Cooling effect of urban parks and their relationship with urban heat islands

YANG Ping\textsuperscript{a,b}, XIAO Zi-Niu\textsuperscript{c} and YE Meng-Shu\textsuperscript{a}

\textsuperscript{a}China Meteorological Administration Training Center, Beijing, China; \textsuperscript{b}Institute of Urban Meteorology, China Meteorological Administration, Beijing, China; \textsuperscript{c}Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

\textbf{ABSTRACT}

It is claimed that open spaces in cities, such as parks, have an urban cooling effect. However, the relationship between urban parks and adjacent districts is still not explicit. In order to clarify the interaction between urban parks and their urban surroundings, this paper takes the Temple of Heaven Park (THP) as an example of a park station and focuses on analyzing the differences with a nearby urban station. THP is located in the center of Beijing, and the nearest urban station is Tian An Men. It is interesting that the cooling effect of THP reaches a peak and remains stable when its city background urban heat island (UHI) varies within a given range, but becomes unstable when the UHI goes beyond the range. This is called an enhanced cooling effect in this paper. As a result, the UHI intensities (UHIIs) are calculated in order to comprehend the role of the park cooling effect in the urban heating characteristics of Beijing. By comparison with five other park–district pairs, this paper attempts to identify the causes of the enhanced cooling effect. It is found that six park–district pairs consistently demonstrate a persistently stronger cooling rate during the night, and that the water coverage might be a key factor in enhancing the park cooling effect. Based on further investigation of the influence of surrounding UHIIs on the park cooling effect, it is found that the UHII differences in park–district pairs show quasi-linear changes within a given range as the UHII of the surrounding district increases.

\textbf{1. Introduction}

One of the most prominent characteristics of urban climates is the urban heat island (UHI) phenomenon (Landsberg 1981; Limor, David, and Evyater 2009; Hausfater et al. 2013), whereby an urban area has a higher air or surface temperature than the surrounding rural area (Ma and Fu 2003; Grimmond 2006). Significant UHIs have been observed in large metropolitan regions, with differences as high as 10 °C (Sakakibara and Owa 2005; Liu and Yang 2009). UHIs have also been detected in small towns in the USA and mainland China (Ren et al. 2007). Previous research shows that UHIs pose many problems for inhabitants of developed cities (Jansson, Jansson, and Gustafsson 2007; Memon, Chirarattananon, and Vangtook 2008).

Urban green spaces are expected to mitigate UHIs (Akbari, Pomerantz, and Taha 2001) and surface water runoff. Because of transpiration, greenery plays a significant role in alleviating UHIs by dropping temperature and increasing humidity. Their cooling effects are especially important and they have been regarded as natural resources for city planning (Narita et al. 2002; Sandra, Henrique, and Teresa 2011). The cost for city planning and construction, as well as the ecological efficiency of a park, are decided by the controllable factors including the scale, shape, and species of plants in the park. Many studies on the cooling effect of urban parks or green spaces in various countries and cities have revealed that the park cooling effect varies in timing, magnitude, and spatial distribution (Chang, Li, and Chang 2007; Bowler et al. 2010; Lu et al. 2013). Meanwhile, most of these studies have involved relatively short periods or representative cases, so little information is available for a universal description of the...
urban cooling effect. Another problem in previous studies is that, when planning for urban green spaces or parks as urban cooling islands, information on whether urban parks have a heat effect compared to rural areas has been neglected. Therefore, detailed studies of urban parks are required to clarify the park cooling effect and its possible influences.

A dense automatic weather station (AWS) network of more than 200 stations has been installed in urban and rural areas around Beijing, China. The network provides hourly temperature data (CMA 2003). In the present study, to delve into the climatological features of urban parks, statistics on the cooling effect and UHI intensity (UHII) results for Temple of Heaven Park (THP) are analyzed and the cause of the difference is identified. The cooling effect is expressed in terms of the cooling rate (%), defined as $\Delta T_{\text{urban - park}} / T_{\text{urban}} \times 100$, where $T_{\text{urban}}$ is the average temperature from 2007 to 2011 of each urban site. Also, we define the UHII as $\Delta T_{\text{u - r}} = T_{\text{urban}} - T_{\text{rural}}$, where $T_{\text{rural}}$ is the average temperature of eight reference stations and $T_{\text{urban}}$ is the temperature of any urban station.

