The Urban Heat Island of Cincinnati, Ohio

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The city of Cincinnati, Ohio, occupies a continental position in mid-latitude North America. With a metropolitan population of about 2 million, the city core area is heavily urbanized. Using a network of data loggers to monitor air temperature every 15 minutes, we demonstrate the existence of a strong urban heat island (UHI). The urban core area averaged 2.0° C warmer than a rural reference site over a one-year period, but the heat island was stronger in summer due to solar forcing. Heat advected from the city center toward nearby sites in wooded highlands appear to increase the air temperature by about 1.0° C. The strength of the UHI increased as wind velocity decreased. On a daily basis, the UHI in the city core reaches its peak intensity in the mid-afternoon but persists throughout the evening hours. Heat advected to surrounding sites demonstrates a similar but modulated daily pattern. These effects are strongly influenced by meteorological conditions; during cloudy and windy periods, the UHI is weak and the spatio-temporal variability is limited.

Keywords: *Air temperature, instrumentation, urban climatology, urban heat island, urban meteorology*

INTRODUCTION

Urbanization represents one of the most extreme and concentrated expressions of environmental modification by humans. The thermal impact has two primary components. First, the preexisting vegetation cover is replaced with materials that are largely impermeable, of low albedo and with large thermal inertia (Landsberg, 1981). Horizontal and vertical surfaces composed of brick, asphalt and concrete alter the surface energy balance, especially given the altered geometry of the incident surfaces (Grimmond and Oke, 1999). The net effect is to increase the absorption and retention of solar and thermal radiation. Second, urbanized areas entail an increased concentration of human activities, both sedentary and transient (Douglas, 1983). There is enhanced energy utilization for industrial purposes, space heating and cooling, lighting and transportation. Nearly all of the energy contained in fossil

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Geography Research Forum • Vol. 27 • 2007: 10-28

fuels is converted to heat in the internal combustion engine, which ultimately adds to the enthalpy of the urban atmosphere. Secondary effects associated with urbanization are increased cloudiness and precipitation, enhanced pollution effects, and local modification of the wind regime (Oke, 1987).

The alteration of the surface and concentration of energy utilization typically results in warmer urban temperatures, and is termed the "urban heat island"or UHI. As urban and suburban areas expand and coalesce, isolated heat islands merge and tend to intensify. On a global basis, three percent of the terrestrial surface is currently characterized as urban and, by 2025, 60 percent of the world's population are projected to live in urban areas (UNPF, 1999).

Urbanization effects on the local climate have been the subject of intensive research for the past four decades (Oke, 1987). The impact is typically quantified as the urban heat island magnitude (UHIM), defined as the difference between the air temperature (ΔT) measured at one or several rural sites (T_r) and the temperature measured at urban sites (T_u) over a given time period. If analyzed over a daily (d) period, the UHIM = $\Delta T_{d,\ u\text{-}r}$, and similar calculations can be performed for hourly (h), monthly (m), seasonal (s) and annual (y) periods (Hinkel et al., 2003). More recently, thermal satellite imagery has been incorporated to understand the spatial patterns and variability of temperature in the urbanized area. Such imagery measures the emission temperature of the surface of the ground, roofs, and tree tops, and is not directly related to near-surface air temperature (Prihodko and Goward, 1997). Further, satellite scenes are available only periodically or episodically, with the acquisition frequency dependant on the sensing platform and local atmospheric conditions. Thus, air temperature measurements are used to calibrate satellite imagery and obtain continuous estimates of the air temperature field over time and space (Voogt and Oke, 1998; Gonzales, 2005).

The objectives of this study are to: (1) quantify the urban heat island magnitude in the core area of the city of Cincinnati, Ohio as it varies over the daily and annual time periods; (2) estimate the impact of heat advection by wind from the city core to nearby sites; and (3) quantify the degree of spatial variability in the UHIM using a network of monitoring sites.

STUDY AREA AND PREVIOUS STUDIES

The City of Cincinnati is in the mid-latitudes at around 39°N 84°W. The climate is classified as humid-subtropical continental (Cfa of Köppen), with distinct seasons ranging from warm and humid summers to moderately cold winters. Most precipitation occurs as snow and rain during winter and spring, while the driest seasons are late summer and autumn (NCDC, 2004). The greater Cincinnati-Northern Kentucky area has an approximate population of 2 million (U.S. Census Bureau, Population Division, 2004).

The bedrock in the study area is horizontal Paleozoic sedimentary rock that forms a plateau. The Ohio River and tributaries have incised deep channels into the strata, yielding a dissected plateau with steep-sided stream valleys. Cincinnati is located on the north side of the Ohio River, where the valley is somewhat broader due to tributary confluence. The Mill Creek enters from the north and is associated with a broad, oversized valley. The Licking River drains central Kentucky and enters from the south. The Ohio River at Cincinnati is 137m asl., and the city center is developed on a series of fluvial terraces extending from 152-183 m asl. Steep wooded slopes separate the city from the upland plateau, which lies ~ 245m asl. Thus, the relief between the city center and surrounding uplands is 60-90m, sufficiently small that it is not necessary to adjust temperatures using the normal lapse rate.

