# Spatial and Temporal Characteristics of Beijing Urban Heat Island Intensity

PING YANG

China Meteorological Administration Training Center, Beijing, China

GUOYU REN

Laboratory for Climate Studies, National Climate Center, China Meteorological Administration, Beijing, China

WEIDONG LIU

Institute of Urban Meteorology, China Meteorological Administration, Beijing, China

(Manuscript received 15 May 2012, in final form 12 March 2013)

#### ABSTRACT

An hourly dataset of automatic weather stations over Beijing Municipality in China is developed and is employed to analyze the spatial and temporal characteristics of urban heat island intensity (UHII) over the built-up areas. A total of 56 stations that are located in the built-up areas [inside the 6th Ring Road (RR)] are considered to be urban sites, and 8 stations in the suburban belts surrounding the built-up areas are taken as reference sites. The reference stations are selected by using a remote sensing method. The urban sites are further divided into three areas on the basis of the city RRs. It is found that the largest UHII generally takes place inside the 4th RR and that the smallest ones occur in the outer belts of the built-up areas, between the 5th RR and the 6th RR, with the areas near the northern and southern 6th RR experiencing the weakest UHI phenomena. On a seasonal basis, the strongest UHII generally occurs in winter and weak UHII is dominantly observed in summer and spring. The UHII diurnal variations for each of the urban areas are characterized by a steadily strong UHII stage from 2100 local solar time (LST) to 0600 LST and a steadily weak UHII stage from 1100 to 1600 LST, with the periods 0600–1100 LST and 1600–2100 LST experiencing a swift decline and rise, respectively. UHII diurnal variation is seen throughout the year, but the steadily strong UHII stage at night is longer (shorter) and the steadily weak UHII stage during the day is shorter (longer) during winter and autumn (summer and spring).

## 1. Introduction

Human activities have modified the composition, structure, and energy balance of the earth's surface and the lower atmosphere in highly industrialized regions such as Europe, North America, and eastern Asia. These artificial factors determine a distinct local climate in big cities, expressed as urban climate. With the urban modification to the natural land cover, surface air temperature (SAT) in the urban areas increases significantly relative to the SAT in surrounding suburbs. This phenomenon is known as the urban heat island (UHI) effect. Two different heat islands composed of a canopy layer and a boundary layer have been identified. The first layer is of a microscale nature, being dominated by the immediate surroundings, and the second layer is of a local or mesoscale nature, being affected by the presence of an urban area at its lower boundary (Oke 1976). The most important features of urbanization are the urban structure, the urban cover, the urban fabric, and the urban metabolism (Oke 2006).

The features of the UHI have been extensively studied during the past several decades (Landsberg 1981; Oke 1988; Arnfield 2003). Large UHI effects have been measured and reported for most regions of the world (Morris et al. 2001; Grimmond 2006; Grimmond et al. 2010). A UHI intensity (UHII) of up to 10°C has been observed for some large cities on clear and calm winter nights (Jáuregui 1973; Sakakibara and Owa 2005; Rosenzweig et al. 2005).

In parallel, of particular interest for investigators are the causes of UHI formation. It has been demonstrated

*Corresponding author address:* P. Yang, Training Development Dept., China Meteorological Administration Training Center, 46 Zhongguancun Nandajie, Haidian, Beijing 100081, China. E-mail: zz96998@163.com

DOI: 10.1175/JAMC-D-12-0125.1

that the UHI effect is closely related to urban/rural energy-balance differences. It is also found that the impact of urbanization is to favor partitioning of energy into sensible heat rather than latent heat and to increase the importance of heat storage by the system. The mechanisms for the canopy-layer anomaly are not the same as those in the boundary layer, with the former consisting of a wide range of energy-balance systems and being largely the result of the immediate site character and the latter probably representing both an advective accumulation and internal radiative effects (Oke 1982, 1987). Also, city size and synoptic weather conditions are both essential causes, especially for long time periods (Oke 1988; Karl et al. 1988). For shorter periods, however, the local-scale factors such as site exposure, land cover, surface moisture, human activity, and so on are more important (Davey and Pielke 2005; Peterson 2003; Kim and Baik 2005; Stewart and Oke 2012).

