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Higher Temperatures in Socially Vulnerable US Communities Increasingly Limit Safe Use of Electric Fans for Cooling

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Key Points:

- Maximum temperatures are 1–2°C higher in locations in the United States with more socially vulnerable communities
- Communities with high social vulnerability experience faster increases in hours with temperatures too high for safe fan use
- The geographic extent of regions with hours with temperatures too hot for safe fan use is expanding

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

As the globe warms, people will increasingly need affordable, safe methods to stay cool and minimize the worst health impacts of heat exposure. One of the cheapest cooling methods is electric fans. Recent research has recommended ambient air temperature thresholds for safe fan use in adults. Here we use hourly weather reanalysis data (1950–2021) to examine the temporal and spatial evolution of ambient climate conditions in the continental United States (CONUS) considered safe for fan use, focusing on high social vulnerability index (SVI) regions. We find that although most hours in the day are safe for fan use, there are regions that experience hundreds to thousands of hours per year that are too hot for safe fan use. Over the last several decades, the number of hours considered unsafe for fan use has increased across most of the CONUS (on average by ~70%), with hotspots across the US West and South, suggesting that many individuals will increasingly need alternative cooling strategies. People living in high-SVI locations are 1.5–2 times more likely to experience hotter climate conditions than the overall US population. High-SVI locations also experience higher rates of warming that are approaching and exceeding important safety thresholds that relate to climate adaptation. These results highlight the need to direct additional resources to these communities for heat adaptive strategies.

Plain Language Summary

As the globe warms, use of electric fans can help people stay cool if they can remain hydrated and if temperatures are low enough. Yet, there are limits to how hot it can be to safely use a fan because when temperatures are too high, a fan will increase the amount of heat traveling over the skin. We use data based on historical meteorological observations to study the number of hours in the continental US that exceed recommended temperature thresholds for safe fan use. We also examine where climate conditions considered unsafe for fan use overlap with socially vulnerable communities. We find that the geographic extent of temperatures too high for safe fan use is expanding, and the number of safe hours is decreasing. In the last two decades people have experienced double the number of hours with outdoor temperatures that are too hot for safe fan use compared to 50–70 years ago. Additionally, communities in socially vulnerable areas are experiencing higher rates of increases in unsafe hours than the overall population. Locations of particular concern include the southern and western US, highlighting the need to direct resources to invest in alternative forms of cooling in these regions.

1. Introduction

High temperatures can have serious adverse health effects on humans, and extreme heat is already one of the leading causes of weather-related deaths in the United States (US) (National Weather Service, 2023). All-cause mortality, heat-related emergency room visits, and hospital admissions increase with high temperatures (Gasparrini et al., 2015; Liss & Naumova, 2019; Wald, 2019), and adverse health outcomes due to heat are expected to continue to increase for every additional increment of warming in the future (Weinberger et al., 2017).

Heat risk can be thought of as a function of (a) the heat hazard, or the potentially destructive physical phenomena, (b) the vulnerability, or the predisposition of a person to be adversely affected by the heat hazard, (c) the exposure, or the presence and degree to which people are affected by the hazard, and (d) adaptive capacity, or the ability to mitigate potential harm by taking action to reduce vulnerability and exposure (Figure S1 in Supporting Information S1). The frequency, intensity and duration of heat waves adversely impacts mortality (Gasparrini et al., 2015; Song et al., 2017; Weinberger et al., 2020). Individuals vulnerable to excess heat include the elderly, the very young, people with chronic diseases, and people on medication with side effects that decrease

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the sweating response (Bunker et al., 2016; Cheshire & Fealey, 2008; Sheffield et al., 2018; Yu et al., 2012). Additionally, being less educated or belonging to a non-white racial or ethnic group in the US has been found to correlate with having less adaptive capacity to high temperatures (Basu, 2009; Rosenthal et al., 2014; Schmeltz et al., 2016). Access to and use of cooling methods is one strategy to increase adaptive capacity, but this strategy can be impacted by lack of financial and social resources (Lim & Skidmore, 2020; Rosenthal et al., 2014; Schmeltz et al., 2016). Most heat-related morbidity and mortality can be prevented with planning and avoidance of exposure (Ebi et al., 2021). To evaluate heat risk, information is needed about where, when, and how intense the heat hazard is, and who is vulnerable. To reduce heat risk, strategies need to increase adaptive capacity. Here we analyze electric fan usage as one potential strategy to increase adaptive capacity to reduce heat risk. We focus on electric fans because they can be a more accessible and sustainable method of cooling than air conditioning.

Fans cool a person via evaporation of liquid water from the skin's surface and advection of air, rather than cooling of the surrounding environment, thus making them effective outdoors or in unconfined spaces. However, there are temperature limits at which electric fans can no longer cool a person because at high temperatures, fans can increase heat transfer to the body from advection of hot air. Previously the World Health Organization and World Meteorological Organization recommended that fans only be used at air temperatures up to 35°C (McGregor et al., 2015). However, these recommendations neglected to consider evaporative cooling due to sweat or moisture on the skin. Morris et al. (2021) used human energy balance models of evaporative and dry heat transfer to develop temperature and humidity thresholds recommended for safe fan use. For ease of understanding for the public, they generalized the results to only temperature thresholds by identifying the lowest temperature, regardless of ambient humidity, for which fan use was 100% effective. They developed three simplified temperature thresholds for different demographics, which have been suggested for widespread use in the *Lancet* review on reducing the health effects of hot weather and heat extremes (Jay et al., 2021).

Morris et al. (2021) and Tartarini et al. (2022) used weather station data around the globe to determine if fans could be safely used as a cooling strategy. Despite the important advances made by these studies, the global results prevent more granular analyses of local and regional heat hazard that could allow for targeted mitigation and intervention measures. Additionally, weather station data only provide temperature data at specific geographic points, which can exclude large land areas and populations. In this study, we focus on temperatures in the continental US using spatially continuous, hourly data spanning 1950–2021 to assess the heat hazard associated with ambient temperatures (37°C, 39°C) too high for safe fan use. We assess population-weighted heat hazard using gridded population data (e.g., Rogers et al., 2021) and population-weighted heat hazard as a function of vulnerability using the Centers for Disease Control and Prevention (CDC) Social Vulnerability Index (SVI) (Center for International Earth Science Information Network-CIESIN-Columbia University, 2021). We hypothesize that vulnerable populations in the US are located in regions that disproportionately experience high temperatures (e.g., Hoffman et al., 2020; Hsu et al., 2021; Keith & Meerow, 2022; Manware et al., 2022; Park et al., 2018; Voelkel et al., 2018) and higher rates of warming (Alizadeh et al., 2022). Disproportionate high temperature hazard would have implications for the ability of socially vulnerable communities to safely use fans. We expect knowledge about where it is already too hot to safely use fans and how locations with high temperatures overlap with socially vulnerable populations to help direct resources that can be used for other additional heat risk mitigation strategies to vulnerable communities.