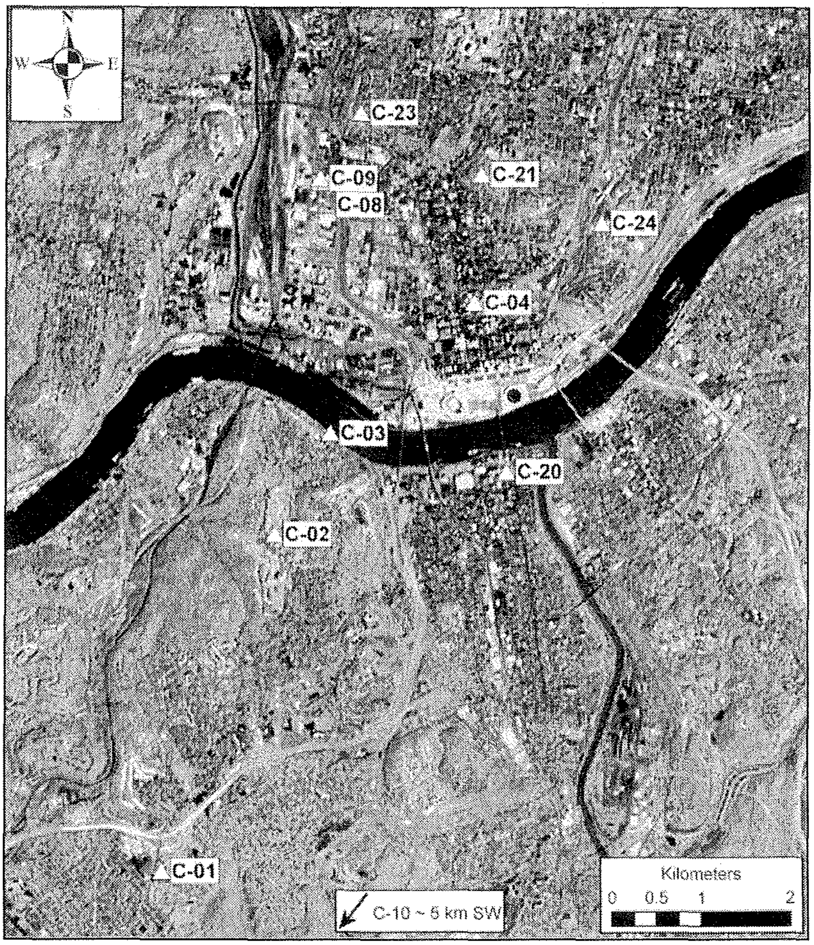
A recent study was conducted by Bell (2004) using a network of thirteen sites deployed along a 70-km transect oriented NNE by SSW. The transect incorporates the greater Cincinnati area, and bisects the city center with rural sites anchoring each end of the transect. The initial network was established in June 2002 and collects high-frequency (15-minute) measurements of air temperature. By analyzing the record for a one-year period (June 2002-June 2003), Bell documented an average UHIM of ~ 2° C for sites in the city center. However, there was pronounced seasonal variability with the summer period exhibiting the strongest UHIM, a pattern typical for mid-latitude cities (Arnfield, 2003). Bell also verified what other researchers have observed: that low wind speeds and increased ambient temperatures result in greater UHI magnitudes (Landsberg, 1981; Oke, 1987).

The methodology for this study was to surround the city core area with additional temperature recording instruments (Figure 1). These are positioned on the wooded slopes near the plateau surface, and record the temperature signal entering and leaving the city given sufficient wind. Several instruments are deployed in the city center to monitor local heating, and several others are positioned along the banks of the Ohio River to measure the impact of the water body and fog formation on air temperature.

INSTRUMENTATION AND METHODOLOGY

The data loggers used in this study are the StowAway XTI model manufactured by Onset Computer Corporation®. These units have a range of -37 to 46° C, with a nominal resolution of 0.32° C. All loggers were set to record temperature at a 15-minute time interval and are synchronized to record on the hour. Thus, the daily record consists of 96 readings, which are used to calculate the mean daily temperature and daily temperature extremes. Thermistors are mounted in a 6-plate radiation shield attached to an instrument mast, with the thermistor positioned 1.8 m above the ground surface.

Figure 1: Location of Temperature Recording Devices.

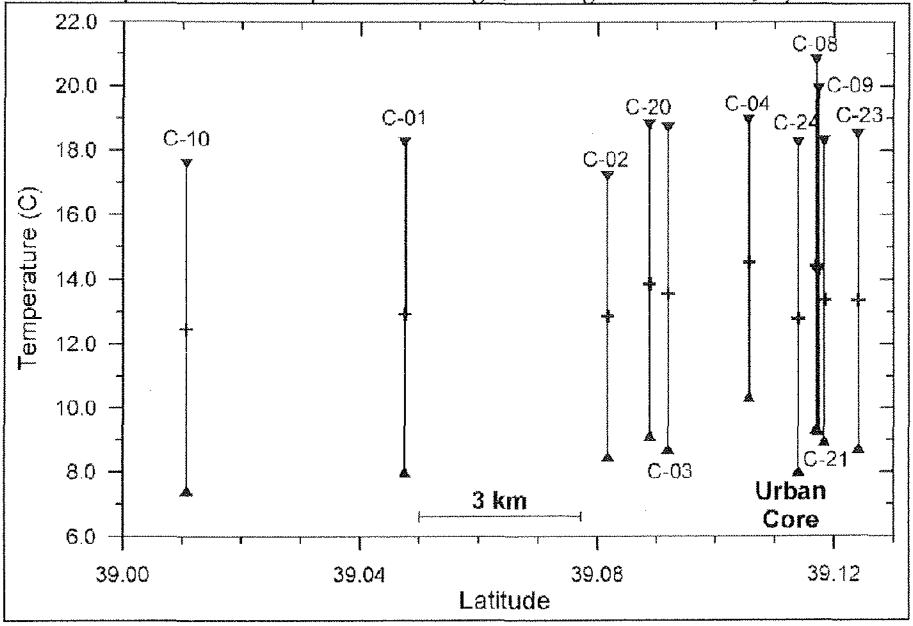


Source: Landsat-7 scene from 17 July 2000 (Path 20, Row 33, contrast enhanced and sharpened) showing location of study sites near downtown Cincinnati.

To quantify the magnitude and spatial variability of near-surface air temperature near the city center, eleven sites from the expanded network were used (Table 1). Some sites were established in 2002, whereas others were installed in May 2004. Several loggers were vandalized, malfunctioned, or the record was contaminated. The records were largely intact for the period 1 August 2004 to 31 July 2005, so this 365-day period (N=35,040) will be analyzed in this paper.

There are two sites that are used as reference owing to their location and quality of the record. C10 is a rural location in a farmer's meadow about 10 km south of the city center (Figure 2). Annual statistics (Table 2) demonstrate that this was the coolest site, with a mean annual temperature of 12.46° C. Site C02 is a suburban reference site located in Devou Park just south of the Ohio River and about 3 km south of the city center. The column labeled "vs. C-10" in Table 2 is the difference between the site-specific mean annual temperature and the reference ($\Delta T_{y,\, u\text{-}C10}$); note that the suburban C02 site averages 0.42° C warmer than the more rural C10 site. A similar comparison is performed for reference site C02 and all other sites ($\Delta T_{y,\, u\text{-}C02}$).

