JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D20109, doi:10.1029/2008JD010311, 2008

Diurnal cycle of the Oklahoma City urban heat island

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Received 22 April 2008; revised 14 July 2008; accepted 20 August 2008; published 22 October 2008.

[1] Between the dates of 28 June and 31 July 2003, the Joint Urban 2003 (JU2003) field project was conducted in Oklahoma City and was the largest urban dispersion experiment ever in North America. Because the focus of JU2003 was on atmospheric processes within the urban environment, an extremely dense network of instrumentation was deployed in and around the central business district (CBD) both prior to and during the field experiment. Among the variables collected were high-resolution observations of air temperature from various instrument sources. Additional observations of air temperature were also collected at Oklahoma Mesonet stations in the rural areas surrounding Oklahoma City. Using an index value, the diurnal cycle of the urban heat island (UHI) for Oklahoma City, with respect to the surrounding rural terrain, was quantified. The results revealed a consistent mean nocturnal UHI greater than 1.5°C at both 2 and 9 m. However, observations at 2 m during JU2003 revealed a significant urban "cool" island during the convective portion of the day. The mean variability of temperature within the urban core of Oklahoma City increased significantly after sunrise, increased to a maximum near solar noon, and decreased following sunset. These results were inconsistent with the rural observations wherein the variability among sites was maximized during the nocturnal period. Finally, the vertical temperature gradient between 2 and 9 m demonstrated a clear and strong diurnal trend at the rural locations, whereas observations from the urban environment were nearly isothermal and consistent with near-neutral conditions throughout JU2003.

Citation: Basara, J. B., P. K. Hall Jr., A. J. Schroeder, B. G. Illston, and K. L. Nemunaitis (2008), Diurnal cycle of the Oklahoma City urban heat island, *J. Geophys. Res.*, *113*, D20109, doi:10.1029/2008JD010311.

1. Introduction

[2] The percentage of humans living in urban areas continues to grow worldwide. Currently in the United States, 64% of the population lives within less than 2% of the U.S. land area [*Dabberdt et al.*, 2000]. In addition, a recent study by the United Nations found that by 2025, 80% of the world's population will live in cities [*United Nations*, 2003], and by 2015, 26 megacities will exist worldwide with populations in excess of 10 million inhabitants [*United Nations Human Settlements Program*, 1997]. As such, the rapid urbanization process has created a critical issue facing the global society: the impact of urban environments on human health.

[3] The results of increased urbanization and environmental hazards lead to more direct and indirect weather-related accidents and deaths as well as significant economic loss [*Changnon*, 1992]. For example, heat waves had devastating impacts in Chicago in 1995 [*Changnon et al.*, 1996; *Semenza et al.*, 1996] and Paris in 2003 where people died due to heat-related illnesses. Unfortunately, the frequency and intensity of heat waves will likely increase in the future [*Meehl and Tebaldi*, 2004]. Many cities have instituted heat watch-warning technologies to mitigate impacts of heat waves [*Ebi et al.*, 2004; *Sheridan and Kalkstein*, 1998, 2004].

[4] The need to quantify urban-atmosphere relationships has spurred research in numerous areas, including changes to surface humidity [*Richards and Oke*, 2002; *Richards*, 2004], varying roughness and turbulence [*Grimmond et al.*, 1998; *Grimmond and Oke*, 1999; *Roth*, 2000; *Kastner-Klein et al.*, 2001], the energy and radiation budgets [*Kalanda et al.*, 1980; *Grimmond and Oke*, 2002; *Christen and Vogt*, 2004], the development of the urban boundary layer [*Angell et al.*, 1973; *Piringer*, 2001; *Cleugh and Grimmond*, 2001; *Martilli*, 2002; *Nair et al.*, 2004], precipitation and hydrological processes [*Dettwiller and Changnon*, 1976; *Shepherd et al.*, 2002; *Rozoff et al.*, 2003], and air quality, dispersion, and pollution [*DePaul and Sheih*, 1985; *Dabberdt and Hoydysh*, 1991; *Kastner-Klein et al.*, 1997; *Kastner-Klein and Plate*, 1999; *Ratti et al.*, 2002; *National Research Council*, 2003]. However, a critical phenomenon which links the aforementioned processes to one another, and poses a significant human impact, is the urban heat island (UHI) that results from differential thermal storage between rural and urban areas [*Bornstein*, 1968].

[5] Urban heat islands have been measured worldwide in climates that are arid such as Mexico City, Mexico [*Oke et*

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0148-0227/08/2008JD010311$09.00

al., 1999], Tuscon [*Comrie*, 2000], and Pheonix [*Hawkins et al.*, 2004; *Fast et al.*, 2005], in temperate zones near large bodies of water including Melbourne, Australia [*Morris et al.*, 2001] and Athens, Greece [*Livada et al.*, 2002], in intercontinental regions with cool climates (e.g., Lodz, Poland) [*Klysik and Fortuniak*, 1999], and in arctic regions (e.g., Barrow) [*Hinkel et al.*, 2003]. In addition, the UHI phenomenon has been observed for megacities (e.g., Mexico City, New York City, etc.) as well as relatively minor urban areas (i.e., population centers less than 500,000 inhabitants) such as Durham [*Kopec*, 1970].

[6] In general, the UHI is determined by measuring temperatures within the urban area and comparing the observations to nearby rural measurements (i.e., temperatures away from the city). Typically, the UHI is greatest at night where temperatures measured within the city are warmer than rural temperatures. In addition, the magnitude of the UHI is dependent upon the location within a city. For example, the core of the city has more impact on the temperature than suburban areas due to the increased heat capacity of the man-made structures versus native vegetation [*Martilli*, 2002]. As for ambient atmospheric conditions, wind speed and cloud cover also impact the magnitude of the UHI [*Nkemdirim*, 1980; *Kidder and Essenwanger*, 1995; *Lu and Arya*, 1997]. High winds and/or cloud cover disrupt the cooling differences between the urban and rural areas and reduces the UHI effect [*Kidder and Essenwanger*, 1995] while calm conditions with clear skies are optimal for large UHI effects [*Nkemdirim*, 1980; *Oke*, 1987; *Lu and Arya*, 1997]. In short, the UHI is most noticeable at night and under synoptic high-pressure systems [*Bornstein*, 1968; *Vukovich*, 1975; *Oke*, 1987, 1988].

[7] The impacts of the UHI effect are not limited to the surface. *Bornstein* [1968] and *Oke* [1987] revealed vertical increases in temperature over urban landscapes compared with rural areas. While surface inversions are rare for cities, due to heat release from urban surfaces, elevated inversion are frequent but weak over the urban area [*Bornstein*, 1968]. There are also many consequences of the UHI. *Gallo et al.* [1996] found that the mean average temperature of a region was affected up to 10 km downstream of an urban area. *Dixon and Mote* [2003] concluded the UHI of Atlanta, GA, did initiate convective precipitation especially during the night. Finally, the effects of the UHI have air quality ramifications. *Bornstein* [1968] concluded that an elevated inversion develops over urban areas at night. This inversion traps pollutants within the city instead of allowing the dispersion to rural areas. Furthermore, a direct, nonlinear relationship exists between ozone formation and temperature [*Kamens et al.*, 1982; *Grey et al.*, 1987]. The UHI can lead to locally higher concentrations of ground-level ozone [*Quattrochi et al.*, 2000], and ground-level ozone would increase 2–4% with a 2°C increase in temperature and 5–10% with a 5°C temperature increase [*Grey et al.*, 1987].

