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# Defining the Spatial and Average Intensity of the Louisville Urban Heat Island

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# Defining the Spatial and Average Intensity of the Louisville Urban Heat Island

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**Abstract:** The urban heat island (UHI) effect, a phenomenon where the urban area will be warmer than the rural surroundings, may adversely impact human health and energy consumption via heat waves and rolling blackouts. A quantitative assessment of the UHI in Louisville, Kentucky was conducted through climatological analysis of five observation stations over a 5-year period from 2009 –2013. Results indicate the presence of a large UHI extending beyond 40 km, with an average intensity of 4.84°C between the most rural station and the urban control. By analyzing the temperature differences between all stations based on time and meteorological conditions, it was found that the UHI is especially amplified during the nighttime hours of 2300-0700 LST and in the presence of weak winds (< 3.0 $ms^{-1}$), little to no cloud cover, and no precipitation. This study indicated the necessity of more observing stations in this region, given the poor spatial resolution of the existing network.

**Keywords:** *urban heat island, urban climate, climate of Louisville, Kentucky, urban climatology*

The development of urban environments (specifically those with high population densities) have contributed to the existence of a phenomenon termed the urban heat island (UHI) effect, first documented nearly two hundred years ago (Howard, 1833). In these locations, an average difference between urban surface temperatures and the surrounding rural areas is typically 2°C to 9°C (Oke, 1982). Most critical to the formation of a UHI is anthropogenic heating, impervious surfaces, the increased sensible heat capacity of building materials, increased absorption of solar radiation because of building geometry (the urban canyon effect), and the reduction of evapotranspiration through the elimination of vegetation and waterproofing in urban structures (Myrup, 1969; Nunez & Oke 1977; Oke 1987). These processes are especially amplified in the presence of weak synoptic flow, and most notable temperature anomalies occur at night when long-wave radiation emitted from buildings acts to negate the cooling generally associated with the radiative heat loss of a typical landmass (Oke, 1987).

Mitigating the effects of urban heat islands has become a principal concern for local governments looking to enhance public health and comfort. Warming in areas of higher population densities has resulted in the increased demand for cooling and therefore increased the demand on electricity (Grimmond, 2007). This has global implications, as increased electricity consumption will enhance the intensity of greenhouse gases. Further, heat waves through large urban areas place significant populations at risk for heat related injuries, particularly the elderly and those who are unable to afford air conditioning (Grimmond, 2007).

From 2000—2010, the Louisville population increased by nearly 10.5% (or 121,591 people). The resulting burden on power production and land development could be contributing to a rise in local temperatures. Stone (2012) indicated that Louisville experienced the highest average temperature increase (0.83°C) each decade from 1961-2010 while the combined average of the other top fifty metropolitan areas was 0.30°C. In the same study, the Louisville area demonstrated a 1.67°C per decade change in temperature between the rural and urban areas, the highest rate among all metro areas and 0.71°C greater than second-ranked Phoenix, Arizona. These results suggest that Louisville is experiencing accelerated warming trends when compared to all other major cities.

In 1989, Westendorf, Leuthart, & Howarth (1989) showed, through analysis of the sky view factor (a consequence of building geometry), that there exists the presence of a large heat island under ideal meteorological conditions in Louisville. In the twenty-five years since, the Louisville area has not been assessed quantitatively, although many other cities of a humid subtropical climate have been well modeled. In Oklahoma City, Oklahoma, a 1.5°C mean air temperature difference between the central business district and rural sites was observed by employing a dense observational network supplemented by the Oklahoma Mesonet (Basara et al., 2008). In Houston, Texas, and Atlanta, Georgia, Streutker (2003) and Hafner and Kidder (1999) utilized the Advanced Very High Resolution Radiometer (AVHRR) instrument aboard the NOAA-14 satellite to obtain mean heat island signatures of 3.19°C and 0.8°C, respectively. The UHI is present in cities of varying climate extremes as well. For the subarctic climate of Fairbanks, Alaska, Magee, Wendler, and Curtis (1999) found a 1.0°C UHI, generated mostly by a 500% increase in population over the previous 49-year period. In a subtropical highland climate such as Mexico City, Mexico, Jauregui (1997) utilized hourly data recorded by two observational stations to observe a maximum heat island intensity of 7.8°C.