In China, analysis of the UHI has been conducted for big cities, and interesting conclusions have been drawn thereby. The previous works were mostly based on SAT data from meteorological stations (Wang et al. 1990; Zhou et al. 2004; Chu and Ren 2005; Feng et al. 2010; A. Y. Zhang et al. 2010), and vehicle temperature traverses and remote sensing technology were also used to investigate the spatial structure of the UHI (Weng 2001; Zhang et al. 2005; Xu et al. 2006; Xie and Yang 2008; Fang et al. 2011; Ren and Ren 2011). The investigation of UHI features in Shanghai, China, has shown that the UHII is stronger at night and in autumn/winter than during the day and in summer (Deng et al. 2001). Other research by different authors for Beijing, China, has also found an apparent UHI in the urban area (Zhang et al. 2002; Xu et al. 2006; Yang et al. 2013). In addition, for different sizes of cites, the increases of UHII near most meteorological stations have significantly enhanced the SAT trends in mainland China over the past 50 years (Zhou et al. 2004; Chu and Ren 2005; Hu et al. 2006; Ren et al. 2007, 2008, 2010; A. Zhang et al. 2010). There are also some analyses of the UHI effects for big cities of China using the data of land surface temperature retrieved from satellite products such as the Landsat Thematic Mapper (TM) and the Earth Observing System Moderate Resolution Imaging Spectroradiometer (MODIS; e.g., Zhang et al. 2005; Fang et al. 2011). The results are relevant, but they are not directly comparable to those obtained by using surface air temperature data (Roth et al. 1989).

A major problem in the previous studies on the climatological features of UHII in China is that if the detailed diurnal variation is considered then the spatial distribution is often ignored (Hu et al. 2009). Likewise, the diurnal characteristics of the UHII have often been neglected when in-depth study is given to the spatial structure of the UHII (J. Zhang et al. 2010). For example, Li et al. (2007) revealed the characteristics of the Beijing UHI in July on the basis of both manual stations and automatic weather stations (AWS), demonstrating the spatial distribution and the diurnal variation of the UHII. Because only the data from two AWSs in 2003 were used, the detailed features of the spatial and temporal variation still need to be examined. Other studies were also restricted to an outline description of the UHI or to a single season by using data from only urban–rural station pairs. The main reason for this contradiction is the insufficiency of observations, especially the limited routine meteorological observations.

AWSs were not deployed over mainland China until the end of the 1990s, and the countrywide installations and applications of AWSs at national meteorological stations were completed only by ~2004. Since then, a huge number of AWSs have been installed and applied in urban and rural areas in the country as based on the operational standard issued by the China Meteorological Administration (China Meteorological Administration 2003, 104–125). By 2010, for example, a dense AWS network with more than 200 stations had been established in Beijing Municipality. This network can provide hourly SAT data, helping in investigations into the UHII features in big cities like Beijing.

By applying the hourly SAT data from AWSs in Beijing, the climatological features of UHII are investigated in detail in this paper. In the following sections, the basic conditions, including the stations' information and climatological characteristics, are introduced at first, and then the spatial distribution, seasonal variation, and diurnal cycle of UHII in urban areas are examined. Furthermore, the urban region of Beijing is divided into three belts for analyzing the spatial differences of UHII in detail. The causation of the UHII variation is briefly discussed before the conclusions are drawn.

#### 2. Study area, data, and methods

Beijing Municipality, with an area of 1.6 million km<sup>2</sup>, is located in the north of the North China Plain and to the south of the Yanshan Mountains. The southeast plain occupies 38.8% of the total area of Beijing. Most parts of the plain are below 100 m above sea level. Beijing is characterized climatologically by a typical temperate continental climate, with a hot summer and a cold winter, and a seasonally highly concentrated summer precipitation regime.

Since the 1980s, Beijing has experienced rapid urbanization. Through 2007, the urbanized regions have extended and covered a much larger area than that of the 1980s. The present extent of the built-up areas is



FIG. 1. Study region and locations of the 4th–6th Ring Roads and the 98 temperature gauge stations used in this study, including 8 reference stations marked in blue and 56 urban stations marked in red. Abbreviations of the station names are FHL for Feng Huang Ling, YLD for Yong Le Dian, PGZ for Pang Ge Zhuang, AD for An Ding, NZ for Nan Zhao, DXC for Dong Xin Cheng, DSGZ for Da Sun Ge Zhuang, and LWT for Long Wan Tun. Abbreviations marked in black are for the 10 districts of Beijing Municipality: CP is Chang Ping, SY is Shun Yi, TZ is Tong Zhou, DX is Da Xing, FS is Fang Shan, MTG is Men Tou Gou, SJS is Shi Jing Shan, HD is Hai Dian, FT is Feng Tai, CY is Chao Yang, and CA is Central Area.

