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Desert heat island study in winter by mobile transect and remote sensing techniques

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Abstract A familiar problem in urban environments is the urban heat island (UHI), which potentially increases air conditioning demands, raise pollution levels, and could modify precipitation patterns. The magnitude and pattern of UHI effects have been major concerns of a lot of urban environment studies. Typically, research on UHI magnitudes in arid regions (such as Phoenix, AZ, USA) focuses on summer. UHI magnitudes in Phoenix (more than three million population) attain values in excess of 5°C. This study investigated the early winter period—a time when summer potential evapotranspiration >250 mm has diminished to <90 mm. An analysis of the winter magnitude of the heat island in Phoenix has been studied very little, and therefore with the aid of automobile transects, fixed stations, and remote sensing techniques, we investigated a portion of the large Phoenix metropolitan area known as the East Valley. The eastern fringes of the metropolitan area abut against breaks in sloping terrain. The highest UHI intensity observed was >8.0°C, comparable to summertime UHI conditions. Through analysis of the Oke (1998) weather factor Φ_W, it was determined thermally induced nighttime cool drainage winds could account for inflating the UHI magnitude in winter.

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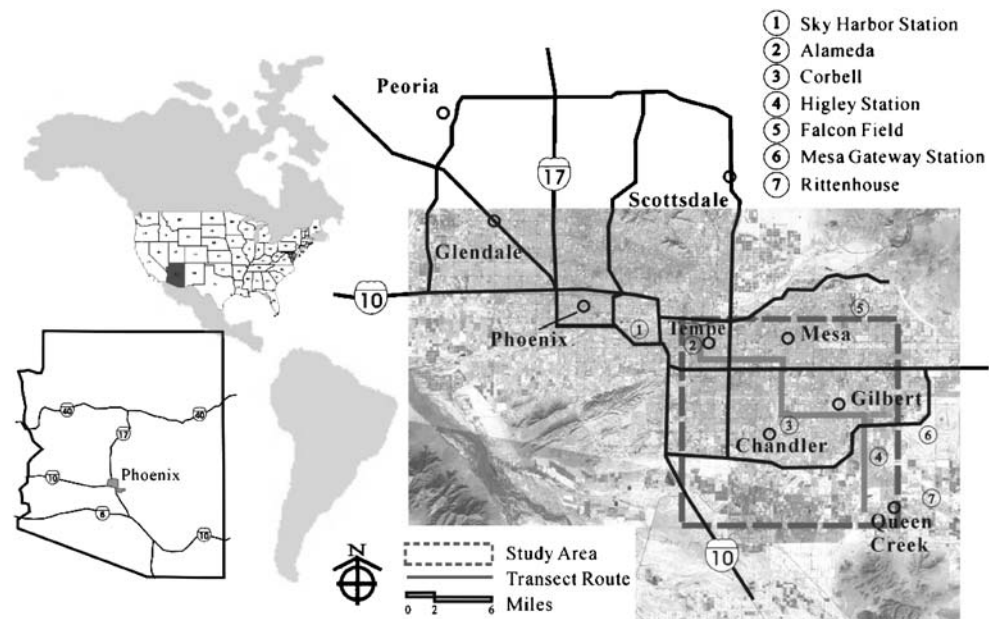Tempe, AZ 85287-6305, USA

1 Introduction

In the Phoenix metropolitan area, one of the marked urban climate features is the urban heat island (UHI) effect (e.g., Brazel et al. 2007). Since the 1920s, there have been several studies that have yielded insights into the UHI either directly in researching the UHI, or indirectly through analysis of the temperature distribution in the region that was conducted for other purposes, for example: (a) a cursory climate survey in the 1920s by agriculturalists as background to identifying where to grow citrus crops in and around the metropolitan area (Gordon 1921), (b) automobile microclimate transects in the summer period in 1976 along gradients in land cover (Brazel and Johnson 1980), (c) an investigation to study the association between a developing urban heat island and local monthly averaged wind speeds (Balling and Cerveny 1987), (d) an analysis of temperature records from 29 stations for assessing the time and space characteristics of the urban heat island (Balling and Brazel 1987), (e) a field study of the variability of the rural surroundings in Phoenix in determining a UHI magnitude (Hawkins 2004), (f) a study employing an array of temperature data loggers and surface meteorological stations across the Phoenix metropolitan area (Fast et al. 2005), (g) recent repeat sampling in 1999 (Stabler et al. 2005) of some of the same transects from 1976 studied by Brazel and Johnson (1980), and, most related to our present study, (h) a mobile transect, fixed station, and remote sensing sampling study of the East Valley of the Phoenix Metropolitan Area (Hedquist and Brazel 2006). Our research involved a four-period diurnal sampling of temperature and dew point over a 10-day period of November, 2007 utilizing mobile transect techniques, supplemented by remote sensing to derive an Normalized Difference Vegetation Index (NDVI) and a few fixed

Fig. 1 The map of the study area

stations to analyze cloud cover and wind speed. The metropolitan area is so large (2,000 km^2) that mobile transects across its entire area are prohibitive due to large traffic volumes and cause the observations to take too long. Thus, the route of this study was designed to sample across a typical land cover gradient from urban to rural in the southeastern portion of the metropolitan area known as the East Valley, from urban-residential to agricultural and desert terrain (Fig. 1).

2 The study area, observations, and methodology

2.1 Description of the study area

There are four cities/towns along the span of the transect interspersed in a mosaic landscape typical of the metropolitan region from urban surfaces to agricultural and desert rural areas in the study area. Tempe, Mesa, Gilbert, and Queen Creek are all communities located in the southeastern part of the Phoenix metropolitan area (Table 1). Tempe represents the central business district of the whole study area and the starting point and ending point of the mobile transect. Mesa also has developed residential and commercial districts, especially along a significant stretch of the

transect. In these areas, there are some shopping malls which have a lot of parking lots with asphalt or concrete pavement. Gilbert, a newly developing area, is located south of Mesa and was also the fastest-growing place among all cities and towns of any size in Arizona between 1990 and 2000. From the census in 2000, there were 109,697 people residing in the Gilbert, and the population density was 985.9 people per square kilometer. In 2006, Gilbert has 191,517 residents and high population density (1,711.5/km^2). It can be regarded as the boundary between city and rural area in this study. Queen Creek, a whole new developing district since the 1990s, is located in the southeast region of the study area. The population of Queen Creek was 4,316 in the 2000 census. According to the Census Bureau estimates, even though the population of the town has risen to 20,818, it still has high percentage of land such as farmland, pastureland, and uncultivated land. Therefore, Queen Creek was taken to be the rural area in this study. Table 1 illustrates the population and density database of the study area. Compared with the population (1,512,986) and density (1,188.4/km^2) of Phoenix, Tempe, Mesa, and Gilbert can be regarded as the typical satellite cities and Queen Creek can be taken as a rural area of the Phoenix metropolitan area. The period of observation was November 6–15, 2007. The data from Sky Harbor Airport

Table 1 The population, area, and density of cities and towns in this study in 2006

Source: http://en.wikipedia.org/ (U.S. Census Bureau 2008)

Cities/towns data	Phoenix	Tempe	Mesa	Gilbert	Queen Creek
Level	City	City	City	Town	Town
Population	1,512,986	169,712	447,541	191,517	20,818
Area (km^2)	1,230.5	104.1	324.2	111.9	66.8
Density	1,188.4	1,570.6	1,365.6	1,721.4	248.9

Table 2 Weather conditions in Phoenix, AZ

Element	November, 2007	November means
Daily mean maximum temperature (°C)	27.7	23.9
Daily mean temperature (°C)	21.2	17.1
Daily mean minimum temperature (°C)	14.6	10.2
Daily mean dew point (°C)	0.6	2.6
Daily mean wind speed (m s^{-1})	1.8	2.2
Daily prevailing direction (deg)	10.0	11.0

indicate that month of November, 2007 was warmer and drier than normal, with winds slightly below normal (see Table 2), and extensive clear periods during the month, especially early in the month when transects were run.