Figure 2: Mean daily (cross), mean daily maximum temperature (triangle), and mean daily minimum temperature (triangle), 1 August 2004 - 31 July 2005.



Note: Sites are plotted by latitude.

Site C01 is located in a cemetery about 4 km south of C02. Summary statistics indicate that the record is very similar to C02 (Table 2; Figure 2), so this site will not be extensively analyzed. Sites C03 and C20 are located on the south bank of the Ohio River; C03 is on the bank ~20 m above river level and situated in an area vegetated with shrubs, vines and grasses. C20 is located in a small park in downtown Covington, Kentucky. Note the slightly elevated temperature at C20; both sites are somewhat warmer (0.7-1.0° C) than C02.

Table 1: Location and description of sites used in this study.

Location	Lat	Long	Elev (m)	Description
Highland Cemetery	39.04753	-84.55096	265	Suburban, well exposed site on lawn
Devou Park	39.08166	-84.53831	248	**Suburban Reference**; near hill summit in park, well exposed
Harbour House Apts	39.09200	-84.53173	160	Scrub brush on edge of cut bank of Ohio R.
Cinti-Ham Co Library	39.10563	-84.51398	168	Urban; small vegetated courtyard of library with high brick wall
I-75, East	39.11703	-84.53355	152	Urban; in scrub brush east of I-75 near road edge
I-75, West	39.11739	-84.53446	151	Urban; scrub brush west of I-75 near road edge, 150 m from C08
Tree Farm	39.01062	-84.58478	268	**Rural Reference**; rural in middle of large meadow in tree farm
Memorial Park	39.08882	-84.50896	152	Middle of small grassy park near Ohio R.
Jackson Hill Park	39.11841	-84.51379	245	Hidden in sapling grove with good southern exposure
Clifton Hts	39.12404	-84.52955	227	Hidden in sapling grove with good southern exposure
Eden Park, Art Museum	39.11406	-84.49802	232	Well exposed in high grass

Table 2: Summary air temperature statistics for the period of record.

Site No.	AvgDaily Temp-C	Year Minimum	Year Maximum	AvgDaily Max-C	AvgDaily Min-C	AvgDaily Range-C	vs. C-10	vs. C-02
C01	12.94	-12.70	30.82	18.26	8.00	10.26	0.48	0.06
C02	12.88	-12.45	29.98	17.19	8.49	8.70	0.42	
C03	13.56	-11.25	30.86	18.70	8.73	9.97	1.10	0.67
C04	14.55	-9.92	32.21	18.94	10.35	8.60	2.09	1.67
C08	14.42	-11.14	33.10	20.82	9.34	11.47	1.96	1.54
C09	14.32	-11.87	32.32	19.93	9.29	10.63	1.86	1.44
C10	12.46	-13.14	29.83	17.59	7.44	10.15		-0.42
C20	13.86	-10.68	31.87	18.79	9.14	9.65	1.40	0.98
C21	13.36	-11.10	30.90	18.29	8.96	9.33	0.90	0.48
C23	13.36	-10.79	30.13	18.51	8.76	9.74	0.90	0.48
C24*	12.78	-11.49	31.18	18.25	8.02	10.23	0.32	-0.10

Note: The table shows average daily temperature, daily extremes (maximum and minimum) during the year, average daily maximum and minimum temperatures, and average daily temperature range. The final two columns reflect the comparison of the site-specific mean annual temperature (ΔTy, u-r) to the two reference sites (C10 and C02, in italic).

Three sites are in or near the city center. Site C04 is located in a small vegetated walled courtyard of the Cincinnati-Hamilton County Library; it is within the central business district and experiences significant shading and heat retention from nearby buildings. Sites C08 and C09 are located on the east and west side of Interstate 75, respectively; both sites are in the shrubby vegetated apron within m of the highway. At these sites, the radiation shield is mounted on saplings. The records for these two sites are very similar, so only C08 will be analyzed here.

There are three sites positioned near the top of the steep slopes to the north and east of the city, but within 1-2 km of the city core. They are located in parks or extensive areas of vegetation (Spronken-Smith and Oke, 1998). C23 is located directly north of the city in low shrubs and grass. During the period of record, the logger had to be relocated when the homeowner moved. Site C21 is located in Jackson Park to the northeast of the city center; the radiation shield is attached to a sapling in a dense stand of immature trees that produce some shading. The park is heavily used, so it was not feasible to locate the instrument in an open area. Site C24 is located east of the city in Eden Park, on the grounds of the Cincinnati Art Museum. This site is well exposed, grassy, and secure. However, the instrument failed to record temperatures for a 26-day period in late spring 2005.

Since some records are faulty and others redundant, only key sites will be further analyzed. This is also necessary to reduce clutter in subsequent figures.

THE ANNUAL PATTERN

Mean daily temperatures for the period are plotted in Figure 3 for selected sites. There are several things to note. First, synoptic-scale variations are apparent as semi-cyclical peaks and troughs in the traces, and these reflect air mass replacement typical of this part of the continent. Second, winter 2004-05 experienced a singularity as a prolonged warm spell from the end of December to mid-January; temperatures were well above normal (10-15° C). Finally, the urban core sites (C04 & C08) and C21 are substantially warmer than the reference site (C02) in summer, but very similar in winter. As shown in Table 2, a comparison of the urban core sites (C04, C08 & C09) averaged over this time period yields a UHIM of ~2.0° C relative to C10.

The seasonal pattern becomes more apparent in Figure 4, which shows the temperature difference between several sites and the reference C02 site. Using 15-minute measurements, the time-specific temperature of the C02 site was subtracted from the individual site temperature ($\Delta T_{15,\ u\text{-}C02}$), and the resulting trace was smoothed. Note that the two urban sites, C04 and C08, have consistently higher temperatures (positive values) than the reference site; averaged over the year, these are 1.67° C and 1.54° C respectively as shown in Table 2. Note, however, that there is a seasonal pattern to the traces, with greater temperature difference in summer and reduced differences in winter as noted by others (Arnfield, 2003; Oke, 1982). During the summer months (June-September), the two core urban sites average ~2.0° C warmer; in winter (December-February), the two urban sites are 1.4° C warmer. Thus, the average values mask the seasonal pattern. This suggests that the UHIM is partially driven by the seasonal cycle of insolation, and emphasizes the importance of heat absorption and retention in the downtown core area (Landsberg, 1981; Klysik and

Figure 3: Time series of mean daily temperatures for period of record (1 August 2004 – 31 July 2005).