marked in pink in Fig. 1 (Mu et al. 2012), and the current population of the Beijing Municipality is 20 million, which is 2 times the census result in 1986. Over 50% of the population lives in the downtown areas and the nearby suburban areas, which together make up the study area of this paper as outlined in Fig. 1.

As a result of the bewildering urban sprawl, an express transportation system became a necessity in Beijing City, and a multiple-ring-road (RR) system of transportation (Fig. 1) was developed (Wang et al. 2010). The 4th RR was opened in 2001 and is 65.3 km in length, and the area inside the 4th RR reaches about 300 km<sup>2</sup>. The 5th RR (98.6 km long) was opened in 2003 and is  $\sim$ 10 km away from the city center. Six years later, the 6th RR (187.6 km long) was built to relieve the traffic pressure in Beijing City (red loops in Fig. 1). The areas inside the different RRs actually represent the radial extensions of the urban areas with varied densities of population and buildings as well. In this paper, the sites located inside the 6th RR in Beijing are considered to be urban stations, and those inside the 4th RR are considered to be central urban stations (Fig. 1).

Hourly temperature data from 185 stations across Beijing Municipality for the time period 2007–10 were obtained from the Meteorological Information Center of the Beijing Meteorological Bureau (MIC/BMB). The height of the AWS temperature sensors from the ground surface is 2 m, which is consistent with those of the manual stations. By considering the urban structure, the urban cover, the urban fabric, and the urban metabolism (Oke 1981, 2006), the BMB installed the AWSs in accord with the operational standard issued by the China Meteorological Administration (China Meteorological Administration 2003, 104–125), which is based on World Meteorological Organization guidance.

To increase the robustness of our analyses, all hourly temperature data from MIC/BMB have been checked and quality controlled. The missing values, which account for 0.37% of the total records, were replaced by the instantaneous valid values of the nearest five stations by using spatial interpolation with the inverse-distanceweighting technique (Lin et al. 2002). The possible erroneous data have been detected, proved, and adjusted, and those stations with too many erroneous records have been ruled out. The details of the quality control have been provided by Yang et al. (2011).

Thus, 98 observation stations evenly distributing in the entire study area were chosen (Fig. 1) for describing the climatological features. In the following analysis of the UHII characteristics, however, only the 56 urban stations inside the 6th RR and 8 reference stations are used. Indeed, it is noteworthy that the selection of the reference stations surrounding the built-up areas is a key to determining the UHII of a city. We choose the eight reference stations according to a strictly defined standard using a remote sensing method (Ren and Ren 2011). By specifying the locations of the suburban stations in the fields of land surface temperature distribution, those that are unaffected by the UHI or are located in the background climatic conditions are identified. Relative to the other approaches used for classifying climatic stations, the remote sensing method does not rely so much on social and economic data, and data updating can be easily done (Ren and Ren 2011).

In addition, the reference sites, far enough from the built-up areas and in different directions from the urban center, are all located within a distance of 53.7 km [Long Wan Tun (LWT)] from Tiananmen Square, the center of the city. All of the reference stations lie on open ground with a countryside setting, completely away from the impacts of high buildings. The average elevation of the reference stations is 39.6 m, which is only 8.8 m lower than that of the 56 urban stations (48.4 m), ensuring more accurate estimation of the UHII because of similarities in the topography.