2.2 Mobile transect survey, fixed sites, and remote sensing

Mobile transects were conducted four times throughout the day in order to measure the UHI effect over the diurnal period. The data of this study consisted of 20 mobile transects, the use of three fixed stations, and a remote sensing image in November, 2007. Mobile transects were run from November 6 to November 15, 2007 during the diurnal cycle centered on 1600, 2000, 2400, and 0500 local standard time (LST) and over a prescribed route. The route began from Downtown Tempe and ended in an undeveloped area, the boundary between Gilbert and Queen Creek. The eastward route was retraced back to Downtown Tempe, so that an average data could be made of the entire path, making a more accurate temporal adjustment of temperature and humidity change rates over the study area. Even though the survey route of this study was similar to the previous study, it was nevertheless extended to include more rural areas because the urban area has spread since 2001. In order to avoid the influence of highway traffic and different driving speeds, on the one hand, the mobile transect route in this study was modified away from the old route and used the local road instead; on the other hand, the average driving speed was set up around 35 to 45 miles/h. All transects had been done within 2 h in similar traffic condition and by the same route. The mobile transect instruments which were used in this study were the TR-72U

Thermo Recorder and the Qstarz BT-Q1000 Global Positioning System (GPS) Data Logger Travel Recorder. The TR-72U Thermo Recorder can measure and record temperature (in a range of −60°C to 155°C with 0.1°C resolution and ±0.3°C accuracy) and relative humidity (in a range of 10% to 95% with 1% resolution and ±5% accuracy). To allow for comparisons of humidity independent of temperature variations, we used Wexler's equation (Wexler 1976) to calculate saturation vapor pressure and subsequently derive dew point temperatures for analysis with UHI in this study. A BT-Q1000 GPS recorder was used to monitor time, altitude, longitude, and latitude data automatically synchronized to observations. This function was very useful for tracing the exact locations where the temperature and humility data were collected during the analysis process. The thermorecorder and GPS recorder had both been set for collecting data automatically with a 2-s interval. The thermorecorder was fit inside a polyvinyl chloride tube to avoid the influence of direct sunlight. The tube was placed outside, in front and on the right side of the vehicle. This position was far enough away to avoid recording any temperature and humidity data being influenced by the waste heat from the engine.

2.3 Fixed weather stations

Several hourly recording surface weather stations from various weather networks were used in this study to evaluate general weather conditions along and during the transects, in addition to accessing data on wind speed, wind direction, and cloud cover, and providing the ability to calculate the "weather factor" (Φ_W) after Oke (1998),

Table 3 Fixed sites used in this study (see map for location)

Fixed site	Elevation (m)	Latitude (north)	Longitude (west)
Sky Harbor	345	33.43	112.05
Alameda	360	33.41	111.93
Corbell	369	33.36	111.83
Higley	396	33.31	111.72
Falcon Field	416	33.45	111.73
Mesa Gateway	418	33.32	111.65
Rittenhouse	426	33.25	111.64

Fig. 2 The NDVI imagery of study area
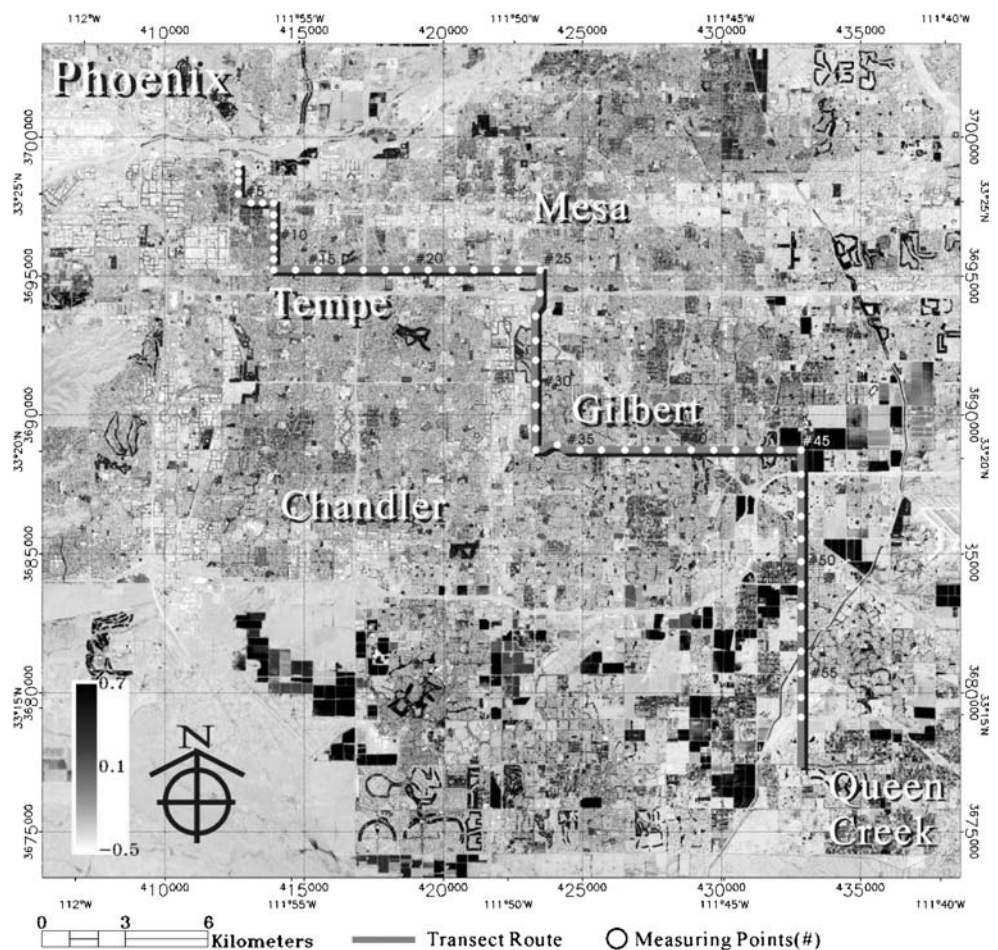
explained below. The stations are shown in Table 3 coded by latitude, longitude, elevation, and the type of weather network. Figure 1 shows the positions of the stations relative to the mobile transect route. Table 3 lists latitude, longitude, and elevation of the sites. These stations in the East Valley range in elevation from 345 to 425 m and form a spatial arrangement adequate to note the drainage wind effects upon this region (Brazel et al. 2005).

