Spring 4-29-2018

An Analysis of Urban Heat Islands in Kentucky

Logan Mitchell
Western Kentucky University, logan.mitchell818@topper.wku.edu

Recommended Citation

Mitchell, Logan, "An Analysis of Urban Heat Islands in Kentucky" (2018). *Honors College Capstone Experience/Thesis Projects.* Paper 730.
https://digitalcommons.wku.edu/stu_hon_theses/730

AN ANALYSIS OF URBAN HEAT ISLANDS IN KENTUCKY

A Capstone Project Presented in Partial Fulfillment
of the Requirements for the Degree Bachelor of Science
with Honors College Graduate Distinction at
Western Kentucky University

By
Logan T. Mitchell
April 2018

*****

CE/T Committee:
Professor Rezaul Mahmood, Chair
Professor Gregory Goodrich
Professor Audra Jennings

I dedicate this to my parents, my teachers, and my professors.

Their shared belief in my education made this possible.

ACKNOWLEDGEMENTS

I recognize and thank my advisor, Dr. Rezaul Mahmood, for his contributions and guidance of this project. I also thank Dr. Gregory Goodrich, Dr. Stuart Foster, and Dr. Audra Jennings for their comments regarding both my thesis paper and defense presentation. I would like to thank the WKU Office of Research and Creative Activity's FUSE Program, the Mahurin Honors College, the Ogden College of Science and Engineering, and the Department of Geography and Geology for their generous support. Finally, a very special thanks to Mr. Kyle Thompson and Ms. Dolly Na-Yemeh for use of their land cover aerial photographs.

ABSTRACT

The purpose of this research is to increase understanding of the Urban Heat Island (UHI) effect in Kentucky by studying its three largest cities: Louisville, Lexington, and Bowling Green. By examining the UHIs of these three cities, two major attributes can be determined: if there is a relationship between the size of the city by population and the UHI magnitude, and if UHI magnitude follows any diurnal and/or seasonal cycles.

Data was collected from weather stations within the three major cities, as well as from weather stations located in the rural areas surrounding them. The length of the time series being considered is from 12/01/2009 through 11/30/2014. Urban stations are from the Automated Surface Observing System (ASOS) network, which is a quality-controlled weather data collection network operated by the National Weather Service (NWS). Rural stations are from the Kentucky Mesonet (KYMN), which is a mesoscale weather and climate observing network operated by the Kentucky Climate Center at WKU. This is the only world-class research-grade network to operate in Kentucky.

Daily maximum and minimum temperature data, as well as monthly maximum and minimum temperature data were obtained for each of the weather stations. The pairwise difference between urban and rural observations was calculated, resulting in the UHI magnitude for each city. The analysis and visualization were conducted using MATLAB, a sophisticated computing software. The resulting graphs showed that a correlation between size of city and UHI magnitude does exist in Kentucky, as the largest city has both diurnal and seasonal cycles, Lexington has a weak seasonal cycle, and Bowling Green has no strong UHI cycles.

VITA

EDUCATION

BS in Meteorology **May 2018**
Western Kentucky University – Bowling Green, KY
Minors: Water Resources, GIS, and Mathematics
Honors Thesis: *An Analysis of Urban Heat Islands in Kentucky*
Committee: Rezaul Mahmood, Gregory Goodrich, Audra Jennings0

BA in Chinese **May 2018**
Western Kentucky University – Bowling Green, KY

Gatton Academy (*Honors with Distinction)* – Bowling Green, KY **May 2014**
Conner High School (*Summa Cum Laude*) – Hebron, KY **May 2014**

PROFESSIONAL EXPERIENCE

QA/QC Student Operator **2014 to 2018**
Kentucky Mesonet, Western Kentucky University

Intern **2014 to 2018**
Center for HumaN Geo-Environmental Studies (CHNGES), Western Kentucky University

Intern **2013 to 2014**
Hoffman Environmental Research Institute, Western Kentucky University

HONORS AND AWARDS

First Place (Natural Sciences Undergraduate Poster Session 51) **Apr 2016**
46th Annual WKU Student Research Conference.

First Place (Poster Session I, Gatton Session V) **Mar 2014**
44th Annual WKU Student Research Conference.

FUSE Grant (Honors Thesis Research) **2015 to 2017**
Office of Research and Creative Activity, Western Kentucky University.

Gatton Academy Alumni Research Grant (Hydrology Research) **2014 to 2018**
Office of Scholar Development, Western Kentucky University.

Research Internship Grant (Hydrology Research) **2013 to 2014**
Carol Martin Gatton Academy of Mathematics and Science.

John and Jacque Hughes Jarve Scholarship (Storm Chase) **May 2016**
Mahurin Honors College, Western Kentucky University.

PROFESSIONAL MEMBERSHIPS

- American Meteorological Society (AMS)
- National Weather Association (NWA)
- American Water Works Association (AWWA)
- World Environment Federation (WEF)

INTERNATIONAL EXPERIENCE

WKU Iceland: Perspectives and Realities of Climate Change **Summer 2017**
Akureyri and Reykjavik, Iceland.

North China Electric Power University HSK Summer Program **Summer 2015**
Beijing and Shanghai, China.

Confucius Institute Summer Bridge **Summer 2014**
Beijing and Changchun, China.

Gatton Academy Italy Experience **Winter 2014**
Rome and Florence, Italy.

Gatton Academy Harlaxton Experience **Summer 2013**
Grantham and London, United Kingdom.

Gatton Academy Greece Experience **Winter 2013**
Athens and Thessaloniki, Greece.

CONFERENCE PRESENTATIONS

“An Analysis of Urban Heat Islands in Kentucky,” 97th Annual American Meteorological Society Meeting. Seattle, WA. January 2017.

“A Comparison of Air Temperatures at Irrigated and Non-Irrigated Sites in Andalucía, Spain,” 98th Annual American Meteorological Society Meeting. Austin, TX. January 2018.

“An Analysis of the Lost River Karst Aquifer’s Hydrometeorological Response to Storm Events,” 21st Annual National Cave and Karst Management Symposium. Cave City, KY. October 2015.

“A Policy Critique of China’s National Action Plan of Air Pollution Control in the Jingjinji Area,” 3rd Annual WKU Chinese Flagship Symposium. Bowling Green, KY. April 2018.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Urban Heat Island (UHI) is a phenomenon whereby the temperatures of urban areas are effectively warmer than the surrounding rural areas (Baik et al. 2007, Han and Baik 2008, Kalnay 2003, Loridan 2012, Mahmood 2014). This mainly occurs because cities trap more heat energy than rural land uses. Albedo is the proportion of solar irradiance that is reflected off a surface. Urban surfaces (such as blacktop roads), tend to have much lower albedo than rural surfaces (such as bare soils, grasses, crops, and forests). This results in urban areas absorbing more incoming solar shortwave radiation, increasing the heat energy of the system. Most factories and power plants are also located in or near urban centers. These industrial facilities usually burn fossil fuels, which results in the release of large quantities of greenhouse gases into the atmosphere. Greenhouse gases reflect upward longwave radiation at various wavelengths back to the surface, which traps the heat energy within the system.

Urbanization and industrialization bring with them many adverse impacts to human health, including heat stress and smog (Huang et al. 2008). Heat stress can cause heat stroke, heat exhaustion, and dizziness. Smog can cause coughing, lung damage, and reduced visibility. Thus, the determination of UHI magnitude and seasonality will aid public health in predicting when these environmental factors are most likely to be detrimental. It also grants the opportunity for city planners and engineers to reduce the effects of UHI by strategically locating industrial facilities and developing high albedo surface materials.

An improved understanding of UHI can also help with numerical weather prediction of urban areas at the local scale, especially for convection and air quality.

With better models, operational meteorologists will be able to make more accurate forecasts. This, in turn, allows for emergency managers to more effectively respond to extreme weather events. Overall, quantifying UHI has enormous benefits for the economy, human welfare, and the environment.