To differentiate the UHII among the distinct sites of the built-up areas, we examined three groups of urban stations in the analysis, including those inside the 4th RR (composed of 25 stations), those in the zones of the 4th 1806





FIG. 2. Spatial distributions of the mean temperature (°C) during (a) the whole year, (b) spring, (c) summer, (d) autumn, and (e) winter in Beijing during 2007–10.

and 5th RRs (composed of 14 stations), and those in the zones of the 5th and 6th RRs (composed of 17 stations). The reason for applying the classification is that the city RR loops were constructed surrounding the city center and they well differentiated the urban features in terms of densities of population, buildings, and, to some extent, the functional areas (He et al. 2002; Miao et al. 2011). He et al. (2002) indicated that the urbanization

rate by 1997 had reached 94.6% within the 4th RR while it had reached only 68.4% within the 4th–5th RR and was lower outside the 5th RR. The RR loops represented well the urban–rural boundaries for different time periods in Beijing during 1984–2007 (Mu et al. 2012), with the densest and tallest buildings and almost all of the central commercial areas appearing within the 4th RR. It is therefore reasonable to make such a first-order



FIG. 3. (a) Pentad averaged and (b) annual-averaged diurnal cycle of mean temperature in urban and rural areas in the study region.

classification of the urban stations for showing the macro- and integrated features of UHI effects.

In the study, UHII is estimated by calculating the SAT difference between urban and rural stations (areas). The rural SAT  $T_{\text{rural}}$  is the average SAT of the eight reference stations, and the urban SAT  $T_{\text{urban}}$  is the SAT of any urban station or the average SAT values of the urban stations inside any specific urban area. Therefore, UHII, or  $\Delta T_{u-r}$ , can be defined as

$$\text{UHII} = \Delta T_{u-r} = T_{\text{urban}} - T_{\text{rural}}.$$
 (1)

#### 3. Characteristics of temperature

The annual and seasonal mean SATs over the study region are shown in Fig. 2. During the 4-yr period, the annual mean SAT over the study region is 13.04°C, with

the highest value (14.71°C) appearing in He Ping Xi Qiao (HPXQ) near the joint belt of the Central Area (CA) and Chao Yang (CY) districts. The lowest record (11.82°C) is seen in Shun Yi Sai Ma Chang (SYSMC) in the southwestern Shun Yi (SY) district. Centers of relatively high temperature can be identified inside the 4th RR or in CA, the adjacent zones to the 4th RR such as CY, Feng Tai (FT) district, and Hai Dian (HD) district. The secondary high centers mainly occur in the southwestern part in FT, Men Tou Gou (MTG), and HD districts and in the northern part of the CY district. In the northwest and northeast, the annual mean SAT is generally less than 12°C.

In a similar way, high-temperature centers for each season mostly concentrate on the 4th RR (Figs. 2b–e), and low-temperature centers often appear over the northwestern and northeastern parts of the study

TABLE 1. Annual and seasonal mean temperatures (°C) for the whole urban area, the urban station groups (inside the 4th RR, 4th–5th RRs, and 5th–6th RRs), and the rural areas.

	Inside 4th RR	4th–5th RRs	5th–6th RRs	Urban areas	Rural areas
Year	13.90	13.24	12.96	13.36	12.21
Spring	14.79	14.30	14.08	14.39	13.51
Summer	26.57	26.08	25.80	26.15	25.36
Autumn	14.09	13.30	13.00	13.46	12.13
Winter	-0.01	-0.88	-1.19	-0.69	-2.20

region. The spatial variability varies by season, however. The spatial variability of SAT is small in spring. The mean SAT differences among the sites are consistently larger in summer than those in spring, and they are even larger in autumn and winter. Although the scope of the centers of high seasonal mean SAT in autumn is smaller than that in winter, and only a few sporadic high centers are observed inside the 4th RR, the site-to-site SAT contrast reaches 3.79°C, which is slightly larger than that in winter. It is obvious that the large spatial contrasts of annual mean and seasonal mean SAT result from the UHI effects, which lead to a significant increase in temperature over the built-up areas relative to the surrounding countryside (Xu et al. 2006; Lin and Yu 2005; Liu et al. 2009).

Figure 3 displays the seasonal and diurnal cycles of SATs over the urban area represented by the 56 urban stations and the rural areas represented by the 8 reference stations. Similar variations appear in urban and rural areas, but there is a systematic positive SAT difference between the urban and rural areas throughout the year. The difference clearly indicates the UHI effect over the urban areas. Table 1 shows that the hourly mean SAT in the urban areas is 13.36°C but varies from 13.90°C in CA to 12.96°C between the 5th and 6th RRs. Mean urban SATs in various seasons all appear to be the highest in CA, followed by the 4th and 5th RRs, with the lowest record registered in the 5th and 6th RRs. The SAT differences between adjacent urban areas generally decrease from CA to the outskirts for all seasons, with the largest difference occurring between CA and the 4th and 5th RRs in wintertime and the smallest one between the 4th and 5th RRs and the 5th and 6th RRs in springtime.

