Rise in Heat Related Mortality in the United States

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Abstract

Over the past century, extreme heat events (EHE) have become more frequent and intense, resulting in significant health impacts and economic challenges worldwide. In the United States, extreme heat is the leading weather-related cause of death, claiming more lives annually than hurricanes, floods, and tornadoes combined. However, the characteristics of EHEs can vary significantly between events and over time, with some events perceived as more severe producing vastly different health and societal outcomes and these factors are largely understudied. In this paper, we explore regional trends in heat severity and mortality rates across the conterminous United States from 1981-2022 and provide a regional examination of how specific EHE characteristics impact heat mortality. We find that the number of extreme heat days has the strongest influence on heat related mortality. We observe increasing trends in heat-related mortality in every climate region throughout the U.S., except for the Western North Central region. These increases, likely connected to increases in annual EHE days during the period, suggest a significant escalation in heat related risk in the United States. Further, we find in the Southwest and Southeast regions, heat-related mortality is increasing at a higher rate than heat severity, suggesting potential for modification by community and individual level social vulnerability. Future heat mortality models should be holistic in their approach, incorporating not only multiple characteristics of heat but also measures of vulnerability to fully capture the complex dynamics of risk and exposure.

1. Introduction

Over the past century, extreme heat events (EHE) throughout many parts of the world have become more frequent and intense [1–3] resulting in significant health impacts and economic challenges worldwide [4,5]. Major global events, such as the 2003 European Heatwave (>70,000 deaths) [6] and the 2010 Northern Hemisphere Heatwaves (estimated 56,000 deaths) [7], along with thousands of smaller events each year, have contributed to the global estimate of 489,000 excess deaths occurring during the first two decades of the 21st century [8]. In the United States, EHEs are the leading cause of weather-related deaths [9], resulting in more deaths annually than hurricanes, floods, and tornadoes combined [10]. Between 1999 and 2023, over 20,000 deaths have been attributed to extreme heat in the U.S. [11]. While EHEs can and have occurred in all 50 states of the U.S., mortality responses to extreme heat are not equally distributed throughout the country. Rather, mortality rates can vary significantly by region and are strongly influenced by both *social and human environmental factors* such as previous heat exposure, socioeconomic status, and the built environment [12–14] as well as heat *event characteristics* like event frequency, intensity, and duration [12]. Recent findings from Jones et al. [13] suggest that regions unaccustomed to frequent heat extremes, such as the urban areas of the U.S. Midwest and Northeast, exhibit a higher mortality response to heat exposure, compared to regions frequented by heat extremes [13]. These findings support an earlier investigation by Anderson and Bell [14] who found that the impact of EHEs on mortality, as well as the influence of specific heat event characteristics like intensity and duration, were more pronounced in the Midwest and Northeast compared to the South. Simultaneously, patterns of heat related mortality can be connected to socioeconomic status, race, and housing characteristics. For example, non-Hispanic black individuals and those living in areas with a higher rate of public assistance utilization have been found to carry higher odds of mortality during EHEs compared to other groups [15]. These observations, likely attributable to a combination of regional variations in both human factors (e.g., acclimatization, social vulnerability) and the physical dimensions of the hazard and environment (such as event characteristics, timing, and geographical features), suggest an important linkage between human vulnerability and specific characteristics of EHEs.

Differences in regional trends in heat characteristics—such as event intensity, size, and duration—have also been observed at both global [2,16] and national [13,17] scales. However, studies comparing the influence of individual heat characteristics and their relationship with mortality remain limited. Many U.S. based studies have focused on identifying socioeconomic and demographic factors associated with heat mortality [13,15,18], however the specific drivers of heat-related mortality, particularly in relation to event characteristics, remain under-researched in the United States. Current analyses of heat characteristics often concentrate on localized regions (e.g., the U.S. state of Alabama, [19] and the Eastern U.S., [20]) or fail to capture all regions within the U.S. equally [14,21,22]. For example, while Anderson and Bell [14] were able to produce a comprehensive examination of heat in the U.S. Northeast, Midwest, and South, limited characterizations and trends were recorded in the Northwest and Western North Central regions, likely due to limited event observations during the study period (1987–2005). Similarly, Shindell et al. [21] applied generalized heat exposure response models (derived from data from 10 major U.S. cities) to estimate future heat mortality for the entire conterminous U.S. While both these studies contribute to the working knowledge surrounding heat mortality, they illustrate common limitations in regional coverage and representation in climate research; the analysis by Anderson and Bell [14], constrained by sparse data in the Northwest and Western North Central regions, reflects challenges of uneven geographic data distribution, while the approach by Shindell et al. [21] to generalize urban data to the entire U.S. may overlook critical regional differences in climate, demographics, and infrastructure, risking inaccurate estimations. In this paper, we analyze trends in heat severity and mortality rates from 1981-2022 across nine regions of the conterminous U.S., examining specific characteristics (size, intensity, and days of exposure) of EHEs and their association with heat-related mortality. Building on prior research that suggests the impacts of heat cannot be fully explained by variations in single event characteristics [23–25], we compare the influence of individual characteristics to the cumulative effect of multiple characteristics (total heat severity). Additionally, we investigate differences in predictive capability when using individual versus collective heat characteristics to model heat-related mortality.

