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RESEARCH ARTICLE

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More hots: Quantifying upward trends in the number of extremely hot days and nights in Tallahassee, Florida, USA: 1892–2018

James B. Elsner | **Svetoslava C. Elsner**

Department of Geography, Florida State University, Tallahassee, Florida

Correspondence
James B. Elsner, Department of Geography, Florida State University, Tallahassee, FL 32306.
Email: jelsner@fsu.edu

Abstract

Hot day and night occurrences in Tallahassee, Florida, USA are analysed and modelled. A hot day is defined as one during which the high temperature exceeds 100°F (37.8°C). A hot night is defined as one during which the low temperature fails to drop below 77°F (25°C). The U.S. National Weather Service Office (WSO) Tallahassee official record shows an upward trend in the number of hot days at a rate of 2.1% (±.96% margin of error [moe]) per year and a more pronounced upward trend in the number of hot nights at a rate of 4.5% (±.71% moe) per year. Increasingly frequent hot days and nights result from more and longer hot events (consecutive hot days/nights). Upward trends estimated from a 127-year time series of annual hot day/night counts, with the years prior to 1940 adjusted for location, are consistent with upward trends estimated over the shorter, more recent, period. With projected continued warming we expect more hot days and nights making uncomfortable and unhealthy conditions more common in the city.

KEYWORDS

climate change, Florida, hot daily high and low temperatures, human health and comfort, Tallahassee, upward trends

1 | INTRODUCTION

Heat waves are getting hotter and becoming more frequent around the globe (Brown *et al*., 2008). Heat waves are associated with excess mortality in humans (Pirard *et al*., 2005; Åström *et al*., 2013; Mitchell *et al*., 2016; Mora *et al*., 2017) and warm nighttime temperatures are linked to an increased risk of preterm births (Zhong *et al*., 2018). Temperature records from 50 large cities in the United States show that heat waves are lasting longer and getting more intense. Sixty-one percent of major cities across the southeastern part of the country show worsening heat-wave conditions (Habeeb *et al*., 2015). On an annual basis extreme heat is the number one weather-related killer in the United States (Borden and Cutter, 2008; Luber and McGeehin, 2008).

Heat waves have a broad spatial extent so climate change impact studies typically examine a collection of records across many locations. Because long, complete, and homogeneous records are difficult to find analyses tend to be conducted over a limited time period. Here, we are interested in analysing and modelling the occurrence of extreme heat at one location; Tallahassee, Florida. By focusing on a single city we are able to consider changes over a much longer period of record than is typically the case (see, e.g., King *et al*., 2015).

We define a hot day as one during which the high temperature as recorded by the Tallahassee, Florida, U.S. National Weather Service Office (WSO) reached at least 100°F and a hot night as one during which the low temperature failed to fall below 77°F and then analyse and model the frequency of these hot days and nights. Rationalization for the choice of the temperature thresholds is provided in Section 3. Our approach is similar to that taken by Gershunov and Guirguis (2012) who divided California heat waves into dry daytime events and humid nighttime events and found that both event types are projected to increase in the 21st century with the nighttime events intensifying more than daytime events.

The present study differs from earlier studies in a few distinct ways. First we focus exclusively on the annual absolute hottest days and nights. This contrasts to a recent national climate assessment that considered temperature anomalies with respect to *average* values (Peterson *et al*., 2013). In that case extremely high minimum temperatures are equally likely to occur during winter, when they might be comforting, as in summer, when they can be deadly. It also lets us focus on *absolute* threshold temperatures rather than percentiles as is done in DeGaetano and Allen (2002). Second, we focus exclusively on hot days and nights occurring within a single city (see also Royé, 2017). This allows us to consider changes to the occurrence of hot days over a longer period of time than is typically the case. The trade-off is that we ignore the spatial extent of the heat events examined.

In this study, hot day and night occurrences in Tallahassee, Florida are analysed and modelled. The first aim is to demonstrate statistical models that are useful in analysing the occurrence rates of extreme weather days in the context of climate change. The second aim is to quantify the increase in hot days and hot nights in Tallahassee from the longest available records using these methods. The third aim is to show that increases result from more and longer heat waves. The results and methodology have broader impacts because warming temperatures are exposing more people to heat waves and increasing the risk of disease spread and other adverse health outcomes, especially in urban areas (Luber *et al*., 2014). The WSO Tallahassee record is described in the next section. Results are presented in Sections 3–7. Section 8 summarizes the analyses, highlights the main results, and provides context for interpretation.

2 | WSO TALLAHASSEE DAILY MAXIMUM AND MINIMUM TEMPERATURE RECORD

Tallahassee is the capital of Florida (USA). It is located in the northern part of the state and is the only incorporated municipality in Leon County (Figure 1). The Köppen climate type for Tallahassee and surrounding north Florida is humid, subtropical. Its proximity to the Gulf of Mexico lowers the potential for extremely hot days relative to locations farther to the north across central Alabama and Georgia due to sea breezes.