OBJECTIVES

The overarching goal of this research is to increase understanding of UHI in Kentucky by studying its three largest cities: Louisville, Lexington, and Bowling Green, respectively. Two major objectives have been set to help the project achieve this goal:

1) To determine if a positive correlation between city population size and UHI magnitude exists. If this hypothesis holds true, then it would be expected that Louisville would have the greatest UHI magnitude, then followed by Lexington, then by Bowling Green.
2) To determine if the UHI of Kentucky follow diurnal and seasonal cycles. This will reveal the time of day and season where UHI magnitude is the greatest and when it is the weakest. These cycles assist in further quantifying UHI. Based on the findings of many other studies, strong UHI signals would be given by locations that have greatest magnitudes at night and during the Summer.

LITERATURE REVIEW

In analyzing the causes of global warming, Karl et al. (1993) found that cloud cover was increasing in many parts of the world, resulting in decreases in diurnal temperature range (DTR). DTR is simply the difference between the maximum daily temperature and the minimum daily temperature. They postulated that DTR decreases could be due to increases in greenhouse gas emissions, increases in aerosol particles, and some natural climatic variability. Since most power generation and heavy industry is concentrated in cities, urban areas were thought to greatly contribute to climate change.

While studying global temperature trends, Easterling et al. (1997) found that urbanization doesn't influence DTR decreases as much as previously thought. They concluded that urban land use contributions to global or hemispheric warming were negligible, but that they could still have large impacts on local forcings.

In analyzing the impacts of urbanization and land use change on climate, Kalnay and Cai (2003) found that land use changes could account for up to half of the decrease in DTR. By including land use changes in their models (as opposed to just urbanization) their calculated mean surface warming per century value doubled. This shows that although understanding UHI and other urbanization processes are critical to modelling climate change, this knowledge must be paired with land use and land cover, which many of the UHI studies discussed below have successfully integrated into their methods.

In his review of the progress of urban climatology research from 1980 to 2000, Arnfield (2003) noted that there are many diverse types of UHIs. UHI classification will vary by the remote sensing system employed, as well as what target features were being sensed. It is therefore important to thoroughly explaining what parameters were used to quantify a certain UHI, and only compare with other UHI studies that use those same parameters. While this study will preclude any remote sensing techniques, it should be noted that the UHI magnitude of each city will be calculated the same way (using pairwise temperature differences), thus allowing for the UHIs to be compared.

During his comprehensive study of UHIs within the contiguous United States, Peterson (2003) used only urban and rural stations that had high data quality and few differences in latitude, elevation, observation times, and instrumentation. He found that, for 40 clusters of 289 stations from 1989 to 1991, no statistically significant difference existed between urban and rural sites. He suggested that this could be due to microscale impacts dominating over the mesoscale UHI, along with many urban stations being located within relatively cooler urban parks. Although metadata for each site used in this project was thoroughly analyzed to select only the best stations for each comparison, some major differences will exist between the urban and rural sites used. Since this currently cannot be avoided for examining Kentucky's UHI, the reasoning behind why each site was chosen and the effects that differences between urban and rural sites might have on the results will be discussed in-depth later in the study.

By comparing temperature values recorded by Oklahoma Mesonet and Cooperative Observer Network (COOP) weather stations, Fiebrich and Crawford (2009) uncovered that large disparities can exist between differently-operated weather networks, which is especially true for the use of manual vs. automated collection systems. In some cases, the temperature difference between two spatially-similar sites could be as high as 0.5 °C, with 55% of paired observations differing by at least 1 °C. The authors suggest that more networks move towards automated observations, especially in light of the regular server errors that occur in manual systems. This issue is somewhat alleviated through the project’s use of the Automated Surface Observing System (ASOS) network, which is automated, has better temporal resolution, and higher data quality that COOP stations. However, many of the authors’ other points regarding comparing differing weather networks are still valid and should be taken into consideration when viewing the results of the pairwise differences.

In a study of South Korea’s six largest cities, Kim and Baik (2004) found that larger cities (by population) tend to have greater UHI magnitudes than smaller cities. However, this was complicated by the fact that some of the cities were coastal, while others were located further inland. It was determined that coastal cities tend to have smaller UHI magnitudes than inland cities, and that this factor is more influential to UHI magnitude than population size. One of the main goals of this project is to determine if such a correlation between city size and UHI magnitude also exists in Kentucky, which is aided by the fact that none of the cities being examined are located on the coast.

While comparing the UHIs of New York City and Washington, DC, Hicks et al. (2010) found that both UHIs followed diurnal cycles. The established diurnal cycles for UHI magnitude are greater values at night (minimum temperature) and lesser values during the day (maximum temperature). This increased UHI during nighttime is due to the slow release of heat energy from low-albedo urban surfaces after dusk. Since urban temperature values in both cities were shown to follow these trends, it can be said that both cities have strong UHI signatures. A major goal of this project is to use a similar diurnal cycle analysis to establish the strength of Kentucky’s UHI signatures.

While conducting a comprehensive analysis of the effects of urban land use on increases in heat energy, Loridan and Grimmond (2012) discussed how urban areas tend to follow seasonal cycles. This is due to the fact that the number of daylight hours and amount of direct sunlight vary throughout the year, with both being maximized during Summer and minimized during Winter. The low-albedo surfaces of urban areas are better able to absorb this heat energy than their rural counterparts, which means that this seasonal cycle is also reflected in UHI. One of the main goals of this project is to examine Kentucky's UHIs to determine if a seasonal cycle exists in these locations as.

In a study of the UHIs of Japan's largest cities, Fujibe (2010) analyzed how UHI magnitude follows weekly cycles. He found that cities of at least 300 people per 1,000km^2 had a statistically significant decrease in temperatures from weekdays to the weekend, which is mostly attributed to the extra traffic and energy consumption affiliated with the standard workweek. He also found that holidays can cause a decrease in UHI magnitude of about -0.20 °C to -0.25 °C but noted that this did not align well with modelled data. Although weekly cycle and holiday anomaly analysis is outside the scope of this project, any Kentucky city found to have a strong UHI signature can later be subject to these analyses.

While studying the UHIs of the Anatolian Peninsula's eight largest cities, Ozdemir et al. (2012) found that urban temperatures significantly increased from 1965 to 2006. The increase was as great as 5 °C in some places. However, rural temperatures during the same time period remained relatively stable. This suggests that UHI magnitude is increasing over time, which can further contribute to climate change issues. Although it would be extremely interesting to determine if Kentucky's UHIs are also following this trend, the lack of rural temperature values until the inception of the Kentucky Mesonet in 2007 means that such an analysis can't be carried out by this project, and must instead wait several decades until a suitable time scale is available.

Through modelling the effects of Brussel's UHI on climate, Weverberg et al. (2008) found that examining individual meteorological episodes could greatly increase scientific knowledge about the UHI's overall impacts. Using four weather events, they determined that heavy cloud cover resulted in an average UHI magnitude of 0.77 °C, while clear skies resulted in an average UHI magnitude of 1.13 °C. This makes sense given that less cloud cover allows for more solar radiation to absorbed and emitted by urban surfaces. Individual weather event case studies could be analyzed in Kentucky's UHIs at a later date.

Through extensively modelling various UHI scenarios, Ohashi and Kida (2002) were able to outline the major applications of UHI research. This includes understanding complex flow patterns, simulating sea breeze and mountain breeze interactions with UHI, predicting pollutant flow, and developing cities in a sustainable way. By this project laying the groundwork for assessing UHI in Kentucky, it opens the door for more complex studies to help address such major issues in the future.

While studying the effects of land cover and vegetation on Nanjing's UHI, Huang et al. (2008) discussed some of the limitations to UHI research that they encountered. They found that it was difficult to uniformly define land cover types and suggested using density factors and landscape indices to approximate areas that are difficult to directly survey during fieldwork. Their study showed that the importance of correctly modelling land cover type increases as climatic scale decreases, with the best accuracy being necessary at the microscale. Following this line of thinking, this project only examines land cover at the most basic level due to its large spatial scale. Further studies that examine Kentucky’s UHIs at smaller scales will require more in-depth approximations of land cover type.