[8] Unfortunately, in North America, the majority of real-time, continuous, research-quality atmospheric observations are not collected within the core regions of cities. To date, much of the current understanding of the impacts of urban areas on atmospheric processes results from a number of field programs including those conducted in a number of North American cities, including St. Louis (Metropolitan Meteorological Experiment, METROMEX [*Changnon et al.*, 1971; *Lowry*, 1974]), Chicago [*Changnon and Semonin*, 1978], Los Angeles, Vancouver, Montreal [*Mailhot et al.*, 1998], Mexico City, Tucson, Salt Lake City [*Allwine et al.*, 2002], and Phoenix [*Grimmond and Oke*, 1995]. Because of the complex atmospheric processes involved in urban areas, field experiments of this nature are critical to scientific advancements in this area.

[9] During June and July 2003, the Joint Urban 2003 field experiment (JU2003) was conducted in Oklahoma City (OKC). The primary objective of JU2003 was to collect observations of atmospheric conditions and tracers for the purpose of improving urban dispersion models. A vast array of atmospheric sensors collected high-resolution observations in and around the central business district (CBD) of Oklahoma City. Prior to JU2003, instruments were temporarily installed to acquire preliminary measurements of the urban atmosphere in Oklahoma City from July 2002 through May 2003.

[10] Due to the extensive data set collected during JU2003, this study focused on (1) consolidating the available air temperature observations collected prior to and during the JU2003 period and (2) quantifying the magnitude of the urban heat island of Oklahoma City, its diurnal characteristics, and overall variability.

2. Background

2.1. Oklahoma City

[11] In 2003, Oklahoma City spanned approximately 1610 km^2 with a population of approximately 523,000 citizens. The former characteristic places Oklahoma City within the top 10 largest cities by land area in the United States, and the largest city that is not a consolidated city-county. However, the urbanized area of Oklahoma City spanned approximately 630 km^2, which is considerably less than the total area. Embedded with the urbanized area is a well-defined central business district that spanned approximately 20 km^2 with buildings to 120 m in height.

2.2. Joint Urban 2003

[12] Between the dates of 28 June and 31 July 2003, the JU2003 field project occurred in Oklahoma City [*Allwine et al.*, 2004]. JU2003 was the largest urban dispersion experiment ever conducted in North America and focused on understanding atmospheric processes within the urban environment. As such, an extremely dense observing network was installed in and around downtown Oklahoma City including over 140 three-dimensional sonic anemometers for surface-based and tower-based measurements, 13 two-dimensional sonic anemometers, over 30 surface meteorological stations, seven surface energy budget stations, two CTI wind tracer lidars, three radiosonde systems, three wind profiler/RASS systems, one FM-CW radar, three ceilometers, and nine sodars (including midi- and minisodars). These instruments continuously gathered data from surface-based and tower-based measurements at ground level, on traffic poles, the sides of buildings, and on rooftops [*Allwine and Flaherty*, 2006].

3. Data and Methods

[13] This study utilized two main data sets collected prior to and during Joint Urban 2003. The first included temper-

Figure 1a. The location of the PWIDS deployed in the central business district of Oklahoma City from July 2002 to May 2003.

ature values collected from several Portable Weather and Information Display Systems (PWIDS) stations deployed within Oklahoma City on traffic poles as well as observations from six Oklahoma Mesonet sites for the period spanning 1 July 2002 until 9 May 2003. The second data set focused on the JU2003 period and included PWIDS and Oklahoma Mesonet data as well as observations collected from 33 HOBO temperature data loggers installed across Oklahoma City at a height of 2 m.

3.1. PWIDS

[14] As part of a preliminary study for JU2003, PWIDS sites were installed in and near the CBD of Oklahoma City for nearly a year beginning in July 2002. The PWIDS sites measured wind speed, wind direction, temperature, and relative humidity. Thirteen of the PWIDS sites were mounted atop street light/traffic light poles, approximately 9 m above ground level within the CBD (Figure 1a). Two additional PWIDS sites were located on a building rooftop approximately 1 km south of the CBD, and were not used for this study.

[15] During JU2003, the location of the PWIDS sites were changed to better support the field experiment. Again, 13 of the PWIDS sites were located on street light/traffic light poles, approximately 9 m above ground level. How-

Figure 1b. The location of the PWIDS deployed in the central business district of Oklahoma City during JU2003.

ever, the distribution of PWIDS spanned a larger spatial area in and around the CBD (Figure 1b).

3.2. HOBO Temperature Data Loggers

[16] During JU2003, 33 HOBO temperature data loggers [*Whiteman et al.*, 2000] were deployed in and near the CBD to measure the air temperature at 2 m above ground level. Seventeen HOBOs were deployed along a north-south transect centered on the CBD, while the remaining 16 were deployed along a similar east-west transect through the CBD (Figure 2). Six of the HOBOs were colocated with PWIDS stations.

3.3. The Oklahoma Mesonet

[17] The Oklahoma Mesonet is an automated network of over 100 remote, meteorological stations across Oklahoma [*Brock et al.*, 1995; *Shafer et al.*, 2000; *McPherson et al.*, 2007]. Each station measures core parameters that include air temperature and relative humidity at 1.5 m, wind speed and direction at 10 m, atmospheric pressure, downwelling solar radiation, rainfall, and bare and vegetated soil temperatures at 10 cm below ground level. In addition, a majority of the sites measure soil moisture at four depths (5, 25, 60, and 75 cm; *Illston et al.* [2008]) and over 100 sites measure air temperature at 9 m. In an effort to avoid anthropogenic