2. Data and Methods

2.1. Climate Data

We use fifth generation reanalysis data (ERA5) from the European Center for Medium Range Weather Forecasting (Hersbach et al., 2020). The ERA5 data include hourly estimates of ambient 2-m air temperature from 1 January 1950 to 31 December 2021. ERA5 data are provided at a spatial resolution of ~0.25° × 0.25° (~31 km) for the entire globe, but here we focus on temperatures over the Continental US (CONUS) where the CDC provides SVI data (Section 2.2). We use bilinear interpolation to spatially regrid the ERA5 data to the ~1 km grid resolution of the population and SVI data (Section 2.2). Use of ~0.25° × 0.25° temperature data interpolated to a ~1 km grid resolution will underestimate temperature variations at fine spatial scales (e.g., Shandas et al., 2019). However, Mistry et al. (2022) show that ERA5 data generally compare well to station data over North America, and estimates of non-optimal temperature-related risks derived from station and reanalysis data are similar. Furthermore, Rogers et al. (2021) compare station and ERA5 temperature data and conclude that the station and reanalysis differences are small over most mid-latitude locations, and ERA5 data are suitable for studying temperature extremes, particularly in locations with high station density and low topographic complexity.

2.2. Population and Social Vulnerability Data

We use high spatial resolution (∼1 km) gridded population data from Gridded Population of the World, version 4 revision 11 (GPWv4) (Center for International Earth Science Information Network-CIESIN-Columbia University, 2018) to determine where people are currently exposed to temperatures that exceed safe fan use thresholds. We use GPWv4 spatial population data from the year 2020 to estimate population-weighted hazard 1950–2021. Therefore, our results do not show changes in risk due to changes in US population demographics. Instead, we are comparing present-day hazard with what the present-day population would have experienced had it had the same geographic distribution of population and SVI in the past to isolate the effect of changing climate on population heat hazard through time. GPWv4 also provides spatial population data for the years 2000, 2005, 2010, and 2015; in Section 4, we assess the impacts of changing population demographics on our results. Using bilinear interpolation, we spatially interpolate the ERA5-based temperature data and temperature threshold exceedance counts to the GPWv4 spatial grid to estimate population-weighted hazard (Text S1 in Supporting Information S1).

We use gridded, census tract ∼1 km spatial resolution 2010 US Census data provided by the Socioeconomic Data and Applications Center (SEDAC) (Center for International Earth Science Information Network-CIESIN-Columbia University, 2017) to calculate the fraction of population at each ∼1 km location in the US that is greater than or equal to 65 years old to estimate heat hazard for older adults. We were unable to find gridded age structure data for the year 2020, so we rely on the 2010 data. Although the overall US 65+ age demographic has grown in the last decade, a 2022 Census Bureau report indicates that only 6% of older adults have moved in the last several years, and over half of these moves occurred in the same county (Mateyka & He, 2022), so we would not expect the changing geographic locations of older adults in the last decade to noticeably impact our population-weighted averages. However, because the 65+ age demographic has grown since 2010, our analysis underestimates people-hours exceeding temperature thresholds for this age demographic.

Spatial data from the CDC SVI for the year 2018 is provided as a ∼1 km spatial resolution gridded spatial data set similar to GPWv4, but at the census tract level (Center for International Earth Science Information Network-CIESIN-Columbia University, 2021). The CDC SVI uses factors that include socioeconomic status, household composition and disability, minority status and language, and housing type and transportation. The SVI is a percentile ranking that represents the percentage of census tracts that are equal to or lower than the census tract of interest in terms of social vulnerability. For example, an SVI of 0.75 indicates that 75% of census tracts in the nation are less vulnerable than the census tract of interest. The CDC SVI is associated with heat-related health outcomes in locations in the US (Lehnert et al., 2020) and can help with planning for mitigation of natural hazards due to climate change (Berke et al., 2015). Here we use these datasets to identify where vulnerable communities intersect geographically with climate conditions considered unsafe for low-cost cooling options (i.e., fan use). We spatially interpolate climate information to the CDC SVI grid to estimate SVI-weighted heat hazard (Text S1 in Supporting Information S1).

2.3. Temperature Thresholds for Safe Fan Use

Here we use results from a biophysical modeling study (Morris et al., 2021) that reports air temperature thresholds considered safe for fan use: 39°C for young, healthy adults (aged 18–40 years), 38°C for older, healthy adults (aged 65+ years), and 37°C for older adults (aged 65+ years) taking anticholinergic medication. Older adults have a 25% reduction in the ability to sweat compared to young healthy adults, and older adults on anticholinergic medication have a further 25% reduction in ability to sweat (Gagnon et al., 2017; Hou et al., 2006; Inoue & Shibasaki, 1996; Morris et al., 2021). For context, recent studies report that ∼9%–21% of older adults in the US used anticholinergic medication (Kachru et al., 2015; Lockery et al., 2021). We focus on the lower (37°C) and higher (39°C) thresholds to highlight where some of the most vulnerable populations (older adults on medications) and less vulnerable populations (healthy adults) would be unable to safely use fans given ambient climate conditions. These recommended temperature thresholds are conservative because they assume high humidity (see Section 1 for further explanation).

2.4. Calculating Threshold Exceedance

We combine hourly ERA5 data with these temperature thresholds to count the number of hours between 1950 and 2021 showing 2-m ambient air temperatures that exceed recommended thresholds for safe fan use. First, we count the number of hours each year at each location in the ERA5 data (at a ~31 km spatial resolution, see Section 2.1) that exceed each threshold. Next, for each period (early: 1950–1969, late: 2002–2021), we calculate the average numbers of hours per year over the "early" and "late" 20-year time segments that exceed this threshold for each location. We test the sensitivity of our results to the choice of a 20-year as opposed to a 30-year time window (early: 1950–1979, late: 1992–2001) and discuss these differences in Section 3.1 and Section 3.2.

