The Study of Urban Heat Islands in the Birmingham and Auburn-Opelika, Alabama Urban Areas, Using Satellite and Observational Techniques.

by

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Abstract

Urban heat islands (UHI) are created by cities because buildings, impervious surfaces, energy and transportation, and reduced amounts of evapotranspiration increase temperatures compared to their rural surroundings. Because of their thermodynamic nature, UHIs can exacerbate the effects of severe weather events including heat waves and heavy precipitation. It is important to understand the characteristics of city UHIs and how they modify the dynamism of urban areas. This study compared the UHIs of a large sized metropolitan area in Alabama (Birmingham) to a mid-sized urban area in Alabama (Auburn-Opelika). To conduct this research, remotely-sensed images as well as observational data were analyzed to determine the rural and urban temperature differences. Temperature-monitoring instruments called iButtons were installed around the cities for the spring and summer months of 2014 (1 March to 31 August) to record hourly temperature data in order to analyze temperature patterns and variability. The research objectives of this study are: a) to quantify magnitudes and intensities of the average monthly diurnal UHIs in Birmingham and Auburn-Opelika by measuring atmospheric temperature 6-8 feet above the ground (i.e. atmospheric UHI), using iButtons; b) to quantify the surface UHI of Birmingham and Auburn-Opelika using remotely-sensed images and compare it to the atmospheric UHI. This research is significant given the likelihood of extreme climatic events like hurricanes, heat and cold waves, and increased global temperatures as stated in the Intergovernmental Panel on Climate Change (IPCC) V report. The results of this research will highlight the importance of mitigation procedures such as increased vegetation, green spaces, energy-efficient building practices, and a reduction in emissions; all of which would ameliorate the UHI effects. These measures would make Auburn-Opelika and Birmingham more sustainable and habitable agglomerations.

Keywords: urban heat island, inverse distance weighted (IDW), Birmingham, Auburn, Opelika, extreme events, and mitigation

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List of Abbreviations

UHI	Urban heat island
IPCC	Intergovernmental Panel on Climate Change
MODIS	Moderate Resolution Imaging Spectroradiometer
LST	Land Surface Temperature
IDW	Inverse Distance Weighted
TIR	Thermal Infrared
EPA	Environmental Protection Agency
AVHRR	Advanced Very High Resolution Radiometer
SPOT	I’Observation de la Terre
TM	Thematic Mapper
ETM	Enhanced Thematic Mapper
UAB	University of Alabama at Birmingham
H:W	Building Height to Street Width
BJCC	Birmingham Jefferson Civic Center
AU	Auburn University
CST	Central Standard Time
CDT	Central Daylight Time
UTM	Universal Transverse Mercator
RMSE	Root Mean Square Error

CBD	Central Business District
F	Fahrenheit
C	Centigrade
NASA	National Aeronautics and Space Administration
USGS	United States Geological Survey
TOA	Top of Atmosphere
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
EROS	Earth Resources and Observation Science Center
HIRI	Heat Island Reduction Initiative

Chapter 1: Introduction to Thesis

1.1 Introduction

The 21st century has witnessed extensive urban growth, and evidence of human impacts on the environment continues to increase. A report by the United Nations forecasts 70 percent of the world's population to be living in urban areas by 2050 (United Nations 2007). Urbanization has a direct impact on the size and intensity of the urban heat island (UHI), which is unique to the city and described as the difference in temperature between urban areas and surrounding rural locations (T_{urban}-T_{rural}) (Hinkel et al. 2003, Sullivan and Collins 2009). UHI studies have been done for a number of cities worldwide, including New York City, New York (Bornstein 1968);, Huntsville, Alabama (Lo 1997); Atlanta, Georgia (Bornstein and Lin 2000); Barrow, Alaska (Hinkel et al 2003); Singapore (Chow and Roth 2006); Dhaka, Bangladesh (Raja 2012); and Mexico City, Mexico (Cui and De Foy 2012). UHIs are strongest in the summer and are further exacerbated during heat waves (Tan et al. 2010). They also contribute to a number of environmental and health factors including increases in temperatures, water usage, and heat-and-respiratory related health problems (Borden and Cutter 2008; Krayenhoff and Voogt 2010; Cui and De Foy 2012). UHI studies have been done for decades, but research on urban influences is increasingly paramount as societies continue to urbanize. Ultimately studies such as this could contribute to a better and more sustainable future.

Previous research has employed a number of different methods to detect and analyze UHIs. For example, the Bornstein study of New York City (1968), used a meteorologically-equipped helicopter to collect vertical temperature in and around New York City. Oke (1976) used cars to gather temperature and lapse-rate data for the Vancouver, B.C. area in the mid-1970s. Cui and De Foy (2012) utilized moderate-resolution-imaging spectroradiometer (MODIS) and land-based meteorological weather stations to compare land-surface temperature (LST) and atmospheric temperature in Mexico City. While all of the aforementioned studies focused on large cities, only Cui and De Foy (2012) compared atmospheric temperatures; though it lacked the density of instruments which the present study offers. This is especially important considering the relationship between LST and atmospheric temperature remains one of the greatest unknowns in remotely-sensed evaluations of UHIs (Voogt and Oke 2003). In addition, no literature was found which used atmospheric temperatures from a high density of land based temperature logging instruments to do a comparative analysis with surface temperatures obtained using remote sensing techniques. Specifically, this study seeks to address the following research objectives:

1. Successfully measure the magnitude and intensity of the atmospheric UHI from 1 May 2014 to 31 August 2014 in the Birmingham, Alabama and Auburn-Opelika, Alabama urban areas using iButton data (see chapter 2, section 2.1 for iButton description and specifications) and inverse distance weighted (IDW).

2. Utilize remote sensing and GIS techniques to measure the magnitude of the surface UHI in the Birmingham and Auburn-Opelika urban areas and compare it to the magnitude of the atmospheric UHI, quantified in objective 1.

Although the definitions of UHI magnitude and UHI intensity vary somewhat in pervious literature, they refer to the spatial extent of the UHI, and the difference between urban and rural temperatures (T_{urban}-T_{rural}), respectively for the current study. A larger difference in urban and rural temperatures constitutes a higher intensity and vice-versa (UHI intensity was only graphed/calculated for the atmospheric UHI). This study took place over the spring and summer seasons; from 1 March to 31 August 2014. Those seasons were chosen because literature shows that UHI effects are magnified with higher temperatures, causing heat-related health concerns (Patz and Khaliq 2002).

1.2 Thesis Structure

The remainder of chapter 1 provides a review of literature describing the impacts of urbanization and UHIs followed by the introduction of the study area. Short summaries of the methodologies applied in the following chapters are given below.

Chapter two employs hourly observational atmospheric temperature data obtained from widespread networks of iButtons to quantify the magnitude of the surface UHI effect in both study areas. The data were segregated according to month of study in addition to time of day. The IDW function in ArcGIS was used to display the spatial distributions of the atmospheric temperatures through 24 different maps.

Chapter three utilizes thermal infrared (TIR) band 10 of Landsat 8 to quantify surface temperatures and compare them to the atmospheric temperatures. The quantized digital numbers were converted to LST values through a two-step process. Maps, graphs and paired t-tests were all employed to compare LST to atmospheric temperature.

Chapter four summarizes the findings and significance of this study and highlights the effects and influences of UHIs. Mitigation strategies and techniques are also briefly discussed.

1.3 Impacts of Urbanization.

Urbanization has increased tremendously over the past century and is defined by the Environmental Protection Agency (EPA) as the concentration of human populations into discrete areas, leading to the transformation of land for residential, commercial, industrial, etc. purposes (EPA 2012). Populations are becoming increasingly concentrated in urban areas throughout the globe. In 1900, 10 percent of the world population resided in 142 cities; by 2008, 50 percent of the population resided in 171 cities, and, predictions indicate that by 2050, 70 percent (6.5 billion) of the population will reside in cities (United Nations 2007, Ashley et al. 2012).

Land use and land cover changes are among the most profound influences of urbanization in the form of conversion of pervious surfaces (including soil and vegetation) to impervious surfaces (including buildings, asphalt, and concrete) (Tang et al. 2005). An effect of this conversion is an increased amount of solar radiation absorbed, producing a greater thermal capacity and conductivity, thereby storing more heat within urban surfaces. Impervious surfaces can be used as a measure of urbanization and are defined as any material that prevents infiltration of water into the soil. Roads and rooftops are among the most common types; other examples include patios, bedrock outcrops, sidewalks, parking lots, and compacted soils (Arnold Jr. and Gibbons 1996).

Consequences of this conversion process include increased surface runoff, meaning more local flooding (because there is less soil surface, less water infiltrates the ground, which in turn, produces more drainage), reduced residential and municipal water supplies, increased lake and wetland levels (level becomes more dependent upon individual rainfall events) less water for groundwater recharge, decreased evaporation and reduced evapotranspiration (Tang et al. 2005, Mills 2007, Cui and De Foy 2012). Moreover, impervious surfaces collect hazardous materials that are either dissolved in runoff or are associated with sediment such as heavy metals, pesticides, grease, oil, and fecal coliform bacteria, which are then washed off and distributed by storm water (Tang et al. 2005).

1.4 Impacts of UHIs

Luke Howard was the first to notice the UHI effect back in the 1800s; however urban environments were not studied in detail until the early 20th century (Oke 1982, Sullivan and Collins 2009). The term UHI was first coined in the 1940s, and is measured by remote sensing and existing ground based weather stations (Cui and De Foy 2012). Remotely-sensed UHIs measure the surface UHI via satellite, while ground-based instruments measure the temperature of the atmospheric UHI 2-3 meters above the surface (Arnfield 2003). Surface UHIs are most spatially extensive and strongest during the daytime hours, unlike airborne UHIs, which are most expansive at night when daytime heat is released (Arnfield 2003). This process is mainly due to limited outgoing long wave radiation, which produces cooling at the surface assuming the long-wave radiation is allowed to escape. Outgoing long wave radiation is reduced in urban areas due to buildings and other impervious surfaces, which hinder the cooling effect and hold in heat (Unger 2004).

Reasons for the variance in urban and rural temperatures include changes in the albedo, heat conductivity, and thermal capacity of the surface, attributed to 1.)

replacement of vegetative surfaces with impervious, urban surfaces, 2.) reduction in evapotranspiration due to decreased availability of vegetation and surface moisture, 3.) changes in the near surface air flow due to street and building geometry, and 4.) emission of heat from anthropogenic sources (Xian and Crane 2006). However, according to Streutker (2003), impervious surfaces in an urban environment are the main cause of variances in land-surface temperatures. Previous analyses of the relationship between land cover and LST include Dousset and Gourmelon 2003; this study investigated the effects of downtown surface physical properties using Advanced Very High Resolution Radiometer (AVHRR) and Satellite Pour I'Observation de la Terre 2 (SPOT-2) (a commercial high-resolution optical imaging satellite based in Toulouse, France).

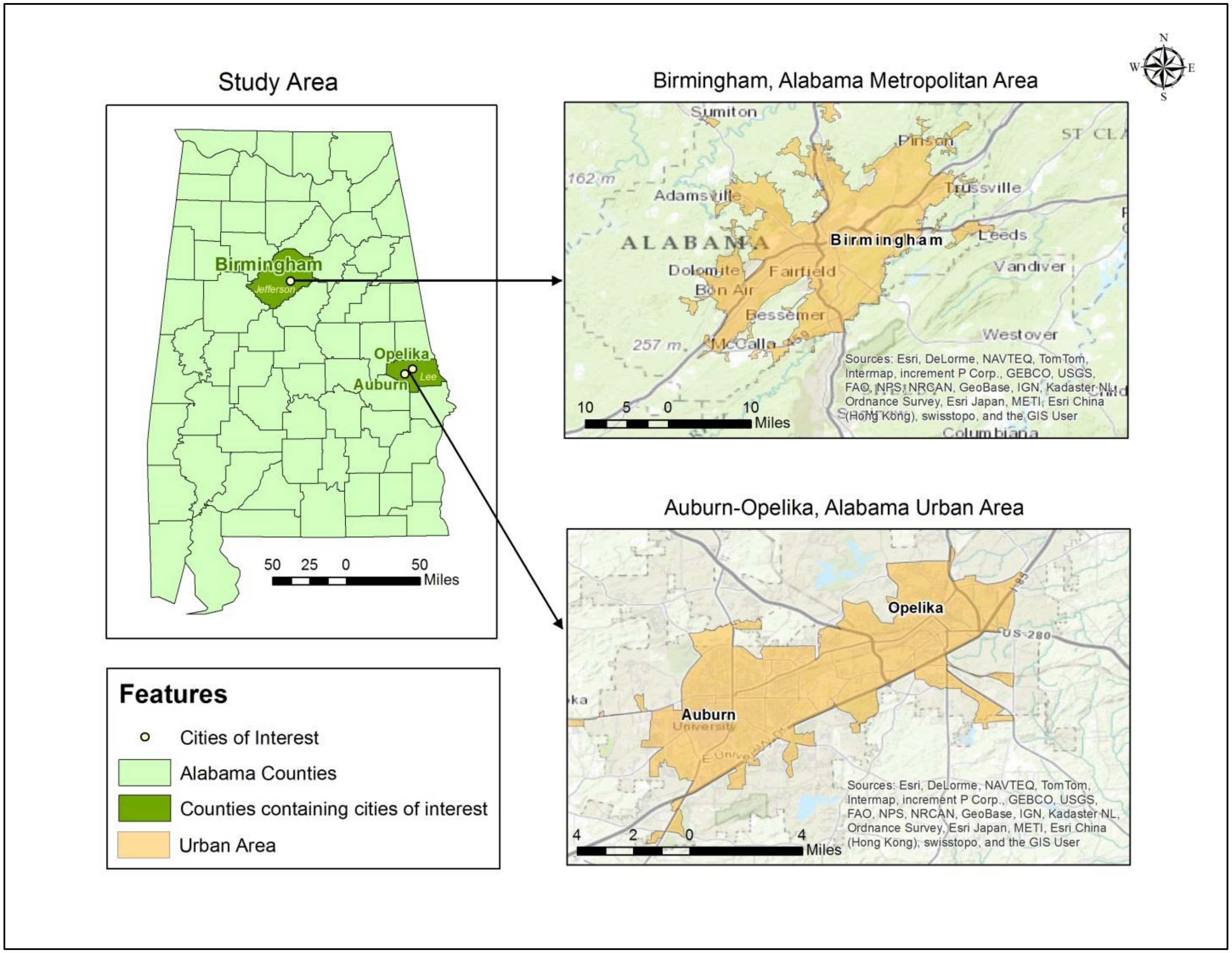
Other LST studies have used Landsat imagery (as does this study) to analyze surface temperatures, including Weng (2001), which explored the relationship of land cover and LST in the Zhujiang Delta, China. Yang et al. (2003) utilized Landsat ETM to show that urban surfaces alter the sensible and latent heat fluxes existing between the urban surface and boundary layers, which in turn affects urban surface temperatures. Jiang's 2006 study of Beijing, China incorporated Landsat data to show an average increase of 4.5°C to 9°C in downtown Beijing compared to surrounding rural areas. Other research includes a study which used Landsat 5 and Landsat 7 data to assess the thermal effects produced by urbanization in the Tampa Bay, Florida Watershed and the city of Las Vegas, Nevada (Xian and Crane 2006). In addition, Raja (2012) employed Landsat thematic mapper (TM) and enhanced thematic mapper (ETM) imagery from 1989 to 2010 and supervised classifications to study the relationship between land cover change and LST. In the present study, the purpose of Landsat is to quantify and compare the magnitude of the surface UHI in both Birmingham and Auburn-Opelika utilizing Landsat 8's thermal band with the atmospheric UHI quantified through atmospheric temperature data collected from the iButtons.

1.5 Study Areas

Many UHI studies have been done for large cities such as New York City (Bornstein 1968); Atlanta, GA (Bornstein and Lin 2000); Singapore (Chow and Roth 2006); and Mexico City, Mexico (Cui and De Foy 2012). However, very few studies have focused on small to mid-size urban areas such as Auburn-Opelika, AL which has seen a substantial amount of population and urban growth (Rahman et al. 2013). This study focuses on the urban and nearby rural areas of Birmingham and Auburn-Opelika, AL (Hinkel et al. 2003, Sullivan and Collins 2009).

Birmingham is located in east central Jefferson County, at 33.6333° north and 86.8333° west and has a rich industrial and civil rights heritage. The city's population grew so fast during the height of the nation's manufacturing period that it was dubbed the "Magic City." Birmingham was chosen for this study because it ranks 13th among the largest southeastern metropolitan areas, and it is the largest city in Alabama, with an estimated population of 242,820. As a relatively large city, it can be effectively compared to a midsized city such as Auburn-Opelika. The average elevation of Birmingham is 620 ft. and ranges between 538ft. and 1,200 ft. Average annual rainfall for Birmingham is 54.8 in. with an overall average temperature of 61.8°F. It is home to ten colleges, including University of Alabama at Birmingham (UAB) and Birmingham Southern (Birminghamal.gov 2014).

Auburn and Opelika are two separate, neighboring towns (central downtowns are about 6.5 miles apart) dubbed a single urban area for this study. Auburn is located in the southwestern part of Lee County at 32.6097° N, 85.4808° W, while Opelika is located in north central Lee County at 32.6453° N, 85.3783° W (City of Auburn 2014, City of Opelika 2014). Auburn-Opelika has an overall average temperature of 63.0°F and an average annual rainfall of 56.6 in. With elevation averaging at approximately 777 feet, it serves as the highest point between Atlanta, GA and New Orleans, LA (City of Auburn 2014, City of Opelika 2014). Both towns are well connected by Opelika Road/Pepperell Parkway, a well-developed, four-lane highway. According to the city of Auburn's vision statement, Auburn is committed to being an attractive, environmentally conscious community that is progressive, responsible, and hospitable. It is home to Auburn University and has a population of 54,566 (excluding college students) (City of Auburn 2014). Opelika is home to Southern Union State Community College and since 2007 has officially been a "City of Character" since April of 2007. It also holds the county seat and has a total population of just under 28,000. Opelika defines itself as a progressive city of the South that is "rich in heritage with a vision for the future" (City of Opelika 2014). Both study areas are shown on the map in Figure 1.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User

Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User

Figure 1. Study area locations

Chapter 2: Quantification of Atmospheric Temperatures using iButtons.

2.1 Overview

This chapter is divided into five main sections. The selection, specifications, and description/operation of the iButtons are all discussed in the first section, entitled iButton Background. The second section, entitled iButton Placement, addresses sensor selection and general criterion placement throughout the two study areas before being divided into two subsections (one subsection for each study area). A more detailed discussion regarding iButton placement occurs in the two sub-sections. The third section, entitled Data Processing and Analysis Methods, provides a detailed account of the methods used to process and analyze the observational temperature data. The fourth section, entitled Results, contains 25 sub-sections, which discuss the monthly average daytime and nighttime UHI patterns from 1 March 2014 to 31 August 2014 in both Birmingham, AL and Auburn-Opelika, AL. Average diurnal temperature data for each month for both study areas is included in Appendix A.

2.2 iButton Background

Budgetary concerns were an important concern in the selection of a Dallas Semiconductor product called the iButton, which is a low cost, high frequency recording temperature monitoring instrument purchased through Embedded Data Systems.

There are a variety of iButton models, including the DS1921G, DS1921H, and DS1922L (embedded data systemes, 2014). All of the models listed above were considered for this study, but the DS1922L was selected because of its temperature range and accuracy. It is pictured below in Figure 2 just to the left an eight-track cassette used for scale.

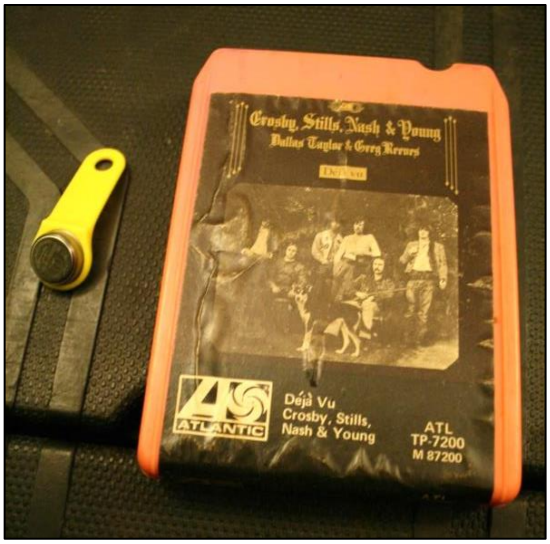


Figure 2. DS 1922L iButton

The DS 1922L has a temperature recording range of -15°C to 85°C and an accuracy of 0.5°C, versus the 1°C accuracy of the other models considered. The DS1922L also has a programmable recording frequency between 1 second and 273 hours and a programmable resolution of 0.0625°C or 0.5°C. The resolution is defined as the minimum change in environmental temperature necessary for the iButton to recognize the change in temperature. The higher resolution option (0.0625°C) was selected for this study, and the recording frequency was programmed to one hour. Embedded Data Systems advertises the maximum recording capacity to be 4,096 temperature readings before data loss or "rollover" occurs, assuming a resolution of 0.0625 ° C. Rollover is an option that permits the memory in the sensor to write over the earliest recorded data when the recording capacity has been exceeded (embedded datasystems 2014). If rollover is not enabled, the instrument will stop collecting data after the maximum recording capacity has been met but will resume again following data collection.

In order to collect data, researchers traveled to each iButton location with a laptop computer equipped with 1-wire data software and a cord supplied by embedded data systems used to connect the computer to the iButton. Given the one-hour temperature recording frequency and the recording limit of the instruments, data were collected on or before the 170th day following the start of temperature recording, to prevent data loss. Data were saved in the versatile .csv file format. Once the data were collected, researchers programmed the devices to begin recording again using the provided software. Temperature was recorded in Fahrenheit, and each iButton was synchronized to the time clock on the laptop computer to assure that the temperature recording times were accurate.

2.3 iButton Placement

As in Hinkel et al. (2003) and Sullivan and Collins (2009) studies, a widespread network of iButtons was created in and around the Birmingham, AL and Auburn-Opelika, AL urban areas. When selecting iButton sites, even spatial distribution was considered, as well as individual environments. iButtons were placed in downtown areas dominated by concrete, city parks near downtown areas, and rural locations several miles outside of downtown. Although not evenly spatially distributed, the rationale was to record the expected differences in temperature over pervious and impervious surface types and varying building height to street width (H:W) ratios.

H:W ratio refers to the heights of the buildings in relation to the width of the adjacent street(s). Previous studies, including Ahmed (1994) and Johansson and Emmanuel (2006), have shown that daytime temperature peaks in urban areas with a low/small H:W ratio (i.e. areas with long, low-rise buildings), while nighttime temperatures peak in urban areas with a high/large H:W ratio (i.e. areas with dense, high-rise buildings). Although the high-rise buildings act as heat sinks during the day, they reduce local urban temperatures thanks to the shade they provide at the street level; unlike low-rise buildings. However, the high-rise buildings release that heat after sunset, increasing local urban temperatures at night. The low-rise buildings provide little to no shade, increasing local urban temperatures by day, but reduce local urban temperatures by night because they do not hold in thermal energy as the high-rise buildings do.

A total of forty site locations were chosen based on site characteristics and availability of architecture on which to install instruments. Permission was granted by Birmingham, Auburn, and Opelika to place these inconspicuous devices on the backs of traffic signs, using zip ties. Each sensor was installed in a plastic bracket facing north and away from the traffic sign pole at 2-3 meters above ground level (Oke 2004, Arnfield 2003). Although concerns of the metal street sign influencing temperature readings developed, it was decided that the obtuse angle of the plastic brackets containing the instruments shielded them from direct contact with the metal poles. In addition, the temperature recording sensor is on the side of the iButton which faces away from the street sign pole (see Figure 3). In rural areas where traffic signs were not present, utility poles were used as installation structures (Sullivan and Collins 2009). Identification tags were drafted, printed and laminated before being attached the outsides of the iButton and bracket assemblies. Typical installation of an iButton is shown in Figure 3. All instruments had identification tags, as seen in the right side photo.

Figure 3. iButton installation on the back of a street sign. The photo on the left is the iButton in the bracket without the id tag. The photo on the right is the iButton in the bracket with the id tag.

Although factors such as aspect and height from the ground were considered in both study areas, additional site placement criteria were somewhat different (mainly due to urban topographic differences). A table of general site environments used for all iButton locations in both Birmingham and Auburn-Opelika is provided in Table 1.

Table 1. General site environments and descriptions.

Urban	≥ 75 % urban surface. Dominated by concrete, asphalt, and other impervious surfaces.
Peri-urban	Heterogeneous mix of urban and rural surfaces. ≤ 60 % urban surface
City Park	≤ 40% urban surfaces. Well defined green space in an otherwise urban area.
Rural	≤ 20 % urban surfaces. Dominated by soil and vegetation.

Explanations of the site placement factors for each study area are explained below in sections 2.3.1 and 2.3.2.

2.3.1 Birmingham iButton placement

Twenty-one of the forty installation sites were chosen throughout and around downtown, including highly urbanized sites, city park sites, suburban neighborhood sites surrounding downtown, and various rural sites with an average distance of 23 miles outside the city. Birmingham is Alabama's largest city, with a relatively expansive downtown area containing a modest number of high rise buildings or skyscrapers. This configuration creates a short, deep street canyon (Superczynski and Christopher 2011). Previous research (Ahmed 1994, Johansson and Emmanuel 2006,) has shown street canyons with high H:W ratios to contain the most intense locations of the UHI effect nocturnally, and the least intense locations of the UHI effect during the daytime hours. Therefore, sensors were placed near the Regions Bank Financial Headquarters on 5th Ave north and near the Birmingham Jefferson Civic Center (BJCC). Both sites are in the midst of the high rise buildings where the H:W ratio is the highest. Unfortunately, the City of Birmingham replaced the street sign on which the iButton at the BJCC location was mounted. It was not recovered and no data were acquired from that sensor for any part of the study.

Research has also shown that long, low-lying buildings generate less of a nocturnal UHI effect, but more of a daytime UHI effect (Johansson and Emmanuel 2006). Therefore, a couple of sensors were placed in more industrial parts of town that have the aforementioned building architecture in order to compare temperatures in high-rise sections to those in the industrialized sections.

The presence of city parks was also considered. Birmingham has a rich civil rights history, and Kelly Ingram Park was created to recognize that. An iButton was placed there in addition to Linn Park after considering previous studies, which proved that city parks in highly urbanized areas can reduce temperatures by 10°F. (Spronken-Smith and Oke, 1998, Barradas, 1991)

Another consideration was the presence of neighboring cities, or “satellite towns.” Hoover and Bessemer lie to the south and southwest of Birmingham, respectively, representing the largest of the satellite towns. One sensor was placed in the Hoover Mall parking lot, and another in the middle of downtown Bessemer. Two sensors were also placed in the suburban areas around Birmingham, and the remaining eight sensors were installed in remote areas outside of downtown, creating a perimeter around the city. The Birmingham iButton sites are numbered and displayed on the map in Figure 4. Site descriptions are given in Table 2, on page 18.

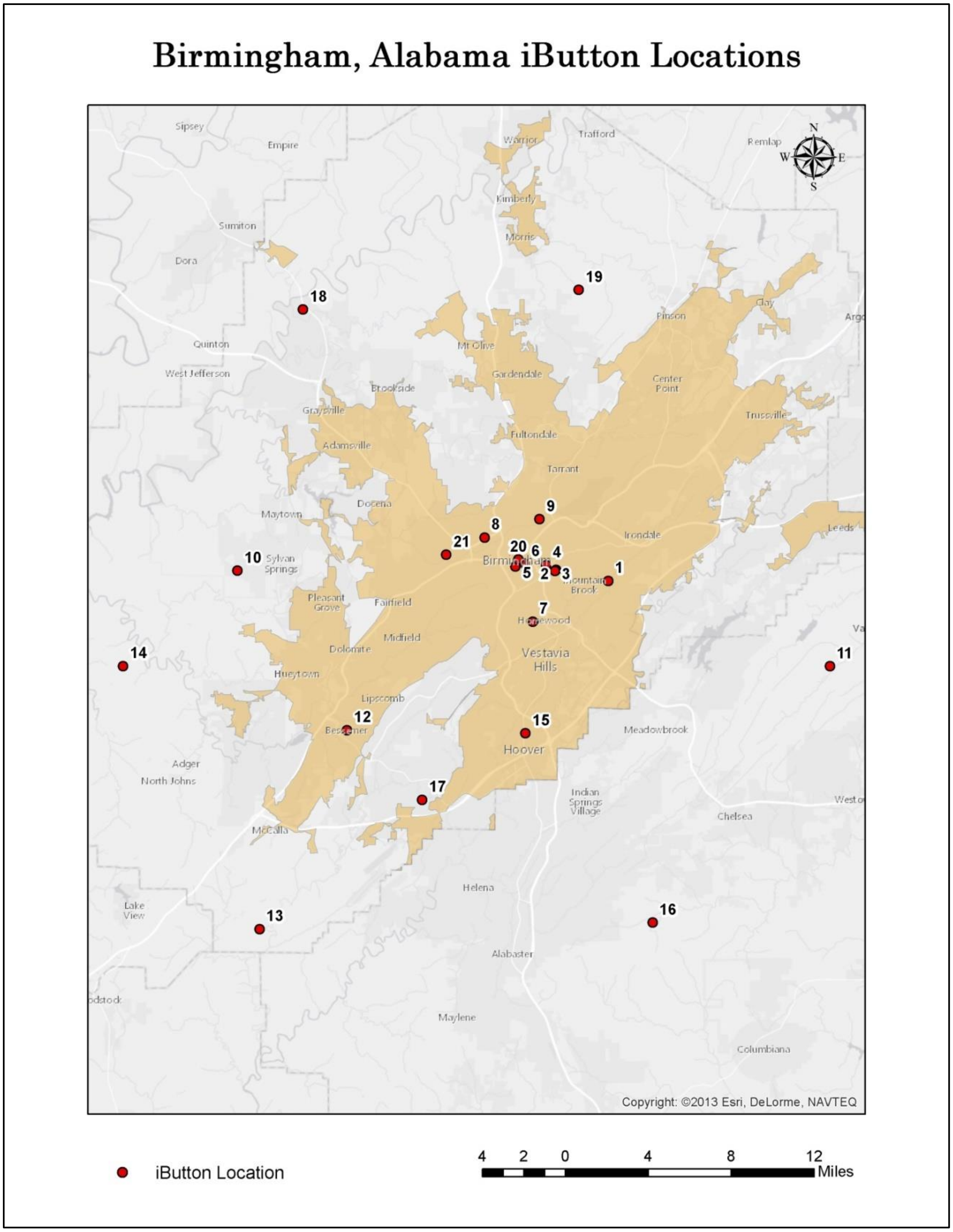


Figure 4. Birmingham iButton locations

Table 2. Birmingham, AL iButton site names and descriptions.

iButton Site Number	Latitude	Longitude	Site Name	Site Description
1	33.506070	-86.735470	Winston Way and Churchill Circle	Peri-urban
2*	33.513780	-86.779150	34th St. S. and 8th Alley	Peri-urban
3*	33.513040	-86.780120	The Pig	Urban
4	33.517120	-86.787400	31st St. S and 3rd Ave S.	Urban
5	33.516280	-86.812980	Kelly Ingram Park	City Park
6	33.518030	-86.805390	Regions Bank, 5th Ave. N	Urban
7*	33.477620	-86.798790	Parkridge Dr. and Manhattan St.	Peri-urban
8	33.536540	-86.838700	2nd Street W.	Urban
9	33.549290	-86.792810	Pull-A-Part	Urban
10	33.513420	-87.045440	Blackwell Dr.	Rural
11	33.445860	-86.550620	Bob Hood Branch	Rural
12	33.401840	-86.954050	Bessemer	Urban
13	33.262720	-87.026950	Old Serene Dr.	Rural
14	33.446630	-87.140790	Lock 17	Peri-urban
15	33.399520	-86.805070	Mall in Hoover	Urban
16	33.266850	-86.699310	Firetower Road	Rural
17	33.353170	-86.891240	County Rd. 6	Rural

18	33.696150	-86.990540	Littleton Sayre	Rural
19	33.709700	-86.759590	Castle Heights	Rural
20	33.521090	-86.810696	Linn Park	City Park
21*	33.524600	-86.870820	BJCC	Urban

Note: * indicates sites with incomplete data. Pig is short for Piggly Wiggly.

Although twenty-one sensors were installed, data were collected from just eighteen. Only data from March and April from the 34th Street and 8th Alley site is included in this study. The iButton disappeared prior to the second data collection date of 5 September 2014. No data were collected from site number seven. The street sign on which the Parkridge Drive and Manhattan Street iButton was mounted was replaced prior to the first data collection date of 1 May 2014. The same problem occurred at the BJCC site. The iButton at the Pig site failed before the first data collection date; therefore, no data were retrievable.

2.3.2 Auburn-Opelika iButton Placement

Although Auburn and Opelika are two separate towns, they are well connected by Opelika Road, and there is consistent, urbanized development in-between thems. Several sites were selected along Opelika Road to provide continuity between these two towns, with the intention of creating a single study area. Because significantly smaller than the Birmingham study area, only eighteen sites were selected for sensor installation (the remaining iButton was installed at the Auburn University Regional Airport for temperature validation purposes). Fewer factors were considered in the placement of these sensors because this study area does not have high rise buildings or satellite towns.