The hourly SAT difference between urban and rural stations is also evident, and the urban SAT is higher at all times during a day. The diurnal cycle is smaller in urban areas than in rural areas. This is consistent with previous research reporting that the pace of SAT decline in urban areas is slower than that in the rural areas after sunset (e.g., Oke 1982; Li et al. 2008).



FIG. 4. Spatial distribution of the annual mean UHII in the urban areas during 2007–10. Blue, pink, purple, red, and black lines mark the UHII isotherms of,  $0^{\circ}$ ,  $0.6^{\circ}$ ,  $1.2^{\circ}$ ,  $1.8^{\circ}$ , and  $2.4^{\circ}$ C, respectively. Blue points represent the stations in the urban areas.

### 4. Characteristics of UHII in urban areas

## a. Spatial distribution of UHII

The spatial distribution of annual mean UHII over the urban areas (corresponding to the built-up areas inside the 6th RR) is shown in Fig. 4. The maximum UHII center (2.45°C) appears at HPXQ (39.97°N, 116.41°E), in the northeastern part of CA. This station is surrounded by dense buildings and several expressways (Fig. 5a). The only station with negative UHII ( $-0.16^{\circ}$ C) is Dao Xiang Hu (DXH; 40.10°N, 116.18°E) in the northwest part of the built-up areas. The sparser buildings and a nearby small lake might be reasons for the negative UHII recorded at this station (Fig. 5b).

Figure 6 shows the spatial distribution of the seasonal mean UHII over the urban areas of Beijing. The high UHII centers, such as those around CA, CY, and HD, are all economically developed and densely populated parts of the city. It is obvious that the UHII is stronger in winter and autumn than in spring and summer. The feature of a seasonal cycle is supported by previous studies, including Xie et al. (2006), Lin and Yu (2005), and Chu and Ren (2005) for Beijing City and Liu et al. (2005) and Han et al. (2007) for Shijiazhuang and Tianjin, the nearby big cities in the North China Plain. The lowest seasonal mean UHII is identified in spring, with most areas outside the central urban area being less than 1.2°C. Areas with spring mean UHII of less than 0.6°C are found in the northeastern and northwestern parts of the domain. In autumn, the seasonal mean UHII experiences a considerable increase, with the 1.2°C isotherm covering most areas inside the 5th RR and the maximum UHII in the northern CA



(a)



(b)

FIG. 5. Stations and the surrounding landscapes: (a) HPXQ and (b) DXH. [Photographs are from Google Earth; ©2011 Google; image ©2011 DigitalGlobe.]

reaching 3.15°C. The winter has the largest seasonal mean UHII, and almost the entire central urban area is surrounded by the 2.4°C isotherm, with the maximum value reaching 2.90°C, whereas the minimum UHII of  $-0.07^{\circ}$ C occurs at DXH in the northwestern most part of the domain.

Table 2 illustrates the considerable differences among the seasons. The largest seasonal mean UHII of the whole urban areas is 1.65°C in winter, followed by 1.38°C in autumn, 0.92°C in summer, and 0.80°C in spring. The largest seasonal difference between winter and spring reaches 0.85°C.

The fact that UHII is largest in winter can be explained by rural areas cooling more rapidly under strong inversions and radiation-type weather at night during this season in the North China Plain. Heat release by building heating in winter might be another reason (Chen and Shi, 2012). The maximum wind speeds in the urban areas occur in spring, reaching  $1.84 \text{ m s}^{-1}$  on average while the average UHII is  $1.05^{\circ}$ C, and strong wind is therefore





(b)



FIG. 6. As in Fig. 4, but for (a) spring, (b) summer, (c) autumn, and (d) winter.

very important for weaker UHII during spring. The autumn mean UHII is larger, and this is usually associated with calm weather and a stable lower atmosphere. Of the four seasons, autumn is the one in which urban areas have the lowest average wind speed  $(1.19 \text{ m s}^{-1})$ . Previous research indicated that frequent rainfalls and the unstable lower atmosphere in the monsoon might have been the most important reason for the smaller UHI during summer (Zhang et al. 2005). To examine this, we compared the average UHIIs of total urban areas in summer for rainy days and no-rain days and preliminarily found a good association of the UHI with the weather phenomena, with the UHII on rainy days much lower than on sunny days.