This study quantitatively defines the spatial extent and maximum intensity of the Louisville heat island using hourly temperature observations from the existing network of meteorological observing stations for the period 2009 to 2013 with particular interest in verifying several generalizations of the UHI. This will be shown later in the results section where several filters were implemented to discuss the diurnal and seasonal frequency of the UHI and its sensitivity to both time of day and meteorological conditions.

## METHODS

### Study site

Located in the central United States at a latitude of 38°N and elevation of 142 m, Louisville is the largest city in the Commonwealth of Kentucky and the seat of Jefferson County. The Louisville-Jefferson County, KY-IN Metropolitan Statistical Area (MSA), colloquially referred to as “Kentuckiana” by residents, includes eight other counties in Kentucky and five in southern Indiana. In total, the combined population of Kentuckiana was 1,283,566 during the 2010 census, making it the 42$^{nd}$ largest MSA, directly behind the metropolitan areas of Oklahoma City, Oklahoma and Memphis, Tennessee (U.S. Census Bureau, 2011).

The area has a humid subtropical climate with cool, mild winters and warm, humid summers. Most recent annual climatology (1981 – 2010) shows that the average annual maximum temperature is 19.89°C and the average low is 9.22°C with the average annual temperature being 14.56°C (National Weather Service, 2013). Louisville experiences an active severe weather season and relatively heavy precipitation during the early spring months while the fall season is generally drier with yearly minimum precipitation and little to no snow accumulation. Summers may be especially hot, with high temperatures ranging from 32°C – 38°C for several days. Air pollution is a particular problem for the city, as it is located in the Ohio River Valley, which acts to trap ozone smog and pollen pollution (Knowlton, Rotkin-Ellman, & Solomon, 2007). This is exacerbated by the rise in local urban temperatures likely caused by the heat island effect.

### Stations and Data

The most common methods of determining the urban heat island effect include climatological analysis of two or more meteorological observation stations, modeling, satellite imagery examination, and automobile temperature traverse (Hafner and Kidder, 1999; Jauregui, 1997; Klysik and Fortuniak, 1999). Although satellite imagery and modeling methods have been utilized more in recent years, climatological analysis remains the most direct and practical method of assessing the UHI. Using this method, Klysik and Fortuniak (1999) discovered that the Łódz, Poland heat island (located in a warm summer continental climate) yielded a 2-4°C difference between urban and rural areas during 80% of the observed nights over three years of meteorological observations. They also found that the maximum intensity was around 8°C or greater on cool, winter nights.

We conducted a climatological comparison of five existing meteorological stations in the

