

Delineating and characterizing changes in heat wave events across the United States climate regions

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Abstract

Exposure to extreme heat, or heat waves, represents a public health threat as well as an environmental health threat. With projections for further increases in temperature in some regions, resulting from global environmental change, it is important to understand the spatiotemporal impacts of heat waves in order to minimize risk. To understand heat wave impacts one cannot look solely at the spatial and temporal temperature regimes but must also consider key heat wave characteristics: duration, size, magnitude, frequency, and region of impact. To understand the consequences of heat wave events it is critical to analyze such extreme events based on the cumulative impacts of these characteristics. This study, which is conducted across the whole of the continental United States, looks to map, and analyze such cumulative impacts of heatwave characteristics. Heat waves were spatially defined for the period of May-September of each year. Using persistence analyses and the development of a new index (Combined Heat wave Characteristics Index; CHCI) we can define regions of consistent heat wave exposure and impact. Results show that there are large differences across the United States in terms of heat wave exposure and impacting heat wave characteristics. Across much of the analysis a clear east versus west difference in patterns is seen. Overall, such work shows how and where differing, but covarying heat wave characteristics impact the United States. Information from this work can be combined with demographic and health metrics to better pinpoint susceptibility to heat waves – and therefore inform better management decisions.

1.0 Introduction

A single extreme event (e.g. flood, drought, heat wave, etc.) can, without a doubt, have a large impact on the socioeconomic condition as well as environmental and human health (Kravchenko et al. 2013; Keellings & Waylen 2014; Chen & Li 2017). However, when an area is repeatedly impacted by extreme events, especially ones as impactful as heat waves, there are long-term socioenvironmental impacts to consider. The frequency, intensity, and duration of heat wave events have increased over time as seen in regions such as Europe, China, Australia, and the United States (US) (IPCC 2012; Seneviratne et al. 2014; Keellings & Moradkhani 2020). Additionally, these events are projected to increase as climate change progresses leading to more frequent, more intense, and longer-lasting events in the future (Meehl & Tebaldi 2004; IPCC 2014). Recent work suggests that around half of the world's population will be annually exposed to deadly heat waves by 2100 and that even in the US there will likely be a four-to-six-fold increase in exposure to heat waves by 2070 (Jones et al. 2015; Mora et al. 2017). Despite the severity of these projections, heat waves are not universally defined thus hindering inter-regional transferability of knowledge about these events.

Heat waves are typically defined as a sequence of days with temperature exceeding a high threshold of daily maximum or mean temperatures. The heat wave threshold is often between the 90th and 99th percentiles of the local temperature distribution and it may or may not include some measure of humidity. Numerous heat wave metrics have been developed (Meehl & Tebaldi 2004; Hajat et al. 2006; Tan et al. 2007; Anderson & Bell 2009; Peng et al. 2011; Keellings & Waylen 2014; Photiadou et al. 2014; Russo et

al. 2014) yet there is still much debate as how best to define heat waves, and no definition or metric has been widely accepted (Perkins-Kirkpatrick et al. 2016). In practice, the US National Weather Service (NWS) issues excessive heat watches and warnings based on elevated heat index (combination of temperature and relative humidity) temperatures. However, the NWS-defined heat index temperature threshold for excessive heat varies across forecast offices and is based on a collaboration between local NWS offices and local partners. Unlike other extremes, such as hurricanes and tornadoes, heat waves have no universally accepted definition, and this complicates comparisons between heat wave events and the analysis of their impacts. This lack of an accepted definition of heat waves highlights the need for exploration of how best to conceptualize these events and how to develop a more unified definition. There is substantial knowledge on physical drivers of heat waves, but there is need for further quantification of the relationships between drivers and heat wave characteristics across larger regions and more events (Perkins 2015).

Extensive research has been conducted to understand, characterize, and predict heat waves (Baldwin et al. 2019). Recent research has found that heat waves in North America are increasing in number and spatial extent at the continental scale, but they are becoming smaller and more fragmented at the local level (Keellings et al. 2018). Adverse impacts of these events have been reported, including declines in agricultural yields (Mishra & Cherkauer 2010; Wreford & Neil Adger 2010), elevated human mortality (Guo et al. 2015; World Meteorological Organization & World Health Organization 2015; Merte 2017; Singh et al. 2021), failure of critical infrastructure (Clark et al. 2019), and increased energy demands (Miller et al. 2008; Zhao et al. 2018). The level of vulnerability of a system to the effects of heat waves varies by location, dictated by the system's physical, social, and demographic characteristics. For example, urban residents are more vulnerable to the impacts of heat waves due to the compounding effect of urban heat island effect (Habeeb et al. 2015; Zhao et al. 2018), and even in these areas, vulnerability is highest in inner-cities compared to peripheral locations (Fenner et al. 2019). Yet, lacking in current literature is an understanding of the spatial dynamics and what drives aspects like areal extent and intensity of heat waves as changes in these spatial characteristics could have serious implications for socio-ecological impacts (Hattis et al. 2012; Kloog et al. 2015; Lee et al. 2016; Keellings & Moradkhani 2020). In addition, only a few heat wave characteristics have been studied (especially frequency, magnitude, and/or intensity), leaving out other important characteristics that potentially drive observed heat wave patterns. The current study presents a novel approach for characterizing spatial dynamics in heat waves across the contiguous US by assessing spatiotemporal patterns in most persistent and longest/shortest-duration heat wave events.

In this study we present a methodology for identifying regions impacted by heat waves based on quartile thresholds. We use GIS and overlay analysis to identify regions where temperatures are persistently extreme, and compute, at multiple scales (monthly, seasonal, decadal) various characteristics associated with the heat wave regions. This study looks to highlight a new approach to studying heat wave impacts that is both multivariate in nature and spatially explicit. Two metrics are developed in such a nature: persistence and the Combined Heat wave Characteristics Index (CHCI). Analysis in this study was

performed per climate region in the contiguous US and a comparative analysis was performed to reveal patterns and any significant differences in the occurrence of heat waves in the regions.

2.0 Materials And Methods

2.1 Data

The Parameter elevation Regression on Independent Slopes Model (PRISM) daily temperature are utilized to identify heat waves. These data are a combination of meteorological station observations with a digital elevation model that yields a gridded surface for the continental US with a spatial resolution of 4 km from 1981 through 2018 (Daly et al. 2008; Thornton et al. 2014). PRISM has gone through quality control, been validated against heat wave metrics from four reanalysis products, and is widely used in climatological studies (Schoof et al. 2017).

This study was conducted across the continental US, though analysis was subdivided by the NOAA climate regions (Karl & Koss 1984) (Figure 1). There are nine climate regions in total: Northwest, Southwest, West, West North Central, South, East North Central, Central, Northeast, and Southeast. While the analysis was done at the regional level, the comparison and statistical analysis highlights patterns across the continental US. NOAA climate regions were selected as the unit of analysis given that climate patterns extend beyond state borders.

Heat waves are delineated using the methodology outlined by Keellings and Moradkhani (Keellings & Moradkhani 2020). A threshold equal to the 95th percentile of local (grid cell) daily maximum temperature for each summer month (May through September) is used to define heat waves. Heat wave events must also last for at least three consecutive days and events are considered temporally independent if separated by four or more days of below threshold temperatures. A hierarchical clustering algorithm works in combination with indicator semivariograms to identify clusters of heat and delineates heat wave events by Euclidean distance between clusters. A bounding polygon is then drawn around all heat clusters belonging to a single heat wave and the polygon is tracked spatially at the daily time-step. As the heat wave is tracked from genesis to lysis, metrics are calculated daily to determine the heat wave area, magnitude, duration, and fragmentation of heat within the bounding heat wave polygon.

2.2 Methods

This section describes methods used in this study. These include systematic data thresholding, polygon flattening, and variable compositing applied to various heat wave characteristics.

2.2.1 Computing heat wave persistence

A Geographic Information System (GIS) model was developed to compute heat wave persistence. This model, developed in ArcPy and implemented in ArcGIS Pro, was generally used to flatten, and count the number of overlapping heat wave polygons at a location. The initial heat wave polygons can be thought

of as a set of rings A, B and C with overlaps (Figure 2). This tool will flatten the rings and produce polygons with no overlap. The output includes more features than the input and each feature has a count equivalent to the number of polygon overlaps. The counts represent heat wave persistence. The methodology for computing heat wave persistence is as follows: initially, the model creates an empty point feature class. It then creates a feature class containing polygons generated from areas enclosed by input heat wave polygons, while using the empty point feature class to label the polygons. The output polygons are then converted to points. Finally, attributes from the point feature class are spatially joined with the polygons. At this step, only important heat wave characteristics (see Table 1) are recalculated and retained in the output feature class.

2.2.2 Identifying regions of most and least extreme heat waves

This analysis was initially conducted per climate region. To identify areas with most (least) extreme heat waves, we selected areas in the upper (lower) quartile based on the heat wave duration variable. This data reduction step allowed us to compare between most (TOP25) and least (BOTTOM25) extreme heat wave events within each climate region. Next, we computed heat wave persistence using the model described in Figure 2. A second round of thresholding was performed by identifying regions in the upper quartile based on heat wave persistence. The outputs were then merged to generate regions across the US on which the next part of the study focused. This was done on both TOP25 and BOTTOM25 polygons. Descriptive statistics were computed to characterize average temperatures, area, duration, fragmentation, persistence, magnitude, and number of patches for the identified heat wave regions.

2.2.3 Combined heat wave characteristics

Since multiple heat wave variables were assessed in this study, it was necessary to generate composites, with the aim of identifying patterns in the ways these variables covaried across the climate regions. To achieve this, heat wave fragmentation, mean magnitude, number of patches and mean area were each standardized and then combined by multiplication to compute a Combined Heat wave Characteristics Index (CHCI). See **Equation 1** below.

$$CHCI = Mean Area * Mean Mag * Mean NP * Mean Frag \quad (1)$$

where *CHCI* is the combined heatwave characteristics index, *Mean Mag* is the mean magnitude, *Mean NP* is the mean number of patches and *Mean Frag* is the mean fragmentation score.