2. Background

2.1. Study area, data, and method

Beijing has a typical temperate continental climate, with hot summers, cold winters, and a highly concentrated summer precipitation regime (Lu 2002). A multiple ring road (Figure 1(a)) system of transportation has been developed. In general, weather stations located inside the 6th ring road in Beijing are considered urban sites (Wang, Li, and Feng 2010).

Hourly temperature data of 57 urban stations and eight reference stations during 2007–2011 were obtained from the Meteorological Information Center, Beijing Meteorological Bureau. The eight reference stations (Figure 1(a)) lie in open ground with vegetation surfaces and are away from the impact of high buildings to a large degree, and were selected using a remote sensing method (Ren and Ren 2011). In order to increase the robustness of the analysis, all hourly temperature data used here have been checked and quality-controlled. A detailed description of the methodology used for the quality control is provided by Yang et al. (2011), Yang, Xiao, and Liu (2013), and Yang, Ren, and Liu (2013).

2.2. UHII distribution

The annual mean UHII (Figure 1(b)) shows that the UHII is stronger in the city center, except for a site in southeastern central Beijing, where it is relatively low. This site is THP, which is located near Tian An Men (TAM) — the central business district in Beijing. THP consists of a complex of grassland and forests, with an area of 273 hm². Figure 1(b)
shows that only THP displays an obvious cooling feature among 57 urban sites in Beijing. Although THP has a cooling effect on surrounding districts’ UHIs, it still belongs to UHIs, with annual intensities as weak as 0.44 °C. However, it is much cooler than its adjacent district TAM, with a UHII of 1.77 °C. The same is true for the seasonal UHII. There are other urban parks in the center of Beijing, but none of them exhibit a strong cooling effect. Hence, further research on THP with comparison to other urban parks is necessary.

To summarize THP’s climate features and explore the possible reasons for its significant cooling effect, the urban district close to THP (i.e. TAM) was selected for a paired park–district analysis. Five other park–district pairs inside the 4th ring road were also selected (Figure 1(c)) as comparisons, and the detailed information of them is shown in Table 1.

### Table 1. Location and other details regarding the six selected urban parks.

| Abbreviated park name | Full park name               | Longitude/latitude (°) | Height (m) | Park size (hm²) | Greening rate | Watering rate | Resting rate |
|-----------------------|-----------------------------|------------------------|------------|-----------------|---------------|---------------|--------------|
| CYp                   | Chao Yang Park              | 39.94/116.48           | 40         | 288.7           | 66.5          | 23.6          | 9.9          |
| LTHP                  | Long Tan Hu Park            | 39.87/116.43           | 44         | 49.2            | 26.1          | 39.6          | 34.3         |
| OG                    | Olympic Green               | 40.02/116.39           | 41         | 680             | 66.2          | 17.9          | 15.9         |
| THP                   | Temple of Heaven Park       | 39.88/116.41           | 47         | 273             | 84.3          | 0             | 15.7         |
| YYTP                  | Yu Yuan Tan Park            | 39.91/116.31           | 51         | 136.7           | 54.5          | 44.6          | 0.9          |
| ZZYP                  | Zi Zhu Yuan Park            | 39.94/116.61           | 55         | 47.35           | 51.0          | 33.6          | 15.4         |

3. Results

### 3.1. Features of THP

The average annual UHII for six urban parks and corresponding districts and the UHII differences were calculated. A UHII is still evident for the city parks, but the values are lower than those of the adjacent urban sites. The lowest mean UHII is for THP (0.44 °C). The UHII difference for each park–district pair was determined. The UHII difference between THP and TAM is 1.33 °C, which is much higher than that for the other park–district pairs. The second largest UHII difference is for LTHP (0.56 °C) — less than half the value of THP. Both THP and LTHP are located inside the 2nd ring road, and the temperatures of their urban surroundings are higher than other regions. It seems that a park in a strong temperature background may have a more significant cooling effect, but more evidence is required for a firm conclusion.

Figure 2(a) shows the UHII frequency plots at intervals of 1.0 °C for THP and TAM. For THP the UHII frequency exhibits a normal distribution, while the distribution for TAM is right-skewed. Thus, the probability of positive hourly UHII in THP is almost the same as the probability of negative hourly UHII. In addition, TAM is almost always controlled by UHIs because the possibility of a negative UHII in TAM is very low. This is in agreement with previous research revealing that the park has a cooling effect (Yokohari et al. 1997).