2.5. Population Heat Hazard and Social Vulnerability

We combine spatial information related to the number of hours considered cool enough for safe fan usage (Sections 2.1 and 2.2) with spatial population data to estimate heat hazard for various populations: (a) all people in the CONUS, (b) communities ranked "high" on the social vulnerability index (SVI), and (c) communities ranked "low" on the SVI. To show summary statistics and change through time, we calculate average temperatures and average hours of threshold exceedance over the CONUS. We calculate three types of averages (see Text S1 in Supporting Information S1): area-weighted averages (including all land area in the CONUS), population-weighted averages (including all population in the CONUS), and SVI population-weighted averages (including population only in either high-vulnerability locations where SVI > 0.75 or low-vulnerability locations where SVI < 0.25 in the CONUS). For the 37°C threshold, we population-weight heat hazard using spatial population count estimates of older adults age 65+ (Section 2.2).

2.6. Statistical Testing

We assess significance of trends through time using the Mann-Kendall test (Gilbert, 1987; Kendall, 1948; Mann, 1945). We assess significance of difference in distributions using a Mann-Whitney test (Mann & Whitney, 1947). All analysis is conducted in Python, and statistical analysis uses the pymannkendall package (Hussain & Mahmud, 2019) and the scipy.stats mannwhitneyu package.

3. Results

3.1. Geography of Maximum Temperatures, Population, and SVI

To understand the geography of the hottest historical temperatures in the US, we use hourly ERA5 data to analyze the annual maximum temperature over the last 20 years (annual maximum temperature is calculated from hourly data, then averaged over the 2002–2021 period). ERA5 data show ambient maximum air temperatures exceed 40°C across much of the Southwest, West, and east of the Rockies in the Plains, with temperatures reaching 36–38°C across much of the Southeast and east of the Appalachians along most of the Atlantic coast (Figure 1a). We test if use of a traditional 30-year climatological average (including years 1992–2021) noticeably changes our results and find that the locations that exceed these thresholds are similar using both averaging windows (Figure S2 in Supporting Information S1). The locations that show maximum temperatures exceeding 36°C are co-located with some locations with large populations (Figure 1b) and many high-SVI locations (Figure 1c). Many high-SVI locations are located in the southern part of the CONUS, where it also tends to be the warmest.

We find that at the CONUS-scale, high-SVI locations disproportionately experience higher temperatures. We assess the variability through time of average maximum temperature over the CONUS using three metrics: (a) area-weighted average maximum temperature, (b) population-weighted annual maximum temperature, and (c) population-weighted annual maximum temperature in high-SVI locations (Section 2.5). Although annual average maximum CONUS temperatures are increasing at a similar rate using the three metrics (0.12°C/decade, $p = 0.002$; 0.09°C/decade, $p = 0.02$; 0.11°C/decade, $p = 0.01$; respectively), locations with high SVI are on average 1–2°C warmer than the area-weighted geographic average or the population-weighted average over the CONUS (Figure 1d). This disparity between population-weighted temperatures and high SVI-weighted temperatures indicates that communities considered more vulnerable are, on average, experiencing higher heat extremes in the CONUS. To test this, we also compared high-SVI weighted and low SVI-weighted mean maximum temperatures over the last 20 years in the CONUS; low-SVI weighted temperatures were 35.4°C, and high-SVI weighted temperatures were 36.7°C. A Mann-Whitney test shows that the distributions of population-weighted maximum temperatures (2002–2021) in low-SVI and high-SVI locations are significantly different ($p < 0.001$), confirming that those considered socially vulnerable are disproportionately located in geographies with higher temperatures in the CONUS (Figure 2).