Several iButtons were installed in the CBDs of Auburn and Opelika. One was installed in the center of downtown Auburn, at the celebratory location of Toomer's Corner, while another was installed near the fountain in heart of downtown Opelika. Sites were also chosen near isolated buildings with expansive parking lots, such as the Auburn University (AU) Hotel and Southern Union State Community College (Southern Union). Sensors were also placed in urban green spaces such as Samford Park, about 500 feet north of the AU Hotel.

Similar sites were chosen in downtown Opelika. One sensor was placed in downtown between the Irish Bred Pub and Restaurant and Jefferson's Restaurant, on the corner of South Railroad Street and North 9th Street. An additional sensor was placed at another location just southeast of the Irish Bred Pub and Restaurant adjacent to the fountain in the heart of downtown. As with the Birmingham site placement, surrounding suburban neighborhoods were also chosen because they offer a heterogeneous mixture of urban and rural surfaces. In order to create one study area, a few sites were also selected between Auburn and Opelika along Opelika road including, the Village Mall and Tigertown (a large assemblage of home improvement, department, and electronics stores). Considering the size of Auburn-Opelika, only six rural locations were selected. Again, these six locations created a perimeter around the urbanized areas and were an average of eight miles outside of the downtowns. Because Auburn-Opelika is less developed than Birmingham, satisfactory rural locations were found an average of 8 miles outside of the downtown areas. The Birmingham iButton sites are numbered and displayed on the map in Figure 5. Site descriptions are given in Table 3, on page 22.

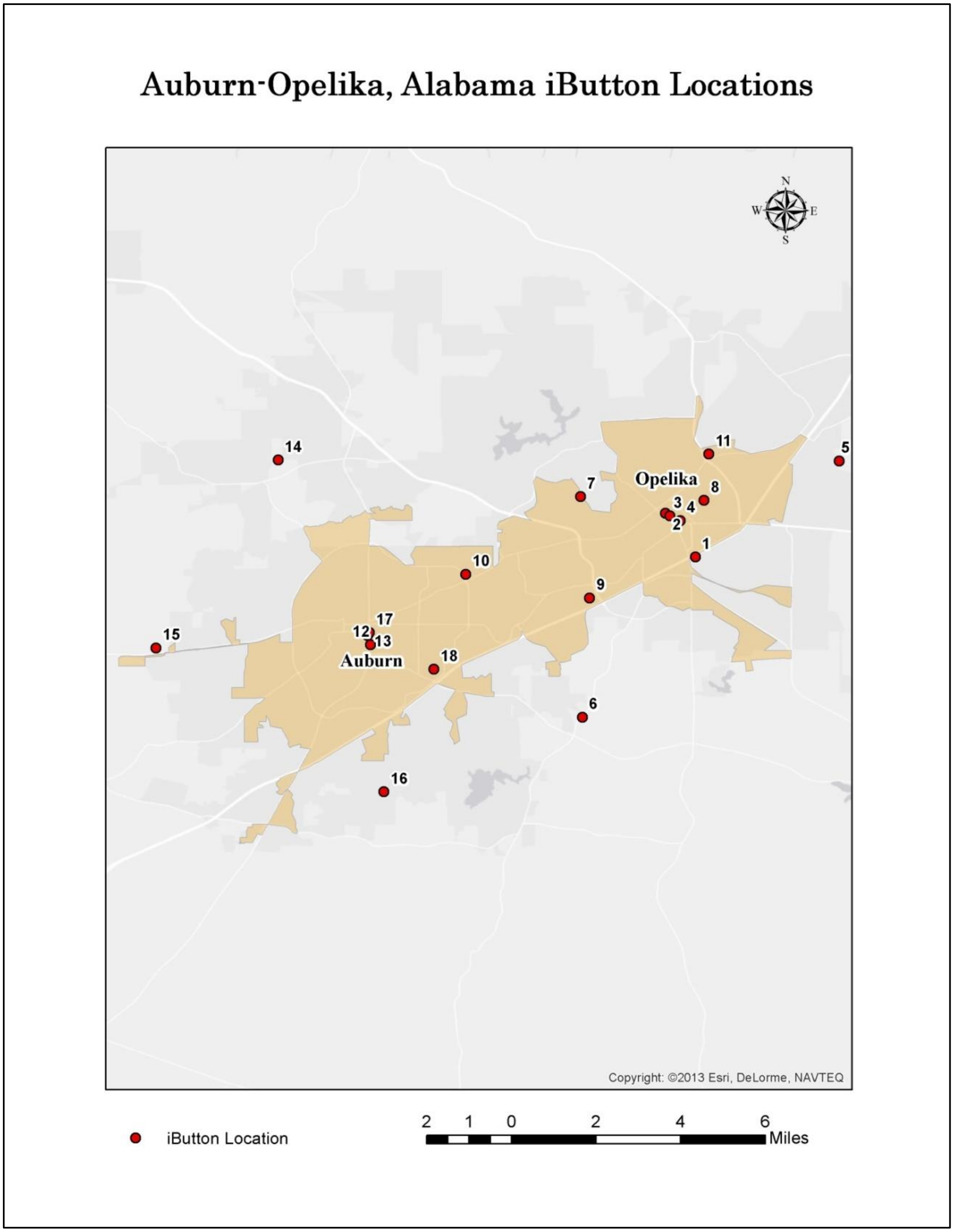


Figure 5. Auburn-Opelika iButton locations.

Table 3. Auburn-Opelika, AL iButton site names and descriptions.

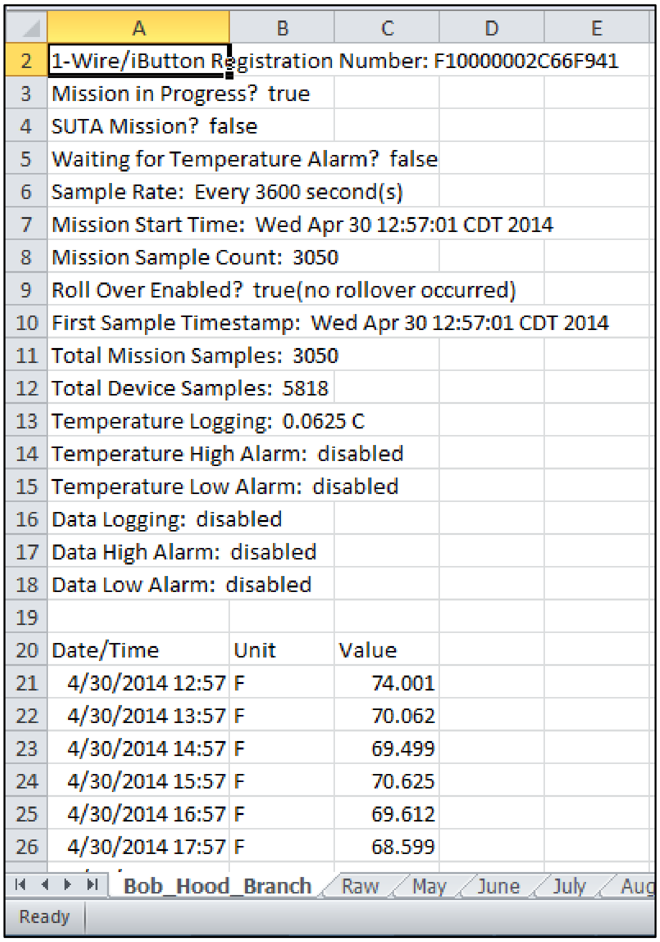
iButton Site Number	Latitude	Longitude	Location	Site Description
1	32.632190	-85.370060	I- 85	Peri-Urban
2	32.647210	-85.380280	Irish Pub	Urban
3	32.646280	-85.378830	Downtown Fountain*	Urban
4	32.644670	-85.375300	Ave. D and S 8th St	Peri-Urban
5	32.665100	-85.320920	County Rd. 161	Rural
6	32.577380	-85.408770	Lee Rd. 110	Rural
7	32.652880	-85.409380	White Rd.	Rural
8	32.651610	-85.367110	Oak Ct. and Darden St.	Peri-Urban
9	32.618170	-85.406280	Tigertown	Urban
10	32.626320	-85.448720	Village Mall	Urban
11	32.667480	-85.365520	Southern Union	Urban
12	32.602116	-85.481213	AU Hotel	Urban
13	32.605380	-85.482300	Samford Park	City Park
14	32.665450	-85.512900	Pepperwood Trail	Rural
15	32.601080	-85.554640	County Rd. 060	Rural
16	32.551790	-85.476720	Chewacla State Park	Rural
17	32.606330	-85.481630	Toomer's Corner	Urban
18	32.593790	-85.459540	Green St.	Peri-Urban

Note: * indicates sites with incomplete data.

Data were collected from all eighteen iButtons for March and April; however the Fountian iButton failed prior to data collection on 3 September 2014, making the May-August data irretrievable. It is therefore excluded from this study.

2.4 Data Processing and Analysis Methods

Following data collection, Microsoft Excel 2010 was used to open the hourly temperature data from each station. Upon opening the file, the specifications of the iButton are displayed in column A, rows 1-18, followed by the actual temperature data starting in column A, row 20, as pictured below in Figure 6.



	A	B	C	D	E
2	1-Wire/iButton Registration Number: F10000002C66F941				
3	Mission in Progress? true				
4	SUTA Mission? false				
5	Waiting for Temperature Alarm? false				
6	Sample Rate: Every 3600 second(s)				
7	Mission Start Time: Wed Apr 30 12:57:01 CDT 2014				
8	Mission Sample Count: 3050				
9	Roll Over Enabled? true(no rollover occurred)				
10	First Sample Timestamp: Wed Apr 30 12:57:01 CDT 2014				
11	Total Mission Samples: 3050				
12	Total Device Samples: 5818				
13	Temperature Logging: 0.0625 C				
14	Temperature High Alarm: disabled				
15	Temperature Low Alarm: disabled				
16	Data Logging: disabled				
17	Data High Alarm: disabled				
18	Data Low Alarm: disabled				
19					
20	Date/Time	Unit	Value		
21	4/30/2014 12:57	F	74.001		
22	4/30/2014 13:57	F	70.062		
23	4/30/2014 14:57	F	69.499		
24	4/30/2014 15:57	F	70.625		
25	4/30/2014 16:57	F	69.612		
26	4/30/2014 17:57	F	68.599		

Figure 6. iButton specifications and data

The temperature data are composed of three columns: “Date/time”, which displays the month/day/year and time using the twenty-four hour time clock for temperature readings, “unit” which indicates the temperature scale selected for temperature recording (Fahrenheit was used in this study), and “value,” the temperature recording itself.

The temperature data were processed by segregating it according to month of study. Next, individual hourly temperatures from a specific site for every day of an individual month were averaged over that entire month to create a diurnal climatic profile for each month and site (Alexandri and Jones 2008). Using the month of March and the Kelly Ingram Park site in Birmingham as an example, all temperature readings taken in the midnight CDT hour from Kelly Ingram Park over the thirty-one days of the month were averaged to achieve a single value for that site, showing the average midnight temperature for the entire month. Then, all thirty-one 1:00 CDT temperatures for the month of March were averaged to yield a single value, followed by all thirty-one 2:00 CDT temperatures, etc. This process was employed on all twenty-four hours for all iButton sites for all months of the study. This technique yielded a total of twenty-four values for each site over a specific month, indicative of the fluctuation in temperatures on an average day during that month. Next, data were segregated into days and nights, according to sunrise and sunset times in order to show the variability of the atmospheric temperature and UHIs between day and night. Because of seasonal and time changes during the study, small variations in time periods were selected to define daytime and nighttime temperatures during the study period. These time periods are listed in Table 4. Because this study took place during the change from central standard time (CST) to central daylight time (CDT) (change took place at 2:00 CST on 9 March 2014), times for March 1-8 are given in CST and times for Mach 9-31 are given in CDT.

Table 4. Temperature recording periods according to month of study.

Month of Study	Time of day	Time period
March 1-8	Day	7:00-18:00 CST
March 1-8	Night	19:00-6:00 CST
March 9-31	Day	7:00-19:00 CDT
March 9-31	Night	20:00-6:00 CDT
April	Day	7:00-18:00 CDT
April	Night	19:00-6:00 CDT
May	Day	6:00-19:00 CDT
May	Night	20:00-6:00 CDT
June	Day	6:00-20:00 CDT
June	Night	21:00-5:00 CDT
July	Day	7:00-20:00 CDT
July	Night	21:00-5:00 CDT
August	Day	7:00-19-00 CDT
August	Night	20:00-6:00 CDT

A total of twenty-four maps were made using ArcGIS 10.1 to show atmospheric temperature for both study areas through the following process. IDW interpolation in ArcGIS 10.1 was used to create a raster surface over each study area, displaying the monthly daytime and nighttime atmospheric temperature data for each month of the study. IDW is a well-documented procedure for spatially mapping atmospheric variables. Dodson and Marks (1997) used an IDW algorithm to interpolate daily maximum and minimum air temperatures over a mountainous region in the Pacific Northwest. Vicente-Serrano et al. (2003) used IDW interpolation to map average temperatures at sea level in the middle Ebro Valley of Spain. Nenyerola et al. (2007) used the IDW function to map monthly mean minimum, monthly mean and monthly mean maximum air temperature using data from meteorological stations. In addition, Chen and Liu (2012) used IDW to predict rainfall in the middle of Taiwan.

IDW's principles of operation are based on Walter Tobler's first law of geography (all things are related, but near things are more related than distant things). This method was developed in 1972 by the National Weather Service and works on the principle of distance decay (Chen and Liu 2012). It is based on the supposition that the predicted value at an unsampled point is a distance weighted average of observed values at sampled points within a certain radius around the unsampled point (Vicente-Serrano et al. 2003). In other words, IDW assumes that the observed values nearest the location of predicted values have more leverage on the predicted values than the observed values at more distant locations (Legates and Willmott 1990; Stallings et al. 1992; Luo et al. 2008).

Different scenarios for each map were modeled by adjusting the cell size and the number of points (the number of points was changed to indicate the number of data points, or iButtons, considered for each model run, and the output cell size value was changed multiple times for each model run). The power was left at 2 and the maximum distance option was not used. Next, values for each model run were extracted to points in order to calculate the root mean square error (RMSE) and p-value, using a paired t test to check the validity and statistical significance of each model. The RMSE indicates the standard deviation of the difference between the observed values (i.e. the recorded on-site temperature values from the iButtons) and the predicted values (i.e. the interpolated temperature values from the IDW model) (Chen and Liu 2012). The equation is given below.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Y_i - \hat{Y}_i\right)^2}$$

Finally, the monthly average diurnal temperature data from all urban and rural sites (city parks and peri-urban sites were excluded) were used to graph the average daytime and average nighttime urban and rural temperatures to indicate the UHI intensity over the entire study period.

2.5 Results.

All IDW models used to create the maps in this study had p-values greater than 0.05 and RMSE values well below 1; thus every model was valid and statistically significant at the 0.05 significance level. The RMSE and p-values are listed below according to figure number in Table 5.

Table 5. IDW model RMSE and p-values.

Description	RMSE value	p-value
Figure 7	0.00	0.92
Figure 8	0.00	0.99
Figure 9	0.02	0.91
Figure 11	0.01	0.98
Figure 14	0.00	0.96
Figure 15	0.01	0.91
Figure 16	0.01	0.89
Figure 17	0.00	0.92

Figure 18	0.03	0.99
Figure 19	0.01	0.92
Figure 20	0.02	0.99
Figure 21	0.03	0.90
Figure 22	0.03	0.96
Figure 23	0.02	0.88
Figure 24	0.03	0.97
Figure 25	0.02	0.92
Figure 26	0.02	0.91
Figure 27	0.02	0.91
Figure 28	0.02	0.98
Figure 29	0.02	0.91
Figure 30	0.02	0.91
Figure 34	0.02	0.92
Figure 36	0.02	0.95
Figure 38	0.06	0.99
Figure 40	0.04	0.99

Overall results showed well-developed UHIs in both study areas throughout all months of the study, regardless of days or nights. Daytime UHIs developed around the small H:W ratio urban sites characterized by low-rise buildings, while nighttime UHIs developed around relatively large H:W ratio urban sites characterized by the tallest buildings in each study area. As expected, temperatures between the two study areas differed. The Auburn-Opelika overall average daytime temperatures were 1.6°F higher than Birmingham, while Birmingham's overall average nighttime temperatures were

0.2°F higher than Auburn-Opelika's. Largest temperature differences between study areas were observed in the urbanized areas. Auburn-Opelika's urban sites exhibited average temperatures of 2.7°F higher than Birmingham's by day, while Birmingham's urban sites exhibited average temperatures of 1.3°F higher than Auburn-Opelika's by night. This is a well-documented phenomenon and is supported by Ahmed (1994) and Emmanuel and Fernando (2007). Both found daytime maximum temperatures to occur in small H:W ratio urban areas and nighttime maximum temperatures to occur in large H:W ratio urban areas. These results are further supported by Oke (1973), which found a positive relationship between city size determined by population and UHI. Birmingham's population is 46 percent larger than Auburn-Opelika's. In addition, Birmingham has high-rise buildings in its CBD, resulting in a relatively large H:W ratio, whereas Auburn-Opelika has only mid-rise buildings, resulting in a relatively small H:W ratio. These factors could account for the temperature differences between the study areas. Monthly results for Birmingham and Auburn-Opelika are discussed below.

2.5.1 Birmingham Daytime Results for March 2014

March daytime temperatures in Birmingham ranged from 24.7°F recorded at the Firetower Road location at 7:01 CDT on 26 March 2014, to 90.3°F at the Lock 17 location on 31 March 2014 at 14:57 CDT. The warmest site on average, Pull-A-Part at 60.9°F, was an urbanized, industrial area characterized by low-rise buildings. Both city park sites were relatively warm, with temperatures between those at the Regions and Pull-A-Part sites. Kelly Ingram Park was 2.8°F cooler than Pull-A-Part, while Linn Park was within 1.0°F of Pull-A-Part. The Lock 17 site was an especially warm rural site, with an average temperature of 59.8°F, making it the third warmest location. The coolest site was Old Serene Drive, exhibiting an average temperature of 56.0°F. To illustrate temperature distribution, average atmospheric daytime temperatures in Birmingham for March is shown in Figure 7.

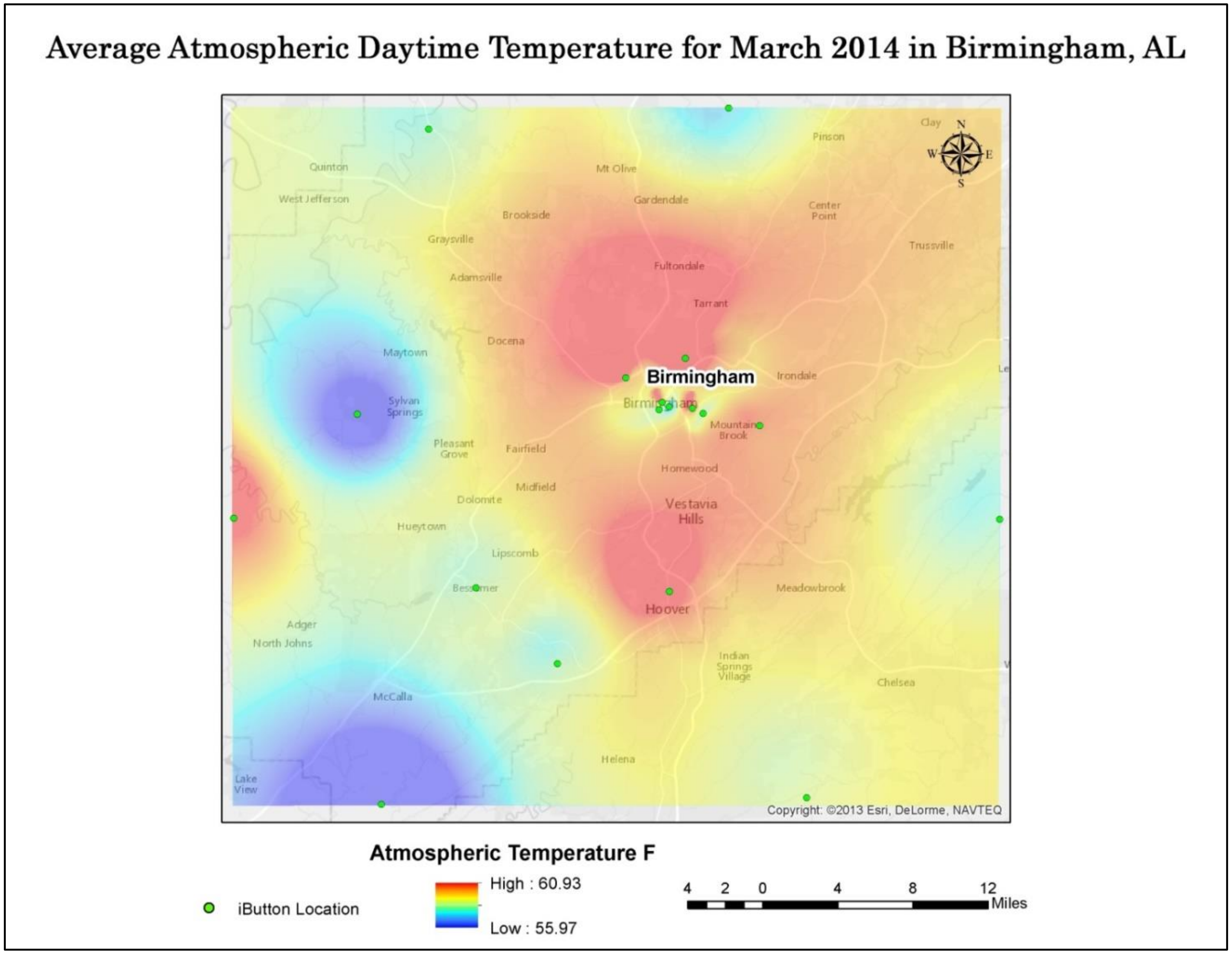


Figure 7. Average atmospheric daytime temperature for March 2014 in Birmingham

As seen in Figure 7, daytime average temperatures had a range of 4.96°F, and fell between 55.97°F and 60.93°F. The larger H:W ratio areas, such as Regions, exhibited relatively low temperatures by day compared to the smaller H:W areas, such as Pull-A-Part, which experienced relatively high temperatures by day. While not apparent in Figure 7, these findings are evident in the average temperature data (see Appendix A), Noticeable temperature differences were observed among the Regions, Bessemer, and Pull-A-Part sites. Regions had the lowest urban temperature, at 57.3°F, while Pull-A-Part had the highest urban and overall temperature, at 60.9°F. Bessemer served as a relatively accurate midpoint between those two (with respect to H:W ratio), exhibiting an average temperature of 58.0°F. This paradox is well documented, and is supported by the findings in previous studies. For example, Ahmed (1994) found lower maximum air temperatures in areas with higher H:W ratios in the hot and humid climate of Dhaka, Bangladesh. The Johansson (2006) study of Fez, Morocco (hot, arid climate) found very similar results showing that deeper street canyons had lower maximum air temperatures than shallow street canyons.

Although March was the coolest month of the study, well-developed heat island effects were still identifiable at two separate sites (characterized by the highest temperatures on the map, indicated by the deepest shades of red in Figure 10). The largest, northernmost heat island, enveloping the northern section of downtown Birmingham and surrounding towns (including Fultondale and Tarrant), measured 60.89 mi^2. The area within the southernmost heat island around Hoover was less than half that size, at 26.56 mi^2. There was one remaining hot spot centered around the peri-urban site of Lock 17, measuring 10.60 mi^2 in area.

2.5.2 Birmingham Nighttime Results for March 2014

The nocturnal results were quite different from the daytime results. The highest temperature of 73.0°F was recorded at the urban location of Bessemer on 22 March 2014 at 20:00 CDT. The lowest temperature, 23.0°F, was recorded at the rural Castle Heights site at 5:57 CDT on 26 March 2014. Given that March was the coolest month of the study, the thermal effects of urban surfaces were still prevalent.

Regions was the warmest site on average, exhibiting an average nighttime temperature of 52.4°F; 3.1°F warmer than the Pull-A-Part site. Contrary to the daytime results, temperatures at the sites with the deepest street canyons were the highest of the urban sites at night, and the sites with the shallowest street canyons were the lowest; again supporting the results found in the Johannson and Emmanuel (2006) study. Temperatures at both Linn and Kelly Ingram parks (located in the same high-rise district as Regions) fell between those at Regions and Bessemer, averaging 52.0°F and 51.8°F, respectively. Littleton Sayre was the coolest site, exhibiting an average temperature of 44.6°F. A map displaying average nighttime March temperatures in Birmingham is shown in Figure 8.

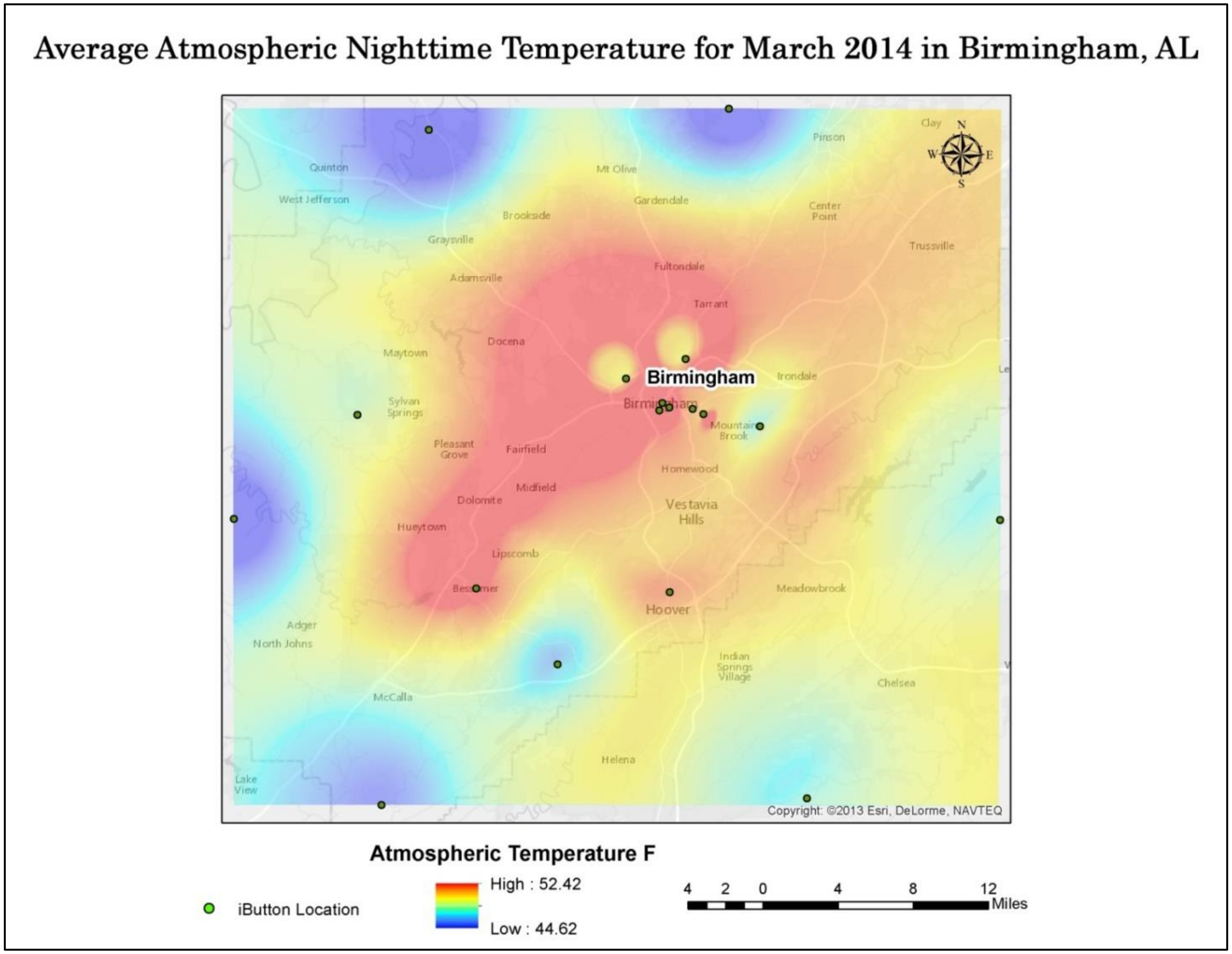


Figure 8. Average atmospheric nighttime temperature for March 2014 in Birmingham.

Nighttime average atmospheric temperatures exhibited a considerably wider but cooler overall range than the daytime average atmospheric temperatures, at 7.80°F vs. 4.96°F. However, nighttime data analysis revealed only one expansive heat island encompassing the downtown Birmingham area and the city of Bessemer, covering a total area of 150.1 mi^2. It is important to note the relative cooling effects of the Pull-A-Part and 2nd Street west sites (Between Tarrant and downtown Birmingham), which produced two cool spots within the heat island around downtown Birmingham, measuring 6.0 mi^2 and 5.8mi^2 respectively. The heat island on the northern side of Hoover, quite evident in the daytime results, was hardly distinguishable at night for the month of March.

2.5.3 Auburn-Opelika Daytime Results for March 2014

On average, March average daytime temperatures in Auburn-Opelika were 2.6°F warmer than the March daytime temperatures in Birmingham. This anomaly may be the result of the 0.93 degree difference in latitude between the two study areas. A more likely cause is the fact that, unlike Birmingham both Auburn and Opelika have low to mid rise buildings in their CBDs, creating a large H:W ratio. The highest recorded temperature was 93.3°F on 22 March 2014 at 14:59 CDT and again on 31 March 2014 at 15:59 CDT at the AU Hotel site. The lowest temperature of 27.6°F was recorded on 26 March 2014 at 7:00 CDT at the Lee Road 110 site.

The warmest location on average was the AU Hotel, at 67.6°F. The Irish Pub site, located on the very northern edge of the mid-rise building section in downtown Opelika, was 4.6°F cooler than the AU Hotel site. Samford Park, located within a city block of the AU Hotel, was 6.0°F cooler on average, exemplifying the cooling effects that urban greens space provides, as documented in Spronken-Smith and Oke (1998) and Barradas (1991). The heavily wooded Pepperwood Trail site was the coolest on average, at 58.4°F. The map displaying the average daytime temperatures for March is displayed in Figure 9.

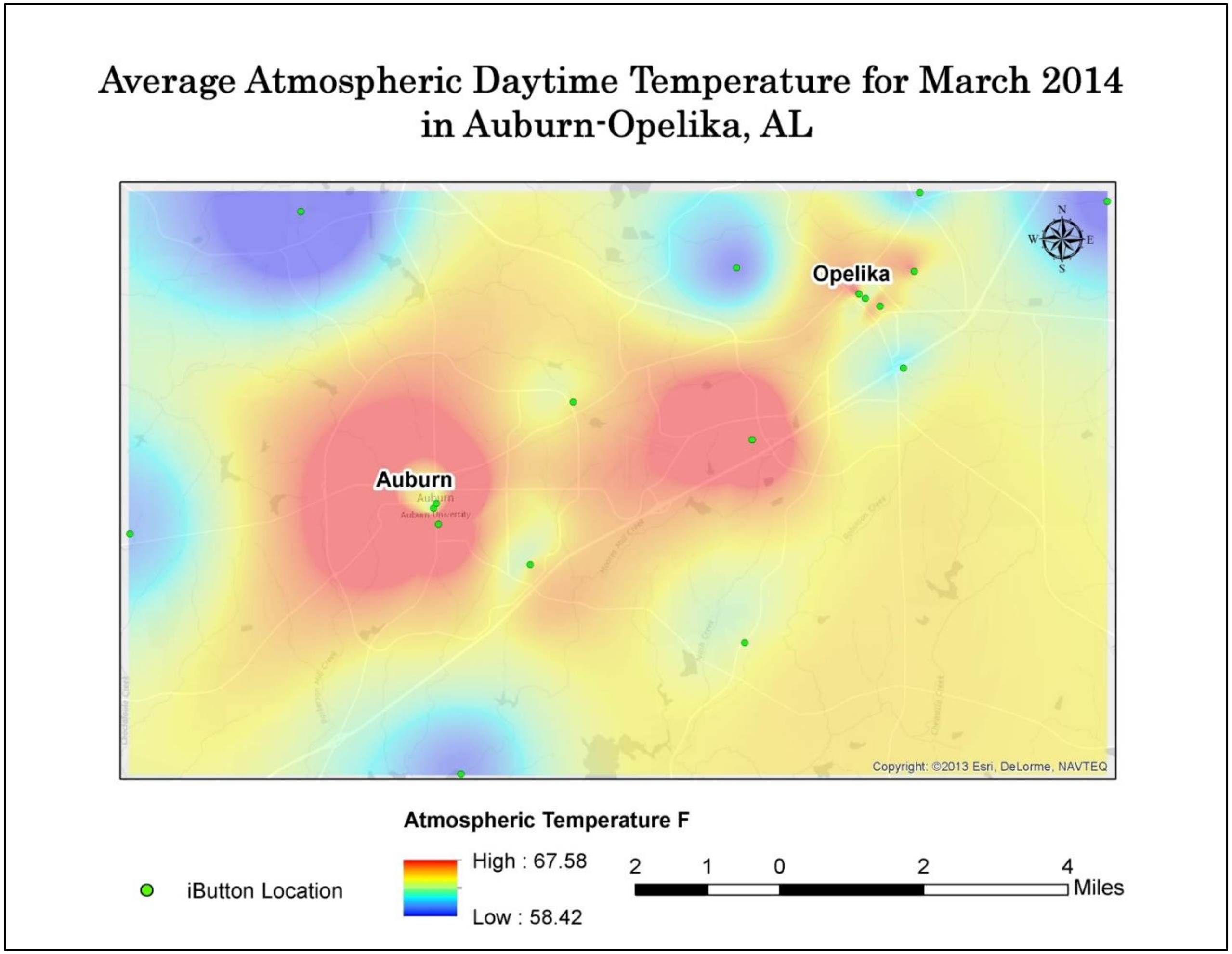


Figure 9. Average atmospheric daytime temperature for March 2014 in Auburn-Opelika.