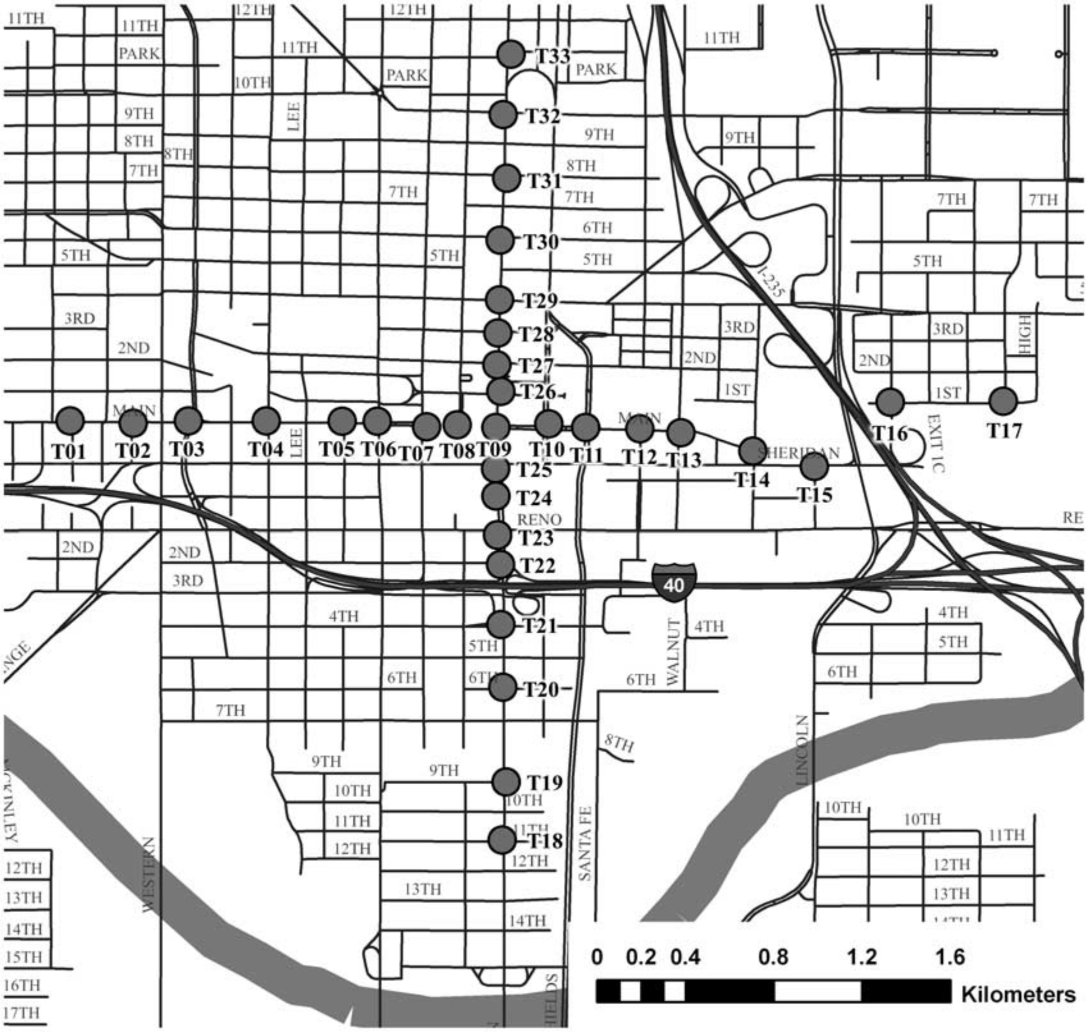

Figure 2. The location of the HOBO temperature data loggers deployed in Oklahoma City during JU2003.

influences, most Oklahoma Mesonet sites are located in rural areas. Mesonet data are collected and transmitted to a central point every 5 minutes where they are quality controlled, distributed and archived [*Shafer et al.*, 2000; *McPherson et al.*, 2007]. This study used data collected from the six sites surrounding the Oklahoma City metropolitan area in 2002–2003: ELRE, GUTH, KING, MINC, NRMN, and SPEN (Figure 3).

3.4. Urban Heat Island Index

[18] The UHI intensity is often defined according to the availability of observations. For example, when a limited number of observation sites are present, the UHI intensity [*Oke*, 1987] is often calculated as the difference between the peak urban-rural temperatures [e.g., *Ackerman*, 1985] using individual observing locations. However, when numerous observation sites are available, UHI intensity can be calculated as the difference between mean urban and rural temperatures [e.g., *Kim and Baik*, 2005]. *Hawkins et al.* [2004] demonstrated that the rural variability of air temperature could impact the calculation of the magnitude of the urban heat island. Thus to eliminate the impact of site-specific variability of temperature for both the urban and rural zones, an index value was used to quantify the composite magnitude of the urban heat island for Oklahoma City:

$$\mathrm{UHII_z} = \mathrm{Tu_z} - \mathrm{Tr_z} \tag{1}$$

Where Tu is the mean temperature of the urban observations, Tr is the mean temperature of the rural observations, and z is the height of the measurements. As such, the $\mathrm{UHII_9}$ was computed for the pre-JU2003 period using the difference between mean temperature collected at the PWIDS (urban temperature mean) and the mean Mesonet temperature (rural temperature mean) at a height of 9 m. Similar computations were applied to the JU2003 data set at both the 2- and 9-m height values.

3.5. Data Quality and Processing

[19] During the 10-month pre-JU2003 period, between 10 and 15 PWIDS were deployed near the CBD. Because PWIDS 9 and PWIDS 10 were deployed on the rooftop and tower of the post office building south of the CBD, data

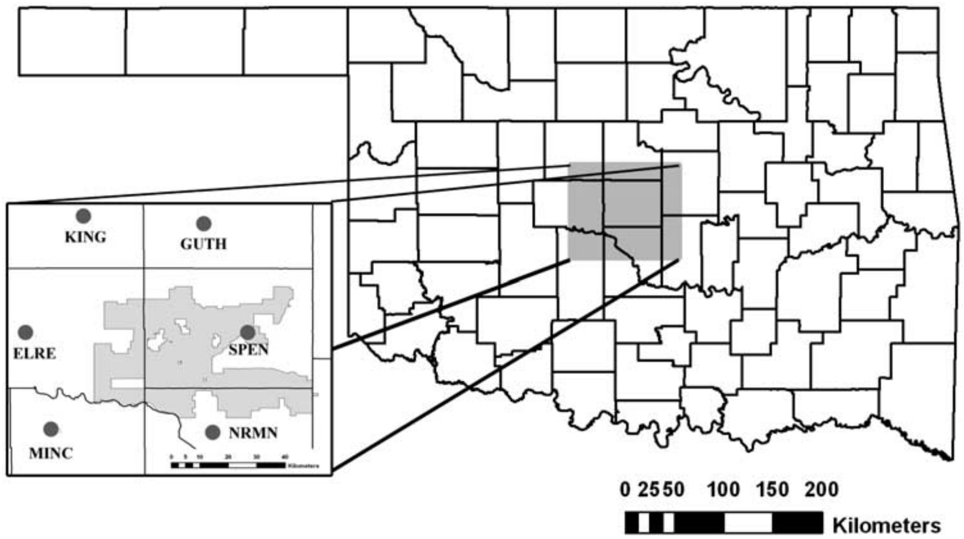

Figure 3. The location of Oklahoma Mesonet stations used in this study. The outline of Oklahoma City appears as the shaded region among the Mesonet sites.

from these sites were not used in this study. Immediately preceding JU2003, the PWIDS were redeployed (and subsequently renumbered) to meet the needs of JU2003. As a result, the naming order of the PWIDS was altered. Again, two of those sites were deployed on the rooftops (PWIDS 14 and 15) at the convention center and post office and were not used during the analysis. Additional observations were periodically excluded from the study due to missing data or data that failed quality control range tests, like instrument analyses, and visual inspection.

[20] Once quality controlled, the data from the various sources were consolidated into a JU2003 period, a pre-JU2003 period, and monthly subsections during the pre-JU2003 period. Further, various statistical measures were applied to the 5-minute observations including the mean, standard deviation, and absolute deviation values. Next, after the computations were completed, diurnal averages of the mean temperature, temperature difference, standard deviation, and absolute deviation of temperature were calculated for the monthly, pre-JU2003, and JU2003 periods.

4. Oklahoma City Heat Island

4.1. Pre-JU2003 Analysis

[21] To quantify the overall UHI in Oklahoma City during the 10-month period prior to JU2003, a composite diurnal analysis utilizing the UHII was performed for the whole pre-JU2003 period. Figure 4 demonstrates that at the 9-m

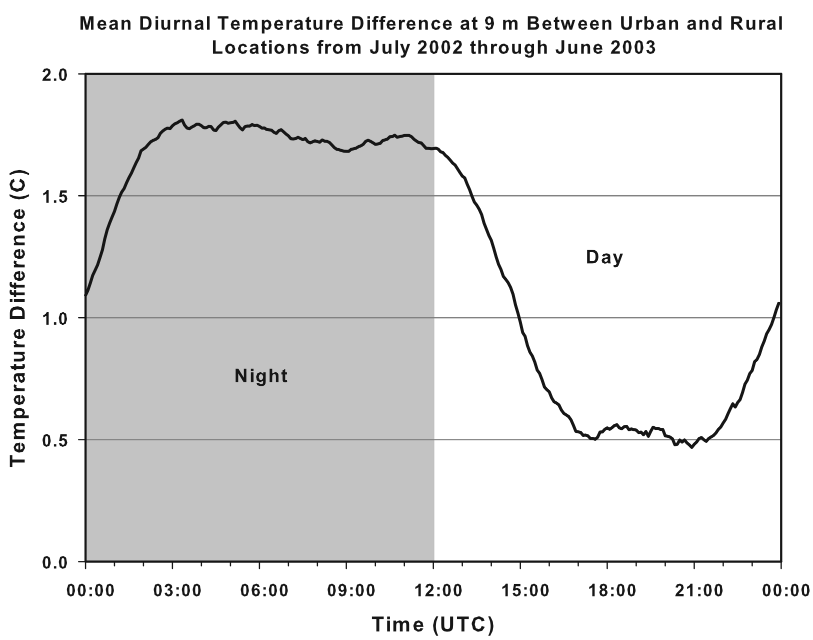

Figure 4. Mean diurnal temperature difference between urban and rural locations at 9 m during the 10-month pre-JU2003 time period. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