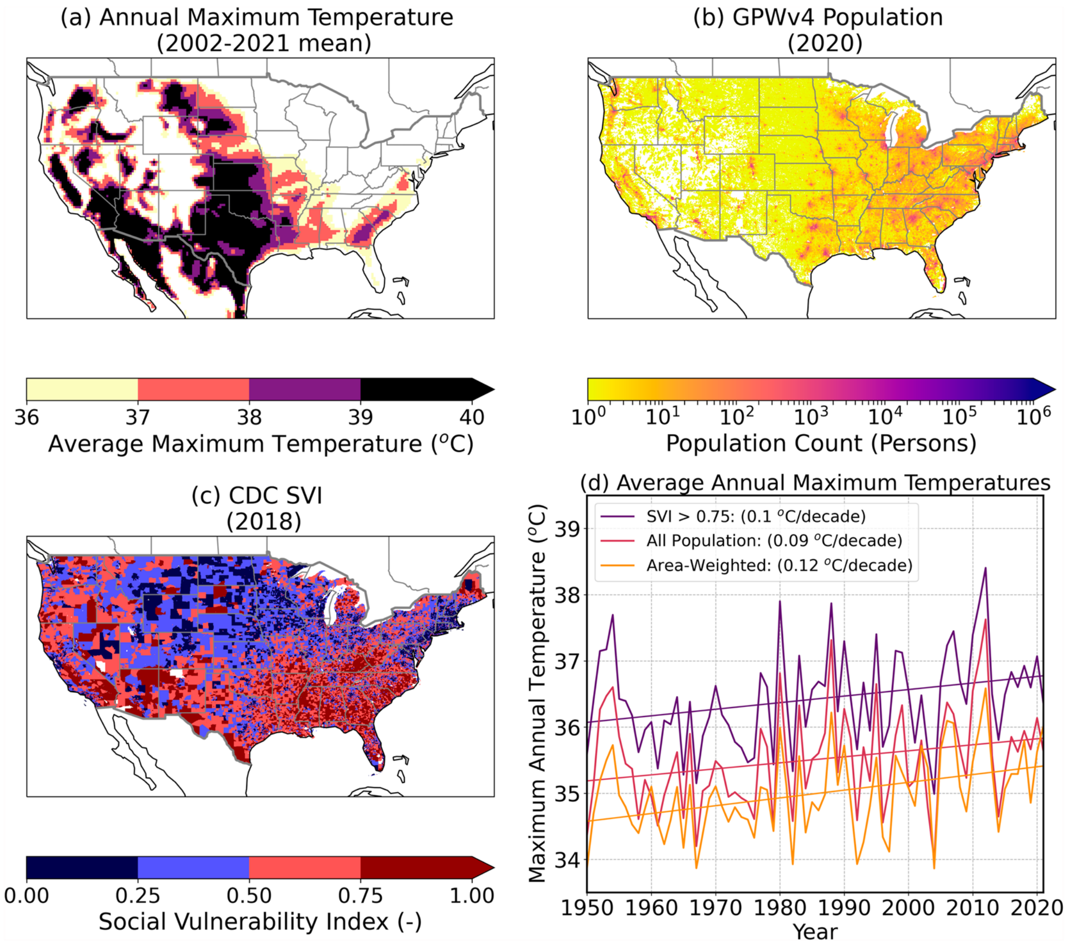

Figure 1. Maps of average annual maximum temperatures, population, Centers for Disease Control Social Vulnerability Index (CDC SVI), and time series of weighted average annual maximum temperatures over the Continental United States (CONUS). (a) Average maximum annual temperature over the CONUS 2002–2021, with white areas showing where maximum annual temperatures are <36°C. (b) 2020 population count data over the CONUS region from Gridded Population of the World, v4 data (GPWv4). (c) CDC SVI for the year 2018, with higher SVI values indicating higher vulnerability. (d) Time series of SVI-weighted (purple line), population-weighted, (red line), and CONUS area-weighted (orange line) average maximum annual temperatures, with best fit trend shown by straight lines through the time series, and trends/decade shown in the legend. A Mann-Kendall test indicates that all time series show significant positive trends through time ($p = 0.002$, $p = 0.02$, $p = 0.01$, respectively). Population-weighted averages use GPWv4 2020 population statistics for all years to isolate the effect of changing climate on population heat hazard through time.

3.2. Number of Hours Exceeding Thresholds for Safe Fan Use Across the CONUS

We assess the average hours per year considered unsafe for fan usage for the two 20-year periods of 1950–1969 ("early") and 2002–2021 ("late"), and the change between these two periods (Figure 3). An average diurnal cycle for Yuma, Arizona in July shows that the hottest hours of the day typically occur during the afternoon to late evening (Figure S3 in Supporting Information S1). In summer months in particularly hot locations such as Yuma, most daylight hours exceed the 37°C threshold, and several consecutive afternoon and evening hours can exceed the 39°C threshold (Figure S3 in Supporting Information S1). Across much of the US, we find the number of hours exceeding temperature thresholds for safe fan use has increased in the last 70 years. In the early period, the 37°C threshold was reached at least once across most locations in the CONUS (colored shading in Figure 3a), except higher elevation locations and some locations in the northeastern CONUS. Some locations in the southwestern CONUS experience over 800 hr/year (or an average of over 34 days/year). In the later time period, the 37°C threshold is reached over 1,000 hr/year (or over 44 days/year) in some locations. Notably, there are large increases in the number of hours that reach this 37°C threshold between the two time periods, particularly in the southwestern US along the US/Mexico border and from southern Texas to Oklahoma, in the central valley of

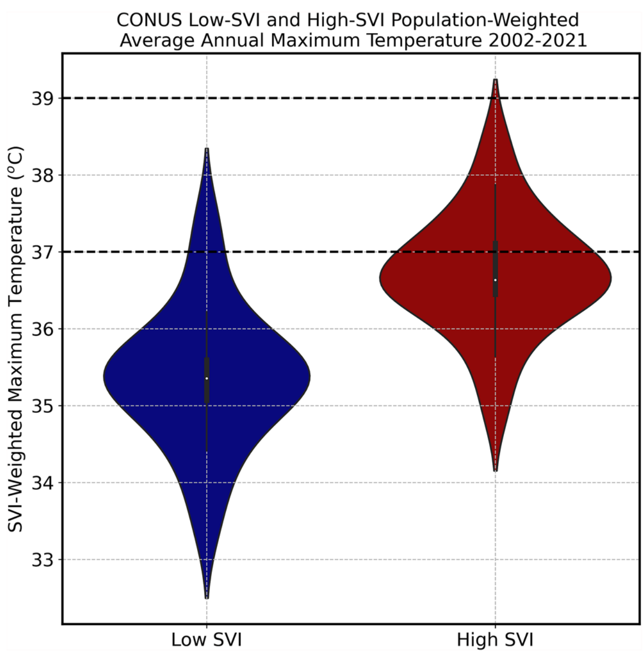

Figure 2. Violin plots showing the distribution of population-weighted average maximum annual temperatures (2002–2021) in low-social vulnerability index (SVI) locations (blue) and high-SVI locations (red). Violin plots show the probability density of the data at different values and are smoothed by a kernel density estimator. Horizontal dashed lines mark 37°C and 39°C temperature thresholds discussed in text. Population-weighted averages use GPWv4 2020 population statistics for all years.

California, and in some locations in the mountainous West (Figure 3c). Some locations in the southwestern US show an increase of more than 260 hr/year (over 11 days/year).

The 39°C threshold shows a similar geographic pattern to the 37°C threshold, but with fewer hours/year that exceed this higher threshold. Regions with particularly high exceedance counts for the 39°C threshold include the California/Arizona/Mexico border, California Central Valley, and southern Texas/Mexico border. In the early period, some locations show upwards of 479 hr/year (on average almost 20 days/year) that exceed the higher threshold. In the later period, some locations show up to 686 hr/year (over 28 days/year) that exceed the higher threshold. The largest increases between the two time periods are found along the southern Texas/Mexico border, and near the Colorado River along the Arizona/California border, with some locations showing at least 210 more hr/year between the two time periods (or almost 9 days/year). We test the sensitivity of our results to using a 30-year average (1950–1979 and 1992–2021) and find the results are nearly identical, but the change in threshold exceedance between the early and late time periods is slightly decreased using the 30-year window because the 1992–2021 period includes, on average, slightly cooler years than the later 2002–2021 time period (Figure S4 in Supporting Information S1).