2.4 Vegetation index

In this study, plant cover density surrounding each measuring point was evaluated using the NDVI map (Fig. 2) produced from an Advanced Spaceborne Thermal Emission and Reflection Radiometer image of the Phoenix metropolitan area, taken on November 1, 2007. The spatial resolution of this NDVI map was 15 m per pixel. NDVI values were calculated as the ratio between measured reflectance in the red (R) and near infrared (NIR) spectral bands of the imagery using the Eq. 1. Green vegetation commonly has a larger reflectance in the near infrared than in the visible spectrum. Clouds, water, and snow have a larger reflectance in the visible than in the near infrared, while the difference is nearly zero for rock and bare soil.

Therefore, typically, vegetation NDVI ranges from 0.1 up to 0.75, with higher values associated with greater density and greenery of the plant canopy. Surrounding soil and rock values are close to zero, while water bodies, such as rivers and dams, have negative index values (Turcker et al. 1986).

$$NDVI = (NIR - R)/(NIR + R). \tag{1}$$

Index value may range from -1.0 to 1.0, with higher values associated with higher levels of healthy vegetation cover. In this study, NDVI be calculated by 750 and 1,500 m scale, respectively.

3 Results and analysis

3.1 Heat island effect during the daytime and night time

Figures 3 and 4 show the average temperature and relative humidity data of 20 transects. The UHI was not conspicuous in the daytime data. In this study, the result indicated that the temperature variation along the transect route was very small by day. In the whole study area, the biggest daytime temperature variation which was observed on

Fig. 3 The average temperature distribution of November, 2007
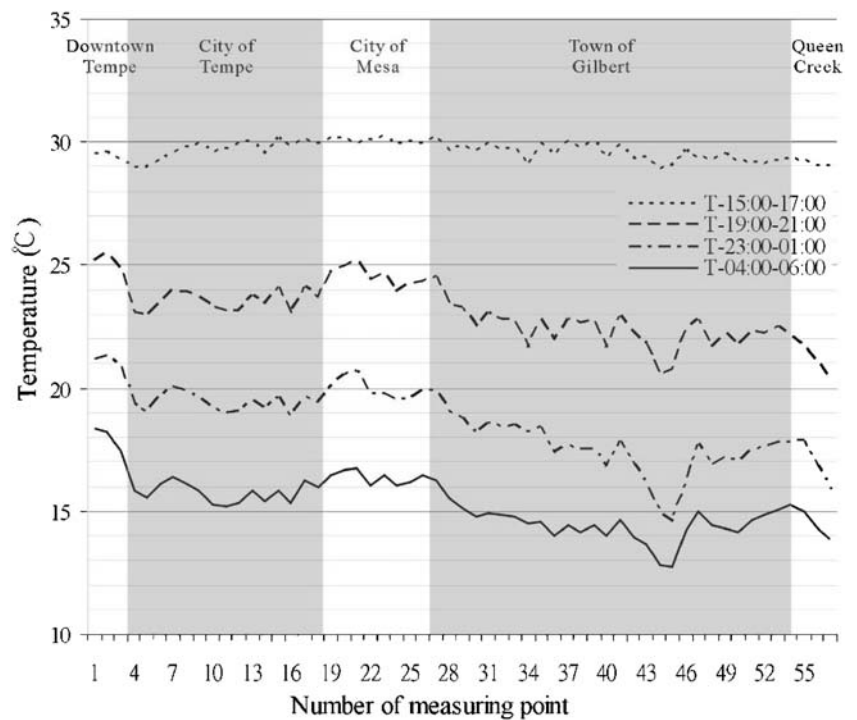
November 6 was 2.5°C (Table 4); moreover, the average daytime temperature variation was only 1.34°C. Past research has indicated that the possible heat island cyclonic circulation relative to the urban center commenced at 2100 LST and was more pronounced toward midnight in Phoenix (Brazel et al. 2005). In this observation, similar results have

been found. After sunset, the average times of sunset and sunrise in the study period are 0720 and 0553 hours; the temperature in rural area was cooled down rapidly. Contrary to the rural areas, concrete, asphalt, and pavement start to release the heat and cause the surrounding air temperature stay as warm as it was before sunset. Therefore,

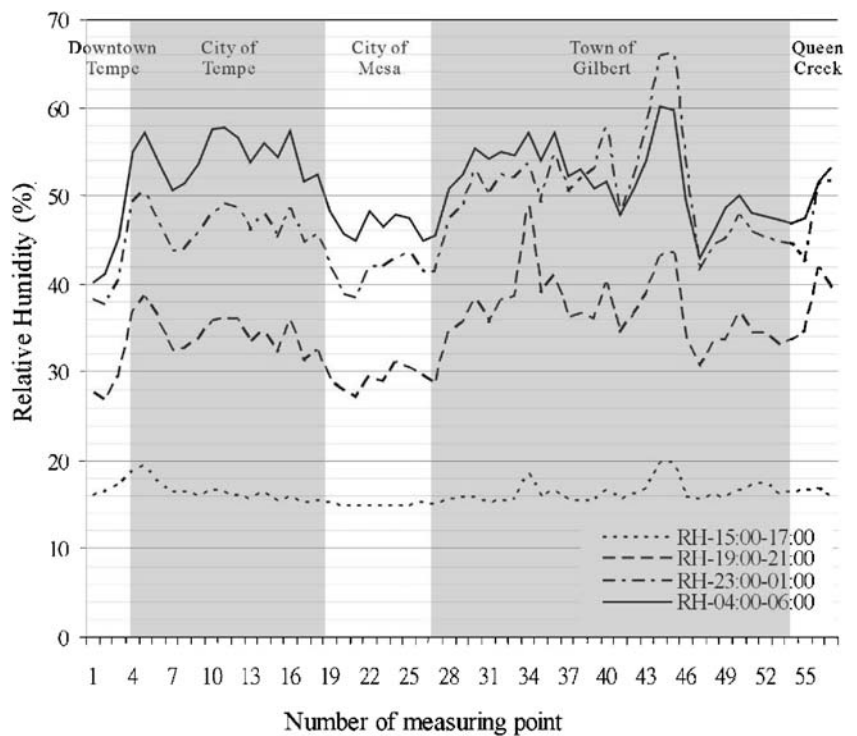**Fig. 4** The average relative humidity distribution of November, 2007

