Trends in Extreme Apparent Temperatures over the United States, 1949–2010

ANDREW GRUNDSTEIN

Climatology Research Laboratory, Department of Geography, The University of Georgia, Athens, Georgia

JOHN DOWD

Department of Geology, The University of Georgia, Athens, Georgia

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ABSTRACT

Biometeorological indices, such as the apparent temperature, are widely used in studies of heat-related mortality to quantify the human sensation to the environmental conditions. Increases in the frequency of environmentally stressful days as indicated by biometeorological indices may augment the risk for heat-related morbidity and mortality. This study examines trends in the frequency of days with extreme maximum and minimum apparent temperatures across the United States for 1949–2010. An increase in occurrence of 1-day extreme minimum apparent temperatures is particularly notable, especially in the eastern and western United States, with 44% of stations exhibiting positive trends. About 20% of stations have positive trends in 1-day extreme maximum apparent temperature, mostly in the western United States. The median trend for both 1-day extreme maximum and minimum apparent temperature is approximately 2 days per 10 yr, indicating that by 2010 there were 12 more days with extreme apparent temperatures than there were in 1949. Few stations with trends in 4-day extreme minimum or maximum apparent temperatures were noted. An important finding is that there has been a 53% increase in stations with positive trends in 1-day extreme minimum apparent temperatures and a 63% increase in stations with positive trends in 1-day extreme maximum apparent temperatures since a similar study by Gaffen and Ross was conducted using the period 1949–95. Although there is a clear increase in the hazard for days with extreme apparent temperatures, changes in health outcomes are modulated by factors, such as the age of the population and access to air conditioning, that affect social vulnerability.

1. Introduction

Extreme heat events are the leading cause of weather-related mortality in the United States (National Weather Service 2011). The health impact from extreme heat events is likely to increase because of greater risks of high temperatures from climate change and urbanization and because of greater social vulnerability arising from factors such as an aging population (Luber and McGeehin 2008). To account for the human sensation to environmental conditions, a combination of meteorological variables is often employed (Robinson 2001). The apparent temperature (AT), which is based on a human heat-balance model that accounts for temperature and humidity (Steadman 1979, 1984), has been used in many studies of heat-related mortality (e.g., Smoyer 1998; Smoyer et al. 2000; Davis et al. 2002, 2003; Sheridan and Dolney 2003; Hajat et al. 2006, Baccini et al. 2008; Basu and Ostro 2008; Zanobetti and Schwartz 2008; Michelozzi et al. 2009). An operational version of the AT, called the heat index, is used by the National Weather Service (NWS) in issuing excessive heat watches and warnings/advisories (Robinson 2001).

Changing patterns of biometeorological indices such as the AT may have health implications. Gaffen and Ross (1998) examined trends in the frequency of days with anomalously high ATs across the United States from 1949 to 1995. They observed that the annual frequency of extreme minimum ATs increased at the greatest number of stations, particularly in the eastern and western United States. Fewer stations, mostly confined to the western United States, exhibited increases in days with extreme maximum ATs. Stone et al. (2010) computed

Corresponding author address: Andrew Grundstein, Dept. of Geography Climatology Research Laboratory, University of Georgia, Athens, GA 30602.
E-mail: andrewg@uga.edu

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trends for the annual frequency of days with extreme minimum ATs for 53 U.S. metropolitan areas from 1956 to 2005, noting positive trends in all cities. On average, U.S. cities experienced 10 more days with extreme minimum ATs in 2005 than in 1956.

No study has reexamined trends of the broader network of stations used by Gaffen and Ross (1998) in conjunction with both extreme minimum and maximum ATs. Since the conclusion of their study in 1995, all but one year have had annual average U.S. temperatures that were among the hottest 35% of years, including five years among the top 10 and the two hottest years ever recorded, in 1998 and 2006 (NCDC 2011a). Thus, our study seeks to build upon Gaffen and Ross (1998) by extending the period of study to include the years through 2010. We investigate spatial and temporal patterns in 1-day and 4-day extreme maximum and minimum ATs.

2. Method

Our study utilized apparent temperature datasets compiled by the National Climatic Data Center (NCDC) for 187 stations (NCDC 2011b). The datasets were assembled following a method that is similar to one used by Gaffen and Ross (1998). The AT thresholds for extreme heat stress conditions at each station were determined from the 85th percentile of July and August daily maximum and minimum ATs over the 1961–90 base period. The 85th-percentile values have been shown to be closely correlated with weather-related mortality (Gaffen and Ross 1998). Also, the use of locally derived thresholds rather than fixed values accounts for local adaptation to the climate conditions. NCDC (2011b) used the TD3280 dataset of hourly and 3-hourly meteorological observations from first-order NWS stations in computing AT values. The highest and lowest hourly or 3-hourly AT values for each day were extracted and were used to represent the maximum and minimum daily AT, respectively. The results are four datasets of the number of days per month that exceed the local 85th percentile for 1-day maximum and minimum ATs and 4-day maximum and minimum ATs.

