wave. Retrieved from http://ndma.gov.in/images/guidelines/guidelines-heat-wave.pdf
Lauwaet, D., De Ridder, K., Saeed, S., Brisson, E., Chatterjee, F., van Lipzig, N. P. M., et al. (2016). Assessing the current and future urban heat island of Brussels. *Urban Climate*, *15*, 1–15. https://doi.org/10.1016/j.uclim.2015.11.008
Nasim, W., Amin, A., Fahad, S., Awais, M., Khan, N., Mubeen, M., et al. (2018). Future risk assessment by estimating historical heat wave trends with projected heat accumulation using SimCLIM climate model in Pakistan. *Atmospheric Research*, *205*, 118–133. https://doi.org/10.1016/j.atmosres.2018.01.009
Nitschke, M., & Tucker, G. (2009). The unfolding story of heat waves in metropolitan Adelaide. Adelaide, Australia. Retrieved from https://www.sahealth.sa.gov.au
Polioptro, F., Peláez, M. A., & Bandala, E. R. (2016). Maximum temperatures and heat waves in Mexicali, Mexico: Trends and threshold analysis. *Air, Soil and Water Research*, *9*, 21–28. https://doi.org/10.4137/ASWR.S32778
Roshan, G. R., Ghanghermeh, A. A., & Kong, Q. (2018). Spatial and temporal analysis of outdoor human thermal comfort during heat and cold waves in Iran. *Weather and Climate Extremes*, *19*, 20–28. https://doi.org/10.1016/j.wace.2018.01.005
Tan, J., Zheng, Y., Tang, X., Guo, C., Li, L., Song, G., et al. (2010). The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology*, *54*(1), 75–84. https://doi.org/10.1007/s00484-009-0256-x