Table 4 The maximum, minimum, and variation temperature of 20 transects (°C)

| Maximum/minimum/variation (hours)	November 6, 2007	November 8, 2007	November 10, 2007	November 12, 2007	November 14, 2007	Average
Maximum (1500–1700)	34.70	32.40	27.90	27.45	30.20	30.20
Minimum (1500–1700)	32.20	30.70	26.55	25.35	28.05	28.86
Variation (1500–1700)	2.50	1.70	1.35	2.10	2.15	1.34
Maximum (1900–2100)	28.15	26.70	23.45	24.05	25.15	25.48
Minimum (1900–2100)	22.15	19.55	17.65	21.05	18.05	20.33
Variation (1900–2100)	6.00	7.15	5.80	3.00	7.10	5.15
Maximum (2300–0100)	23.90	21.75	20.75	20.30	20.05	21.32
Minimum (2300–0100)	16.55	13.55	13.80	14.40	14.05	14.55
Variation (2300–0100)	7.35	8.20	6.95	5.90	6.00	6.77
Maximum (0400–0600)	21.60	18.55	16.70	16.65	18.45	18.38
Minimum (0400–0600)	14.70	12.15	10.80	11.35	12.90	12.74
Variation (0400–0600)	6.90	6.40	5.90	5.30	5.55	5.64

the UHI effect starts to become obvious during the early evening. On a typical winter's day in Phoenix, November 14, 2007, the UHIs was 7.1°C on this very cloudless and calm day. The highest temperature in the whole study area was found in Downtown Tempe and Mesa city and the lowest temperature in rural areas such as Gilbert or Queen Creek; Table 4 illustrated that the UHIs on November 6, 8, and 10 were very pronounced. During 1900 to 2100 LST, the UHIs of these 3 days were 6.00°C, 7.15°C, and 5.80°C separately. Nevertheless, due to the almost overcast sky, the UHIs was 3.00°C at 1900 to 2100 LST on November 12. Table 4 shows that the UHIs were 7.35°C, 8.20°C, 6.95°C, 5.90°C, and 6.00°C on November 6, 8, 10, 12, and 14. Most large UHIs happen on these periods. Furthermore, some urban areas, especially Downtown Tempe, have continuous human activity. The huge traffic and anthropogenic heat play important roles in warming up surrounding air in urban areas. Therefore, the average UHIs at midnight was 6.77°C in this study. Even though it was a cloudy day, the UHIs of November 12 was still 5.90°C.

Table 5 Weather condition of every mobile transect survey

Date	Time	UHIs	Temperature	Dew point	Wind speed	Sky condition
November 6	1500–1700	2.50	33.35	−0.83	1.75	Mostly clear
	1900–2100	6.00	28.04	1.56	0.75	Partly cloudy
	2300–0100	7.35	23.29	3.04	4.00	Partly cloudy
	0400–0600	6.90	20.99	1.54	3.50	Partly cloudy
November 8	1500–1700	1.70	31.44	1.69	4.75	Partly cloudy
	1900–2100	7.15	26.25	4.07	1.50	Mostly clear
	2300–0100	8.20	20.94	5.74	5.67	Mostly clear
	0400–0600	6.40	17.76	4.01	9.00	Partly cloudy
November 10	1500–1700	1.35	27.47	2.90	3.00	Partly cloudy
	1900–2100	5.80	22.75	5.43	3.25	Mostly clear
	2300–0100	6.95	19.82	6.17	2.75	Clear
	0400–0600	5.90	15.97	4.57	6.75	Clear
November 12	1500–1700	2.10	27.10	3.99	4.25	Mostly cloudy
	1900–2100	3.00	24.29	5.06	0.75	Overcast
	2300–0100	5.90	20.15	6.50	0.00	Partly cloudy
	0400–0600	5.30	16.14	6.42	3.75	Partly cloudy
November 14	1500–1700	2.15	29.26	2.17	3.75	Clear
	1900–2100	7.10	24.03	4.04	2.75	Clear
	2300–0100	6.00	20.00	5.31	3.00	Clear
	0400–0600	5.55	17.50	4.01	0.00	Mostly clear

Fig. 5 The average dew point distribution of November, 2007
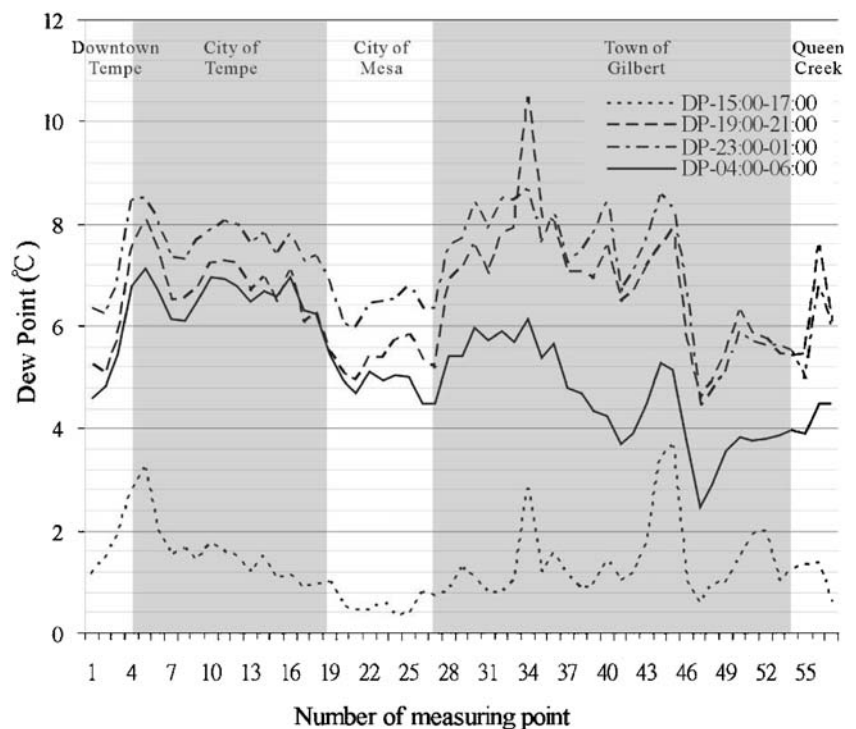
Before sunrise, both urban and rural areas had very little human activity effect. The rural area kept a low temperature but the temperature in urban area was obviously much higher. Because it has some large shopping districts, a narrow street, and a lot of streetlights, Downtown Tempe became the highest temperature location of the whole study area. Another hot spot in this study was the intersection of West Southern Avenue and North Alma School Road, where several huge shopping malls were located. In this area, big parking lots and shopping mall buildings provided the heating source for the ambient environment before dawn. Table 4 and Fig. 3 illustrate the UHIs of every transect survey and show that the UHI was virtually always more than 5°C before dawn. By contrast, the UHIs was not as obvious in the afternoon. The afternoon temperature variation ranged between 1.35°C and 2.50°C. Table 4 shows that the highest UHIs which had been found on November 8 was 8.20°C and the UHI effect was virtually maintained at that level through the night until dawn.

Land use and land cover are the main factors which can influence UHIs. As the results shown in Figs. 2 and 3 illustrate, there are large acreages of agricultural land at the intersection of Warner Road and Higley Road (point 45); therefore, the point 45 has lower temperature and higher humidity. Similarly, the point 34 has high dew point and low temperature during night because a big artificial lake surrounds this area. The amount of evaporation by water and the evapotranspiration by vegetation can help to cool down the ambient temperature and diminish UHIs.