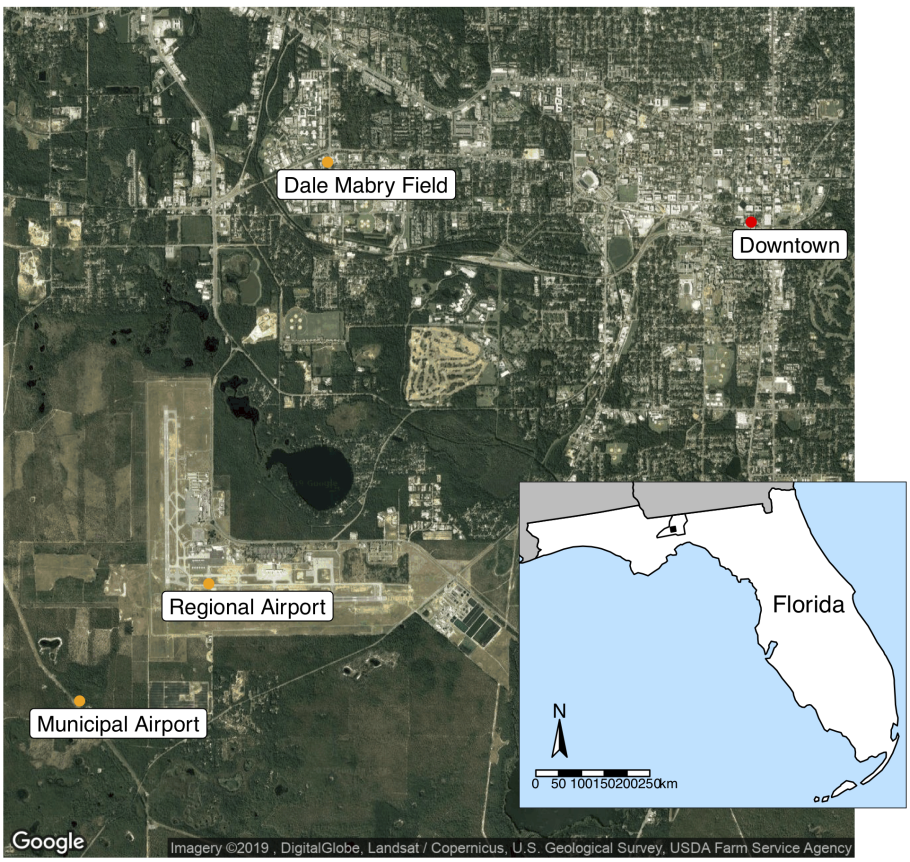

FIGURE 1 Satellite image marking the locations of the sites where official daily temperature records were taken in the city of Tallahassee over the period 1892–2018. The red dot indicates the earliest location, which is not part of the GHCN. The precision given at the location of the Municipal Airport site is approximate within a one kilometre square area centred on the dot. Inset: The location of Leon County, Florida. The black square inside the county border defines the boundaries of the satellite image [Colour figure can be viewed at wileyonlinelibrary.com]

The local WSO, on the campus of Florida State University, keeps the log of daily maximum and minimum temperatures as part of the Cooperative Observing Program (COOP). The program includes officially documented station histories that adhere to the U.S. National Weather Service (NWS) approval process. Daily weather records by the WSO become part of the Global Historical Climate Network (GHCN) developed to meet the needs of climate analysis and long-term monitoring studies. The GHCN identification for the WSO Tallahassee records is USW00093805. We obtain the daily high and low temperatures for USW00093805 from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI). The NCEI is responsible for preserving, monitoring, assessing, and providing public access to historical weather data and information.

The observation site for the WSO Tallahassee record moved a few times since 1940. (Figure 1). Initially, the site was located at Dale Mabry Field with a ground elevation of 19.5 m. In March 1961, the site was moved to the Municipal Airport with a ground elevation of 16.8 m. In April 1996, it was moved again to its current location at the Tallahassee Regional Airport also with a ground elevation of 16.8 m (Table 1). The areas surrounding the current and previous sites are described in NCEI's Historical Observing Metadata Repository as slightly rolling, partially wooded with deep sandy soils. Rolling hills with elevations between 30 and 60 m lie 5–8 km to the north and east. No description is given for the Dale Mabry Field site. Our knowledge of the area describes it as flat, partially wooded with sandy soils. Rolling hills 30–60 m in elevation lie 2–4km to the east. More information on the regional-scale exposure at the location of the current instrumentation and elsewhere in Tallahassee are provided in Elsner *et al*. (1996) and Kara *et al*. (1998). Before May 1, 1988 a maximum/minimum thermometer was used to record both the highest and lowest temperature for each day after which a hygro-thermometer was used.

According to the U.S. Census Bureau the population of Tallahassee in 2019 was 193,551 making it the eighth largest city in Florida and the 125th largest city in the United States.

TABLE 1 Locations where daily temperature readings were taken as part of the GHCN USW00093805 (WSO Tallahassee) record

Attribute	1937-01-31	1961-03-28	1996-03-31
Name	Dale Mabry Field	Municipal Airport	Regional Airport
Latitude (decimal degrees)	30.44	30.38	30.39306
Longitude (decimal degrees)	−84.338	−84.37	−84.35333
Ground elevation (m)	19.5	16.8	16.8

Note: Note the differences in precision on the location (latitude and longitude) attributes.

Population growth rates have averaged in double figures in most decades since the 1930s. But the observation site is located at the Regional Airport, which lies between the Apalachicola National Forest to the southwest and Lake Bradford and Cascades Lake to the northeast. Urbanization has largely been confined to areas north and east of the lakes away from the airport (e.g., the city bus system does not include a route that stops near the airport).

The available WSO Tallahassee record from NCEI begins on March 1, 1940. Thus the period over which the WSO record is analysed in this study is March 1, 1940 to December 31, 2018 (28,764 days). Since we are interested in daily temperatures that occur only during late spring and summer, the missing months of January and February in 1940 do not influence the results.

3 | HOT DAYS AND NIGHTS

We define a hot day as one during which the high temperature in the WSO Tallahassee record reached at least 100°F and a hot night as one during which the low temperature failed to fall below 77°F. We pick 100°F (the century mark) as the extreme high daytime temperature threshold because it adds a psychological component to the perception of a hot day that provides a way to anchor the results of this study to local experiences (given a hot stretch of weather there tends to be additional media attention around the potential for a 100 degree day). We pick 77°F as the extreme high night-time temperature threshold to best match the percentiles with hot days. Also, 77°F is exactly 25°C.

To our knowledge, the threshold temperatures used here to define hot days and nights have not been used elsewhere. According to these definitions over the period of record used in this study there are 128 hot days and 162 hot nights. These counts represent the 99.555th and 99.4368th percentile of all daily high and low temperatures, respectively. The percentiles amount to 4.4 hot days and 5.6 hot nights per 1,000 days. The high temperature threshold is 2° higher than the highest threshold used in DeGaetano and Allen (2002), who examined trends in daily extremes over the United States.

These percentiles represent the extreme right tail of the distributions (Figure 2). The most common high temperature (mode) is 90°F and the most common low temperature is 72°F. Modal temperatures are on the far right side of their respective distributions relatively close to the threshold temperatures used in this study (100°F and 77°F). The number of days that it reached 98°F is 202, 99°F is 111, 100°F is 70, and 101°F is 24. The number of nights that the minimum temperature only dipped to 75°F is 490, 76°F is 234, 77°F is 99, and 78°F is 51.