3.3. Threshold Exceedance in Populated Locations and in High-SVI Locations

We are interested in how heat hazard affects people in socially vulnerable communities, so we assess where high temperatures geographically overlap with high-SVI locations. Figure 4 shows maps of people-hours in locations where SVI > 0.75 ("high" social vulnerability locations) in the early and late time periods. Spatial estimates of population aged 65+ years are used for the 37°C threshold because this is the temperature threshold for older adults taking medication (left column, Figure 4). Similar to total hours across all locations (Figure 3), person-hours are relatively high across the US-Mexico border, particularly near southern Texas and near the California/Arizona border, as well as in southeastern Washington state. Additionally, person-hours are relatively high on the east coast due to large populations with a comparatively low to moderate number of hours exceeding the thresholds. Although warming has increased the number of hours that exceed these thresholds across almost all regions, an area between the eastern Great Plains and the southern central US (including parts of South Dakota, Kansas, Missouri, Arkansas, and Mississippi) has experienced a small decrease in the number of people-hours. This small decrease in hours (Figure 3) is multiplied by several locations with large populations (Figure 1b), creating moderate decreases in people-hours in this region. However, despite the decrease in person-hours in the last 70 years in some locations, the average person-hours/year for the recent 20-year period (exceeding the 37°C threshold) is greater than 5,000–8,000 in many of these locations. Note that the geographically widespread "hotspot" of locations with large numbers of hours exceeding temperature thresholds for safe fan use in southwestern Arizona, southeastern California, and southern Nevada (Figure 3) is much smaller when evaluated with person-hours. The population density is generally smaller across relatively large areas that are hot, so the population heat hazard is lower (Figure S5 in Supporting Information S1 shows population where SVI > 0.75).

3.4. Threshold Exceedance Through Time

Individuals living in high-SVI locations not only experience warmer temperatures (more threshold exceedance), but also higher rates of warming that are relevant for safe fan use (increases in threshold exceedance through time) than the overall CONUS population. Figure 5 shows the temporal evolution (1950–2021) of population-weighted hours considered unsafe for fan usage for the 37°C and 39°C thresholds for the high-SVI and low-SVI regions in the CONUS. Older adults living in high-SVI locations, on average, experienced up to a maximum of 60–70 hr/year (~2–3 days/year) that exceed the 37°C threshold, whereas older adults in low-SVI locations, on average, only

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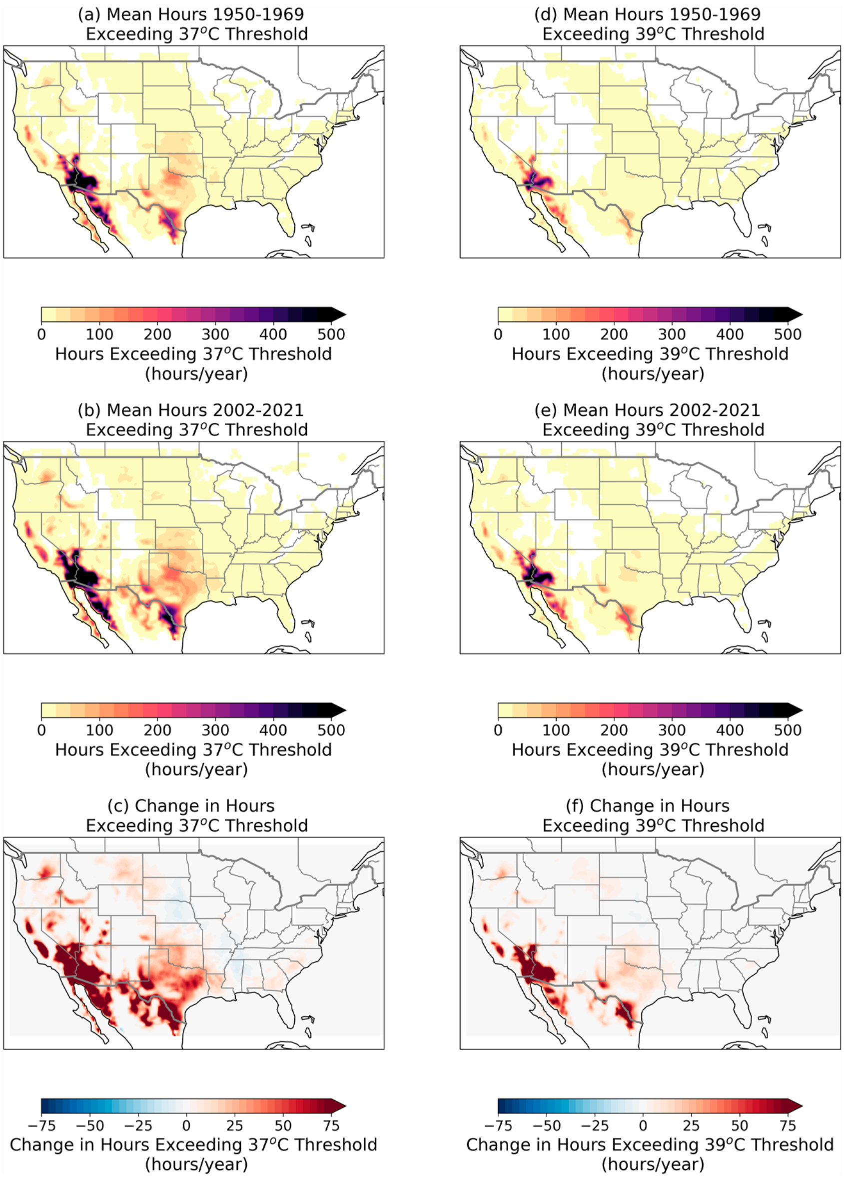

Figure 3. Mean number of hours per year considered unsafe for fan use in 1950–1969 (top), 2002–2021 (center), and the change in hours between these two time periods (bottom) for the 37°C threshold (left) and 39°C threshold (right). Note that due to computational demands, data have been spatially cropped to only show latitudes between 24°N and 50°N.

experienced up to a maximum of 40 hr/year (∼1.5–2 days/year). We find average threshold exceedance experienced by older adults is similar to the overall CONUS population (Figure 5, Figure S6 in Supporting Information S1). Importantly, the high-SVI locations show trends that are two times higher than the trends in the low-SVI locations (Figure 5) and about 50% higher than the all-CONUS population-weighted hours (Figure S6 in Supporting Information S1). For example, the population-weighted number of hours more than doubled between 1950–1969 and 2002–2021 for the 37°C threshold in high-SVI regions (from about 25 to 50 hr/year, or from about 1 day/year to about 2 days/year), but only increased from about 10 hr/year to about 20 hr/year (from <0.5 days/year to <1 days/year) for people in low-SVI locations (Figure 5).