While modelling the effects of UHI on circulation, Baik et al. (2007) found that UHI can produce dry convection and initiate moist convection downstream of the urban center, which is also reflected by an observed increase in precipitation in the aforementioned areas, especially with late afternoon and evening thunderstorms. Their models showed that as boundary layer stability decreases, the intensity of moist convection increases. It also showed that even weak UHI signatures can result in large contributions to convection, even in neutral and slightly unstable conditions. This study shows that even if Kentucky’s UHIs have moderate or weak signatures, they can still affect land-atmosphere interactions, especially convection.

By modelling the effects of UHI on circulation and precipitation, Han and Baik (2008) found that greater UHI magnitudes and larger UHI spatial sizes were both correlated with increases in circulation/convection intensity and precipitation amount. They also found that UHI can cause precipitation to be spread out across a larger area. This displays that Kentucky’s UHIs may be able to significantly enhance precipitation events that occur downstream.

In a thorough review of land cover studies, Mahmood et al. (2014) noted that UHI can enhance low-level convergence during the daytime and initiate strong circulation at night. This explains why urban-influenced precipitation anomalies can occur at any time. The causes of these UHI circulations are mostly attributed to the increased sensible heat flux and surface roughness associated with urban areas. Since Kentucky's three largest cities have more low-albedo surfaces and taller buildings than the surrounding rural areas, both sensible heat flux and surface roughness are likely to be at play.

By modelling the effects of UHI on circulation in the Pearl River Delta, Lo et al. (2007) found that greater UHI magnitudes enhanced the effects of mesoscale sea breeze circulations. They also showed that better modelling of urban land use, thermal gradients, wind vectors could aid in prediction of pollution flow. While none of Kentucky's largest cities are located near the coast, it is possible that Lexington's UHI could interact with Appalachian mountain breezes, which could be the subject of future research.

Through studying the UHI of Ouagadougou, Burkina Faso, Offerle et al. (2005) found that increased urbanization resulted in greater dry season UHI magnitudes. This was offset somewhat by the local bare soil having thermal characteristics that allow it to emit more heat energy than urban surfaces, showing that other anthropogenic variables besides surface type are contributing to the heating. Based on these results, urbanization would have an even greater effect in Kentucky than in Burkina Faso due to the lowering in albedo from temperate soil to urban surfaces being more pronounced.

Through use of mobile laboratory equipment, Elansky et al. (2012) were able to map the structure of UHI magnitudes for 32 Russian cities and towns. They found that the largest group of towns (by population) had the greatest UHI magnitudes, then followed by the intermediate group, then by the smallest group. The UHI magnitude ranges were also consistently increasing with town size, since minimum UHI magnitudes remained fairly constant. The UHI magnitude was always greatest in or around the town center, with lower values in the suburban areas, and the lowest values in the rural areas. This correlation of city size and UHI magnitude is directly related to the goals of this project, but may have differing results due to their use of a large, categorical sample size, which is unavailable to this project.

In a study on estimating UHI magnitude, Murata et al. (2013) demonstrated that it can be useful to compare observational data with modelled results. Doing so enhanced the models, as observational data was able to account for the effects of urbanization. This results in rural areas displaying a difference of zero between modelled and observational results, isolating the urban areas for analysis. Although this method will not be used in this project, climate models could be contrasted with observed values in future studies of Kentucky's UHI.

In their study of the effects of seasonality and vegetation on Mexico City's UHI, Cui and Foy (2012) measured UHI both using satellite imagery and air temperature observations. They found that these two methods for measuring UHIs can result in outputs that behave very differently from one another. Focusing on air temperature UHI, it was found that increased urban vegetation could somewhat reduce nighttime UHI magnitudes, but that it had very limited effects on daytime UHI magnitudes. This study shows that Kentucky's city planners should take the UHI-reducing effects of urban vegetation into account when deciding upon future projects.

DATA AND SOFTWARE

In order to determine the UHI magnitude of a city, two weather stations must be compared: an urban station and a rural station. Urban stations were selected from the ASOS network, which is an hourly resolution quality-controlled weather station network operated by the National Weather Service (NWS). These stations are located at airports, primarily for assisting in aviation forecasts. ASOS stations sample every ten seconds, which are used to calculate one-minute temperature averages. Rural stations were selected from the Kentucky Mesonet (KYMN), which is a five-minute resolution mesoscale weather and climate observing network operated by the Kentucky Climate Center (KCC) at Western Kentucky University (WKU). The Kentucky Mesonet is one of the best research-grade weather networks in the world, currently with 69 stations operating across the Commonwealth. KYMN stations sample every three seconds, which are used to calculate five-minute temperature averages.

ASOS KSDF (located at Louisville International Airport) was selected for Louisville's urban station. Although KLOU (located at Bowman Field) was also considered, it was not chosen because the ASOS station was relocated during the study period, which enters extra bias into the equation. KYMN CRMT was selected for Louisville's rural station due to it being the closest site and surrounded by grassland. Location metadata for the sites used in the Louisville comparison can be found in Table 1. Land cover aerial photos of the Louisville sites can be found in Figure 1.

Table 1. Site metadata for the Louisville UHI comparison.

Type	Station	City	County	Latitude	Longitude	Elevation (m)
ASOS	KSDF	Louisville	Jefferson	38.18	-85.74	149
KYMN	CRMT	Shepherdsville	Bullitt	37.92	-85.66	166

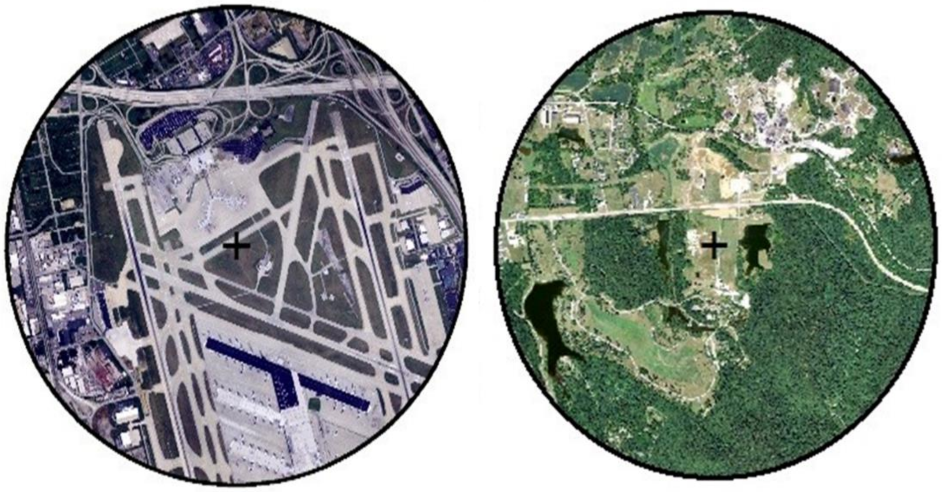

Figure 1. Land cover aerial photographs of KSDF and CRMT, respectively.

ASOS KLEX (located at Bluegrass Airport) was selected for Lexington's urban station due to it being the only available ASOS or Cooperative Observer Network (COOP) site within the city. KYMN LSML was selected for Lexington's rural station. Although the closer sites of ELST and WNCH were also considered, their surrounding land use was determined to be too urban for the purposes of this study. Location metadata for the sites used in the Lexington comparison can be found in Table 2. Land cover aerial photos of the Lexington sites can be found in Figure 2.

Table 2. Site metadata for the Lexington UHI comparison.

Type	Station	City	County	Latitude	Longitude	Elevation (m)
ASOS	KLEX	Lexington	Fayette	38.04	-84.61	299
KYMN	LSML	Frankfort	Franklin	38.12	-84.88	155

Figure 2. Land cover aerial photographs of KLEX and LSML, respectively.