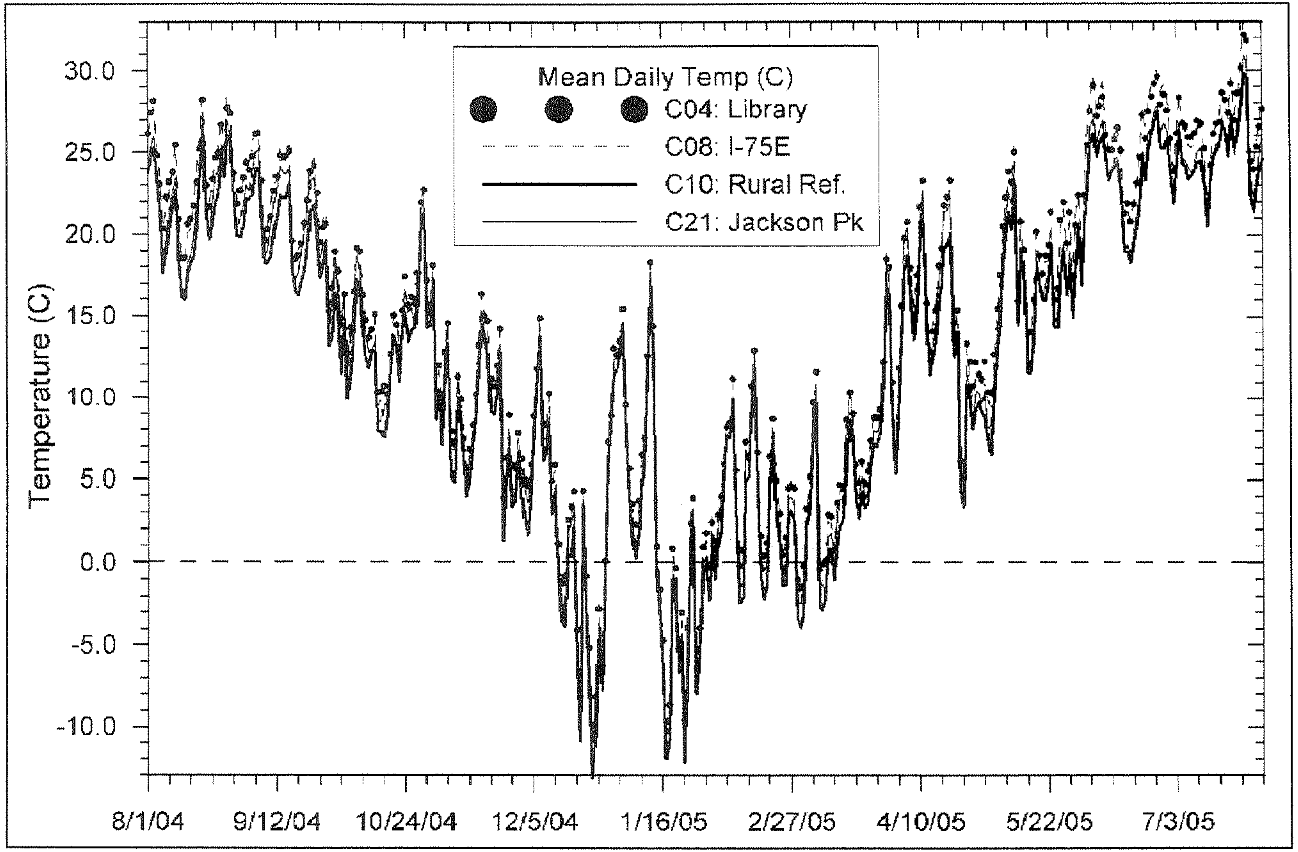
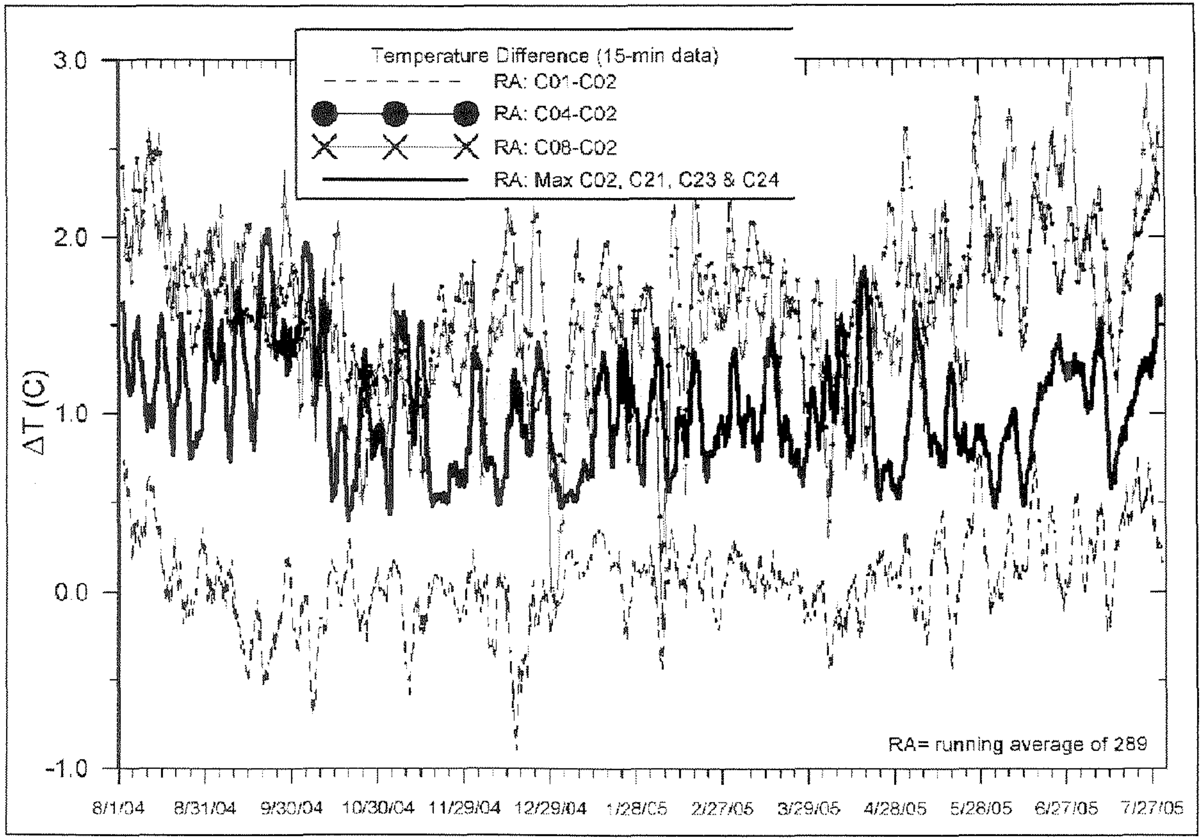