Heat hazard disproportionately impacts communities in high-SVI locations both in terms of higher average heat hazard, and faster increasing hazard over time, with people-hours in high-SVI locations exceeding low-SVI locations despite the lower population in the high-SVI locations. Figure 6 shows the number of people-hours exceeding the 37°C and 39°C thresholds in high-SVI versus low-SVI locations. In the CONUS in the year 2020,

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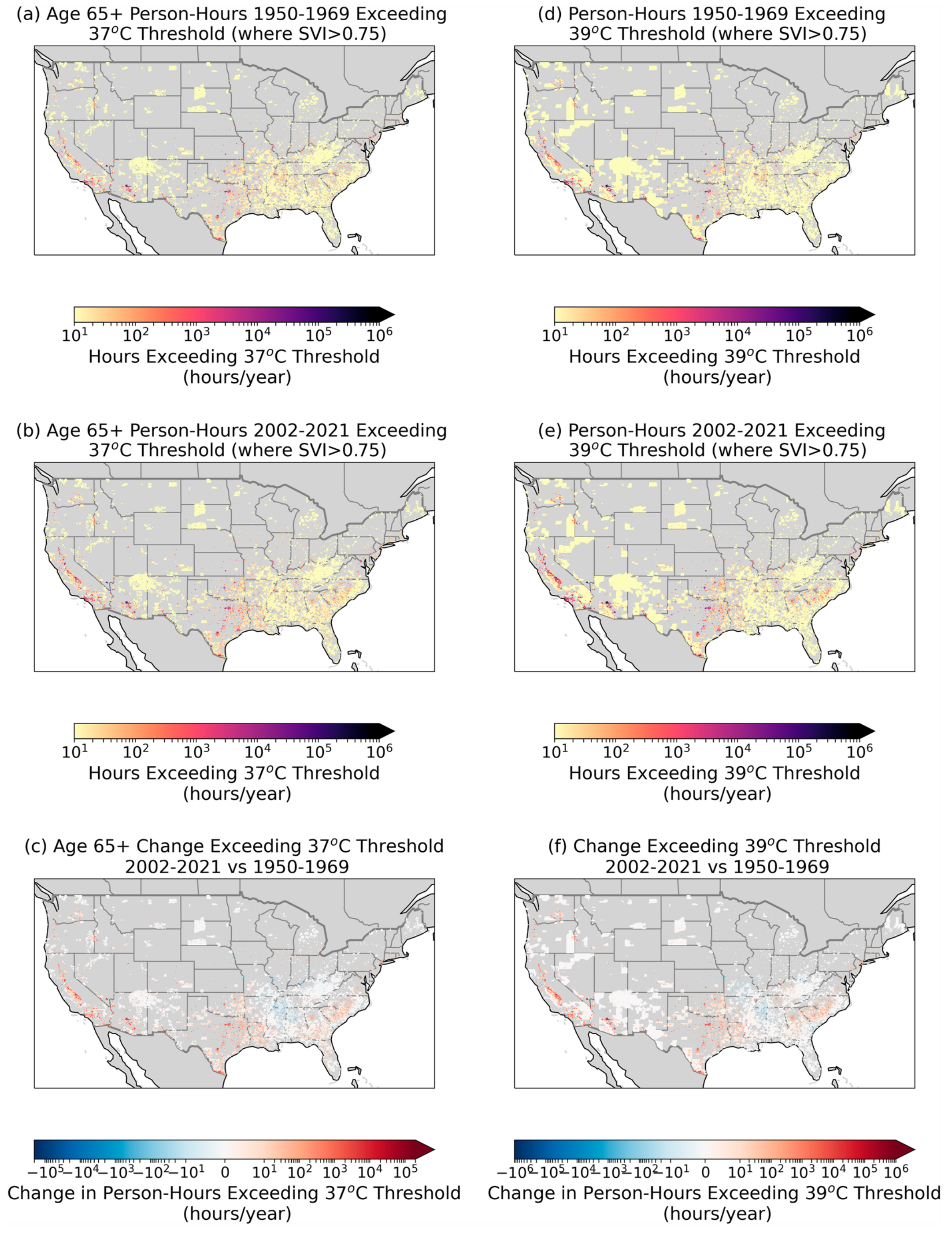

Figure 4. Average number of people-hours per year considered unsafe for fan use in 1950–1969 (top), 2002–2021 (middle), and the change in hours between these two time periods (bottom) for the 37°C threshold for socially vulnerable older adult populations (left) and 39°C threshold for socially vulnerable healthy adults (right). Left column uses spatial population estimates of the fraction of adults aged 65+ from the United States Census. Background gray shading on maps shows where social vulnerability index (SVI) is <0.75. High social vulnerability is defined as locations where SVI > 0.75. Calculation of person-hours uses GPWv4 2020 population statistics for all years to isolate the effect of changing climate on population heat hazard through time.

approximately 64 million people lived in high-SVI locations, and 91 million people lived in low-SVI locations. Similarly, about 7 million older adults lived in high-SVI locations, and about 12 million older adults lived in low-SVI locations. Therefore, if the heat hazard was similar in low- and high-SVI locations, we might expect