The outputs here would therefore represent the spatiotemporal variability of heat waves driven by these four variables at locations with longest (or shortest) and most persistent heat wave events. Another composite was generated to indicate categorized values for each of the four variables at a location using **Equation 2** below. To do this, we first reclassified the standardized variables into three classes defined below.

1. Low – values from 0 to the lower quartile

2. Mid – values from the lower to the upper quartiles

3. High – values from the upper quartile to 1

$$Comp = (Mean Area * 1000) + (Mean Mag * 100) + (Mean Frag * 10) + (Mean NP * 1) \quad (2)$$

where *Comp* is the component of CHCI, *Mean Mag* is the mean magnitude, *Mean NP* is the mean number of patches and *Mean Frag* is the mean fragmentation score. All four heat wave variables in this equation were reclassified into the three classes above.

The results from this computation were maps indicating the categorized components of heat wave events at each location. For instance, a pixel with a *Comp* value of 3213 indicates that the heat wave at the pixel had high mean area, mid mean magnitude, low mean fragmentation, and high mean number of patches. This composite would therefore help in explaining the observed patterns in the CHCI.

To ensure a detailed characterization of heatwave events in the US, we performed these analyses over several temporal scales including the entire 38 years (1981-2018), by decade (1981-1990, 1991-2000, 2001-2010 and 2011-2018), and by month (May, June, July, August, and September). This would provide better insights into how most (and least) extreme heatwave events have changed over time in the US. The flowchart below (Figure 3) shows the main steps and analyses performed.

3.0 Results

This study delineates (using GIS overlay, thresholding, and data compositing methodologies) and characterizes long-term seasonal, decadal, and monthly heatwave patterns in US climate regions.

3.1 Heat wave extent per climate region

This study found that generally, longer heat wave events (TOP25) covered vastly more of the climate regions compared to shortest events (BOTTOM25). TOP25 heat wave regions constituted as much as 57% of the land area in Northwest, 51% of the Southwest and 47% of the area in Eastern North Central (refer to Figure 4). Top three climate regions by area include the Southwest (>557,000 km²), South (>524,000 km²) and Northwest (>368,000 km²). Proportions of area with BOTTOM25 events, on the other hand, ranged from 11% in Central US to 41% in the Southwest. Based on land area, Southwest, South, and Western North Central regions were top ranked for BOTTOM25 events, with shortest-duration heat waves extending over >452,000 km², 262,000 km², and >229,000 km², respectively. Regions affected by BOTTOM25 and TOP25 events were similar (in size and location) for Western North Central (19% vs 22%), Western (32% vs 39%), and the Southwest (41% vs 51%).

Different patterns were observed in heat waves over the decade scale (Figure 5). In the 1980s, TOP25 events were commonest in the Northeast (>73% of land area), Northwest (>64% of area) and Central US (>53%). In the 1990s, the Northwest topped with over 70% of its area experiencing TOP25 events,

followed by the Southwest (>65%) and the Northeast (>55%). Different patterns were observed in 2000s, in which the West region was ranked second (having TOP25 events in over 70% of land area) after the Northwest (>72%). The Southeast was ranked third in this decade with over 67% of its land area experiencing these extreme heat events. Northwest, West, and Northeast regions had the highest proportions of area under TOP25 heat waves (approx. 67%, 62% and 59%, respectively). Proportions of area under BOTTOM25 events were always lower than those for TOP25 events, except for West North Central (in 1980s), Southwest (1980s), Central (in 1990s), East North Central (in 1990s and 2010s), and South (in 2000s). Proportions of land under heat waves generally increased from a decade to the next in Northwest and Southeast, except for the 2000s to 2010s. Consistent expansion of area under heat waves was observed in the West North Central region.

The study found that, for some climate regions, heat waves extended over more land in the months when extremely high temperatures were expected to subside (Figures 6A and B). For instance, highest proportions of area under TOP25 heat waves were observed in the month of May for the Southwest, Southeast, Northeast, and South (84%, 78%, 71% and 60%, respectively, see Figure 6A). Similar patterns were observed in Northwest and Central regions for the month of September (Figures 6A and B). Here, heat waves were respectively identified in approx. 96% and 81% of the land area (Figure 6A). This indicates that the severe heat wave period is expanding for these climate regions. Proportions of land under TOP25 heat waves generally exceeded proportions of land under BOTTOM25 events, except for Northwest in May (0% vs 22%) and West North Central in August (16% vs 17%).

3.2 Long-term heatwave characteristics

Heat wave characteristics generally showed similar patterns among shortest- and longest-duration events. While area of heat waves was significantly higher for the TOP25 group compared to BOTTOM25 (US averages of 606,000 vs 481,000 km², respectively), there were similar spatial patterns in distribution (Figure 7A). In both groups, heat wave events were highly extensive in the South and Southwest regions. Events in these regions respectively had average areas of 887,000 km² and 758,000 km² (TOP25) and 597,000 km² and 667,000 km² (BOTTOM25).

The least expansive heat wave events of all were found in Northeast in both TOP25 and BOTTOM25 groups (average area of 312,000 km² and 254,000 km², respectively) and East North Central (265,000 km²) in the BOTTOM25 group. Average temperatures ranged between 28 and 38 °C for shortest-duration events (US average of 32.7 °C) and 30 to 38 °C for longest-duration events (US average of 34.6 °C). BOTTOM25 events in the Northwest, and Northeast regions experienced comparatively lower temperatures (Figure 7B). Temperatures averaged 28.4 and 30.1 °C in these regions, respectively.

West region events in both groups were found to have the highest mean magnitude (Figure 7F) – averaging 1.83 for BOTTOM25 events and 1.94 for TOP25 events. TOP25 events in this region were also the most persistent of all (Figure 7E). Heat wave persistence averaged 2,000 for this region compared to a

US average of 475. Least persistent heat wave events were found mainly in the East North Central, Central, and Northeast regions (mean persistence <183). Further, heat wave events experienced in the eastern half of the US were more cohesive than the western ones as shown by the fragmentation statistic (Figure 7D). Events in the East North Central were most cohesive of all with an average fragmentation statistic of 0.69 and 0.76 for shortest-duration and longest-duration events, respectively. The Southwest had the most fragmented events, with the fragmentation statistic for shortest-duration and longest-duration events averaging 0.18 and 0.2, respectively. The study also found that shortest-duration events were generally less patchy (ranging from 2,200 to 12,000 patches) compared to longest-duration events which ranged from 4,200 to over 19,700 patches (Figure 7G). Longest-duration events in the South, East North Central, and Central had the greatest number of patches (>15,000). TOP25 events exhibited significantly different durations compared to BOTTOM25 events. The former events lasted longer (14-99 days) than the latter (2.8-9.6 days) on average (Figure 7C). However, this results from the initial use of this variable in defining BOTTOM25 and TOP25 heat wave events. Clear inter-region differences were observable in this variable especially in the TOP25 events. The West and South events lasted the longest (more than 98 and 71 days, respectively).

3.3 Decadal heat wave characteristics

Spatial patterns observed in the decadal distribution of heat wave characteristics were similar to those found in 1981-2018. For example, heat wave events in both groups were most cohesive in East North Central and generally most fragmented in Southwest (compare Figures 8 and 7D). However, the study found that the higher-than-average fragmentation statistic in East North Central was influenced greatly by events in 1980s and 2000s (average fragmentation statistic was 0.77 and 0.73 respectively). Further, highest magnitude (for both groups) and most persistent events (for the longest-duration group) were consistently observed in the West region. In this region, mean magnitude was >1.79 overall while mean persistence ranged 399-620 (for longest-duration events). However, by splitting the data into individual decades, the study found that while shortest-duration events occurred in each decade for all climate regions, longest-duration events were absent in East North Central (in the 1990s and 2010s) and Central region (in the 1990s). Furthermore, number of individual patches in TOP25 heat waves varied significantly – highest in the South in 1990s and 2010s and only average in 1980s and 2000s. The high number of patches in East North Central in the 1981-2018 period are attributed to the highly patchy events in 1980s.

In addition, the study quantified changes in average heatwave characteristics per climate region. Results indicate that generally, average heat wave characteristics varied more for the longest-duration events compared to shortest-duration events. Among the characteristics, number of patches and heat wave persistence showed greater variability across the decades (Figure 9). Highest increases in average heat wave persistence occurred in TOP25 events in West North Central (+377% in 1990s-2000s), Southwest (+306% in 1990s-2000s), Southeast (+279% in 1980s-1990s), and South (+251% in 1980s-1990s and +125% in 2000s-2010s). Greatest changes in number of patches were found in West North Central

(+318% in 1990s-2000s), and South (+128% and +176% in 1980s-1990s and 2000s-2010s, respectively). Other TOP25 heat wave characteristics that saw major increases include mean area (+75% in South in 2000s-2010s, +71% in West North Central in 1990s-2000s); average fragmentation (increase of 67% in West North Central in 1990s-2000s); and mean magnitude (58% increase in South in 2000s-2010s). Greatest changes in BOTTOM25 events were found in number of patches in the Southwest, West (respective increases of 96% and 70% in 1990s-2000s), and Central (+72% in 2000s-2010s) regions. Average temperatures showed the least variability across decades for both event groups. Rates of change for most of the variables in the South were lower for 1990s-2000s compared to the other two periods. Contrasting patterns were seen for most heat wave characteristics in West North Central, as well as some elsewhere (e.g., number of patches and persistence in the Northwest, Southwest, and West). These patterns are more detectable in TOP25 events.