## b. Diurnal variation of UHII

Figure 7 shows the annual mean diurnal UHII in the three urban areas divided by the 4th, 5th, and 6th RRs.

TABLE 2. Annual and seasonal means, maximum, minimum, and range values of UHII over the urban areas of Beijing (°C).

	Mean	Max	Min	Range (max – min)
Year	1.23	2.45	-0.16	2.61
Spring	0.80	1.53	-0.12	1.65
Summer	0.92	1.98	-0.24	2.23
Autumn	1.38	3.15	-0.22	3.37
Winter	1.65	2.90	-0.07	2.97



FIG. 7. Diurnal variations of UHII in the urban areas inside the 4th RR and between the 4th and 5th and 5th and 6th RRs.

Among the three belts, a common diurnal variation pattern has been found to contain two relatively stable stages separated by two swiftly changing stages. One stable stage is characterized by strong UHII lasting from 2100 LST until early the next morning (about 0600 LST), and another is characterized by weak UHII lasting from 1100 to 1600 LST. The two swiftly changing stages are from 0600 to 1100 LST and from 1600 to 2100 LST, characterized by a fast decline and an abrupt rise, respectively.

Table 3 shows the average UHII for the 24-h and the steadily strong and weak UHI stages. We can see that inside the 4th RR the largest annual mean UHII occurs during the steadily strong UHI stage in CA, reaching 2.37°C, and the smallest annual mean UHII of 0.21°C appears during the weak UHI stage in the area between the 5th and 6th RRs. The 24-h average UHII difference between CA and the 4th-5th RR area is 0.65°C, and that between the areas of the 4th-5th RRs and 5th-6th RRs is only 0.27°C. This spatial contrast is more remarkable during the steadily strong UHI stage, with the difference between CA and the 4th-5th RR area reaching 0.97°C, which is almost 3 times the difference between the areas of the 4th–5th RRs and 5th–6th RRs (0.34°C). On the contrary, the spatial contrasts for the neighboring areas are small for the steadily weak UHI stage.

The average UHII isotherms in the two stable stages are shown in Fig. 8. During the strong UHI stage, the central urban area is almost surrounded by the 2.4°C UHII isotherm, and UHII values of 1.2°C or greater are recorded at 39 out of the total 56 urban stations (Fig. 8a). Only three stations near the 6th RR exhibit notably weak UHII (lower than 0.6°C). Nevertheless, noticeable discrepancies are observed in the UHII isotherm distribution during the steadily weak UHI stage (Fig. 8b).

TABLE 3. Average UHII for 24 h and for the steadily strong and weak UHI stages (°C).

		Strong UHI stage	Weak UHI stage
	24-h avg	(2100–0600 LST)	(1100–1600 LST)
Inside 4th RR	1.65	2.37	0.60
4th–5th RRs	1.00	1.40	0.38
5th-6th RRs	0.73	1.06	0.21

Although the central area is surrounded by the  $0.6^{\circ}$ C isotherm, nowhere inside the 4th RR does the UHII surpass  $1.2^{\circ}$ C, and the area between the 5th and 6th RRs has a very low UHII of only  $0^{\circ}$ – $0.3^{\circ}$ C.

#### c. Seasonal variation of UHII

The pentad-mean UHII for the three urban areas for the time period 2007–10 is shown in Fig. 9. The seasonal



FIG. 8. As in Fig. 4, but for the spatial distribution of the UHII for (a) a strong UHII stage (2100–0600 LST) and (b) a weak UHII stage (1100–1600 LST).



FIG. 9. Variations in pentad-mean UHII for the three urban areas: squares indicate the CA, circles are for the area between the 4th and 5th RRs, and triangles are for the area between the 5th and 6th RRs. Dashed vertical lines mark the boundaries of the four seasons.