Figure 2(b) shows the distribution of UHII differences between THP and its surroundings (TAM). It can be seen that the THP UHII decreases smoothly at first and then increases with fluctuations as the TAM UHII increases. A more detailed analysis of the TAM UHII values within 7.0 °C is demonstrated in Figure 2(c).

Figure 2(c) shows that the THP UHII correlation is rather stable when the mean TAM UHII is less than 3.0 °C, and oscillates significantly when the mean TAM UHII is more than 7.0 °C. This can be explained by the low frequency of THP UHII values greater than 7 °C, which leads to randomness in its correlation with the TAM UHII. This implies that the park THP has a remarkable cooling effect that resists increase in the UHII for the surrounding area. In addition, as the TAM UHII increases, the THP UHII actually decreases rapidly when the TAM UHII is within the range of 3.0 °C. The THP UHII only increases rapidly when the TAM UHII is more than 6.0 °C. This decrease in THP UHII is referred to as ‘an enhanced park cooling effect’, when the TAM UHII increases. This feature goes beyond the phenomenon whereby a park or green space relieves urban heat effects and exhibits a cooler temperature than its surroundings. THP is taken as an example to analyze this enhanced cooling effect. It is evident that the THP UHII does not linearly increase with the TAM UHII threshold is reached (3.0 °C), remains at a minimum until another TAM UHII threshold at 6.0 °C, and then increases with the TAM UHII. Thus, it is hypothesized that for some parks, such as THP, the cooling effect reaches a peak and remains stable when the city background UHII varies within a given range. Outside this range, the cooling effect of the park fluctuates and becomes unstable when the UHII goes beyond the given range.

### 3.2. Enhanced cooling effect of THP

To identify the reason for the conspicuous cooling effect of THP, the cooling rates of the six park–district pairs
are shown in Table 2. The results show that, in terms of the yearly average, the differences for THP are apparent. Its cooling rate is 9.63% — much higher than that of the other parks. The cooling rate in autumn reaches 13.76%, which is usually associated with the calm weather and stable lower atmosphere. Strong wind may be a key factor for the weak cooling effect in spring. Frequent rainfall and the unstable lower atmosphere in the monsoon season may be the important reason for the weaker cooling effect during summer. Besides, in terms of the diurnal variation at THP, it is found that the cooling effect increases rapidly at sunset but decreases rapidly at sunrise. This shows that a persistently stronger cooling rate at the night may be one of the important reasons behind the enhanced cooling effect of THP. Weather conditions, solar radiation etc. also have an influence on the enhanced cooling effect.

The diurnal UHI variations for the six park–district pairs were calculated (Figure 3). Overall, except for THP–TAM, the pairs exhibit a similar pattern in which the mean UHII is higher at night and lower during the day. The other parks generally have a higher daytime UHII and a lower nocturnal UHII. The most notable feature is the daily UHII variation for THP, which is totally different to the variation for all the other district and park sites studied. The UHII for THP is more marked before noon and remains weak at ~0 °C at night, while its comparative urban site follows the same daily variations as the other five groups. This characteristic UHII for the park (THP) indicates a significant enhanced cooling effect. Previous research has demonstrated that microclimate conditions are consistent with the shade of trees, depending on the tree species (Narita et al. 2002). Furthermore, oxygen production and carbon dioxide absorption (among other substances) by shrubs and some other trees are 38.5 times more than that of grassland (Liu, Li, and Yang 2008). Consequently, the species of plants present in the park have a considerable impact on the cooling effect of the park, i.e. decreasing the temperature of surrounding district UHIs. In this respect, the enhanced cooling effect of THP can be explained by the abundance of trees, amounting to over 60,000.

To investigate the influence of surrounding UHIs on the park cooling effect, the variations in UHII differences

| Year   | CYP    | LTHP   | OG     | THP    | YYTP   | ZZYP   |
|--------|--------|--------|--------|--------|--------|--------|
| Spring | −0.552 | 4.112  | 0.247  | 7.081  | −0.079 | 0.775  |
| Summer | 0.697  | 4.092  | −0.469 | 7.215  | 0.396  | 3.002  |
| Autumn | 1.264  | 5.251  | 2.117  | 13.76  | 1.992  | 2.828  |
| Winter | 1.600  | 2.643  | 1.684  | 10.59  | 1.549  | 0.421  |