3.4 Monthly heat wave characteristics

The temporal results all fall in line with seasonal temperature patterns common in the summer months. Across this period heatwave persistence, for both the top and bottom 25% events, shows a distinct pattern that varies both temporally and spatially (Figure 10). Highest persistence is seen in events in July and August (for the TOP25 group) and in May and September (for the BOTTOM25 group). For the top 25%, in May, the average persistence across the US was 20. However, the South and Southeast regions were above this average with 41 and 25, respectively. In June the average US-wide persistence for the top 25% was 71, 255% higher than May. This average was greatly influenced by persistence in events occurring in West, Southwest, and South which respectively had persistence values of 333 (+1981% from May), 78 (+457% from May), and 71 (+73% from May). In July the West persistence values further increased by 77% compared to June. Overall, in July the US-wide persistence averaged 168 but the West, Southwest and parts of the Northwest were above this average. August had a shockingly similar spatial pattern to the July persistence with a US wide average of 170. Lastly, in September the persistence dropped to 58 across the US. All regions exhibited a sharp decline in the persistence values at this time. Overall, in September the US pattern of persistence was homogenous, except for events in the West (average persistence of 339).

A higher persistence of heatwave events was seen in the beginning of the season for the bottom 25% events but a switch was observed as summer progressed, and the persistence numbers were higher for the top 25%. In May the average persistence value for the bottom 25% was 144, almost six times greater than during top 25%. Average persistence in June reached 107 for the US which was 49% higher than the top 25%. These values continued dropping to 87 in July. However, in August the average persistence switched to 94, and continued to increase to 128 in September. For the bottom 25%, there was a distinct difference in the persistence between the eastern and western portions of the country. In May, the western regions (West, Southwest, and Northwest) had the highest persistence across the whole country. In June, this pattern was observed in the same western regions and West North Central in addition. It was also

observed that bottom 25% events were generally homogenous across the summer months compared to top 25% (which had many extremely persistent events especially in West).

Across the summer months differing numbers of heat wave patches were exhibited across the climate regions (Figure 11). Within the top 25% group the maximum number of patches, generally, was seen in May (US mean of 16,100), June (US mean of 14,100), and September (US mean of 15,000), a result in contrast to the persistence results which exhibited higher values during the months of July and August. Further, for the top 25%, the South region consistently had the highest number of patches compared to all other regions (ranging 12,500-29,600). The West coast regions, Northwest and West, had some of the lowest number of patches, for the top 25%, across May, July, and August when compared with the other regions. In May, for instance, number of patches for heat wave events in the West averaged 5,042 compared to the US average of 16,058. The number of patches for the lower 25% heat waves was significantly lower than the top 25% (e.g., US average of 5,249 and 14,084 patches for bottom 25% and top 25% events, respectively, over the month of June). Additionally, there is not a large difference in number of patches across the summer months for shortest-duration events. Highest numbers were observed in the West North Central region (average range of 5,664-13,075 across the summer months) compared to the rest of study area.

Other major changes include significant increases in mean magnitude (+72%), fragmentation (+57%), and mean area (+47%), in the West North Central during the August-September period. Mean magnitude also increased consistently in the South region from a -26% change in June-July to a +84% in August-September. Events in East North Central also experienced a similar change in mean magnitude with a 30% decrease in June-July and a 51% increase in July-August.

3.5 Combined heat wave characteristics

The CHCI values ranged from 0 to about 0.145 (Figure 12A). The top 25% version of the CHCI exhibited the highest values overall. For this group, CHCI values ranged from 0 to 0.145 and averaged 0.031 across the US. The highest CHCI averages occurred in the East North Central (0.086), South (0.085), and Central (0.063) regions. Ironically, while the three regions with higher CHCI values are adjacent to one another, the variables driving the index pattern differ (Figure 12B). Within the South region the CHCI components were either 3223 or 3233. These index values show that heat waves in this region were of mid (average) magnitude and higher-than-average area and number of patches. What differs across the South region is the fragmentation of the heatwaves. Regions in yellow (Figure 12B) had heatwaves that were significantly more cohesive (higher fragmentation statistic). Within the Central region, all the CHCI component values were the same (2233). This value indicates an average area and magnitude but a significantly above average fragmentation pattern (more cohesive events) and number of patches. Lastly, within the East North Central, the CHCI component values included 1233 and 1333. This indicates that heat wave events around the Great Lakes and into Wisconsin and parts of Minnesota were highly cohesive, had more than average number of patches and lower than average area, while their magnitude

varied from average in some locations to greater than average in others. Across the entirety of the region most of the heat waves had a larger than average fragmentation pattern and number of patches.

In terms of the bottom 25% CHCI, a completely different pattern and distribution of CHCI is exhibited (Figure 12A). Overall, CHCI values ranged from 0 to 0.097 across all the US with an average of 0.0124. Regions exhibiting the highest CHCI values include West North Central and South. Within the West North Central, the CHCI values range from 0.005 to 0.097, with the higher values occurring across Montana and Wyoming. Within the South region the values ranged from 0.009 to 0.059 with component scores including 3133, 3233, 2233, and 2133. Such CHCI component values highlight that the fragmentation and number of heat wave patches were significantly high across those areas with significant CHCI. What varies, in terms of heat wave characteristics, across the region is the mean area and magnitude of the heat wave.

4.0 Discussion And Conclusions

4.1 Spatial patterns of heat waves across US climate regions

This study comprehensively characterized spatial patterns in longest/shortest-duration and highly persistent heat waves in US climate regions. Varying spatial patterns were observed per heat wave characteristic and climate region and this variability influences the level of heat wave impacts on socio-ecological systems. For instance, both longest and shortest-duration events in the West region had the highest magnitude. Highest persistence was observed in longest-duration events in West, while longest-duration events in the South and Southwest were the most expansive. Events with the highest number of patches were found in the South, East North Central and Central regions, mostly in the longest-duration group. Highly cohesive events were observed in the East North Central region. In addition, significant variability was found in these events over decades and summer months, indicating the dynamic nature of heat waves. Prior studies have found that generally, heat waves in the US are intensifying in duration, intensity, and frequency (Habeeb et al. 2015; Schoof et al. 2017). Due to the enhanced soil moisture-temperature coupling, warming temperatures have been found to amplify the intensity of heat waves in dry areas of southern and southwestern US but not in energy-limited regions of northern and northeastern US (Cheng et al. 2019). Such conclusions underscore the importance of characterizing spatial dynamics in heat waves per climate region and calls for region-specific measures to deal with the impacts of heat waves.

4.2 Novelty and meaning of persistence

At its simplest, the persistence metric highlights how many times a heat wave, over time, has consistently impacted the same area. With our differentiation of top and bottom 25%, based on duration of events, we can further identify whether a region has been consistently impacted by long- or short-duration events.

Persistence analysis was developed to follow trends in environmental health and/or productivity using the Normalized Difference Vegetation Index (NDVI) (Tsai et al. 2014; Waylen et al. 2014; Bunting et al. 2018). Within the original context of persistence, one can see the landscape impacts over time, even being able to pinpoint the time in which landscape change occurred and its duration. However, the NDVI version of persistence does not give context as to the drivers of change, such as climate extremes. With our application of persistence, we look to further define the spatial dimensions of heat waves as it can impact socioenvironmental health. This metric maps regions consistently impacted by heat waves of intensities which, when overlaid with information on human demographics, health, and environmental health can be used to pinpoint not only triggers and timeframe of change but also rates of and susceptibility to change. For instance, the highly persistent 2013-2015 North Pacific marine heat wave (Lorenzo & Mantua 2016) has been linked to significant alterations in the biological composition and structure of the ocean and coastal ecosystems (Cavole et al. 2016). Changes in heat wave persistence may be more relevant to society than changes caused by mean temperature changes alone (Lorenz et al. 2010).

4.3 Novelty and meaning of CHCI index

It is widely recognized that heat waves will intensify as the climate changes. Hence, effective tools are necessary for quantifying and assessing heat wave incidences for better planning and management (Das et al. 2020). Indices have commonly been used as they reveal how multiple variables interact, aggregate, and affect a given location (Defne et al. 2020). In heat vulnerability studies, several indices have been proposed including heat wave duration index, HWDI (Frich et al. 2002), heat wave magnitude index, HWMI (Russo et al. 2014), and excess heat factor, EHF (Nairn & Fawcett 2014), among others. Over time, the combined effects of heat wave characteristics have been recognized and necessitated the need for indices that integrate different aspects of heat waves. Recently, the combined heat-wave index (CHI) was proposed (Das et al. 2020). By integrating heat wave magnitude, duration, and extent, CHI allows for greater discrimination among events, thus enabling one to chronicle fine scale impacts on the landscape. Elsewhere, the Heat Severity and Coverage Index (HSCI) combines magnitude, frequency, areal extent, and duration to characterize heat waves more comprehensively (Keellings & Moradkhani 2020). The CHCI index presented in our study looks to build on such work by highlighting the combined heat wave impacts in a cumulative fashion that is both spatially explicit and representative of temporal variations. First, through quartile thresholding of heat wave events based on duration and persistence, and finally computing CHCI using magnitude, number of patches, fragmentation, and areal extent parameters, heat wave events were comprehensively characterized using all six variables. Secondly, standardized variables were used in computing CHCI, thus permitting a comparative assessment of heat waves across climate regions in the contiguous US. Lastly, by exploring the components of CHCI for each pixel, important information was revealed about the main characteristics driving heat wave impacts in each climate region. For instance, the high CHCI values in the South were related to high mean area and number of patches, average magnitude, and at least average fragmentation statistic. In the East North Central region, on the other hand, CHCI was associated with events that were highly cohesive, had more-than-

average number of patches, lower-than-average area, and at least average magnitude. CHCI is calculated at the finest spatial resolution possible, as dictated by the data. The CHCI index represents a novel means to understand the impact of heat waves across the US.