Daytime average temperatures for March had a significantly larger range in Auburn-Opelika than in Birmingham (9.16°F vs. 4.96°F). Although smaller in both area and population than Birmingham, two distinguishable, well defined heat islands were evident: one around downtown Auburn, measuring 5.54 mi^2 and the other centered around Tigertown, measuring 3.10 mi^2. The daytime cooling effects of Samford Park were evident, creating a cool spot measuring 0.39 mi^2 near the center of the heat island around Auburn. An unexpected cool spot also developed in the northeastern part of the map, at the urban location of Southern Union.

2.5.4 Auburn-Opelika Nighttime Results for March 2014

Auburn-Opelika's average nighttime temperatures for March were 1.0°F warmer than Birmingham's. The warmest nocturnal temperature of 70.8°F was recorded on 11 March 2014 at 20:01 CDT in the heart of downtown Opelika at the fountain site. The coolest recorded temperature was 25.8°F on 26 March 2014 at 5:56 CDT at the County Road 161 location.

The warmest nocturnal site on average was Toomer's Corner, located in the heart of the CBD in downtown Auburn, at 51.7°F. The Fountain site in downtown Opelika was a close second, at 51.2°F. Samford Park was within 1°F of both the Toomer's Corner and the AU Hotel sites. On average, the coolest location was the County Road 161 location, at 46.2°F. Average nocturnal temperatures for March are displayed in Figure 10.

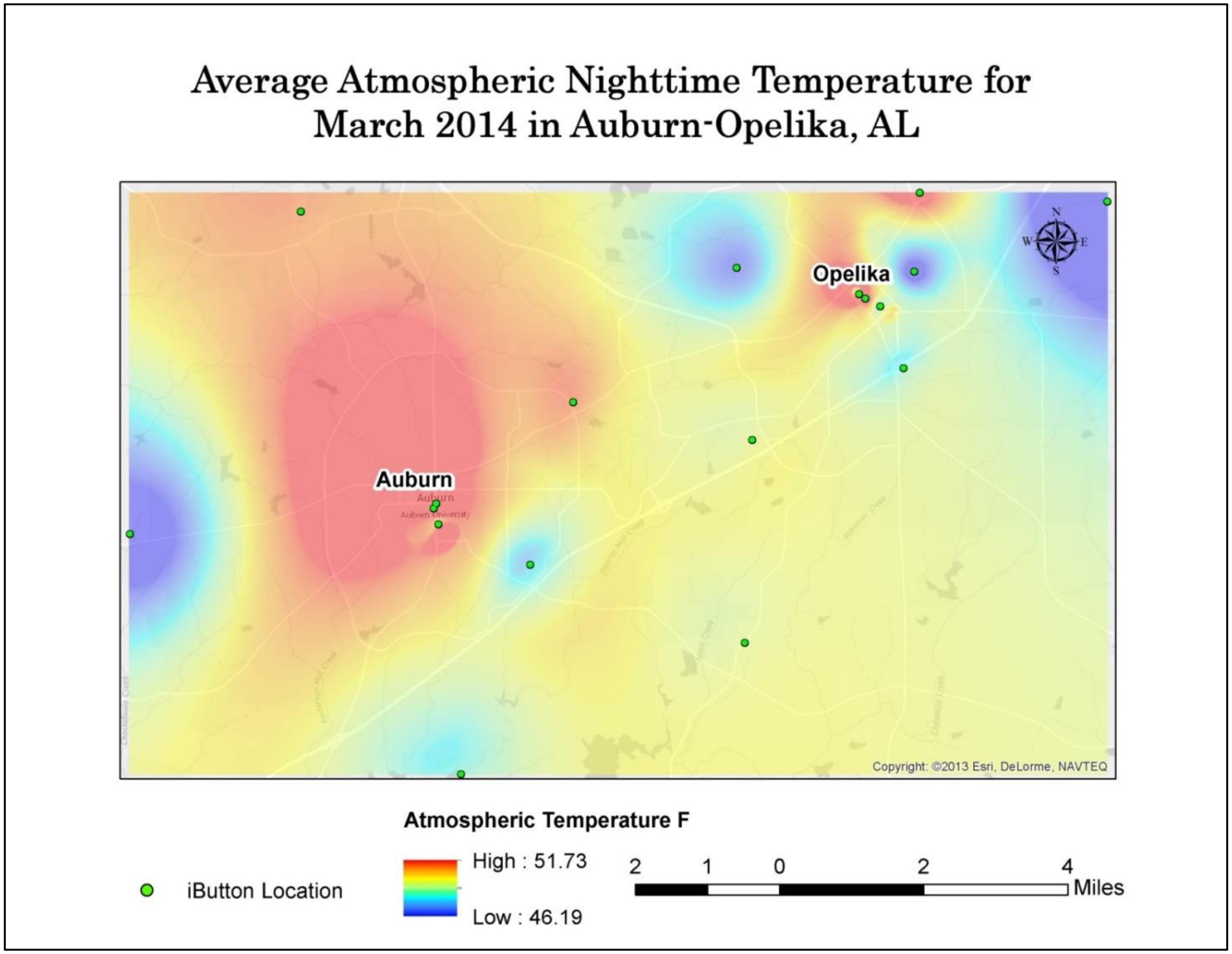


Figure 10. Average atmospheric nighttime temperature for March 2014 in Auburn-Opelika.

Nocturnal results for Auburn-Opelika had a considerably different spatial pattern and distribution compared to the daytime Auburn-Opelika results. There was a relatively large heat island over and north of downtown Auburn, encompassing an area of 8.72mi^2; 36.5 percent larger than the heat island observed in the daytime. An interesting phenomenon to note was the small, relatively cool spot produced by the AU Hotel. It appears it has a nocturnal cooling effect similar to that at the Pull-A-Part site in Birmingham. The heat island around Tigertown disappeared, again demonstrating the thermal property advantages of low-rise buildings. A much smaller heat island developed around the Fountain site in downtown Opelika, measuring 0.38 mi^2.

2.5.5 Birmingham Daytime Results for April 2014

April daytime temperatures were 10.6°F warmer, on average, than the Birmingham March daytime temperatures. The highest recorded temperature during the daytime hours in April was a surprisingly warm 102.8°F at 18:01 CDT on 26 April 2014 at the Firetower Road site, while the coolest temperature was 32.5°F at 7:16 CDT on 16 April 2014 at the old Serene Dr. location.

The warmest site on average was Pull-A-Part again, at 72.5°F. Regions was again the coolest urban site, and the second coolest site overall, with an average daytime temperature of 67.3°F. The Linn Park and Bessemer sites were within 0.1°F of each other, averaging 68.5°F, while the Kelly Ingram Park site was slightly warmer, at 69.2°F. Both city park locations were more than 3°F cooler than the Pull-A-Part site. The coolest average location was old Serene Dr., at 65.6°F. Average April daytime temperature is shown in Figure 11.

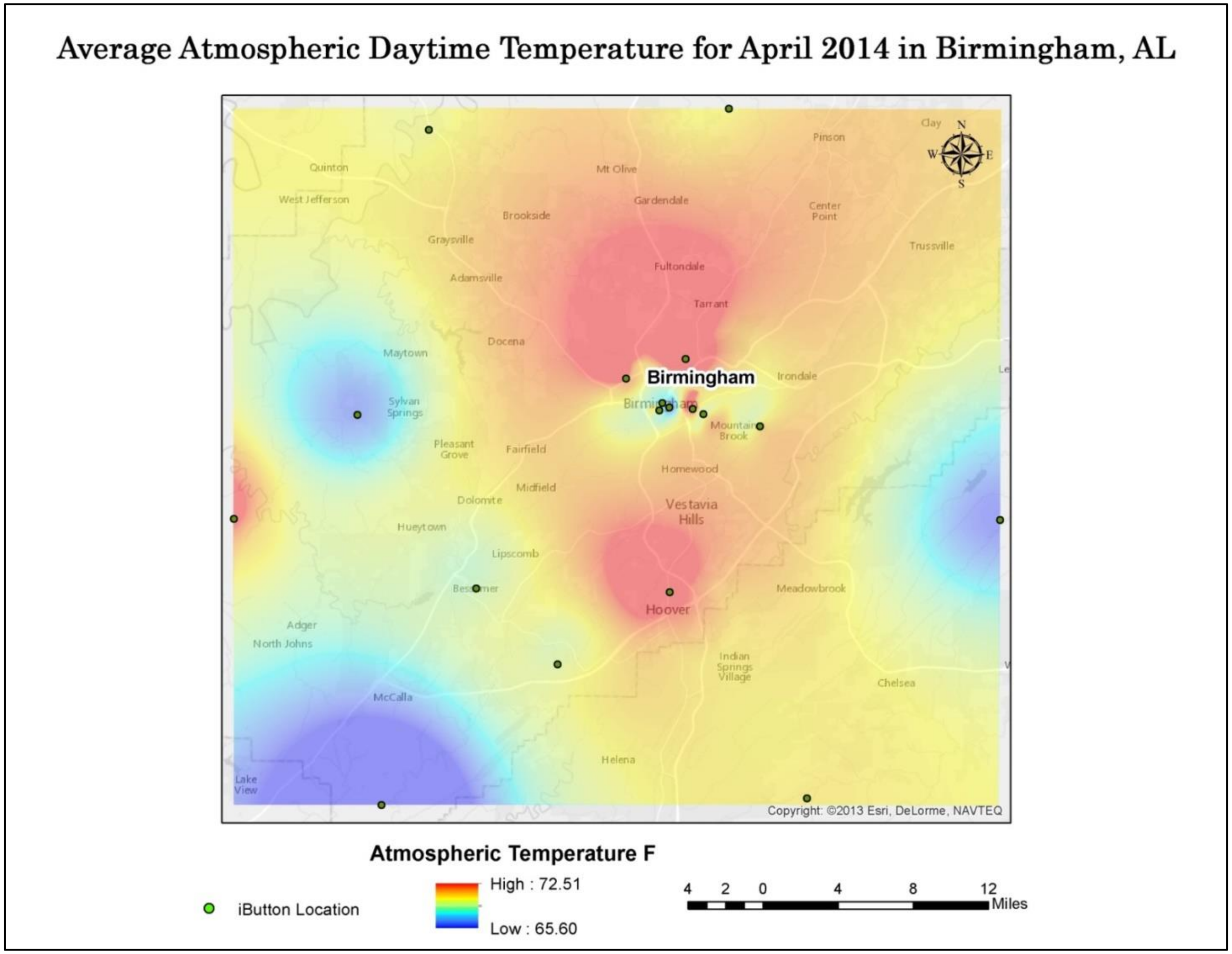


Figure 11. Average atmospheric daytime temperature for April 2014 in Birmingham.

The spatial location and extent of the heat islands in Figure 11 were very similar to the Birmingham March average daytime results in Figure 7. The heat island just north of downtown Birmingham was measured at 59.2 mi^2, while the heat island around Hoover measured 24.1 mi^2. Also, the hotspot around the peri-urban location of lock 17 was less developed in April compared to March, measuring just 3.4 mi^2.

2.5.6 Birmingham Nighttime Results for April 2014

Birmingham's April average nighttime temperatures were 10.1°F warmer than in March. The highest recorded nocturnal temperature in April of 78.8°F occurred at the Bessemer site (vs. Regions in March) at 20:30 CDT on 28 April 2014. Regions was a close second at 78.5°F; recorded on the same date within the same hour. The coolest temperature recorded was 28.4°F on 16 April 2014 at 5:57 CDT at the Castle Heights site.

Regions was the warmest on average, at 62.3°F. Kelly Ingram Park and Linn Park were within 0.5°F of Regions, but were warmer than the Bessemer site, which was 61.6°F on average. Littleton Sayre was the coolest average site, at 54.7°F. A map showing the Birmingham average nighttime temperatures for April is shown in Figure 12.

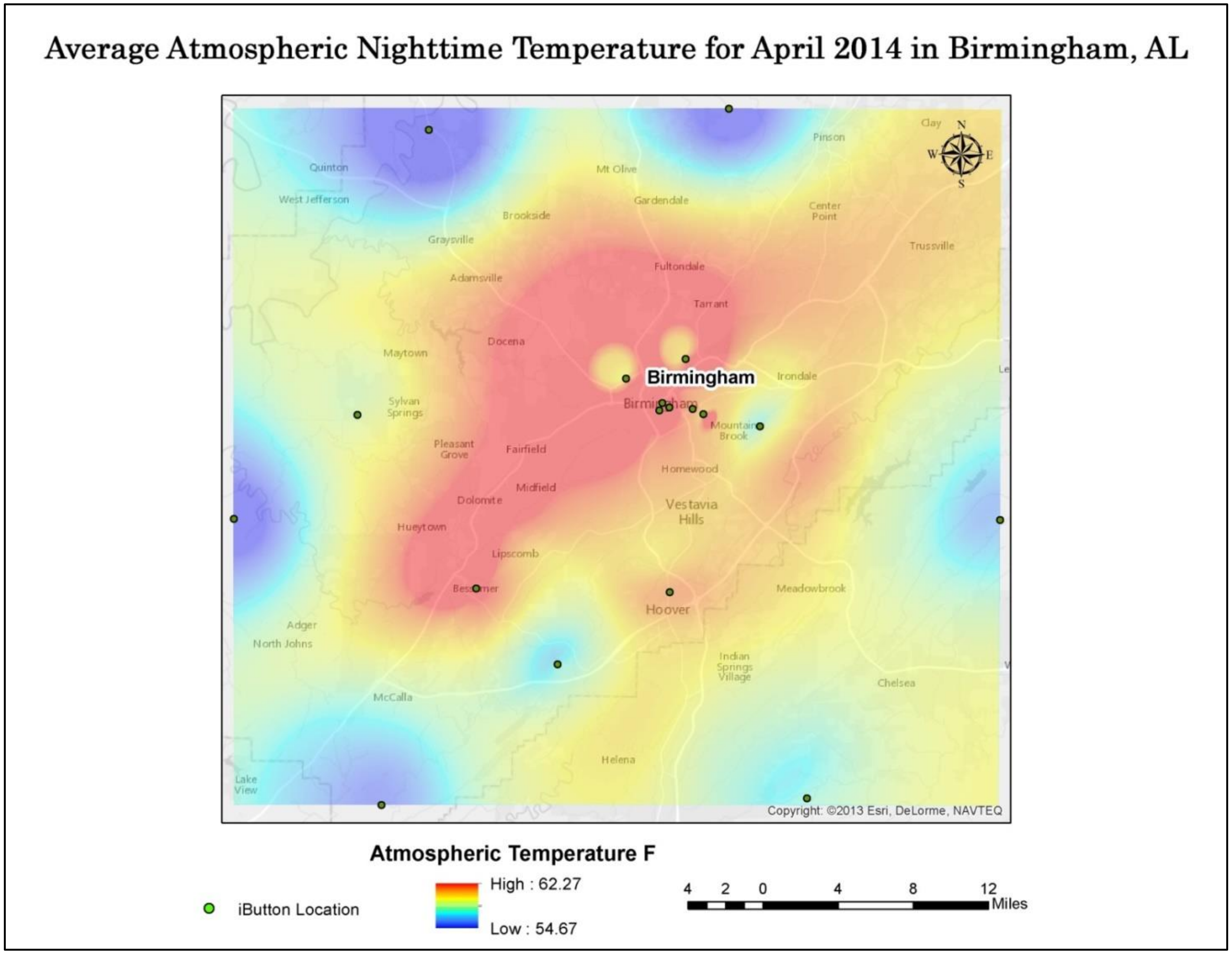


Figure 12. Average atmospheric nighttime temperature for April 2014 in Auburn-Opelika.

Average nighttime temperatures for April had a range of 7.60°F; between 54.67°F and 62.27°F. As with March nighttime averages, the highest temperatures occurred in the downtown high-rise district. The spatial extent and distribution of the heat island in April were nearly identical to those of the Birmingham heat island in March (see Figure 8). However, the area of the heat island was slightly larger, at166.7mi^2 (versus 161.8 mi^2 in March). Also, the industrial sites of Pull-A-Part and 2nd Street west yielded smaller cool spots (1.8 mi^2 and 3.1 mi^2, respectively) in April.

2.5.7 Auburn-Opelika Daytime Results for April 2014

Daytime temperatures were 8.8°F warmer on average those in the previous month in Auburn-Opelika and 0.85°F warmer than the Birmingham daytime average temperatures for April. The highest daytime temperature for April was 101.6°F, recorded at the AU Hotel site on 24 April 2014 at 16:59 CDT. The coolest temperature, 34.8°F, occurred at the Pepperwood Trail location on 16 April at 7:06 CDT.

Locations for the highest and lowest average temperature sites were again the AU Hotel and Pepperwood Trail sites, respectively. The AU Hotel was 77.4°F on average, while Pepperwood Trail was 66.0°F on average. Surprisingly, Tigertown was 2.4°F cooler on average than the AU Hotel. Samford Park was also considerably cooler, at 70.1°F. Average daytime temperatures for April in Auburn-Opelika are displayed in Figure 13.

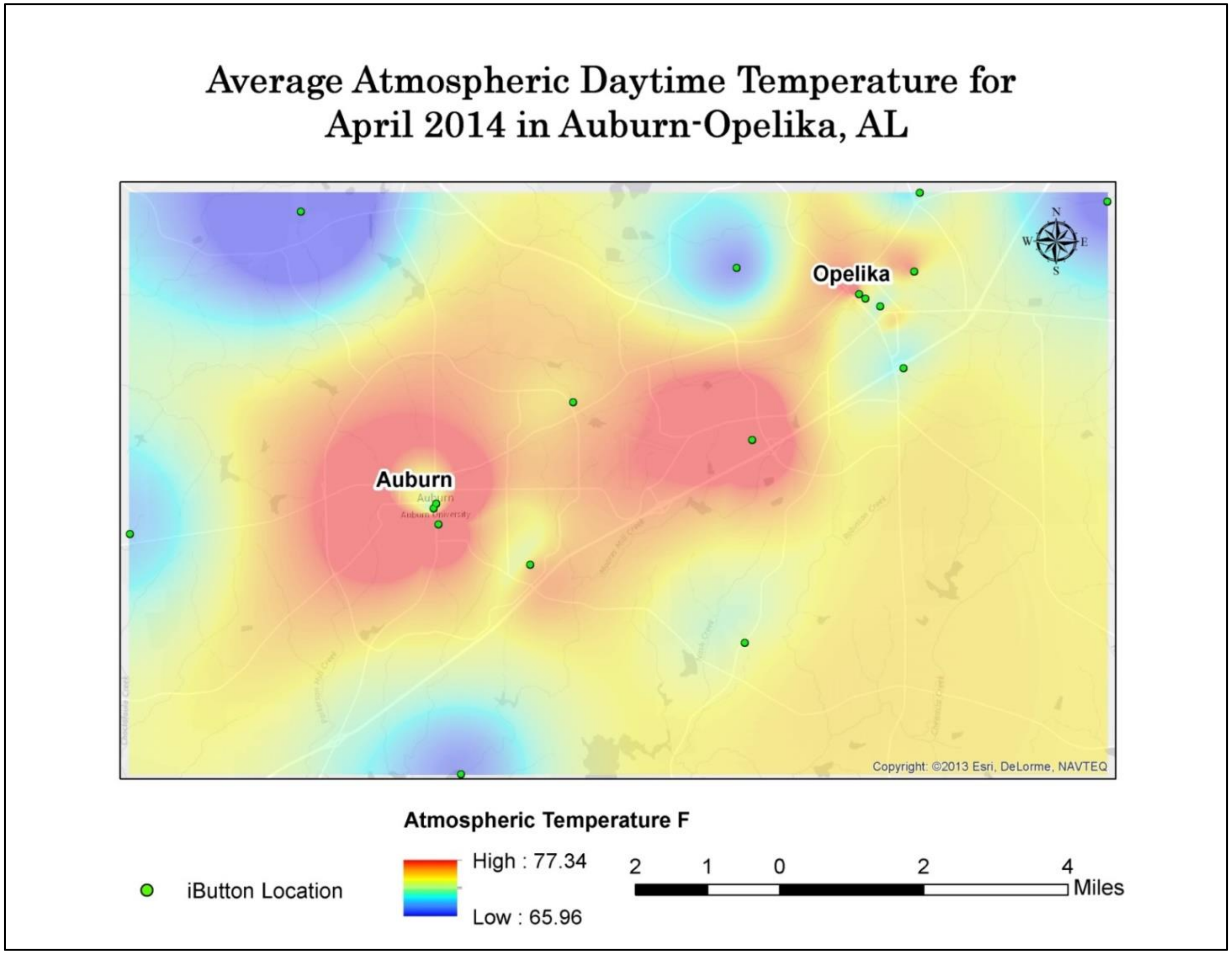


Figure 13. Average atmospheric daytime temperature for April 2014 in Auburn-Opelika.

There was quite a wide range of temperatures, 11.38°F, between 65.96°F and 77.34°F. The spatial distribution and extent of the daytime heat island effect for April 2014 were very similar to the March daytime results, shown previously in Figure 9. The area contained within the heat island around downtown Auburn shrank 22 percent; while the cool spot created by Samford Park grew 43.5 percent, to encompass an area equal to 0.69 mi^2.

2.5.8 Auburn-Opelika Nighttime Results for April 2014

Interestingly, Auburn-Opelika temperatures were 1°F cooler than the nocturnal Birmingham temperatures for April, but 8.1°F warmer than the Auburn-Opelika nocturnal March temperatures. The warmest recorded temperature was 76.2°F on 26 April 2014 at 20:59 CDT at the Toomer's Corner location. The coolest recorded temperature was 32.0°F on 16 April 2014 at 5:56 CDT at the County Road 161 location.

Sites of the highest and lowest average temperatures and of absolute highest and lowest temperature were identical. Toomer's Corner was the hottest, at 60.0°F, while County Road 161 was the coolest, at 54.6°F. Samford Park had a stronger nocturnal cooling effect; it was 1.0°F cooler than Toomer's Corner. April nighttime temperatures are displayed in Figure 14.

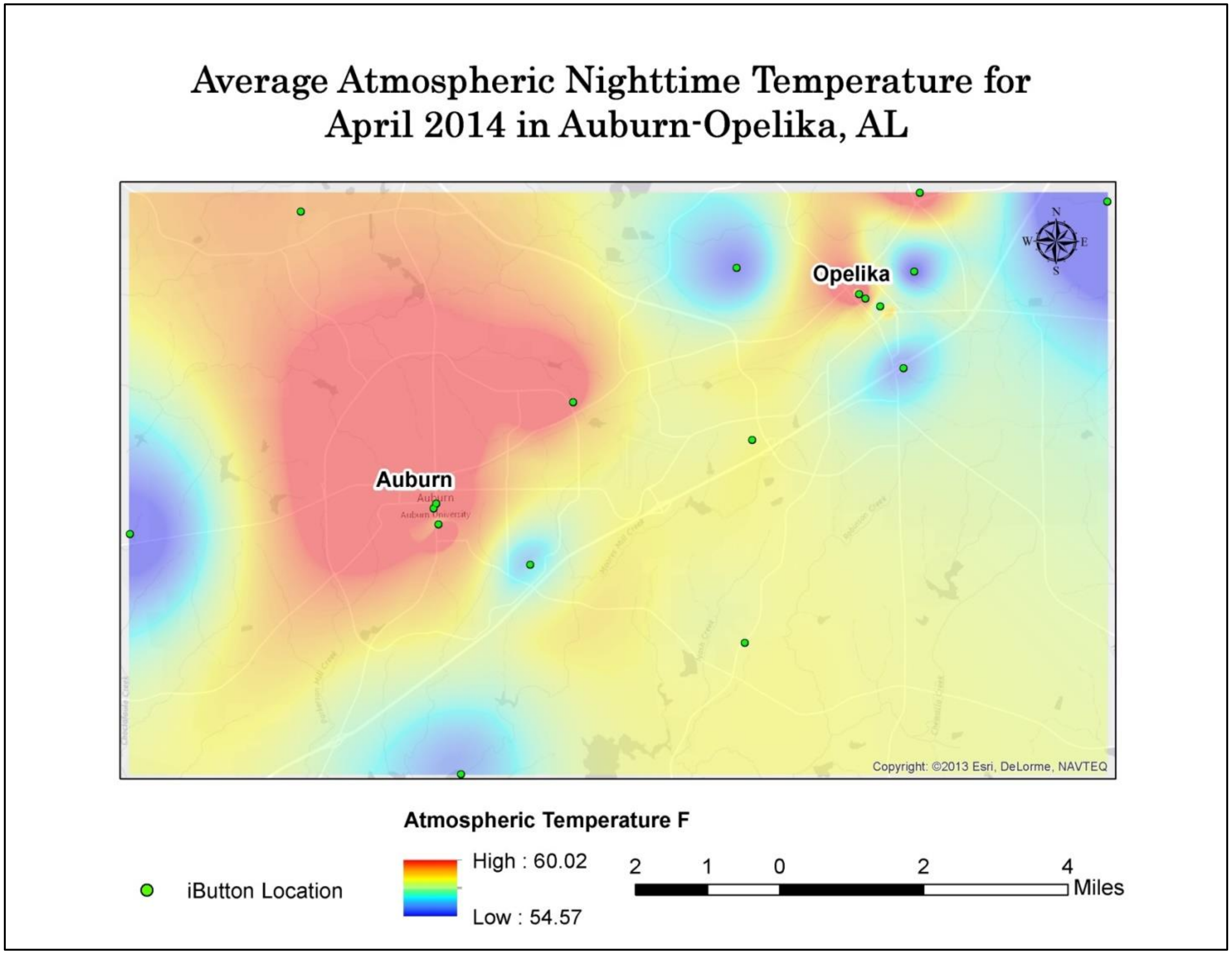


Figure 14. Average atmospheric nighttime temperature for April 2014 in Auburn-Opelika.

Overall distributions of the heat islands are quite similar to the March nighttime results. However, the heat island around downtown Auburn grew substantially to include the area between downtown Auburn and the Village Mall. The area contained within the heat island was 11.62 mi^2, an increase in size of 25 percent. The heat island around Opelika shrank slightly, to 0.27 mi^2.

2.5.9 Birmingham Daytime Results May 2014

Birmingham average daytime temperatures for May were 7.5°F warmer than those for April. The hottest observed temperature in Birmingham, 105.1°F, was again recorded at the rural location of Firetower Road on 7 May 2014 at 17:23 CDT. The coolest observed temperature, 41.0°F, was recorded on 3 May 2014 at the peri-urban location of Lock 17 at 6:30 CDT.

In the April daytime results for Birmingham, Pull-A-Part was again the warmest location, with an average temperature of 82.0°F. The higher temperatures in May increased the temperature differences between the urban green space and strictly urban sites. Linn Park was 6.7°F cooler than Pull-A-Part, while Kelly Ingram Park was 5.0°F cooler. Both were within 1°F of the Regions site. The Old Serene Drive location was again the coolest on average, at 71.5°F. Average daytime atmospheric temperatures in Birmingham for May are shown in Figure 15.

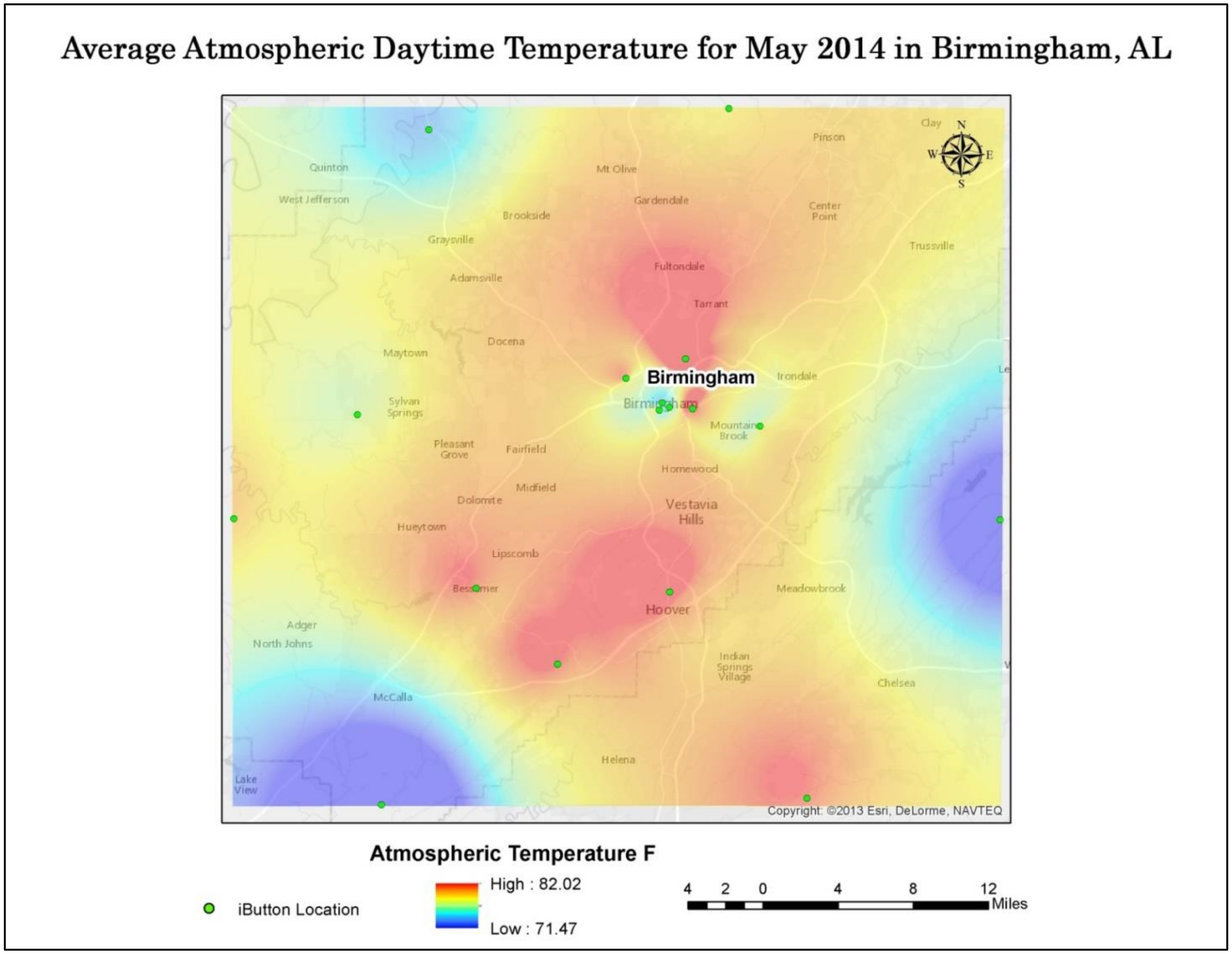


Figure 15. Average atmospheric daytime temperature for May 2014 in Birmingham.

As in April, there were two intense heat islands, in roughly the same locations: one in northern portion of downtown Birmingham, and the other around Hoover. The island around northern downtown Birmingham shrank 52 percent compared to the April daytime results, while the heat island around Hoover grew 35.6 percent and extended southwestward to include the County Road 6 location between Hoover and Bessemer. The hotspot around the Lock 17 location that shrank between March and April was nearly non-existent in May. There were however, relatively small, weak hotspots around the Bessemer and Firetower Road sites.

2.5.10 Birmingham Nighttime Results for May 2014

As with the daytime temperatures, the May nighttime temperatures exhibited an average increase, of 6.9°F, over the April nighttime temperatures in May. The highest temperature recorded was 84.2°F in downtown Bessemer at 20:30 CDT on 25 May 2014. The coolest temperature of 40.9°F was recorded at the Castle Heights site on 3 May 2014 at 5:56 CDT.

The familiar Regions site was again the warmest on average, exhibiting a temperature of 70.2°F. Pull-A-Part was 2.5°F cooler, while both city parks were again within 1°F of the Regions site. Castle Heights was the coolest site on average, at 61.5°F. Average nocturnal atmospheric temperatures in Birmingham for May are displayed in Figure 16.