Table 2. The average annual and seasonal cooling rates of the six parks.
For the latter pairs, the park–city UHII difference increases slowly with the district UHII and the maximum UHII differences are never greater than 2.0 °C. In other words, the cooling effect of park stations is almost unrelated to the surrounding UHI conditions. Conversely, for the THP–TAM and CYP–CY pairs, the park–district UHII difference rapidly increases and reaches a maximum of 8.0 °C with increasing district UHII. Specifically, it is found that the variation of CYP–CY for park and district pairs are analyzed as a function of changes in district UHII. For all six pairs, variations in the district–park UHII difference were calculated using mean UHII values (Figure 4). The significant oscillations in the plot for district UHII values greater than 7.0 °C are due to the low frequency of UHII values for the parks in this range. Therefore, the 0–7.0 °C interval for district UHII values is emphasized. Analysis reveals that THP–TAM and CYP–CY differ significantly from the other four park–district pairs. For the latter pairs, the park–city UHII difference increases slowly with the district UHII and the maximum UHII differences are never greater than 2.0 °C. In other words, the cooling effect of park stations is almost unrelated to the surrounding UHI conditions. Conversely, for the THP–TAM and CYP–CY pairs, the park–district UHII difference rapidly increases and reaches a maximum of 8.0 °C with increasing district UHII. Specifically, it is found that the variation of CYP–CY
is not the same as THP–TAM. The curve of THP–TAM is stable and smooth, while it is oscillating and unstable for CYP–CY. Overall, we find that the cooling effect of CYP is the lowest among all the parks. Also, the UHII of CY is the lowest (0.1 °C) of all urban sites. So, the inconspicuous UHII of CY might lead to the unstable relationship between CYP and CY.

Among the six parks, only THP and CYP share the common attribute of almost no water surfaces, while the other four parks differ in their water coverage. Water bodies absorb solar heat and are favorable in maintaining a higher UHII. Therefore, the absence or presence of water surfaces might be a key factor in the enhanced park cooling effect.
Analysis reveals that water surfaces play an important role in the cooling effect. To remove the influence of the city background, two parks surrounded by similar districts were compared. Figure 1(c) shows that LTHP is the nearest park to THP (6 km away) and its surrounding district exhibits similar behavior to TAM (district for THP). Therefore, we compared the LTHP–GGXP and THP–TAM pairs. The water surface in LTHP accounts for 39.6% of the total area, which is very different to the situation for THP. Comparison of these two pairs can provide an insight into the influence of water surfaces in urban parks.

Calculating the frequency distribution of UHII differences between LTHP and GGXT, we also found both LTHP and GGXT exhibit a right-skewed UHII distribution. This means that LTHP shows similar behavior to the urban sites. The LTHP UHII increases linearly with the GGXT UHII, which is very different to the relationship between THP and TAM. Further analyses of parks with large water coverage, such as ZZYP and YYTP, revealed similar results to those for the LTHP–GGXT pair. Therefore, a large water surface in a park seems to reduce the enhanced cooling effect.

4. Discussion

The cooling effect of urban parks is not a new topic. Previous studies show that urban parks can usually cool their surroundings (Yokohari et al. 1997). In fact, research concerning the park cooling effect in Beijing can be traced back to the 1980s (Chen, Cui, and Liu 1983). However, the majority of these studies (Liu, Li, and Yang 2008) related to urban parks were focused on comparing the distribution of the properties, species, and communities of vegetation in parks. Few studies have been based on integrated data on both temporal and spatial scales, meaning quantitative evaluation of the urban park cooling effect on surrounding district UHIs is currently insufficient. Given that a park contributes to improving the urban microclimate, which is an important aspect of city planning and construction, further quantitative research is therefore worth pursuing.

In this paper, based on a new data-set, the general spatial UHII distribution over urban areas in Beijing is demonstrated. It is found that the UHII is stronger in the city center, aside from certain individual sites. Further study shows that these individual sites with lower UHII in the city center are often park stations, and the most obvious among them is THP, making it an interesting case worthy of further exploration. Through analysis, it is revealed that urban parks not only present the different properties of urban areas, but also have a cooling effect. It is concluded that the UHII of urban parks does not linearly increase with the UHII of the surrounding district – a result rarely mentioned before, and one for which the underlying mechanism still needs to be studied in the future.