Using these AT datasets, we followed the approach of Gaffen and Ross (1998) in using a median pairwise slopes regression to calculate trends in the frequency of days with extreme AT values (Lanzante 1996). This method calculates the slopes of lines connecting all possible pairs of points and then selects the median value as the linear slope (Lanzante 1996). The advantage of this approach is that it is resistant to outliers and is appropriate for nonnormal data distributions (Wilks 1995). We utilized two different methods to assess the statistical significance of the trends. The first approach, employed in Gaffen and Ross (1998, 1999), uses the Spearman rank-order correlation coefficient between the frequency of extreme days and time to test for a monotonic trend using a two-tailed t test (significance level $\alpha = 0.05$). The second approach tests the hypothesis that the slope of the regression is equal to 0 with a two-tailed t test ($\alpha = 0.05$). Both approaches provided similar numbers and geographical patterns of stations with statistically significant trends, although they were not in perfect agreement. The method using Spearman's rank-order correlation, however, results in slightly more stations with trends, including some cases in which a trend is indicated even though the slope of the regression line is equal to 0. Thus, we present results using the second approach because it yielded fewer significant stations. Only stations that were $\geq$90% complete were used in the analysis, reducing the available stations to 157 or 158, depending on the dataset.

3. Results

Trends in 1-day and 4-day extreme maximum and minimum ATs were computed for 1949–2010 and for comparison with Gaffen and Ross (1998) for 1949–95. Over 40% (69) of the stations have statistically significant positive trends in 1-day extreme minimum ATs (Fig. 1a). The median trend is 2.0 days $(10\ \text{yr})^{-1}$, with 28% of the stations with <1.5 days $(10\ \text{yr})^{-1}$, 49% with 1.5–3.0 days $(10\ \text{yr})^{-1}$, and 23% with >3 days $(10\ \text{yr})^{-1}$. In geographic terms, the patterns are particularly noticeable in the eastern and western United States as well as in Alaska and Hawaii. When compared with trends for 1949–95, there has been a considerable increase in the number of stations with positive trends, increasing by 53%, from 45 to 69 stations, and spreading into the Midwest and the southern plains (Fig. 1b).

Approximately 20% of stations also have statistically significant positive trends in 1-day extreme maximum ATs (Fig. 2a). The median trend is 1.9 days $(10\ \text{yr})^{-1}$, with 39% of the stations having <1.5 days $(10\ \text{yr})^{-1}$, 39% with 1.5–3.0 days $(10\ \text{yr})^{-1}$, and 22% with >3 days $(10\ \text{yr})^{-1}$. These stations are located in the western United States as well as in Alaska, Florida, and Texas. No significant trends are evident across the Midwest or the eastern United States. Also, the number of stations with statistically significant positive trends increased by 63%, from 19 to 31 stations, when compared with the 1949–95 period (Fig. 2b).

Fewer stations have trends in 4-day extreme maximum and minimum ATs. Nine stations have positive trends in 4-day extreme minimum apparent temperatures; these are located in Arizona (Phoenix), Arkansas (Fort Smith), California (San Francisco), Florida (Miami

