SUMMER HEAT CLIMATOLOGY FOR URBAN ALABAMA, 1958-2017

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ABSTRACT

In this study, we focus our attention on urban regions in the State of Alabama to create a better understanding of changing summer heat trends. Rising summer temperatures, prolonged heat waves, and high heat index values are cause for public health concerns. Additionally, an increase in summer heat poses a stress on energy demands, costs to consumers, and health risks to the most vulnerable populations. Alabama is within the "warming hole" of the twentieth century warming trend in the U.S.; however, we hypothesize that summer urban temperatures have been on the rise over the past 60 years. To test our hypothesis, we analyze daily maximum and minimum temperatures for the months of June, July, and August between two, thirty-year time periods: 1958 to 1987 and 1988 to 2017. We also calculate cumulative summer cooling degree days (CDD) for each year, June 1st through August 31st. Statistical comparisons suggest a rising maximum and minimum temperature and CDD for 80 percent of the cities in this study (α = 0.05).

Keywords
Applied climatology, climate change, temperature extremes, urban heat

INTRODUCTION

Purpose

This paper addresses summer heating trends in Alabama cities over a 60-year time frame, 1958 to 2017. We investigate whether there have been any statistically significant shifts in daily summer maximum temperature, minimum temperature, and cumulative cooling degree days (CDD). We define summer as June 1st through August 31st (JJA). Throughout Alabama, these months are the hottest of the year. We chose summer over annual temperature and CDD patterns for the purpose of understanding potential health and energy concerns. Although Alabama has not shown to have an average annual temperature increase from 1901 to 2015 (NOAA 2016), there has been a steady warming since the 1970s (Runkle *et al.* 2017). Specifically, our intent is to better understand summer heating trends for urban areas, a spatial and temporal scale not currently well represented in the academic literature.

Heat-related Illnesses and fatalities

Interest in this research arises from concern for urban Alabama populations exposed to heat stress and increased energy demands. Common heat-related illnesses vary from heat rash, sunburn, and heat cramps to the more severe heat exhaustion and heat stroke (CDC 2017; Mørch, Andersen, and Bestle 2017). Heat exhaustion and heat stroke can lead to nausea, vomiting, and fainting. Heat stroke is considered to be a medical emergency and may cause death. The most vulnerable to heat-related illnesses include: infants, children, adults 65 years of age and older, people with chronic medical conditions, outdoor workers, and people in low-income households (CDC 2018). People living without adequate shelter, particularly urban homeless populations, also have a higher risk of exposure (Nicolay 2016).

From 1900 to 2017, there have been 4,801 fatalities resulting from heat extreme temperatures (CRED 2018). Heat waves ranked 4th in all U.S. natural hazard deaths behind tropical cyclones (16,297), convective storms (7,699), and storms (no subtype; 6,408). When considering our years of study, there were 1,870 deaths in the U.S. resulting from heat waves between 1958 and 1987, compared to 1,587 deaths in the more recent time period, 1988 and 2017. Although fatalities have dropped, the number of heat waves has risen from eight to thirteen between these two thirty-year periods (CRED 2018). Work with global coupled climate models suggest that areas in North America and Europe that have been experiencing strong heat waves (e.g., the U.S. Southeast) will see more intense heat waves in the near future (Meehl and Tebaldi 2004).

An in-depth study conducted by the Center for Disease Control (Choudhary and Vaidyanathan 2014) tracked and analyzed heat stress illness (HSI) hospitalizations across the U.S. between 2001 and 2010. Of the 20 states involved in the study (not including Alabama), 28,133 HIS hospitalizations were documented. Florida, the only bordering state with Alabama in the study, experienced a significant increase of HSI hospitalizations. All 20 states of the study had a positive statistical correlation between monthly average number of HIS hospitalizations and average monthly maximum temperature. Furthermore, the South and Midwest regions were found to have the highest rate of HSI hospitalizations, 2001 to 2010 (Choudhary and Vaidyanathan 2014).

Heat and energy consumption

Rising summer temperatures also contributes to urban energy demand. Increasing the amount of energy needed to cool buildings results in higher costs and potentially impacts how well buildings can be kept at reasonable temperatures (Santamouris 2014). In order to address these energy concerns, we compare the cumulation of summer CDD. CDD are calculated as how many degrees higher a day's average mean temperature is above 65º F and are commonly used as a way to measure the potential energy requirements to cool a building (NOAA 2009). Heating degree days (HDD) are a similar measurement, differing in that they cumulate degrees below 65º F during cooler months.

CDD are a practical way to study temperature patterns because 65º F is commonly the temperature at which buildings are switched from heating to air conditioning (Santamouris 2014). In national surveys studied by the U.S. Climate Change Science Program, energy requirements were set to increase by 5% to 20% per every 1º C (1.8º F) rise in temperature. These estimates fluctuated based on differences in locality and energy type (Scott and Huang 2007). Degree day projection models suggest large scale increases in CDD values in the Southeast, with cities such as Memphis and Atlanta predicted to increase by over 1,000 CDD by the end of the 2000s (Petri and Caldeira 2015).

Other economic impacts of increased CDD include influences on the weather derivative market. CDD directly affect temperature derivatives, which are purchased and traded by individuals and companies facing significant temperature related risks (e.g., farmers and utility companies) (Erhardt 2014). Degree days are a standard measurement in the formulas used to calculate payments for these derivatives. For example, for each CDD above the marked 1,000 in June, an additional payment of $150 would be charged.

$$P = 150 \cdot \max\left(\sum_{d \in July} max(T_d - 65{,}0) - 1000, 0\right)$$

The potential impact on prices and contingent contracts could greatly influence the weather derivative market, estimated at $11.8 billion as of 2011 (Erhardt 2014).

CDD are predicted to rise faster than HDD in the Southern U.S. Energy providers will likely be impacted by the change in demand (Petri and Caldeira 2015). These demands have raised concerns over energy availability, as well as the environmental impact of electricity generation from fossil fuels. The U.S. Southeast is heavily reliant on fossil fuels, which are not sustainable from an environmental or economic standpoint.