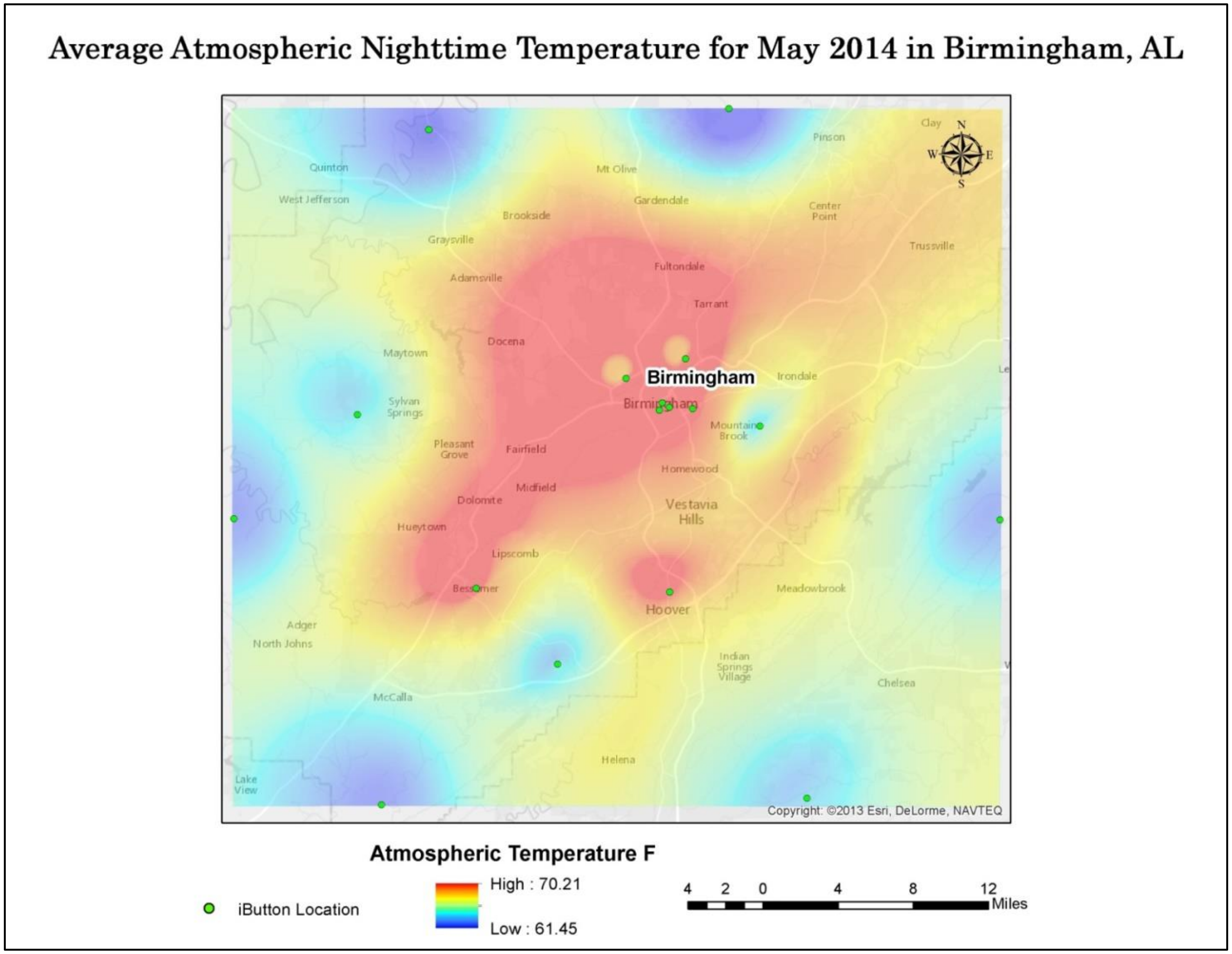


Figure 16. Average atmospheric nighttime temperature for May 2014 in Birmingham.

Average nighttime temperatures for May had a slightly larger range of 8.76°F, between 70.21°F and 61.45°F. The heat island spatial extent and distribution in May were similar to those of the April nighttime map (see Figure 12). A single, expansive heat island engulfed the downtown Birmingham area and extended southward to include Bessemer, covering roughly the same area it did in April, at 167.6 mi^2. The cool spots produced by the industrial sites of 2nd Street west and Pull-A-Part were reduced, covering 0.88 mi^2 and 0.69 mi^2 respectively. An additional, much smaller heat island developed around the city of Hoover, covering an area of 8.5 mi^2.

2.5.11 Auburn-Opelika Daytime Results for May 2014

Unfortunately, the atmospheric results for May-August do not include data from the Fountain site because that sensor failed; no data were retrievable from the instrument. Daytime temperatures for May increased 9.5°F over the average daytime temperatures in Auburn-Opelika for April, and 2.8°F compared to average daytime temperatures for May in Birmingham. The highest recorded temperature was 110.9°F, at the AU Hotel site on 26 May 2014 at 15:18 CDT. The lowest recorded temperature was 68.1°F cooler, archived at the County Road 161 location on 17 May 2014 at 6:21 CDT.

The warmest location on average was the AU Hotel, with a temperature of 88.8°F. Tigertown was a fairly close second, at 87.1°F. As previously mentioned, increased temperatures significantly affect the cooling properties of urban green space, further exemplified in May. Samford Park was 9.1°F cooler than the AU Hotel on average and 7.4°F cooler than Tigertown on average. The coolest average location was Pepperwood Trail, at 79.3°F. Average atmospheric daytime temperatures in Auburn-Opelika for May are displayed in Figure 17.

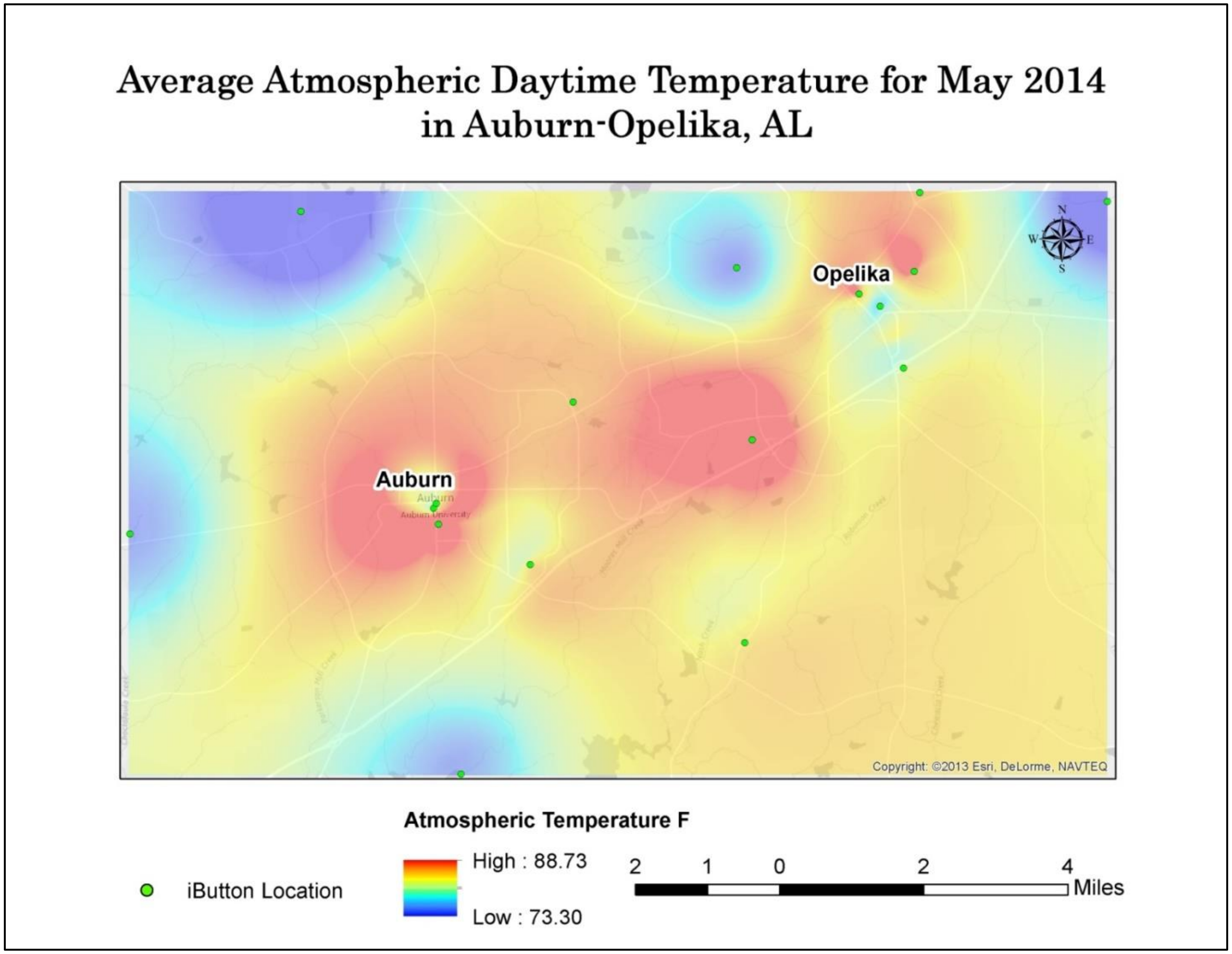


Figure 17. Average atmospheric daytime temperature for May 2014 in Auburn-Opelika.

Daytime temperatures for May exhibited a fairly wide range of 15.43°F, between 88.73°F and 73.30°F. The spatial distribution of the three heat islands is similar to the Auburn-Opelika April daytime results (see Figure 13). However the spatial extent of the heat island around downtown Auburn is significantly different. The Samford Park site had a stronger cooling effect and is likely responsible for the 50 percent reduction in size of the heat island around downtown. While the heat island completely surrounded downtown in April, the top portion dissipated in May. The outer perimeter of that heat island was smaller for the month of May as well, reducing the total size of that heat island. Meanwhile, the heat island around Tigertown increased 5.7 percent, to cover an area of 3.17 mi^2. A third heat island, east northeast of downtown Opelika, covered 0.26 mi^2.

2.5.12 Auburn-Opelika Nighttime Results for May 2014

Nighttime temperatures for May increased 7.8°F over those recorded in April. Auburn-Opelika's nighttime temperatures for May were 0.1°F warmer than those recorded in Birmingham for the same time period. The highest temperature recorded was 85.6°F at 20:09 CDT on 25 May 2014 at the Toomer's Corner location. The lowest temperature recorded was 42.7°F at the County Road 161 site on 17 May 2014 at 5:21 CDT.

The warmest location on average was Toomer's Corner, at 68.9°F. Although considerably closer to nighttime's warmest location by night, Samford Park was still 2.3°F cooler. The coolest location on average was County Road 161, at 62.5°F. Average nighttime temperatures for May are shown in Figure 18.

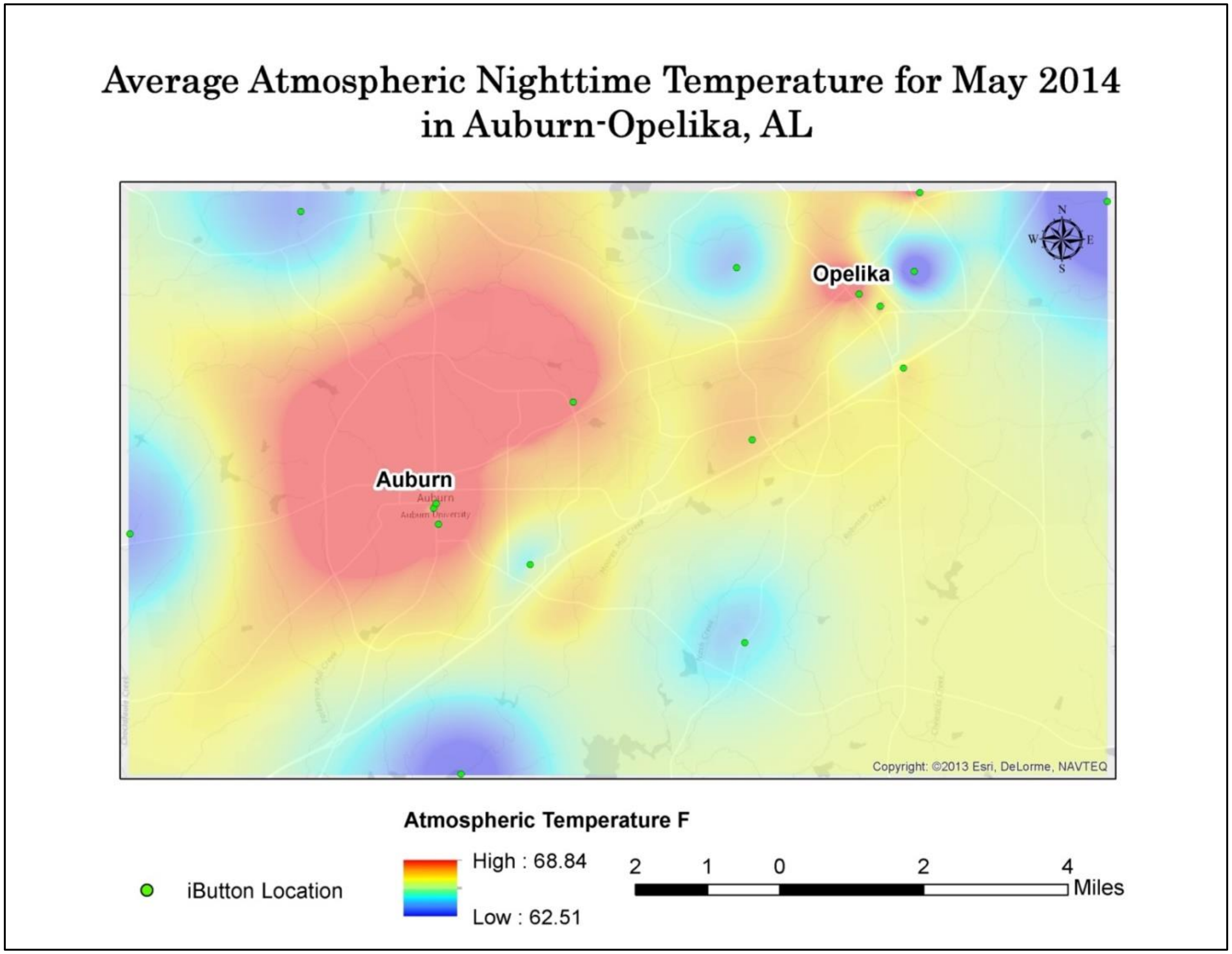


Figure 18. Average atmospheric nighttime temperature for May 2014 in Auburn-Opelika.

The average nighttime temperatures for May had a range of 6.33°F and fell between 68.84°F and 62.51°F. May’s nighttime results closely resembled those for April (see Figure 14). One very large, well-define heat island that covered all of downtown Auburn and extended northeast to the Village Mall before extending northward. Although the area of the heat island was only negligibly different than in April, the shape of the heat island changed. While the nighttime heat island in April was more round or bubble like and extended farther north, the heat island was flatter and extended farther eastward at its northernmost part. Despite the lack of data at the Fountain site, the heat island around Opelika remained basically unchanged between April and May. One other observation: the I-85 location appeared to have less of a cooling effect in May than in April.

2.5.13 Birmingham Daytime Results for June 2014

Daytime temperatures in Birmingham increased 6.0°F between May and June. The highest temperature of 112.6°F was recorded at the County Road 6 location at 17:18 on 17 June 2014. The coolest record of 63.0°F was archived at the Lock 17 site on 14 June 2014 at 16:18 CDT. The warmest site on average was Pull-A-Part, at 87.9°F. The city parks were, on average, 6.5°F cooler than the Pull-A-Part site. Old Serene Drive was the coolest, at 77.1°F. Average daytime atmospheric temperature is shown in Figure 19.

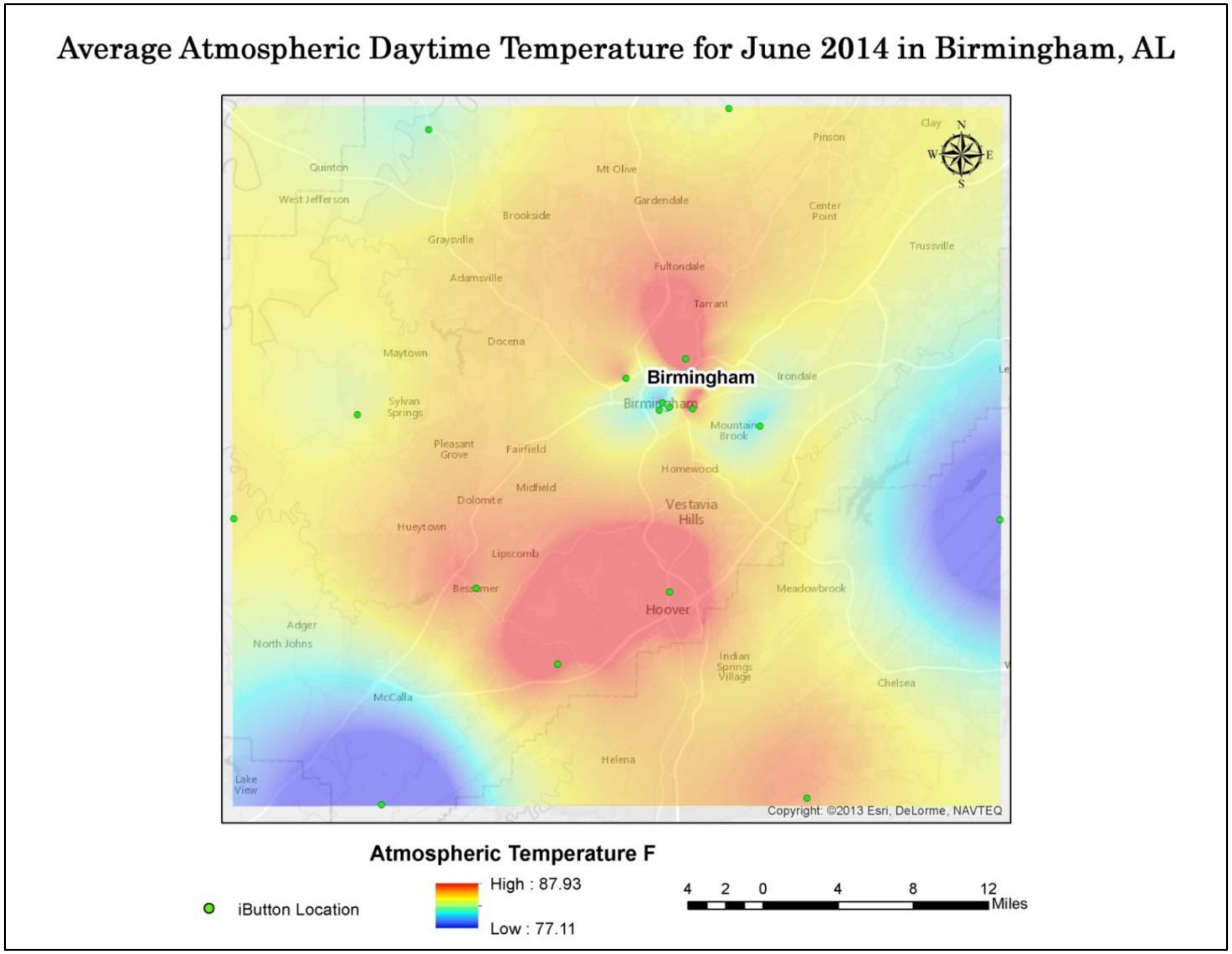


Figure 19. Average atmospheric daytime temperature for June 2014 in Birmingham.

The temperature range increased to 10.82°F, versus 10.55°F for May daytime temperatures. Two distinct heat islands appeared in locations similar to the May daytime map (Figure 17), albeit the heat island in northern downtown Birmingham shrank 49.4 percent to 14.39 mi^2, while the heat island around Hoover grew 46.1 percent to 69.2 mi^2 to include the County Road 6 site.

2.5.14 Birmingham Nighttime Results for June 2014

The change from spring to summer was evident in nighttime temperatures, which increased 7.8°F between May and June. The highest temperature, 88.8°F, was recorded at the Hoover Mall on 19 June at 20:00 CDT. The lowest temperature 62.9°F, was recorded at the Blackwell Drive location on 14 June 2014 at 4:58 CDT.

As expected, Regions was the warmest location on average, exhibiting a temperature of 76.3°F. Strangely, Kelly Ingram Park was nearly the same temperature, at 76.0°F, while Linn Park had a slightly cooler average temperature of 75.2°F. Castle Heights was the coolest site on average, at 70.4°F. Average nocturnal June atmospheric temperatures for Birmingham are shown in Figure 20.

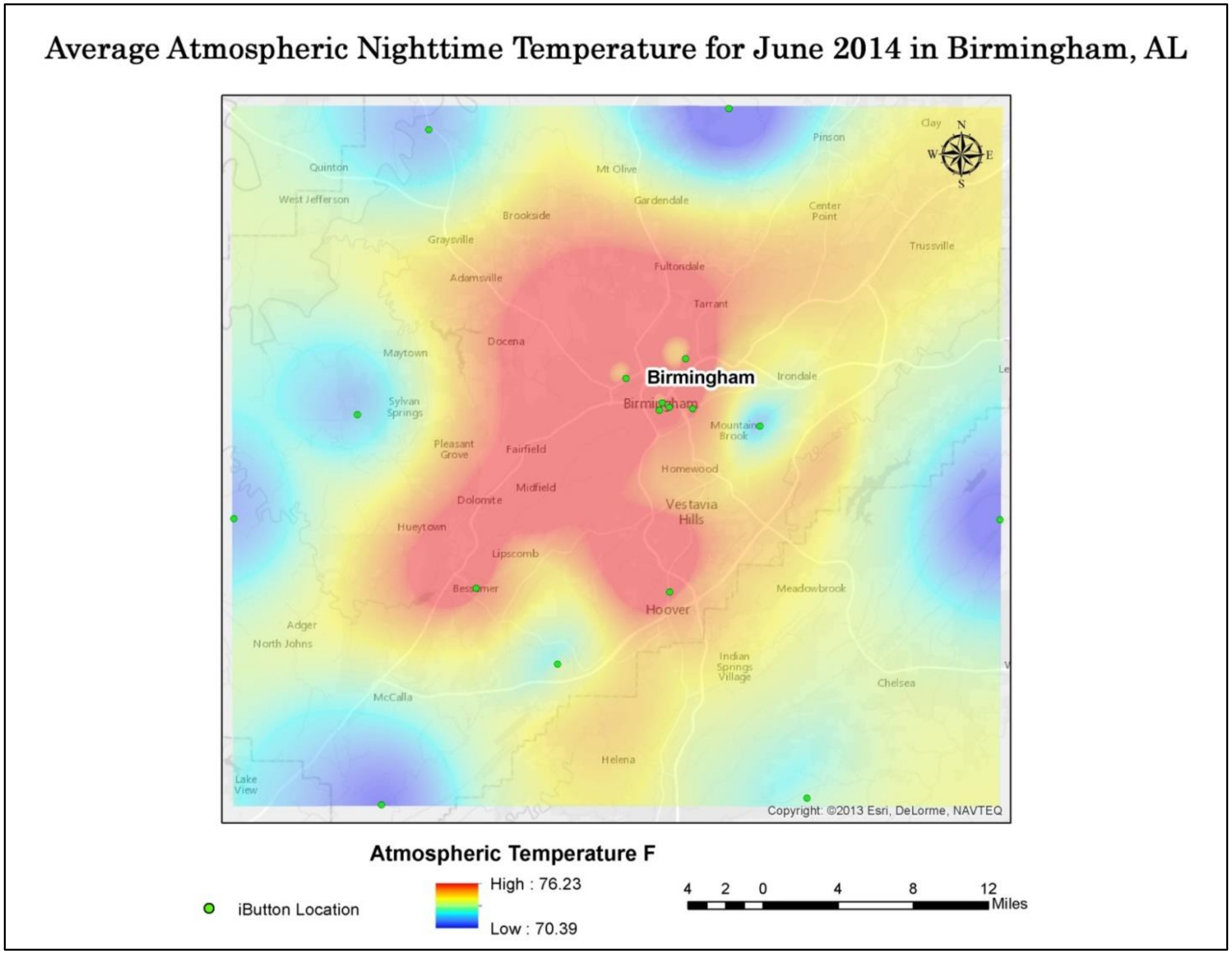


Figure 20. Average atmospheric nighttime temperature for June 2014 in Birmingham.

Average temperatures were within 5.8°F, from 70.39°F to 76.23°F. As seen in the previous nighttime temperature maps, there was an expansive, well-developed heat island which engulfed downtown Birmingham and Bessemer. However, rather than there being an additional, separate, heat island around Bessemer, as seen in the nocturnal results for May (Figure 18), the two merged to produce a single, large heat island, encompassing downtown Birmingham, Bessemer, and Hoover.. This single, expansive heat island covered 190.4 mi^2 versus 167.6mi^2 in the May nighttime map. In addition, the cool spots around 2nd street west and Pull-A-Part also shrank; measuring 0.3 mi^2 and 1.1 mi^2, respectively. These results demonstrate the effects of increased summer temperatures urban areas.

2.5.15 Auburn-Opelika Daytime Results for June 2014

Nighttime temperatures for June were 5.2°F warmer than those for May, and 2.0°F warmer than the Birmingham average daytime temperatures for June. Tigertown had the highest recorded temperature, at 116.2°F, occurring on 19 June 2014 at 15:55 CDT. County Road 161 again had the coolest recorded temperature, at 64.8°F, on 16 June 2014 at 6:30 CDT.

The hottest location on average was the AU Hotel, with a temperature of 93.8°F. Tigertown was second hottest; just 2.4°F cooler than the AU Hotel. As in the daytime results for May, Samford Park was significantly cooler, exhibiting an average temperature of 85.0°F. Pepperwood trail was the coolest site, with an average temperature of 78.4°F. Average daytime temperatures for June is displayed in Figure 21.

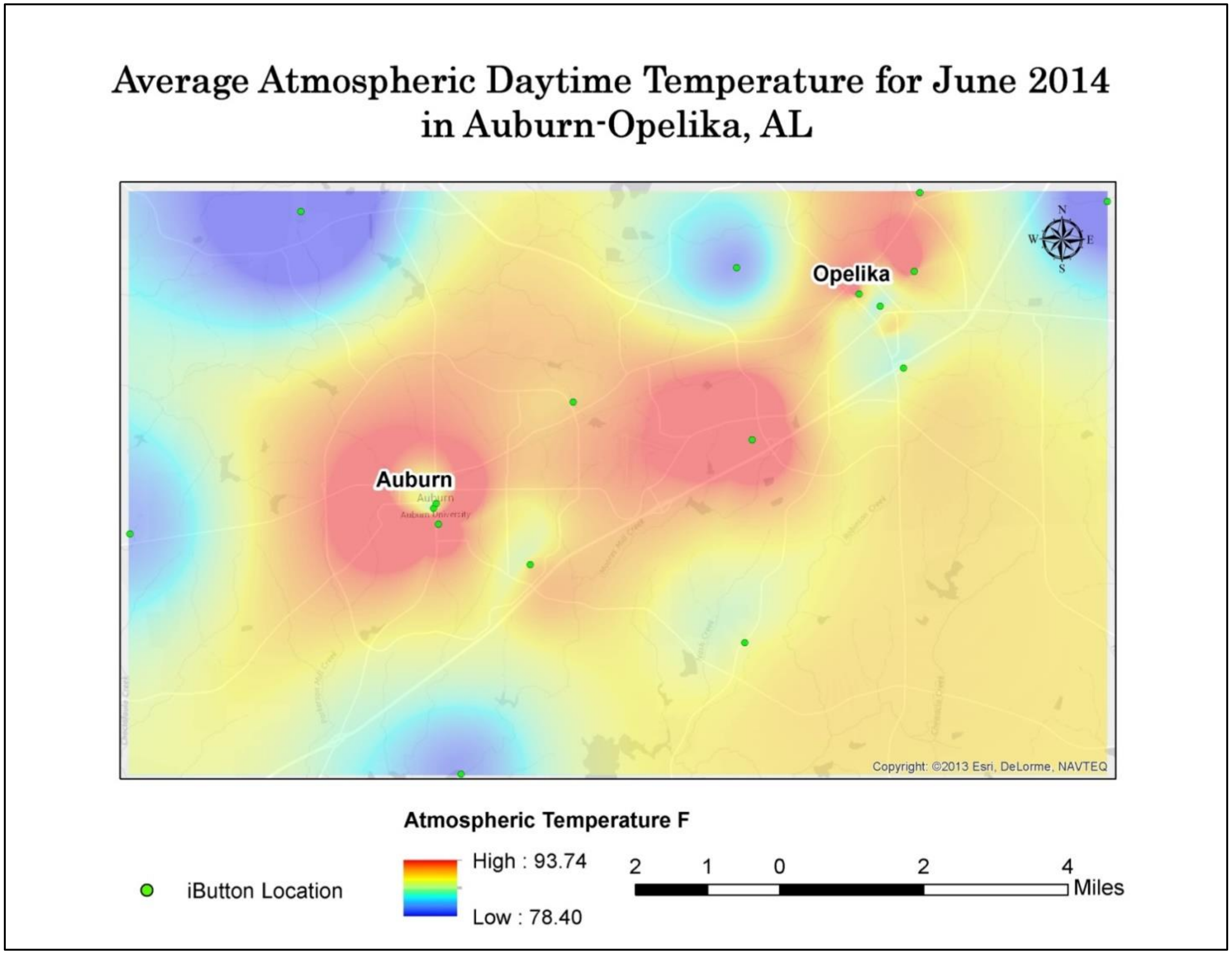


Figure 21. Average atmospheric daytime temperature for June 2014 in Auburn-Opelika.

Temperatures exhibited a wide range, 15.34°F, from 93.74°F to 78.40°F. The heat islands were existent in the same three locations as in the daytime results for May (Figure 17). Heat islands developed around Auburn completely encompassed its downtown area as in April's daytime results, save for the cool bubble around Samford Park. This differed from the May results in which the northern part of the heat island was substantially weaker. The overall area of said heat island was 3.2 mi^2; the same size as in the daytime results for May, but differently shaped and distributed. The area covered by the heat island around Tigertown was 3.0 mi^2; slightly less than April daytime results. Finally, the area covered by the very small heat island north northeast of Opelika grew considerably, to 0.4 mi^2.

2.5.16 Auburn-Opelika Nighttime Results for June 2014

June nighttime temperatures in Auburn-Opelika were 7.7°F warmer than in May but 0.2°F cooler than the June nighttime temperatures recorded in Birmingham. The highest temperature recorded was 87.7°F at Toomer's Corner on 20 June 2014 at 20:09 CDT. The lowest temperature recorded was 65.1°F at Southern Union on 12 June 2014 at 4:46 CDT.

The warmest location on average was again Toomer's Corner, at 76.0°F, although the AU Hotel was within 1°F of Toomer's Corner. The Samford Park site was again considerably closer to the urban temperatures, at 73.9°F. The coolest location was County Road 161at 70.9°F. Average atmospheric nighttime temperatures for June are displayed in Figure 22.

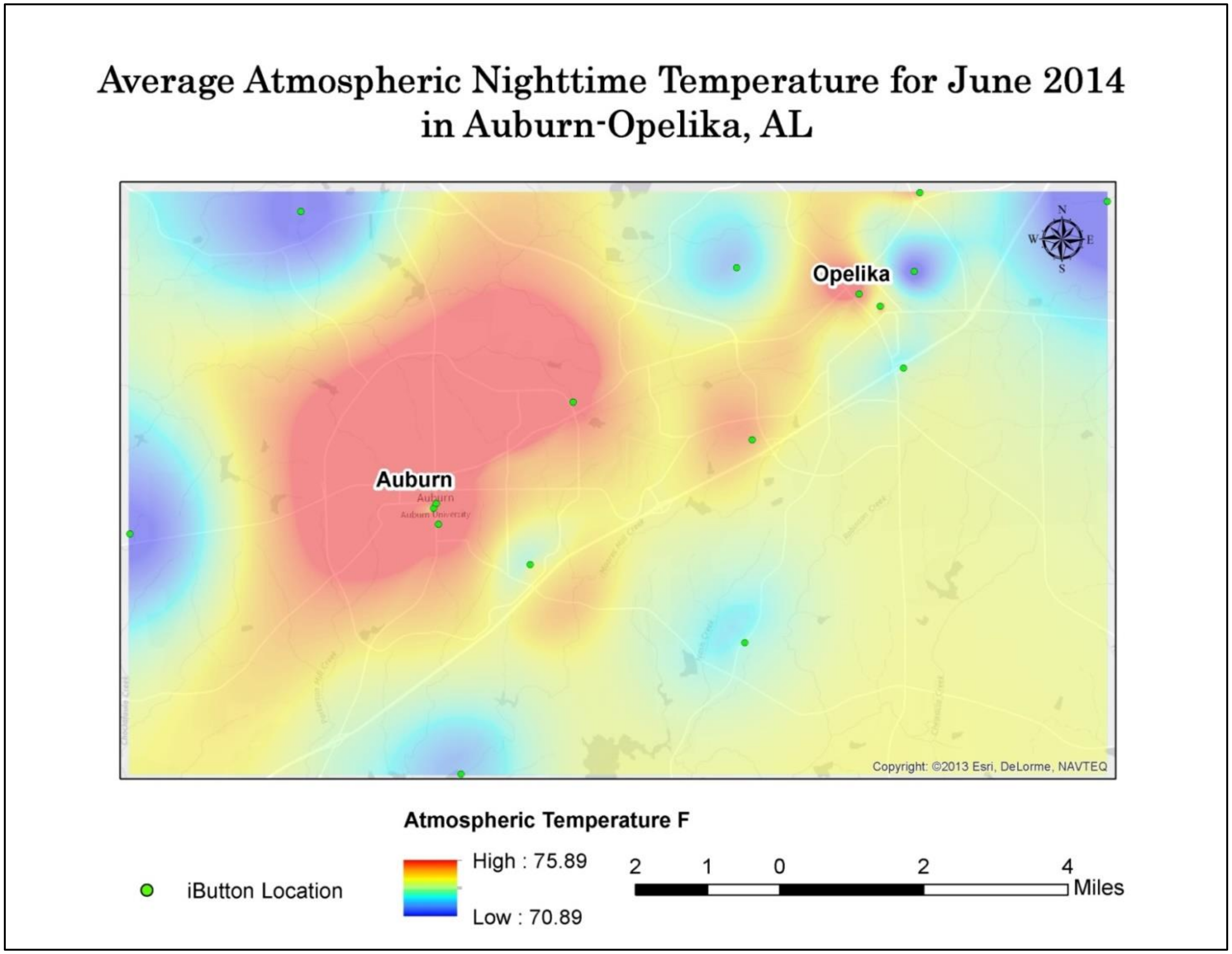


Figure 22. Average atmospheric nighttime temperature for June 2014 in Auburn-Opelika.