Figure 4: Site-specific temperature difference (ΔT) for selected sites using C02 (Devou Park) as the reference.



Note: ΔT is calculated using the 15-minute data set, traces are smoothed using a running average (RA) of 289. Positive values indicate that the site temperature is warmer than C02. The bold trace is the maximum difference between the upland sites C02, C21, C23 and C24.

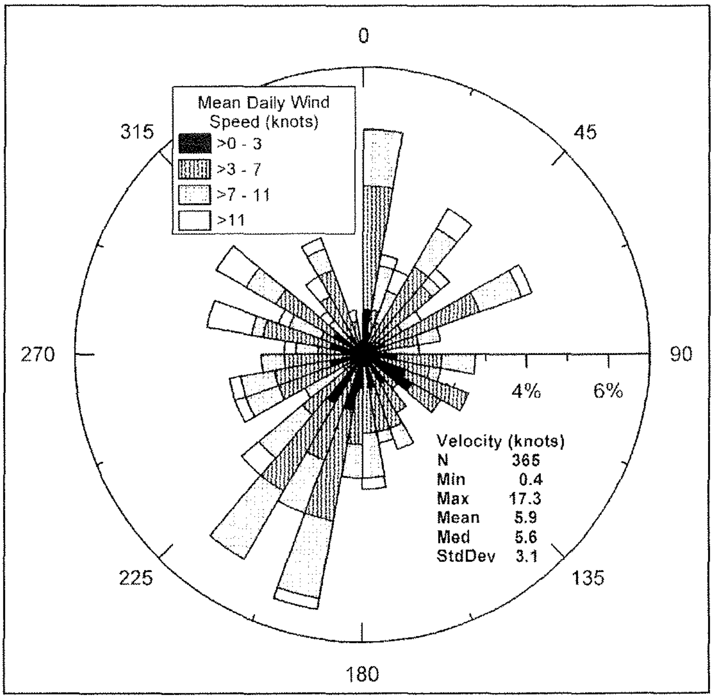
Fortuniak, 1999; Philandras et al., 1999).

By contrast, C01 is several km south of C02. The difference trace demonstrates no seasonal pattern and the average annual temperatures are nearly identical.

THE IMPACT OF WIND

The previous analysis assumes that site C02 consistently represents the input signal to the city, while the remaining upland sites (C21, C23 & C24) represent the response due to urbanization. This scenario is likely only when the wind is from the south or southwest. However, as Figure 5 demonstrates, there is a significant occurrence of winds from other directions and, in these instances, site C02 may record the response. To account for this, the maximum observed difference for sites C02, C21, C23 and C24 is calculated and plotted in Figure 4. The trace is displaced by an average of 1.03° C above the base, and shows a slight seasonal pattern with enhanced temperature difference in the summer months. This more likely represents the signature of heat advection since it crudely accounts for variable wind direction.

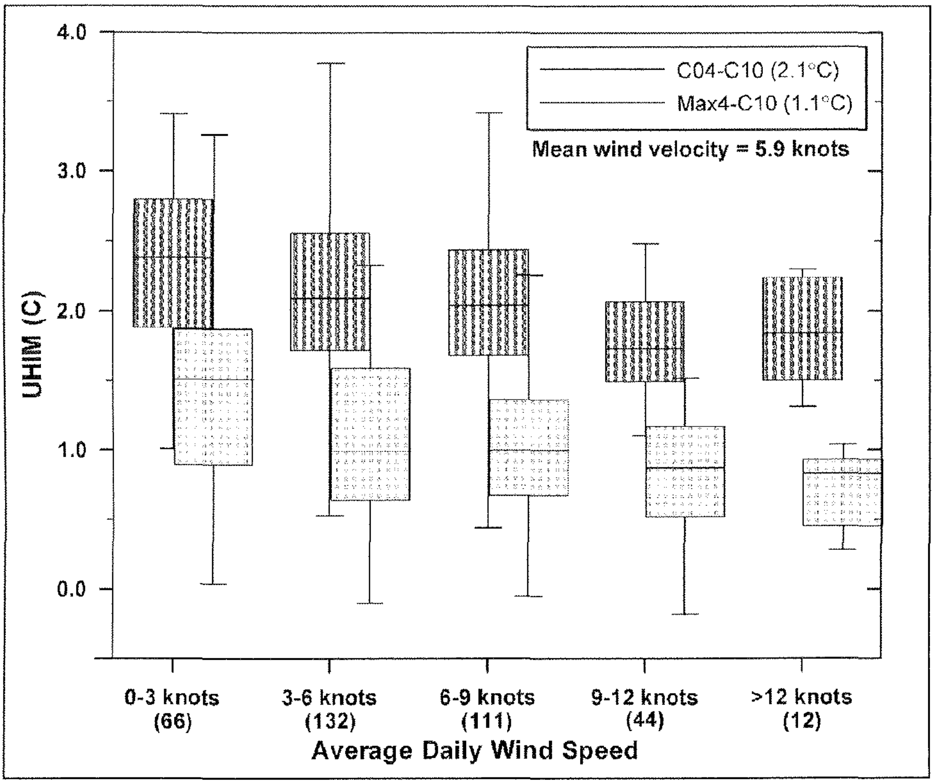
Figure 5: Average daily wind velocity (in knots, where in knot ~ 0.5 $\mathrm{m\ s^{-1}}$) and direction for period of record, with summary statistics.