2. Materials and Methods

2.1 Measuring Total Heat Severity

To examine the impact of individual versus combined heat characteristics on mortality, we calculated the total annual heat severity of EHEs occurring during the summer months (May, June, July, August, September; MJJAS) from 1981 to 2022. We define annual heat severity as a cumulation of three measurable heat characteristics: size, intensity (exceedance above the 95th percentile), and total number of extreme heat days and measure it using a modified version of the Heat Severity and Coverage Index (HSCI) [26]. The HSCI was developed to perform holistic assessments and comparisons of EHEs, accounting for intensity, duration, and areal extent [26]. A humidity modified version of the HSCI was later introduced to account for humid conditions during EHEs ($HSCI_H$) [27] and is used in this study to measure total heat severity year-to-year (Equation 1).

(Equation 1)

$$\mathrm{HSCI}_H = \sum_{i=1}^{n} m_i * a_i$$

Here, m_i denotes the average magnitude of heat index temperature exceedance above a predefined threshold, measured in degrees Celsius, and a_i represents the proportion of the total area affected by the EHE relative to the NOAA Climatically Consistent Region [28] where the event predominantly occurs. Each component, m_i and a_i is calculated daily throughout the duration of the event, designated by n days.

EHEs are defined as 2 or more days of hot-humid temperatures above the historical 95th percentile (1981-2022). For each day of each extreme event, the $\mathrm{HSCI_H}$ value is calculated and summed to create event scores using daily gridded temperature and dew point temperature data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; available at https://prism.oregonstate.edu/). Annual Total Heat Severity are assessed by summing daily $\mathrm{HSCI_H}$ values for each EHE occurring during the summertime period of each year. Heat assessments are performed at the climate region level, defined using NOAA Climatically Consistent Climate Regions [28].

2.2 Individual Component Analysis

The relationship between the individual characteristics of extreme events—intensity, total number of extreme heat days, and areal extent—and mortality is analyzed using two methods: Pearson Correlations to assess linear relationships and multiple linear regression to evaluate the impact of each characteristic on mortality. To identify the most influential characteristic of heat related to mortality, standardized beta coefficients and their associated p-values are compared for each characteristic and climate region. Since the exposure and outcomes (mortality) are measured cumulatively (annually) rather than for each individual event, our calculations compare the *annual total event intensity*, *average areal extent*, and *total number of extreme heat days (exposure)* to the crude heat mortality rate for each year. The annual total event intensity is the sum of the degrees (°C) above the 95th percentile for each event throughout the year. The average areal extent represents the mean event size annually. Lastly, the total number of extreme heat days counts all days classified as part of extreme heat events during the summertime period of each year.

To further evaluate the effectiveness of different predictors of heat-related mortality across various climate regions, a series of regression analyses are conducted, fitting and comparing multiple models for each region. Four distinct models were specified: a comprehensive model including event size, event intensity, and total heat days; and three simpler models, each focusing on one of these characteristics individually. Each model is fitted using Ordinary Least Squares (OLS) regression. We then use the Akaike Information Criterion (AIC) to assess the relative quality of these models, identifying the model with the lowest AIC as the best fit for each region. Additionally, we perform a Likelihood Ratio Test (LRT) to compare the comprehensive model with each of the simpler models, evaluating whether the more complex model provided a significantly better fit.

2.3 Heat Mortality Analysis

Annual summertime mortality data from 1981 through 2022 was collected from the Center for Disease Control (CDC) WONDER (Wide-Ranging OnLine Data for Epidemiologic Research) database [29]. For the long-term trend analysis between heat severity and heat-related mortality, underlying causes of death were filtered by International Classification of Diseases Ninth (ICD-

9) and Tenth Revision (ICD-10) codes for hyperthermia (1981-1998 ICD-9: E900.0; 1999-2022 ICD-10: X30) and aggregated by climate region. Ideally, mortality data for all years would be available at a monthly resolution, allowing for the isolation of heat-related mortality specifically during the MJJAS period. However, due to limitations in data availability, the analysis of mortality was conducted on an annual basis. Through CDC WONDER (http://wonder.cdc.gov), mortality data from 1999-2022 can be filtered by both year and month, however, data prior to 1999 is only available on an annual basis. While previous investigations by Vaidyanathan et al. [30] indicates that 90% of heat-related deaths occur from May through September, it is important to consider that heat-related deaths outside these months may still be present in the dataset for the years 1981-1998.