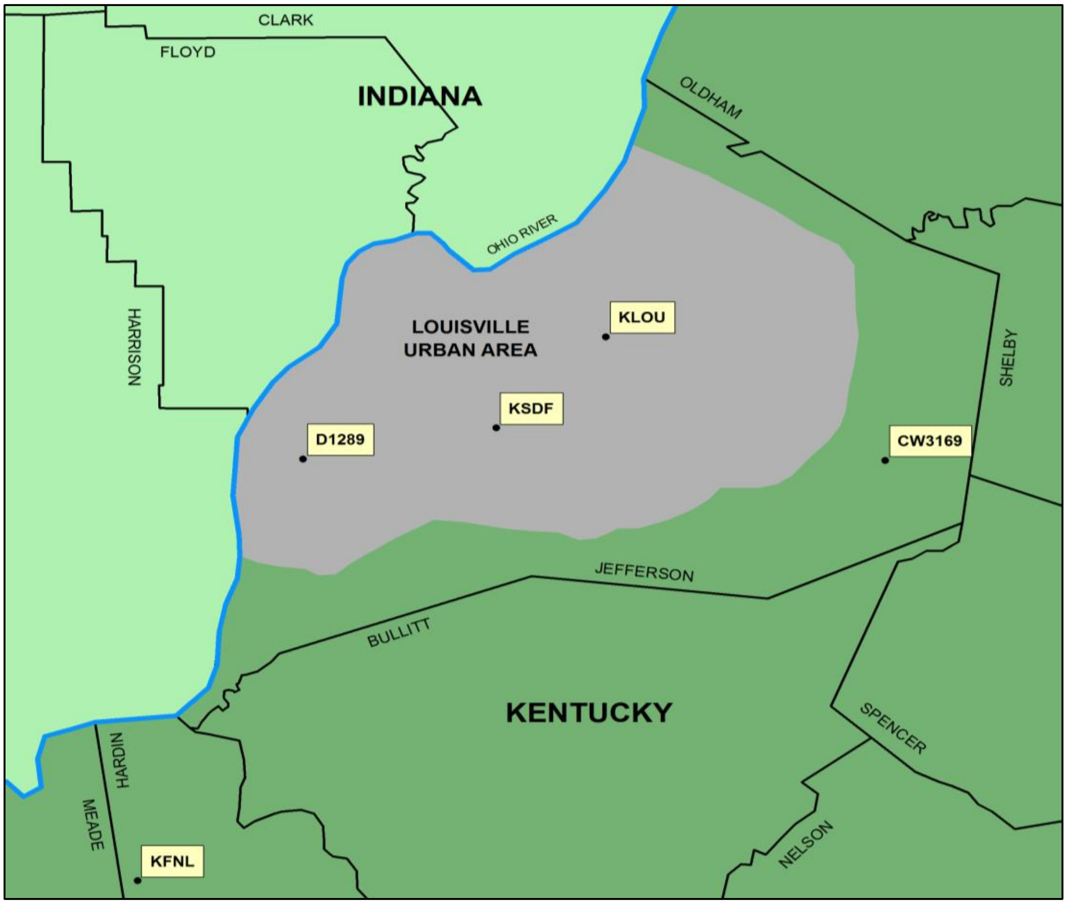


*Figure 1*. The locations of the meteorological observation stations used in this study. The control station, KSDF, is located in the center of the urban area approximately 10 km SE from the urban center. Areas outside of the urban area are of rural and industrial/military land use.

Louisville area for the 5-year period between 2009 and 2013. The stations used were identified by the assigned code created by either the National Weather Service (NWS) or the Federal Aviation Administration (FAA). This included one urban station operated by the NWS Louisville (KSDF), one urban station operated by the Louisville Regional Airport Authority (KLOU), one industrial/military use station maintained by the Department of the Army at Fort Knox (KFTK), and two Citizen Weather Observer Program (CWOP) stations, labeled D1289 and CW3169, of suburban and rural land use, respectively (Figure 1).

For the control station, KSDF was selected because the location at the Louisville International Airport was of the closest proximity (10 km south) to the urban center. Reliable sky cover, precipitation, and wind measurements were also obtained at this station, making it ideal for determining interactions between the UHI and these variables. All of the data was provided via the MesoWest meteorological data repository that is maintained by the University of Utah and each measurement was given as hourly observations of temperature. We computed the difference between observations at each experiment station (KLOU, KFTK, CW3169, and D1289) and the control station for each hour over the entire period without consideration of any meteorological forcing. The resulting values were considered as the "unfiltered" intensity of the urban heat island. Missing data for any hourly observation was replaced by the average values of the previous and subsequent observation. Days in which at least ¼ of the 24-hour period (6 hourly observations) was missing were eliminated from the analysis.

### Filtering by time and conditions

The urban heat island demonstrates several commonalities across many of the cities studied. Both Figuerola and Mazzeo (1998) and Magee et al. (1999) determined that the minimum heat island occurs during the day, whereas the maximum occurs between 0400 and 0600 LST. In order to determine the diurnal cycle of the Louisville heat island, we divided the daily period into six groups of observations at four-hour intervals for the 5-year period. The results comprise the "time-filtered" dataset. Values for only the period between 0400 – 0600 LST were also obtained as a measure of comparison to other studies.