4.4 Utilization of such data

Heat waves impact a wide variety of processes including human health, environmental health, and management of systems. CHCI provides another context to study and develop policy within these arenas as the index highlights both the cumulative pattern of impact, spatial dimensions, and driving factors.

Heat-related deaths occur when a rapid rise in temperatures outpaces the body's ability to cool itself (Habeeb et al. 2015). All heat wave variables have been studied in relation to their impacts on human health. For instance, heat wave duration has been shown to modify mortality rates (Kalkstein & Smoyer 1993). Longer heat waves have been noted to increase dangerous thermal exposure, particularly in urban areas (Hajat et al. 2002; Anderson & Bell 2009). Longer heat waves have also been shown to impact mortality rates in major cities such as Madrid and St. Louis (Smoyer 1998; Díaz et al. 2002). Timing of the event has shown to impact overall risk (Anderson & Bell 2011). Lastly, heat-related mortality increases during heat waves with greater intensity (Anderson & Bell 2009). Though all these aforementioned studies highlight the impact of a single heat wave variable on mortality, they also note that one variable could not fully explain catastrophic heat wave impacts. There is no doubt that susceptibility to heat varies across the population and from region to region but with the CHCI index we can more holistically look at heat wave-related mortality rates and better pinpoint susceptibility by combining this data with demographic and health metrics.

4.5 Drawbacks in heat wave studies

The study of heat waves faces numerous challenges. In general, heat waves are defined as extended periods of extreme heat, though no consistent definition exists regarding the actual temperature threshold, metric, and event duration that definitively defines a heat wave. In this study we utilized a standard definition for heat waves, using the climatological literature to guide us. A relative location specific percentile-based threshold has been widely utilized across previous heat wave studies. However, differing heat wave definitions can result in inconsistent data and results. For example, research indicates that significant positive associations between heat waves and health outcomes (preterm birth and nonaccidental death) are more common when relative (rather than absolute) heat wave indices were used to define exposure (Kent et al. 2014). However, the approach employed in this study, using a percentile-based threshold, is common within climatological extreme studies and therefore the results highlight realistic heatwave patterns and impacts.

Declarations

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Author Contributions

EB conceived the study and developed the methodology. DW led the data analysis. DW, EB, and DK led in writing and interpretation of results.

Data Availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

Ethical Approval

This original manuscript has not been submitted to another journal. The publication represents a single study that is free of fabrication or falsehoods.

Consent to Participate and Publish

All authors have consented to this submission and to undertaking edits during the review process.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose

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table

Table 1. Heat wave characteristics analyzed in this study.

Variable	Definition
Average heat	Average temperature (°C) for the heat wave
Fragmentation	Connectivity index indicating fragmentation of heat within a heat wave polygon, ranges from 0 (fragmented) to 1 (cohesive)
Heat wave duration	Length of the heat wave in days
Mean magnitude	Average magnitude of the heat wave above the threshold
Number of patches	Number of individual isolated patches of heat within each heat wave
Heat wave persistence	Number of heat wave areas identified for each region
Area	Area extent of the heat wave in km ²

Figures

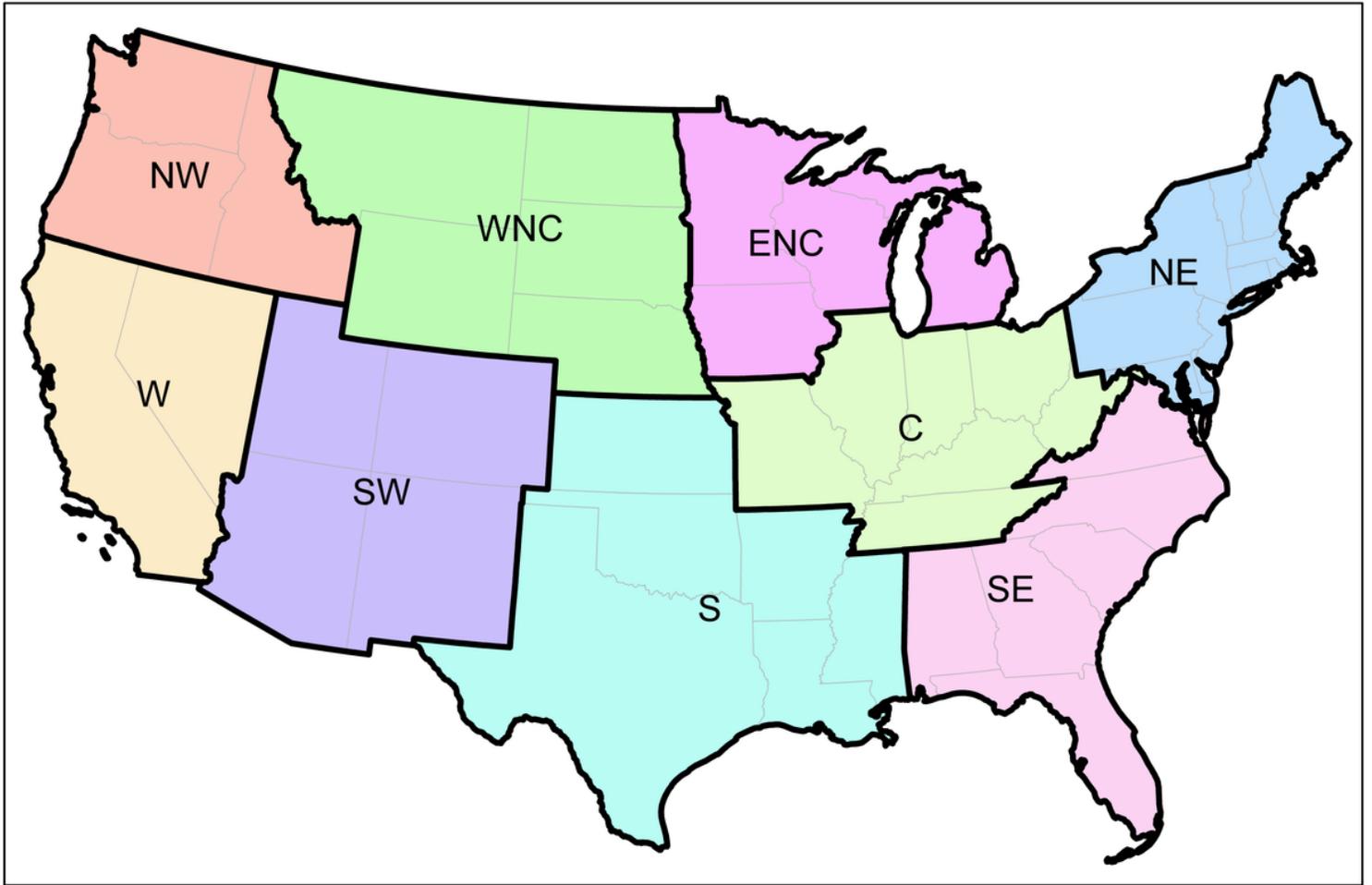


Figure 1

NOAA's US climate regions used in this study. These regions include Northwest, Southwest, West, West North Central, South, East North Central, Central, Northeast, and Southeast.

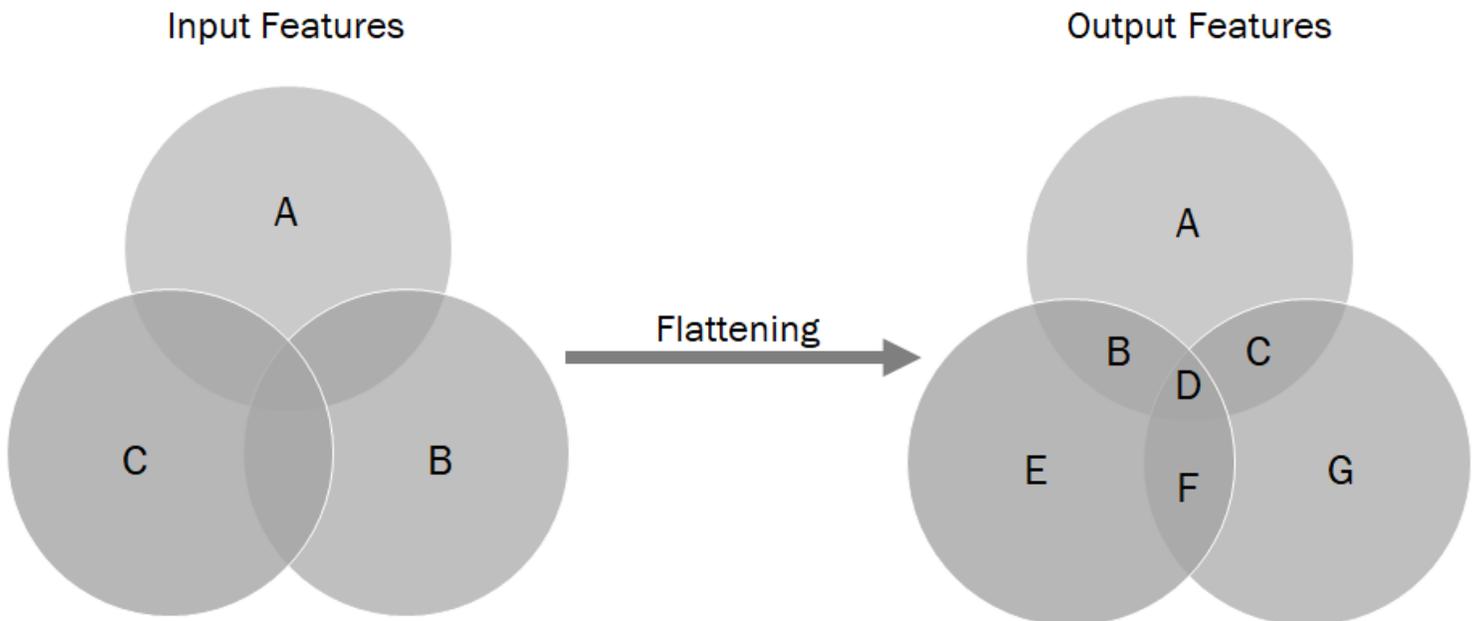


Figure 2

Illustration of how heat wave persistence was computed in this study. Output features in this illustration will have persistence values of 1 (A, E and G), 2 (B, C and F) and 3 (D).