The potential for a hot day or a hot night begins in late May (Table 2). In the WSO record, a hot day has never occurred after August but there have been hot nights in September and

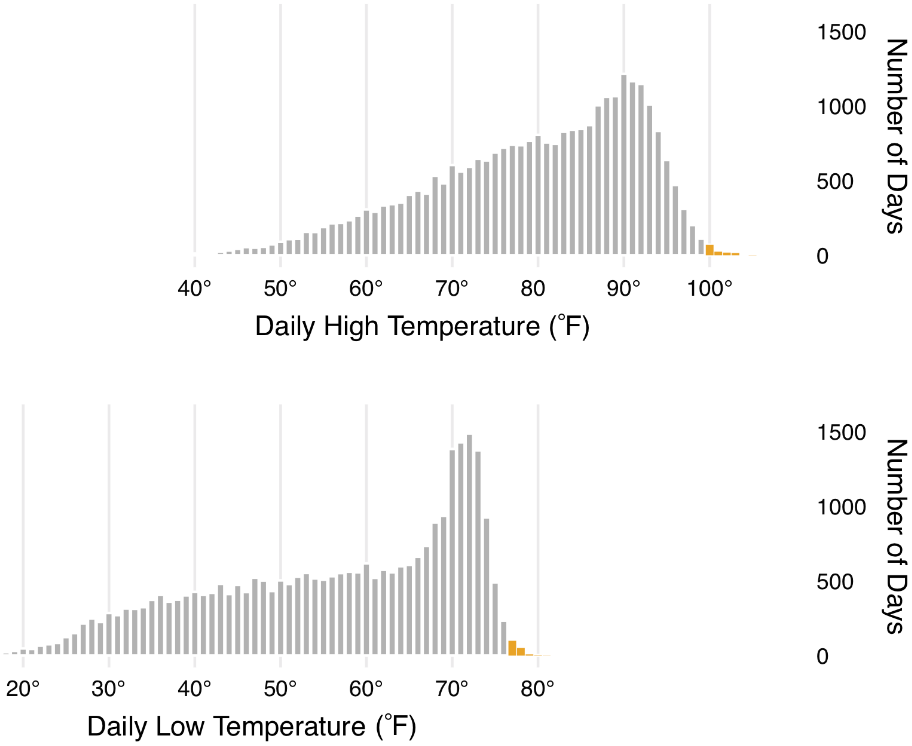

FIGURE 2 Number of days by daytime high temperature (top) and number of days by nighttime low temperature. Orange bars indicate hot days and hot nights, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Monthly occurrence of hot days and nights

Month	Hot days	Hot nights
May	5	3
June	58	21
July	44	47
August	21	82
September	0	7
October	0	2

Note: A hot day is one during which the high temperature reaches 100°F. A hot night is one during which the low temperature fails to drop below 77°F.

even a few in October. The frequency of hot days peaks in June and the frequency of hot nights peaks in August. The earliest calendar date for a hot day is May 25 (in 1953). The latest calendar date for a hot day is August 29 (in 2011) at the end of a 4-day event (consecutive string of 100+°F days). The earliest calendar date for a hot night is May 26 (in 1953) and the latest date for a hot night is October 9 (in 2017).

The seasonal difference in occurrence rates between hot days and hot nights is evident by examining Figure 3. Hot days tend to occur earlier in the summer compared with hot nights. The median date for a hot day is July 1 and the median date for a hot night is August 6. This difference can be explained by the climatological tendency toward more humid conditions in the city from late spring into late summer. The increase in humidity is accompanied by a higher chance of afternoon thunderstorms as the air near the ground has a lower convective temperature (due to a lower convective condensation level) when it is more humid. Oftentimes thunderstorms initiate along the sea-breeze front. Due to the sea-breeze front, Tallahassee gets fewer hot days, on average, than locations farther from the coast across central Alabama and central Georgia.

Using precipitation values from the WSO record we find the daily chance of measurable rainfall exceeds 50% during most days in July and August, on average, with a peak (near 60%) during the week of July 19–26. When thunderstorms occur the chance of the temperature reaching 100 F is reduced due to downdrafts and cloud cover. In contrast, hot nights remain possible throughout the summer because higher humidity levels limit cooling by radiation.

As expected in a warming climate and from earlier studies using daily temperatures at other locations across the southeastern United States, counts of hot days and nights by year in Tallahassee show upward trends (Figure 4). The trend is more pronounced for the occurrence of hot nights. Only relatively few years had a hot day or a hot night before 1980. Since then, more years have at least one hot day and hot night. There were 16 hot days in 1998, 14 in 2011 and 11 in 2000. There were 21 hot nights in 2010, 15 in 2015, 14 in 2016 and 13 in 2005.

4 | QUANTIFYING THE UPWARD TRENDS IN HOT DAYS AND NIGHTS

We quantify the upward trends in the number of hot days and hot nights using a negative binomial regression model. The model is chosen because the counts of hot days (and nights) are over-dispersed relative to a Poisson distribution (the distribution

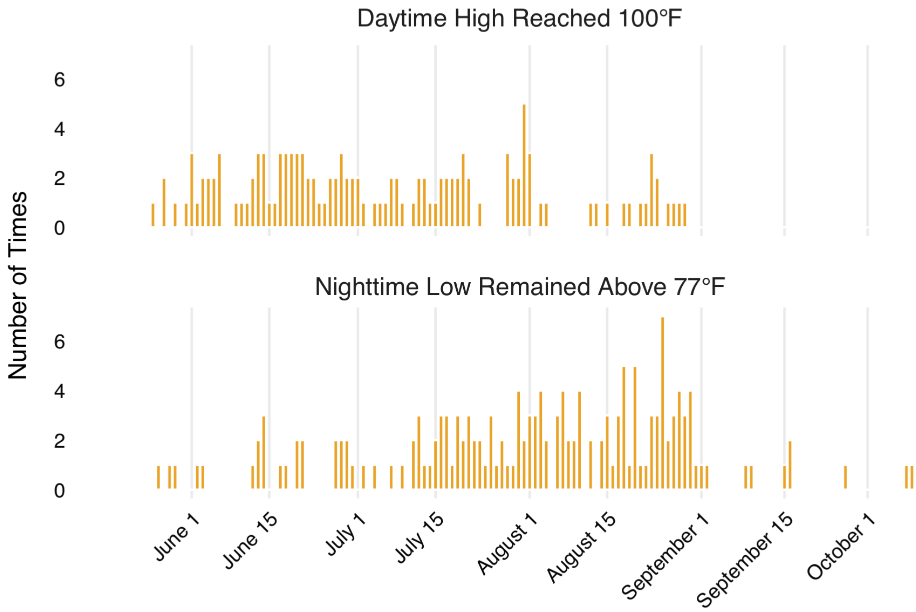

FIGURE 3 Number of times by day of the year the daytime high reached 100°F (top) and the number of times the nighttime low remained at or above 77°F (top) and the number of times the nighttime low remained at or above 77°F [Colour figure can be viewed at wileyonlinelibrary.com]