A "warm hole" over Alabama

An overall global warming trend in recent decades is well established (Stocker *et al.* 2013). Within the U.S., annual average temperatures have risen for most of the contiguous states over the past century. An interesting exception is the U.S. Southeast with nearly the entire state of Alabama experiencing a cooling trend from 1901 to 2015 (NOAA 2016). This phenomenon has been referred to as the "warming hole" and has received substantial academic attention (Robinson, Reudy, and Hansen 2002; Trenberth *et al.* 2007; Portmann *et al.* 2009; Leibensperger *et al.* 2012; Yu *et al.* 2014; Maleski and Martinez 2017; Partridge 2018).

In Alabama, temperatures were at their hottest during the 1920s and 1930s and began to cool approximately 2º F into the 1960s and 1970s (Runkle *et al.* 2017 and references therein). A warming of 1.5º F has been documented since then. There is supporting evidence that the cooling period may have been driven by an increase in aerosols and sulfates by means of unregulated industry into the regional atmosphere. The end of the cooling period aligns well with the timing of the Clean Air Act of 1970 (amended in 1977 and 1990) (Leibensperger *et al.* 2012). Another recent explanation of the warming hole indicates possible influences of jet stream shifts in the late 1950s, bringing cooler air to the U.S. Southeast (Partridge 2018).

In recent decades, the number of hot summer days (maximum temperatures exceeding 95° F) has been much less across Alabama when compared to the 1930s and early 1950s (Runkle *et al.* 2017). There has also been a drop in the number of very warm nights (minimum temperatures above 75° F) in recent decades; although these have been on the rise in the last several years.

METHODS

Study Area

Alabama, the Yellowhammer State, is home to 4.9 million people (U.S. Census 2017). Positioned in the U.S. Southeast, the humid subtropical climate is similar to that of the region. Alabama experiences year-round precipitation, moderate winters (monthly averages above freezing), and hot, humid summers. Thunderstorms and tropical cyclones are common during the late spring and summer months. Tornadoes and severe weather are common across the state. Between 1988 to 2017, Alabama experienced 1,354 tornadoes, averaging 46 per year (NWS 2018). There are two severe weather seasons, one in the spring and another, shorter season in the fall; however, tornadoes and severe weather may occur during any time of year (NWS 2018).

Interested in urban heat, we decided to study the five most populated cities in Alabama: Birmingham, Montgomery, Huntsville, Mobile, and Tuscaloosa (Figure 1). Each city has a population near or above 100,000 and together compose approximately 18 percent of Alabama's population (Figure 2) (U.S. Census 2010).

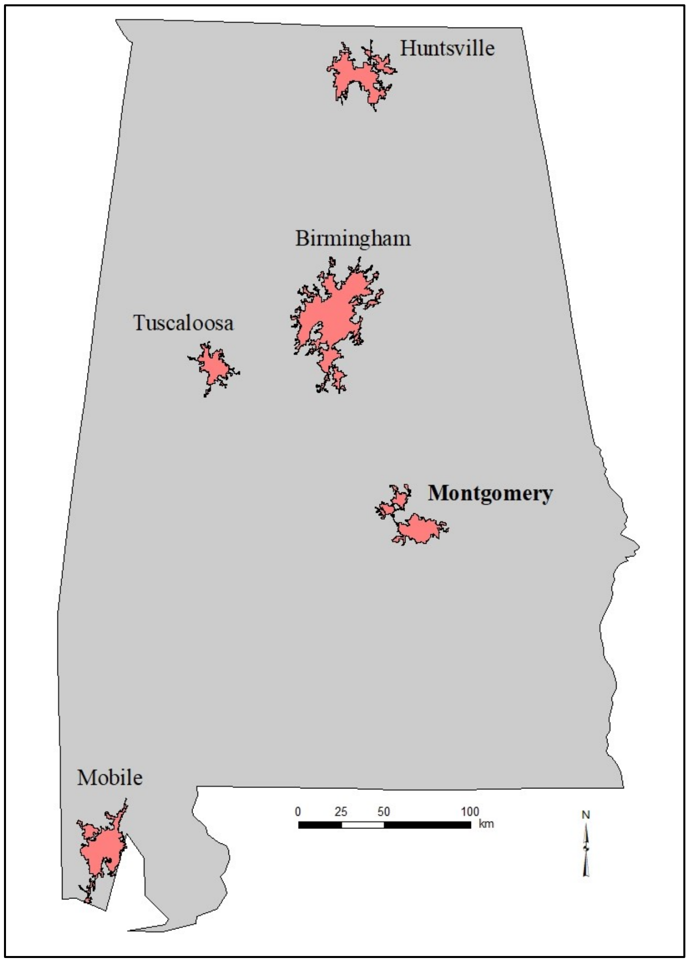


Figure 1. A map of Alabama highlighting the urban areas in this study. Montgomery, the state capital, is in boldface.