ASOS KBWG (located at Bowling Green-Warren County Regional Airport) was selected for Bowling Green’s urban station. Although COOP 150904 (located at the Bowling Green Water Treatment Plant) was also considered, perusing its site photos and metadata revealed that large amounts of latent heating are likely to occur near the equipment, which would bias temperature values and any resultant UHI magnitude calculations. KYMN FARM was selected for Bowling Green’s rural station due it being the closest available site and surrounded by cropland. In addition, the site is extremely close to Kentucky Mesonet headquarters, meaning that any equipment issues are dealt with almost immediately, increasing data quality. Location metadata for the sites used in the Bowling Green comparison can be found in Table 3. A land cover aerial photo of the rural Bowling Green site (such a product was unavailable for the urban site) can be found in Figure 3. A map displaying the locations of all of the sites used in the study can be found in Figure 4.

Table 3. Site metadata for the Bowling Green UHI comparison.

Type	Station	City	County	Latitude	Longitude	Elevation (m)
ASOS	KBWG	Bowling Green	Warren	36.96	-86.43	167
KYMN	FARM	Bowling Green	Warren	36.93	-86.47	170

Figure 3. A land cover aerial photograph of FARM.

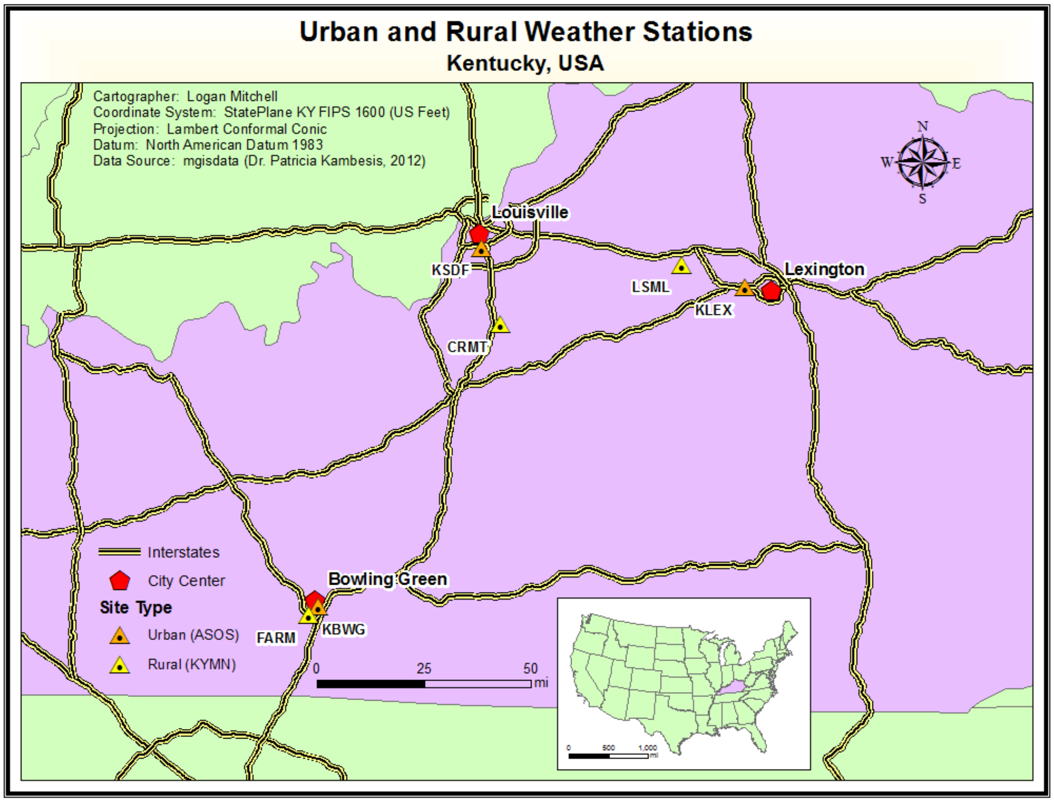

Figure 4. A map of the urban and rural sites used for this study.

The temporal scope of the collected data is from 12/01/2009 to 11/30/2014. This follows the climatological year instead of the civil year because it allows for December to not be cut off from the rest of its related Winter season. Although five years is a short time span for considering climatological phenomena, it is necessary for this study due to the relatively recent installation of Kentucky Mesonet stations (since 2007). This precludes the research from discovering any overall trend in UHI magnitude over time, but such studies will be possible for future analysis.

Hourly time scale maximum and minimum temperature values (°F) were acquired for the ASOS stations through use of the Midwestern Regional Climate Center's (MRCC's) cli-MATE application in the form of an Excel spreadsheet (file type .xlsx). Five-minute time scale maximum and minimum temperature values (°F) were also provided by the Kentucky Mesonet. Site metadata about each urban and rural station was also recorded from their respective website and stored in an Excel spreadsheet.

ArcGIS for Desktop 10.3.1, a geospatial analysis and modelling software package developed by Esri, was used to create maps displaying the locations of each pairing of urban and rural stations from the site metadata. This was also supplemented by available land cover analyses that were conducted for five of the six sites. The ArcGIS software includes ArcCatalog and ArcMap, both of which were utilized in creating the maps.

MATLAB, an advanced statistical analysis and computational software developed by MathWorks, was used to alter data time scales, perform calculations, and create graphs. These actions were performed by creating new scripts through its own programming language.

METHODS

In order for urban and rural temperature values to be compared, they must first be the same time scale. ASOS data was downloaded at the hourly time scale, while KYMN data was downloaded at the five-minute time scale. Separate MATLAB scripts were created to average the raw values into daily maximum and minimum temperatures. Similar scripts were also created to determine monthly maximum and minimum temperatures, followed by seasonal maximum and minimum temperatures. The seasons were defined as follows: Winter (December through February), Spring (March through May), Summer (June through August), and Fall (September through November).

Now that the data is in the proper time scale, monthly and seasonal UHI magnitudes can be calculated for each comparison. This is completed through yet another MATLAB script, this time calculating the pairwise difference (Mahmood et al. 2006) by taking the urban ASOS values minus the rural KYMN values. The output of this operation is stored in Excel spreadsheets for later analysis.

UHI magnitude was measured at the monthly and seasonal time scales for each year by using maximum and minimum temperature differences between the sites as a proxy. The five-year average of each site paring’s UHI magnitudes were also displayed in separate figures. The analysis is useful for understanding temporal variations in UHI magnitude throughout the time span, a concept that will become even more important once the time series is long enough to have predictive capabilities. The latter analysis is useful for diagnosing the overall strength of each city’s UHI by showing how well they follow diurnal and seasonal trends, which is discussed further in the following section.

RESULTS

First, the UHI magnitude for Louisville is assessed. At the monthly time scale, maximum temperature UHI magnitude (Figure 5) tends to be positive throughout the period. The single exception is during January, which dips from December into slightly negative values, then returns in February to slightly positive values. This is followed by an increase in UHI magnitude until August, with a maximum UHI magnitude of 2 °C. UHI magnitude then decreases until November (at a value of about 0.3 °C).

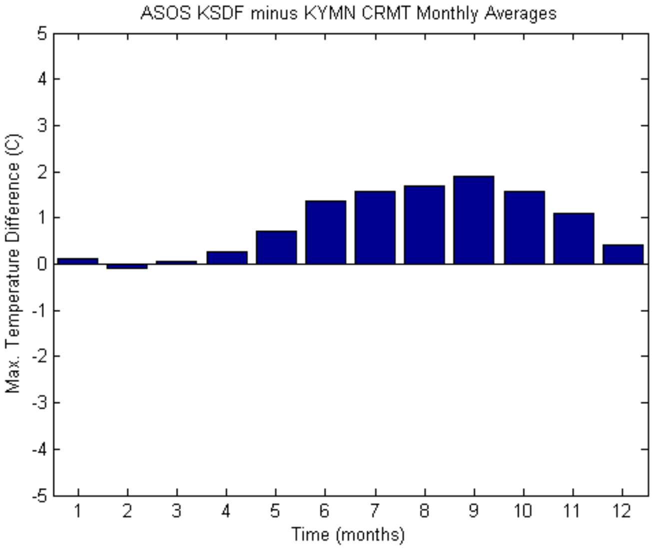

Figure 5. Monthly time scale (December to November) maximum temperature UHI magnitude for Louisville (ASOS KSDF minus KYMN CRMT).