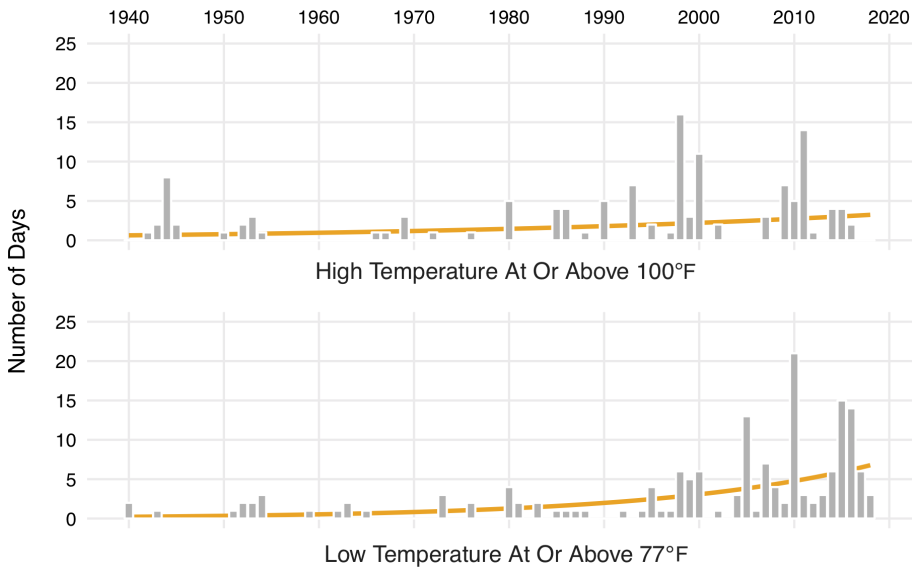

FIGURE 4 Time series of the annual number of hot days (top) and nights. Trend lines (orange) are from a negative binomial regression of annual counts onto year (see text for details about the regression) [Colour figure can be viewed at wileyonlinelibrary.com]

often used in modelling counts). The mean annual number of hot days is 1.62 with a variance of 9.44. The mean annual number of hot nights is 2.05 with a variance of 13.7. The variance is too large relative to the mean assuming the counts are described by a Poisson distribution (in this case the variance would be the same as the mean). The extra variation is the result of clustering. Given a day when the high temperature reaches 100°F, the probability that the next day will get at least this warm is above what would be expected if each day is independent. Hot days and nights tend to occur in streaks rather than independently random as we discuss further in Section 5.

Negative binomial regression is similar to linear least-squares regression except that the dependent variable is an observed count. It relaxes the assumption that the variance must equal the mean as required for a Poisson regression. Possible values for the dependent variable are 0, 1, 2, 3, and so on. As such, it is not advisable to use linear regression (see Elsner and Jagger, 2013). Here we use the negative binomial regression as a trend model with the only independent "variable" being the year. The trend model is:

$$\log(\mu_t) = \beta_0 + \beta_1 \mathrm{Year}_t, \tag{1}$$

where μ is the mean occurrence rate of hot days in year t, and where (intercept) and (annual trend) are the regression coefficients determined by the observed number of hots. The probability that the hot-day count C for a year equals any value (n = 0, 1, 2, …) is:

$$\Pr(C = n | \mu_t, \alpha) = \frac{\Gamma(n + \alpha^{-1})}{\Gamma(\alpha^{-1})\Gamma(n+1)} \left(\frac{1}{1 + \alpha\mu_t}\right)^{\alpha^{-1}} \left(\frac{\alpha\mu_t}{1 + \alpha\mu_t}\right)^{n}, \tag{2}$$

where α is the dispersion parameter and $\Gamma()$ is the Gamma function. Maximum likelihood estimates for the regression coefficients and for α are determined with the glm.nb function from MASS package in R (Venables and Ripley, 2002).

We fit a regression model to the annual number of hot days and fit a separate model to the annual number of hot nights. Results show that the magnitude of the upward trend in the number of hot days is 2.1% per year with a margin of error (moe) equal to ±.96% per year. The magnitude of the upward trend in the number of hot nights is 4.5% per year with a moe equal to ±.71% per year. The hot-day model estimates an average annual rate of .63 (±.282 moe) hot days in 1940; a rate that increases to 3.24 (±1.337 moe) hot days by 2018. These rate changes translate to an increase in the chance of at least one 100+°F day from 38.6% in 1940 to 76.4% in 2018. Corresponding increases in the chances of at least n hot days over the 79-year period are given in Table 3. The hot-night model estimates an annual average rate of .22 (±.083 moe) hot nights in 1940 that increases to 6.77 (±1.71 moe) hot nights by 2018. These rate changes are even larger than the hot-day rate changes and translate to increases in the chance of at least one 77+°F night from 18.1% in 1940 to 87.1% in 2018. Corresponding increases in the chances of at least n hot nights over the 79-year period are also given in Table 3.

5 | HOT EVENTS

Weather conditions that produce extreme heat in Tallahassee tend to cover a broad spatial scale. This means that the responsible high pressure ridge expands across several states and implies that the occurrence of a 100°F day is often followed by a better than average chance of another hot day. Local feedback mechanisms like drying soils can also play a role. The "clustering" of hot days is the reason we fit a negative binomial regression to the hot-day counts rather than a Poisson regression as discussed in the previous section. The same argument about clustering holds for the occurrence of hot nights.

Because hots tend to cluster, insight is available by analysing hot events and separating occurrence (how many events?) from duration (how long do the events last?) and from magnitude (how hot do the events get?). Here we define a hot-day event as one or more consecutive days over which the daytime temperature reached at least 100°F on each day. An event might consist of a single day or it may consist of several consecutive days (heat wave). We expect consecutive hot days to result in the hottest days. Similarly, we define a hot-night event as one or more consecutive nights over which the nighttime temperature failed to drop below 77°F.

These definitions result in 70 hot-day events and 120 hot-night events. Given a hot day the chance that it will be followed by another hot day is 41%. Given a hot night the chance that it will be followed by another hot night is 23%. The longest time between hot-day events is 4,393 days starting after July 8, 1966. The longest time between hot-night events is 2,937 nights starting after August 30, 1951. The median time between hot-day events is 3 days and the median time between hot-night events is 7 days. The average hot-day event length is 1.83 days with the longest lasting seven uninterrupted days between June 17 and June 23 of 1998. The average hot-night event length is 1.35 nights with the longest lasting seven uninterrupted nights between July 29 and August 4 of 2015. The number and the length of hot events are increasing (Figure 5).