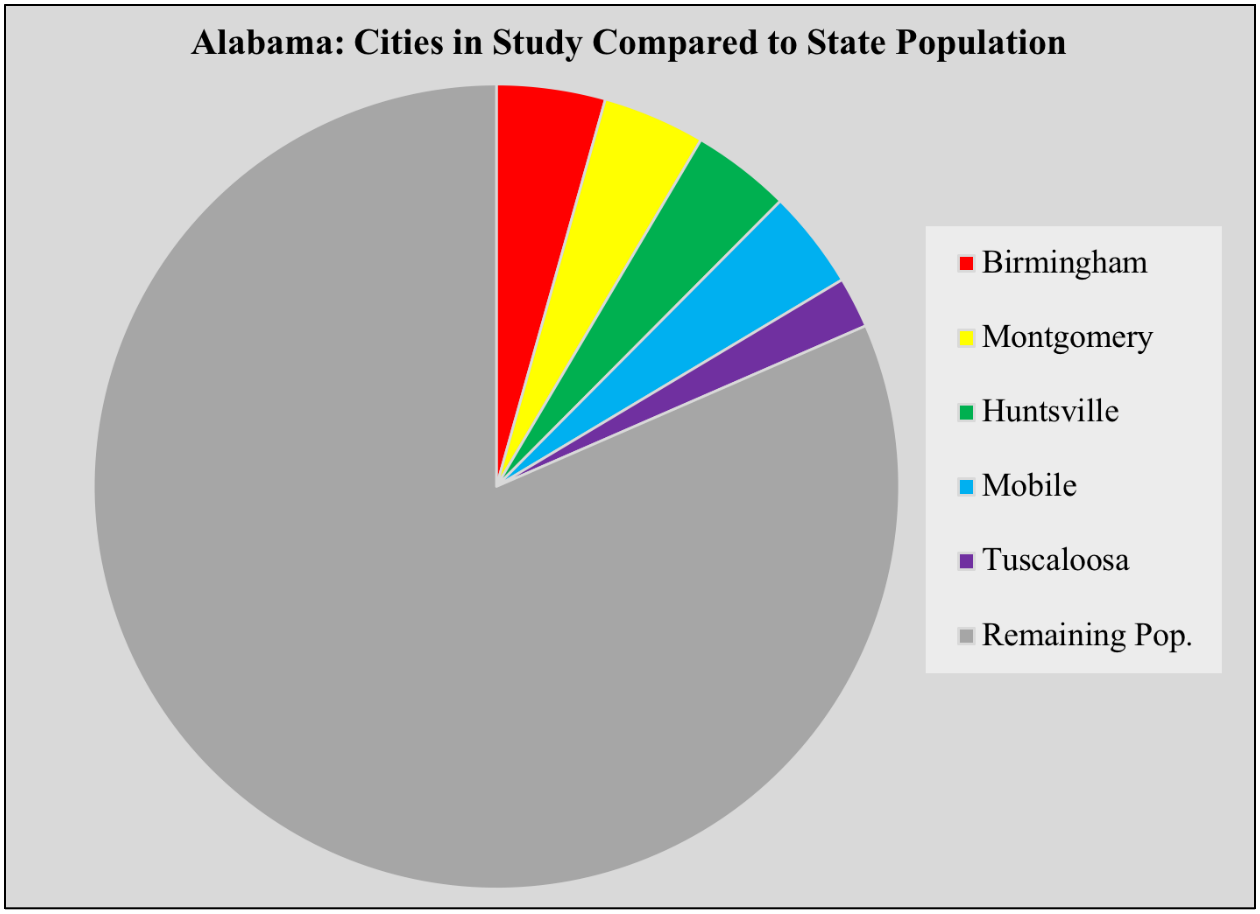


Figure 2. Population of Alabama cities in this study compared to the state population.

Temperature dataset

Data for daily maximum and minimum temperatures were accessed via the National Centers for Environmental Information (NCEI), formally known as the National Climatic Data Center (NCDC), for each of the five cities in the study for the years 1958 to 2017. Although each of the cities have a variety of weather stations to choose data from, very few began continuous recording of maximum and minimum temperature as early as 1958. As is typical across the U.S., the longest and most complete weather stations were those associated with a city airport. Each city in our study had an airport weather station to select data from in the NCEI database.

We recognize that a single station is not the most effective representation for the entire city, but we were constrained by the lack of weather stations encompassing our timeframe. Another concern is that the airports are located on the fringe of the urban regions, which may not accurately reflect the temperature of the more central locations of the cities. While these concerns are viewed as weaknesses to the study, the temperature data do serve as a basis for comparison both spatially and temporally. It is also important to note that the NCEI data from the Tuscaloosa Airport have a five-year gap (1994 to 1998). Since a nearby weather station in Tuscaloosa had temperature data available for most of this timeframe (with the exception of 1995), the gap years were filled in from the alternative station.

Once obtained, the data were organized into a database and filtered to show daily maximum and minimum temperature values for the months of June, July, and August (JJA) for the time period of 1958 to 1987 and 1988 to 2017. These months compose meteorological summer and are the warmest months of the year in Alabama. Cooling degree days (CDD) were calculated by the following formula: $C_d = T_{da} - 65°F$, where C_d is the daily CDD value, T_{da} is the daily average temperature (calculated as the average between the daily maximum and minimum temperature), and 65°F is used as the standard reference in a CDD calculation (NWS 2005). We then took the daily CDD from June 1st to August 31st and summed them for a cumulative CDD value for each year in the study. This variable is unique in that we do not start the cumulation from the first calendar day to exceed 65º F but rather start with a value of zero and adding the CDD solely for JJA.

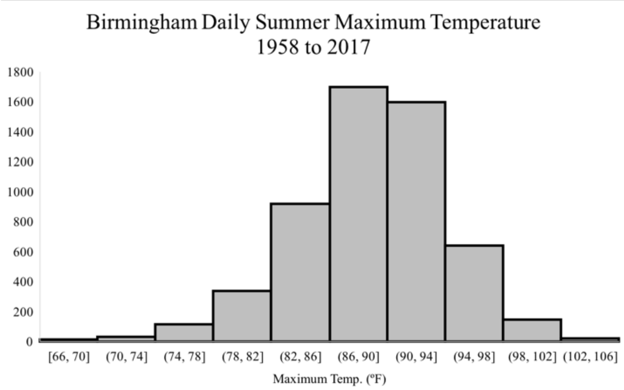
Hypothesis and statistical testing

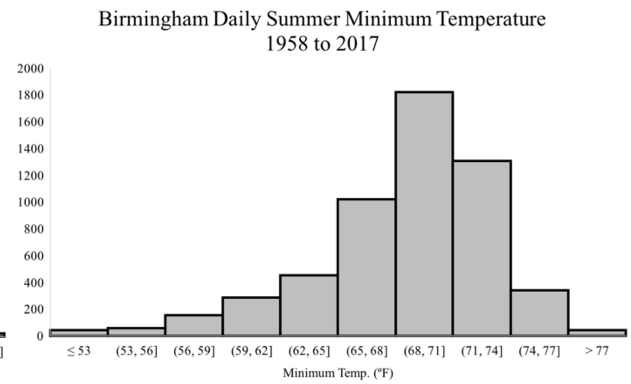
The first step in our hypothesis and statistical testing was to determine the distribution of our variables: maximum temperature, minimum temperature, and cumulative CDD. Our datasets contain very large samples for each of the three variables (Table 1). It is important to note that the n-values for maximum and minimum temperature are much higher than the CDD for each city. This is because CDD is one value per year, the cumulative CDD for June 1st through August 31st, while the n-values for maximum and minimum temperature datasets are the daily value, so there are a maximum of ninety-two values per summer (thirty days of June plus thirty-one days in July and August).