Temperatures ranged from 70.89 to 75.89; a difference of 5.0°F. The spatial extent and distribution of the two heat islands are negligibly different from the Auburn-Opelika nocturnal results for May (see Figure 18). The heat island encompassing downtown Auburn and the Village Mall developed a flatter appearance (as opposed to the rounder appearance seen in the May nighttime results), and covered an area of 11.2 mi^2. The heat island around Opelika covered 0.22 mi^2.

2.5.17 Birmingham Daytime Results for July 2014

July daytime temperatures were quite close to those in June; only increasing by 1.0°F. The highest temperature recorded was 111.5°F at the perri-urban location of Winston Way and Chruchill Circle on 2 July at 14:26 CDT. The lowest temperature was an unseasonably cool 54.7°F archived at another peri-urban location, Lock 17, on 30 July 2014 at 6:18 CDT.

The warmest location on average was Pull-A-Part at 88.4°F. Hoover Mall was a close second, with a temperature 0.5°F less. Linn Park was 6.7°F cooler than the Pull-A-Part, while Kelly Ingram Park was a bit warmer, at only 5.3°F cooler. The coolest site was Old Serene Drive at 78.7°F. Average atmospheric temperature for July is shown in Figure 23.

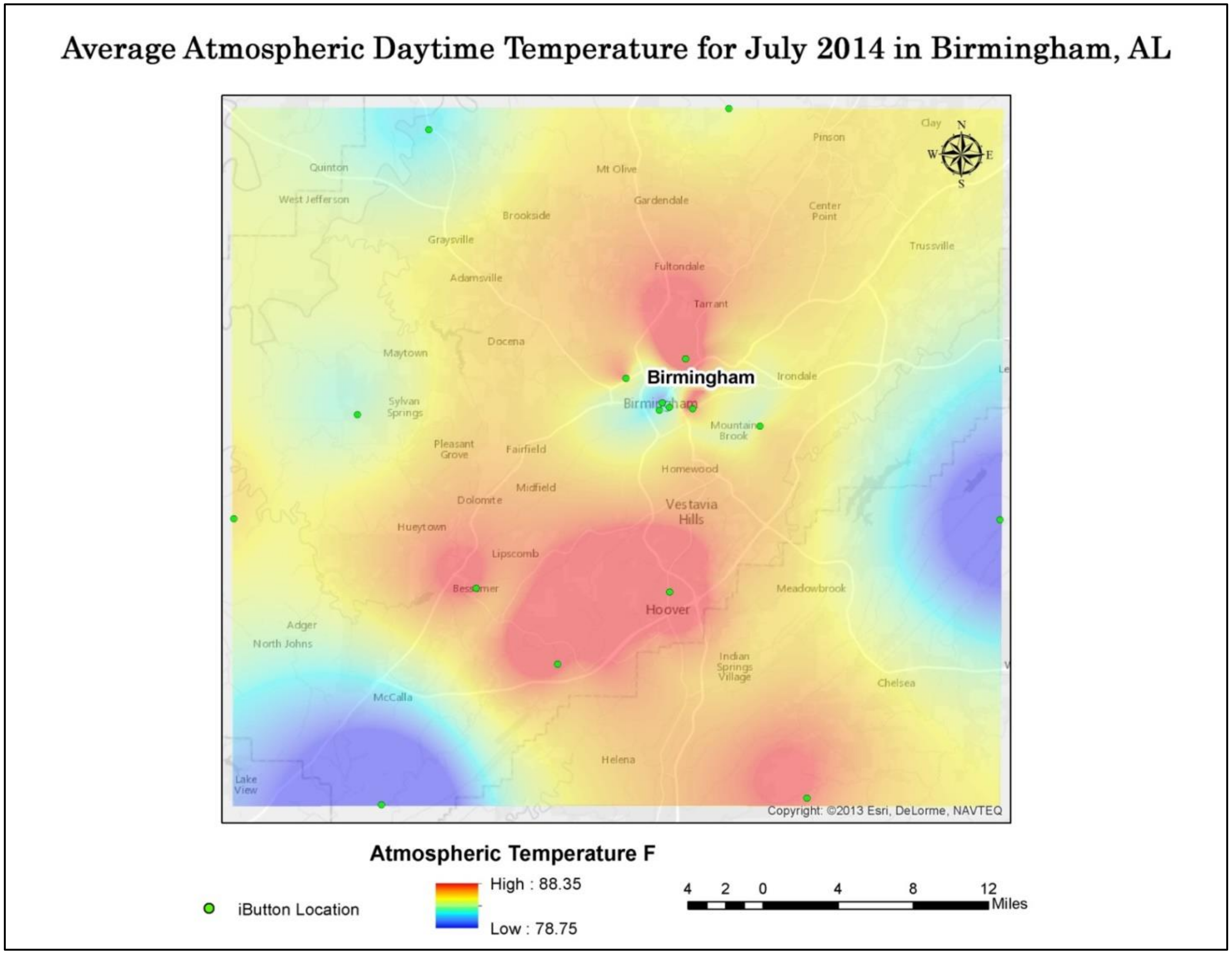


Figure 23. Average atmospheric daytime temperature for July 2014 in Birmingham.

July's daytime temperatures were close to June's, ranging from 78.75°F to 88.35°F. The July daytime temperature map for Birmingham looks virtually identical to the one for June (see Figure 19); however, a more developed hot spot emerged around the Firetower Road location. The area of the heat island around the northern part of downtown Birmingham remained very consistent with the June daytime results, while the heat island around Hoover shrank some 5.5 percent.

2.5.18 Birmingham Nighttime Results for July 2014

Nocturnal temperatures for July were very close to June's; increasing by a mere 0.5°F. The highest temperature, 89.5°F, was recorded twice at the Hoover Mall; once on 2 July 2014 at 20:00 CDT, and again on 27 July at the same time. The coolest temperature, 53.7°F, was recorded at the Castle Heights site at 4:30 CDT on 30 July.

The warmest average location was again Regions, at 77.1°F. Both city parks were within 1.2°F of the Regions site. The coolest site on average was again Castle Heights, with a temperature of 69.9°F. Average atmospheric nighttime temperatures are displayed in Figure 24.

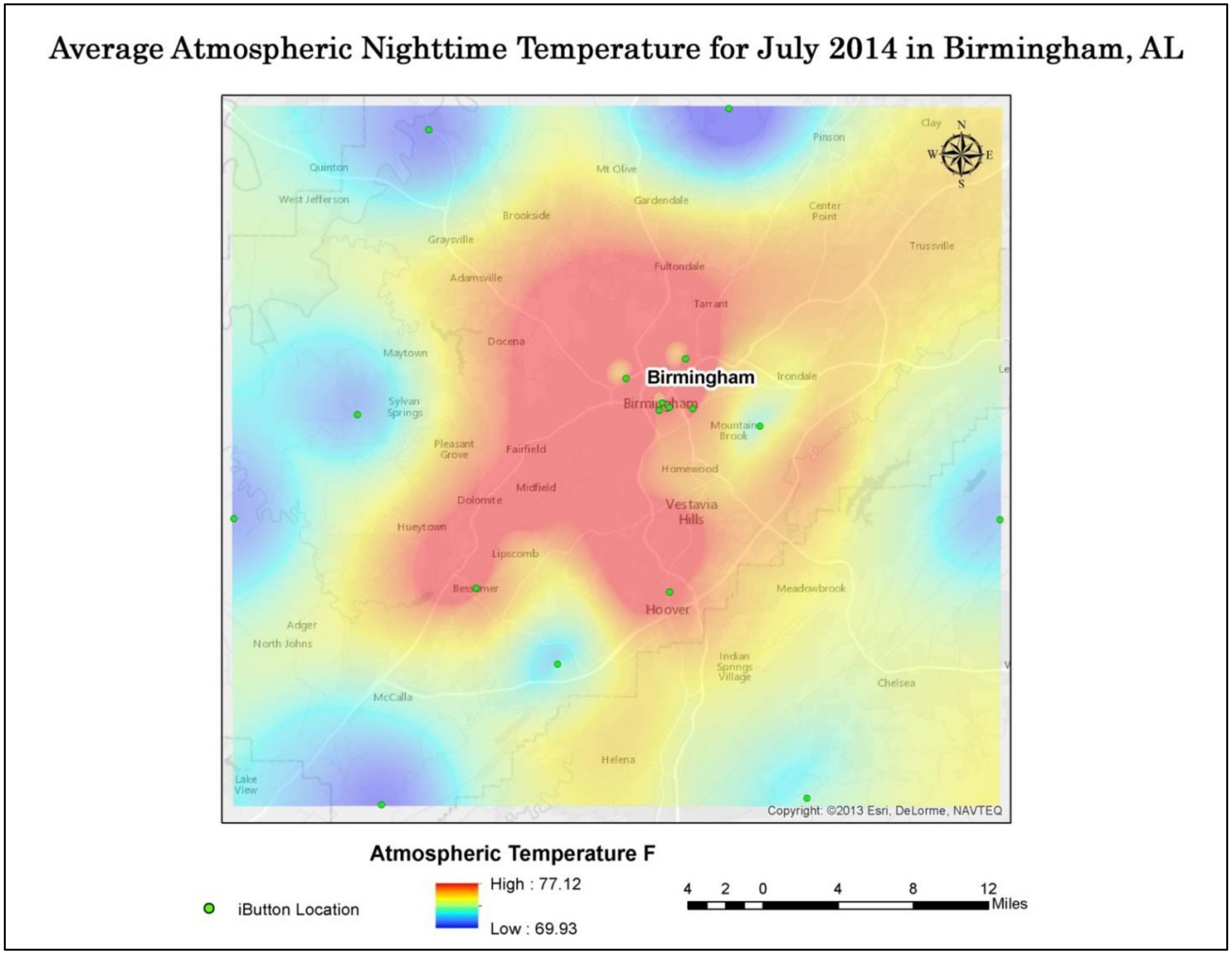


Figure 24. Average atmospheric nighttime temperature for July 2014 in Birmingham.

Average temperatures exhibited a wider range than June, 7.19°F, from 69.93°F to 77.12°F. As seen in the June nighttime temperature map (Figure 20), a single expansive, well-developed heat island encompassed downtown Birmingham, Bessemer, and Hoover. It covered an area of 183.1 mi^2; 5.2 percent smaller than the heat island in the June nighttime results. The two cool spots also changed. 2nd street west grew slightly, to 0.71 mi^2, while the cool spot around Pull-A-Part shrank 53.4 percent to 0.51 mi^2.

2.5.19 Auburn-Opelika Daytime Results for July 2014

Although Auburn-Opelika's average daytime temperatures for July were virtually the same as for June, July temperatures were actually 0.02°F cooler than the average daytime temperatures for June, and 1.0°F warmer than the average daytime July temperatures in Birmingham. The highest temperature, 115.5°F, was recorded at the AU Hotel on 6 July 2014 at 16:018 CDT, while the lowest temperature, 57.4°F, was recorded at County Road 161 on 30 July 2014 at 6:21 CDT

The hottest location on average was the AU Hotel site, at 93.4°F. As usual, Tigertown was the second warmest location; just 2.1°F cooler. The Samford Park site was 8.5°F cooler than the AU Hotel site. The coolest location on average was the Pepperwood Trail site, at 78.6°F. Average daytime temperatures for July are displayed in Figure 25.

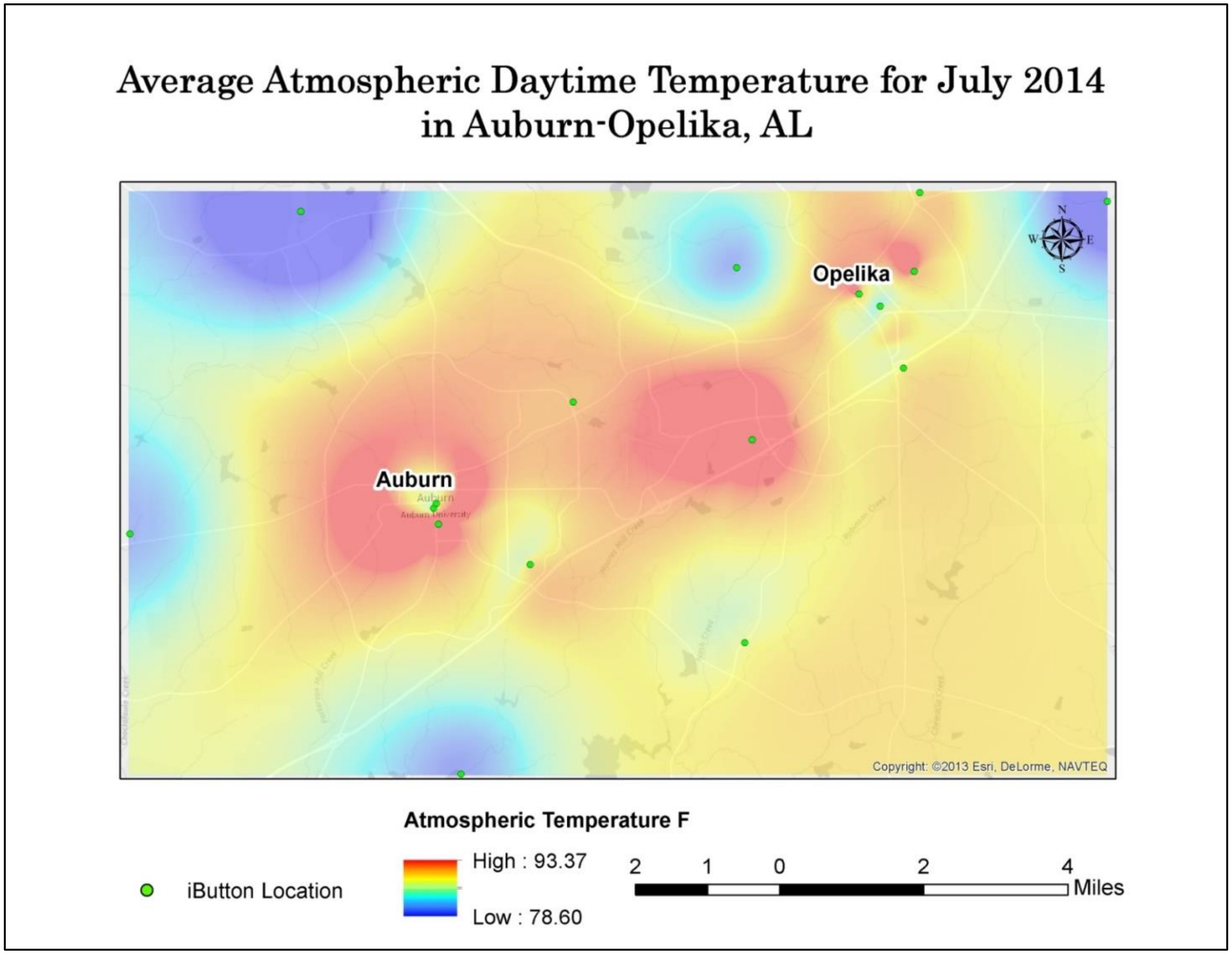


Figure 25. Average atmospheric daytime temperature for July 2014 in Auburn-Opelika.

Temperatures were nearly identical to the daytime June results, ranging from 78.60°F to 93.37°F. The spatial extent and distribution of the three heat islands were nearly identical to the daytime June results as well (see Figure 21). The heat island around downtown Auburn and the heat island around Tigertown each covered 3.1 mi^2. However, the small heat island around Opelika shrank considerably compared to June, covering an area of 0.19 mi^2; a difference of 52 percent.

2.5.20 Auburn-Opelika Nighttime Results for July 2014

Auburn-Opelika nighttime temperatures for July were almost the same as the June's; only 0.5°F warmer. They were, however, 0.2°F cooler than the Birmingham average nighttime temperatures for July. The highest temperature recorded was again Toomer's Corner, at 88.36°F on 12 July 2014 at 20:09 CDT. The lowest temperature of 58.7°F was again recorded at County Road 161 on 30 July 2014 at 4:21 CDT.

As expected, Toomer's Corner had the highest average temperature, at 76.4°F. The AU Hotel was second warmest, at 75.6°F. The temperature difference between Toomer's Corner and Samford Park was the same as it was nocturnally in June: 2.1°F. The site with the coolest average was County Road 161, at 70.8°F. Nocturnal atmospheric temperatures for July are shown in Figure 26.

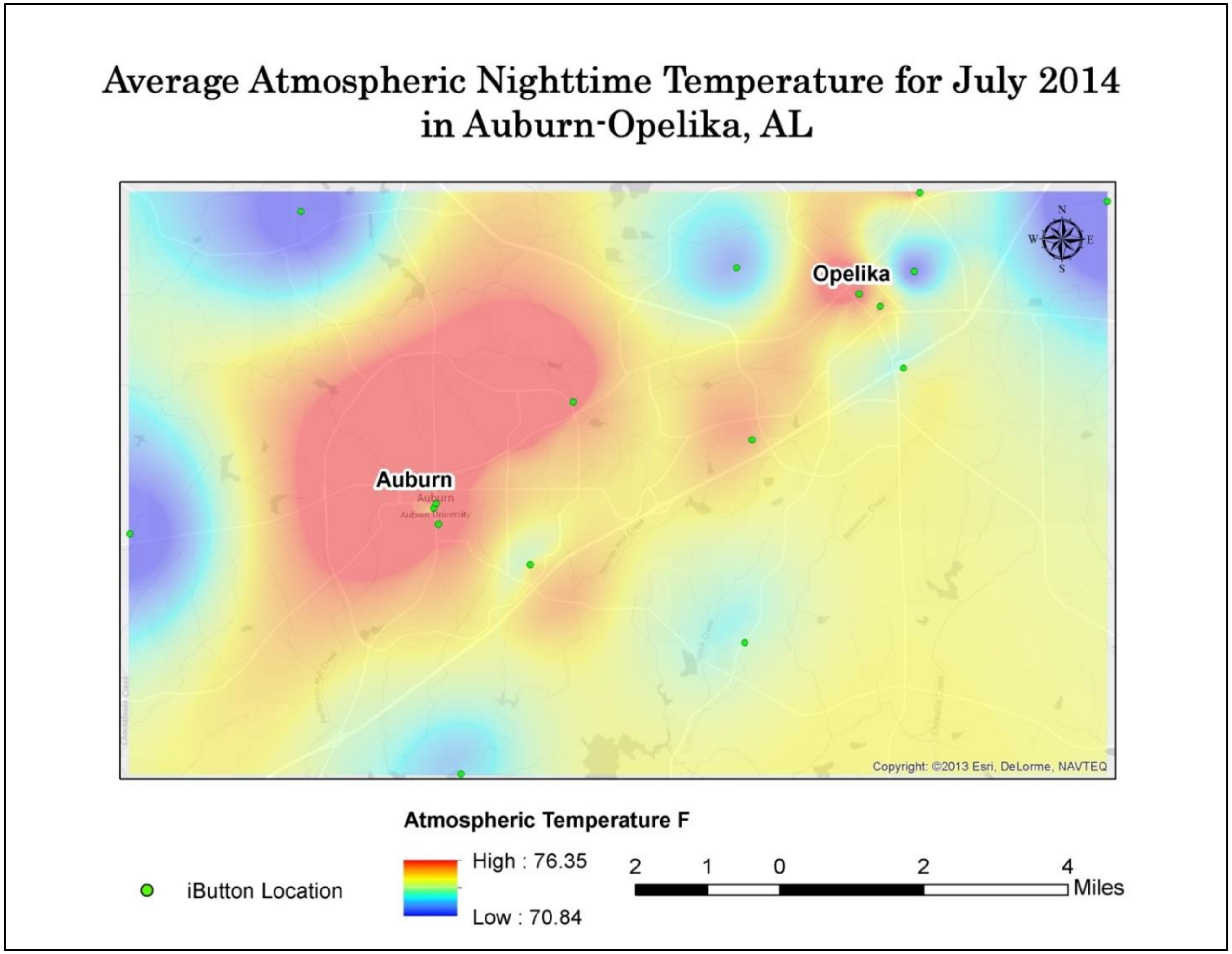


Figure 26. Average atmospheric nighttime temperature for July 2014 in Auburn-Opelika.

The map in Figure 26 is very similar to that in Figure 22 displaying the nighttime June results, right down to the temperature range. The spatial extents and distributions of the heat islands in the two aforementioned figures are virtually identical, while the differences between areas covered by the heat islands are negligible.

2.5.21 Birmingham Daytime Results for August 2014

Daytime temperatures for August increased 2.9°F over the July averages. The highest temperature, 116.0 ° F, was recorded at the County Road 6 site at 17:18 CDT on 22 August 2014. The lowest temperature was an unseasonably low 57.7°F, recorded at the Old Serene Drive location at 7:30 CDT on 14 August 2014.

The warmest location on average was Pull-A-Part again, exhibiting a temperature of 91.4°F. Linn Park was 6.8°F cooler, while Kelly Ingram Park was 5.0°F cooler than the Pull-A-Part site. The coolest location on average was Old Serene Drive at 82.3°F. Average atmospheric daytime temperatures are shown in Figure 27.

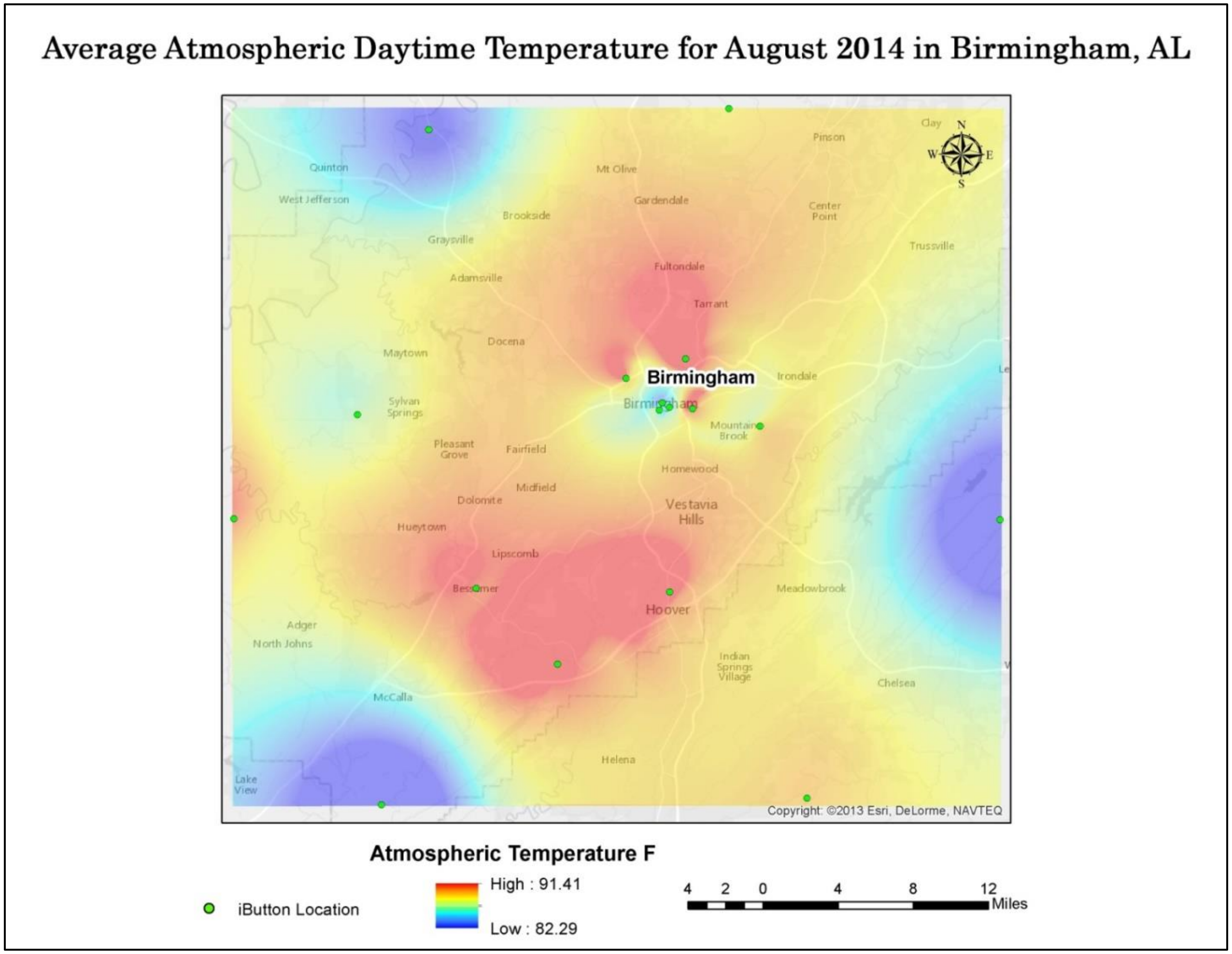


Figure 27. Average atmospheric daytime temperature for August 2014 in Birmingham.

As seen in the previous daytime maps, there were two well-developed heat islands; one near downtown Birmingham and the other around and west of Hoover. The heat island around downtown Birmingham grew substantially, at 24.7 percent, while the heat island around Bessemer remained the same size.

2.5.22 Birmingham Nighttime Results for August 2014

Nocturnal Birmingham temperatures for August increased only 0.9°F over July's. The highest temperature, 92.2°F, was recorded at the Hoover Mall on 22 August 2014 at 20:00 CDT, while the unseasonably low 55.6°F was recorded at 5:56 CDT on 14 August 2014 at the Castle Heights site.

As in all previous months of this study, Regions in central downtown Birmingham was the warmest site on average, with a temperature of 78.8°F. Both city park sites were within 1.4°F of the Regions site, while Castle Heights was the coolest, with an average temperature of 70.4°F. Average nighttime temperatures for August are displayed in Figure 28.

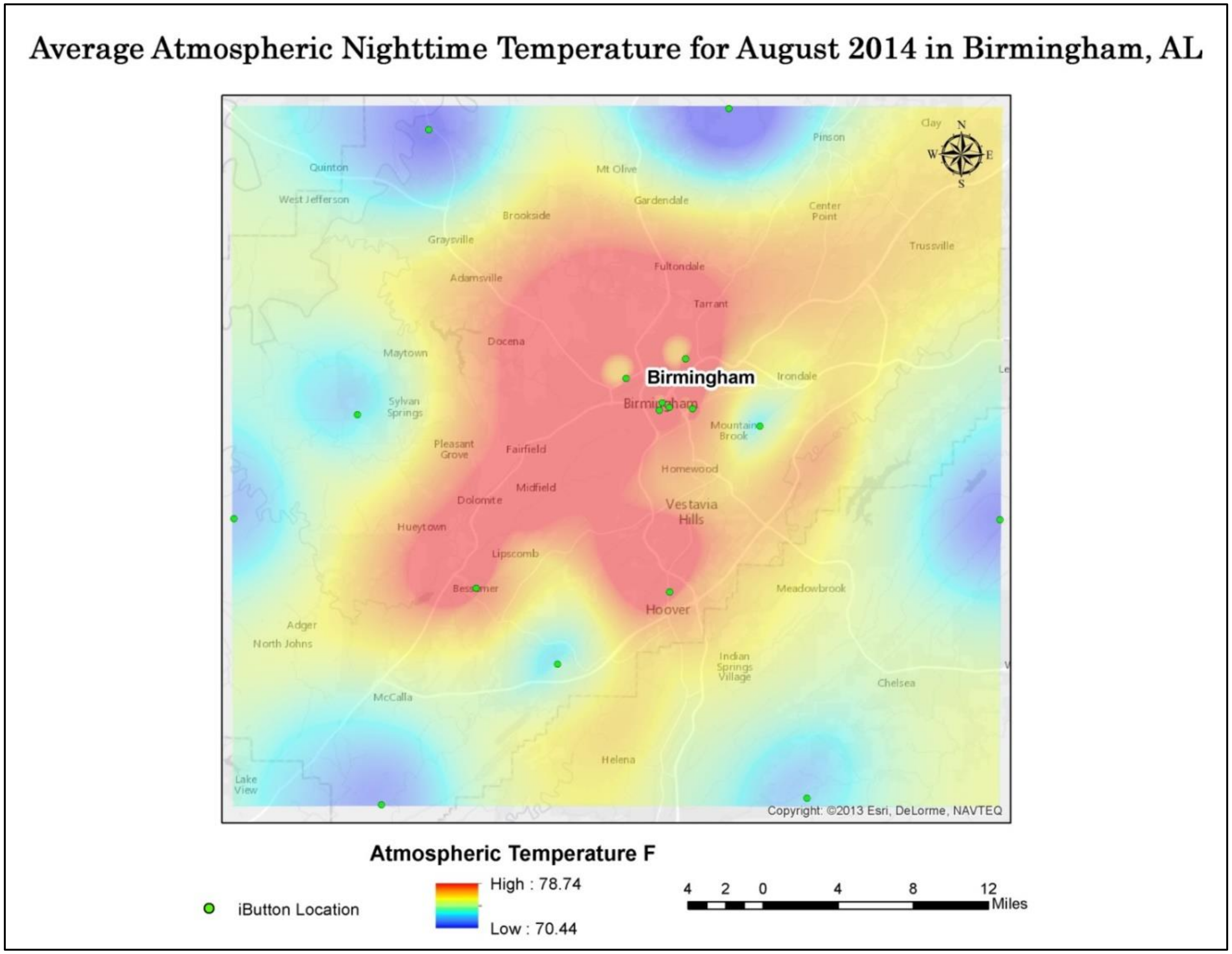


Figure 28. Average atmospheric nighttime temperature for August 2014 in Birmingham.

The spatial distribution of the heat island was nearly identical to that of the previous two months, extending out from downtown Birmingham to include Bessemer and Hoover. The same two relatively cool spots were more pronounced around the industrial sites of Pull-A-Part and 2nd street west, measuring 1.3 mi^2 and 1.4 mi^2, respectively. The area within the heat island in August was slightly larger than the area of the heat island in July, at 192.4 mi^2; a 4.8 percent increase.

2.5.23 Auburn-Opelika Daytime Results for August 2014

Temperatures were 2.4°F warmer than those recorded in Auburn-Opelika for July, and 0.5°F warmer than the daytime temperatures for Birmingham in August. The highest temperature recorded, 117.5°F, was at the AU Hotel on 7 August 2014 at 15:18 CDT. The lowest temperature recorded was 60.9°F at County Road 161 on 26 August 2014 at 7:21 CDT.

The warmest site on average was the AU Hotel, at a very warm 96.8°F. Even Tigertown was 2.8°F cooler. Samford Park was 9.1°F cooler than the AU Hotel, while County Road 161 was the coolest site, at 80.8°F. Average August daytime temperatures are shown in Figure 29.