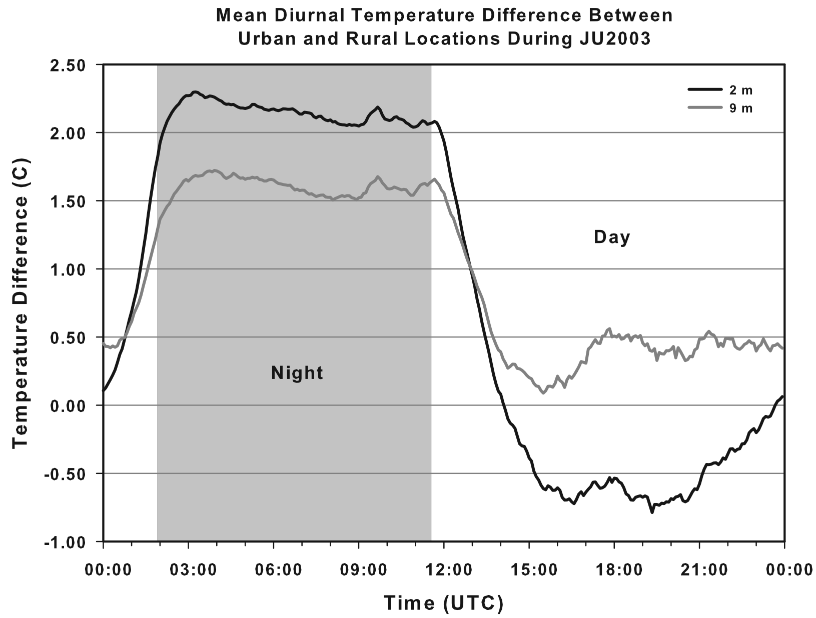

Figure 5. Mean diurnal temperature difference between urban and rural locations at 2 and 9 m during JU2003. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

height, the UHII was consistently 0.5–1.75°C greater in the urban core of OKC than the surrounding rural locations. Further, as noted with previous UHI studies, the UHI impact was strongest during the overnight hours and weakest during the day.

[22] A similar analysis was performed for the individual months prior to JU2003 at the 9-m level. Again, the composite values represented by the UHII were consistently greater within the CBD of Oklahoma City than the surrounding rural areas by 0.5–2.25°C (not shown). In fact, during the period of study, the overall magnitude of the UHII values changed little from month to month even as the seasons and the magnitude of downwelling solar radiation changed.

[23] Inspection of the temperature data also revealed a slight lag between the rural and the urban data. In this case, the rural values warmed quicker than the urban values following sunrise and cooled quicker following sunset. This lag is likely due to multiple factors: the greater turbulent mixing in the rural locations following sunrise coupled with the shadowing of urban sites by large buildings, the greater heat storage in the urban zone following sunset, and the greater spatial variability of temperatures measured by the rural Mesonet sites.

4.2. JU2003 Analysis

[24] A separate analysis of the 9-m observations was performed for the JU2003 data due to the fact that the PWIDS were redeployed through the urban zone for the project. Even so only minimal differences existed between the UHII values between the JU2003 and the pre-JU2003 period. As such, during the overnight hours, or roughly 0300–1200 UTC, the urban environment was approximately 1.5°C warmer than the rural environment while during the daytime (1400–0100 UTC) the UHII decreased to approximately 0.5°C (Figure 5).

[25] A second analysis was performed using JU2003 data whereby observations from the Hobo sensors (urban) were compared with observations at Mesonet sites (rural) for the 2-m height. During overnight hours the UHII values were typically greater than 2°C warmer than surrounding rural location (Figure 5). Conversely, during daytime the UHII was actually negative and revealed that the urban core was over 0.5°C *cooler* than the rural locations. Thus during the peak heating of the day, the urban core behaved as an urban cool island (UCI) at 2 m during JU2003.

5. Analysis of Variability

5.1. Distribution of UHII Values

[26] For each 5-minute observation period throughout the entire study, an UHII value was computed. Then, for various time intervals including each month of the pre-JU2003 period, the JU2003 period, and the combined (total) study period, the percentage of UHII observations within specific temperature ranges were calculated (Table 1). For

Table 1. Percentage Values for the Number of UHII Observations Within Various Temperature Ranges

	>3	2–3	1–2	0–1	0– –1	<–1
August 2002 (9 m)	2.2	17.1	27.2	46.6	6.4	0.5
September 2002 (9 m)	10.5	23.1	26.7	36.6	2.9	0.2
October 2002 (9 m)	7.8	9.6	27.8	48.8	6	0
November 2002 (9 m)	14.9	23.7	25.2	27.3	8.5	0.4
December 2002 (9 m)	11	15	31.6	38.1	4.3	0
January 2003 (9 m)	4.1	15.1	36.7	37.6	6.4	0.1
February 2003 (9 m)	6.5	12.4	26.1	49.4	5.4	0.3
March 2003 (9 m)	5.2	15.6	30.7	42.4	5.7	0.4
April 2003 (9 m)	8.8	11.3	30.6	41.3	7.2	0.7
May 2003 (9 m)	12.5	9.9	30.5	40.1	5.9	1
Pre-JU2003 (9 m)	7.7	15.2	29.2	41.4	6.1	0.5
JU2003 (2 m)	9.9	14.9	15.3	24.6	28.4	6.9
JU2003 (9 m)	1.2	14	27.7	46.9	8.2	2

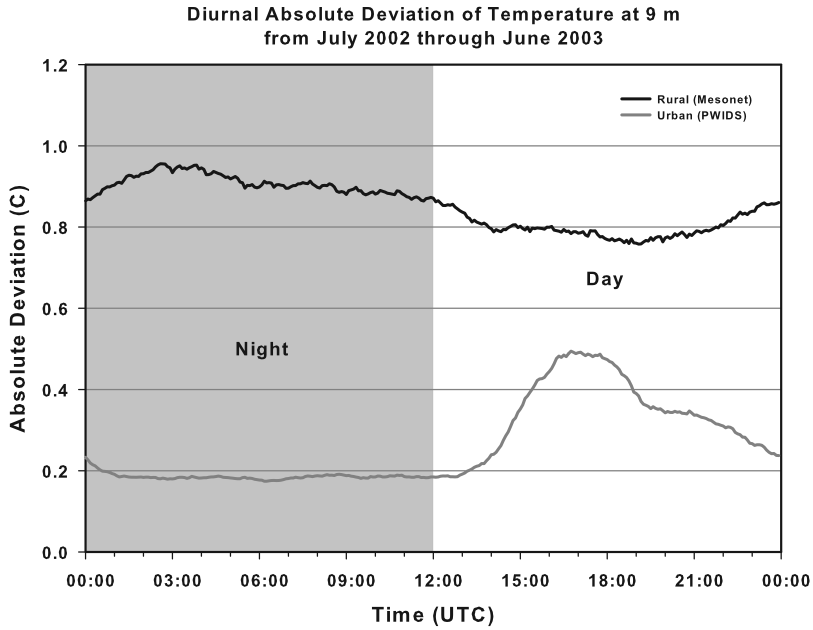

Figure 6. The diurnal average absolute deviation (DAAD) of temperature between stations for urban and rural locations at 9 m during JU2003. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

example, during November 2002, the percentage of UHII values greater than 3°C was 14.9% while the total percentage of UHII values that were less than zero was 8.9% (i.e., the sum of all percentage values less than 0).