For year-to-year statistical comparison, mortality data is normalized to crude death rates per one million people. Annual population data for normalization are annual Census Bureau estimates provided by CDC WONDER. Correlations between total heat severity, as measured by the $HSCI_H$, and crude mortality rates are assessed using a Pearson Correlation. Additionally, trends in heat severity and crude mortality rates are examined using the Mann-Kendall test [31], and the magnitudes of these trends are quantified using Sen's Slope [32]. To maintain the privacy of individuals, mortality data from the CDC WONDER database is not reported for deaths totaling nine or fewer during any specified period. Therefore, not all climate regions have mortality data for each year during the 1981-2022 period.

To evaluate the impact of various heat event characteristics on mortality rates across different U.S. climate regions, a multiple regression-based scenario analysis was conducted. The analysis focused on understanding how different combinations of Event Size, Intensity, and Exposure affect mortality under five key scenarios: (1) *High Event Size, Low Intensity and Exposure*, (2) *High Intensity, Low Event Size and Exposure,* (3) *High Exposure, Low Event Size and Intensity*, (4) *All Characteristics High*, and (5) *All Characteristics Low*. For each predictor variable, the 1st quartile (Q1) and 3rd quartile (Q3) values were calculated across the dataset to define "low" and "high" levels used in the scenario analysis. These quartiles represent data-driven thresholds for what constitutes low and high levels of the predictors. Before fitting the regression models, Min-Max (0-1) standardization was applied to each variable. This scaling ensured that all predictors were brought to the same range, allowing their contributions to the model to be directly comparable and preventing any variable with a larger numerical range from disproportionately influencing the results.

3. Results

3.1 Trends and Regional Relationships in Heat Severity and Heat Related Mortality

Between 1981 and 2022, heat-related mortality rates increased significantly across all U.S. climate regions except the Western North Central (Table 1). The Southwest exhibited the most pronounced rise, with a Sen's Slope of 0.141, followed by the Northwest (0.056) and South (0.046). In these regions, total heat severity also increased significantly at the 95% confidence level. In contrast, the Central, Eastern North Central, Northeast, Southeast, and West regions experienced more moderate mortality increases, without corresponding significant changes in heat severity. Applying an exponential smoothing function ($\alpha = 0.3$), following Keellings and Moradkhani [26] and Narayanan et al. [27], confirmed these regional disparities in both mortality and heat severity trends, as depicted in Figure 1.

Table 1. Trends in total heat severity and heat related crude mortality rates (per 1,000,000) by climate region. Trends in total heat severity are calculated by matching years where mortality data is available (years where heat related mortality is > 9) across the 1981-2022 period.

Climate Region	Number of observation years	Variable	Kendall tau	Kendall p-value	Sen's Slope	SSR
Central	41	Mortality Rate	0.327	0.003*	0.022	2.04
		Total Heat Severity	0.054	0.621	0.046	
Eastern North Central	26	Mortality Rate	0.292	0.037*	0.030	9.01
		Total Heat Severity	0.200	0.160	0.267	
Northeast	35	Mortality Rate	0.368	0.002*	0.017	12.03
		Total Heat Severity	0.224	0.059	0.203	
Northwest	20	Mortality Rate	0.419	0.010*	0.056	15.04
		Total Heat Severity	0.389	0.016*	0.838	
South	42	Mortality Rate	0.468	<0.001*	0.046	2.36
		Total Heat Severity	0.250	0.020*	0.108	
Southeast	42	Mortality Rate	0.412	<0.001*	0.019	0.10
		Total Heat Severity	0.001	0.991	0.002	
Southwest	40	Mortality Rate	0.659	<0.001*	0.141	0.708
		Total Heat Severity	0.218	0.048*	0.100	
West	42	Mortality Rate	0.570	<0.001*	0.031	3.67
		Total Heat Severity	0.154	0.149	0.113	
Western North Central	13	Mortality Rate	0.027	0.901	0.000	N/A
		Total Heat Severity	0.051	0.858	0.093	

* Indicates significance at the 95 percent confidence level

Figure 1. Smoothed Total Heat Severity and Crude Heat-Mortality Rate per 1,000,000 trend plots for each climate region (1981-2022; $\alpha = 0.3$). For each year, mortality is only assessed if at least 9 cases of heat mortality (hyperthermia) are reported and therefore, trends in regions with less than 42 years should be viewed with some caution.