The magnitude of the urban heat island is greatest during the nighttime in clear skies and light winds (Oke and Maxwell, 1975). Ackerman (1985) considered the modification of the heat island by weather phenomena in Chicago, Illinois and found that UHI intensity was greatest in the presence of weak winds and few clouds, characteristic of high-pressure regimes. Wind speeds of less than 1.5 $ms^{-1}$ resulted in a 1.2ºC increase to the heat island intensity while winds that were greater than 3.5 $ms^{-1}$ acted to negate a positive UHI. Additionally, a decrease in temperature difference was produced as cloud cover exceeded 25%. Anticyclonic conditions contributing to calm, clear nights also directly influenced the 5ºC and 2.02ºC average heat islands in Mexico City and Madrid, respectively (Jauregui, 1997; Yague, Zurita, & Martinez, 1991). Here, we have defined the criteria for our condition-filtered dataset to be: wind speeds not exceeding 3.0 m $s^{-1}$, hazy, clear, or partly cloudy skies, and no precipitation occurring within the hour. Observations that met these criteria were grouped together to assess the potential for weather to modify the UHI. Since the UHI is likely variable throughout the day, the condition-filtered dataset was further categorized by using the time filter mentioned previously to represent the "time and condition filtered" dataset. Applying each of these filters to the observations provided us with several scales to adequately define the Louisville heat island.

## RESULTS

The unfiltered heat island is represented in Figure 2 for each station and displayed as monthly averages overlaid with mean monthly temperature values for the 5-year period. Although there are subtle differences in value, the plots for each station show very good agreement during the traditional winter months (Dec – Feb) where the observed heat island is at a minimum. At three of the stations, seasonal maximum heat island values were observed during the summer months (Jun – Aug). It is considered that the increased usage of air conditioning and vehicles (anthropogenic forcing) likely accelerated daytime surface heating during these months. Additionally, the summers of 2010 – 2012 were unusually warmer than the climatological mean of 25.4°C by a total of 3.72°C. Increased temperatures would have placed more demand on energy consumption and buildings which had absorbed solar radiation during the day and would likely emit a greater amount back into the ambient air at night, causing greater differences between the urban and rural environment.

Those stations that were located within the urban area exhibited temperature values most similar to the KSDF station with 5-year average heat island values of 0.22°C for D1289 and 0.31°C for KLOU. This was expected, as the two stations are of urban/suburban use in areas with greater population density and similar structure density as the control. KFTK, which is has a mixed industrial/military use and is nearly 42 km from the urban center, displayed greater average heat island values on monthly and yearly scales. However, KFTK showed results that were less than anticipated, given its distance from the control, and it is believed that a heat island might exist at this site as well, considering it is located on the 109,000-acre Fort Knox military installation, which sits adjacent to a small town. The true rural station, CW3169, displayed the highest heat island value of 1.87°C. A local forest is located roughly 3.81 km upwind and to the west of the station, and a large tributary of the Salt River, Floyd’s Fork, runs through the area as well, nearly 1.68 km west of the station.

Lastly, 0.31 km to the south is a large creek surrounded by a dense, mature stand of trees. These features and a few nearby manmade reservoirs would likely yield higher soil moisture content and cooler winds near the station, driving temperatures to be less than the urban environment.