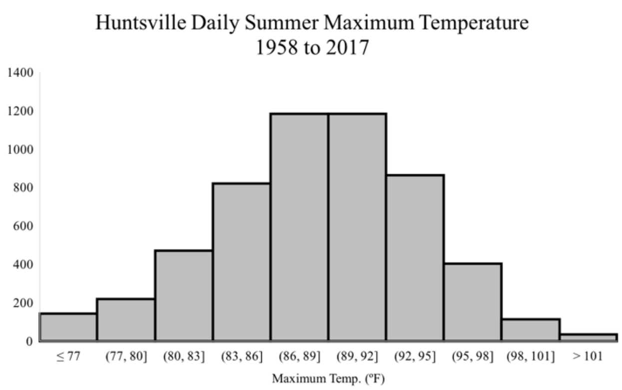
	Max. Temp.	**Min. Temp.**	**CDD**
Birmingham	5520	5520	60
Huntsville	5428	5428	59
Mobile	5520	5520	60
Montgomery	5519	5519	60
Tuscaloosa	5408	5408	59

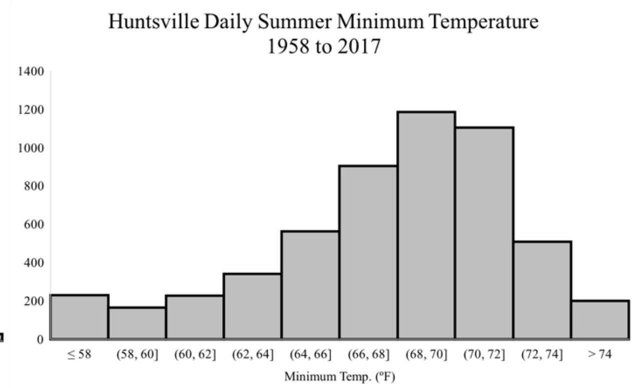
Table 1. N-values for test variables. Gaps exist in several weather station records and are reflected in the inconsistency in n values. The maximum possible n value for daily summer maximum temperature (max. temp.) and minimum temperature (min. temp.) is 5520 (the ninety-two days of one year's summer multiplied by the sixty years in the study) and 60 for CDD (one value of cumulative CDD per year).

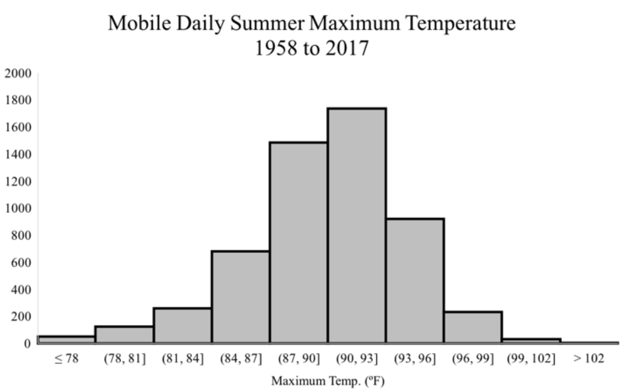
Using R Studio to construct histograms (Figures 3 and 4), q-q plots, and box plots, we interpreted non-Gaussian distributions for all three variables in all five cities. We confirmed non-normal distributions with a Shapiro-Wilk Test of Normality for each dataset using R Studio. Maximum and minimum values for each city had to be broken into the two, thirty-year time periods before running the Shapiro-Wilk test due to R's cap on the sample size. The software is capable of handling larger samples; however, the Shapiro Wilk test has limited power when values in the sample exceed five thousand. According to the Central Limit Theory, one can use parametric mean comparisons given a non-normal distribution if the sample size exceeds 40 (Elliot and Woodward 2007; Ghasemi and Zahediasl 2012). We, however, decided to use non-parametric testing for the following reasons: the non-Gaussian distributions of the data, the notable number of outliers (possibly influencing the means of our datasets), and interest in a more conservative testing. Comparisons made with the non-parametric, two-sample Mann-Whitney U test considers the sum of ranks and median values within the two, thirty-year time periods, rather than the individual sample and mean values. This test is more conservative than a parametric two-sample, unpaired t-test in that it does not make assumptions about the parameters of the datasets (Nahm 2016). In other words, we are less likely to reject the null hypothesis running a Mann-Whitney U rather the parametric equivalent.