To assess changes in mortality relative to heat severity, we calculated the Sen's Slope Ratio (SSR) by dividing the Sen's Slope of total heat severity ($HSCI_H$) by that of the crude heat-mortality rate (per 1,000,000; Table 1). An SSR below 1 indicates a greater relative increase in mortality compared to heat severity, while an SSR above 1 suggests a lesser relative increase in mortality compared to heat severity. The Southeast exhibited the largest relative increase in mortality, with an SSR of 0.10, reflecting a disproportionate rise in deaths despite a minimal change in heat severity over the 42-year period; however, the non-significant heat severity trend in this region (Kendall p-value = 0.991) weakens this finding. In contrast, the Southwest showed a more robust association between heat severity and mortality, with an SSR of 0.708 and significant trends in both variables. The Northwest, however, displayed the smallest relative mortality increase (SSR = 15.04), as its substantial heat severity rise (Sen's Slope = 0.838) was paired with a modest mortality increase (Sen's Slope = 0.056), suggesting potential mitigating factors in this region.

3.2 Individual Characteristic Analysis Results

During the study period, individual heat event characteristics showed few consistent trends across U.S. climate regions (S1 Table), consistent with prior observations by Keellings and Moradkhani [26]. However, in years with high heat-related mortality (>9 annual deaths per region), all U.S. climate regions except the Western North Central showed significant increases in heat exposure (Table 2). Analysis of each characteristic's influence on mortality revealed distinct regional patterns: exposure, defined as the total number of extreme heat days, consistently drove mortality across most regions, except in the Eastern North Central, where intensity was more influential, and the Southwest, where event size played a larger role (Table 3, S1-4 Appendix). In contrast, event size had a limited impact nationally, with significant effects confined to the West and Southwest. Total event intensity, measuring the degree by which temperatures exceeded 95th percentile thresholds, proved less predictive of mortality than exposure duration, suggesting that the persistence of extreme heat outweighs its intensity in driving regional death rates.

Table 2. Trends in humid heat characteristics by climate region, 1981-2022. Trends are calculated using only years where mortality is greater than 9 persons.

Climate Region	Event Characteristic	Kendall tau	Kendall p-value	Sen's Slope
Central	Event Size	-0.039	0.719	-0.00047
	Intensity	0.010	0.928	0.00076
	Exposure	0.539	<0.001*	0.586
Eastern North Central	Event Size	0.102	0.484	0.00074
	Intensity	0.182	0.203	0.0061
	Exposure	0.470	<0.001*	0.538
Northeast	Event Size	0.089	0.452	0.00074
	Intensity	0.153	0.196	0.0055
	Exposure	0.516	<0.001*	0.421
Northwest	Event Size	0.305	0.064	0.0023
	Intensity	0.200	0.233	0.0079
	Exposure	0.620	<0.001*	0.703
South	Event Size	0.233	0.029*	0.0013
	Intensity	0.073	0.495	0.0012
	Exposure	0.599	<0.001*	1.088
Southeast	Event Size	-0.029	0.786	-0.00029
	Intensity	-0.029	0.582	-0.0012
	Exposure	0.621	<0.001*	1.0
Southwest	Event Size	0.0021	0.030*	0.238
	Intensity	0.195	0.077	0.0028
	Exposure	0.546	<0.001*	0.830
West	Event Size	0.315	0.0033*	0.0033
	Intensity	-0.010	0.922	-0.00017
	Exposure	0.528	<0.001*	0.737
Western North Central	Event Size	0.128	0.590	0.0013
	Intensity	-0.154	0.510	-0.0069
	Exposure	0.252	0.241	0.333

* Indicates significance at the 95 percent confidence level

Table 3. Standardized Beta coefficients (β) and associated p-values of individual characteristics from the multiple linear regression. To aid in visual interpretation the influence of each characteristic is ranked within each region using colors, based on β values: red being high influence, yellow being medium influence, and blue being low influence.