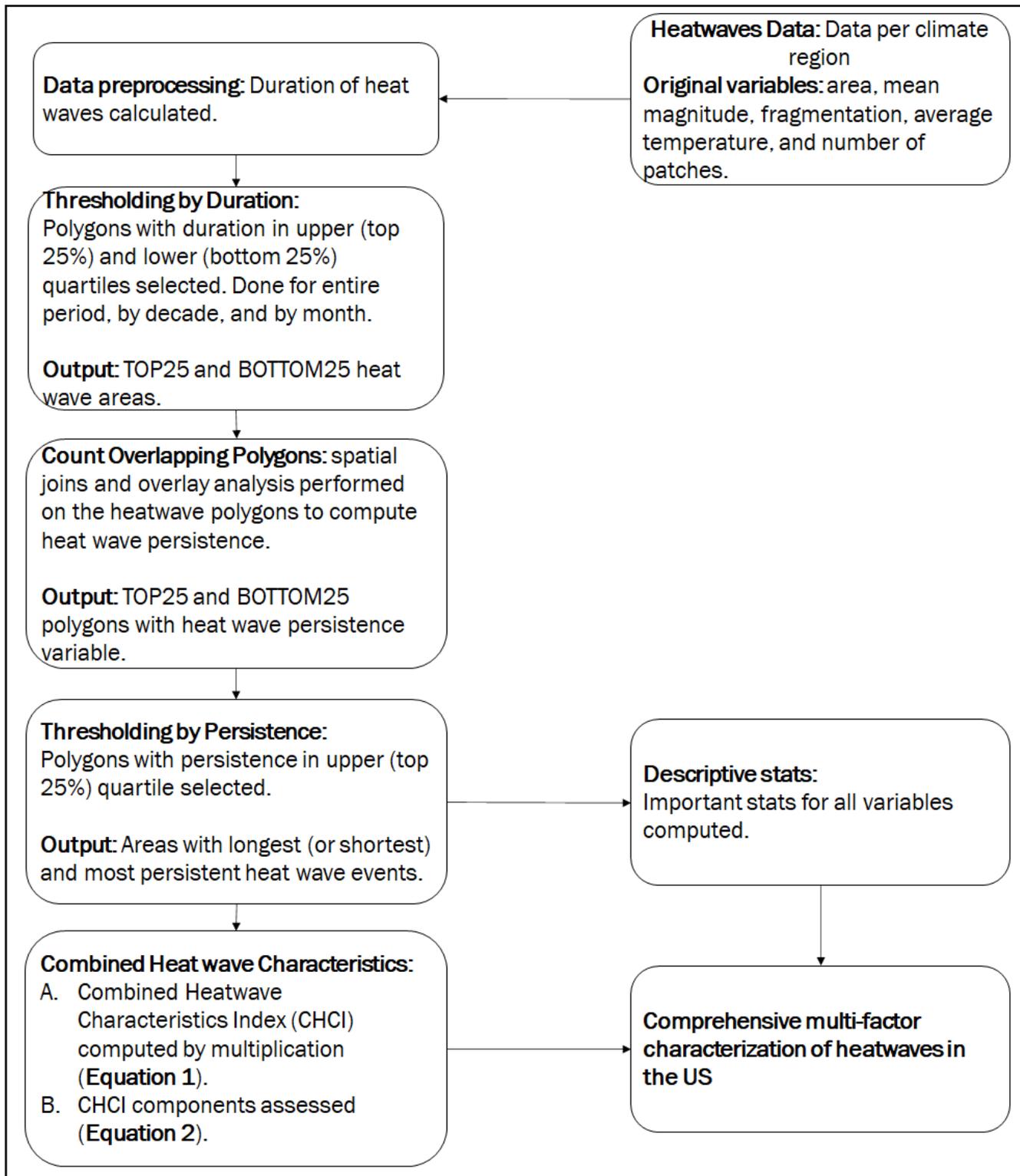


Figure 3

Analyses performed in the study.

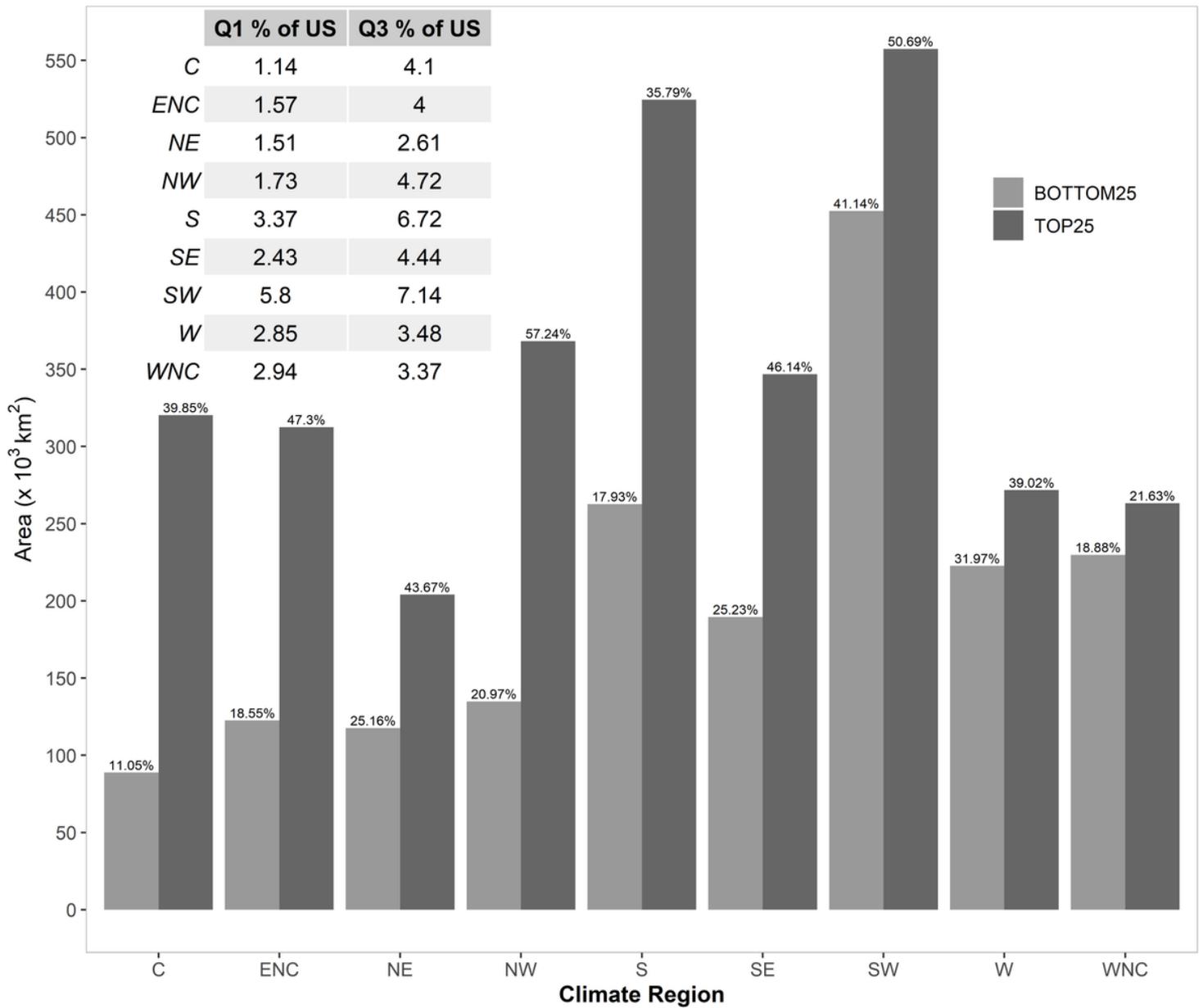


Figure 4

Proportions of area under BOTTOM25 and TOP25 heat waves for each climate region for the entire period (1981-2018). The inset shows the percent proportion of the area under heat waves to the total area of the contiguous United States. It should be noted that Q1 and Q3 represent lower quartile (BOTTOM25) and upper quartile (TOP25), respectively.