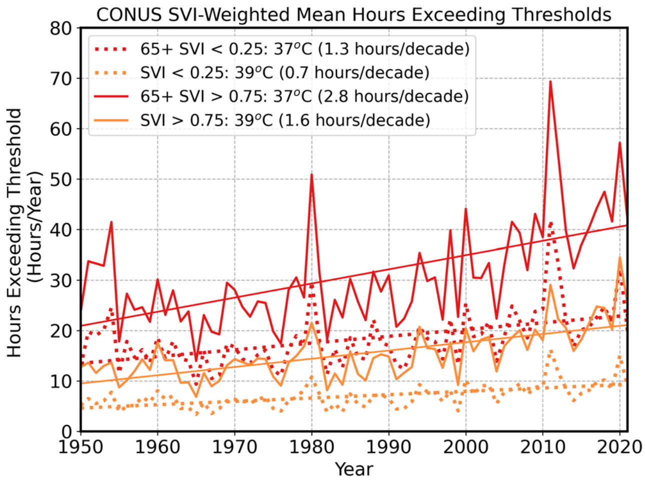

Figure 5. Population-weighted average number of hours per year (1950–2021) considered unsafe for fan use in high-Social Vulnerability Index (SVI) locations (solid lines) and low-SVI locations (dotted lines) for the 37°C (red) and 39°C (orange) thresholds in the Continental US (CONUS). Straight lines show best fit trend lines, and legend shows trends (hours/decade). Red lines (37°C threshold) use spatial population estimates of the fraction of adults aged 65+ from the US Census. A Mann-Kendall test indicates all time series show significant ($p < 0.001$) positive trends through time. Note that the population-weighted trends in high-SVI locations are about twice as large as the population-weighted trends in low-SVI locations. Population-weighted averages use GPWv4 2020 population statistics for all years to isolate the effect of changing climate on population heat hazard through time.

about 50% more people-hours in low-SVI as compared to high-SVI locations. However, we find the opposite; the number of people-hours exceeding both the 37°C and 39°C thresholds is higher in high-SVI locations as opposed to low-SVI locations, and the trends (1950–2021) in high-SVI locations are approximately twice the magnitude of the trends in the low-SVI locations. The number of people-hours exceeding the 37°C threshold in high-SVI locations are similar to the number of the people-hours exceeding this threshold in low-SVI locations, despite the larger number of older adults living in low-SVI locations. This discrepancy in people-hours is even more apparent for the higher 39°C threshold; the high-SVI location mean is ∼44% higher than the low-SVI location mean (Figure 6, Table 1).

4. Discussion and Conclusions

Here we have shown that many locations across the western, southwestern, and southern CONUS (as well as parts of northern Mexico) already experience ambient climate conditions that exceed the recommended temperature thresholds for safe fan use, even for the least sensitive demographic of healthy, younger adults. Hotspots of concern include the California/Arizona border region, the Central Valley region of California, the southern Texas/Mexico border region, much of central Texas and Oklahoma, and southeastern Washington state. In particularly hot locations, most afternoon hours during the hottest months of the year can exceed these thresholds. Some locations show at least 200 more hr/year that exceed the lower 37°C threshold over the last 20 years as compared to the 1950–1969 period.

Here we have focused our analysis on the impacts of climate change by using static 2020 population demographics for all years in the analysis (Section 2.2). We test if our main results, as they relate to increasing heat exposure and temperature threshold exceedance through time, are sensitive to use of changing GPWv4 population demographics for the years 2000, 2005, 2010, and 2015 (Figure S7 in Supporting Information S1). Our main results do not change when using dynamic population demographics, and the impacts of changing population fall well within the impacts of interannual climate variability. However, we find that for the year 2000, CONUS population-weighted average maximum temperatures are ∼0.39°C lower, and CONUS population-weighted threshold exceedance is ∼20% lower if we account for changes in population statistics (Figure S7 in Supporting Information S1). This difference suggests that, on average, populations have been moving to warmer locations in the last 20 years, and our main results are likely under-estimating the combined impacts of shifting population and a warming climate on increasing heat risk over time.

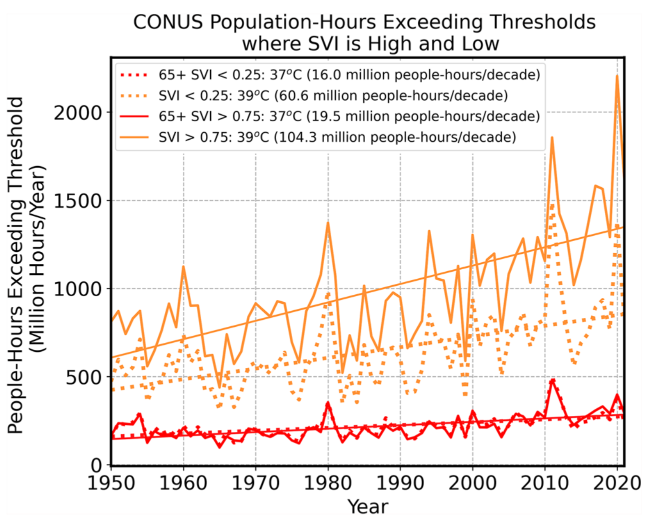

Figure 6. People-hours per year in high-Social Vulnerability Index (high-SVI, solid lines) and low-SVI locations (dotted lines). People-hours take into account the number of people living in high-SVI locations and low-SVI locations multiplied by the hours per year considered unsafe for fan use in 1950–2021 for the 37°C (red) and 39°C (orange) thresholds over the continental United States using static 2020 population statistics to isolate the impacts of warming temperatures. A Mann-Kendall test indicates all time series show significant positive trends ($p < 0.001$).

Many locations with high social vulnerability are co-located with high heat hazard (e.g., Manware et al., 2022). Indeed, we show there is a disproportionate heat hazard and a faster increase in temperature extremes for communities in high-SVI locations compared to communities in low-SVI locations. More hours, on average, exceed thresholds for safe fan use in the communities that are the most likely to have fewer resources and less adaptive capacity to cope with high temperatures. In the last several years, older adults aged 65+ living in high-SVI locations on average experienced more hours that exceeded the 37°C safe fan use threshold for healthy older adults than the general age 65+ CONUS population. Additionally, the high-SVI locations show trends in increasing hours exceeding these thresholds that are ∼50% higher than the trends in overall CONUS population-weighted hours (and over twice those of low-SVI locations), highlighting that individuals

Table 1
Population in the Year 2020 and People-Hours Exceeding the 37 and 39°C Thresholds in High-Social Vulnerability Index (SVI) and Low-SVI Locations in the Continental US (CONUS)

Location	CONUS age 65+ population in 2020 in millions	People-hours exceeding 37°C in millions per year age 65+ (min-max)	CONUS all-age population in 2020 in millions	People-hours exceeding 37°C in millions per year (min-max)	People-hours exceeding 39°C in millions per year (min-max)
High SVI (SVI > 0.75)	7	215 (97–483)	64	2,416 (1,143–5,114)	977 (438–2,204)
Low SVI (SVI < 0.25)	12	218 (111–499)	91	1,604 (794–4,205)	639 (310–1,489)

Note. Mean people-hours for 1950–2021 are shown outside parentheses, and range (minimum to maximum) across the 72-year period is shown in the parentheses. Numbers in the table are shown as millions. Calculation of people-hours uses GPWv4 2020 population statistics for all years.

living in high-SVI locations not only experience warmer temperatures (more threshold exceedance), but also higher rates of the number of hours/year that are approaching and exceeding important safety thresholds that relate to climate adaptation. Future warming will likely exacerbate these inequalities (e.g., Alizadeh et al., 2022).