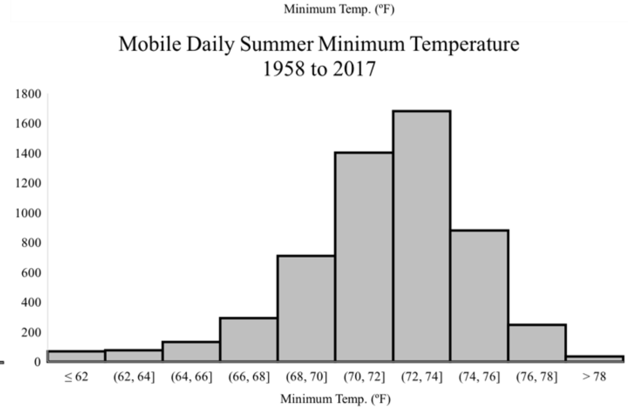


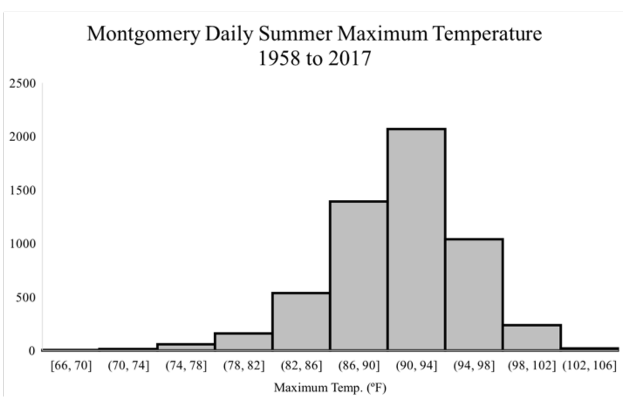


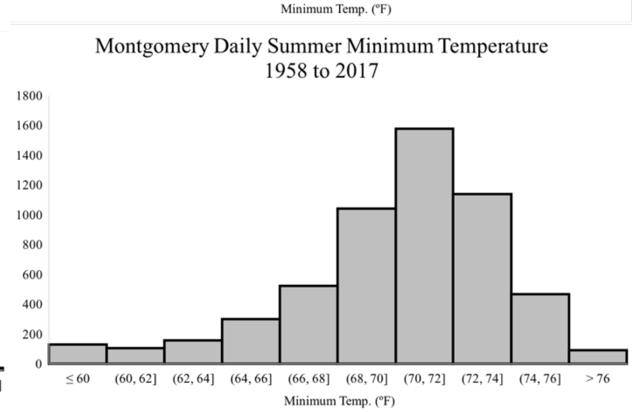












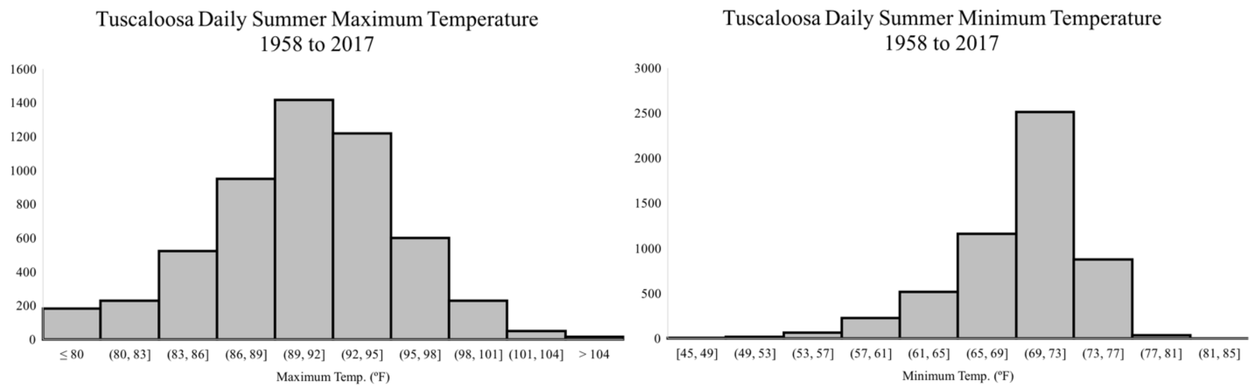


Figure 3. Histograms for maximum and minimum temperature for select cities in Alabama, 1958 to 2017.

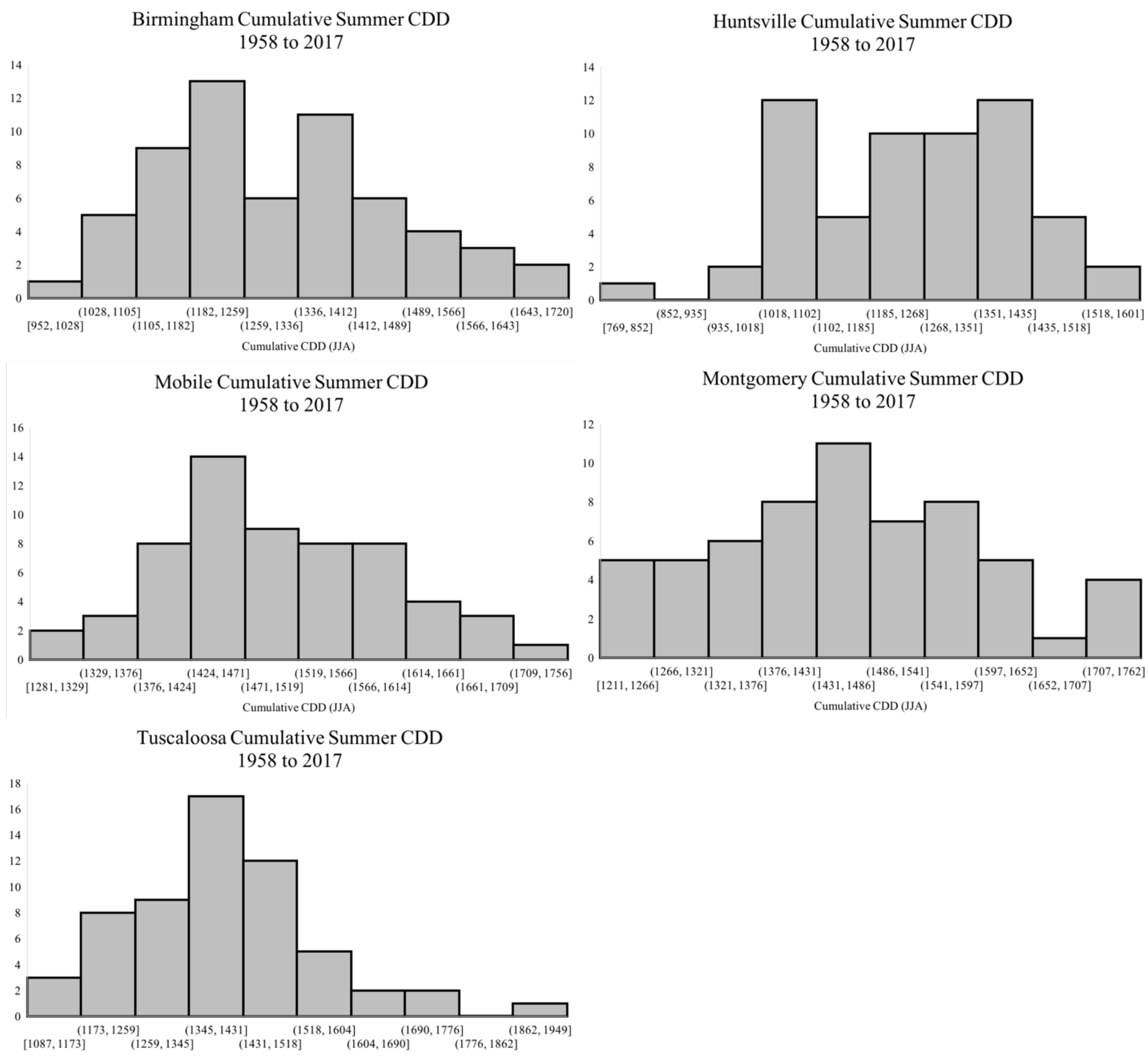


Figure 4. Histograms for cumulative summer CDD for select cities in Alabama, 1958 to 2017.