Through viewing the seasonal time scale, it is apparent that maximum temperature UHI magnitude (Figure 6) remains positive throughout the entire period. UHI magnitude is smallest in Winter at just above 0 °C. This increased until Summer, with a maximum UHI magnitude of slightly below 2 °C, then decreased to about 1 °C in Fall. The fact that maximum temperature UHI magnitude remains positive throughout the period at the seasonal time scale (and mostly positive throughout the period at the monthly time scale) shows that daytime temperatures in urban Louisville tend to be higher than that of the surrounding rural areas during the entire year. The UHI magnitudes also followed seasonal cycles quite well, with minimums in Winter and maximums in Summer, indicating that a Louisville UHI may exist.

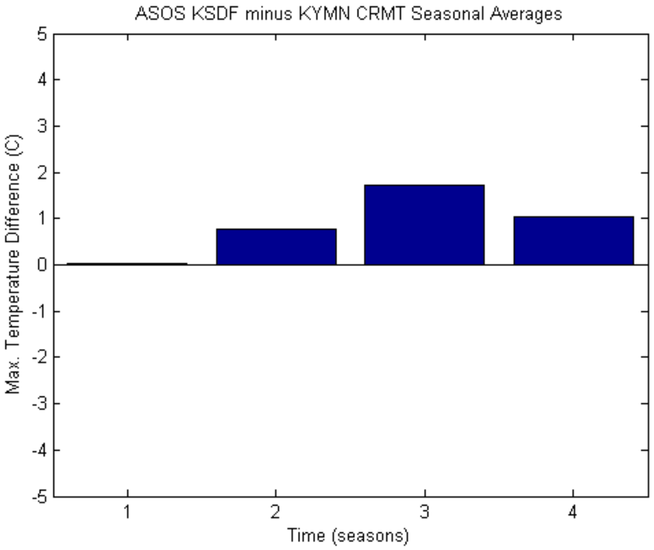

Figure 6. Seasonal time scale (Winter to Fall) maximum temperature UHI magnitude for Louisville (ASOS KSDF minus KYMN CRMT).

When considering the monthly time scale, minimum temperature UHI magnitude (Figure 7) also tends to be mostly positive throughout the period. It again dips from about 0.2 °C in December to about -0.2 °C in January, then returns to slightly above 0 °C by February. This is once again followed by an increase in UHI magnitude until August, this time with a maximum of 2.3 °C. UHI magnitude then decreases until November (at a value of about 0.7 °C).

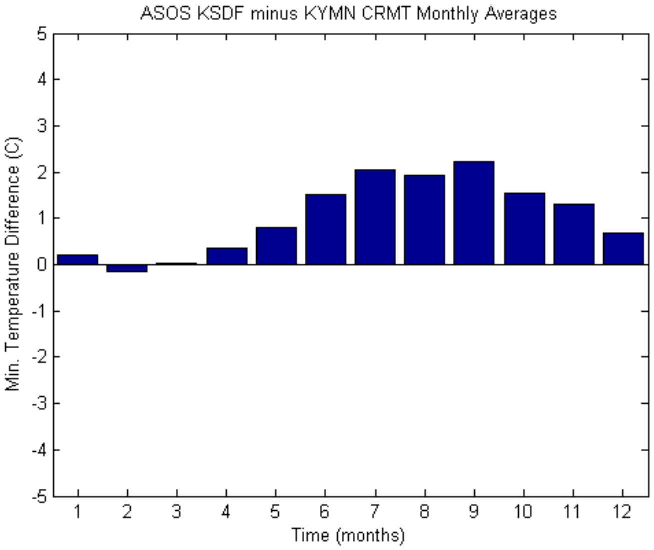

Figure 7. Monthly time scale (December to November) minimum temperature UHI magnitude for Louisville (ASOS KSDF minus KYMN CRMT).

By examining the seasonal time scale, minimum temperature UHI magnitude (Figure 8) is seen to also remain positive throughout the entire period. UHI magnitude is smallest in Winter at just above 0 °C. This increased until Summer, with a maximum UHI magnitude of slightly above 2 °C, then decreased to about 1.2 °C in Fall. The fact that minimum temperature UHI magnitude remains positive throughout the period at the seasonal time scale (and mostly positive throughout the period at the monthly time scale) shows that nighttime temperatures in urban Louisville tend to be higher than that of the surrounding rural areas during the entire year. The UHI magnitudes also followed seasonal cycles quite well, with minimums in Winter and maximums in Summer, further suggesting that a Louisville UHI exists. Although the differences are small, it is also clear that the Louisville comparison is following UHI diurnal cycles, with minimum temperature UHI magnitudes being slightly greater than the maximum temperature UHI magnitudes by about 0.2 °C during the entire year. Since the Louisville comparison follows both cycles, this suggests that a UHI may be present.

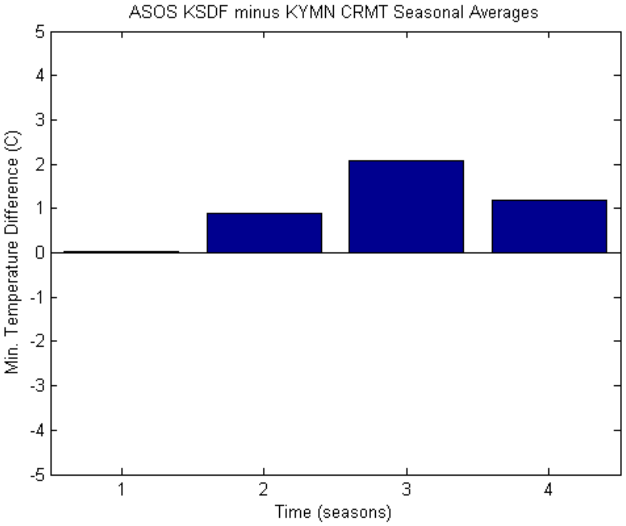

Figure 8. Seasonal time scale (Winter to Fall) minimum temperature UHI magnitude for Louisville (ASOS KSDF minus KYMN CRMT).

The UHI magnitude for Lexington is analyzed next. At the monthly time scale, maximum temperature UHI magnitude (Figure 9) is only positive for seven months. It remains at about -0.3 °C from December to March, becoming positive in April at about 0.2 °C. It then increases until July, reaching a maximum UHI magnitude of about 2.8 °C, before returning to slightly positive (about 0.2 °C) in October and slightly negative (about -0.3 °C) in November.

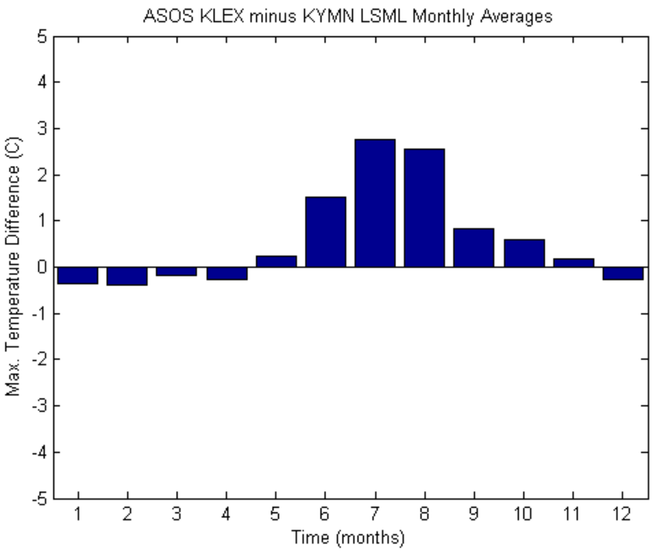

Figure 9. Monthly time scale (December to November) maximum temperature UHI magnitude for Lexington (ASOS KLEX minus KYMN LSML).