Climate Region	*Annual Average Event Size β*	*Annual Average Event Size p-value*	*Annual Total Event Intensity β*	*Annual Total Event Intensity p-value*	*Annual Exposure β*	*Annual Exposure p-value*
Northeast	0.2518	0.091	-0.0318	0.878	0.579	0.007*
Eastern North Central	0.152	0.476	0.4736	0.083	-0.0637	0.789
West	0.2961	0.043*	-0.1237	0.355	0.5539	0.001*
Southwest	0.4337	0.002*	0.0358	0.809	0.3828	0.016*
Western North Central	-0.0705	0.443	0.1838	0.094	0.8678	<0.001*
Northwest	-0.3433	0.18	-0.1571	0.584	0.9096	0.010*
Central	0.2147	0.117	0.051	0.765	0.5653	0.001*
South	0.2105	0.057	-0.0783	0.467	0.7356	<0.001*
Southeast	0.2115	0.079	0.1017	0.506	0.5674	0.001*

* Indicates significance at the 95 percent confidence level

Although event size and intensity showed weaker associations with mortality compared to exposure, incorporating all three characteristics—size, intensity, and exposure—into a comprehensive model enhances the accuracy of heat-related mortality predictions (Table 4). Model comparisons revealed that this full model, integrating all attributes, outperformed simpler models relying on individual characteristics in most U.S. climate regions, as evidenced by lower Akaike Information Criterion (AIC) values (Table 4). Exceptions occurred in the Central, Eastern North Central, Northeast, and Western North Central regions, where models based solely on total exposure or event intensity occasionally matched the full model's fit. Likelihood Ratio Tests corroborated the full model's superior performance across most regions, though simpler models proved adequate in these specific cases (Table 4). These findings highlight the value of a holistic approach to capture the multifaceted drivers of heat mortality.

Table 4. Regression model comparison results for predicting heat-related mortality across climate regions

			AIC				LRT p-value		
Region	*Full Model Adjusted R-squared*	*Full Model F-statistic p-value*	*Full Model*	*Average Event Size*	*Total Event Intensity*	*Total Exposure*	*Full vs. Average Event Size*	*Full vs. Total Event Intensity*	*Full vs. Total Exposure*
Central	0.420	<0.001	73.9	90.03	83.55	73.71*	<0.001	<0.001	0.149
Eastern North Central	0.182	0.060	49.08	49.74	45.8*	51.49	0.097	0.696	0.040
Northeast	0.332	0.001	28.18	38.54	34.21	27.52*	<0.001	0.006	0.188
Northwest	0.316	0.028	104.94	111.55	109.62	103.81*	0.005	0.013	0.237
South	0.664	<0.001	91.72*	119.13	130.98	92.51	<0.001	<0.001	0.091
Southeast	0.450	<0.001	23.44*	43.66	35.92	23.52	<0.001	0.003	0.130
Southwest	0.394	<0.001	188.78*	194.38	204.5	195.71	0.008	<0.001	0.004
West	0.476	<0.001	87.96*	96.16	111.58	89.53	0.002	<0.001	0.061
Western North Central	0.912	<0.001	0.45*	31.77	27.02	0.89	<0.001	<0.001	0.108

* indicates best model by AIC

3.3 Scenario Analysis Results

Scenario analysis of heat event characteristics revealed distinct regional patterns in predicted annual crude mortality rates (deaths per 1,000,000) across U.S. climate regions (Table 5). The scenario emphasizing *high exposure, with low event size and intensity*, consistently produced the highest mortality rates, particularly in the Northwest (7.271), Southwest (3.358), and South (1.935), underscoring their vulnerability to prolonged heat exposure. The West, Central, Southeast, and Northeast exhibited more moderate increases, while the Eastern North Central showed the least sensitivity to extended heat duration, with a rate of 0.164. In contrast, the scenario focusing on *high total intensity, with low event size and exposure*, yielded generally lower mortality rates, though the Southwest (2.134) and Eastern North Central (0.559) displayed greater responsiveness to temperature intensity. The scenario highlighting *high average event size, with low intensity and exposure*, identified the Southwest as most sensitive (4.251), followed by the South (1.718) and West (1.20), while other regions showed moderate to low responses; the Northwest's negative predicted rate (-0.407) in this scenario suggests potential model limitations. The *All Characteristics High* and *All Characteristics Low* scenarios, serving as reference bounds, further contextualized the range of impacts, highlighting the varied influence of heat event characteristics on regional mortality risks.

Table 5. Predicted Annual Crude Mortality Rate (deaths per 1,000,000) under five different event scenarios. "Low" values are defined using the first quartile value of the dataset while "High" values are defined using the third quartile value. Boldened text shows the highest mortality rate amongst the three main scenarios.