Interested in determining directionality of any shifts in distributions determined by the Mann-Whitney U test, we analyzed trend lines for each city's summer maximum temperature, minimum temperature, and cumulative CDD. For maximum and minimum temperature, this meant simplifying our dataset from ninety-two values per year to one value per year; otherwise, the graphs were too overcrowded with the large sample sizes. The yearly value was calculated by the mean summer maximum (minimum) temperature for JJA. A line chart was created using Microsoft Excel to show yearly summer variations from the prior thirty-year period (1958 to 1987) summer mean maximum (minimum) temperature. This reference temperature was calculated by finding the mean average of each year's (1958 to 1987) summer mean maximum (minimum) temperatures ($n = 30$). We constructed similar charts for summer cumulative CDD, but this did not require any additional steps since the CDD datasets already contained one value per summer. As in the maximum and minimum trend line analysis, we compared the yearly summer cumulative CDD with the 1958 to 1987 mean average ($n = 30$) CDD value.

RESULTS

Finding our data to be non-normally distributed, we determined the best means of comparison between time periods for our variables should be made using a non-parametric test, the Wilcox Rank Sum test, also known as the Mann-Whitney U test. This test was used to compare the sum of ranks between the two time periods of 1958 to 1987 and 1988 to 2017 for 1) maximum temperature values and 2) minimum temperature values, and 3) cumulative summer CDD. To determine if temperatures have been on the rise, cooling, or staying the same over the past sixty years, the following hypotheses were tested for each of the five cities in the study:

> H0: The sum of ranks for daily summer maximum temperature (minimum temperature; summer cumulative CDD) for the period 1958 to 1987 is the same as the sum of ranks for daily summer maximum temperature (minimum temperature; summer cumulative CDD) for the period 1988 to 2017.
>
> H1: The sum of ranks between the two time periods are significantly different.

We rejected the null hypothesis for all three questions in four of the five cities in our study (Birmingham, Huntsville, Montgomery, and Tuscaloosa) (Table 2). This suggests these cities have experienced a different maximum temperature, minimum temperature, and cumulative summer CDD in the more recent thirty-year period (1988 to 2017) when compared to the data from the previous 30 years (1958 to 1987).

We failed to reject our null hypothesis for all three variables for the city of Mobile, suggesting that there has been no significant shift in summer maximum temperature, minimum temperature, or cumulative CDD (Table 2).

	n1	M1	n2	M2	U	p value
Birmingham	2760	89	2760	90	3364900	$p < 0.001$
Huntsville	2668	89	2760	90	3273400	$p < 0.001$
Mobile	2760	91	2760	91	3782200	$p = 0.652$
Montgomery	2760	91	2759	92	3052100	$p < 0.001$
Tuscaloosa	2757	91	2651	92	3086700	$p < 0.001$

Daily summer minimum temperature.

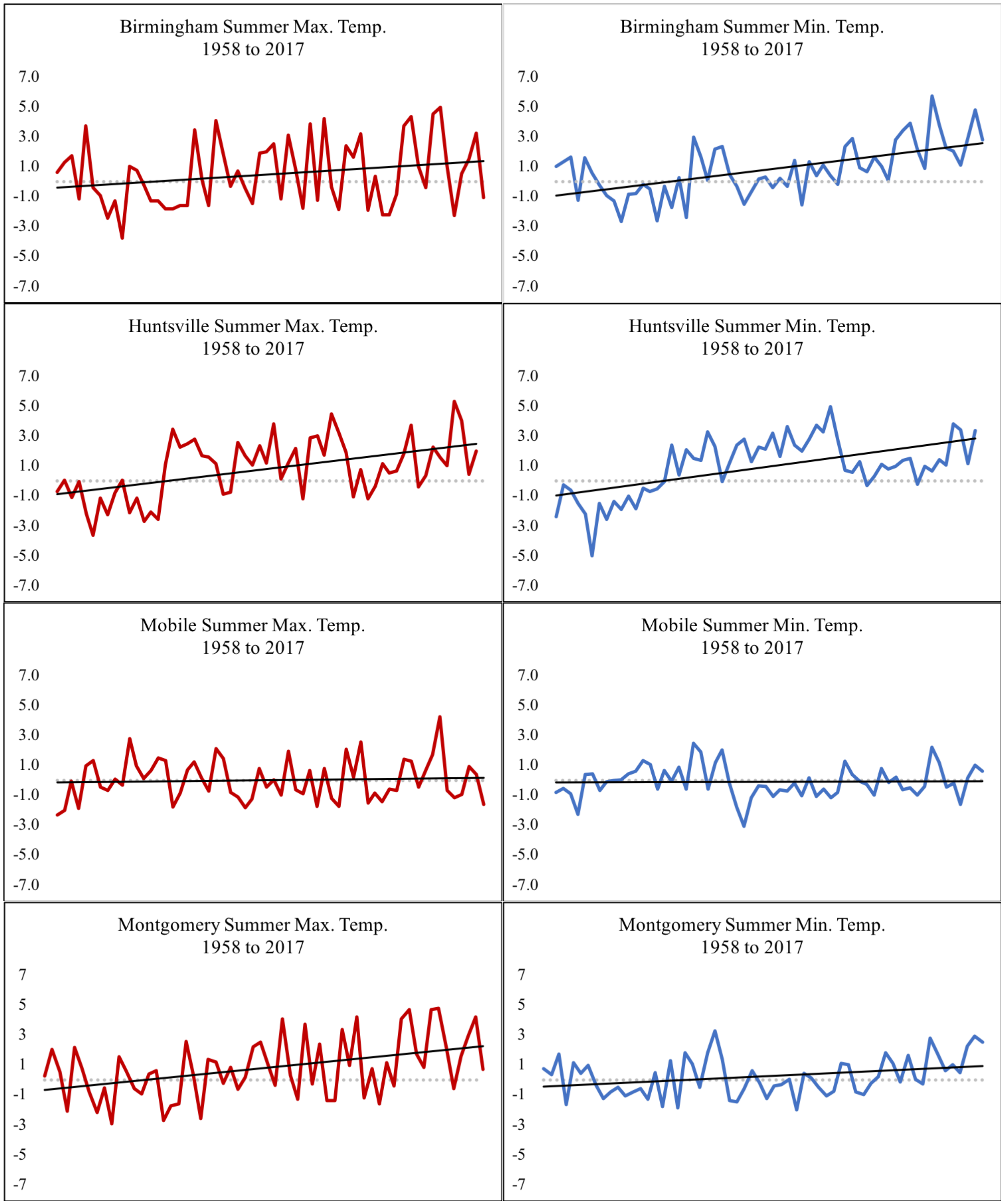
	n1	M1	n2	M2	U	p value
Birmingham	2760	69	2760	71	2902200	$p < 0.001$
Huntsville	2668	68	2760	70	2783600	$p < 0.001$
Mobile	2760	71	2760	71	3920700	$p = 0.057$
Montgomery	2760	71	2759	71	3552200	$p < 0.001$
Tuscaloosa	2757	70	2651	71	3225500	$p < 0.001$