[27] Overall, the results revealed that, while minor variability occurred between individual months, nearly 23% of all 9-m observations during the pre-JU2003 study period (i.e., pre-JU2003, 9 m) yielded an UHII value greater than 2°C with 7.7% greater than 3°C. In addition, over 70% of all 2-m observations of UHII values ranged from 0–2°C, while only approximately 6.6% of 9-m observations were associated with negative UHII values during the study time period. Further, the average UHII for all 9-m observations over the pre-JU2003 period was 1.25°C (not shown) demonstrating the strong UHI signal for Oklahoma City within the data set.

[28] Specifically during the JU2003 period, the percentage of 9-m observations with negative UHII values was slightly greater than any months during the pre-JU2003 period. However, at the 2-m height during JU2003, 35% of the observations yielded negative UHII values which is consistent with (1) the diurnal analysis demonstrated in Figure 5 and (2) the presence of a significant UCI at the 2-m height. Further, the number of 2-m observations with UHII values between 0 and 2°C was substantially less than corresponding observations at the 9-m height (approximately 40% of the total at the 2-m height compared with over 70% of the observations at the 9-m height).

5.2. Diurnal Average Absolute Deviation

[29] For this study, absolute deviation (AD) was chosen as the primary statistical quantity calculated to quantify the variability of the diurnal cycle. AD was selected over other statistical tools (e.g., standard deviation, σ) due to an enhanced resistance to significant outliers [*Huber*, 1981]. As such, for each observation period within the data set (e.g., 1 July 2003 at 0000 UTC), the absolute deviation of temperature was computed for each individual site within the rural and urban networks using:

$$|AD| = |T_o - T_x| \quad (2)$$

where T_o is the temperature observation at the site location and T_x is the mean temperature for either the rural or urban locations. Once the individual values of AD were computed, the values were subsequently averaged across all sites within the rural and urban networks and for each observation period within the diurnal cycle at various periods (i.e., pre-JU2003 or JU2003). The resulting values represented the diurnal average absolute deviation (DAAD). Thus the use of AD was most beneficial when strong cold fronts passed through Oklahoma City and a portion of the sensors were significantly warmer/cooler than the average of all sites. As such, the resistance of AD to outlier values was extremely useful.

[30] Within the urban environment, a strong relationship existed between average DAAD values and the diurnal cycle. Figure 6 displays the composite analysis of DAAD at the 9-m height for the pre-JU2003 period and demonstrates that the DAAD values increased between 1200 and 1500 UTC, which corresponded with local sunrise. Further, the DAAD values remained elevated through the convective portion of the day before decreasing between 2200 and 0200 UTC and remained nearly constant at values between 0.1°C and 0.2°C, during the overnight period.

[31] By comparison, the overall magnitude of the DAAD values throughout the diurnal cycle for the rural areas were greater than the urban values. This is likely due to the overall greater station spacing between sites. However, for the pre-JU2003 period at the rural sites, the maximum

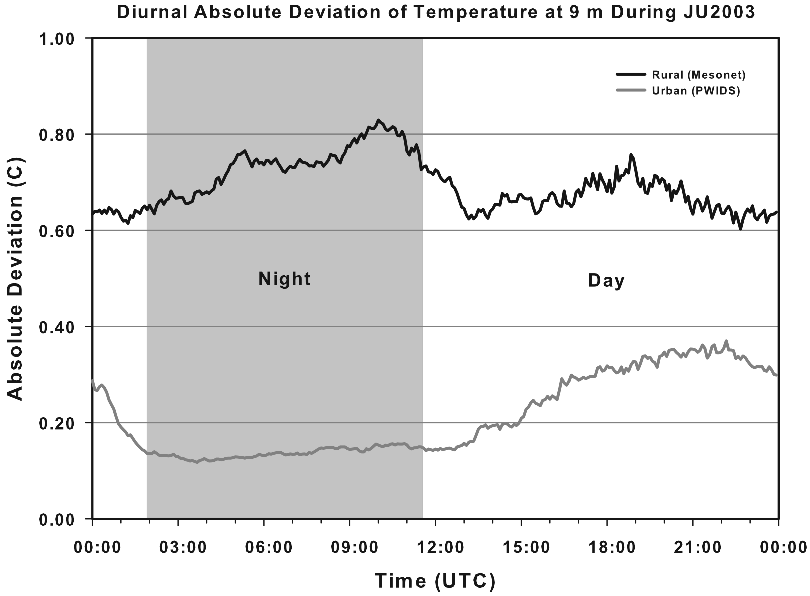

Figure 7a. The diurnal average absolute deviation (DAAD) of temperature between stations for urban and rural locations at 9 m during JU2003. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

values of DAAD occurred shortly after sunset local time (approximately 0300 UTC) while minimum values occurred during the afternoon. These results are consistent with *Hunt et al.* [2007] who showed that the variability of air temperature between Oklahoma Mesonet sites is often greatest beginning shortly after sunset and through the overnight hours due to different rates of nocturnal cooling. At the same time, the temporal trends are very different than for the urban environment.

[32] Observations collected during JU2003 revealed similar DAAD trends as the pre-JU2003 period at both the 2- and 9-m heights (Figures 7a–7b). As such, the overall magnitude of DAAD values was greatest for the rural locations while peak values occurred overnight at the rural sites and during the convective portion of the day in the urban environment. In addition, minimum values of DAAD occurred during the overnight period at the urban sites and just prior to local sunrise (1300 UTC) for the rural sites. However, immediately following the minimum in the rural locations, a secondary maximum occurred at approximately 2000 UTC which coincided with the time of maximum heating. Once the period of maximum heating passed, the

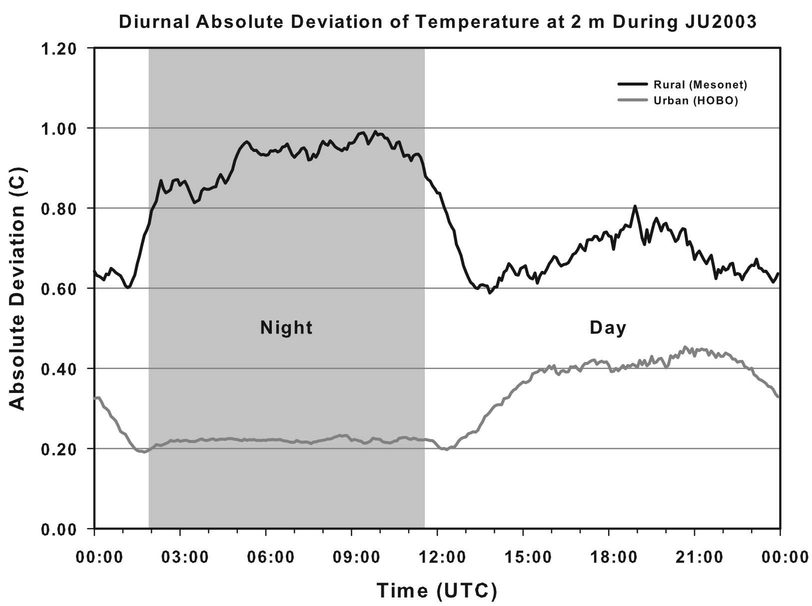

Figure 7b. The diurnal average absolute deviation (DAAD) of temperature between stations for urban and rural locations at 2 m during JU2003. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