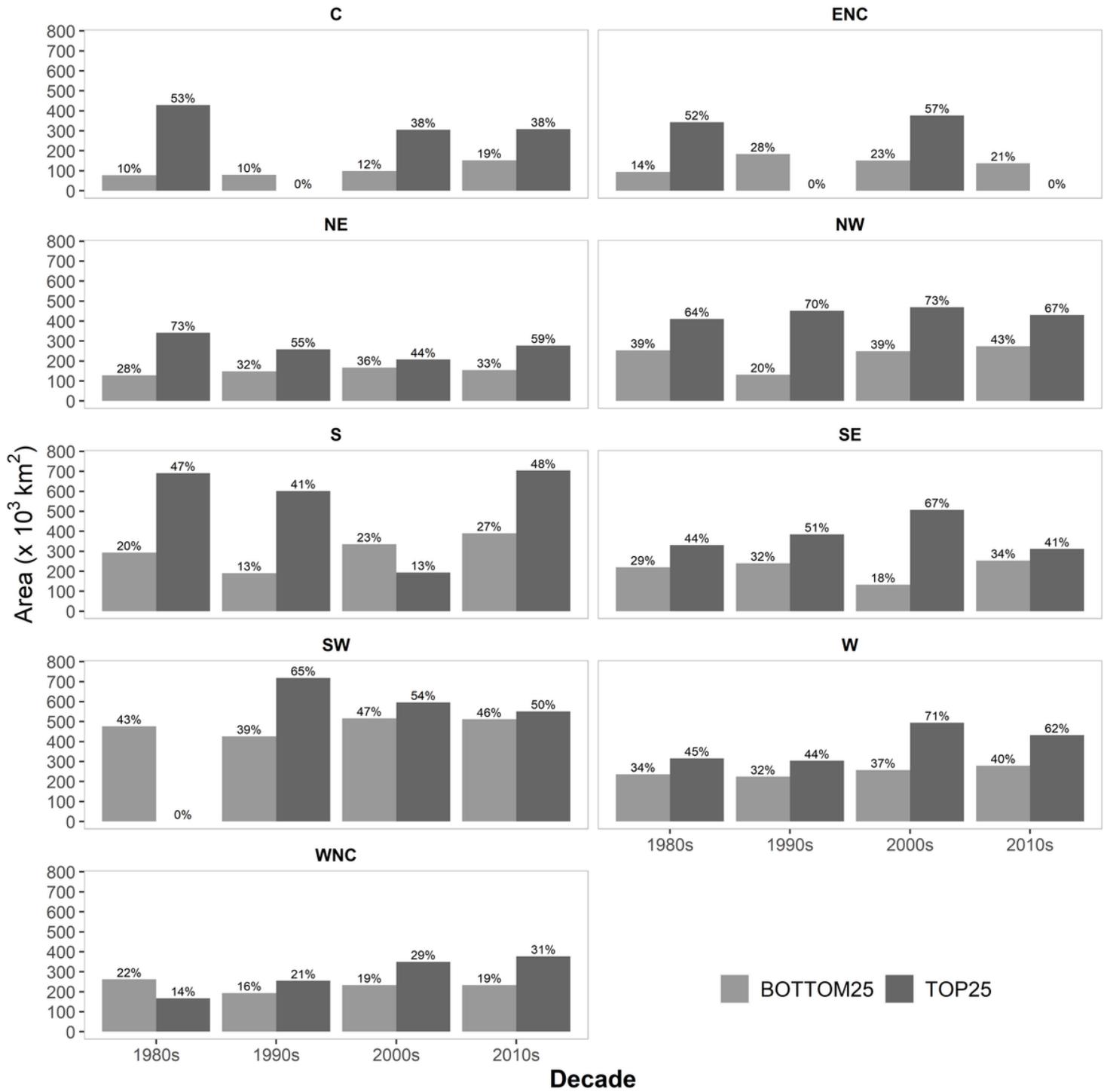


Figure 5

Proportions of area under BOTTOM25 and TOP25 heat waves for each decade per climate region.

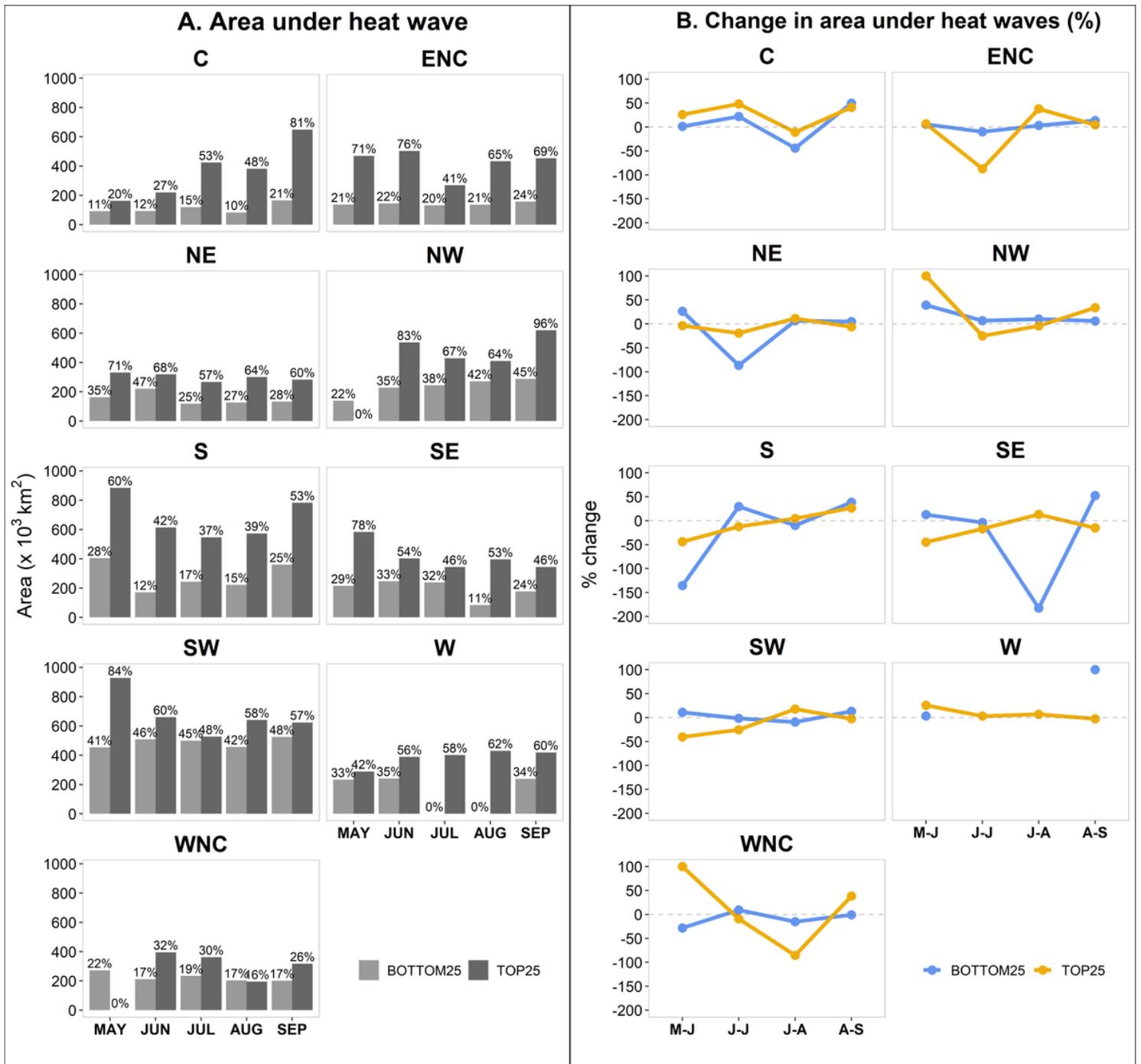


Figure 6

(A) Proportions of area under heat waves for each climate region for each summer month. (B) Percent change in month-to-month areal coverage of heat waves. It should be noted that M-J, J-J, J-A, and A-S represent May-June, June-July, July-August, and August-September changes, respectively.

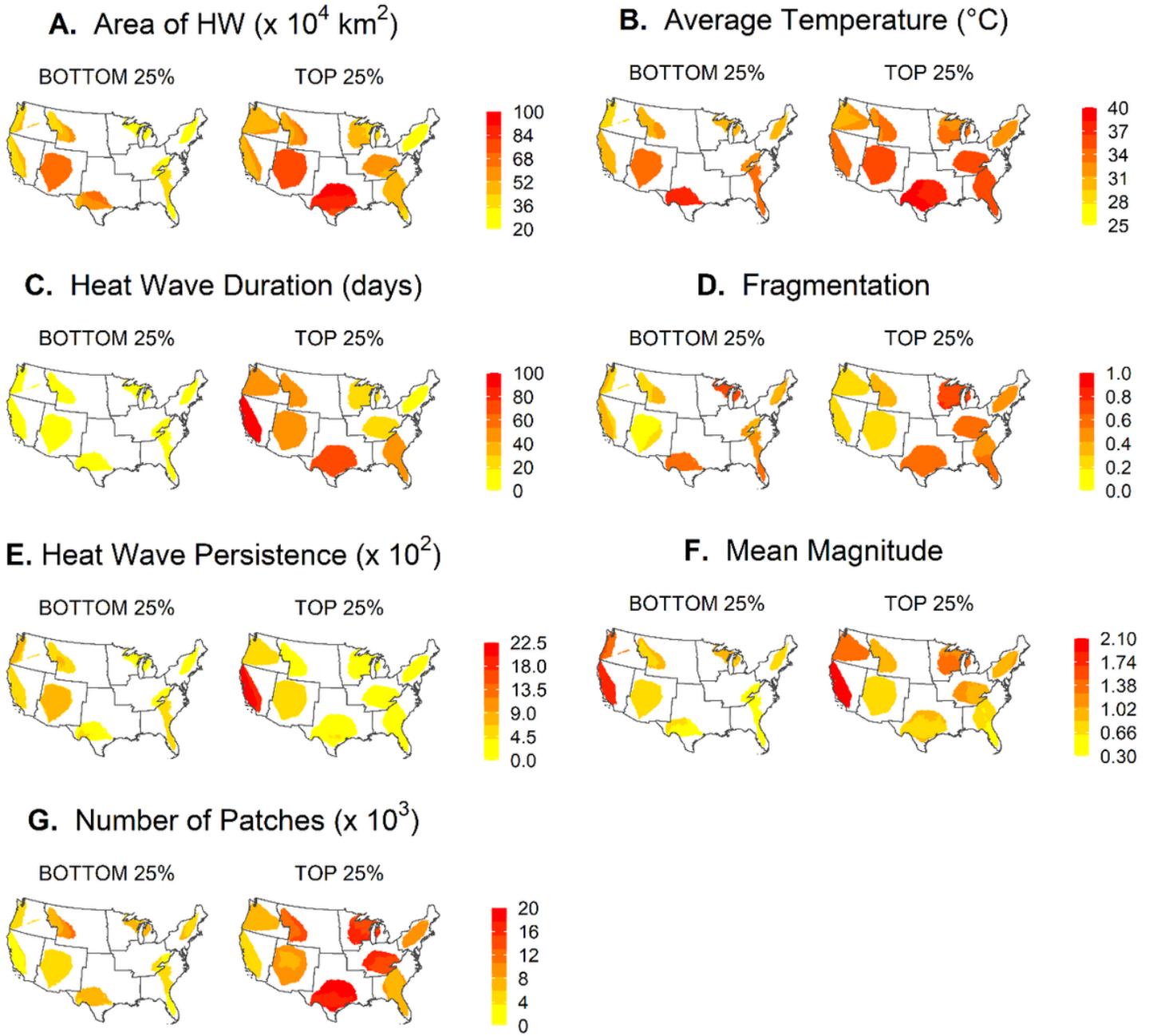


Figure 7

Heat wave characteristics for the entire study period (1981-2018).