Summer cumulative CDD.

	n1	M1	n2	M2	U	p value
Birmingham	30	1236	30	1349	255	$p = 0.004$
Huntsville	30	1123	29	1302	211	$p < 0.001$
Mobile	30	1507	30	1474	485	$p = 0.615$
Montgomery	30	1413	30	1507	291	$p = 0.019$
Tuscaloosa	30	1367	29	1428	287	$p = 0.025$

Table 2. Results of Mann-Whitney U tests, where n1 = sample size for 1958 to 1987; n2 = sample size for 1988 to 2017; M1 = median value for 1958 to 1987; M2 = median value for 1988 to 2017; U = Mann-Whitney U test statistic; p value is the calculated probability. Daily summer maximum temperature.

The Mann-Whitney U tests were run as two-tailed, which does not indicate directionality. To resolve whether there has been a warming or a cooling trend in the four cities for which we rejected the null hypothesis, we compared the medians between groups (1958 to 1987 and 1988 to 2017) for each city and analyzed trend lines across the entire sixty-years (Table 2, Figure 5, and Figure 6). Comparing the medians between the two, thirty-year periods for Birmingham, Huntsville, Montgomery, and Tuscaloosa, we conclude that the directionality has been an increase in maximum temperature, minimum temperature, and summer cumulative CDD in all scenarios, with one exception. The exception being the daily summer minimum temperature medians between the two periods for Montgomery, which was the same median value for both periods, 71º F. Examining the trend line for the sixty-year study period shows increasing temperatures and cumulative CDD for all cities except for Mobile (no trends for any variable), which agrees with our Mann-Whitney U results. Although Montgomery's minimum temperature had the same median for both time periods, the trend line shows an increase in minimum temperature over the sixty years.


Birmingham Summer Max. Temp.
1958 to 2017
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
Birmingham Summer Min. Temp.
1958 to 2017
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
Huntsville Summer Max. Temp.
1958 to 2017
7.0
5.0
3.0
1.0
-1.0
-3.0
-5.0
-7.0
Huntsville Summer Min. Temp.
1958 to 2017
7.0
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-7.0
Mobile Summer Max. Temp.
1958 to 2017
7.0
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Mobile Summer Min. Temp.
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Montgomery Summer Max. Temp.
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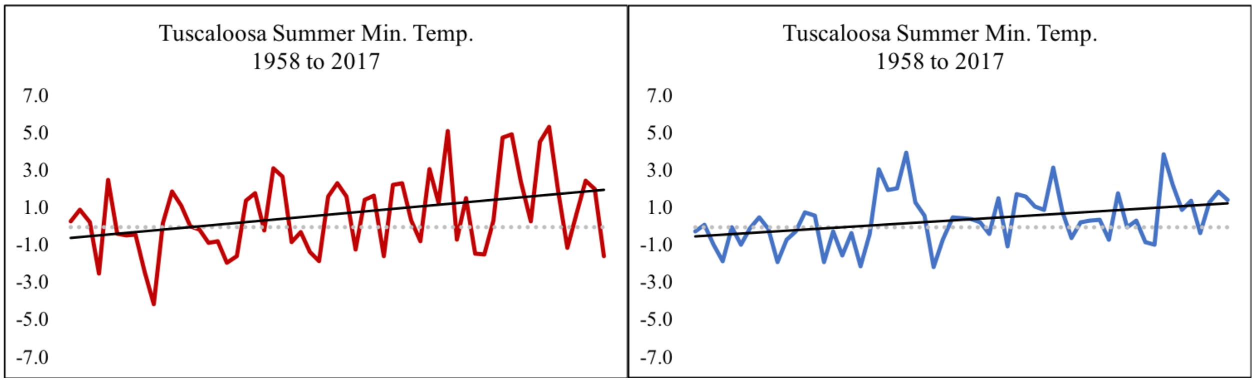

Figure 5. Trend line for summer maximum and minimum temperatures in select Alabama cities, 1958 to 2017.