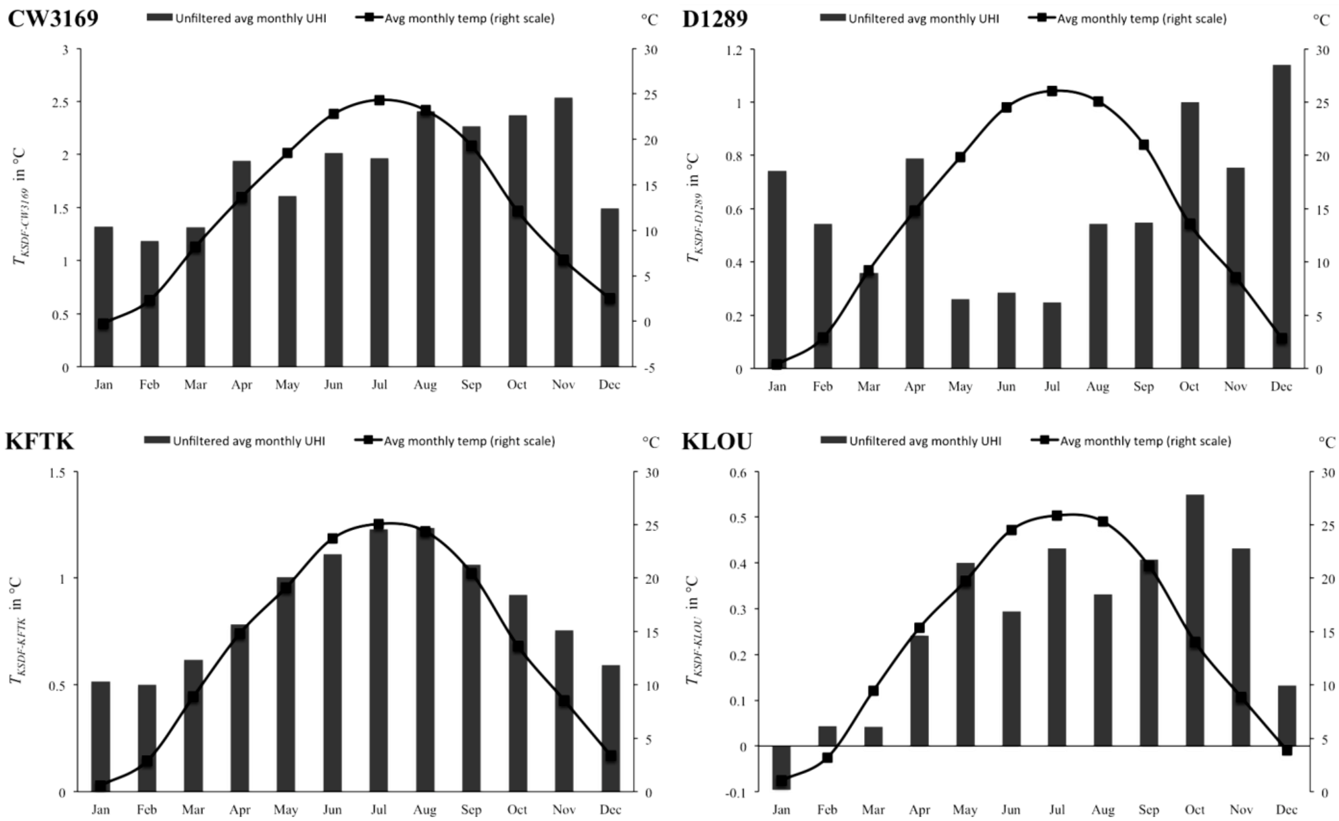


*Figure 2.* The seasonality of the unfiltered Louisville heat island over the 5-year period. Seasonal low values are observed during the winter months and maximum UHI signatures occur during the summer months and October.

The UHI was classified by days that presented positive average heat island signatures greater than 1°C (Table 1). Although there were 1826 days during the observed period, all sites were reduced in sample size after eliminating those days that did not meet the quality criteria mentioned previously in the methods. At CW3169, 68.1% of the days were found to exhibit a positive UHI while those sites within the urban area remained much lower, showing 24.5% and 30.4% exceedance days at KLOU and D1289, respectively. These exceedance counts demonstrate that the UHI is present on a temporal frequency that increases away from the urban area.

*Table 1.* The number of days over the 5-year period during which the average heat island values were greater than 1°C.

***Exceedance days > 1°C of the unfiltered UHI***

| Station | Days | Sample Size (Days)* | % |
|---|---|---|---|
| D1289 | 550 | 1807 | 30.4 |
| KLOU | 448 | 1819 | 24.5 |
| CW3169 | 1224 | 1798 | 68.1 |
| KFTK | 837 | 1821 | 46.0 |

* Sample size is the number of days in which both the control and experimental station recorded observations after quality checks



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## Modification of the UHI by weather

The "condition-filtered" dataset included observations of temperature filtered by threshold values of cloud cover, precipitation, and wind. In general, increasing values of cloud cover, precipitation, and wind were found to mitigate the urban heat island (Table 2). Hourly observations that displayed 1-hour precipitation measurements greater than 0.254 mm were found to have a minimal or more often negative UHI. At three of the stations, observations devoid of any precipitation yielded the greatest heat island signatures. The fourth station, D1289 still experienced a 0.46°C heat island under the same conditions, which leads us to suggest that the Louisville heat island is most directly modified by precipitation.

Sky conditions, in many cases, could be directly linked to occurring precipitation. We assessed hours where the observable sky was hazy, clear, or partly cloudy and determined that the UHI is amplified for all stations under these conditions. This was especially true at KFTK and CW3169, where the stations are likely far enough away from the control to be under the influence of differing cloud or storm cover. Again, KLOU and D1289 showed a lesser UHI but demonstrated some variability during varying sky conditions.