Region	Scenarios				
	High Average Event Size, Low Total Intensity and Exposure	*High Total Intensity, Low Average Event Size and Exposure*	*High Exposure, Low Average Event Size and Total Intensity*	*All Characteristics High*	*Al Characteristics Low*
Central	0.683	0.472	**1.187**	1.499	0.421
Eastern North Central	0.522	**0.559**	0.164	0.741	0.252
Northeast	0.284	0.094	**0.698**	0.857	0.109
Northwest	-0.407	0.830	**7.271**	4.271	1.711
South	1.718	0.772	**1.935**	2.491	0.967
Southeast	0.824	0.712	**0.925**	1.164	0.648
Southwest	**4.251**	2.134	3.358	5.976	1.884
West	1.20	0.579	**1.543**	1.820	0.752
Western North Central	0.085	0.334	**1.471**	1.433	0.228

4. Discussion

We observed increasing trends in heat-related mortality across most U.S. climate regions from 1981-2022, with the exception of the Western North Central region (Table 1). This stands in contrast to earlier findings, which reported declines in heat-related mortality prior to 2005 [33,34]. When isolating years with high heat-related mortality (defined as more than nine deaths from hyperthermia), we noted a corresponding increase in the number of EHE days (exposure; Table 2). Previous studies have highlighted that both morbidity and mortality risks tend to rise on EHE days [14,35,36]. For instance, Khatana et al. [35] found that each additional day of extreme heat per month was associated with an increase of 0.07 deaths per 100,000 adults. Our study, focusing exclusively on mortality directly attributed to heat exposure, suggests that the rising trend in EHE days in regions like the Northwest, Southwest, West, South, and Southeast could lead to higher heat-related mortality in the future if these patterns persist (Table 2).

This study, however, is not without limitations, particularly regarding the definition of heat-related deaths. The standards for defining and reporting heat-related mortality can vary across regions and time periods, which could influence the accuracy of the data [37]. These variations may result in either underestimations or overestimations of heat-related deaths in comparison to earlier decades. Additionally, while hyperthermia is commonly used to identify heat-related mortality, it may fail to capture deaths that occur indirectly due to the exacerbation of pre-existing conditions such as cardiovascular and respiratory diseases. The availability of Underlying Cause of Death data from 1968 to the present via CDC WONDER is beneficial; however, historical Multiple Cause of Death data, which could provide deeper insights into the contributions of heat, is only available from 1999 onward. While organizations like the National Archive of Computerized Data on Aging (NACDA) and the National Bureau of Economic Research (NBER) offer access to simplified versions of this data, grouping various heat-related illnesses under general categories such as “Accidents and adverse effects (E800-E949)” or “All other external causes (E980-E999)” [38], this limits our ability to conduct long-term, nuanced analyses. Expanding the availability of historical data to align with post-1999 standards would significantly enhance future research in this area.

In our analysis, the three heat characteristics—total days of heat exposure, total intensity, and average event size—were significantly correlated with mortality in most regions (S2 Table), though the influence of each characteristic varied across regions (Table 3). In the Northeast, West, Western North Central, Northwest, Central, South, and Southeast regions, the total number of EHE days was the most significant predictor of annual heat mortality. This suggests that increased exposure to heat plays a central role in raising mortality risk, regardless of event size or intensity. In contrast, in the Eastern North Central and Southwest regions, other characteristics proved more influential: temperature intensity was a key driver in the Eastern North Central, while event size had the greatest impact in the Southwest. These findings are consistent with Anderson and Bell [14]'s study, which identified regional variations in the influence of heat characteristics. Their research found that event duration had a stronger impact in some regions, such as the Northeast and Midwest, while other areas were more sensitive to intensity. Our study also found that exposure was the strongest driver of heat-related mortality in the Northeast, Central, and six other regions (Table 3). Though Anderson and Bell focused on event duration (consecutive days of exposure) rather than cumulative exposure, both studies support the critical role of extensive heat exposure in heat mortality.

However, while total days of exposure consistently emerged as a significant predictor of heat-related mortality (Table 2), it is essential to consider all heat characteristics when evaluating the impact of extreme heat. Comparative analysis reveals that models incorporating all three characteristics tend to perform as well as or better than models based on individual characteristics (Table 4). Moreover, heat-related mortality is generally higher when event characteristics are more severe, such as when events are longer, hotter, or involve more frequent exposure (Table 5). This supports the use of holistic models, even when individual characteristics show stronger correlations with mortality (S2 Table). This approach also emphasizes the value of multivariable models for more accurate predictions. Indices like the Heat Severity and Coverage Index (HSCI) [26] and the Heatwave Intensity Duration Frequency Curve (HIDF) [23] reflect the complex nature of heat events, which single-variable models may fail to capture. Similarly, biometeorological indices used in thermal perception prediction, such as the Wet Bulb Globe Temperature (WBGT) [38] and heat index [39], integrate multiple environmental factors, offering a more effective measure of thermal perception than temperature alone. However, some studies suggest that biometeorological indices, while useful, do not always outperform direct apparent temperature measurements in forecasting heat mortality [40,41]. Nonetheless, there is growing support for including multiple heat characteristics to develop a more comprehensive understanding and forecasting of heat mortality [14,42,43]. Yet, the application of multivariable approaches remains limited, often focusing primarily on single characteristics like maximum temperature [44,45], overlooking the broader impacts of other critical factors. Incorporating multi-characteristic heat indices like HSCI/$HSCI_H$ and HIDF into heat risk assessments could provide a more robust foundation for comprehensive risk modeling.