3.2 Heat island intensity in different weather condition

In this study, the mobile transects were undertaken both by day and night over a ten continuous day period during which there were different weather conditions and temperature (T), dew point temperature (DP), wind speed, and sky conditions. Table 5 illustrates the weather condition and UHIs of every mobile transect survey. One result from mobile transects show that the maximum UHIs occurred frequently at midnight and this is consistent with many previous articles. Nevertheless, there are some interesting results as below: (1) smaller UHI magnitude was found by day no matter what kind of weather situation, (2) most of the results showed that the significant UHI effect occurred at night except November 12 (the UHIs on that day is only
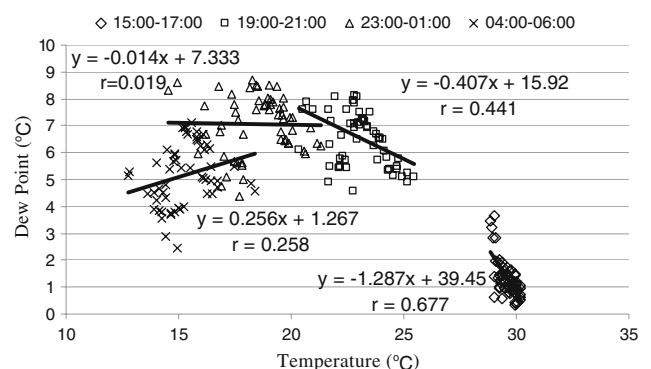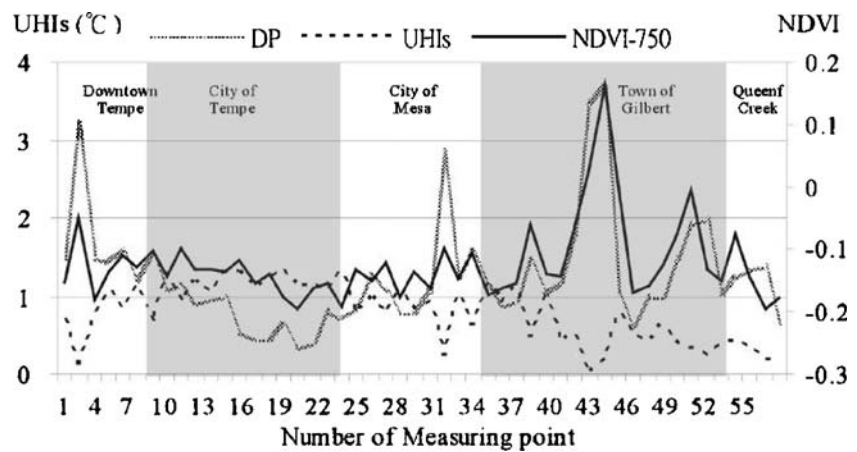

Fig. 6 The relationship between dew point and temperature in four different duration of days

Fig. 7 The distributions of the urban heat island intensity (*UHIs*), dew point (*DP*), and NDVI in the afternoon (1500–1700 hours)

3.00°C), which had a very cloudy sky (this phenomenon indicates that sunlight plays an important role in heating urban areas by day even though the day is also windy, and (3) every mobile transect result illustrated a strongest UHI occurred both at midnight and in the early morning, somewhat independent of the kind of sky condition and what level of wind speed. It means the anthropogenic heat is a key factor dominating the warm temperature at night in urban areas.

3.3 The relationship between dew point and heat island

The temperature to which air must be cooled, at constant pressure, to reach saturation is called the dew point (Moran and Morgan 1989). The dew point is a measure of the air's water vapor content. The higher the dew point, the greater the water vapor concentration. Although the relative humidity is an important consideration, as a rule, many people experience discomfort when the dew point rises above 20°C (Moran and Morgan 1989). Figure 5 shows the average dew point distribution

profile of 20 transects. On average, the dew point was lower during the daytime, but after sunset, the dew point became higher. The high dew point occurred frequently both on golf courses and artificial lakes in rural and residential areas near Arizona State University. The air temperature decreased very conspicuously through those areas in this study. Basically, the coefficient correlations between dew point and heat island intensity were not very high. They were $r=-0.677$, -0.441, -0.019, and 0.258, respectively (Fig. 6). This result indicated that dew points have a negative relationship with urban heat island during the afternoon.

3.4 Vegetation index and heat island intensity

In this study, the NDVI was used to represent the vegetation capacity surrounding every temperature measuring point. The higher the NDVI value, the higher and healthier the vegetation cover. Every measuring point's average NDVI values were calculated by a middle scale (750 m, 2,500 pixels) and a large scale (1,500 m,

Fig. 8 The distributions of the urban heat island intensity (*UHIs*), dew point (*DP*), and NDVI at night (1900–2100 hours)
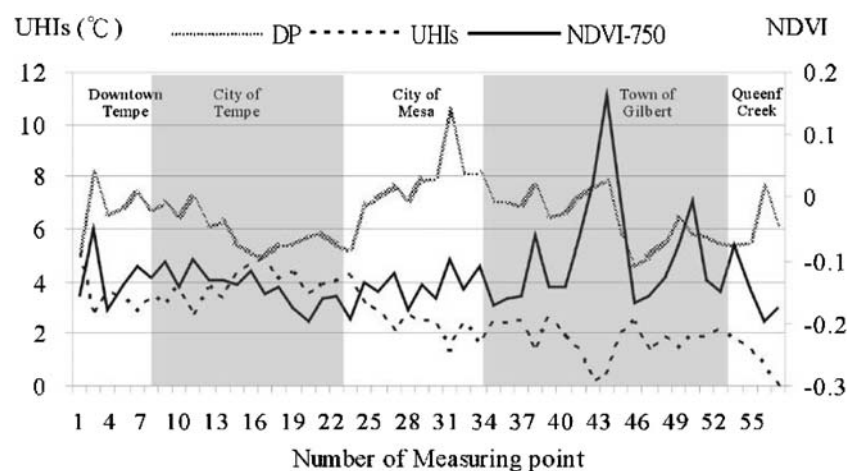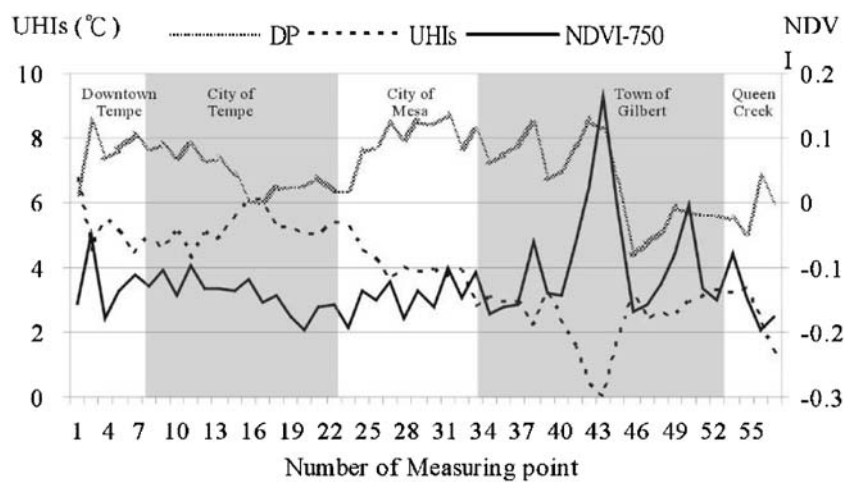
Fig. 9 The distributions of the urban heat island intensity (*UHIs*), dew point (*DP*), and NDVI at midnight (2300–0100 hours)

10,000 pixels) scale, respectively. That means every point has two average NDVI values, NDVI$_{-750}$, and NDVI$_{-1,500}$.