The modification of the UHI by wind speed was found to be the least impactful of the three scenarios. When only wind speeds greater than 3.0 $ms^{-1}$ were considered, the urban and rural temperature difference was less than 1.0°C at all stations. However, calm or light winds at the surface most often demonstrated an increased heat island at each station with CW3169 experiencing a 5-year average UHI of 2.55°C. Although this magnitude is still considerable relative to the other conditions, the advection of surface temperature by the wind at these stations was not as strong of a factor as originally anticipated.

The most pronounced 5-year averages are obtained when no precipitation is occurring, winds are below 3.0 $ms^{-1}$, and favorable sky conditions exist. Combining all factors resulted in a 3.65°C difference at CW3169 and similarly higher values at all other stations. The results found here demonstrate very good agreement with the generalizations made in the literature, where the heat island is most prominent under ideal weather conditions. This can be extended to mean that the presence of synoptic-scale high-pressure regimes most commonly generate the most favorable conditions for the Louisville maximum UHI intensity.

*Table 2.* The modification of the Louisville UHI by differing weather conditions.

***Impacts of Weather Conditions on the Louisville UHI***

| | Unfavorable sky conditions* | Favorable sky conditions^ | Wind speed > 3.0$ms^{-1}$ | Wind speed < 3.0$ms^{-1}$ | Precipitation occurring | No precipitation | Favorable with winds < 3.0 $ms^{-1}$ and no precipitation |
|---|---|---|---|---|---|---|---|
| KLOU | 0.13 | 0.44 | 0.11 | 0.33 | -0.17 | 0.27 | 0.57 |
| D1289 | 0.52 | 0.97 | 0.33 | 1.01 | 0.23 | 0.69 | 1.38 |
| KFTK | 0.70 | 1.30 | 0.67 | 1.08 | -0.07 | 0.99 | 1.51 |
| CW3169 | 1.26 | 2.94 | 0.98 | 2.55 | -0.09 | 1.95 | 3.65 |

* Unfavorable sky conditions are defined as hours with haze, clear, or partly cloudy identifiers
^ Favorable sky conditions are hours where weather may be occurring or the sky is mostly obscured

Most commonly, the occurrence of precipitation during the hour acted to negate the UHI effect for all stations. The stations were most sensitive to the occurrence of precipitation during the hour, while sky conditions also played a significant role in the variability of the UHI. Wind speeds, to a lesser extent, also acted to modify the heat island.

## The diurnal heat island

We divided the daily period into six time intervals of four hours each to represent the urban heat island at different times of the day and then assessed the heat island by examining the unfiltered dataset and the condition-filtered dataset (Table 3).

For the unfiltered data, we determined that the most common hours for the greatest intensity of the urban heat island at three of the stations were from 0300 to 0700 hrs. By midday, heat island values were well diminished at all stations, although a positive signature was still obtained in most cases. This trend of lower values was seen from just after daybreak until well into the evening. By nighttime, the heat island increased in intensity, resulting in relatively higher values between 2300 and 0700 hrs. We reduced the dataset further to include only observations between 0400 and 0600 hours, the period of maximum intensity for several heat islands of similar climate, and found slightly increased temperature differences at all stations.

Applying the same analysis to the condition-filtered group produced the highest UHI values at all stations. Interestingly, the most ideal hours for maximum intensity at three of the stations were from 2300 to 0300. The greatest overall UHI value obtained was 4.84°C at CW3169. Hours from 0300 to 0700 at each station were slightly less but of comparable magnitude to the 2300 – 0300 time period. Values given by the time and condition filtered dataset agree well with the time filtered dataset in that the lowest UHI values are during the daytime, typically from 1100 to 1900 hrs. Thus, it can be said that the Louisville urban heat island is most prominent during the nighttime hours while the minimum UHI is generally observed during midday – afternoon hours.

*Table 3.* The diurnal heat island.