variations in the UHII in the different areas are consistent. The largest pentad-mean UHII of 2.75°C occurs in the urban center in the 70th pentad, and the smallest pentad-mean value of 0.27°C appears in the 5th-6th RRs in the 38th pentad. The winter mean UHIIs are 2.15°, 1.27°, and 0.96°C for CA, the area between the 4th and 5th RRs, and the area between the 5th and 6th RRs respectively. The weakest UHII take place in spring, with the seasonal mean values being 1.29°, 0.79°, and 0.58°C for the three areas, respectively. Figure 10 shows the hour-pentad plots of the UHII averaged for all of the urban areas for the time period 2007–10. Figure 10 clearly shows that the UHII in summer experiences a smaller diurnal variation in comparison with the other seasons. It also indicates that the night-to-day shift is large in winter and small in autumn, which might be to some extent due to the heat release by building heating during the cold and long winter nights. It is interesting to note that, although the UHII at nights in summer is weaker than those in winter and autumn, the UHII during the daytime in summer is obviously the strongest among the seasons. A similar conclusion has been reported by Zhang et al. (2005) using remote sensing data. In addition, there are obvious multipentadal fluctuations in nighttime UHII, especially in winter and autumn. The frequency of the fluctuations is lower in autumn and early winter but becomes higher in the first 10 pentads, or later in the winter. Whether this phenomenon is related to the local weather disturbances needs to be investigated in the future.

Figure 11 presents hour-pentad plots of UHII averaged for the different urban areas for the time period



FIG. 10. Hour-pentad plots of the UHII averaged for the whole urban area for the time period 2007–10. Dashed horizontal lines mark the boundaries of the four seasons.

2007-10. Considerable differences exist among the urban areas. In the central urban area, the hourly mean UHII can reach as high as 3.0°C during the nighttime strong UHII stage in winter-a value is approximately 1.2°C higher than that in summer. Once again, the hourly mean UHII during the daytime shows obviously higher values in summer than in the other seasons in the central urban area. Nevertheless, higher summer daytime UHII is not captured within the areas of the 4th-5th and 5th-6th RRs. For example, the maximum UHII in the 4th-5th RRs reaches 2.7°C around 0800 LST in the 70th pentad (early winter), and the relatively stronger UHII phenomenon during the summer daytime is not notable. Between the 5th and 6th RRs, extremely low UHII values prevail in daytime in every season, especially on spring afternoons, and even a few negative values are registered in the early afternoon around the 18th pentad (Fig. 11c).

#### 5. Discussion

The analysis performed here shows that the number of observational sites, the length of the dataset, and the selection of the reference or rural stations are all important for analyzing the UHI. Many studies of urban climate have been conducted for Beijing City, and they have reported some basic features of the UHI (Xie et al. 2006; Xu et al. 2006; Zhang et al. 2002; Chu and Ren 2005; Liu et al. 2009; Wang and Lu 2005; Wang et al. 2011). The previous studies could barely describe the fine-resolution structure of the UHII in Beijing urban areas, however, because of the lack of observational



FIG. 11. Hour-pentad plots of the UHII averaged for (a) the central urban area, (b) the 4th–5th RRs, and (c) the 5th–6th RRs for the time period 2007–10. Dashed horizontal lines mark the boundaries of the four seasons.

data, and most of the studies could not give precise estimates of the UHII for any urban sites because of the incomplete method for selecting reference stations. In choosing rural stations, for example, previous studies often took terrain and elevation into consideration (e.g., Wang et al. 2011) or simply relied on administrative boundaries to classify stations (e.g., A. Zhang et al. 2010) but did not at the same time take into account the specific positions of the observational stations in the urban thermal fields.

Applying densely distributed AWS observations for 2007-10, we extend our analysis to reveal the detailed features of the fine-resolution diurnal and seasonal variations and spatial distribution of the UHII in the Beijing urban areas. The objective criteria used for selecting reference stations can guarantee the accuracy of the estimates of the UHII. Moreover, unlike in previous studies, we perform the regionalization of the urban areas by referring to the positions of the three ring roads. This procedure better reveals the spatial differentiation of the Beijing urban climate, because the urban area has sprawled outward from the center and the ring roads are consistent with the boundaries of past urban areas at different urbanization stages (He et al. 2002; Li et al. 2009). To separate the urban areas into residential and business districts is a common practice (e.g., Liu and Yang 2009), but there is often a mosaic distribution in Beijing, and, although the procedure would be better to be applied in a functional classification, it might be not be proper for use in urban regionalization in the city. The ring-road-based regionalization applied in this paper represents well the spatial differentiation of the urban climate.