We define the intensity of a hot event as the highest temperature occurring during the event. We fit a linear regression model to the intensity (in °F) using event length (in days/nights) as the independent variable and determine that, on average, the hottest temperatures occur with the longest duration events. Quantitatively, for every one additional day the hot-day event continues, the highest event temperature increases by almost one half of a degree (.49°F per day with a moe equal to ±.090°F per day). For every one additional night the hot-night event continues, the maximum event temperature increases by .46°F per night (±.047°F per night, moe).

The combination of hot days and hot nights is particularly threatening to health. Here we count the occurrence of events defined as a hot day preceded, or followed, by a hot night (combined hot event). We find 33 combined events over the 79-year period with a third of them occurring since

TABLE 3 Model estimated chances for hot days and hot nights

	Chance of at least *n* hot days in the year		Chance of at least *n* hot nights in a year	
n	1940	2018	1940	2018
1	38.60%	76.40%	18.10%	87.10%
2	14.90%	58.40%	3.27%	75.90%
3	5.75%	44.60%	0.59%	66.20%
4	2.21%	34.10%	0.11%	57.60%
5	0.85%	26.00%	0.02%	50.20%

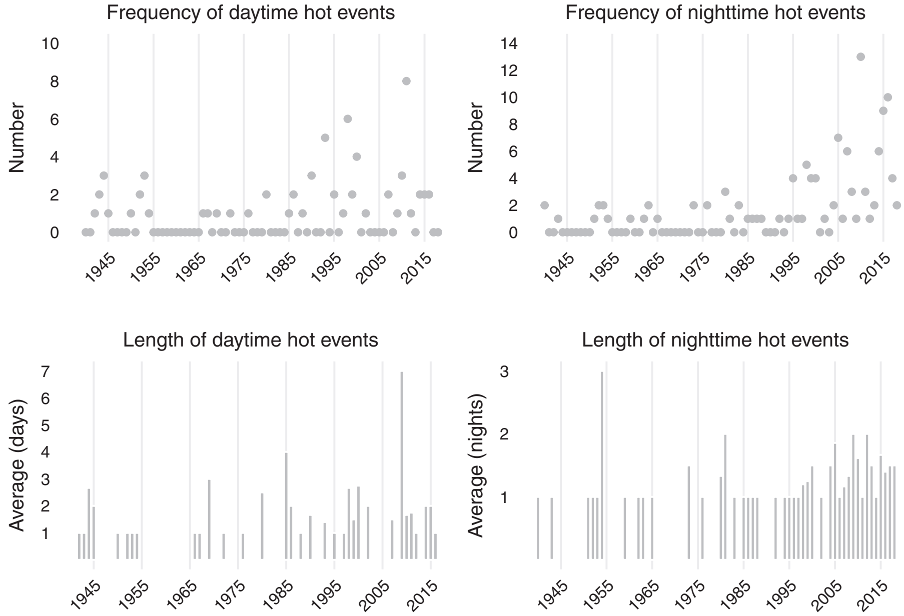

FIGURE 5 Frequency and duration of hot-day and hot-night events

TABLE 4 Number of combined hot events

Decade	Combined hot events
1940–1949	0
1950–1959	3
1960–1969	0
1970–1979	0
1980–1989	6
1990–1999	4
2000–2009	9
2010–2018	11

2010 and more than 90% of them occurring since 1980 (Table 4). July is the most common month with more than half of all combined hot events occurring then. Only one time did such extreme conditions occur in May (1953).

6 | SHIFTING EXTREMES

The above results quantify the increasing number of hot days and nights in Tallahassee. The upward trends are consistent with the expected consequence of rising concentrations of greenhouse gases in the atmosphere. Changes to the occurrence rates of extremes in a warming climate are often described through changes in the parameters of some statistical distribution. For example, with warmer average temperatures comes a greater chance for more extreme hot days. We illustrate this change in the WSO record by dividing the 79-year period into two epochs; 1940–1979 and 1980–2018. We then plot separate density curves through the histograms of counts by temperature using only days during the hot season (Figure 6).

Hot seasons for hot days and hot nights are defined separately by the first and last dates that the temperature reached 100°F and failed to drop below 77°F, respectively. The distribution of hot season daily highs during the recent epoch is shifted to the right and is flatter relative to the earlier epoch. The modal (most common) daytime high went from 92°F to 93°F and the modal frequency dropped from 11.1% to 10.2% (percentage of days during the hot season with that high temperature). Overall, the chance that the high temperature for the day reached any temperature warmer than 92°F is higher in the more recent epoch. Similar distributional changes between the earlier and later epochs are noted for nighttime lows. The modal nighttime low went from 72°F to 73°F and the modal frequency dropped from 14.6% to 13.5%. Overall, the chance that the low temperature at night stayed above any temperature warmer than 72°F is higher during the more recent epoch.

7 | HOT DAYS AND NIGHTS BEFORE 1940

7.1 | An early temperature record

An earlier temperature record for the city that extends back to 1883 is also available. Thus it is interesting to consider the recent (since 1940) hot occurrences in the context of hot occurrences during this earlier time. Temperature measurements were made at a few different locations in Downtown Tallahassee within a one square kilometre area centred at 30.43°N latitude and 84.283°W longitude (see Figure 1). These measurements were collated into a single station with identification number USC00088754 as part of the COOP

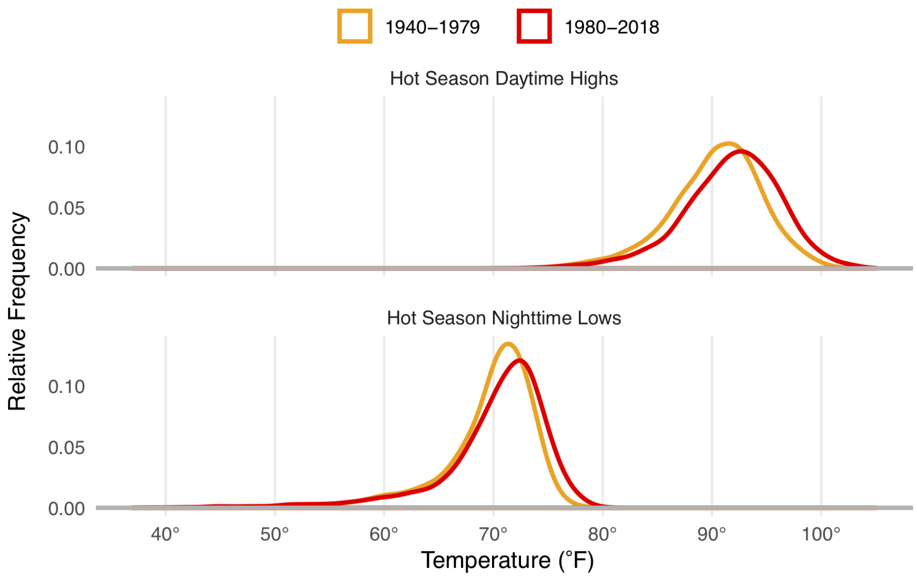

FIGURE 6 Distribution of hot season daily highs and lows in two non-overlapping time periods (epochs). Lines are from a kernel density smoother on the histogram of daily counts over the years in each epoch using a bandwidth of 1. Relative frequency is the percentage of days (or nights) with that high (or low) temperature. Relative frequency is the percentage of days (or nights) with that high (or low) temperature [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Location information for the temperature readings taken as part of the USC00088754 (Downtown) record