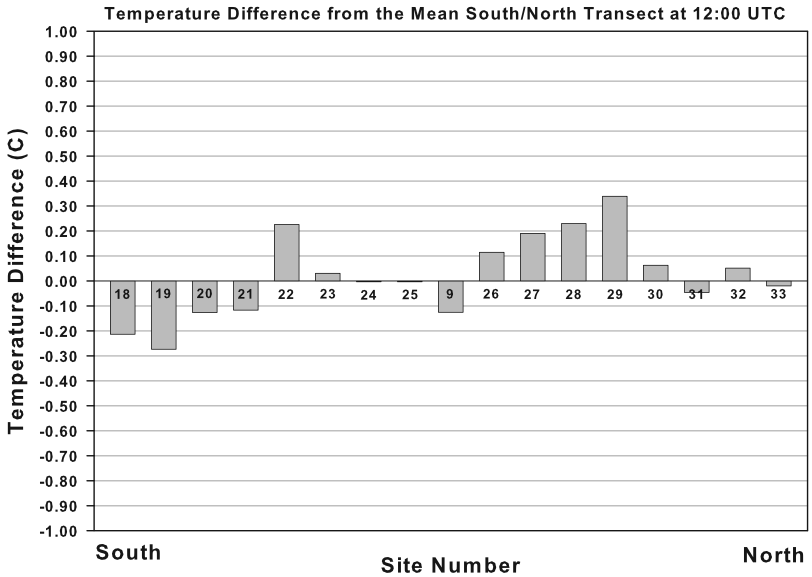

Figure 8a. Mean temperature difference at 2 m (HOBO temperature data logger locations) along the north-south transect during JU2003 at 1200 UTC. Sites warmer than the mean transect value are positive and sites cooler than the mean transect value are negative.

DAAD values at rural locations decreased until local sunset and then rapidly increased.

5.3. Transect Analysis

[33] The distribution of the HOBO sensors provided an opportunity to quantify the spatial distribution of the UHI in Oklahoma City along transects. Thus for the JU2003 period, transect mean values were computed for each observation time (e.g., all measurements taken at 0000 UTC, 0005 UTC, etc.). Next, the mean value of the individual HOBO sensors for each observation time was subtracted from the corresponding transect mean to quantify the temperature deviation of each site from the mean temperature along the transect.

[34] An example of the analysis is plotted for the south-north (Figure 8a) and west-east (Figure 8b) transects at 1200 UTC (approximate time of sunrise). For the north-south transect, the warmest temperatures during the JU2003 period at 1200 UTC occurred at locations near or just to the north for the CBD, while the coolest locations were generally along the southern portion of the transect. This result is consistent with the predominant southerly winds during JU2003 (Figure 9) and demonstrates that the core of the UHI at 2 m was advected to areas just north of the center of

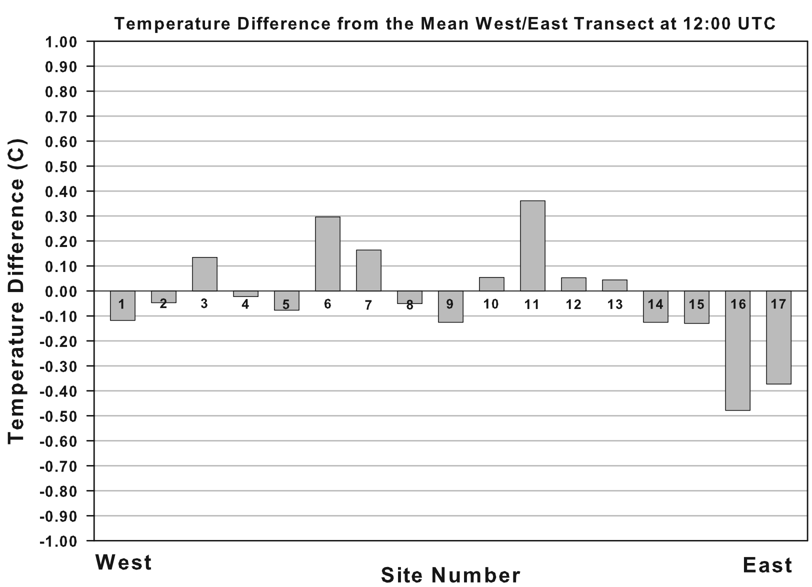

Figure 8b. Mean temperature difference at 2 m (HOBO temperature data logger locations) along the east-west transect during JU2003 at 1200 UTC. Sites warmer than the mean transect value are positive and sites cooler than the mean transect value are negative.

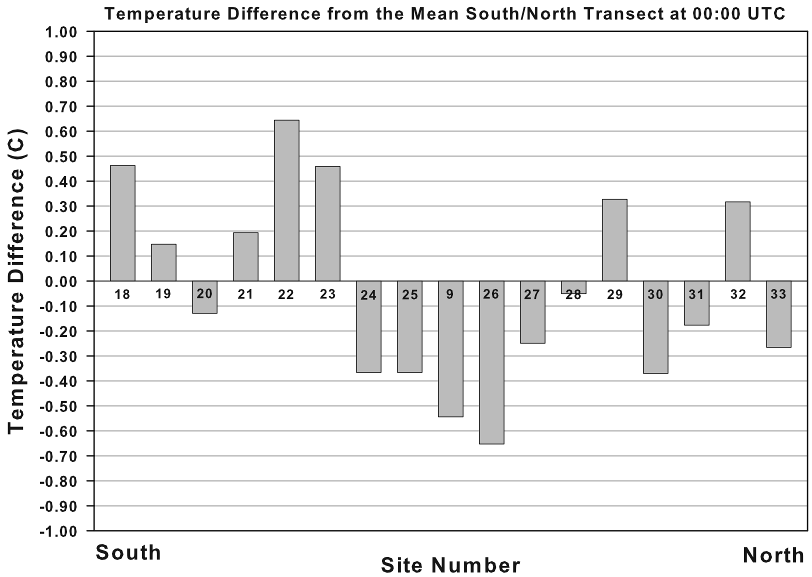

Figure 8c. Mean temperature difference at 2 m (HOBO temperature data logger locations) along the north-south transect during JU2003 at 0000 UTC. Sites warmer than the mean transect value are positive and sites cooler than the mean transect value are negative.

the CBD and away from the upstream locations. For the west-east transect at 1200 UTC, those sites on the periphery of the CBD (6, 7, 11) were the warmest while those on the easternmost portion of the transect were coolest. The latter impact (i.e., cooler sites) was likely due to the deployment of the sites in a highly vegetated portion of Oklahoma City with fewer buildings.

[35] Conversely, the results of the transect analysis were quite different at the 0000 UTC time period (late afternoon local time). Along both the south-north (Figure 8c) and west-east transects (Figure 8d), the coolest sites were located within the CBD while those sites on the periphery were warmest. This result is consistent with the UCI previously noted, and demonstrates that those locations within the CBD were the strongest contributors to the UCI. Furthermore, along both transects, the spatial dimension of the cool anomaly extended approximately 0.5 km from the CBD, consistent with the greatest density of urban structures.