The results of our study are generally consistent with previous works using daily or hourly records from a smaller number of meteorological stations (e.g., Wang and Hu 2006; J. Zhang et al. 2010; Dong et al. 2011). These other studies also found that winter is the season that is most influenced by the UHI effect, despite the fact that J. Zhang et al. (2010) showed the weakest UHII in summer rather than in spring as we found. The differences are likely related to the different densities of station networks and the criteria for defining urban and rural stations. The weakest UHII in spring could be well explained by the more frequent windy conditions and the largest seasonal mean wind speed from March to May in northern China (Zhang and Ren 2003; Liu et al. 2004). A steadily strong UHII stage was found at night, whereas a steadily weak UHII phase is evident during the daytime. We also calculated the urban area-averaged hourly mean UHII and show that the steadily strong and weak UHI stages have the same timing and duration in the three urban areas, but with varied magnitudes.

The daytime UHII in summer is higher than those in other seasons. This phenomenon was also found by J. Zhang et al. (2010). Our results indicate, however, that it is most evident in the central urban area. Relative to the urban area, the rural area has a stronger evapotranspiration and latent heat flux exchange during the daytime in summer, and this fact might contribute to the UHII difference. It is also possible that the larger anthropogenic heat release in the central urban area during summer afternoons results in a stronger UHII in comparison with the rural area.

Zhang et al. (2005) investigated the seasonal features of the UHII in Beijing in 2001. They used land surface temperature products from EOS MODIS, and showed that the UHII in Beijing urban areas is strongest in summer and weakest in winter. By using data of seasonal land surface temperature from the Landsat TM in 2005 and 2006, Fang et al. (2011) also drew the conclusion that the urban areas of Beijing have a more evident UHI effect in summer. These results from remote sensing products are different from our analyses, which show that the largest seasonal mean UHII for total urban areas occurs in wintertime (1.65°C) and that the seasonal mean UHII in the Beijing urban areas in summer is only 0.92°C, marginally higher than the smallest seasonal mean UHII in spring (0.80°C). Our result is consistent with the general sense of a strong temperature inversion and stable lower atmospheric layer in winter nights and the extra heat release by heating in buildings (Chen and Shi 2012). The reasons for the large differences between our analysis and previous works are not clear at present, but they indicate that the land surface temperature retrieved from satellite products might have been representing a different physical quantity from that measured by thermometers at the meteorological stations. An alternative explanation is the difference in the definitions and calculation methods of the UHII that were used in the previous studies versus those of this study.

## 6. Conclusions

A study was conducted to analyze the UHI phenomenon in Beijing urban areas through an application of a quality-controlled hourly dataset of AWSs. The following four meaningful findings are drawn from the study:

 The strongest annual mean UHII occurs in the central urban area inside the 4th RR, whereas weaker UHIIs generally occur between the 4th and 5th RRs and the 5th and 6th RRs, including the urban areas in HD, FT, southwestern CY, and northern DX. In addition, the weakest UHII appears in the area between the 5th and 6th RRs, with sites near the northern and southern 6th RR having the smallest UHI phenomena.

- 2) The annual mean UHII for the whole urban area is 1.23°C, and the seasonal mean UHIIs for the urban area are 1.65°C for winter, 1.38°C for autumn, 0.92°C for summer, and 0.80°C for spring. Most of the urban stations experience their strongest UHII in winter, but a few record their strongest UHII in autumn.
- 3) The diurnal variations of hourly mean UHII are characterized by a stage with steadily high values from 2100 to 0600 LST and a stage with steadily low values from 1100 to 1600 LST, with the 0600– 1100 LST period containing the swiftly declining stage and the 1600–2100 LST period representing the rapidly rising stage. The annual and seasonal mean UHI differences among the three divided regions result mostly from the different contributions in the nighttime UHII.
- 4) There are always a steadily UHI strong stage and a stable weak UHI stage during the diurnal variation all through the year. Moreover, the steadily strong UHI stage during nighttime is longer and the steadily weak UHII stage in daytime is shorter in winter and autumn.

Acknowledgments. This study is supported by the National Natural Science Foundation of China (Grant 41005043), National Basic Research Program of China (Grant 2012CB955901), and Special Fund Projects for Public Welfare (Grant GYHY201206012). We are grateful to Dr. Y. Y. Ren for her help in drawing the isotherms of remote sensing-based land surface temperature in the study region.

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1814

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