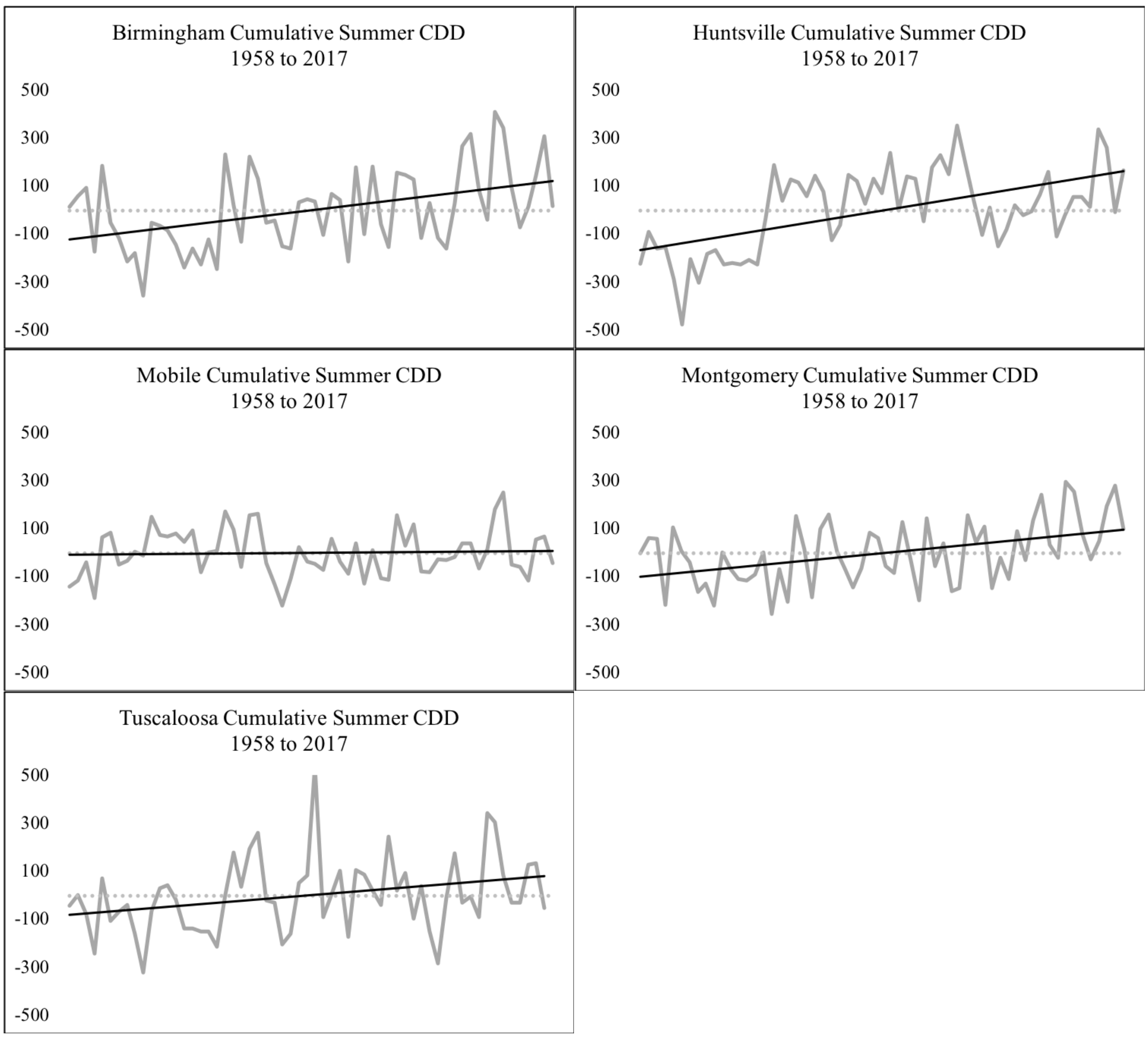

Figure 6. Trend line for summer cumulative CDD in select Alabama cities, 1958 to 2017.

DISCUSSION

Alabama experienced an overall cooling during the twentieth century, with temperatures at their warmest during the 1920s and 1930s. Average annual temperatures across the state cooled by nearly 2º F going into the 1960s and 1970s. The proceeding decades have seen a return of the warmth with an increase of 1.5º F, nearing the temperatures of the warmest time period of the 1900s (Runkle *et al.* 2017).

Our study focuses on summer heat rather average temperatures and specifically on the major urban locations of Alabama rather the entire state. Further distinction of our study is the time frame of the previous sixty years rather stretching back to 1900. With these distinctions, we were able to highlight the increase of three heat-indicating variables across 80 percent of our study region (four out of five cities). Birmingham, Huntsville, Montgomery, and Tuscaloosa have all experienced a significant shift in their daily summer (JJA) maximum temperatures, minimum temperatures, and cumulative summer CDD.

An increase in daily maximum temperature means that summer days have been hotter between 1988 and 2017 than they were between 1958 and 1987. At the same time, an increase in nighttime low temperatures in the more recent time period is made evident by a significant shift in daily summer minimum temperatures. The combination of hotter days and warmer nights can lead to an increase in heat-waves (see Kent *et al.* 2014 for thorough comparison of heat wave measurements and correlation with heat-related illnesses in Alabama).

Measuring CDD is typically done throughout the year. We decided to analyze a cumulation for just the JJA period to use as an indicator of summer heat and energy demand. Rather having 92 values per year (days in JJA) as in our daily maximum and minimum temperature datasets, we calculated one value per year, the cumulation of CDD from June 1st through August 31st. A significant increase in CDD suggests demands of summer energy consumption will likely be needed. Huntsville experienced the greatest shift in the median, 179 CDD, followed by Birmingham (113 CDD), Montgomery (94 CDD), and Tuscaloosa (61 CDD). Mobile's median dropped 33 CDD; however, this was not statistically significant, so we report no change over the sixty years.

We can only speculate as to why Mobile was the only city not to have increasing heating trends over the past sixty years. Mobile is the only coastal city in our study, located along the Gulf of Mexico at the Mobile Bay. The maritime location may be the most governing factor in its distinction from the warming pattern exhibited by the other four cities. Mobile is also the furthest south, which may place it outside of the range of an influencing atmospheric circulation or other contributing factor.

CONCLUSION

In recent decades, average annual temperatures throughout Alabama are still below where they were in the 1920s and 1930s; however, there has been a state-wide warming trend since the 1970s. It is likely that, in the coming decades, Alabamians will be facing daily highs and nighttime lows exceeding the averages of the past one hundred years.

Excessive summer heat poses health risks and creates a stress on energy demands required to cool buildings and houses. Our study of heat trends in urban Alabama over the past sixty years compared distributions of daily summer maximum and minimum temperatures and cumulative summer CDD for the five largest cities in the state. The results indicate there has been a significant warming shift for each of these variables in four of the five cities, or 80 percent of our study area. Alabamians living in Birmingham, Huntsville, Montgomery, and Tuscaloosa have been experiencing hotter summer days, warmer summer nights, and an increase in cumulative summer CDD. Mobile, AL has not experienced a similar shift in summer heat. The reason or which is outside the scope of this paper but may be attributed to the maritime influences of their coastal location.

The importance of adaptation, mitigation, and preparation for heat-related hazards should be a priority for city planners, government officials, emergency response, and other related organizations in the likely-hood of Alabama facing hotter summers in the coming decades. Rising summer heat should also be the concern of individuals living in urban locations throughout the state. Properly educating the public on the recent warming trends, heat-related illnesses, and budgeting for energy costs of summertime cooling is recommended.

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