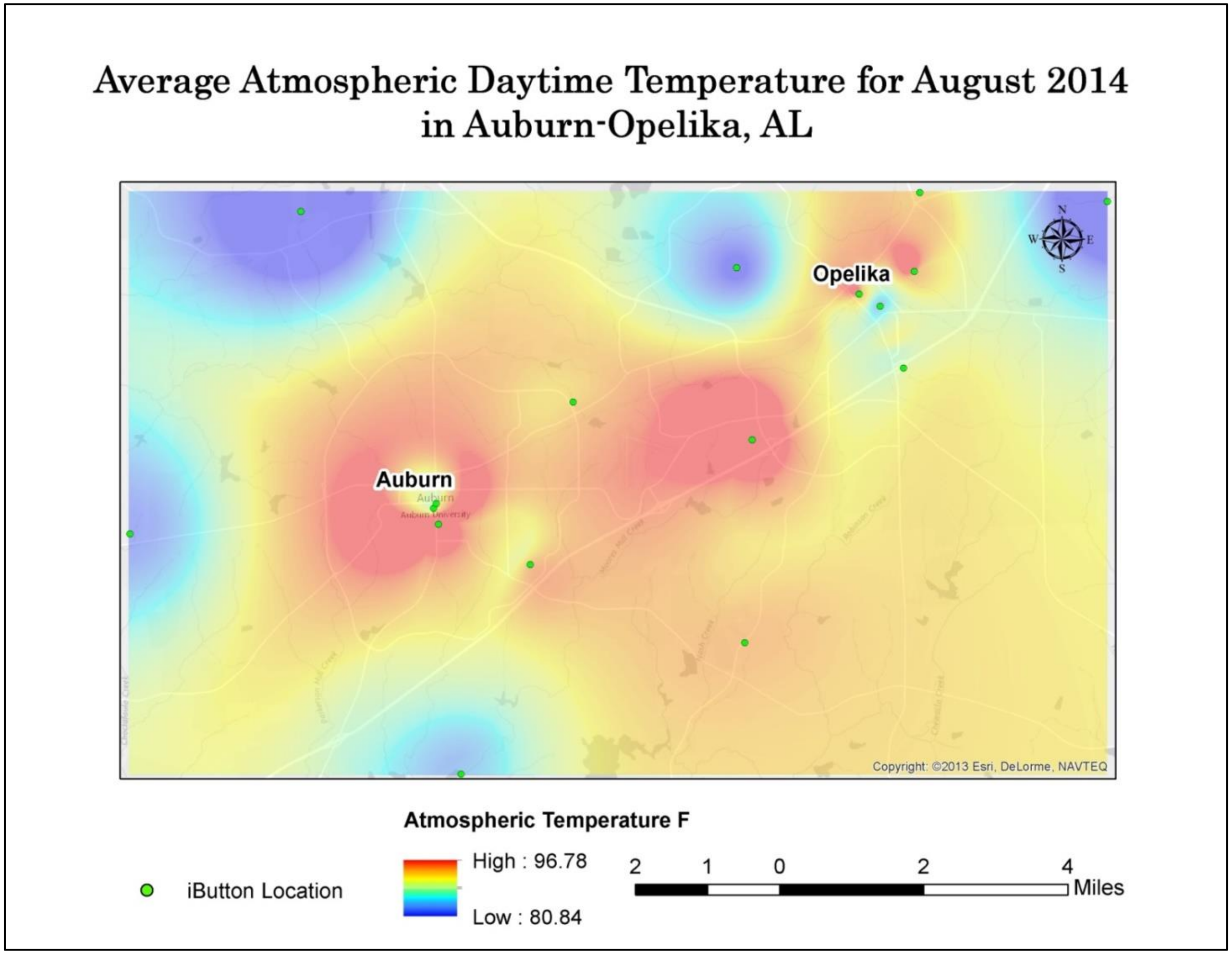


Figure 29 Average atmospheric daytime temperature for August 2014 in Auburn-Opelika.

Temperatures in August exhibited the widest range of the study, at 15.94°F and fell between 80.84°F and 96.76°F. As in previous daytime results for Auburn-Opelika, three heat islands were present, around downtown Auburn, Tigertown, and a relatively small one north northeast of Opelika. The spatial extent and distribution of all three heat islands resembled those of the Auburn-Opelika daytime results for May (see Figure 17). However, rather than completely encircling downtown, the top portion of the heat island was significantly weaker, as reflected in the May daytime results. The area of the heat island around downtown was measured at 2.2 mi^2. The heat island around Tigertown was reduced to 2.6 mi^2, compared to 3.2mi^2 in May, and 3.05 mi^2 in July. The last heat island in Opelika shrank in size (compared to July) and was measured at 0.15 mi^2.

2.5.24 Auburn-Opelika Nighttime Results for August 2014

Nocturnal temperatures for Auburn-Opelika in August were 0.1°F warmer than those recorded for Auburn-Opelika in July, and 1.0°F cooler than the Birmingham nocturnal temperatures recorded in August. The highest temperature recorded was 90.3°F at Toomer's Corner on 22 August at 20:09 CDT, while the coolest temperature recorded was over 40.0°F cooler, recorded at County Road 161 at 3:21 CDT on 26 August 2014.

The warmest site on average was yet again Toomer's Corner, at 77.0°F. Samford Park was 2.3°F cooler than the Toomer's Corner site, and the coolest site on average was County Road 161 at 70.8°F. The map displaying nighttime atmospheric temperature is displayed in Figure 30.

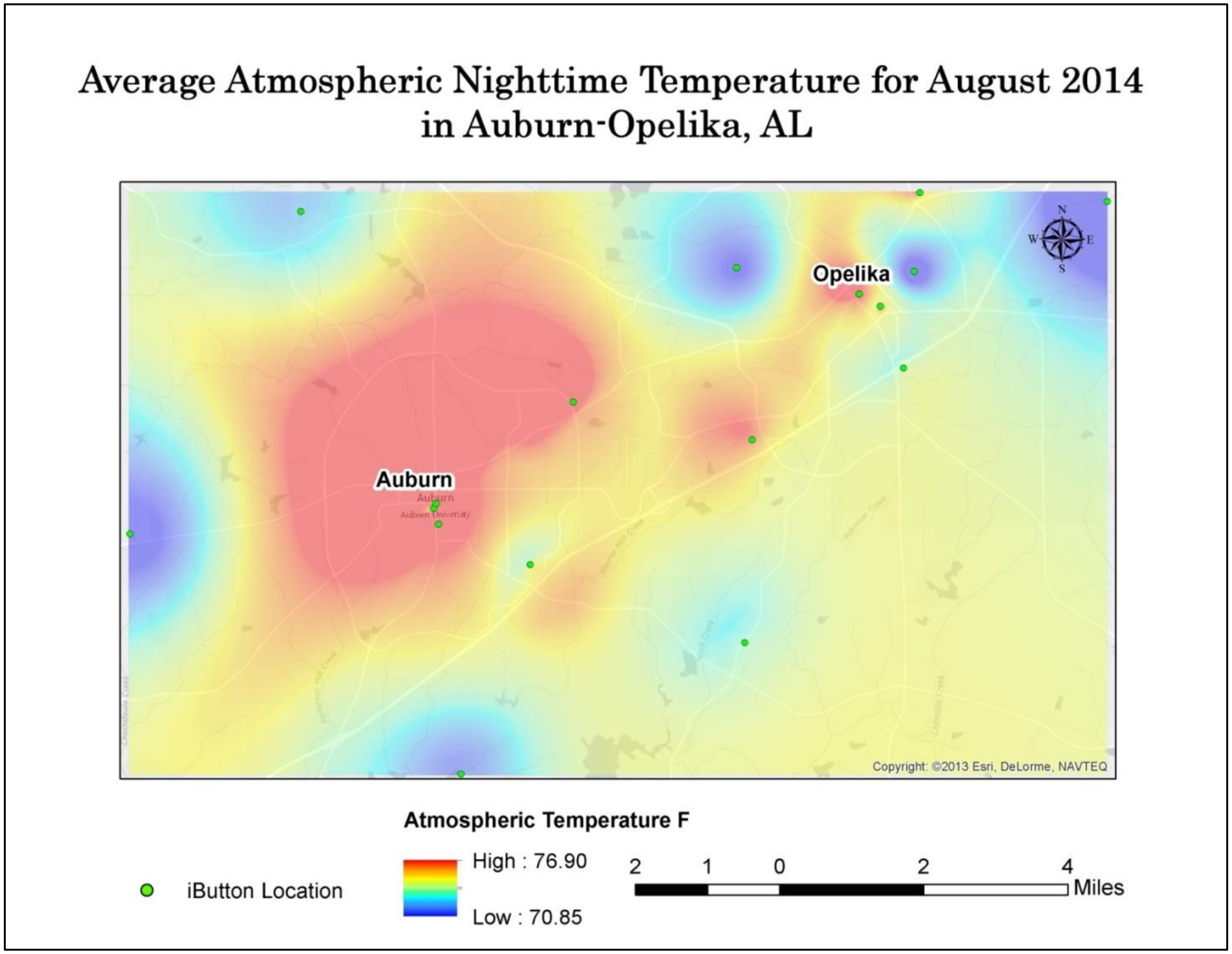


Figure 30. Average atmospheric nighttime temperature for August 2014 in Auburn-Opelika.

The temperature range was virtually the same as the June and July nighttime temperature ranges, as were the spatial extent and distribution of the heat islands. Again, the main heat island was centered around downtown Auburn, with a much smaller heat island centered around Opelika. The main heat island around Auburn grew to 12.0 mi^2, while the heat island around Opelika remained virtually unchanged, at 0.2mi^2.

2.5.25 Average UHI Intensity

In addition to the UHI magnitude being analyzed, average monthly diurnal UHI intensity was also analyzed. Average monthly urban and rural daytime and nighttime temperatures were graphed and are displayed below in sections 2.5.25.1 and 2.5.25.2.

2.5.25.1 Birmingham

A line graph showing the behavior of urban and rural diurnal temperatures for Birmingham over the entire study period is shown below in Figure 31.

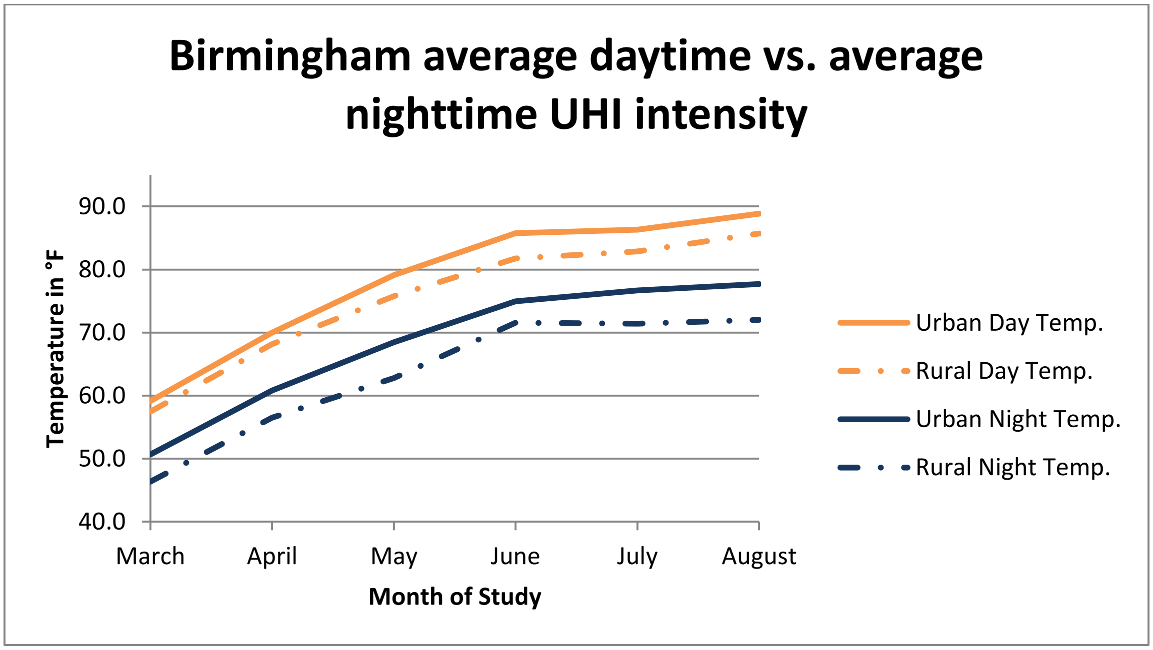


Figure 31. Average urban and rural temperatures for Birmingham.

On the graph in Figure 31, daytime temperatures are displayed in orange, and nocturnal temperatures are displayed in dark blue. All temperatures showed similar, rather homogeneous warming trends over the first three months of the study, before leveling off for the summer months. The average UHI intensity for Birmingham was consistently higher during the nighttime (i.e. greater difference in T_{urban}-T_{rural}) hours for all months of the study, exhibiting an overall average of 4.8°F. The average nocturnal UHI intensity culminated over the warmest month of the study, August, reaching 5.7°F. The lowest average nocturnal UHI intensity, 3.4°F, was observed over the month of June. Daytime UHI intensity displayed a different pattern over the study period and was noticeably weaker than the nighttime intensity, exhibiting an overall average of just 2.9°F. The average intensity climaxed during the month of June, though August was the warmest month of the study, reaching 4.0°F. It was weakest during the coolest month of the study, March, reaching only 1.6°F.

2.5.25.2 Auburn-Opelika

The same procedure was used for Auburn-Opelika to show changes in temperature over the six-month study period. The graph is shown in Figure 32.

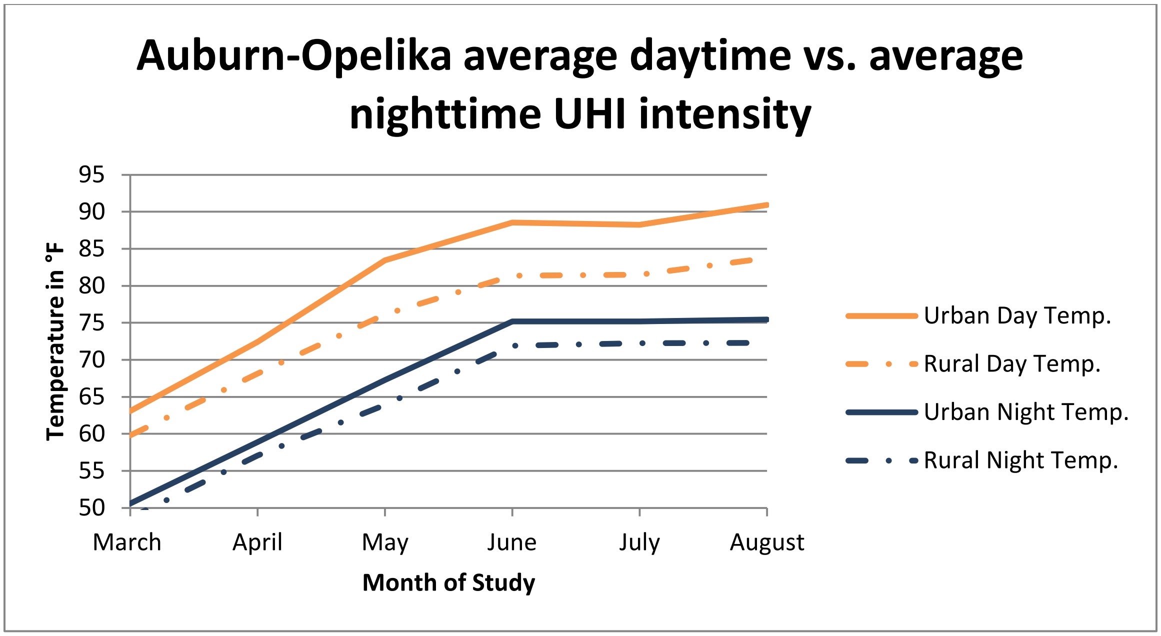


Figure 32. Average urban and rural temperatures for Auburn-Opelika.

Like temperatures in Birmingham, both daytime and nocturnal temperatures for Auburn-Opelika exhibited a consistent warming trend from March through May and leveled off in June through August. However, the UHI intensity was stronger and consistently peaked during the day, rather than nocturnally as seen in Birmingham, averaging 6.0°F over the entire study period. Daytime average UHI intensity achieved its peak during two months in this study area; once in June and again in August, reaching 7.2°F. Daytime average UHI intensity was weakest in March, reaching just 3.3°F. The nocturnal UHI intensity was substantially weaker than the observed daytime UHI intensity. On average over the entire study period, the daytime UHI intensity reached 2.8°F, culminating in May at 3.4°F. The weakest observed monthly average nocturnal UHI intensity was recorded over the month of April at 1.8°F.

The difference in the times of day (daytime vs. nighttime) when average UHI intensities peaked in the two study areas may be attributed to city landscape. Although literature is limited on small to medium-sized cities, previous literature on large cities shows that UHI intensity peaks during the nighttime hours, mainly due to the thermal effects of high-rise buildings. As mentioned previously, Birmingham has a CBD with high rise buildings (creating a relatively high H:W ratio and a deep street canyon), which absorb extensive amounts of solar radiation during the day and release it at night. During the daytime hours, however, the average daytime UHI intensity was substantially stronger in Auburn-Opelika than in Birmingham. Auburn-Opelika's CBD is composed exclusively of low to mid-rise architecture (creating a relatively low H:W ratio), which supports maximum UHI intensities during the daytime and minimum intensities at nighttime. The thermal characteristics of the different building architectures in Birmingham and Auburn-Opelika almost certainly explain some of the differences in UHI intensity culmination times.

2.6 Summary

A widespread network of low-cost temperature recording instruments, called iButtons, were strategically placed throughout and in between urban and rural areas in Birmingham and Auburn-Opelika, Alabama, after careful individual site analysis. Following data processing, the IDW function was utilized to make 24 maps by creating a raster surface over both study areas to display atmospheric temperature data acquired from the iButtons and thereby visually depict the UHI effect.

Results showed a very noticeable UHI effect in both Birmingham, AL, and Auburn-Opelika, AL, over the entire six-month study period. Although maximum temperatures occurred during the day, the UHI magnitude culminated during the nighttime hours in both locations, following the cessation of daytime heating. Birmingham had a larger UHI magnitude and consistently higher nocturnal urban temperatures than did Auburn-Opelika, supporting Oke (1973), Ahmed (1994), and Emmanuel and Fernando (2007), showing that larger city size and increased H:W ratios created by high-rise buildings exaggerate the magnitude of UHIs By day, however, Auburn-Opelika had consistently higher urban temperatures than Birmingham did, exemplifying the mitigating effects that the relatively deep street canyons in large cities provide, as stated in Emmanuel and Fernando (2007).

In addition, the city parks in both locations provided very noticeable cooling effects, especially during the day. Samford Park temperatures in Auburn-Opelika were nearly 9°F cooler on average in the summer than the warmest daytime location, the AU Hotel, less than half of a city block away. Linn Park in Birmingham exhibited temperatures 6.9°F cooler than the warmest daytime location, Pull-A-Part. The lower temperatures in the city parks show the cooling benefits from evapotranspiration provided by vegetation which is often lacking in urban areas, as documented in Spronken-Smith and Oke (1998) and Barradas (1991).

The UHI intensity was calculated and graphed as a final part of this chapter. Results showed the Birmingham UHI intensity to consistently peak during the nighttime hours and the Auburn-Opelika UHI intensity to consistently peak during the daytime hours. This phenomenon is thought to be attributable to the difference in building heights and H:W ratios.

Chapter 3: Quantification and Comparison of Surface Temperatures to Atmospheric Temperatures

3.1 Overview

The relationship between surface temperatures and atmospheric temperatures is one of the greatest unknowns in remotely-sensed UHI studies (Voogt and Oke 2003). This research used Landsat 8 imagery to study the surface UHI effect of Birmingham and Auburn-Opelika, AL and compare it to the atmospheric UHI effect, obtained through observational data from iButtons.

Satellite imagery has been used since the early 1960s, with the launch of TIROS II, to record land surface temperatures (NASA 2014). Landsat represents the longest continuously acquired collection of space-based moderate-resolution land-remote sensing data, worldwide. Originally launched on July 23, 1972, Landsat 1 (called ERTS-A at the time) had four spectral bands and an 80-meter spatial resolution. Throughout the past 40 years, seven subsequent Landsat satellites have been launched (Landsat 6 was unsuccessful), with the current satellite being Landsat 8 (USGS, 2014). This study used Landsat 8 imagery exclusively to study the surface UHI effect.

Landsat 8 was launched on 11 February 2013 and boasts numerous improvements over all previous Landsat platforms. It has eleven spectral bands as opposed to the seven had by Landast 4 and 5, and eight with Landsat7. Considering the focus of this study, the two TIRS bands (10 and 11) of Landsat 8 were of most value; particularly band ten, with a wavelength of 10.6-11.19 micrometers and a ground resolution of 100 meters. Like previous platforms, Landsat 8 has a sun-synchronous orbit and a 16-day data acquisition period. Standard Landsat 8 products are delivered to users in a quantized-and-calibrated scale digital number format corresponding to multispectral image data recorded by the eleven spectral bands. The products are made available in a 16-bit unsigned-integer format and can be rescaled through mathematics and radiometric rescaling coefficients provided in the header file to top of atmosphere (TOA) reflectance and/or spectral radiance values. The header file also contains the necessary thermal constants to convert the TIR data to LST (USGS 2014). For this study, the quantized digital numbers from TIR band 10 were first converted to TOA spectral radiance before being converted to LST to analyze the UHI effects in Birmingham, AL and Auburn-Opelika, AL.

Numerous UHI studies worldwide have used Landsat data to evaluate the surface UHI effect. For example, a study of Beijing, China utilized Landsat data to show an average increase of 4.5°C to 9°C in downtown Beijing compared to surrounding rural areas (Jiang 2006). Other studies include a 2007 UHI study of Greece that used the thermal band of Landsat 7 to spatially analyze the daytime UHI effect in the urban areas of Athens, Patra, and Volos (Stathopoulou and Constantinos 2007). A 2006 study of Tampa Bay and Las Vegas employed Landsat 5 and Landsat 7 data to assess the thermal effects produced by urbanization. Nichol et al. (2009) used a single advanced spaceborne thermal emission and reflection radiometer (ASTER) thermal image of Hong Kong combined with a 148 km vehicle traverse (used to record atmospheric temperatures 2 meters above the surface at the same time the MODIS satellite passed over the study area) (ASTER is on board the MODIS satellite) to compare surface and near surface atmospheric temperatures.

However, a literature search returned no results which used a spatially widespread network of temperature recording instruments with high temporal resolution combined with satellite imagery to compare surface and atmospheric temperatures. Many previous comparative studies, including Cui and De Foy (2012), have relied on a limited network of pre-existing weather stations, relying on temperatures from a single weather station to represent the near surface temperature over an entire urban area. Microthermal properties of a city vary with the complex surface structure, creating extreme diversity in near surface temperature observations, making a single urban temperature site problematic when used to represent a whole city (Prigent et al. 2003). The purpose of this chapter is to quantify surface temperatures for both study areas using Landsat 8 imagery and compare them to the observed atmospheric temperatures recorded by the iButtons within the same hour as the Landsat scene center time.

3.2 Methodology

Four Landsat 8 scenes were downloaded from the USGS Earth Resources and Observation Science Center (EROS); two scenes for each study area. Cloud free scenes for both seasons over both study areas were optimum. Because Birmingham had minimal cloud cover, both spring and summer scenes were available and acquired. Unfortunately, a relatively cloud-free scene from the summer months of the study was unavailable for Auburn-Opelika. Therefore, back-to-back Landsat scenes were reluctantly chosen since they were the clearest scenes over the entire study period. The Birmingham scenes (row 20, path 37) were recorded on 26 March 2014 and 16 July 2014, while the Auburn-

Opelika scenes (row 19 path 37) were recorded on 6 May 2014 and 22 May 2014.

ERDAS Imagine 2013 was used to create a layer-stacked image (including all 11 bands) for each scene, before subsetting each image to a determined area of interest. All Birmingham and Auburn-Opelika scenes were subset to the approximate extent of the iButton locations for the corresponding study areas. Following this procedure, a model was built in ERDAS Imagine 2013 to convert the quantized digital numbers in TIR band 10 to TOA spectral radiance before converting them to LST, using the following equations:

DN conversion to TOA radiance:

$$L_\lambda=M_LQ_{cal}+A_L$$

Where L_λ is the TOA spectral radiance, M_L is the band-specific multiplicative-rescaling factor (band 10 in this case), Q_{cal} is the quantized-digital number value, and A_L is the band-specific (band 10) additive-rescaling factor (USGS 2014). Once the conversion to TOA radiance was complete, the following equation was applied to convert the radiance values to LST values:

$$T = \frac{K_2}{\ln(\frac{K_1}{L_\lambda} * \varepsilon + 1)}$$

T is the LST value in degrees Kelvin, K_1 and K_2 are the first and second band-specific (band 10) thermal conversion constants (774.89 and 1321.08 respectively), and ε represents land surface emissivity values (Yale Center for Earth Observation 2010, USGS 2014). Values used were 0.92 for urban surfaces, and 0.95 for vegetated and other surfaces, as utilized in the Weng (2001) study of the Zhujiang Delta, China. Finally, the

LST values were converted from Kelvin to Centigrade employing the standard formula of C = K-273.15. The spatial modeler function in ERDAS Imagine 2013 was used to perform this conversion process, shown in Figure 33.

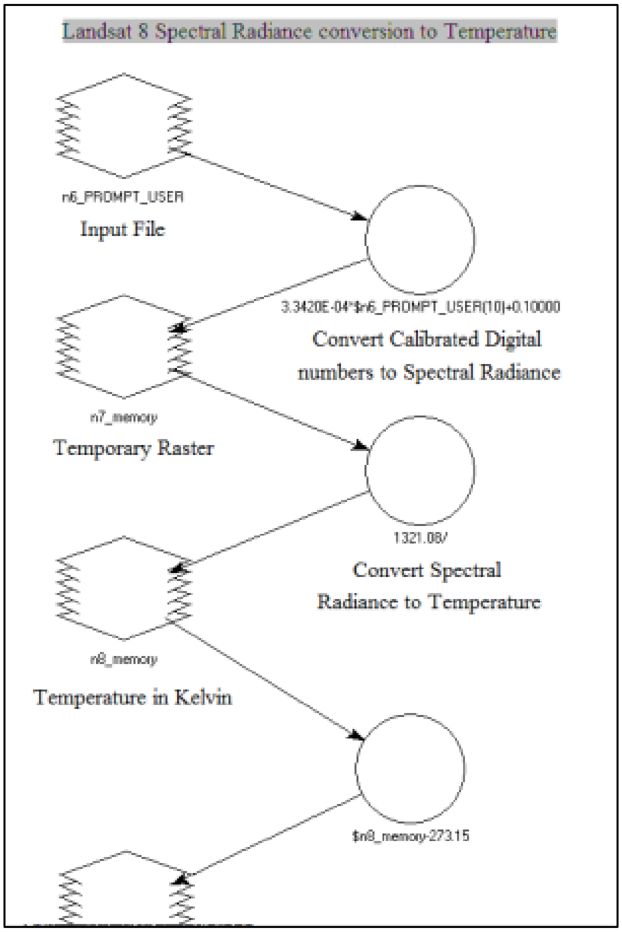


Figure 33. Schematic of ERDAS LST conversion model.

Two models were developed and run (one for each emissivity value) for all Landsat 8 scenes used in the study, resulting in two images per scene. ArcGIS 10.1 was used to analyze the subset LST images. Regardless of the subset process, a large black border was left on the south and west boundaries outside of each subset image, containing false temperature readings of -124°C. Although the black border did not affect the temperature readings within study areas, it did create an inaccurate temperature scale on the maps created to compare LST and atmospheric temperature. To remedy this, all scenes were converted from raster to polygon using the conversion tool in ArcGIS. However, before the conversion process would function, the raster values from the LST images were converted from “floating point” to “integer” to avoid error number 000864, which states that the input raster is not within the defined domain. New LST images were created with integer values rather than floating point values. The surface temperature values were then extracted to the iButton location points for analysis. The urban iButton locations were extracted to the points on the 0.92 emissivity image, while the rural, city-park, and peri-urban locations were extracted to points on the 0.95 emissivity image. Multiple conversion processes were then performed to rectify the temperature scale. The centigrade values on the scales of the map, in addition to the extracted temperature values, were converted to Fahrenheit, using the standard formula of F=°C x 1.8+32 to match the temperature scales of the atmospheric temperature data. In addition, to make maps comparing LST and atmospheric temperatures, the observed atmospheric temperatures recorded within the same hour as each Landsat scene (all scene center times were between 11:10 and 11:20 CDT, so the observed iButton data recorded within the 11:00 CDT hour on the corresponding date was used for comparison) were used as inputs for the IDW function. Both LST and atmospheric temperature values were extracted to the iButton points on the map for further analysis.

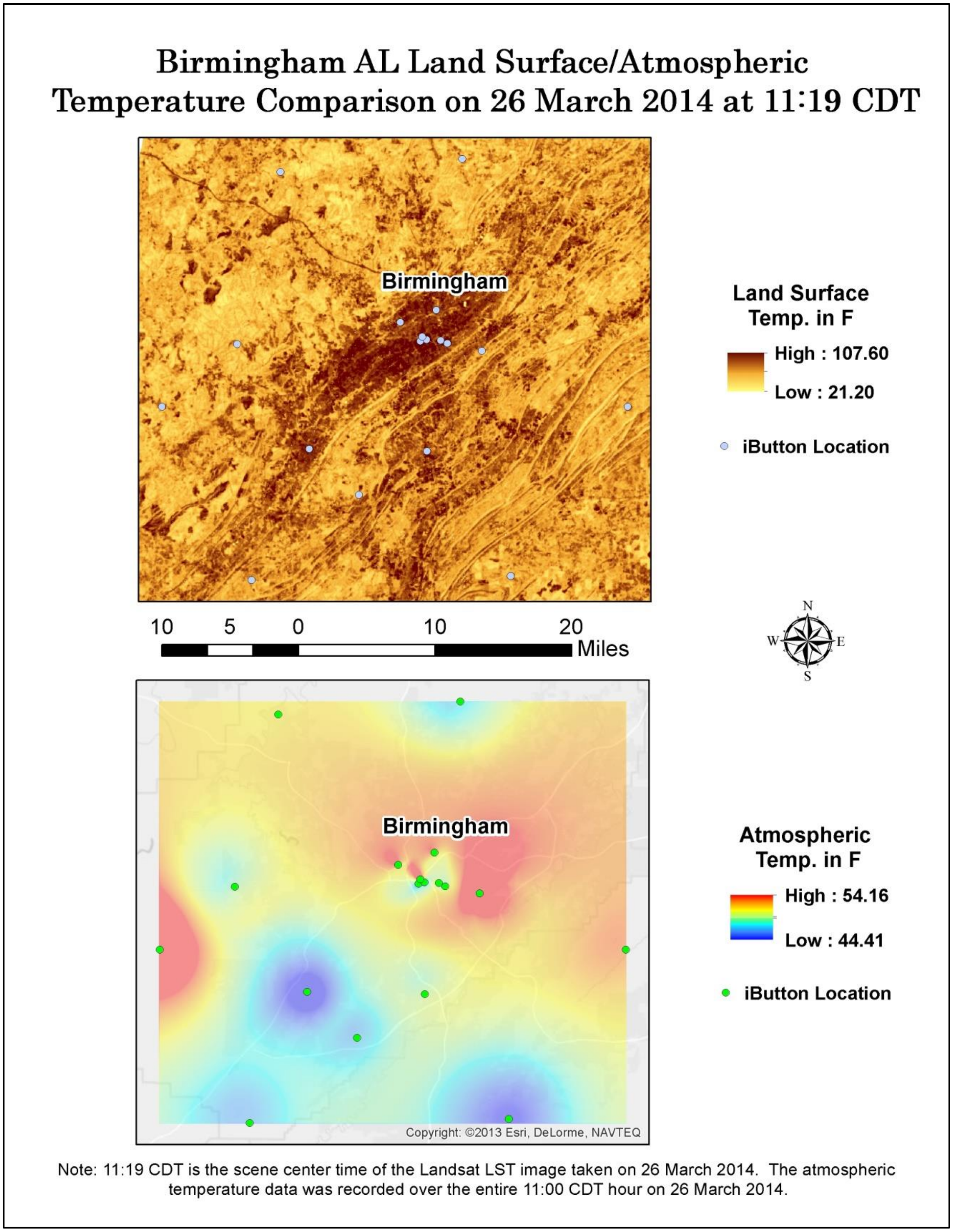
Graphs were made with the extracted temperature data to observe the relationship between LST and atmospheric temperature over the different land cover types used in the study. Following the graphs, a paired t-test for each study area using LST and atmospheric temperature data was performed to check for a statistical difference between

LST and atmospheric temperatures. The results are divided into two subsections according to study area. LST and atmospheric temperature values are displayed in Appendix B.

3.3 Results

3.3.1Birmingham Results for 26 March 2014

As expected, well-developed surface UHIs were observed over the urbanized areas of both study areas. LST was an average of 12.2°F higher than atmospheric temperature, overall. In both study areas, it was consistently higher than atmospheric temperature over all land cover types except rural. LST and atmospheric temperature for 26 March 2014 in Birmingham, AL are displayed in Figure 34.



Birmingham AL Land Surface/Atmospheric Temperature Comparison on 26 March 2014 at 11:19 CDT

Note: 11:19 CDT is the scene center time of the Landsat LST image taken on 26 March 2014. The atmospheric temperature data was recorded over the entire 11:00 CDT hour on 26 March 2014.

Figure 34. LST and atmospheric temperature on 26 March 2014 for Birmingham.

As seen in Figure 34, the surface temperature over the entire subset scene exhibited a wide range, from 21.2°F to 107.6°F. Darker areas represent regions of warmer temperature, while the lighter areas represent regions of cooler temperature. The hottest location on the map was a very large black roof (over 847,000 ft^2), 10 miles northeast of downtown Birmingham. It was the only place over the entire study area in which LST had a temperature over 98.6°F. The coolest site on the map was an even larger light gray roof (over 1,300,000ft^2) at Fred Shuttlesworth International Airport, which ranged from 21.2°F to 48.2°F. Considering time of day and surrounding temperatures, the extreme low temperature was questionable, regardless of the relatively light colored roof. Cirrus clouds were detected directly above the building

A very distinctive surface UHI effect emerged around downtown Birmingham, depicted in dark shades of brown (i.e. high temperature), measuring about 110 mi^2. This same effect was not observed in the observational atmospheric data. Generally, the LST around downtown was considerably warmer than the atmospheric temperature. The atmospheric temperatures suggest that the high-rise downtown area is, in fact, cooler than the neighboring urban areas, while the LST suggests just the opposite. This is a well-documented phenomenon, supported by the results of previous studies, such as (Arnfield 2003), showing that the LST UHI tends to peak during the day, while the atmospheric UHI tends to peak at night. This relationship between LST and atmospheric temperatures within the 11:00 CDT hour on 26 March 2014 in Birmingham was further affirmed as shown in the line graph in Figure 35.