Figures 7, 8, 9, and 10 show the comparisons between the UHIs and dew point (DP) with NDVI at afternoon, night, midnight, and in the early morning, respectively. Table 6 also shows the correlation coefficients of NDVI and these two factors. The vegetation area, composed of grassland, bush, or tree, provides evapotranspiration which can influence ambient air temperature during the daytime. After sunset, the evaporation of vegetation decrease to a minimum. Therefore, on average, the correlation between dew point and NDVI is strong in the afternoon, but less at midnight and in the early morning. According to the result of this study shown in Table 6 and Fig. 11, the UHIs always have a negative correlation with NDVI (−0.42 to −0.56). This result indicates that the UHIs is influenced by the NDVI no matter if it is daytime or nighttime. Nevertheless, because the highest correlation coefficient was only −0.56 in 1,500 m scale, there remains considerable unexplained

variance. Furthermore, the correlation of NDVI and UHIs is more significant at midnight. It means that even the vegetation does not provide evaporation to cool the ambient environment during the night; the green space is still cooler than other kinds of pavement such as concrete and asphalt.

3.5 Meteorological impacts on the nocturnal UHI

The magnitude of the canopy layer heat island has been shown to be impacted by the prevailing meteorological conditions, i.e., wind-speed, cloud cover, and cloud height (e.g., Ackerman 1985; Magee et al. 1999; Chow and Roth 2006). A lack of surface wind allows for ideal conditions for surface cooling in both urban and rural areas, and clear skies also account for unimpeded surface long-wave radiation loss. Nocturnal heat island intensities have been shown to be inversely related to surface wind speed (Oke 1987), with the proviso that UHIs are analyzed under clear weather conditions. To include the simultaneous impact of

Fig. 10 The distributions of the urban heat island intensity (*UHIs*), dew point (*DP*), and NDVI in the early morning (0400–0600 hours)
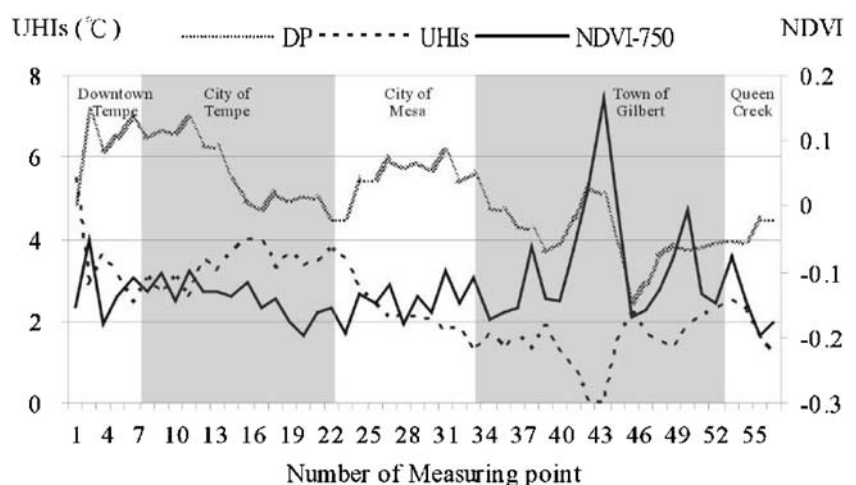
Table 6 The correlation coefficient (*r*) of the urban heat island intensity, dew point, and NDVI in four moments of the day

Factors moment (hours)	UHIs NDVI$_{(750)}$	DP	UHIs NDVI$_{(1,500)}$	DP
1500–1700	−0.47	0.74	−0.42	0.73
1900–2100	−0.44	0.29	−0.43	0.25
2300–0100	−0.54	0.27	−0.56	0.25
0400–0600	−0.49	0.04	−0.50	−0.03

Fig. 12 Correlation between maximum UHI intensity obtained from traverses with the weather factor Φ_W

cloud conditions on heat island intensity, Oke proposed an empirical method to calculate a complete "weather factor" (Φ_W; Oke 1998) that accounts for both wind and cloud impacts in estimating UHI intensity:

$$\Phi_W = u^{-1/2}\left(1 - kn^2\right) \qquad (2)$$

where u is surface wind speed in meter per second, k is the Bolz correction factor that is a coefficient that parameterizes decreasing cloud temperatures with height (Oke 1987), and n is the fraction of cloud cover observed. Given a limit of low wind speeds of 1 m s^{-1}, Φ_W ranges from 0 to 1, with lower values indicating a higher meteorological impact on the heat island. Runnalls and Oke determined a positive correlation ($r^2=0.56$) between maximum nocturnal UHIs with respect to Φ_W in Vancouver (Runnalls and Oke 2000). In this study, maximum UHIs from the 15 nocturnal transects were correlated with Φ_W (Fig. 12). Φ_W was derived from (a) mean surface wind speed measurements ($z=$ 10 m) from all weather stations and (b) from cloud observations (i.e., cloud cover and base height) taken at the Sky Harbor and Mesa stations. The low correlation coefficient ($r^2=0.09$) was unexpected and could be explained by correlating maximum UHIs with surface wind speeds
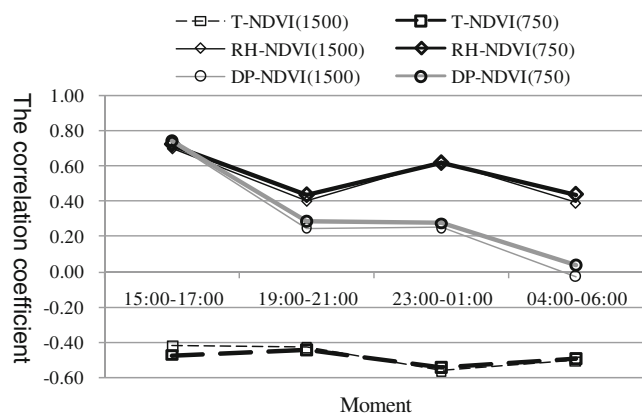
measured on clear nights (Fig. 13). Unlike results seen in other cities where heat island intensity is inversely related with increasing wind speeds, observed UHIs in this study appear to be independent from wind speeds up to 2.5 m s^{-1}. A probable explanation for this anomaly could be related to the origins of winds driven by the city's complex topography. The valley location of the transect route lies adjacent to the Superstition Mountains in the east, and the Santan Mountains located south of the metropolitan area, and therein lies the probability of nocturnal downslope (i.e., katabatic) flows of cold air from these mountains following a slight transitional lag period. This dynamic pattern in advection has been theorized by Hunt et al. (2003), where surface layers of air along a slope become negatively buoyant after radiative cooling, eventually overcoming inertial forces of upward flows around sunset. This phenomenon was observed to occur diurnally throughout the valley when analyzing data from a broad station network throughout the year (Brazel et al. 2005). In this