Source: Data is from the NWS at the Greater Cincinnati/Northern Kentucky International Airport (Station 151855), located 20 km southwest of the city center.

Wind velocity also has an impact on the UHI magnitude. Many researchers report that, as wind velocity increases, the UHIM decreases (Oke, 1973; 1988; Hinkel *et al.*, 2003; Gedzelman et al., 2003). This is attributed to the increased rate of turbulent heat transfer to the atmosphere, and the mechanical mixing of air in an urban landscape with large roughness elements. The impact can be assessed by comparing daily wind velocity to the average daily UHIM, calculated between the rural reference site (C10) and urban sites ($\Delta T_{d,\ u\text{-}C10}$). This is done in Figure 6 for site C04, which had an average UHIM of 2.1° C. Note that the median UHIM decreases from about 2.4° C under calm conditions (0-3 knots, where 1 knot ≈ 0.5 m s^{-1}) to ~1.8° C when wind velocity exceeds 12 knots. A similar pattern is observed for site C08 (not shown), which had an average UHIM of 2.0° C. The pattern for upland sites (maximum of C02, C21, C23 & C24) is similar, but with a reduced magnitude; the average of the maximum daily reading recorded at the four sites is 1.1° C.

Figure 6: The impact of daily wind speed (knots) on the UHI magnitude.



Note: The impact of wind speed is calculated by subtracting the mean daily temperature of reference site C10 from downtown site C04. The same procedure is applied to the maximum reading for the four upland sites (C02, C21, C23 & C24). The number of observations observed in each wind bin is shown in parentheses.

THE DAILY PATTERN

The temporal patterns and magnitude of the urban heat island impact is best understood by examining daily patterns using the 15-minute data set. This is done in Figure 7, which graphs temperature traces for selected sites over the period 22-24 July 2005. During this 3-day period, daily wind velocity and direction averaged 4.6 (330°), 1.0 (70°) and 5.6 (230°) knots, respectively—somewhat less than the annual average of 5.9 knots. Skies were mostly clear though hazy, and there were afternoon thunderstorms. Temperatures were normal for this time of year.

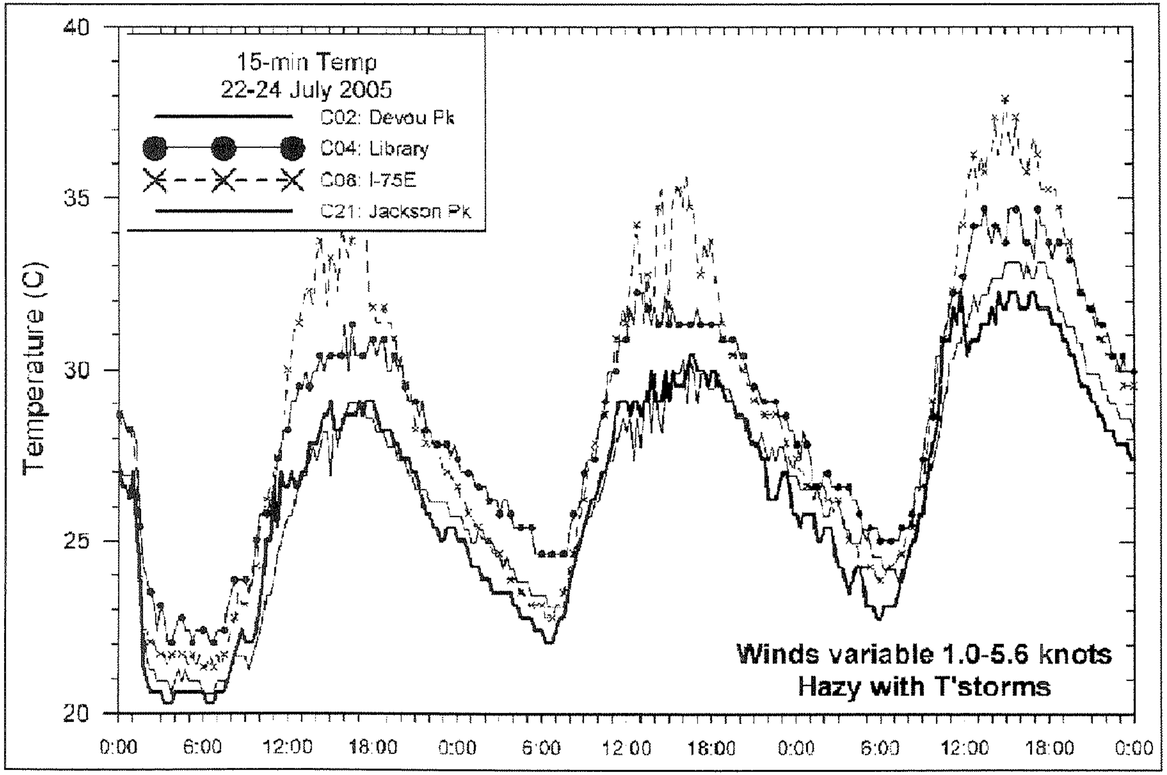
The evening hours consistently demonstrate elevated temperatures at the two urban core sites (C04 & C08) relative to reference C02; to a lesser degree, the same pattern is apparent at the C21 site. From sunrise until around 17:00, the urban core sites show rapid warming and peak temperatures 5-7° C warmer. This pattern persists throughout the remainder of the afternoon and evening. The Library site (C04) does not cool effectively at night, and temperatures remain several degrees warmer; a previous study in Cincinnati (Clarke and McElroy, 1970) also demonstrated the formation of a complex nocturnal UHI. C08 demonstrates cooling during this period, with only slightly elevated (~1.0° C) evening temperatures. The C21 site has a record nearly identical to C02 for the first two days, with similar morning temperatures and slightly elevated evening temperatures. During this period, winds are from the northeast and east. On the third day, however, winds are from the southwest and temperatures in midday and afternoon were elevated ~1.0° C. This likely reflects the effects of heat advection from the downtown core northeast toward site C21. As shown in Table 3, the urban core sites are ~2.1° C warmer than C02 and experienced much higher maximum temperatures. The C21 site averaged 0.3° C warmer.