The role of population characteristics and social vulnerabilities must also be considered when modeling heat-related health outcomes. Research on hazards and vulnerability has long highlighted the links between social vulnerability and recovery outcomes [46–48], prompting more recent studies to focus on the intersection of vulnerability and exposure to better estimate risk [49–52]. While many studies prioritize physical factors like heat intensity, they often fail to integrate key aspects of social vulnerability—such as income, education, and language proficiency—into risk assessments [53]. These factors may play a significant role in this study when comparing changes in heat mortality relative to heat severity (Fig. 1, Table 1). For instance, the ratios of Sen's Slope (SSR; $HSCI_H$ divided by the Heat Mortality Rate) show that the Southeast and Southwest regions experienced the largest increases in heat mortality relative to changes in heat severity (SSR = 0.10 and 0.71, respectively; Table 1). Notably, these regions are also characterized by high social vulnerability [47,54,55] and low resilience levels [46,56]. Despite regular heat exposure and high air conditioner usage—which are known factors that reduce heat-related mortality[13,57] —heat mortality rates in these areas are rising more rapidly than heat severity. These findings suggest possible linkages to persistent regional disparities in social vulnerability. However, it is also conceivable that other factors, such as regional policies or behaviors related to adaptive capabilities (e.g., the availability and utilization of cooling centers, [58] may also be influencing these outcomes. Although there has been a general decline in vulnerability in these regions, pockets of high social vulnerability remain [55]. Research continues to show strong relationships between socioeconomic factors and increased risks and adverse outcomes from heat exposure [59], prompting the development of specialized indices like the Extreme Heat Vulnerability Index (EHVI)[60] and others [18,61]. Despite their demonstrated usefulness, the integration of these indices into mainstream heat risk assessments and emergency planning is still limited. Considering the potential link between social vulnerability and heat health risks, it is imperative to include a broader range of social vulnerability measures in future heat risk models and assessments, beyond just standard demographic data.

5. Conclusion

While previous studies have observed a significant decrease in U.S. heat-related mortality prior to the mid-2000s, we find that heat-related mortality and exposure have increased throughout much of the U.S from 1981 to 2022. This rise in EHE days found throughout much of the U.S. mirrors a global pattern of increasing EHE days [1,3,62]. While exposure was found to be the most consistent indicator of heat-related mortality, the contributing influence of each characteristic—size, intensity, and number of EHE days—can vary between regions. These findings suggest regional variations in heat vulnerability and risk and emphasize an important need for conducting region-specific examinations when modeling heat severity. While each characteristic may exert varying levels of influence on heat mortality, we find that the overall impact of extreme heat is a combination of all its characteristics. Therefore, it is strongly suggested to avoid single attribute characterizations when modeling heat mortality.

Potentially, regional variations in both human factors such as prior acclimatization to heat and social vulnerability, and physical dimensions of the hazard and environment, including event characteristics, timing of heat events, and certain geographical features, contribute significantly to the variations seen in the significance of specific heat characteristics within each region. This research contributes to our understanding of heat-related risks and stresses the importance of a multifaced approach in heat risk assessments and emergency planning. Future research should work to explore linkages between human vulnerability and relationships with specific characteristics of EHEs. Further, integrating finer-scale demographic data and more detailed climate event loggings may enhance predictions and the development of mitigation strategies for the impacts of heat on vulnerable populations.