When observing maximum temperature UHI magnitude (Figure 10) at the seasonal time scale, it becomes apparent that it is only positive for half of the seasons. UHI magnitude is smallest in Winter at about -0.3 °C, which then increases to about 0.4 °C in Spring. UHI magnitude is greatest in Summer at slightly above 2 °C, but this then decreases to about 0.2 °C by Fall. The fact that maximum temperature UHI magnitudes only remains positive for half of the year shows that Lexington’s urban areas aren’t always hotter than the surrounding rural areas during daytime, which is not indicative of UHI presence in Lexington. However, the maximum temperature UHI magnitude does at least follow UHI seasonal cycles, with minimums in Winter and maximums in Summer.

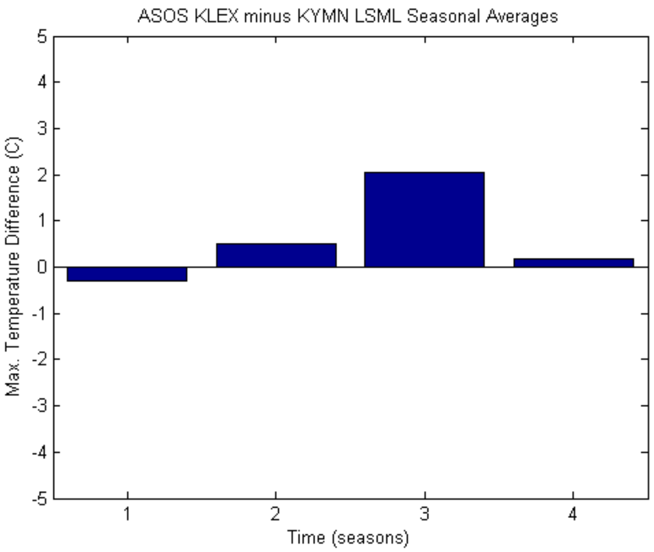

Figure 10. Seasonal time scale (Winter to Fall) maximum temperature UHI magnitude for Lexington (ASOS KLEX minus KYMN LSML).

Through inspecting the monthly time scale, it is revealed that minimum temperature UHI magnitude (Figure 11) is only positive for five months. It decreases from about -0.7 °C in December to a minimum UHI magnitude of about -1 °C in January. This then increases to about -0.3 °C in April, becoming positive in June at about 0.5 °C. The maximum UHI magnitude is reached in July at about 1.3 °C, then decreasing to slightly above 0 °C for August through October, and returns to negative values in November at about -0.4 °C.

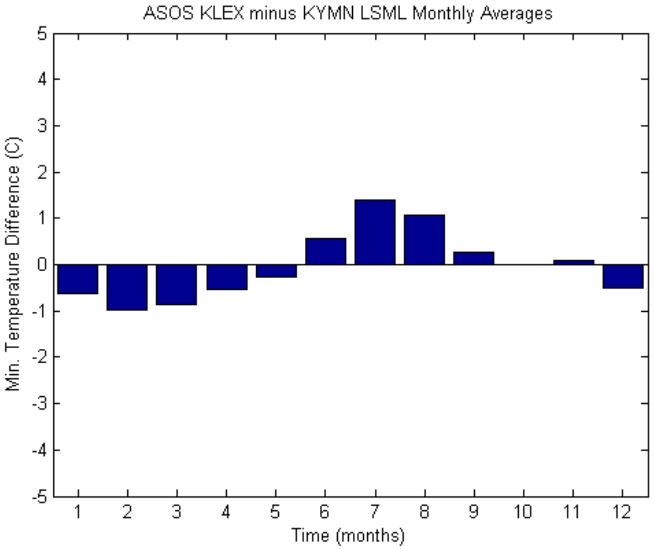

Figure 11. Monthly time scale (December to November) minimum temperature UHI magnitude for Lexington (ASOS KLEX minus KYMN LSML).

Looking at the seasonal time scale, minimum temperature UHI magnitude (Figure 12) is seen to be only positive for one season. UHI magnitude is smallest in Winter at about -0.9 °C, which increases to about -0.1 °C in Spring. This becomes positive and reaches a maximum value of about 0.9 °C in Summer, then decreasing to about -0.2 °C by Fall. The fact that minimum temperature UHI magnitudes are negative for most of the year shows that Lexington's urban areas tend to be cooler than the surrounding rural areas during nighttime, which is not at all indicative of UHI presence in Lexington. However, the minimum temperature UHI magnitude does at least follow UHI seasonal cycles, with minimums in Winter and maximums in Summer. The diurnal cycle, on the other hand, is the opposite of ideal UHI conditions, with minimum temperature UHI magnitudes being about 1 °C cooler than maximum temperature UHI magnitudes at the seasonal time scale. This could be due to station exposure, as the KLEX airport is located two miles outside of town and is surrounded by farm fields, which may be too rural to represent Lexington’s UHI. The abundance of negative UHI magnitude values, combined with the lack of a diurnal cycle, indicates that Lexington currently does not have a UHI. Yet, the presence of seasonal cycles suggests that urban land use is increasing thermal energy, albeit not at rates comparable to full-blown UHIs.

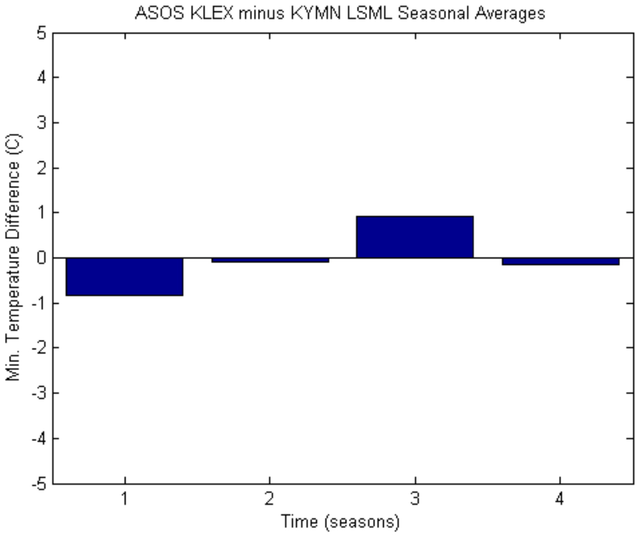

Figure 12. Seasonal time scale (Winter to Fall) minimum temperature UHI magnitude for Lexington (ASOS KLEX minus KYMN LSML).

Finally, the UHI magnitude for Bowling Green is assessed. At the monthly time scale, maximum temperature UHI magnitude (Figure 13) is positive throughout the period. Values remain at a minimum of about 0.6 °C from December to March, increasing to a maximum of about 1.3 °C during June and July, then decreasing to about 0.8 °C by November.

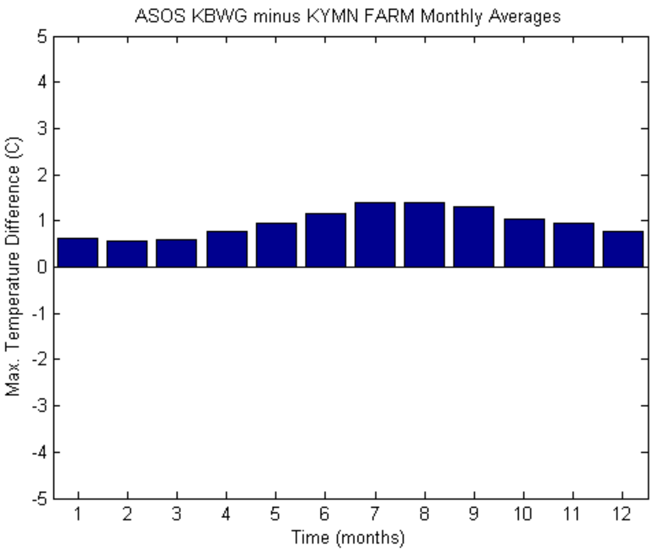

Figure 13. Monthly time scale (December to November) maximum temperature UHI magnitude for Bowling Green (ASOS KBWG minus KYMN FARM).