Table 3: Summary air temperature (°C) statistics for three-day periods (n=288) by site.

22-24 July 05	C02	C04	C08	C21	C04-C02	C08-C02	C21-C02
Min	20.3	22.0	21.3	20.6	-0.4	0.0	-2.8
Max	32.3	34.7	37.9	33.1	3.6	6.1	2.2
Range	12.0	12.7	16.6	12.6	4.0	6.1	5.0
Mean	26.5	28.6	28.8	26.8	2.0	2.2	0.3
Median	27.0	28.9	28.7	26.9	2.0	1.7	0.3
11-13 Jan 05	C02	C04	C08	C21	C04-C02	C08-C02	C21-C02
Min	2.4	4.4	3.9	3.1	-2.0	-2.0	-1.2
Max	18.9	20.3	20.3	19.5	3.4	1.7	1.3
Range	16.6	15.9	16.4	16.5	5.4	3.7	2.5
Mean	14.1	15.1	14.9	14.6	1.0	0.8	0.5
Median	15.7	16.6	16.3	16.3	1.0	1.0	0.6

Note: The last three columns show the difference relative to the reference site (C02) (ΔT 3d, u-C02).

Figure 7: Three-day temperature time series at 15-minute intervals for selected sites during a hot calm summer period 22-24 July 2005 .



Note: Summary statistics are shown in Table 3.

In contrast, the period 11-13 January 2005 was 13-19° C warmer than normal, and was characterized by clouds and rain. Winds were consistently from the southwest (200-220°) and averaged 7.8, 12.3, and 8.5 knots for the three days, respectively. Figure 8 documents the invasion and replacement of the warm air mass, clearly associated with the periods of rapid temperature change at the beginning and end of the period. The figure also demonstrates the lack of diurnal forcing and close tracking of all traces. The urban core sites show elevated temperatures of ~1.0° C, while the C21 site is slightly warmer (~0.5° C) than C02. Again, it appears that C21 is reflecting the effects of heat advected from the city core. Further, as indicated by the mean value (Table 3), the magnitude is actually greater than experienced in the previous example when solar forcing was strong.

This pattern of trace divergence during the day can be further examined by plotting the site-specific temperature difference as a function of time. To do so, only measurements collected on the hour will be used to avoid clutter. In Figure 9, temperatures from C08 and C21 are compared to C02 for each hour throughout the period of record and are presented as Box-and-Whisker plots. Note that the median values for C21 ($\Delta T_{h,\,C21-C02}$) hover around 0.5° C, and there is limited range in the 2nd and 3rd quartiles. For C08, the median value changes dramatically during the daylight period, and the range for the middle quartiles in much larger. Median values for both sites are similar for the period 22:00 to 04:00, after which they diverge and reach a maximum difference of 3.5° C around 14:00. This demonstrates the strong diurnal temporal pattern of the heat island and is clearly related to solar forcing at sites where the surface has been highly modified.

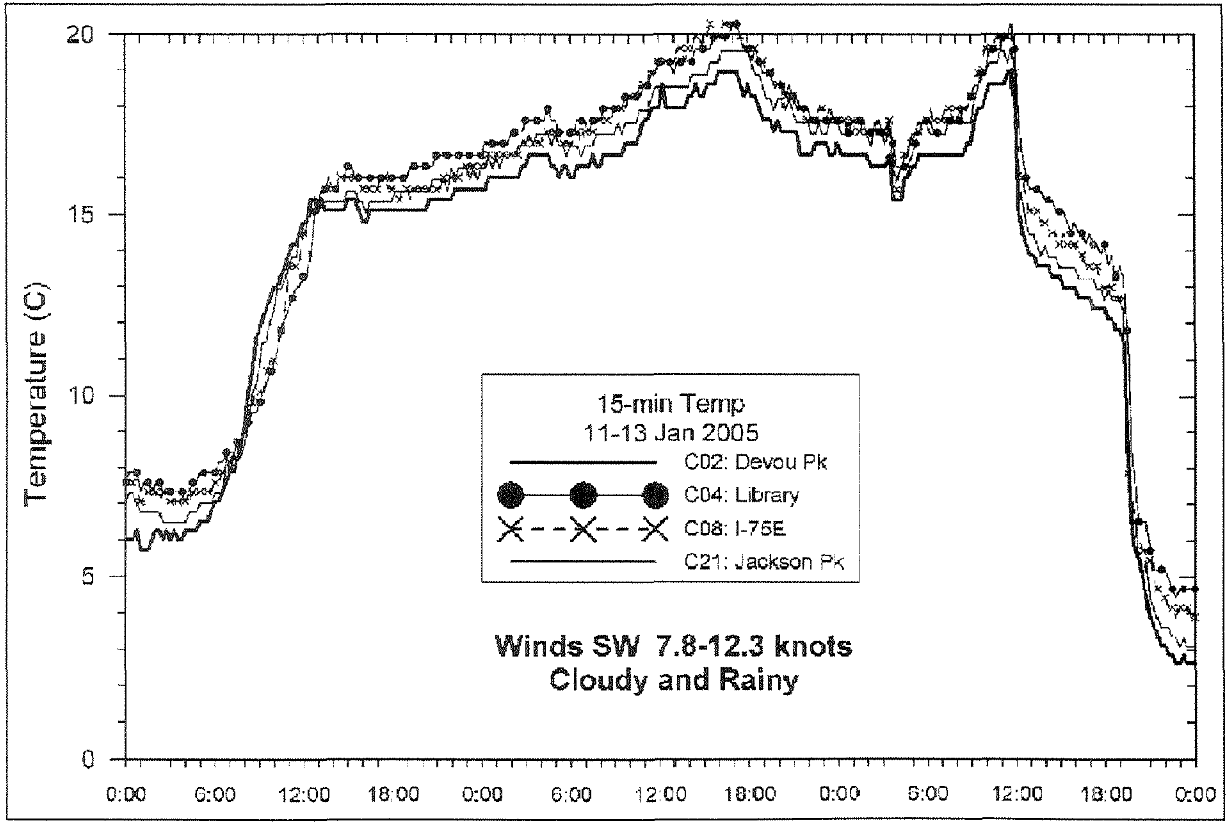
Discussion and Conclusions

The magnitude of the urban heat island has been quantified by a number of researchers. The estimated value depends on the specific city, the sites used to make urban-rural comparisons, and the time period under consideration. Since the UHI has strong spatial and temporal components, it is best examined using a dense spatial network of temperature data loggers collecting measurements at high frequency. This approach is now feasible given the availability of inexpensive precision logging systems. Coupled with high resolution thermal satellite images to accurately calibrate the emission spectra (Quattrochi and Ridd, 1994), UHI dynamics can now be more fully quantified.