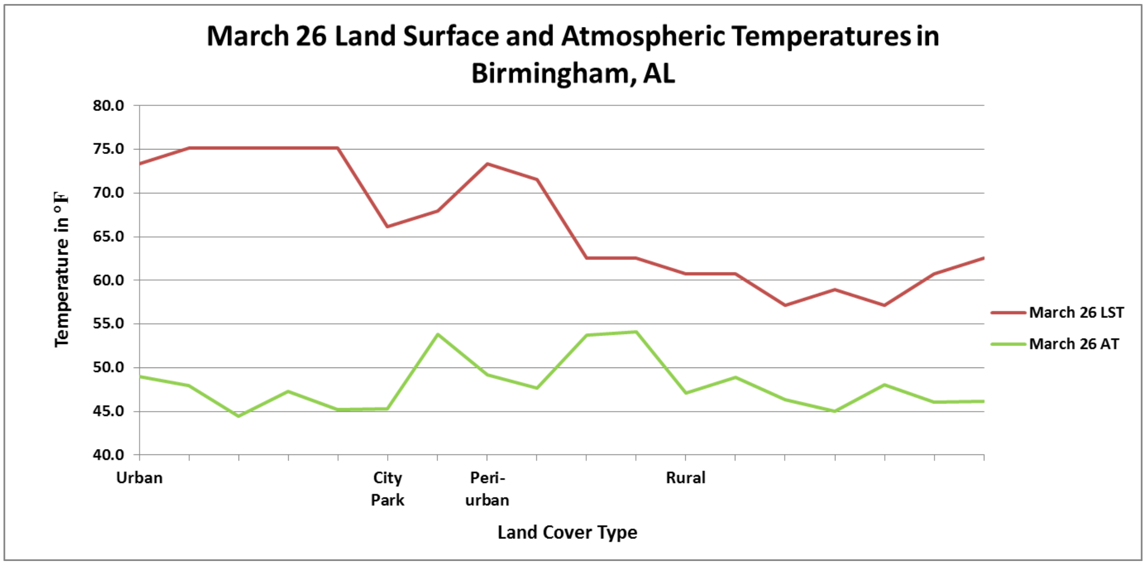


Figure 35. LST and atmospheric temperature vs. land cover on 26 March 2014 in Birmingham

Figure 35 shows March 26 LST in red, and March 26 atmospheric temperature in green. Temperature in °F represents the x-axis, while land cover type represents the y-axis. Figure 35 illustrates how LST and atmospheric temperatures behave over differing land cover types. The LST was consistently higher than the atmospheric temperature, regardless of land cover, averaging 18.4°F warmer (overall) than the observed atmospheric temperatures. The largest difference in LST and atmospheric temperatures occurred at the Bessemer site, while the smallest difference occurred at the Pull-A-Part site.

Generally, the greatest discrepancy between LST and atmospheric temperature existed over urban land cover. However, the discrepancy between the two was reduced with the transition to rural land cover. A contributing factor to this trend could be the tendency of satellites to oversample horizontal surfaces, such as rooftops and parking lots. The typically cooler vertical surfaces of buildings are often neglected, resulting in higher recorded surface temperatures. (Arnfield 2003). LST itself was surprisingly consistent over the urban sites. All sites were 75.2°F except for Pull-A-Part, which was just 1.8°F cooler. Atmospheric temperatures were more variable, but all remained within just over 4°F of each other, from 44.4°F to 49.0°F. The average difference between the LST and atmospheric temperatures was quite large, at 28.1°F for all urban sites.

There was more variability in both LST, and atmospheric temperature over the city park and peri-urban landscapes. City park and peri-urban LST varied 5.0°F on average, exhibiting an overall range between 62.6°F and 73.4°F. The atmospheric temperature varied somewhat less, at 2.8°F on average, exhibiting an overall range from 47.7°F to 54.2°F. Average difference between the two temperature types (LST and atmospheric) was substantially less than the urban average difference, at 16.7°F. The largest discrepancy between LST and atmospheric temperature occurred at the 2nd Street West site, while the smallest occurred at the Winston Way and Churchill Circle site.

LST and atmospheric temperatures were most consistent over the rural land cover sites, varying 13.0°F on average. LST itself varied 1.7°F on average, from 57.2°F to 62.6°F, while atmospheric temperature varied just 1.0°F on average, from 45.0°F to 48.9°F. The largest difference between LST and atmospheric temperatures occurred at Parkwood Road, while the smallest occurred at Littleton Sayre.

3.3.2 Birmingham Results for 16 July 2014

A second LST and atmospheric temperature analysis for Birmingham was done on 16 July 2014. The map displaying surface and atmospheric temperatures is provided in Figure 36.

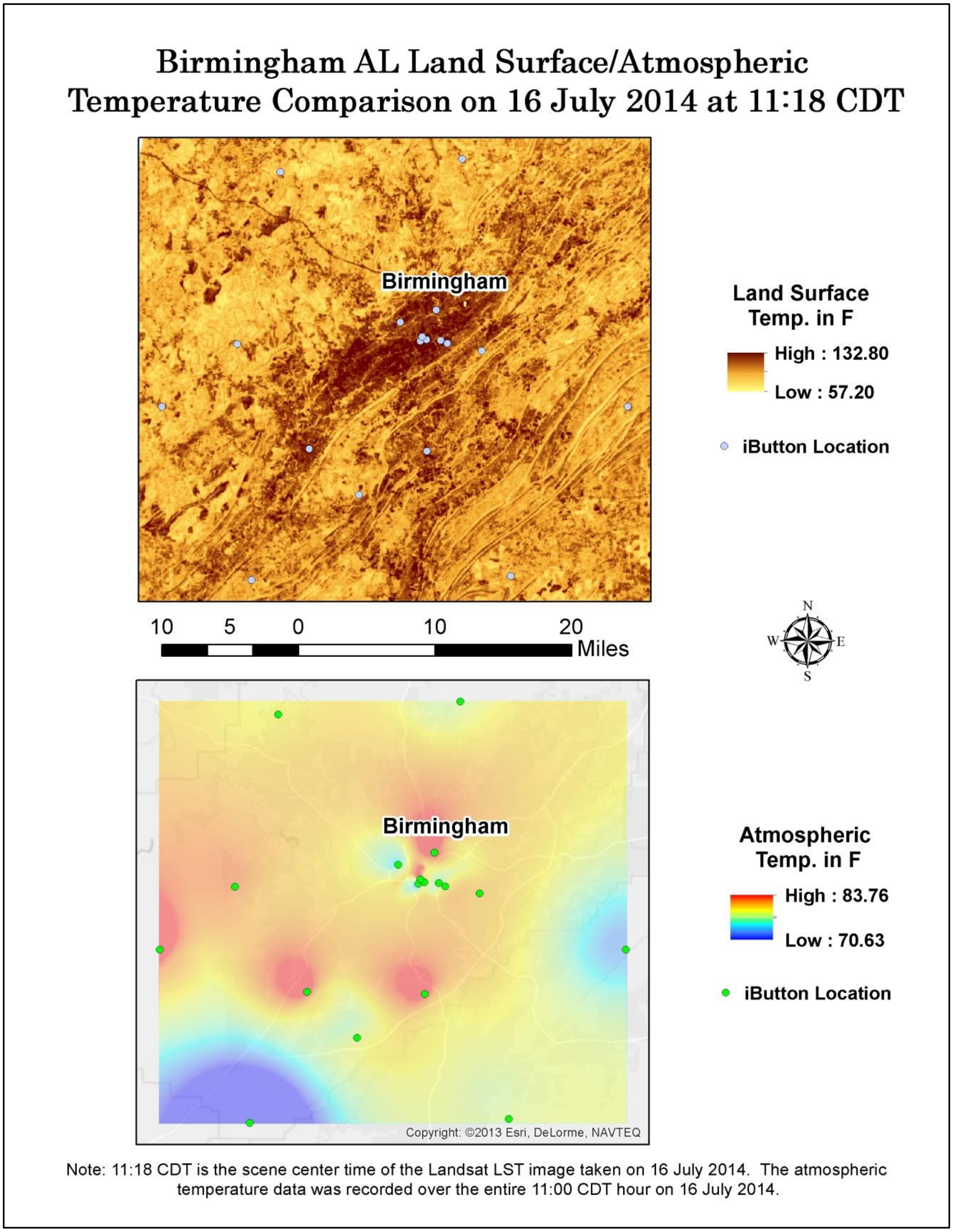


Figure 36. LST and atmospheric temperature on 16 March 2014 for Birmingham, AL.

The results for 16 July were considerably different from those for 26 March. LST was substantially higher, ranging from 57.2°F to 132.8°F. A few stray clouds occur in this image as well, producing the exceptionally cool temperatures. The highest temperature was recorded at the same sight as the March image; it was just 25°F warmer in July. The coolest location was again over an area covered by cirrus clouds. The ovular-shaped surface UHI surrounding downtown maintained roughly the same shape and area as in March.

As expected, atmospheric temperatures were noticeably warmer for July, and ranged from 70.6°F to 83.8°F. The spatial distribution of the atmospheric temperatures changed significantly as well. A number of sites which produced cool spots in March, such as the downtown Bessemer site and the Hoover site, produced hot spots in July. On the other hand, some sites that produced warm spots in May produced cool spots in July, including 2nd Street West, Bob Hood Branch, and Winston Way and Churchill Circle. Surprisingly, the well-developed hot spot around Winston-way and Churchill circle, which measured 25.7 mi^2 in March, had dissipated in July. This anomaly could be attributed to seasonality. During the spring months, the sun is lower in the sky, and it is possible that the iButton at that site received direct sunlight within the 11:00 CDT hours when the temperature was recorded. The sun is positioned differently in the sky during the summer months, perhaps shading the instrument during the 11:00 CDT hour.

A graph was made to further examine the variability of air temperature and surface temperature over different land cover types on 16 July. The graph is displayed in Figure 37.

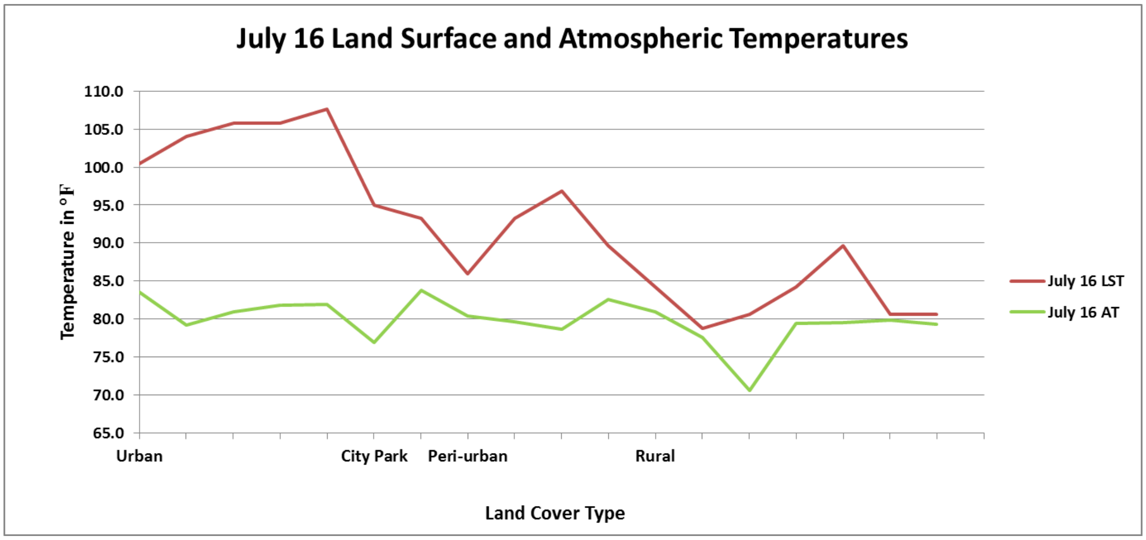


Figure 37. LST and atmospheric temperature change vs. land cover on 16 July 2014 in Birmingham.

As seen in Figure 37, July 16th LST is displayed in red and July 16th atmospheric temperature in green. Although LST was, again, consistently higher than atmospheric temperature, there was considerably less overall discrepancy between the two than on 26 March; differing 12.2°F on average. With respect to land cover, the same overall general trend seen in the 26 March temperatures is seen here in the 16 July temperatures. Urban sites saw the largest difference in LST and atmospheric temperature, while rural sites saw the least difference.

LST over the urban sites was considerably less consistent on 16 July than on 26 March, varying an average of 2.0°F between 100.4°F and 107.6°F. Atmospheric temperatures, on the other hand, were more consistent on 16 July than on 26 March, varying just 1.4°F on average. Overall temperature range for urban atmospheric temperatures was quite narrow, varying from 79.2°F to 83.6°F. Although LST and atmospheric temperatures were closer for 16 July overall, average LST for the urban sites was still 24.8°F warmer than the observed atmospheric temperatures. The largest difference in LST and atmospheric temperature was recorded at the Hoover site, while the smallest difference was recorded at the Pull-A-Part site.

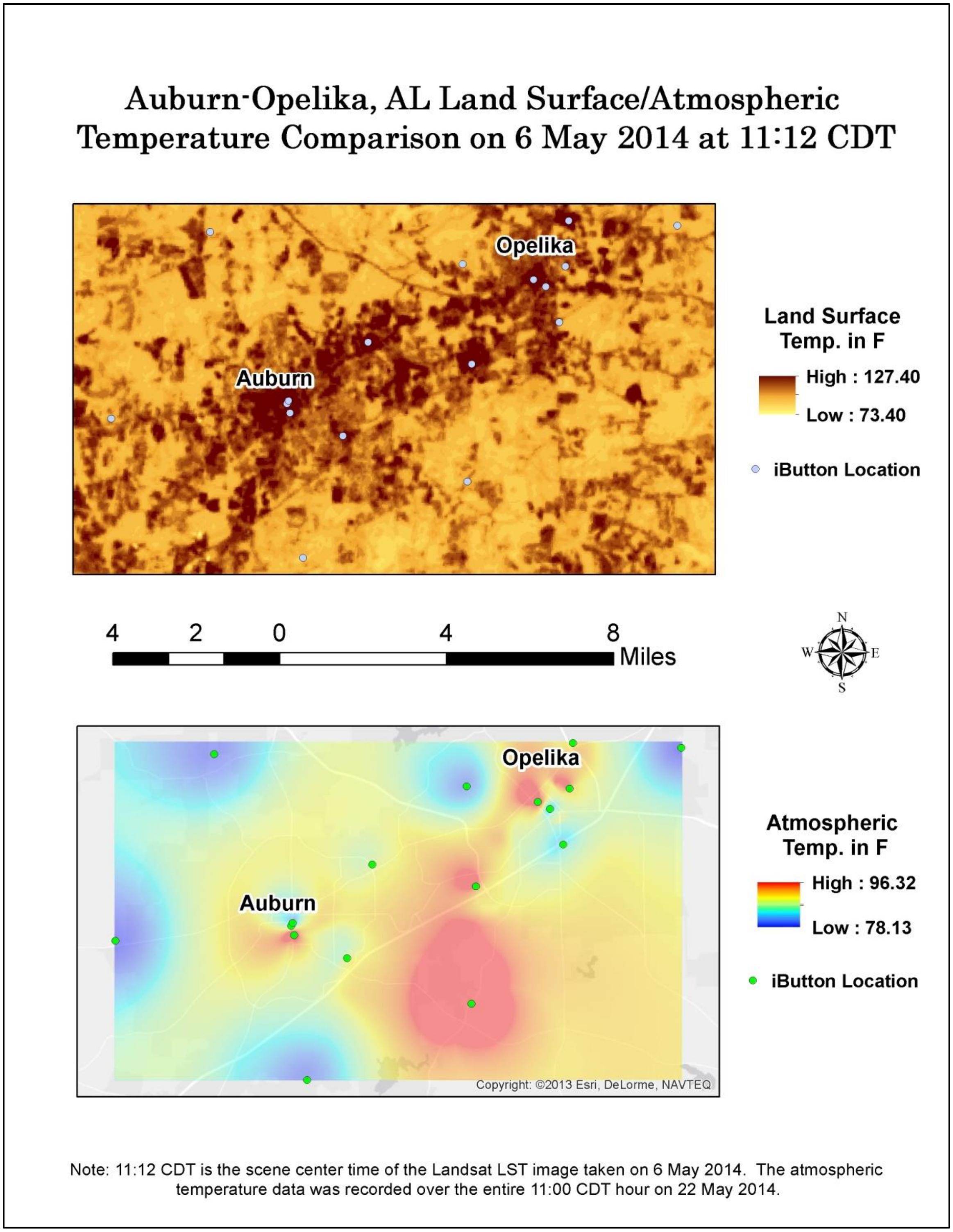
The average difference between LST and atmospheric temperature at the city park/peri-urban sites was 12.0°F, while the variation in LST itself over the city park and peri-urban sites was an average of 3.0°F, ranging from 89.6°F to 95.0°F. Again, the atmospheric temperatures exhibited less variability, differing 1.9°F on average, from 77.0°F to 82.6°F. The largest difference in LST and atmospheric temperatures occurred again at the 2nd Street West site, while the smallest difference occurred at Winston Way and Churchill Circle.

Rural sites again showed the most consistency between LST and atmospheric temperatures; however, 16 July LST and atmospheric temperatures were much closer than on 26 March; differing an average of just 4.5°F (versus 13.0°F in March). Over all rural sites, LST itself varied 2.9°F on average, ranging from 78.8°F to 89.6°F, while atmospheric temperature itself varied slightly less, 2.3°F on average, ranging from 70.6°F to 80.9°F. The largest discrepancy in LST and atmospheric temperature was again recorded at the Parkwood Road site, while the smallest discrepancy was again recorded at the Littleton Sayre site.

As a final step in Birmingham LST and atmospheric temperature analysis, a paired t-test was performed to compare LST and atmospheric temperatures on the dates that both Landsat scenes were taken. IButton sites were used as extraction points for the surface temperature on both the 26 March and the 16 July Landsat LST images. The p-value (2.47E-12) indicated that LST and atmospheric temperatures were statistically different at the 0.01 significance level.

3.3.3 Auburn-Opelika Results for 6 May 2014

The same process was performed for Auburn-Opelika. A map displaying surface and atmospheric temperature on 6 May is provided in Figure 38.



Auburn-Opelika, AL Land Surface/Atmospheric Temperature Comparison on 6 May 2014 at 11:12 CDT

Note: 11:12 CDT is the scene center time of the Landsat LST image taken on 6 May 2014. The atmospheric temperature data was recorded over the entire 11:00 CDT hour on 22 May 2014.

Figure 38. LST and atmospheric temperature on 6 May 2014 for Auburn-Opelika.

As in the Birmingham results, higher LST values are represented by darker shades of brown, while cooler LST values are represented by lighter shades of tan. Surface temperatures were considerably higher in Auburn-Opelika than on either date (26 March or 16 July) in Birmingham, ranging from 68.0°F to 138.2°F. As in Birmingham, the hottest place in the Auburn-Opelika study area was a long, flat expansive building (over 2 million ft^2) with a black roof. The higher range in surface temperatures could be attributed to a higher maximum temperature of 86°F (vs. 56°F for 26 March and 83°F for 16 July, recorded at the Fred Shuttlesworth International Airport in Birmingham) recorded at the Auburn University Regional Airport. Other factors mentioned in chapter two, include the lack of high rise buildings, producing a low H:W ratio. This in turn results in less shade and more open, flat surfaces for long-wave radiation absorption. A very prominent surface-UHI effect was apparent over the Auburn-Opelika study area, as seen in Figure 32. Both downtown areas exhibited relatively high surface temperatures, as did Opelika Road, a well-developed four lane highway that connects the two towns.

Atmospheric temperatures were also higher in Auburn-Opelika on May 6th than they were on either 26 March or 16 July in Birmingham, ranging from 78.1°F to 96.3°F. As in Birmingham, an obvious discrepancy emerged between surface and atmospheric temperatures in Auburn-Opelika. Figure 38 indicates that atmospheric temperatures in downtown Auburn were relatively cool, while surface temperatures were relatively warm. The LST at Toomer's corner, for example, was 29°F warmer than the recorded atmospheric temperature. The relationship between surface and atmospheric temperatures is further depicted in Figure 39.

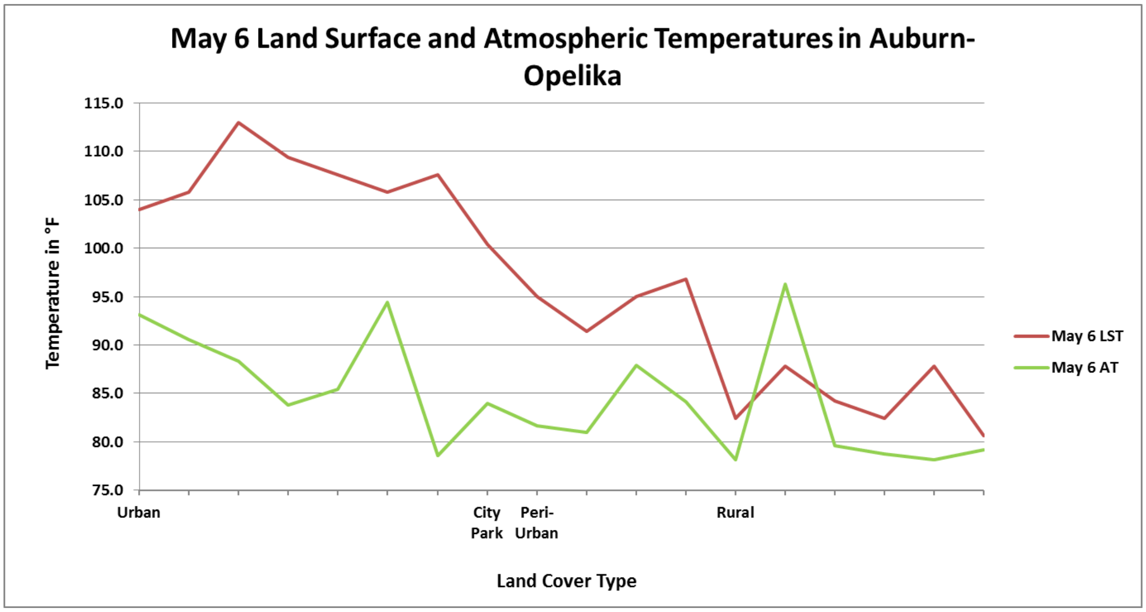


Figure 39. LST and atmospheric temperature change over land cover on 6 May 2014 in Auburn-Opelika

As in the Birmingham graph, LST is displayed in red, and atmospheric temperature in green. Over three of the four land cover types, LST was consistently warmer than atmospheric temperatures on 6 May in Auburn-Opelika. Some rural LST temperatures were cooler than the observational atmospheric temperatures. Overall, LST and atmospheric temperature were closer in Auburn-Opelika on 6 May than on either date in Birmingham; varying just 11.9°F on average.

As in Birmingham, the largest discrepancy between LST and surface temperatures occurred in Auburn-Opelika over urban landscapes. LST itself varied 2.1°F on average, between 104.0°F and 113.0°F over all urban sites. Atmospheric temperatures, on the other hand, experienced more fluctuation, varying 3.3°F on average from 78.6°F and 94.4°F. The average difference between the LST and atmospheric temperatures over all urban sites was relatively large, at 19.9°F. The maximum difference occurred at

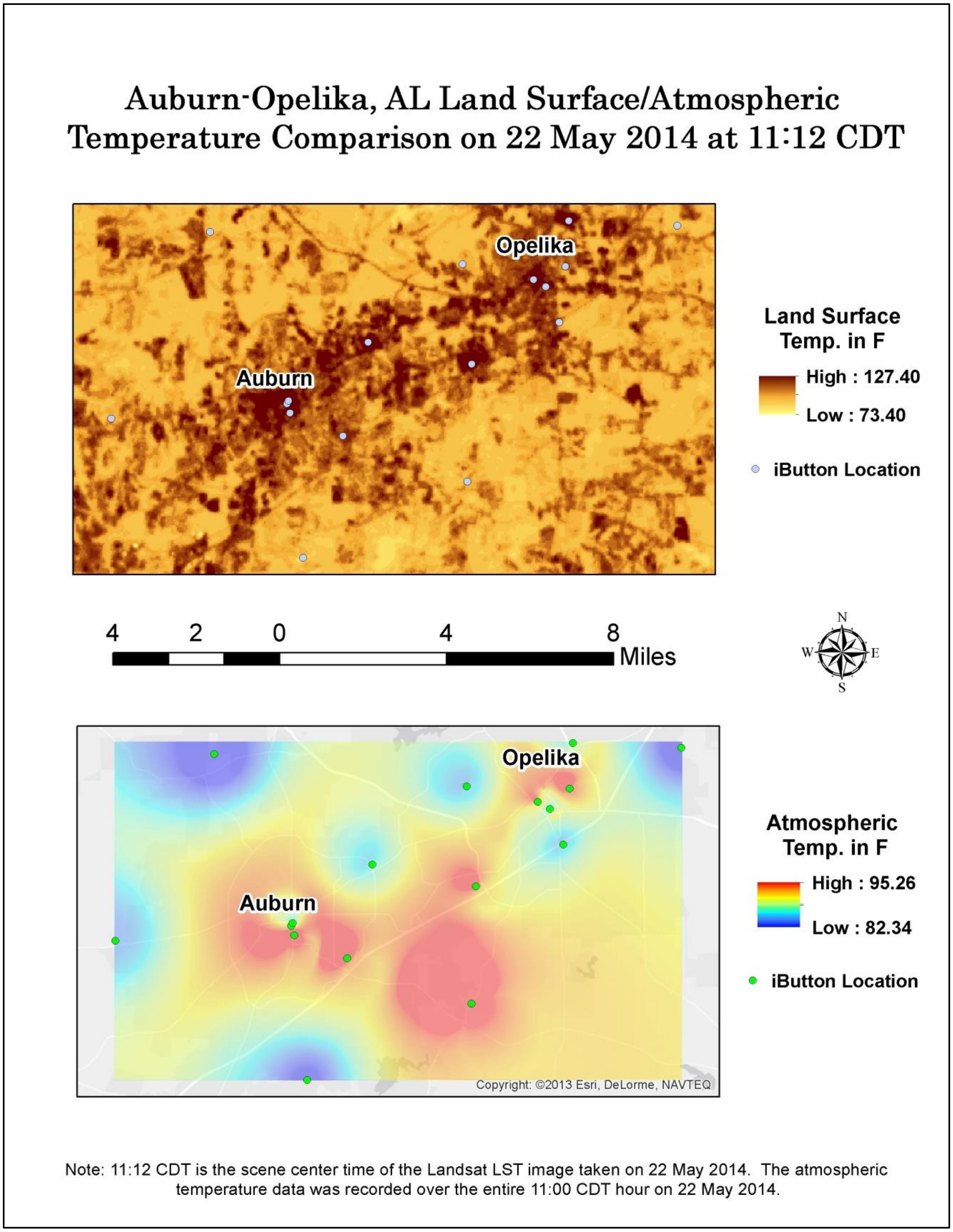
Toomer's Corner; the minimum difference occurred at the Irish Pub, located on the edge of the mid-rise building section of downtown Opelika.

The city park and peri-urban landscapes showed more agreement among LST and atmospheric temperatures (compared to the urban sites); differing by 12.0°F as they did on 16 July in Birmingham. LST varied 2.3°F on average and exhibited a narrower range over the city park/peri-urban landscapes than over the urban landscape, at 9.0°F, while atmospheric temperatures differed 2.0°F, from 81.0°F to 87.9°F. The largest recorded difference in LST and atmospheric temperatures occurred at Samford Park, while the smallest difference occurred at Oak Court and Darden Street.

On average, LST over rural land cover in Auburn-Opelika was closer to atmospheric temperature (2.5°F warmer) than on either date in Birmingham. This was mainly due to a large discrepancy at the Lee Road 110 site, in which LST was 8.5°F cooler than the atmospheric temperature. The atmospheric temperature at that site was the highest of all the sites, at 93.3°F. The next coolest rural site, White Road was 13.7°F cooler. It is possible that the iButton at the Lee Road 110 site received direct sunlight during the time of the temperature recording. Ignoring the Lee Road 110 site, LST was consistently warmer than atmospheric temperature, at 4.7°F on average. Rural LST varied 2.4°F on average, ranging from 80.6°F to 87.8°F, while atmospheric temperature (including the Lee Road 110 site) varied 4.8°F on average and exhibited a relatively wide range, from 78.1°F to 96.3°F.

3.3.4 Auburn-Opelika Results for 22 May 2014

Because May 22nd was the only other relatively cloud-free Landsat image available for Auburn-Opelika during the study period, it was chosen in lieu of a scene taken during the summer months. The map displaying surface temperature and atmospheric temperature is displayed in Figure 40.


Auburn-Opelika, AL Land Surface/Atmospheric Temperature Comparison on 22 May 2014 at 11:12 CDT

Note: 11:12 CDT is the scene center time of the Landsat LST image taken on 22 May 2014. The atmospheric temperature data was recorded over the entire 11:00 CDT hour on 22 May 2014.

Figure 40. LST and atmospheric temperature on 6 May 2014 for Auburn-Opelika.

Surface temperatures on 22 May ranged from 69.8°F to 127.4°F. The hottest location in the study area was again the two-million-ft^2 black-roofed building directly south of downtown Opelika. Spatial distribution of the LST on 22 May appears extremely similar to the spatial distribution on 6 May, albeit the temperature range is lower. There are substantial differences in the atmospheric temperature distribution, however. A hotspot measuring 1.9 mi^2 developed on the southern side of downtown Auburn and stretched across to the Green Street location. The hotspot around the Lee Road 110 location also shrank slightly, from 8.7 mi^2 to 7.5 mi^2. A graph showing surface and atmospheric temperatures is displayed in Figure 41.

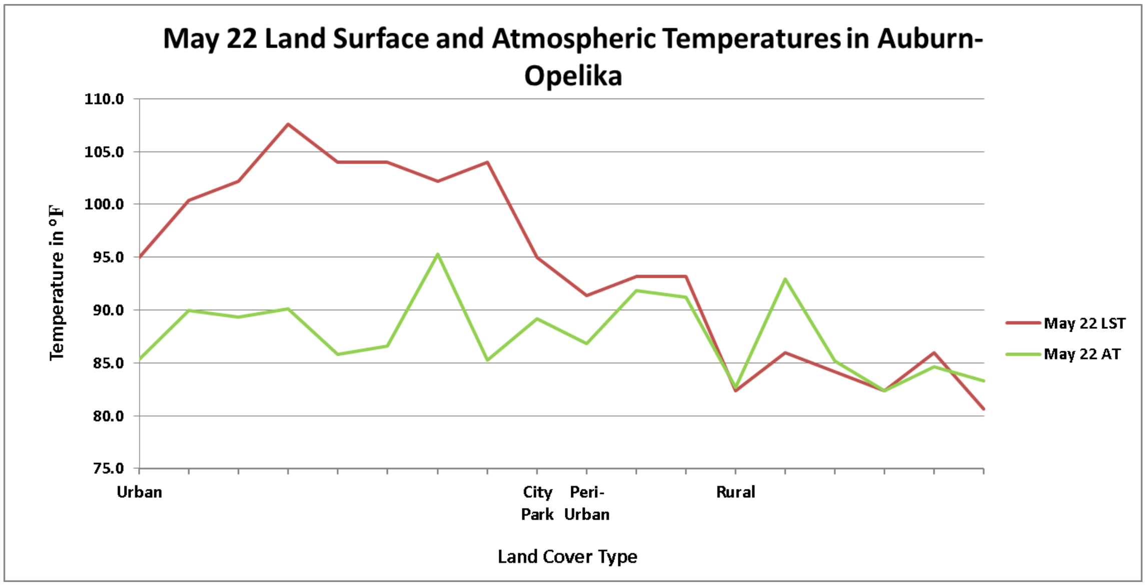


Figure 41 LST and atmospheric temperature change over land cover on 22 May 2014 in Auburn-Opelika

As in all previous graphs, the largest difference between LST and atmospheric temperature occurred over urban land cover, while the smallest discrepancy occurred over rural land cover. Also, in the 6 May graph for Auburn-Opelika, some rural LST temperatures were cooler than observational atmospheric temperatures. Overall, LST was closest to atmospheric temperature on 22 May in Auburn-Opelika than on any of the previous dates, regardless of study area, at only 6.4°F warmer on average. This small discrepancy mainly stems from relatively close rural LST and atmospheric temperatures.