5.4. Vertical Variability

[36] During JU2003 six of the 2-m sensors (HOBOs) were colocated with the 9-m temperature observations collected by the PWIDS (PWIDS 2 and T27, PWIDS 4

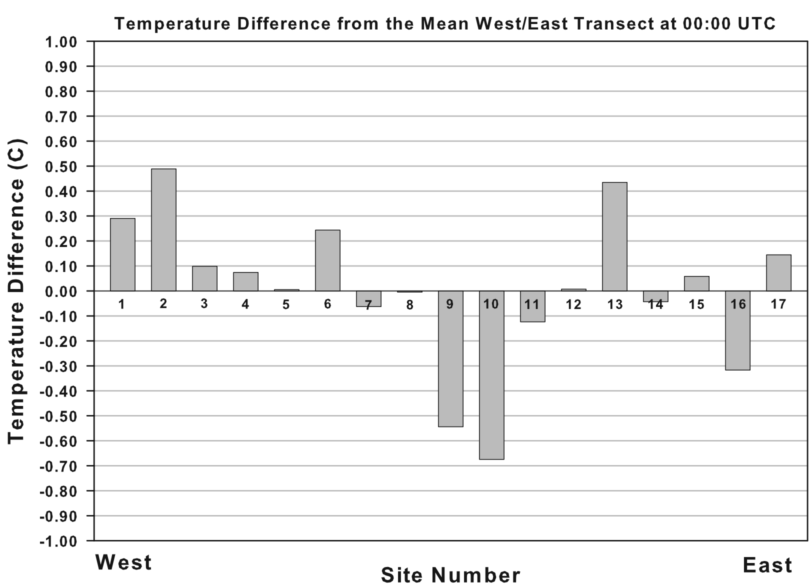

Figure 8d. Mean temperature difference at 2 m (HOBO temperature data logger locations) along the east-west transect during JU2003 at 0000 UTC. Sites warmer than the mean transect value are positive and sites cooler than the mean transect value are negative.

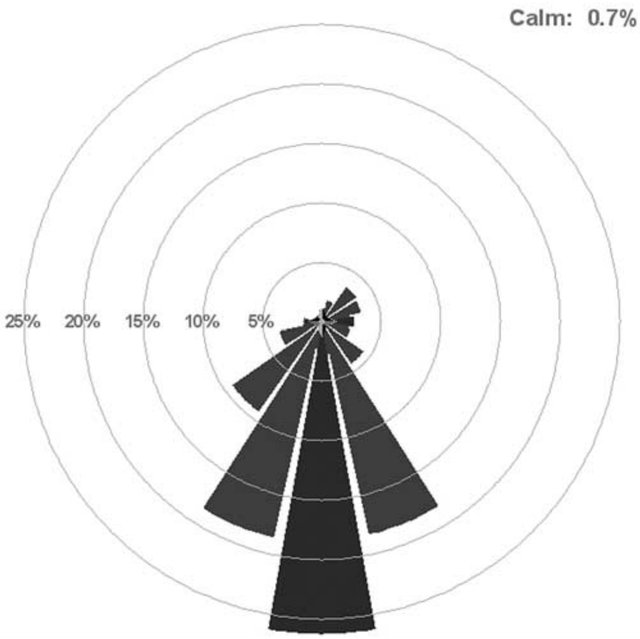

Figure 9. The composite wind rose for central Oklahoma at a height of 10 m during JU2003. The wind observations were obtained from the two Oklahoma Mesonet sites closest to the central business district of Oklahoma City (NRMN and SPEN).

and T26, PWIDS 6 and T07, PWIDS 7 and T09, PWIDS 8 and T10, and PWIDS 9 and T11). Thus an analysis was conducted to quantify the difference in the vertical temperature gradient between the rural and urban areas. First, the difference between the temperature at 9 and 2 m was calculated for all sites within the CBD and at the surrounding Mesonet sites. Then, for each observation period, the values were averaged for the Mesonet (rural) sites and the CDB locations (urban) and were further averaged over the JU2003 period to complete the diurnal analysis.

[37] The results of this comparison are presented in Figure 10 which shows the mean diurnal cycle of the vertical temperature difference for the urban and rural sites during the JU2003 period. In the case of the rural observations, the mean temperature gradient between 2 and 9 m revealed a pronounced diurnal cycle whereby mean values oscillated between approximately −1.5°C (2-m temperature values warmer than the 9-m temperature values) during the day and 0.5°C (2-m temperature cooler than the 9-m temperature) at night. Conversely, little difference was noted in the vertical temperature gradient throughout the diurnal cycle for the urban locations.

[38] The composite results of the vertical thermal gradient analysis yield overall stability conditions within the CBD that are near neutral throughout the diurnal cycle. Such conditions have been noted in past studies for the nocturnal period such as in the works of *Duckworth and Sandberg* [1954], *Uno et al.* [1988], and *Grimmond et al.* [2004]. *Grimmond et al.* [2004] also noted that most pollution dispersion calculations assume unstable or neutral conditions at night. However, the overall, composite absence of a near-surface vertical thermal gradient within the CBD during JU2003 suggests conditions remained near neutral even during daylight hours and near constant neutral stability overall. Such observations are consistent with *Grimmond et al.*'s [2004], who noted that near-surface conditions were neutral more than 60% of the time.

6. Discussion and Conclusions

[39] Observations collected prior to and during the Joint Urban 2003 field experiment were used to quantify the

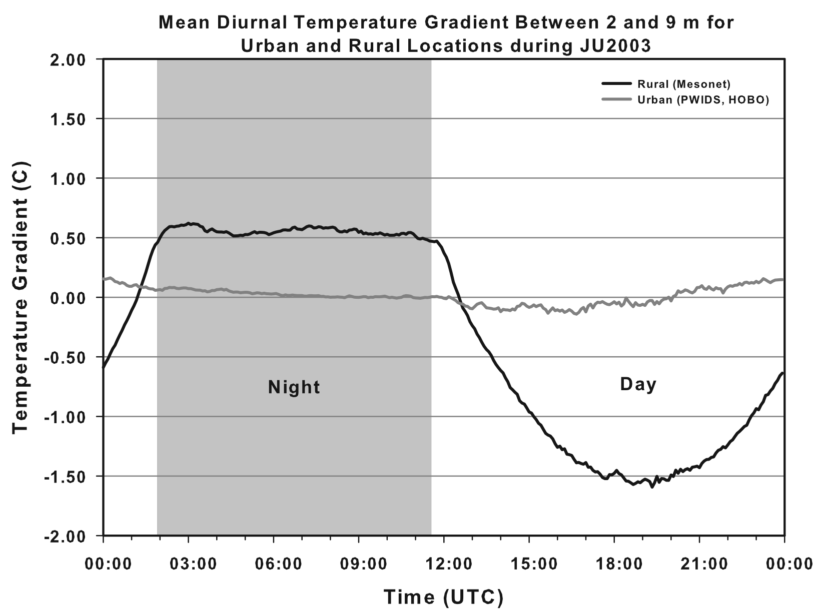

Figure 10. Mean vertical diurnal temperature gradient between observations at 2 and 9 m at the urban and rural locations during JU2003. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