Near the downtown core area of Cincinnati, analysis of the data collected over a one year period using high-frequency site records reveals the following conclusions:

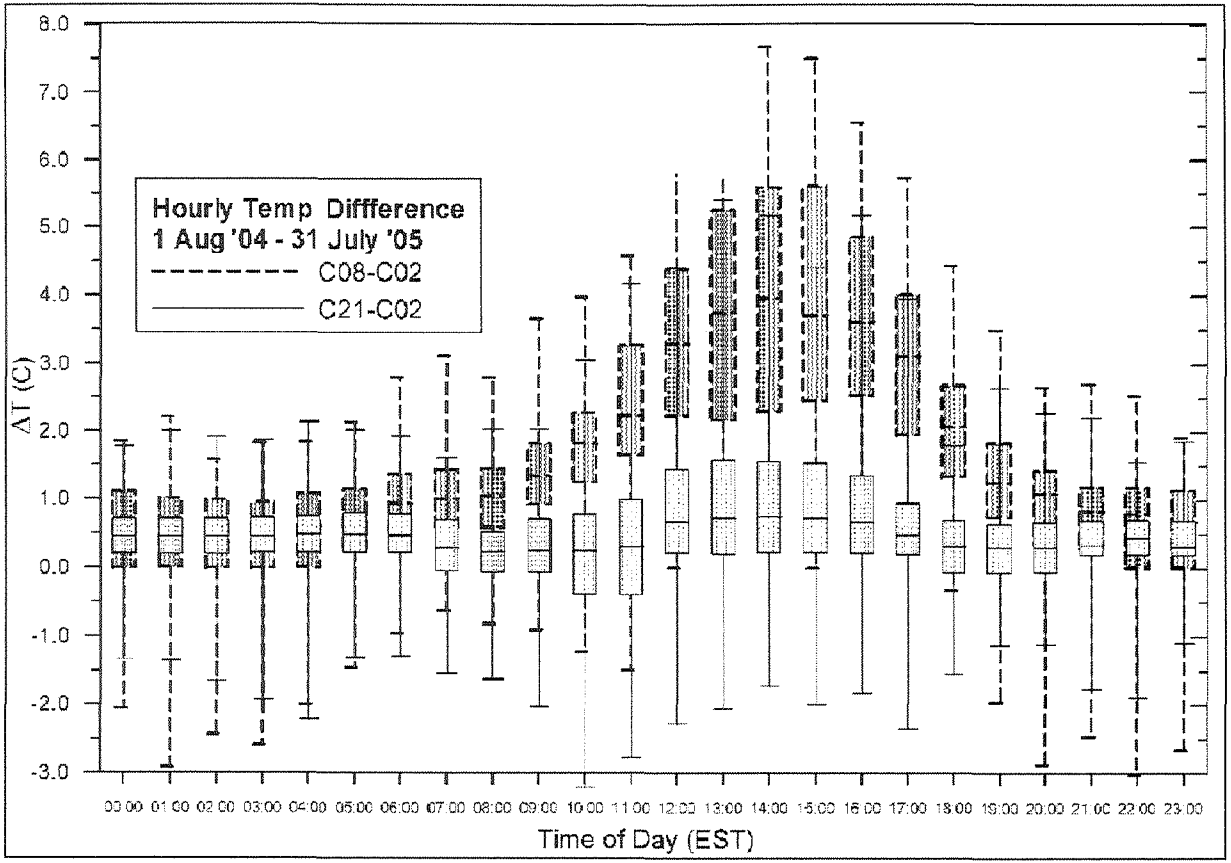
1. Sites in the city core area average ~ 2.0° C warmer than the rural reference site. However, the UHIM is greater in summer and reduced in winter owing to solar forcing;
2. Heat advection from the city center toward highland sites surrounding the city appears to increase the air temperature by an average of 1.0° C. The effect is

Figure 8: Three-day temperature time series at 15-minute intervals for selected sites during a cloudy windy winter period 11-13 January 2005.



Note: Summary statistics are shown in Table 3.

Figure 9: Box-and-Whisker time series plots of hourly temperature differences ($\Delta T_{h,}$C02 reference) for an urban site (C08) and upland site (C21).



Note: Boxes represent the 2nd and 3rd quartiles, with the median value shown as a horizontal line. Outliers are not represented in these plots.

more pronounced in summer;

3. Both the UHIM and the advected heat component decrease with increasing wind velocities;

When considering diurnal time periods:

4. The UHIM varies with the site location and specific meteorological conditions. In general, urban sites have elevated temperatures throughout the period but demonstrate strongest UHIMs in mid-afternoon under clear sky conditions. Under cloudy and windy conditions, there is a weak UHI but little spatial or temporal variation in temperature (Runnalls and Oke, 2000);
5. Urban core temperatures differences are consistently higher throughout the diurnal cycle, but are maximized in the urban center in mid-afternoon. The advected heat component is consistently slightly higher (0.5° C), with only mildly elevated differences in the mid-afternoon.

The seasonal and daily patterns of UHI variation found in this study are consistent with the general conclusions of previous researchers. Studies of North American cities including Cleveland, Boston, Washington, DC and Baltimore showed greatest warming occurred in summer months (Mitchell, 1961; Oke, 1982; Arnfield, 2003). Landsberg (1981) suggests that this supports the view that the primary cause of the UHI is the alteration in the radiation balance, as opposed to anthropogenic heating.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation under grants OPP-9732051 and 0094769 to Kenneth M. Hinkel. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the NSF. Use of tradenames does not imply endorsement by NSF.

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