Dates	Description	Elevation (m)
April 1, 1883 to January 1, 1888	4 Blocks NE of post office, 317 N Calhoun Street	58.5
January 1, 1888 to August 1, 1903	211 N Monroe Street	58.2
August 1, 1903 to August 10, 1942	Near post office	57.9

(see Section 2) that we refer to as "Downtown." Table 5 includes a description of the location and an estimate of the ground elevation at that location. The daily high and low temperatures were taken with a maximum–minimum thermometer regardless of location and the surrounding topography is described as rolling hills. The area contained buildings, homes, and many large trees.

We obtain the daily high and low temperatures for record USC00088754 (Downtown) from NCEI covering the period January 1, 1892 to July 31, 1942. Data during the earlier decade were not available. The physical characteristics surrounding the Downtown locations are different from those surrounding the official WSO locations which can lead to differences in the frequency of hot days and hot nights in these two different records. Fortunately, during the period March 1, 1940 to July 31, 1942, daily temperatures are available in both records allowing us to model the relationship between daily high and low temperatures recorded Downtown and the frequency of hots recorded in the WSO.[1]

During the 852 days when both the WSO and Downtown records have daily high and low temperatures, the average high was 79.3°F in the WSO record and 79.4°F in the Downtown record and the average low was 56.7°F in the WSO and 58.3°F in the Downtown record. The urban effect on the temperature is most pronounced in the daily minima. However, considering the average high only on days that reached 100°F Downtown, we find that the average difference is 1.8°F warmer Downtown. Indeed, the Downtown record contains five 100+°F days and seven 77+°F nights while the WSO record contains only one 100+°F day and two 77+°F nights during these 852 days. As expected, the chance of a hot day or hot night being recorded Downtown is considerably higher than it is at the airport in this overlapping period of time.

7.2 | Estimating the number of WSO Tallahassee "hots" during the earlier period

Since we only have the Downtown record during the early years we quantify the chance that WSO Tallahassee would have recorded a temperature of at least 100°F given the observed high temperature Downtown. Obviously, chances go up with increasing Downtown temperature. We let T_A be a binary variable with $T_{A_i} = 1$ if the WSO temperature on day i reached at least 100°F and $T_{A_i} = 0$ if it did not. And let T_i be the high temperature observed Downtown on day i, then we want to estimate the probability (π_i) that $T_{A_i} = 1$ given the value of T_i [$\Pr(T_{A_i} = 1 | T_i = t_i) = \pi_i$]. The logit function of this probability is the log of the odds ratio, which is linearly related to the Downtown temperature through the coefficients β_0 and β_1 (logistic regression model):

$$\text{logit}(\pi_i) = \log \frac{\pi_i}{1-\pi_i} = \beta_0 + \beta_1 t_i. \quad (3)$$

Posterior distributions on the coefficients are determined with the Stan computational framework (http://mc-stan.org/)

accessed through the brm function from the brms package in R (Bürkner, 2017). We specify mildly informative conservative priors to improve convergence and to guard against over-fitting.

Output from the model shows the utility of this approach (Figure 7). For increasing high Downtown temperatures the chance that the WSO would have recorded a 100°F goes up. When the high temperature Downtown is 102°F, the model estimates a nearly even chance (50%) of at least 100°F in the WSO record. When the temperature Downtown is 104°F it is very likely (75%) that it would have been a hot day at the airport. There is an uncertainty to these estimated probabilities, which is seen by the spread (based on 100 samples) of the dots (in the vertical direction).

The available WSO record from NCEI begins on March 1, 1940. For the 48-year period before then (1892–1939), we estimate counts by first using the model to estimate the probability of a 100°F on each day that it reached at least 92°F Downtown (potentially hot day in the WSO record). The model gives samples (1,000 probabilities) for each potentially hot day. Second, for each probability we get a “yes” or “no” (using a Bernoulli distribution) for whether it would