LST itself varied only 1.6°F on average over all urban sites and ranged between 100.4°F and 107.6°F. Atmospheric temperature fluctuated an average of 2.6°F, from 85.3°F to 95.3°F. On average, LST was 14.6°F warmer than the atmospheric temperature, with the largest difference occurring at Toomer's Corner, and the smallest at the AU Hotel site.

City park and peri-urban landscapes again showed more agreement among LST and atmospheric temperatures (compared to the urban sites); differing only 4.7°F on average. LST varied 1.2°F on average and exhibited a narrower range than it did over the urban landscape, between 91.4°F and 95.0°F. Atmospheric temperatures differed an average of 2.3°F, from 85.3°F to 91.9°F. The largest discrepancy among LST and atmospheric temperatures occurred at the I-85 location, while the smallest discrepancy occurred at the Oak Court and Darden Street site.

A noticeable difference developed on 22 May over the rural land cover sites. Four of the six rural sites had warmer atmospheric temperatures than LST temperatures, which was not the case in any other month. On average, LST was 1.6°F cooler than atmospheric temperature. Rural LST itself varied 1.8°F on average, between 85.4°F and 86.0°F, while atmospheric temperature varied 2.6°F on average, between 82.6°F and 92.7°F. Lee Road 110 was curiously warm again, at 93.0°F; 10.6°F warmer than the next warmest location, White Road. The largest difference in LST and atmospheric temperatures was recorded at Lee Road 110, where atmospheric temperature was 7.0°F warmer than LST. The smallest difference in temperatures occurred at Pepperwood Trail, where LST and atmospheric temperatures were virtually identical.

A paired t-test was also performed for the Auburn-Opelika study area using LST and atmospheric data extracted to the iButton points for both the 6 May and 22 May Landsat scenes. The p-value (6.05E-07) indicates that LST and atmospheric temperatures were statistically different at the 0.01 significance level.

3.5 Summary

Two Landsat 8 scenes for each study area (a total of 4) were used to quantify surface temperatures. First, the quantized digital numbers in TIR band 10 were converted to LST, using two equations and emissivity values of 0.92 and 0.95 for urbanized areas and vegetated areas, respectively. Next, maps were made comparing the LST to the atmospheric temperature, using the iButton temperature data recorded within the same hours as the Landsat 8 scene center time (11:00 am CDT hour). Graphs were also made to further analyze the relationship between LST and atmospheric temperatures. Finally, a paired t-test was performed for both study areas using LST values and atmospheric temperature values recorded within the same hour as the Landsat image scene center time

Results for Birmingham showed LST to be consistently warmer in downtown than in surrounding rural areas (see figures 28 and 30), indicating a very distinctive surface UHI effect. The graphs comparing LST and atmospheric temperature for both dates (Figures 29 and 31) showed LST to be consistently higher than atmospheric temperature, regardless of land cover type. Generally, LST was highest relative to the atmospheric temperature (i.e. largest discrepancy between LST and atmospheric temperatures) over urban land cover, and was lowest relative to atmospheric temperature (i.e. smallest discrepancy between LST and atmospheric temperature) over rural land cover, although still consistently warmer. The paired t-test results for both study areas indicated a statistically significant difference between LST and atmospheric temperatures 2-3 meters above the surface in both study areas.

Results for Auburn-Opelika showed a very distinctive surface UHI effect in both downtowns and in-between as well (see Figures 38 and 40). The graphs comparing LST and atmospheric temperature show LST to be consistently warmer than atmospheric temperature over all land cover types except rural. On both dates (6 May and 22 May), rural atmospheric temperatures were warmer than the rural LST in at least one location. The paired t-test indicated that there was no statistical difference between LST and atmospheric temperatures.

Chapter 4: Conclusion and Significance

4.1 Conclusion

This study used a combination of observational temperature data from a wide-spread network of high frequency temperature monitoring instruments and remote sensing and GIS techniques to address the following research objectives:

1. Quantify the atmospheric UHI effect through observational data acquired from a spatially wide spread network of iButtons in Birmingham, AL and Auburn-Opelika, AL.

2. Quantify the surface UHI effect in Birmingham, AL, and Auburn-Opelika, AL, using Landsat 8 imagery and compare it to the atmospheric UHI effect in Birmingham and Auburn-Opelika, AL.

Results from the observational data showed the atmospheric UHI in both locations is better developed and of larger magnitude during nighttime hours than daytime. The observed nocturnal UHI effect was significantly larger in Birmingham than in Auburn-Opelika, culminating during the summer months (June-August). Birmingham exhibited consistently higher urban nocturnal temperatures in April-August and cooler rural nocturnal temperatures (over the entire study) than Auburn-Opelika. Auburn-Opelika exhibited higher urban and rural daytime temperatures than Birmingham (over the entire study). In addition, the high-rise buildings in Birmingham had the coolest urban temperatures during the daytime; while the low-rise buildings had the highest temperatures during the daytime (Auburn-Opelika does not have high rise buildings).

City parks also showed to provide cooling qualities in this study and were 6-8°F cooler on average than the warmest urban location during the day.

Surface temperatures were consistently warmer than the atmospheric temperatures for Birmingham, AL, regardless of land cover type. However, surface temperatures for Auburn-Opelika were consistently cooler for at least one of the rural sites. The largest discrepancy between LST and atmospheric temperatures occurred over urban land cover, regardless of study area, where LST was an average of 21.4°F warmer. Rural LST and atmospheric temperatures were more consistent but were still considerably different, at 4.6°F on average, overall.

4.2 UHI Mitigation Procedures

Measures can be taken to mitigate and ameliorate the UHI. A number of programs at the state, federal, and local levels were developed in the 1990s. The Heat Island Reduction Initiative (HIRI) was instituted, including members from the U.S. Department of Energy, the Environmental Protection Agency, and National Aeronautics and Space Administration. HIRI suggested the use of light-colored, reflective roofing materials and pavements, in addition to the planting of trees and vegetation (Solecki et al. 2005). Because the mineral-based surfaces (asphalt, rooftops) commonly used in urban environments have a low albedo and store heat, preserving and planting trees can provide a major benefit. Trees shade the ground, reducing incoming radiation and also promoting evapotranspiration. A Brown University study suggests that a well-placed 25-foot tree can reduce heating and cooling costs for a typical household by 8 to 10 percent, i.e. $10 to $25 a month. Furthermore, a national tree planting initiative could save the country $1 billion per year in heating and cooling expenses, thereby reducing fossil fuels burned, carbon dioxide emitted, and foreign oil dependency (Brown University 2010). Another study, done in Providence, Rhode Island, one of the nation's most populous states, showed that street trees absorb some 29 tons of pollution and prevent 12 tons of pollution each year, producing $194,334 in net yearly air quality benefits. Planting trees in Providence will improve citizens' health while bringing the city closer to meeting federal Clean Air Act standards for hazardous air pollutant (Brown University 2010).

4.3 Significance and Future Directions

This study aimed to reduce the lack of literature on small to midsized cities which exhibit significant UHI effects, as proved in this research. Results showed that the smaller study area of Auburn-Opelika consistently exhibited a higher UHI intensity during the day than the larger study area of Birmingham, increasing potential heat-related health risks to Auburn-Opelika residents. This study also provides scientific information for consideration by city planners in mitigating the potential risks and improving the sustainability of urban areas, as well as residents' quality of living.

Temperature is one of the most influential atmospheric variables, directly affecting physical and biological processes (Wu and Li 2013). The interaction between surface temperatures and near surface atmospheric temperatures remains one of the most unstudied relationships in remotely-sensed UHI literature (Voogt and Oke 2003). UHI's contribution to increased urban surface temperatures and its effect on climate change has been proven. Research on China indicates that the urban heat island effect has contributed to 1/5–1/3 of the total warming in China over the past five decades (Zhao et al. 2013). Additional research on the United States indicates that surface air temperature over the entire US increased 0.27° C over the past century, owing to urbanization and land cover changes (Kalnay and Cai 2003).

These disturbing findings are confirmed in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) which states that anthropogenic influences have very likely contributed to changes in the frequency of daily temperature extremes and may have more than doubled the probability of heat wave occurrences in Asia, Australia, and Europe. More frequent hot and fewer cold temperature extremes are now expected over most terrestrial areas on both daily and seasonal timescales, increasing the frequency and duration of heat waves. These are extremely significant factors; afterall, UHIs increase local surface and atmospheric temperatures and are further intensified by heat waves (IPCC 2014). This research contributes to the knowledge of urban climate and aids in mitigation procedures for Auburn-Opelika, AL and Birmingham, AL, other urban areas.

Due to time and budget limitations, a number of significant factors were not considered for this study. First, the study period only covers 1 March 2014 to 31 August 2014, excluding the remaining six months of the year, which would reveal additional UHI trends. Second, the instruments used for this study have an accuracy of 0.5°C, limiting the analysis of the micro environmental temperature changes. Finally, the IDW interpolations were limited by the number of data points (iButtons) in each study area. Future studies would benefit from a complete years' worth of hourly temperature data, using instruments with a higher accuracy and density of temperature data.

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Appendix A: Average Monthly daytime and nighttime temperature Data

March daytime average temperatures for Birmingham, AL

Site Name	Site Type	Mar. Day Avg. Temp.
Old Serene Drive	Rural	55.97
Blackwell Dr.	Rural	56.78
Regions 5th Ave N.	Urban	57.27
Castle Heights	Rural	57.63
Littleton Sayre/Old HWY 78	Rural	57.89
Bob Hood Branch	Rural	57.93
County Road 6	Rural	57.96
Bessemer	Urban	58.02
34th St. South and 8th Alley	Peri-Urban	58.14
Firetower Road	Rural	58.19
Kelly Ingram Park	City Park	58.22
Winston Way/Churchill Circle	Peri-Urban	58.85
2nd Street W.	Peri-Urban	59.23
31st St. South and 3rd Ave South	Urban	59.55
Linn Park	City Park	59.56
Lock 17	Rural	59.75
Hoover Mall	Urban	59.77
Pull-A-Part	Urban	60.93

March nighttime average temperatures for Birmingham, AL

Site Name	Site Type	Mar. Night Avg. Temp.
Littleton Sayre	Rural	44.62
Lock 17	Rural	44.87
Castle Heights	Rural	44.89
Old Serene Drive	Rural	45.88
Parkwood Rd.	Rural	46.68
Firetower Road	Rural	47.24
Bob Hood Branch	Rural	47.49
Blackwell Dr.	Rural	47.74
Winston Way/Churchill Circle	Peri-Urban	47.75
2nd Street W.	Peri-Urban	49.29
Pull-A-Part	Urban	49.37
Hoover Mall	Urban	49.49
34th St. South and 8th Alley	Peri-Urban	50.01
31st St. South and 3rd Ave South	Urban	50.56
Bessemer	Urban	51.58
Kelly Ingram Park	City Park	51.79
Linn Park	City Park	52.02
Regions	Urban	52.42

March daytime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Mar. Avg. Day Temp.
Pepperwood Trail	Rural	58.42
Co Rd. 161	Rural	59.32
White Road	Rural	59.71
Chewacla	Rural	59.83
Co Rd. 060	Rural	60.09
Southern Union	Urban	60.39
I-85	Peri-urban	60.91
Lee Rd. 110	Rural	61.46
Fountain	Urban	61.52
Samford Park	City Park	61.61
Green Street	Peri-urban	61.70
Village Mall	Urban	61.76
Ave D and 8th St.	Peri-urban	62.06
Toomers Corner	Urban	62.16
Oak_Darden St.	Peri-urban	62.39
Irish pub	Urban	62.96
Tigertown	Urban	65.26
AU Hotel	Urban	67.62

March nighttime average temperatures for Auburn-Opelika

Site Name	Site Type	Mar. Avg. Night Temp.
Co Rd. 161	Rural	46.19
Co Rd. 060	Rural	48.20
Oak_Darden St.	Peri-urban	48.31
White Road	Rural	48.62
Andersons	Peri-urban	48.99
Chewacla	Rural	49.16
I-85	Peri-urban	49.20
Ave D and 8th St.	Peri-urban	49.42
Lee Rd. 110	Rural	49.52
Tigertown	Urban	49.54
Pepperwood Trail	Rural	50.05
Village Mall	Urban	50.09
Irish pub	Urban	50.23
AU Hotel	Urban	50.36
Samford Park	City Park	50.90
Southern Union	Urban	51.01
Fountain	Urban	51.21
Toomers Corner	Urban	51.74

April daytime average temperatures for Birmingham, AL

Site Name	Site Type	Apr. Avg. Day Temp.
Old Serene Drive Location	Rural	65.60
Regions	Urban	67.36
Bob Hood Branch	Rural	67.64
Blackwell Dr.	Rural	67.79
Linn Park	City Park	68.55
Bessemer	Urban	68.64
County Rd. 6	Rural	68.82
34th Street South and 8th Alley	Peri-urban	68.93
Littleton Sayre	Rural	68.95
Castle Heights	Rural	69.04
Firetower Road	Rural	69.11
Winston Way/Churchill Circle	Peri-urban	69.12
Kelly Ingram Park	City Park	69.19
Lock 17	Rural	69.96
2nd Street W.	Peri-urban	70.28
31st St. South and 3rd Ave South	Urban	70.72
Hoover Mall	Urban	70.77
Pull-A-Part	Urban	72.51

April nighttime average temperatures for Birmingham, AL

Site Name	Site Type	Apr. Avg. Night Temp.
Littleton Sayre	Rural	54.67
Castle Heights	Rural	55.24
Lock 17	Rural	55.33
Old Serene Drive Location	Rural	56.16
Bob Hood Branch	Rural	56.65
Parkwood Rd.	Rural	57.24
Firetower Road	Rural	57.40
Winston Way/Churchill Circle	Peri-urban	57.91
Blackwell Dr.	Rural	58.05
Hoover Mall	Urban	59.45
2nd Street W.	Peri-urban	59.51
Pull-A-Part	Urban	59.85
34th Street South and 8th Alley	Peri-urban	60.07
31st St. South and 3rd Ave South	Urban	60.98
Bessemer	Urban	61.59
Linn Park	City Park	61.84
Kelly Ingram Park	City Park	61.91
Regions	Urban	62.27

April daytime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Apr. Avg. Day Temp.
Pepperwood Trail	Rural	65.96
Co Rd. 161	Rural	67.49
White Road	Rural	68.05
Chewacla	Rural	68.06
Co Rd. 060	Rural	68.63
Southern Union	Urban	69.32
I-85	Peri-urban	69.71
Ave D and 8th St.	Peri-urban	69.96
Samford Park	City Park	70.10
Lee Rd. 110	Rural	70.10
Toomers Corner	Urban	70.82
Andersons	Peri-urban	70.90
Village Mall	Urban	70.92
Fountain	Urban	71.04
Oak_Darden St.	Peri-urban	71.34
Irish pub	Urban	72.47
Tigertown	Urban	74.99
AU Hotel	Urban	77.35

April nighttime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Apr. Avg. Night Temp.
Co Rd. 161	Rural	54.57
Co Rd. 060	Rural	56.36
Oak_Darden St.	Peri-urban	56.47
White Road	Rural	56.62
I-85	Peri-urban	56.79
Chewacla	Rural	56.84
Andersons	Peri-urban	57.08
Ave D and 8th St.	Peri-urban	57.60
Lee Rd. 110	Rural	57.72
Tigertown	Urban	57.76
Pepperwood Trail	Rural	58.15
Irish pub	Urban	58.46
Village Mall	Urban	58.64
AU Hotel	Urban	58.71
Samford Park	City Park	58.99
Fountain	Urban	59.16
Southern Union	Urban	59.33
Toomers Corner	Urban	60.03

May daytime average temperatures for Birmingham, AL

Site Name	Site Type	May Day Avg. Temp.
Old Serene Dr.	Rural	71.47
Bob Hood Branch	Rural	73.01
Linn Park	City Park	75.36
Littleton Sayre	Rural	75.37
Regions	Urban	76.07
Blackwell Dr.	Rural	76.64
Winston Way/Churchill Circle	Peri-Urban	76.88
Kelly Ingram Park	City Park	77.01
Castle Heights	Rural	77.20
Lock 17	Peri-Urban	77.55
2nd Street West	Peri-Urban	77.88
Bessemer	Urban	78.15
Firetower Road	Rural	78.24
County Road 6	Rural	78.35
Hoover Mall	Urban	79.50
31st St. & 3rd Ave. S.	Urban	79.80
Pull a part	Urban	82.02

May average nighttime temperatures for Birmingham, AL

Site Name	Site Type	May Night Avg. Temp.
Castle Heights	Rural	61.45
Littleton Sayre	Rural	62.11
Old Serene Dr.	Rural	62.50
Lock 17	Peri-Urban	62.51
Bob Hood Branch	Rural	62.79
Firetower Road	Rural	63.38
County Road 6	Rural	63.53
Blackwell Dr.	Rural	63.67
Winston Way/Churchill Circle	Peri-Urban	64.05
Hoover Mall	Urban	67.34
2nd Street West	Peri-Urban	67.54
Pull a part	Urban	67.70
Bessemer	Urban	68.34
31st St. & 3rd Ave. S.	Urban	68.83
Linn Park	City Park	69.30
Kelly Ingram Park	City Park	69.88
Regions	Urban	70.23

May average daytime temperatures for Auburn-Opelika, AL

Site Name	Site Type	May Day Avg. Temp.
Pepperwood Trail	Rural	73.30
Co_Rd_161	Rural	73.96
White Road	Rural	76.31
Co Rd 060	Rural	76.39
Chewacla	Rural	76.61
Ave D and 8th Street	Peri-Urban	77.95
I-85	Peri-urban	79.24
Samford Park	Urban	79.68
Andersons	Peri-Urban	80.20
Lee Road 110	Rural	80.34
Toomers Corner	Urban	80.37
Village Mall	Urban	81.03
Southern Union	Urban	81.20
Irish Pub	Urban	82.25
Oak Court and Darden St.	Peri-Urban	83.47
Tigertown	Urban	87.01
AU Hotel	Urban	88.79

May average nighttime temperatures for Auburn-Opelika, AL

Site Name	Site Type	May Night Avg. Temp.
Co_Rd_161	Rural	62.52
Oak Court and Darden St.	Peri-Urban	63.38
Chewacla	Rural	63.53
Co Rd 060	Rural	64.09
Pepperwood Trail	Rural	64.21
White Road	Rural	64.45
Lee Road 110	Rural	64.57
Andersons	Peri-Urban	65.09
I-85	Peri-urban	65.66
Tigertown	Urban	65.94
Ave D and 8th Street	Peri-Urban	66.29
Southern Union	Urban	66.52
Samford Park	Urban	66.59
Village Mall	Urban	67.32
Irish Pub	Urban	67.35
AU Hotel	Urban	67.65
Toomers Corner	Urban	68.91

June daytime average temperatures for Birmingham, AL

Site Name	Site Type	Jun. Day Avg. Temp.
Old Serene Dr.	Rural	77.11
Bob Hood Branch	Rural	77.92
Linn Park	City Park	80.62
Winston Way/Churchill circle	Peri-Urban	81.98
Littleton Sayre	Rural	82.14
Kelly Ingram Park	City Park	82.18
Blackwell Dr.	Rural	82.88
Regions	Urban	82.94
Castle Heights	Rural	83.00
Lock 17	Peri-Urban	83.37
2nd Street West	Peri-Urban	83.95
Firetower Road	Rural	84.26
Bessemer	Urban	84.32
County Road 6	Rural	85.02
31st St. & 3rd Ave. S.	Urban	85.64
Hoover Mall	Urban	87.91
Pull a part	Urban	87.93

June nighttime average temperatures for Birmingham, AL

Site Name	Site Type	Jun. Night Avg. Temp.
Castle Heights	Rural	70.39
Bob Hood Branch	Rural	70.69
Old Serene Dr.	Rural	71.03
Lock 17	Peri-Urban	71.53
Littleton Sayre	Rural	71.61
Blackwell Dr.	Rural	71.84
Winstn way_churchll_crcle	Peri-Urban	71.98
Firetower Road	Rural	72.54
County Road 6	Rural	72.72
Pull_a_part	Urban	74.78
2nd Street West	Peri-Urban	74.86
Linn Park	City Park	75.16
Hoover Mall	Urban	75.51
31st St. & 3rd Ave. S.	Urban	75.56
Bessemer	Urban	75.61
Kelly Ingram Park	City Park	76.01
Regions	Urban	76.26

June daytime average temperatures for Auburn-Opelika

Site Name	Site Type	Jun. Day Avg. Temp.
Pepperwood Trail	Rural	78.40
Co_Rd_161	Rural	79.71
White Road	Rural	81.67
Chewacla	Rural	81.69
Co Rd 060	Rural	81.86
Ave D and 8th Street	Peri-Urban	84.31
I-85	Peri-urban	84.48
Lee Road 110	Rural	84.81
Samford Park	Urban	85.00
Andersons	Peri-Urban	85.50
Toomers Corner	Urban	85.89
Village Mall	Urban	86.01
Southern Union	Urban	86.74
Irish Pub	Urban	87.47
Oak Court and Darden St.	Peri-Urban	88.28
Tigertown	Urban	91.42
AU Hotel	Urban	93.80

June nighttime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Jun Night Avg. Temp.
Co_Rd_161	Rural	70.89
Oak Court and Darden St.	Peri-Urban	71.66
Pepperwood Trail	Rural	71.66
Co Rd 060	Rural	71.69
Chewacla	Rural	72.24
White Road	Rural	72.29
Lee Road 110	Rural	72.60
I-85	Peri-urban	72.79
Andersons	Peri-Urban	73.02
Ave D and 8th Street	Peri-Urban	73.62
Tigertown	Urban	73.70
Southern Union	Urban	73.71
Samford Park	Urban	73.87
Irish Pub	Urban	74.73
Village Mall	Urban	74.88
AU Hotel	Urban	75.12
Toomers Corner	Urban	75.95

July daytime temperatures for Birmingham, AL

Site Name	Site Type	Jul. Day Avg. Temp.
Old Serene Dr.	Rural	78.75
Bob Hood Branch	Rural	80.13
Linn Park	City Park	81.66
Littleton Sayre	Rural	82.78
Kelly Ingram Park	City Park	83.08
Blackwell Dr.	Rural	83.33
Regions	Urban	83.51
Castle Heights	Rural	83.92
Winstn way_churchll_crcle	Peri-Urban	84.09
Lock 17	Peri-Urban	84.40
2nd Street West	Peri-Urban	84.95
Firetower Road	Rural	85.36
Bessemer	Urban	85.39
County Road 6	Rural	85.66
31st St. & 3rd Ave. S.	Urban	86.25
Hoover Mall	Urban	87.99
Pull_a_part	Urban	88.37

July nighttime average temperatures for Birmingham, AL

Site Name	Site Type	Jul. Day Avg. Temp.
Castle Heights	Rural	69.93
Old Serene Dr.	Rural	70.80
Littleton Sayre	Rural	70.93
Lock 17	Peri-Urban	71.16
Blackwell Dr.	Rural	71.58
Bob Hood Branch	Rural	71.69
County Road 6	Rural	72.31
Firetower Road	Rural	72.59
Winstn way_churchll_crcle	Peri-Urban	73.17
2nd Street West	Peri-Urban	75.64
Pull_a_part	Urban	75.72
Linn Park	City Park	75.99
31st St. & 3rd Ave. S.	Urban	76.58
Bessemer	Urban	76.71
Hoover Mall	Urban	77.11
Kelly Ingram Park	City Park	77.12
Regions	Urban	77.15

July average daytime temperatures for Auburn-Opelika, AL

Site Name	Site Type	Jul. Day Avg. Temp.
Pepperwood Trail	Rural	78.60
Co_Rd_161	Rural	79.59
Chewacla	Rural	81.78
Co Rd 060	Rural	81.98
White Road	Rural	82.11
Ave D and 8th Street	Peri-Urban	84.11
Lee Road 110	Rural	84.87
Samford Park	Urban	84.93
I-85	Peri-urban	85.22
Andersons	Peri-Urban	85.43
Southern Union	Urban	85.63
Toomers Corner	Urban	85.68
Village Mall	Urban	86.21
Irish Pub	Urban	87.23
Oak Court and Darden St.	Peri-Urban	88.06
Tigertown	Urban	91.33
AU Hotel	Urban	93.42

July nighttime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Jul. Night Avg. Temp.
Co_Rd_161	Rural	70.84
Co Rd 060	Rural	71.96
Pepperwood Trail	Rural	71.99
Oak Court &Darden St.	Peri-Urban	72.27
White Road	Rural	72.58
Chewacla	Rural	72.84
Lee Road 110	Rural	73.28
I-85	Peri-urban	73.45
Andersons	Peri-Urban	73.73
Tigertown	Urban	74.23
Southern Union	Urban	74.28
Samford Park	Urban	74.34
Ave D and 8th Street	Peri-Urban	74.57
Village Mall	Urban	75.22
Irish Pub	Urban	75.43
AU Hotel	Urban	75.61
Toomers Corner	Urban	76.41

August daytime average temperatures for Birmingham, AL

Site Name	Site Type	Aug. Day Avg. Temp.
Old Serene Dr.	Rural	82.29
Bob Hood Branch	Rural	82.52
Littleton Sayre	Rural	84.20
Linn Park	City Park	84.64
Regions	Urban	85.87
Blackwell Dr.	Rural	86.28
Kelly Ingram Park	City Park	86.46
Castle Heights	Rural	87.12
Winstn way_churchll_crcle	Peri-Urban	87.21
Firetower Road	Rural	87.50
Lock 17	Peri-Urban	88.15
Bessemer	Urban	88.22
2nd Street West	Peri-Urban	88.49
Hoover Mall	Urban	89.32
31st St. & 3rd Ave. S.	Urban	89.42
County Road 6	Rural	90.08
Pull_a_part	Urban	91.43

August nighttime temperatures for Birmingham, AL

Site Name	Site Type	Aug. Night Avg. Temp.
Castle Heights	Rural	70.44
Littleton Sayre	Rural	71.33
Bob Hood Branch	Rural	71.62
Old Serene Dr.	Rural	71.93
Lock 17	Peri-Urban	72.28
Firetower Road	Rural	72.64
Blackwell Dr.	Rural	72.87
County Road 6	Rural	73.31
Winstn way_churchll_crcle	Peri-Urban	73.54
2nd Street West	Peri-Urban	76.47
Pull_a_part	Urban	76.60
Linn Park	City Park	77.34
Hoover Mall	Urban	77.61
31st St. & 3rd Ave. S.	Urban	77.66
Bessemer	Urban	77.87
Kelly Ingram Park	City Park	78.59
Regions	Urban	78.78

August daytime average temperatures for Auburn-Opelika, AL

Site Name	Site Type	Aug. Day Avg. Temp.
Co_Rd_161	Rural	80.84
Pepperwood Trail	Rural	81.04
White Road	Rural	83.14
Co Rd 060	Rural	83.90
Chewacla	Rural	84.70
Ave D and 8th Street	Peri-Urban	85.03
I-85	Peri-urban	86.98
Samford Park	Urban	87.47
Toomers Corner	Urban	87.67
Village Mall	Urban	88.31
Southern Union	Urban	88.39
Andersons	Peri-Urban	88.67
Lee Road 110	Rural	88.85
Irish Pub	Urban	90.42
Oak Court and Darden St.	Peri-Urban	90.85
Tigertown	Urban	93.99
AU Hotel	Urban	96.84

August average nighttime temperatures for Auburn-Opelika, AL

Site Name	Site Type	Aug. Night Avg. Temp.
Co_Rd_161	Rural	70.84
Oak Court and Darden St.	Peri-Urban	71.90
Co Rd 060	Rural	72.06
White Road	Rural	72.20
Chewacla	Rural	72.49
Pepperwood Trail	Rural	72.78
Lee Road 110	Rural	73.27
I-85	Peri-urban	73.51
Andersons	Peri-Urban	73.74
Ave D and 8th Street	Peri-Urban	74.31
Southern Union	Urban	74.50
Tigertown	Urban	74.50
Samford Park	Urban	74.68
Village Mall	Urban	75.28
Irish Pub	Urban	75.60
AU Hotel	Urban	75.94
Toomers Corner	Urban	76.97

Appendix B: LST and atmospheric temperature Data

26 March 2014 LST vs. atmospheric temperatures (AT) for Birmingham, AL

Site Name	Site Type	26 Mar LST in °F	26 Mar. Atmospheric temp. in °F	LST-AT °F
Pull-A-Part	Urban	73.40	48.98	24.42
31st. & 3rd Ave. S.	Urban	75.20	47.99	27.21
Bessemer	Urban	75.20	44.41	30.79
Hoover Mall	Urban	75.20	47.34	27.86
Regions	Urban	75.20	45.19	30.01
Kelly Ingram Park	City Park	66.20	45.28	20.92
Linn Park	City Park	68.00	53.84	14.16
2nd St. W.	Peri-Urban	73.40	49.23	24.17
34th St. and 8th Alley	Peri-urban	71.60	47.71	23.89
Lock 17	Peri-Urban	62.60	53.79	8.81
Wnstn Way&Chrchl Crcle	Peri-urban	62.60	54.16	8.44
Blackwell Dr.	Rural	60.80	47.11	13.69
Bob Hood Branch	Rural	60.80	48.89	11.91
Castle Heights	Rural	57.20	46.36	10.84
Firetower Rd.	Rural	59.00	45.01	13.99
Littleton Sayre	Rural	57.20	48.05	9.15
Old Serene Dr.	Rural	60.80	46.07	14.73
Parkwood Rd.	Rural	62.60	46.12	16.48

16 July 2014 LST vs. atmospheric temperatures (AT) for Birmingham, AL

Site Name	Site Type	16 Jul. LST in °F	16 Jul. Atmospheric temp. in °F	LST-AT °F
Pull-A-Part	Urban flat	100.40	83.56	16.84
31st. & 3rd Ave. S.	Urban	104.00	79.22	24.78
Regions	Urban	105.80	80.95	24.85
Bessemer	Urban	105.80	81.84	23.96
Hoover Mall	Urban	107.60	81.95	25.65
Kelly Ingram Park	City Park	95.00	76.95	18.05
Linn Park	City Park	93.20	83.76	9.44
Wnstn Way&Chrchl Crcle	Peri-urban	86.00	80.41	5.59
34th St. and 8th Alley	Peri-urban	93.20	79.65	13.55
2nd St. W.	Peri-urban	96.80	78.65	18.15
Lock 17	Peri-urban	89.60	82.62	6.98
Blackwell Dr.	Rural	84.20	80.94	3.26
Bob Hood Branch	Rural	78.80	77.60	1.20
Old Serene Dr.	Rural	80.60	70.63	9.97
Firetower Rd.	Rural	84.20	79.36	4.84
Parkwood Rd.	Rural	89.60	79.48	10.12
Littleton Sayre	Rural	80.60	79.86	0.74
Castle Heights	Rural	80.60	79.27	1.33

6 May 2014 LST vs. atmospheric temperature (AT) for Auburn-Opelika, AL

Site Name	Site Type	6 May. LST in °F	6 May. Atmospheric temp. in °F	LST-AT °F
I- 85	Urban	95.00	81.62	13.38
Irish Pub	Urban	104.00	93.12	10.88
Fountain	Urban	105.80	90.56	15.24
Tigertown	Urban	113.00	88.30	24.70
Village Mall	Urban	109.40	83.80	25.60
Southern Union	Urban	107.60	85.38	22.22
AU Hotel	Urban	105.80	94.43	11.37
Toomer's Corner	Urban	107.60	78.56	29.04
Samford Park	City Park	100.40	83.99	16.41
Ave. D. & 8th St.	Perri-Urban	91.40	80.96	10.44
Oak Ct and Darden St	Perri-Urban	95.00	87.94	7.06
Green St.	Perri-Urban	96.80	84.13	12.67
County Rd. 161	Rural	82.40	78.15	4.25
Lee Rd. 110	Rural	87.80	96.32	-8.52
White Rd.	Rural	84.20	79.59	4.61
Pepperwood Trail	Rural	82.40	78.74	3.66
County Rd. 060	Rural	87.80	78.13	9.67
Chewacla	Rural	80.60	79.13	1.47

22 May 2014 LST vs. atmospheric temperature (AT) for Auburn-Opelika, AL

Site Name	Site Type	6 May. LST in °F	6 May. Atmospheric temp. in °F	LST-AT °F
Irish Pub	Urban	100.40	89.98	10.42
Fountain	Urban	102.20	89.34	12.86
Tigertown	Urban	107.60	90.10	17.50
Village Mall	Urban	104.00	85.82	18.18
Southern Union	Urban	104.00	86.61	17.39
AU Hotel	Urban	102.20	95.26	6.94
Toomer's Corner	Urban	104.00	85.25	18.76
Samford Park	City Park	95.00	89.19	5.81
I- 85	Urban	95.00	85.33	9.67
Ave. D. & 8th St.	Perri-Urban	91.40	86.79	4.61
Oak Ct and Darden St	Perri-Urban	93.20	91.87	1.33
Green St.	Perri-Urban	93.20	91.21	1.99
County Rd. 161	Rural	82.40	82.64	-0.24
Lee Rd. 110	Rural	86.00	92.96	-6.96
White Rd.	Rural	84.20	85.21	-1.01
Pepperwood Trail	Rural	82.40	82.34	0.06
County Rd. 060	Rural	86.00	84.65	1.35
Chewacla	Rural	80.60	83.30	-2.70