Fig. 11 The correlation coefficient of the average temperature (*T*), relative humidity (*RH*), dew point (*DP*), and NDVI in four moments of the day
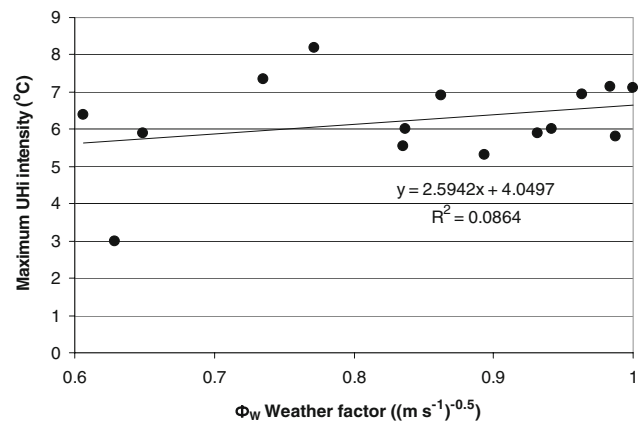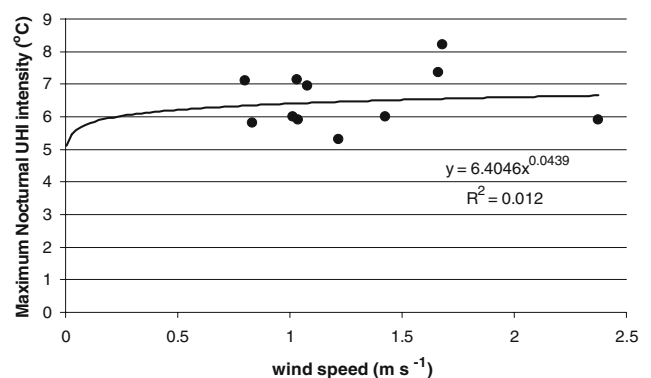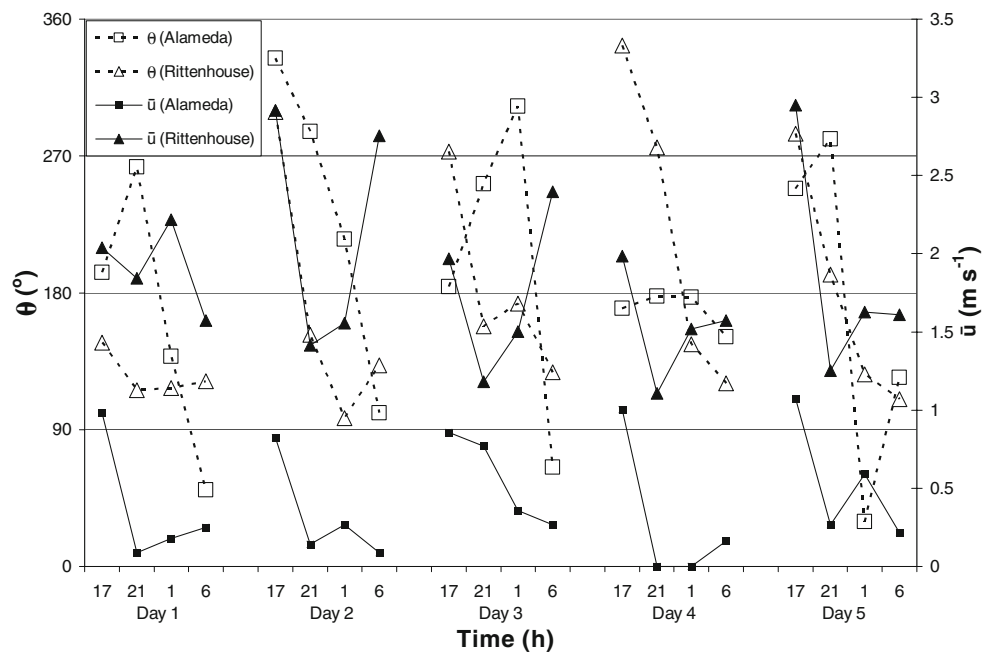

Fig. 13 Relationship between nocturnal maximum UHI intensity with surface wind speed taken at 10 m based on observations taken under clear weather conditions

Fig. 14 Mean wind direction (θ) and mean wind speed ($\bar{u}$) data taken from urban (Alameda—station 2) and rural (Rittenhouse—station 7) meteorological stations during each transect period


study, wind data from an urban (Alameda—station 2) and rural (Rittenhouse—station 7) weather station were examined for possible evening transition events within the urban canopy. These stations were selected due to their proximity to the transect start/end points. Rural wind speeds were higher than urban wind speeds during all transects, and the switch in wind direction from west to east (i.e., greater advection from higher elevations over time) generally occurs earlier within rural areas (Fig. 14). Of interest is that the transition timing generally occurs at similar times of maximum UHI nocturnal intensity (2300–0100 hours). Further, rural wind speeds were observed to increase with these transitions, indicating probable advection of cooler downslope air. This would result in rural areas cooling more rapidly vs. Downtown Tempe, which had lower observed wind speeds. The increased rural

cooling could account for higher UHI intensities during the evening transition events, possibly inflating the temperature differences, and would also explain the persistence of higher UHI intensities under high wind speed conditions, a feature of the Phoenix heat island that is generally not observed in other cities.

3.6 The historical comparison of heat island

In general, there is a consistency in the temperature distribution between this study and previous research which had been conducted in 2001 (Hedquist and Brazel 2006). The conversion of vacant and agricultural lands to residential and commercial area reduced a steep temperature gradient that was observed in both the previous study and in this one. The difference between the two surveys is

Fig. 15 The typical temperature distribution of study area in 2001 and 2007
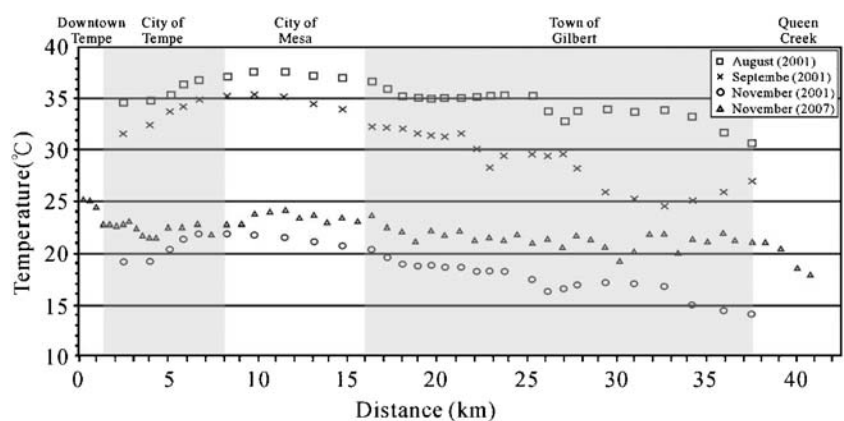
that the location of the steep temperature gradient was a little further away from the urban area compared with the survey in 2001 because the residential region spread within these 6 years.