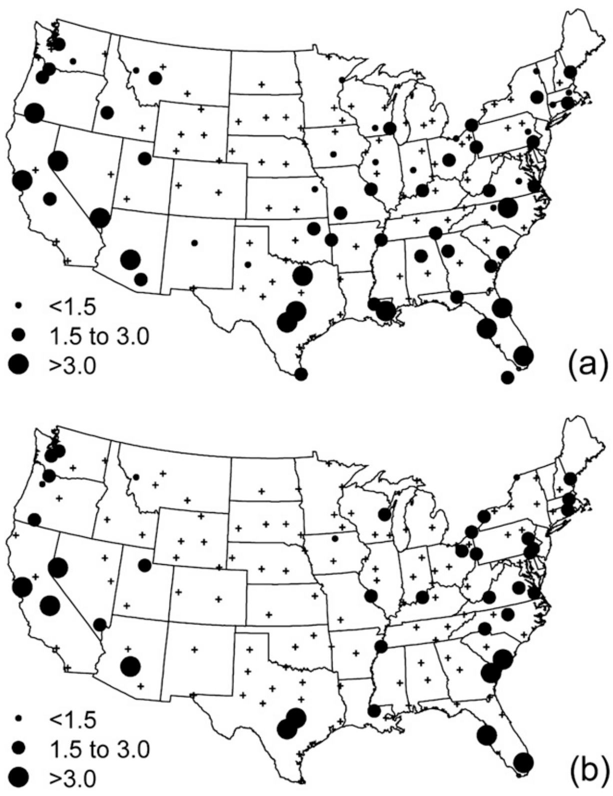

FIG. 1. Trends, in days per decade (10 yr), in annual 1-day extreme minimum AT for (a) 1949–2010 and (b) 1949–95. Three (two) stations in Alaska and two (three) stations in Hawaii have positive trends over 1949–2010 (1949–95). Plus signs show stations with no statistically significant trend.

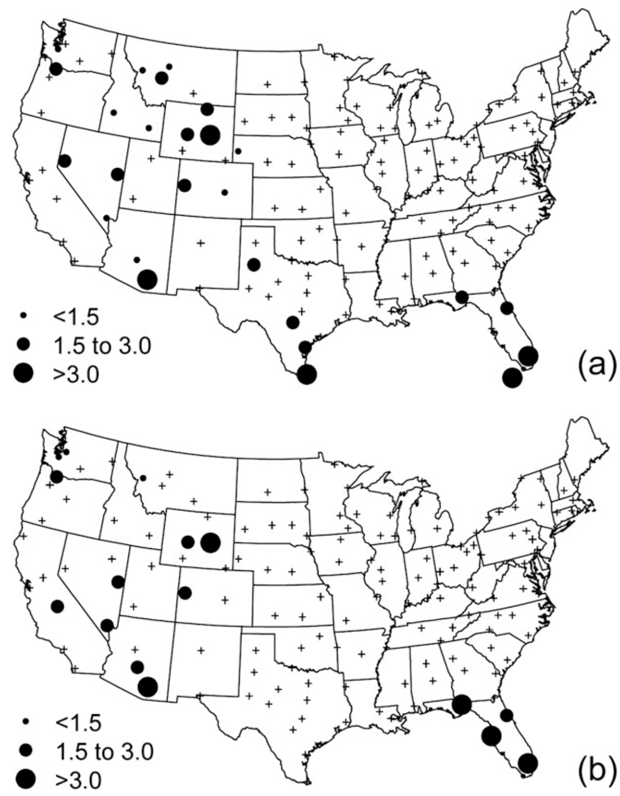

FIG. 2. As in Fig. 1, but for annual 1-day extreme maximum AT. Two (one) stations in Alaska and two (two) stations in Hawaii have positive trends over 1949–2010 (1949–95).

and Tampa), Nevada (Reno), Oregon (Medford), and Texas (Austin). By comparison, we observed no trends over the 1949–95 period. Three stations (Casper, Wyoming; Miami; and Tucson, Arizona) have positive trends in extreme 4-day maximum ATs over the 1949–2010 period; this number was only one station (Hilo, Hawaii) for 1949–95.

4. Discussion and conclusions

Across the United States, many stations exhibit an increasing frequency of days with 1-day extreme minimum or maximum ATs. Trends in 1-day extreme minimum ATs are located mainly in the eastern and western United States, and trends in 1-day extreme maximum ATs are located mainly in the western United States, Texas, and Florida. The number of stations with trends has increased considerably since an earlier study by Gaffen and Ross (1998) was conducted using the 1949–95 study period. Some of the increase in minimum trends may be associated with urbanization and the urban heat island effect, because many of the weather stations are located at airports near cities (Gaffen and Ross 1998). A recent study by Stone et al. (2010) supports this contention by observing the greatest increases in the annual number of extreme minimum AT heat events in the most-sprawling metropolitan regions.

The increasing frequency of days with extreme ATs presents a growing hazard. Yet, the health outcome from these changes is not certain. Davis et al. (2003) observed that, despite increases in AT, heat-related mortality in major metropolitan areas has declined over the 1961–98 period. They argue that this reduction in mortality is related to reduced vulnerability, principally as a result of increased use of air conditioning but also because of factors such as improved health care, implementation of heat watch/warning systems, and human biophysical acclimatization. In extending the study period through 2004, Sheridan et al. (2009) found that the decline in heat-related morality has stopped across the majority of major metropolitan areas since the mid-1990s. They argue that observed decreases in heat-related mortality may not continue as air conditioning has reached near saturation across much of the United States and rising energy costs may limit the use of air conditioning by some.

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