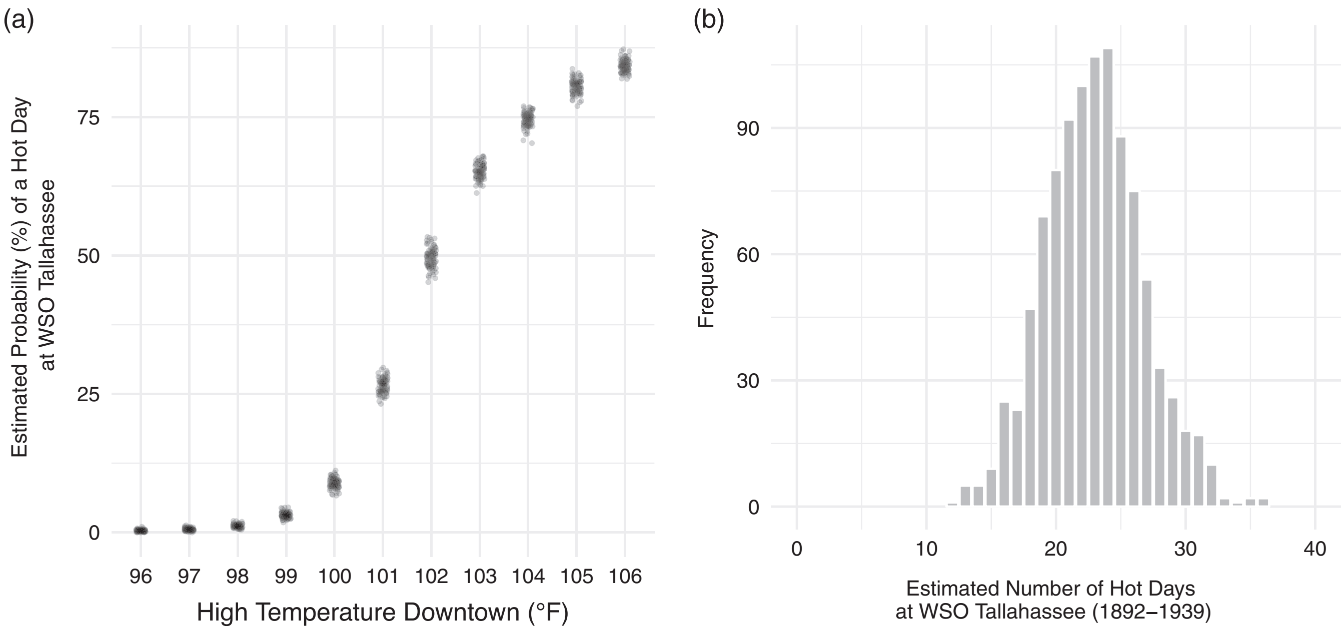

FIGURE 7 Logistic model results. (a) Probability of getting a 100+°F day given the high temperature Downtown. Each dot (horizontally jittered to show greater detail) represents one of 100 posterior estimates for each temperature. (b) Number of hot days estimated to have occurred over the period 1892–1939 if the WSO record was being kept over that time period. The frequencies are based on 1,000 posterior samples

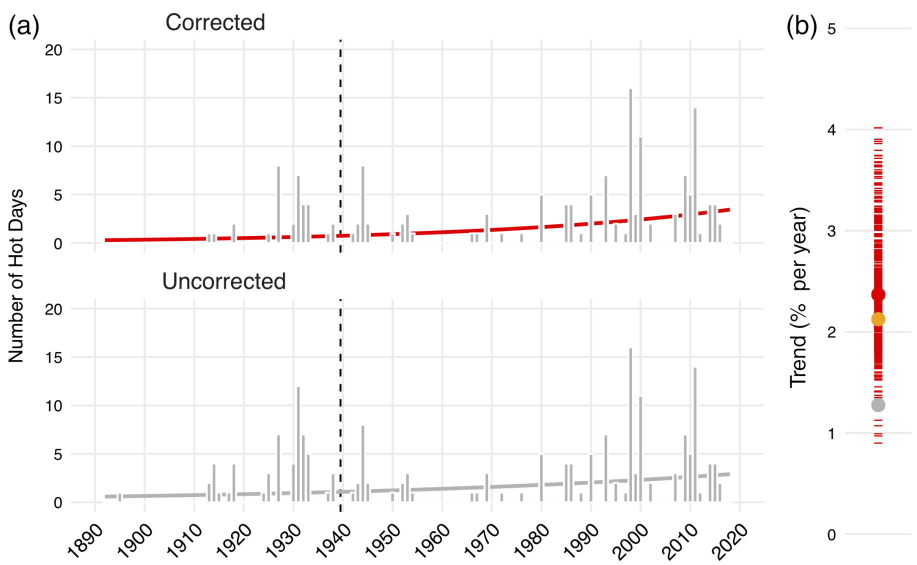

FIGURE 8 Time series and trends of hot day occurrences. (a) A single corrected and the uncorrected time series of annual daily counts. (b) Trend values in percent per year. The red hash marks are trends estimated from samples of corrected counts, the red dot is the median trend over 500 samples, the orange dot is the trend estimated from the WSO record (see Figure 4), and the grey dot is the trend estimated from the uncorrected counts [Colour figure can be viewed at wileyonlinelibrary.com]

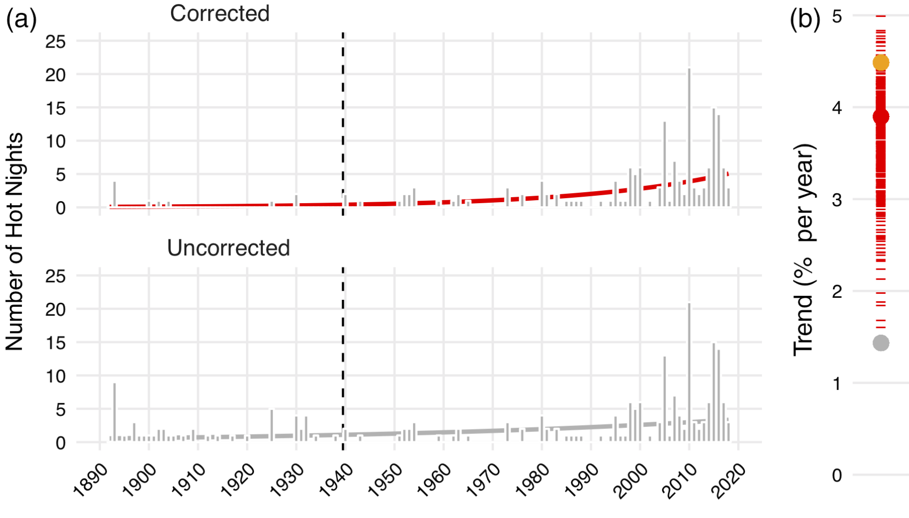

FIGURE 9 Time series and trends of hot night occurrences. (a) A single corrected and the uncorrected time series of annual counts. (b) Trend values in percent per year. The red hash marks are trends estimated from the sample of corrected counts, the red dot is the median trend over the 500 samples, the orange dot is the trend estimated on the WSO Tallahassee record (see Figure 4), and the grey dot is the trend estimated on the corrected counts [Colour figure can be viewed at wileyonlinelibrary.com]