Figure 15 shows that the typical temperature distribution representing the mobile transect route which passed through two urban areas (Downtown Tempe and Mesa), two residential areas (one between Tempe and Mesa, the other located on Gilbert), and finally went deep into the rural area. The transect temperature profile of this study was basically similar to the results in November 2001. Nevertheless, relative to the highest temperature which only appeared in the Mesa city area in the previous article, the highest temperature was observed at the beginning because the mobile transect started from Downtown Tempe in this study.

It should be noted that during 2001, the drop in temperature beyond development of residential construction was ca. 2°C where no such drop is evident in 2007. This is consistent with the empirical findings of Brazel et al. (2007) in assessing metropolitan fixed weather station data under the spreading influence of housing developments over time on the urban fringe (which suggested for a full development of housing around a weather site on the urban fringe that minimum temperatures increase ca. 1.5°C per 1,000 housing units developed within a 0.5-km radius of a site). This present study in comparison to the 2001 also points out the dimension of residential development heating effects as apart of the UHI process, consistent withy Grossman-Clarke's MM5 simulations of heating due to xeric residential development (Grossman-Clarke et al. 2005)

4 Discussion and conclusion

In this paper, mobile transect and remote sensing data were used to analyze the relationship between vegetation index and thermal environment in the Phoenix metropolitan area. First, the transect result shows that the UHIs were obvious during night, midnight, and early morning. The average midnight UHIs was 6.77°C in this study. The highest UHIs which had been observed during midnight (2300–0100 hours) on November 8, 2007 was 8.2°C and the lowest UHIs in this study was 1.34°C occurring on November 10, 2007 with partly cloudy condition. Even though it was a cloudy day, November 12 still has very obvious midnight UHIs (5.9°C). All of mobile transects in this study observed the stable heat island occurs both at midnight and before dawn, no matter what kind of sky condition and what level of wind speed. That indicated the anthropogenic heat may play an important role in dominating the warm temperature at night in urban areas. Dew point data was obtained by calculating temperature and relative humidity data in this paper. Based on transect data, the dew point did not reach the

discomfort limit, 20°C, because the Phoenix metropolitan is located in a desert area. The relationship between dew point and UHIs was not strong but it indicated that dew point has a negative relationship with UHIs during the afternoon. Besides the dew point, vegetation index is the other important factor which can influence the UHIs. According to the result of this study, NDVI values always have negative correlation with the UHIs. It means vegetation can mitigate the UHIs both in daytime and at night time. Even though most of vegetation cannot cool the ambient environment by evaporation after sunset, the green spaces were still cooler compared with other pavements such as concrete sidewalks or asphalt parking lots. In other words, increasing the vegetation area in urban can help to alleviate the UHI effect. It is also suggested that near-surface wind transition of cooler air from higher elevations leads to greater rural cooling as compared to urban areas, possibly contributing to the high midnight UHIs. Lastly, by comparing the tendencies of the 2001 and 2007 transect datasets, this study detected that urban development, as empirically determined by Brazel et al. (2007), does produce a dynamic and significant extension of the UHI effect on the urban fringe areas.

References

Ackerman B (1985) Temporal march of the Chicago heat island. J Clim Appl Meteorol 24:547–554

Balling RC, Brazel SW (1987) Time and space characteristics of the Phoenix urban heat island. J Ariz-Nev Acad Sci 21:75–81

Balling RC, Cerveny RS (1987) Long-term associations between wind speeds and urban heat island of Phoenix, Arizona. J Clim Appl Meteorol 26:712–716

Brazel AJ, Johnson DM (1980) Land use effects on temperature and humidity in the Salt River Valley, Arizona. J Ariz-Nev Acad Sci 15:54–61

Brazel AJ, Fernando HJS, Hunt JCR, Selover N, Hedquist BC, Pardyjak E (2005) Evening transition observations in Phoenix, Arizona. J Appl Meteorol 44:99–112

Brazel A, Gober P, Lee S-J, Grossman-Clarke S, Zehnder J, Hedquist B, Comparri E (2007) Determinants of changes in the regional urban heat island (1990–2004) within Metropolitan Phoenix, Arizona, USA. Clim Res 33:171–182

Chow WTL, Roth M (2006) Temporal dynamics of the urban heat island of Singapore. Int J Climatol 26:2243–2260

Fast JD, Torcolini JC, Redman R (2005) Pseudovertical temperature profiles and the urban heat island measured by a temperature datalogger network in Phoenix, Arizona. J Appl Meteorol 44:3–13

Gordon JH (1921) Temperature survey of the Salt River Valley, Arizona. Mon Weather Rev 49:271–276

Grossman-Clarke S, Zehnder JA, Stefanov WL, Liu Y, Zoldak MA (2005) Urban modifications in a mesoscale meteorological model

and the effects on near-surface variables in an arid metropolitan region. J Appl Meteorol 44:1281–1297

Hawkins TW (2004) The role of rural variability in urban heat island determination for Phoenix, Arizona. J Appl Meteorol 43:476–486

Hedquist BC, Brazel AJ (2006) Urban, residential, and rural climate comparisons from mobile transects and fixed stations: Phoenix, Arizona. J Ariz Acad Sci 38(2):77–87

Hunt JCR, Fernando HJS, Princevac M (2003) Unsteady thermally driven flows on gentle slopes. J Atmos Sci 60:2169–2182

Magee N, Curtis J, Wendler G (1999) The urban heat island effect at Fairbanks, Alaska. Theor Appl Climatol 64:39–47

Moran JM, Morgan MD (1989) Meteorology—the atmosphere and the science of weather, 2nd edn. Macmillan, New York

Oke TR (1987) Boundary layer climates, 2nd edn. Methuen, London

Oke TR (1998) An algorithmic scheme to estimate hourly heat island magnitude. In: Proceedings from the 2nd Urban Environment Symposium, Albuquerque, New Mexico, American Meteorological Society, Boston, MA, pp 80–83

Runnalls KE, Oke TR (2000) Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. Phys Geogr 21(4):283–304

Stabler LB, Martin CA, Brazel AJ (2005) Microclimates in a desert city were related to land use and vegetation index. Urban Forest Green 3:137–147

Turcker CJ, Fung IY, Keeling CD, Gammon RH (1986) Relationship between atmospheric CO_2 variations and a satellite-derived vegetation index. Nature 319:195–199

United States Census Bureau (2008). Population estimates. Available at: http://www.census.gov/popest/estimates.php

Wexler A (1976) Vapor pressure formulation for water in the range 0°C to 100°C. A revision. J Res Natl Bur Stand A Phys Chem 80A (5–6):775–785