Seasonal time scale maximum temperature UHI magnitude (Figure 14) shows that it is positive throughout the period. UHI magnitude is smallest in Winter at about 0.6 °C, increasing to a maximum in Summer of about 1.3 °C, then decreasing to about 0.9 °C by Fall. The fact that maximum temperature UHI magnitude is positive throughout the period shows that Bowling Green’s urban areas tend to be hotter than the surrounding rural areas during daytime, which makes UHI presence possible. Maximum temperature UHI magnitude is also following seasonal cycles, with minimums in Winter and maximums in Summer, further suggesting that a UHI may exist in Bowling Green.

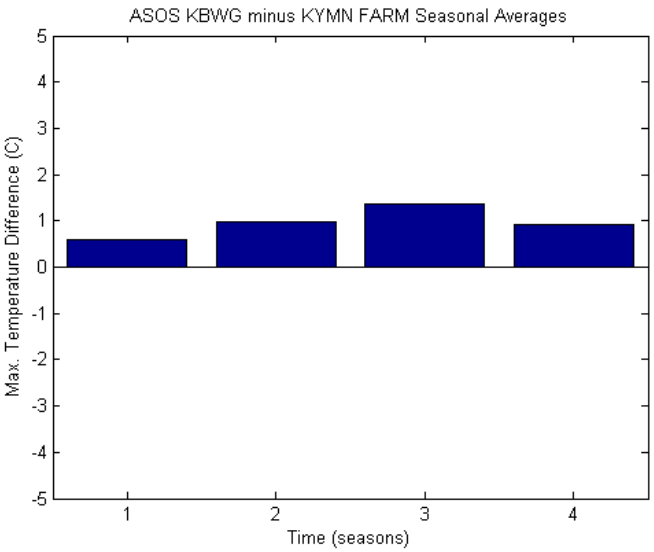

Figure 14. Seasonal time scale (Winter to Fall) maximum temperature UHI magnitude for Bowling Green (ASOS KBWG minus KYMN FARM).

Through examining the monthly time scale, minimum temperature UHI magnitude (Figure 15) is shown to only be positive for three months. It decreases from about -0.4 °C in December to a minimum of about -0.9 °C in February. It then increases to about -0.3 °C for March through May, becoming slightly positive in June. The maximum UHI magnitude is in July at 0.3 °C, then decreases to about 0.1 °C in August. It becomes negative in September (about -0.2 °C), then decreases to about -0.8 °C in November.

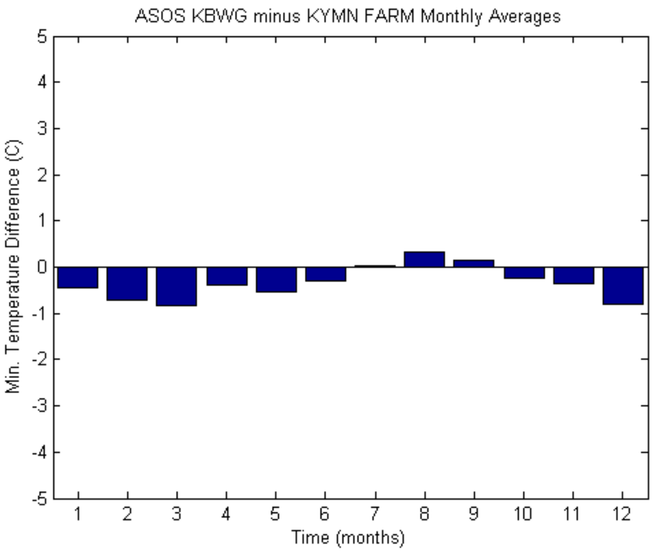

Figure 15. Monthly time scale (December to November) minimum temperature UHI magnitude for Bowling Green (ASOS KBWG minus KYMN FARM).

By inspecting the seasonal time scale, minimum temperature UHI magnitude (Figure 16) is seen to be only positive for one season. UHI magnitude is smallest in Winter at about -0.7 °C, increasing to about -0.3 °C in Spring, becoming positive and reaching a maximum of about 0.2 °C in Summer, then decreasing to about -0.4 °C by Fall. The fact that minimum temperature UHI magnitudes are negative for most of the year shows that Bowling Green's urban areas tend to be cooler than the surrounding rural areas during nighttime, which is not at all indicative of UHI presence in Lexington. However, the minimum temperature UHI magnitude does at least follow UHI seasonal cycles, with minimums in Winter and maximums in Summer. The diurnal cycle, on the other hand, is very different from ideal UHI conditions, with minimum temperature UHI magnitudes being about 1.2 °C cooler than maximum temperature UHI magnitudes at the seasonal time scale. The large amount of negative UHI magnitude values, combined with the lack of a diurnal cycle, indicates that conditions are complex in Bowling Green. Even though KBWG is located on the edge of town and is surrounded by some agricultural fields, this area has also been undergoing some urban development. At the same time, the area surrounding FARM has also been developing, so it is possible that these effects are somewhat cancelling each other out and diminishing changes in UHI magnitude. Seasonal cycles may suggest that urban land use is affecting climatic variables.

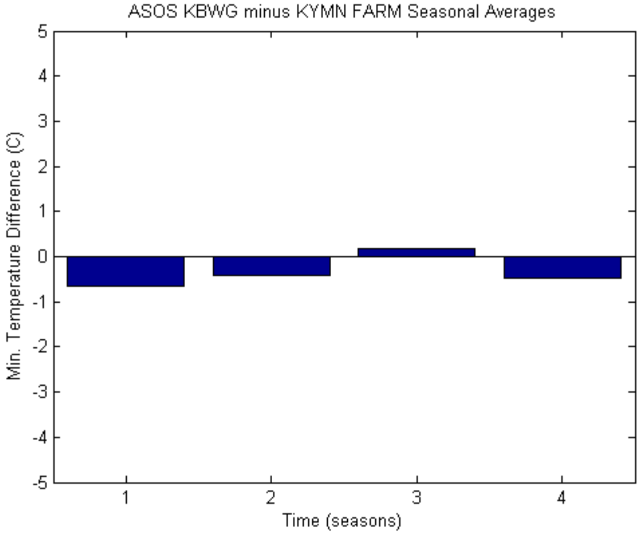

Figure 16. Seasonal time scale (Winter to Fall) minimum temperature UHI magnitude for Bowling Green (ASOS KBWG minus KYMN FARM).

CONCLUSION

The UHI magnitude analyses at the monthly and seasonal time scales (including both maximum and minimum temperatures), the strength of each UHI for Kentucky's three largest cities (Louisville, Lexington, and Bowling Green) were assessed. Louisville has positive UHI magnitudes throughout the period, follows seasonal cycles, and follows diurnal cycles (albeit with only slightly higher minimum temperature UHI magnitude values). This indicates that a moderate UHI is present in Louisville. Lexington has many (or majority) negative UHI magnitudes for both maximum and minimum temperatures, and only follows seasonal cycles, with minimum temperatures being about 1 °C too warm for the proper diurnal cycles to be followed. This indicates that, in Lexington, the characteristics of UHI are complex. Bowling Green has mostly negative UHI magnitudes for minimum temperatures, and only follows seasonal cycles, with minimum temperatures being about 1.2 °C too warm for the proper diurnal cycles to be followed. Hence, generally conditions are comparable to Lexington. Overall, the lack of a classic UHI set-up in Lexington and Bowling Green indicates the challenges in studying UHI, particularly the importance of using similar urban and rural stations that have high data quality. Results also demonstrate site exposure and quality of meteorological instruments may impact UHI assessment. Due to a lack of well-placed urban and rural stations to compare, many regions, especially under-studied areas, will require making do with the best sites available. With the continual expansion and improvement of Kentucky Mesonet stations across the commonwealth, more thorough studies dealing with longer time scales can be carried out in the future.