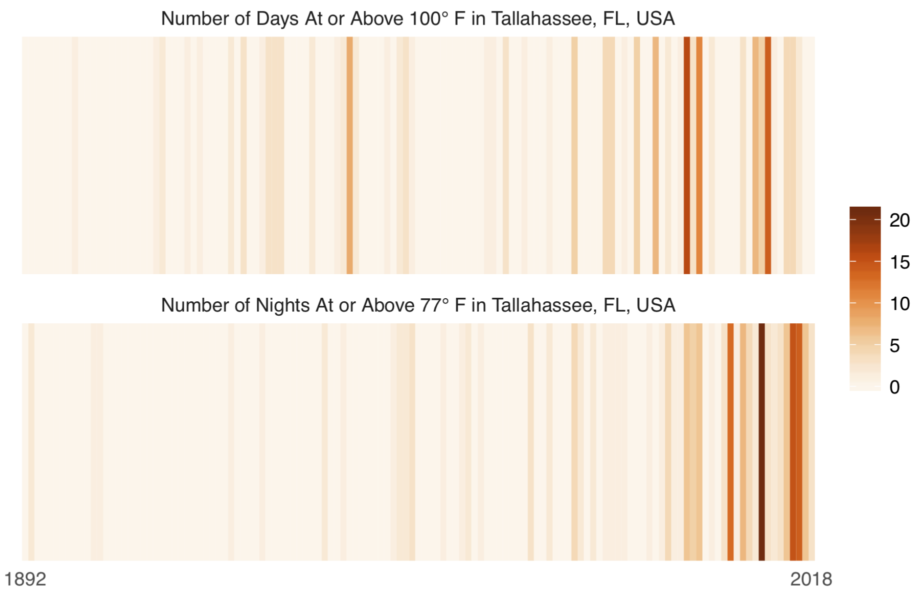

FIGURE 10 A "climate warming stripe" graph for the number of hot days (top) and the number of hot nights. See the text for a description [Colour figure can be viewed at wileyonlinelibrary.com]

have been a hot day if the recording was done at the WSO site. "Yes"'s are tallied for each year and totalled over the entire 48-year period. The estimated total number of hot days that would have been recorded in the WSO record during this time ranges between 12 and 36 days with a median at 23 days (Figure 7). This compares with 55 hot days recorded Downtown over the same period.

To illustrate the difference between the corrected and uncorrected records we plot a single corrected time series together with the uncorrected series and then plot separately the trend values estimated from all corrected samples (Figure 8). The time series for the corrected case is formed by combining model-estimated counts prior to 1940 (grey vertical line) with counts from the WSO record starting with 1940. The time series for the uncorrected case is formed by combining the hot-day counts from the raw Downtown site in the years prior to 1940 with the counts from the WSO record in the years since. Trend lines shown are from a negative binomial regression as explained in Section 4. The median trend estimated using 500 samples of corrected counts is 2.3% per year (red dot) with an interquartile range between 2.0 and 2.8% per year. For comparison, the uncorrected trend is 1.3% per year (grey dot). Recall the trend estimated using only the WSO record since 1940 is 2.1% per year (orange dot).

We repeat the procedure for hot nights. We first fit a model to estimate the probability of a hot night in the WSO record from Downtown temperatures and then use the model to estimate the number of hot nights over the period 1892–1939. A total of 47 hot Downtown nights are noted over this period. The model estimates a corrected total in the range between 3 and 15 with a median of 8 if the measurements were made at the WSO site. Again, to illustrate the difference between using the corrected and uncorrected records we plot a single corrected time series together with the uncorrected series and separately the trend values estimated from all corrected samples (Figure 9). The median trend estimated using 500 samples of corrected counts is 3.9% per year (red dot) with an interquartile range between 3.5 and 4.2% per year. For comparison, the uncorrected trend is 1.4% per year (grey dot). Recall the trend estimated using only the WSO record since 1940 is 4.5% per year (orange dot).

Finally, we use a visual rhetoric to communicate these hot-day frequency trends to a broader audience. A "climate warming stripe" graph (Hawkins, 2018) shows the 127-year record (with corrected counts prior to 1940) with vertical stripes (Figure 10). Each stripe is a year and the colour represents the number of hot days (top) and hot nights (bottom) that year. The years are ordered from the earliest available data (1892) until now (2018). The colours are nine shades of orange with darker hues indicating more hots and therefore more uncomfortable and unhealthy days in Tallahassee. The visual clearly shows how unusual the last couple of decades have been relative to the long run.

8 | SUMMARY AND CONCLUSIONS

We analysed and modelled hot day and night occurrences in Tallahassee using two official city records. The objectives were to demonstrate statistical models for extreme weather days, to document the increase in hot days and nights in the city, and to show that the increases result from more and longer heat waves. A hot day was defined as one during which the high temperature exceeded 100°F. A hot night was defined as one during which the low temperature failed to drop below 77°F. The WSO record, which had three documented location changes, starts on March 1, 1940 and, for the purposes of this study, ends on December 31, 2018. An older record from Downtown locations starts on January 1, 1892 and ends on July 31, 1942.

According to the WSO record the hot season begins in late May and ends in August for hot days and begins in late May and sometimes continues into October for hot nights. June is the peak month for hot days and August is the peak month for hot nights. The difference in seasonal variation is explained by increasingly humid conditions in the city from late spring into late summer. The extra humidity leads to greater chances for afternoon thunderstorms, which limit how hot the day can get due to cloud cover and downdrafts.

The record also shows an upward trend in the number of hot days at a rate of 2.1% (±.96% moe) per year and a more pronounced upward trend in the number of hot nights at a rate of 4.5% (±.71% moe) per year. Increasingly frequent hot days and nights result from an increase in the occurrence of hot events (multiple consecutive hot days/nights) and an increase in the average length of an event. The chance that the high temperature during the day reached any temperature warmer than 92°F and the chance that the low temperature at night stayed above 72°F have increased over the years.

The upward trends were put into a longer context by considering a second record from Downtown. Statistical corrections were made to the Downtown record based on the fact that the Downtown record had more hot days and nights than the WSO record when measurements were made at both locations (March 1, 1940 to July 31, 1942). Magnitudes of the long-term upward trends for both hot days and hot nights are numerically similar to the magnitudes of the upward trends estimated over the shorter, more recent, period.

The increasing number of hot days and hot nights in Tallahassee are consistent with recent studies showing heat waves are lasting longer and getting more intense in the United States (Habeeb *et al*., 2015). Hot days create dangerous conditions when strenuous activities are performed without proper hydration and acclimatization. Indoor conditions are influenced by outdoor heat even when adaptive measures (like air conditioning) are taken (Uejio *et al*., 2015). Hot nights are particularly dangerous to health, especially for the elderly, the homeless, and those with medical conditions (Laaidi *et al*., 2012). Warm nighttime temperatures have recently been linked to an increased risk of preterm births (Zhong *et al*., 2018). Extrapolation into the future of the upward trends quantified in this study is not advisable given the physical limit on how many days there are in a year. But with projected continued warming, there is good reason to think the number of hot days and nights will continue to increase making these uncomfortably and unhealthy conditions more common to the residents of Tallahassee.

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ORCID

James B. Elsner https://orcid.org/0000-0001-6805-7431

ENDNOTE

[1] See DeGaetano *et al*. (2002) for a method to adjust daily extremes in the case of no overlapping period.

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