***Time Filtered UHI in °C***

| | KLOU | D1289 | KFTK | CW3169 |
|---|---|---|---|---|
| 0300 to 0700 | 0.26 | **1.05** | 1.13 | **2.98** |
| 0700 to 1100 | 0.18 | 0.88 | 0.51 | 2.03 |
| 1100 to 1500 | **0.44** | -0.19 | 0.24 | 0.57 |
| 1500 to 1900 | 0.33 | -0.78 | 0.48 | 0.32 |
| 1900 to 2300 | 0.30 | -0.04 | 1.02 | 2.27 |
| 2300 to 0300 | 0.31 | 0.56 | 1.04 | 2.82 |
| **0400 to 0600** | **0.27** | **1.09** | **1.16** | **3.03** |

***Time and Condition Filtered UHI in °C***

| | KLOU | D1289 | KFTK | CW3169 |
|---|---|---|---|---|
| 0300 to 0700 | **0.82** | 1.92 | 1.72 | 4.42 |
| 0700 to 1100 | 0.32 | 1.29 | 1.29 | 2.32 |
| 1100 to 1500 | 0.48 | 0.44 | 0.79 | 1.04 |
| 1500 to 1900 | 0.25 | 0.02 | 0.68 | 1.28 |
| 1900 to 2300 | 0.41 | 1.09 | 1.69 | 4.46 |
| 2300 to 0300 | 0.77 | **1.99** | **1.90** | **4.84** |
| **0400 to 0600** | **0.92** | **1.99** | **1.80** | **4.44** |

Generally, maximum heat island values were found during the nighttime hours while the minimum heat island occurs during the midday – afternoon hours.

## CONCLUSIONS

We assessed the Louisville urban heat island utilizing climatological analysis between one control and four experimental stations for 2009 – 2013. Hourly observations were computed as average differences on several different time scales to adequately define the yearly, monthly, and daily patterns of the heat island. We also determined the validity of several UHI generalizations made in the literature. In general, results from the 5-year observations show:

(a) Seasonally, the Louisville UHI is at a minimum during the winter months December – March. The summer months show relatively higher values, although October seems to be the month of maximum UHI values. This contrasts to what has generally been observed at mid-latitudes and it is considered that climatologically warmer summers for three of the years may have resulted in increased anthropogenic heating and energy consumption, resulting in higher emissions which caused the urban environment to be warmer that the rural surroundings.

(b) KFTK, at 42 km from the urban center, exhibited a more diminished heat island signature on all scales than was expected. A heat island may exist here as the station is not truly rural and instead is surrounded by a military installation and near a small town. A large forest 6 km to the east would provide an excellent contrast of environment for the consideration of a very localized UHI study.

(c) At the rural station, CW3169, the heat island was most pronounced during all of the analysis. This could be attributed to the surrounding environment, which is mostly wooded or agricultural and abundant with water features that could influence soil moisture content and winds. By examining the ‘unfiltered’ dataset, we found that for 68.1% of the days studied, there existed a heat island greater than 1°C. When we reduced the observations at this station to only the hours 2300 – 0300 with ideal meteorological conditions, we discovered a 4.84°C UHI.

(d) Increasing wind speeds, the presence of precipitation and sky conditions of mostly cloudy and above generally act to mitigate the heat island. The UHI effect was least prominent and often negative at all stations when precipitation was occurring. Wind speeds above 3.0 $ms^{-1}$ affected temperature differences the least. During hours where sky conditions were hazy, clear, or partly cloudy, the UHI was seen at all stations and to a much greater degree at CW3169 and KFTK. This could be because the distance between the control and these experimental stations make them less subject to the same cloud or storm coverage.

(e) Segregating the daily period into six time intervals allowed us to obtain that the minimum heat island at all stations occurs during the daytime hours between 1100 – 1900 hours while the maximum signatures occur moreover during the nighttime hours. We were unable to verify that the hours just before daybreak were the most significant.

It would have been beneficial to obtain the entire climatology period of thirty years. Unfortunately, this is not possible, unless comparing only the stations KFTK, KSDF, and KLOU. Using only these stations would yield a low spatial context however, as two of the stations are within the urban area. Only a few CWOP stations exist within 50 km of the urban center that are older than the period of study, but again, the majority of these are within the urban area. Thus, the Louisville area would benefit from the creation of a mesonet (network of observation of stations), to ensure proper quality control and coverage at adequate spatial and temporal scales.

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