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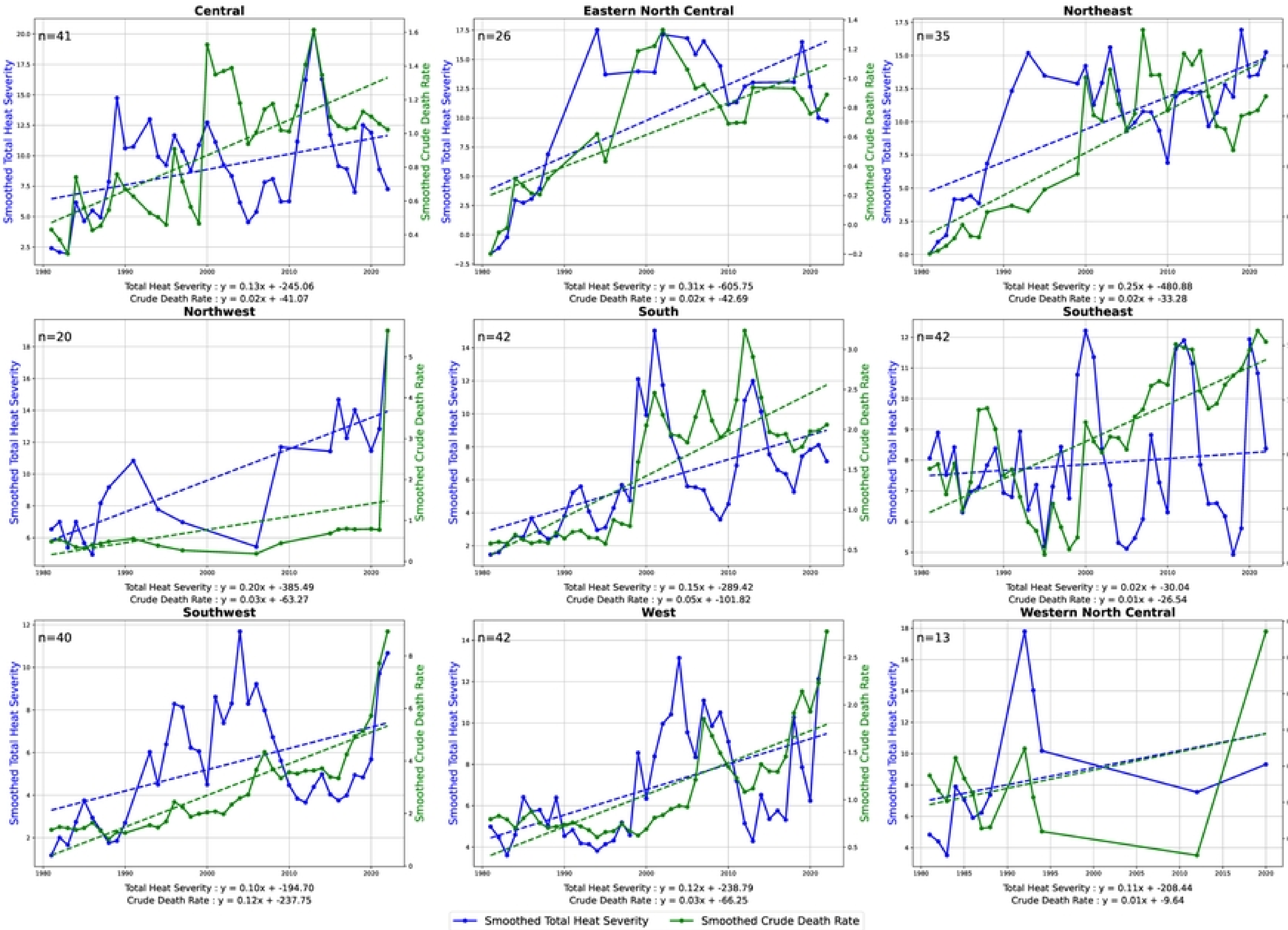
Central
n=41
Total Heat Severity : y = 0.13x + -245.06
Crude Death Rate : y = 0.02x + -41.07
Eastern North Central
n=26
Total Heat Severity : y = 0.31x + -605.75
Crude Death Rate : y = 0.02x + -42.69
Northeast
n=35
Total Heat Severity : y = 0.25x + -480.88
Crude Death Rate : y = 0.02x + -33.28
Northwest
n=20
Total Heat Severity : y = 0.20x + -385.49
Crude Death Rate : y = 0.03x + -63.27
South
n=42
Total Heat Severity : y = 0.15x + -289.42
Crude Death Rate : y = 0.05x + -101.82
Southeast
n=42
Total Heat Severity : y = 0.02x + -30.04
Crude Death Rate : y = 0.01x + -26.54
Southwest
n=40
Total Heat Severity : y = 0.10x + -194.70
Crude Death Rate : y = 0.12x + -237.75
West
n=42
Total Heat Severity : y = 0.12x + -238.79
Crude Death Rate : y = 0.03x + -66.25
Western North Central
n=13
Total Heat Severity : y = 0.11x + -208.44
Crude Death Rate : y = 0.01x + -9.64
Smoothed Total Heat Severity
Smoothed Crude Death Rate

fig1