Despite the importance of these findings for climate adaptation and resilience, there are several limitations to this study. First, this study could benefit from higher resolution observations of temperatures. Here, we downscaled ~0.25°(~31 km) spatial resolution hourly temperature data to ~1 km, but we are underestimating temperature variations at finer spatial scales due to land use and land cover variations, including vegetation cover and type and development intensity (e.g., Shandas et al., 2019). Similarly, the CDC SVI data used here only include social vulnerability at the census tract scale, but within a given census tract vulnerability can vary at even finer spatial scales. Nonetheless, the resolution of the data used here provides results that are actionable for resource allocation or public health decisions made at the county or municipal level. Second, due to data constraints, we used information about the spatial distribution of older adults from the year 2010 to estimate heat hazard for older adults (Section 2.2). Although our results could be improved by using more updated geographic information, a Census Bureau report (Mateyka & He, 2022) indicates that most older adults have not moved in the last several years, so the average temperature exposures we report should not be particularly sensitive to this constraint. Third, although we use ambient (outdoor) 2-m air temperature to estimate geographic population heat hazard as it relates to temperatures above these thresholds, people often stay indoors on hot days and may not sit in the shade outside using a fan. Future work could model indoor temperatures based on building characteristics and outdoor ambient climate conditions (e.g., Sailor et al., 2019). Fourth, we have focused on temperature thresholds recommended in the *Lancet* (Jay et al., 2021). These temperature thresholds are based on the lowest temperature, regardless of humidity, at which a fan is 100% effective (Morris et al., 2021; Tartarini et al., 2022). At low humidity, temperatures up to about 1–2°C above the threshold values used here may still be safe for fan use. Furthermore, reliance on temperature alone may not be suitable for informing the most accurate heat mitigation strategies (e.g., Chakraborty et al., 2022) or communicating dangerous heat wave conditions (e.g., Cvijanovic et al., 2023). Future work could provide a more accurate assessment that accounts for both temperature and humidity, but this added complexity should be treated with caution given public perceptions of the health risks of extreme heat in the US (Howe et al., 2019). Finally, although Morris et al. (2021) focused on three general categories of adults, there are a variety of factors that can make individuals more sensitive to heat (e.g., Ebi et al., 2021 and references therein).

Our results serve as a foundation for future work. For example, the high temperatures discussed here likely create uncomfortable environments, especially in the presence of moderate to high humidity; this study examined safety thresholds, not comfort thresholds, in relation to safe fan use. Future work could explore how fans, evaporative coolers, and air conditioning could be combined to reduce energy use and maintain comfort (e.g., Malik et al., 2022). Additionally, the timing and clustering of hours considered unsafe for fan use could be assessed. Clustering of consecutive hours of high temperatures may have more significant health effects. For example, hot nights that follow hot days have a higher mortality risk than cool nights that follow hot days (Murage et al., 2017). Furthermore, as we have shown here, some of the hottest locations in the CONUS are often located in rural areas (Figures 1 and 3). However, many of the policies intended to combat heat exposure are directed to urban populations (e.g., cooling centers). Rural populations tend to have less access to healthcare to properly manage chronic illnesses, and these populations can have less access to energy-efficient cooling strategies, which can exacerbate heat exposure and heat-related illness (Harduar Morano et al., 2016; Kovach et al., 2015). Work to stratify our findings by rural versus urban could illuminate intersecting disparities in heat hazard and vulnerability.

Climate change is expected to increase the frequency, intensity and duration of high temperatures and associated health impacts (e.g., Guo et al., 2018; Vicedo-Cabrera et al., 2021). Since the use of air conditioning in place of less energy intensive cooling methods (e.g., fans, evaporative coolers) can drive increased energy use and magnify the urban heat island effect, this work serves as a foundation to explore the utility of various cooling methods under 21st century warming projections. As global warming increases local temperatures, these results highlight the need to direct resources to some of the most vulnerable communities who are the most impacted by climate change and the least likely to have the resources to cope with climate change, particularly as global populations age into higher-risk demographics that are more susceptible to high temperatures. These findings also show how the use of fans remains a practical strategy to keep temperatures at safe levels in much of the US (Morris et al., 2021; Tartarini et al., 2022), highlighting how projected increases in energy demand for air conditioning might be reduced through increased fan usage in many areas (e.g., Malik et al., 2022).

We hope stakeholders can use the research presented here to make better-informed decisions about the direction of cooling resources to vulnerable communities to encourage more sustainable and equitable adaptation in a warming world. For example, simply increasing inefficient air conditioning use could elevate electricity demand in cities as well as greenhouse gas emissions. By contrast, deploying heat mitigation strategies intended to reduce the built environment's contribution to urban heat island effects (e.g., urban green forestry) could decrease heat hazard more sustainably. Furthermore, implementation of heat management strategies can help prepare communities to respond to heat via use of strategies such as early heat warning systems, emergency planning, cooling centers, and ensuring access to reliable cooling (e.g., Keith & Meerow, 2022).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data used in this manuscript include: ERA5 hourly data on single levels from 1950 to 2021 (Hersbach et al., 2023), CDC SVI data from the NASA SEDAC (Center for International Earth Science Information Network-CIESIN-Columbia University, 2021), GPWv4 data from the NASA SEDAC (Center for International Earth Science Information Network-CIESIN-Columbia University, 2018), and U.S. Census grids from the NASA SEDAC (Center for International Earth Science Information Network-CIESIN-Columbia University, 2017). The data and Python code that support findings of this study are openly available on Zenodo (Parsons et al., 2023).

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