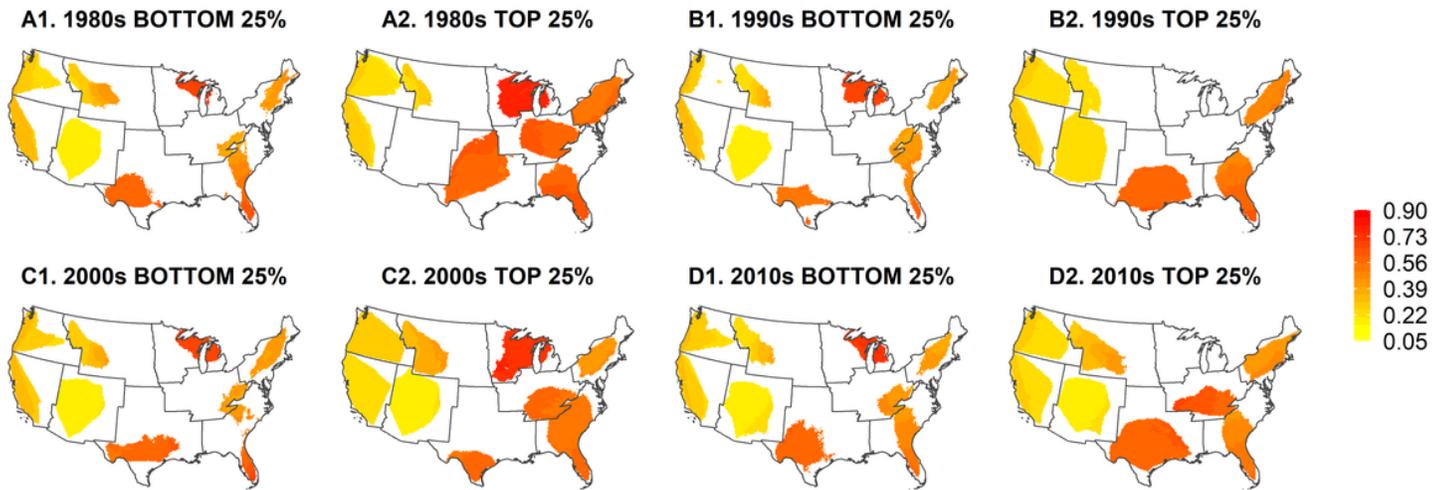


Figure 8

Heat wave fragmentation for shortest-duration (BOTTOM 25%) and longest-duration (TOP 25%) events for the 1980s (A), 1990s (B), 2000s (C) and 2010s (D) decades for the summer months.

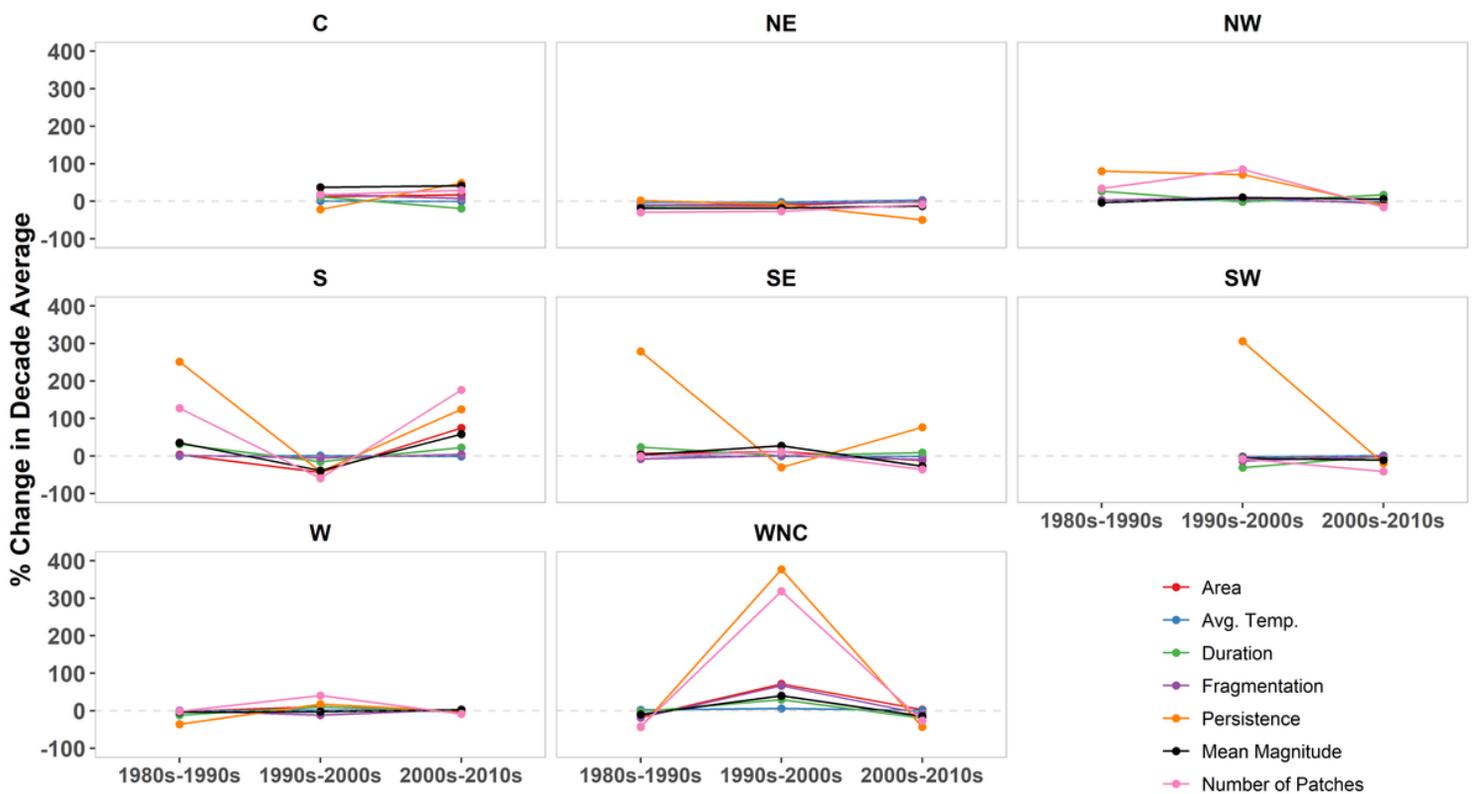


Figure 9

Percent changes in decadal average heat wave characteristics for TOP25 events per climate region. It should be noted that Eastern North Central was excluded because of missing values.

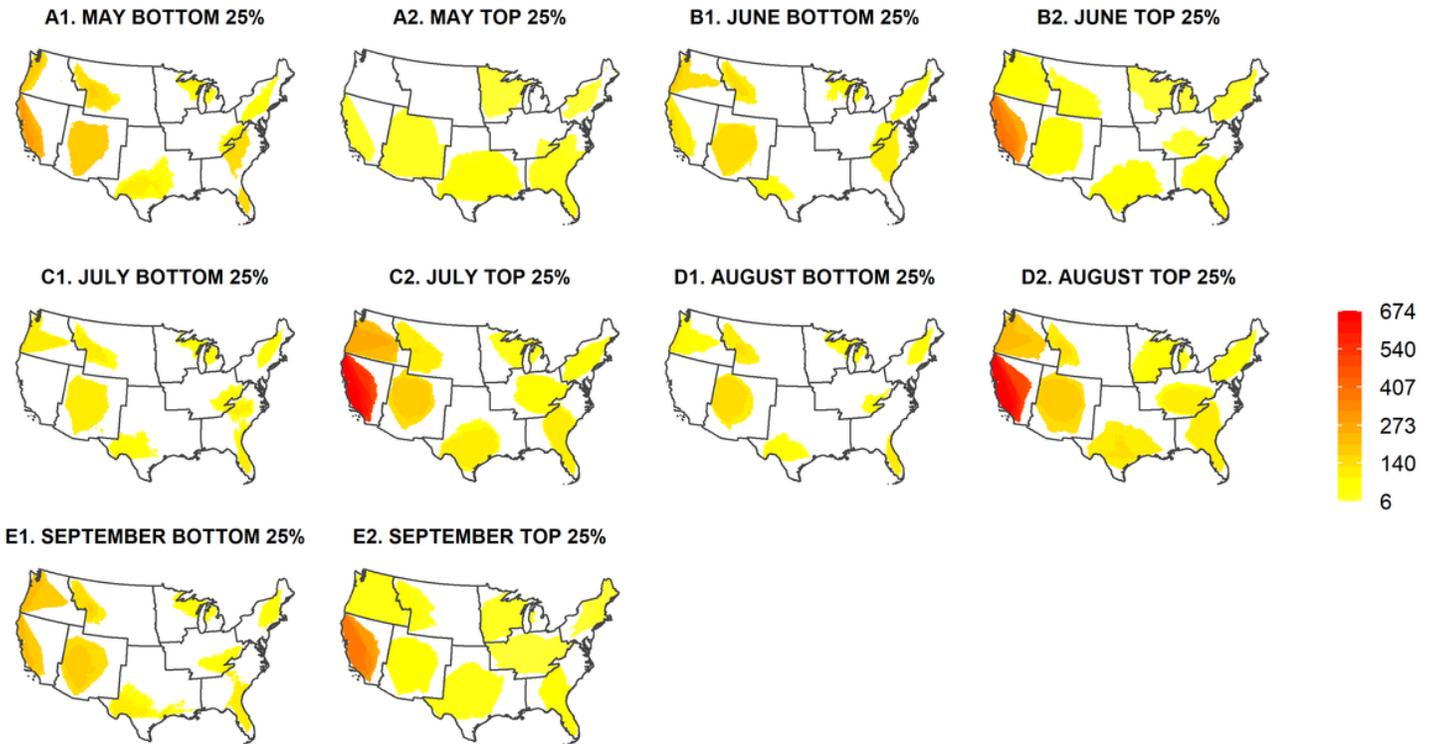


Figure 10

Heat wave persistence for shortest-duration (BOTTOM 25%) and longest-duration (TOP 25%) events for May (A), June (B), July (C), August (D) and September (E) over the 1981-2018 period.