Based upon these results, it can be said that Louisville as the largest city does indeed have the greatest UHI magnitudes, as it displays both of the major cycles that characterize UHI presence. After that, however, Lexington and Bowling Green, despite displaying seasonal cycles, both do not appear to not have enough UHI signals present to classify either of them as a UHI, making a comparison difficult.

This research could be further expanded by conducting descriptive statistics and other statistical analyses to quantify sampling significance and ensure data quality. The relationship between daily time scale UHI magnitude and prevailing air mass type, cloud cover, and teleconnection phases could also be correlated to determine what effects these variables have on day-to-day fluctuations in UHI magnitude. This could also include an investigation of hourly-resolution temperature data to ascertain the rate of nighttime cooling occurring at the site. Once enough time has passed for there to be a climatologically significant amount of overlap between KYMN and ASOS stations (at least 30 years), spectral analysis can be used to ascertain UHI magnitude's rate of change for Kentucky cities, which can aid in efforts to reduce the adverse impacts of climate change. Right now, these kinds of analyses should only be conducted on Louisville, as it was the only city with strong enough UHI signals to warrant these advanced analyses.

REFERENCES

Arnfield, A. J., 2003: Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.*, **23**, 1-26, https://doi.org/10.1002/joc.859.

Baik, J. -J., Y. -H. Kim, J. -J. Kim, and J. -Y. Han, 2007: Effects of boundary-layer stability on urban heat island-induced circulation. *Theor. Appl. Climatol.*, **89**, 73-81, https://doi.org/10.1007/s00704-006-0254-4.

Cui, Y. -Y., and B. D. Foy, 2012: Seasonal variations of the urban heat island at the surface and the near-surface and reductions due to urban vegetation in Mexico City. *J. Appl. Meteor. Climatol.*, **51**, 855-868, https://doi.org/10.1175/JAMC-D-11-0104.1.

Easterling, D. R., and Coauthors, 1997: Maximum and minimum temperature trends for the globe. *Sci. M.*, **277**, 5324, 364-367, https://doi.org/10.1126/science.277.5324.364.

Elansky, N. F., O. V. Lavrova, I. I. Mokhov, and A. A. Rakin, 2012: Heat island structure over Russian towns based on mobile laboratory observations. *Doklady Earth Sci.*, **443**, 1, 420-425. https://doi.org/10.1134/S1028334X12030245.

Fiebrich, C. A., and K. C. Crawford, 2009: Automation: A step toward improving the quality of daily temperature data produced by climate observing networks. *J. Atmos. Oceanic Technol.*, **26**, 1246-1260, https://doi.org/10.1175/2009JTECHA1241.1.

Fujibe, F., 2010: Day-of-the-week variations of urban temperature and their long-term trends in Japan. *Theor. Appl. Climatol.*, **102**, 393-401, https://doi.org/10.1002/joc.2142.

Han, J. -Y., and J. -J. Baik, 2008: A theoretical and numerical study of urban heat island-induced circulation and convection. *J. Atmos. Sci.*, **65**, 1859-1877, https://doi.org/10.1175/2007JAS2326.1.

Hicks, B. B., W. J. Callahan, and M. A. Hoekzema, 2010: On the heat islands of Washington, DC, and New York City, NY. *Boundary-Layer Meteor.*, **135**, 291-300, https://doi.org/10.1007/s10546-010-9468-1.

Huang, L. -M., D. -H. Zhao, J. -Z. Wang, J. -Y. Zhu, and J. -L. Li, 2008: Scale impacts of land cover and vegetation corridors on urban thermal behavior in Nanjing, China. *Theor. Appl. Climatol.*, **94**, 241-257, https://doi.org/10.1007/s00704-007-0359-4.

Kalnay, E., and M. Cai, 2003: Impact of urbanization and land-use change on climate. *Nature M.*, **423**, 528-531, https://doi.org/10.1038/nature01952.

Karl, T. R., and Coauthors, 1993: A new perspective on recent global warming: Asymmetric trends of daily maximum and minimum temperature. *Bull. Amer. Meteor. Soc.*, **74**, 6, 1007-1023, https://doi.org/10.1175/1520-0477(1993)074<1007:ANPORG>2.0.CO;2.

Kim, Y. -H., and J. -J. Baik, 2004: Daily maximum urban heat island intensity in large cities of Korea. *Theor. Appl. Climatol.*, **79**, 151-164, https://doi.org/10.1007/s00704-004-0070-7.

Lo, J. C. -F., A. K. -H. Lau, F. Chen, J. C. -H. Fung, and K. K. -M. Leung, 2007: Urban modification in a mesoscale model and the effects on the local circulation in the Pearl River Delta Region. *J. Appl. Meteor. Climatol.*, **46**, 457-476, https://doi.org/10.1175/JAM2477.1.

Loridan, T., and C. S. B. Grimmond, 2012: Characterization of energy flux partitioning in urban environments: Links with surface seasonal properties. *J. Appl. Meteor. Climatol.*, **51**, 219-241, https://doi.org/10.1175/JAMC-D-11-038.1.

Mahmood, R., and Coauthors, 2014: Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.*, **34**, 929-953, https://doi.org/10.1002/joc.3736.

Mahmood, R., S. A. Foster, T. Keeling, K. G. Hubbard, C. Carlson, R. Leeper, 2006: Impacts of irrigation on 20th century temperature in the Northern Great Plains. *Global & Planetary Change*, **54**, 1-2, 1-18, https://doi.org/10.1016/j.gloplacha.2005.10.004.

Murata, A., H. Sasaki, M. Hanafusa, and K. Kurihara, 2013: Estimation of urban heat island intensity using biases in surface air temperature simulated by a nonhydrostatic regional climate model. *Theor. Appl. Climatol.*, **112**, 351-361, https://doi.org/10.1007/s00704-012-0739-2.

Offerle, B., P. Jonsson, I. Eliasson, and C. S. B. Grimmond, 2005: Urban modification of the surface energy balance in the West African Sahel: Ouagadougou, Burkina Faso. *J. Climate*, **18**, 3983-3995, https://doi.org/10.1175/JCLI3520.1.

Ohashi, Y., and H. Kida, 2002: Local circulations developed in the vicinity of both coastal and inland urban areas: A numerical study with a mesoscale atmospheric model. *J. Appl. Meteor.*, **41**, 30-45, https://doi.org/10.1175/1520-0450(2002)041<0030:LCDITV>2.0.CO;2.

Ozdemir, H., A. Unal, T. Kindap, U. U. Turuncoglu, Z. O. Durmusoglu, M. Khan, M. Tayanc, and M. Karaca, 2012: Quantification of the urban heat island under a changing climate over Anatolian Peninsula. *Theor. Appl. Climatol.*, **108**, 31-38, https://doi.org/10.1007/s00704-011-0515-8.

Peterson, T. C., 2003: Assessment of urban versus rural in situ surface temperatures in the Contiguous United States: No difference found. *J. Climate*, **16**, 18, 2941-2959, https://doi.org/10.1175/15200442(2003)016<2941:AOUVRI>2.0.CO;2.

Weverberg, K. V., K. D. Ridder, and A. V. Rompaey, 2008: Modeling the contribution of the Brussels heat island to a long temperature time series. *J. Appl. Meteor. Climatol.*, **47**, 976-990, https://doi.org/10.1175/2007JAMC1482.1.