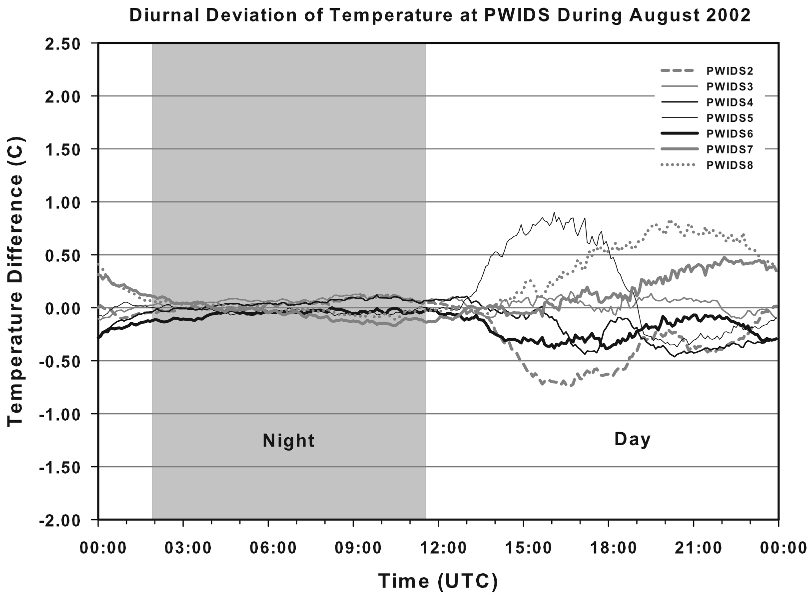

Figure 11. The diurnal cycle of temperature difference at PWIDS locations during August 2002. The approximate nocturnal (shaded) and daylight (unshaded) conditions for the period are noted in the figure.

diurnal cycle of the urban heat island in Oklahoma City. The analyses focused on temperature measurements collected at heights of 2 and 9 m above the surface within the urban core as well as at nearby rural Oklahoma Mesonet sites. The composite diurnal analyses demonstrated that, regardless of period or height, a significant mean UHI existed during the overnight hours (over 1.5°C at 9 m and greater than 2°C at 2 m). In addition, the individual UHII values compiled during the analysis further demonstrated that the urban environment was consistently warmer than the rural areas at both the 2- and 9-m heights (Table 1) with exception to UHII values at the 2-m height during the afternoon period during JU2003. In this case the urban environment was cooler than corresponding temperature values in the rural areas.

[40] The presence of an UCI during the day has been noted for other cities under varying atmospheric conditions including Atlanta [*Hafner and Kidder*, 1999], Melbourne, Australia [*Morris and Simmonds*, 2000], Birminham, England [*Unwin*, 1980], and Guadalajara, Mexico [*Myrup et al.*, 1993]. However, unlike previous studies which were typically limited in the number of research quality observations either (1) within the urban zone, (2) in the surrounding rural areas, or (3) for an extended study period, the results of this study demonstrate a consistent UCI signal approximately 0.5°C throughout the JU2003 period at the 2-m height using a composite analysis technique during the afternoon.

[41] The transect analysis focused on the 2-m temperature values during JU2003 provided additional insight regarding the nature of the UHI (at night) and the UCI that developed during the afternoon. While the transects were located within the urban zone, those sites that were warmest during the nocturnal period were located within and slightly north of the central business district; an area with the densest distribution of buildings and man-made surface material. Thus even though all sites were within the urban core, the sensors detecting the greatest magnitude of the UHI were those very near the center of the CBD. Conversely, during the period associated with the urban cool island, those sites along the transect that were coolest were also located within the densest distribution of buildings. Due to the absence of downwind advection of the UCI from the CBD during the convective portion of the day, the results point to the importance of sky view factor [*Watson and Johnson*, 1987] and building impacts on solar insulation within the CBD as critical in maintaining the UCI in Oklahoma City.

[42] This study also demonstrated the significant difference in the variability between sites within the rural and urban zones. As expected, given the greater station spacing between sites, the magnitude of the variability among sites was largest for the rural locations. For the rural locations, the results of the analyses in this study were consistent with *Hunt et al.* [2007]: the greatest temperature variation between the Oklahoma Mesonet sites often occurs following sunset. Additional studies, including works of *Acevedo and Fitzjarrald* [2001] and *LeMone et al.* [2003], also noted the increased variability in rural areas during the evening transition due to the development of stable conditions near the surface due to radiational cooling and local heterogeneity in local turbulent mixing. Conversely, the analyses for this study within the urban zone during the overnight periods, little variability of air temperature was observed between sites, and consequentially, greatest temperature variability occurred following sunrise through the convective portion of the day.

[43] Individual PWIDS sites were intercompared to further quantify the variability of temperature conditions in and around the CBD, and the composite diurnal plot for August 2002 illustrates the nature of the variability within the urban core (Figure 11). In this case, the observations from seven PWIDS were averaged for each observation interval within the diurnal cycle and subtracted from the mean of each site throughout the diurnal cycle. As such, positive values represent when sites were warmer than the mean of all urban sites, and negative values represents sites cooler than

the mean of all urban sites. During the overnight period, little difference existed between the temperature values of the PWIDS sites. However, at sunrise, the temperature variability dramatically increased as individual sites warmed at varying rates. For example, PWIDS 5 was warmer than all other sites during the morning and early afternoon, both in the example (Figure 10) and throughout the pre-JU2003 period. However, late in the day, PWIDS 5 transitioned to a site that was cooler than the mean of all sites. Examination of PWIDS 5 revealed that the site was oriented such that it received direct solar insulation early in the day, but was significantly shadowed by a building during the afternoon. Conversely, PWIDS 7 and 8, the southernmost sites, were located just outside of the CBD, and were not significantly impacted by building shadows in the late afternoon. As such, the locations received more direct solar radiation throughout the day than other sites, and by late afternoon, were warmer than all other locations. Once sunset occurred, the variability between sites rapidly decreased to values near 0°C.

[44] The results of the transect analysis and the DAAD values demonstrate the role of buildings and sky view factor on the variability of air temperature near the urban core during the daytime period. Unlike the rural zones, the varying warming rates due to differences in solar insulation created increased spatial variability of air temperature during the daytime while the spatial variability was minimized at the rural locations. Conversely, with the loss of solar heating, the variability rapidly decreased and near isothermal conditions occurred horizontally within the CBD.

[45] Examination of the vertical temperature gradient during the JU2003 period revealed a strong diurnal trend at the rural locations whereby solar heating during the day yielded warmer conditions at 2 m versus 9 m. Conversely, during the overnight period, as radiational cooling occurred at the rural locations, the 2-m temperature cooled faster than the 9-m temperature and a nocturnal inversion developed. However, within the urban core, little diurnal variability was noted (Figure 10). As such, throughout the diurnal period, the vertical gradient of temperature between 2 and 9 m within the urban core was approximately 0°C. These results are consistent with past studies [*Duckworth and Sandberg*, 1954; *Uno et al.*, 1988; *Grimmond et al.*, 2004] which demonstrated near-neutral stability conditions within the nocturnal urban boundary layer during the nocturnal period. The composite results also demonstrated near-neutral conditions within the CBD during the convective portion of the day near the surface. Such conditions were significantly different from the surrounding rural areas.

[46] While this study offers new insight into the physical characteristics of the Oklahoma City UHI, observations of air temperature at multiple heights were not collected between the CBD of Oklahoma City and the surrounding rural areas. Thus the current understanding is limited to the fundamental differences between the true urban core and the rural areas. However, the spatial dimensions of Oklahoma City are quite large and a significant transition zone exists between the CBD and the rural sites. Further, the trends of diurnal temperature variability within the CBD versus the rural locations demonstrated that between those locations, a physical transition occurs which impacts the spatial and temporal characteristics of temperature and how it varies within the diurnal cycle. As such, future studies focused on the transition between the urban and rural zones in Oklahoma City are needed to quantify the spatial scales that impact the transition of not only the magnitude of the UHI, but also the horizontal and vertical variability of temperature.

[47] **Acknowledgments.** This study was supported, in part, by funding from National Aeronautics and Space Administration (New Investigator Award NA17RJ1277) and U.S. Department of Defense. The authors would like to thank the various colleagues associated with JU2003 and the Oklahoma Mesonet for their assistance with this project, the anonymous reviewers for their insights which improved the manuscript, and Derek Arndt for his assistance with Figure 9.

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