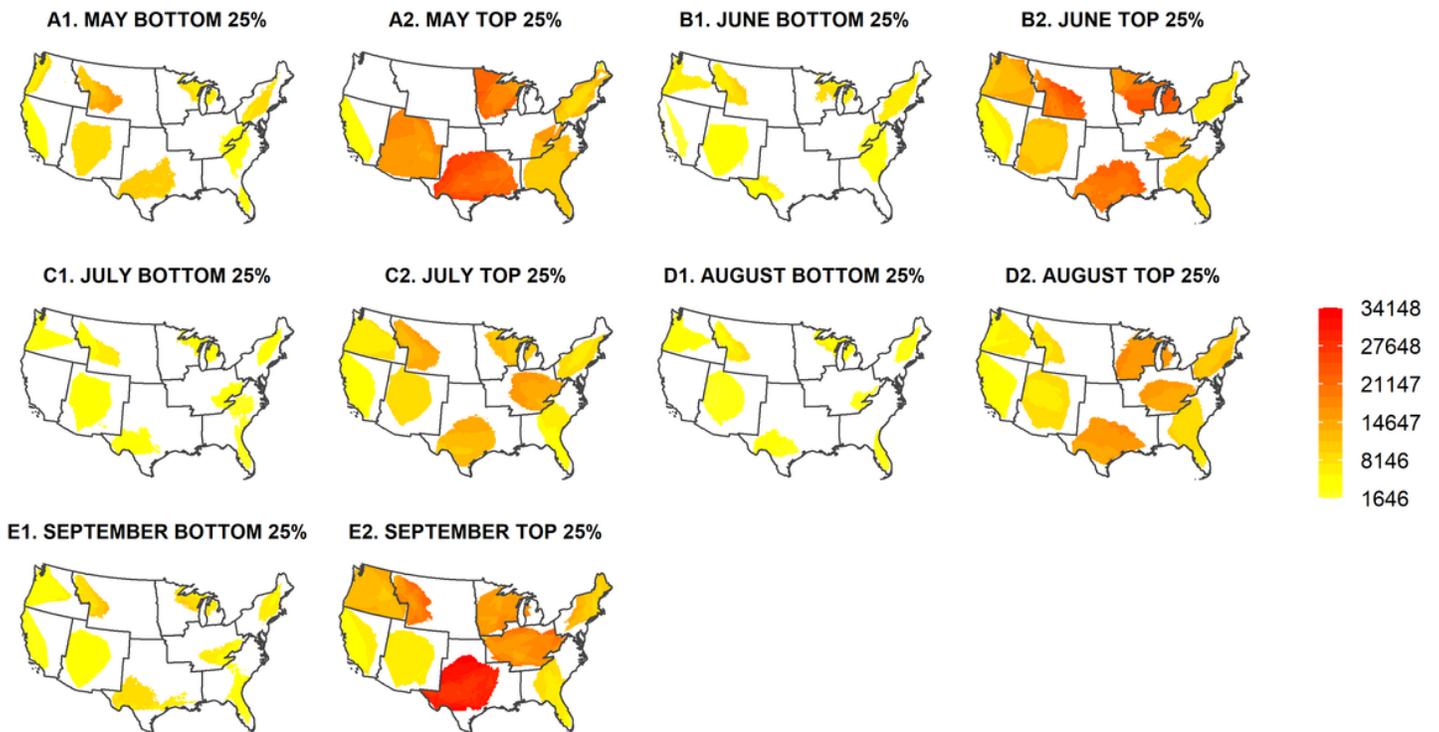
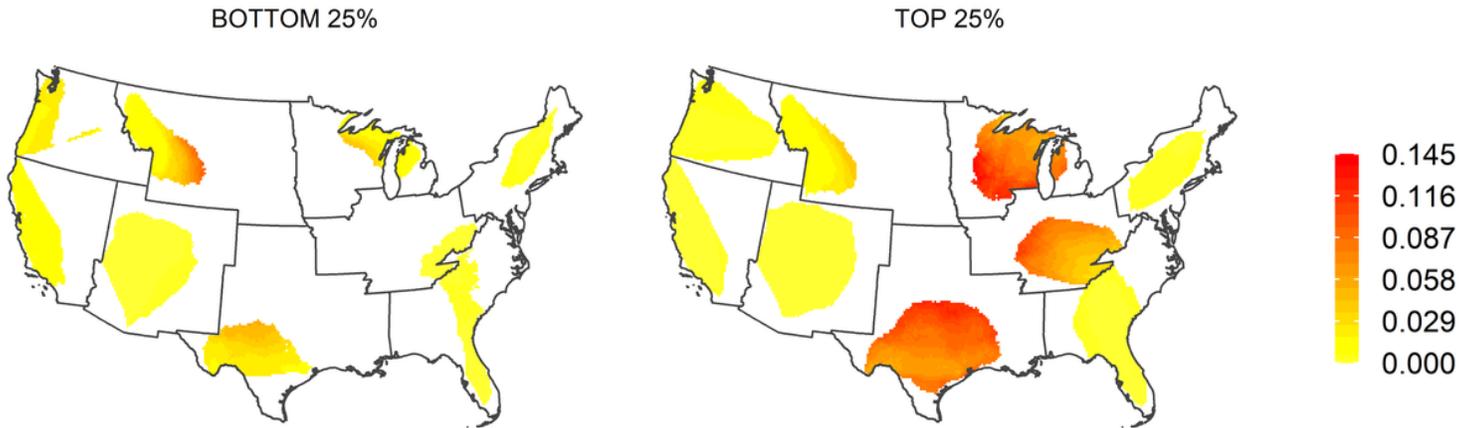


Figure 11

Number of patches for shortest-duration (BOTTOM 25%) and longest-duration (TOP 25%) events for May (A), June (B), July (C), August (D) and September (E) over the 1981-2018 period.

A. CHCI



B. CHCI Components

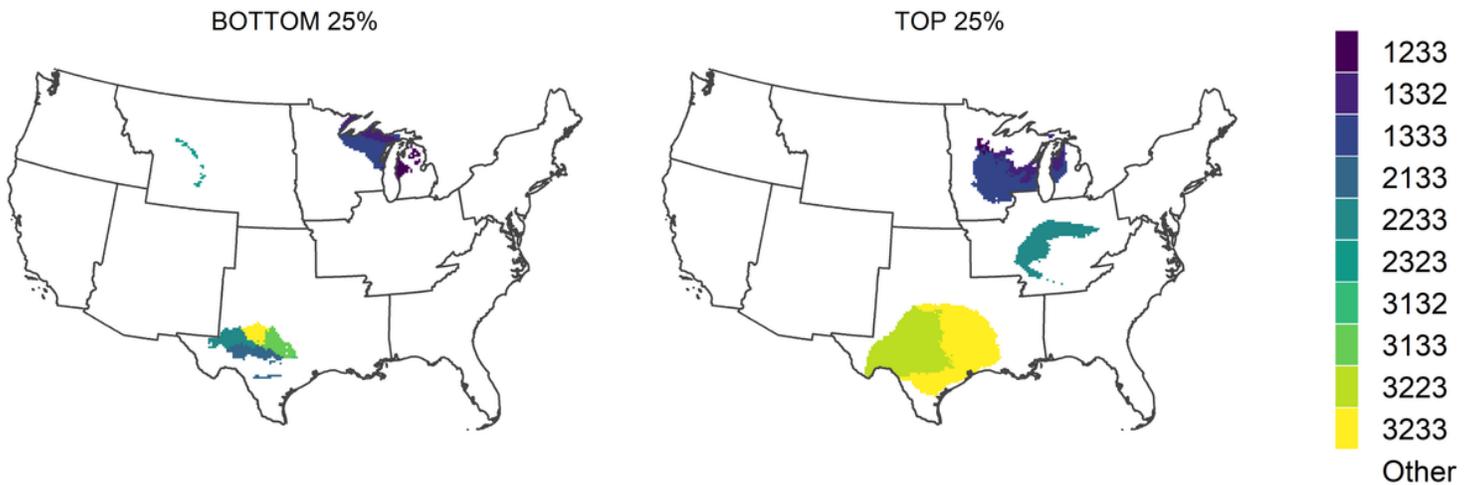


Figure 12

(A) Distribution of CHCI for shortest-duration vs longest-duration events. (B) Locations and important components of CHCI. It should be noted that all areas shown here have at least two of their CHCI variables in the mid class.