It is also revealed that the enhanced cooling effect of urban parks is not everlasting. When the UHII of the urban surroundings reaches a certain threshold, the UHII of the corresponding urban park will increase along with its urban sites. In this respect, it is found that the threshold value is related to the nature of the vegetated area of the urban park. Through further analysis, it is revealed that the coverage of water surfaces is another factor affecting the cooling effect. Also, the species composition of the vegetation might be of importance. These investigations are useful for understanding the reasons behind the enhanced cooling effect of urban parks. Furthermore, in an applied sense, the findings might be useful for designing urban parks. It is shown that urban parks not only reduce UHIs, but also reverse the effects of UHIs when the surrounding UHII is within a certain range. Thus, more parks or green areas built in city centers is one way of resolving urban climate problems. However, the cooling process is complex, affected by the species of plants, water coverage, surrounding climate features, daily changes of UHI, and so on. Thus, it is necessary to further study the relationships between the park cooling effect and the UHI effect, thus contributing to improving the heat environment of cities, optimizing urban infrastructure, and improving urban functions.

5. Conclusions

Using a recently developed and quality-controlled hourly AWS data-set, we investigated the cooling effect of THP in comparison to other urban parks. The following conclusions can be drawn:

1. Only THP has an obvious cooling effect among 57 urban sites in Beijing, which is referred to as the enhanced cooling effect. Importantly, the species of plants in the park being mainly shrubs and trees are a key cause.

2. The UHII of THP is more marked at noon and weak (∼0 °C) at night, while its surrounding site (TAM) shows the same daily variations as other normal stations. This demonstrates that the weak UHI at night for the urban site plays the most important role in its enhanced cooling effect.

3. For parks like THP, the enhanced cooling effect reaches a peak and remains stable when the background city UHI varies within a given range. The UHII for parks is negative and this cooling
effect is enhanced when the surrounding UHII increases within the range. Conversely, beyond the range, the cooling effect of a park fluctuates and becomes unstable.

(4) Water coverage can affect the park UHII, with a large water surface in a park possibly reducing its cooling effect.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
The study was supported by the National Natural Science Foundation of China [grant number 41375069]; National Basic Research Program of China [grant number 2012CB957804]; Young Talent Programming of China Meteorological Administration.

References
Akbari, H., M. Pomerantz, and H. Taha. 2001. “Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas.” Solar Energy 70 (3): 295–310.
Bowler, D. E., L. Buyung-Ali, T. M. Knight, and A. S. Pullin. 2010. “Urban Greening to Cool Towns and Cities: A Systematic Review of the Empirical Evidence.” Landscape and Urban Planning 97: 147–155.
Chang, C., M. Li, and S. Chang. 2007. “A Preliminary Study on the Local Cool-Island Intensity of Taipei City Parks.” Landscape and Urban Planning 80 (4): 386–395.
Chen, J. M., S. H. Li, and Z. F. Yang. 2008. “Temperature and Humidity Effect of Urban Green Spaces in Beijing in Summer.” [In Chinese.] Chinese Journal of Ecology 27 (11): 1972–1978.
Liu, J. M., and Z. F. Yang. 2009. “Dynamics of Temperature and Humidity in under Laying Surface of Different Landscape Type in Winter in Beijing City China.” [In Chinese.] Acta Ecologica Sinica 29 (6): 3241–3252.
Lu, R. Y. 2002. “Separation of Interannual and Interdecadal Variations of Rainfall in North China.” [In Chinese.] Journal of Atmospheric Sciences 26 (5): 611–624.
Lu, W. W., C. Chen, M. R. Su, B. Chen, Y. P. Cai, and T. Xing. 2013. “Urban Energy Consumption and Related Carbon Emission Estimation: A Study at the Sector Scale.” Frontiers of Earth Science 7 (4): 480–486.
Ma, Z. G., and C. B. Fu. 2003. “Interannual Characteristics of the Surface Hydrological Variables over the Arid and Semi-Arid Areas of Northern China.” Global and Planetary Change 37 (3): 189–200.
Memon, R. A., S. Chirarattananon, and P. Vangtook. 2008. “Thermal Comfort Assessment and Application of Radiant Cooling: A Case Study.” Building and Environment 43: 1185–1196.
Narita, K., T. Mikami, T. Honjo, H. SuGWsara, K. Kimura, N. Kuwata. 2002. “Differentiations about Cool-Island Phenomena in Urban Park.” Fourth Symposium on the Urban Environment, American Meteorological Society, Norfolk, Virginia Abs, May 20–24, 2002 8 (2): 86–87.
Ren, G. Y., Z. Y. Chu, Z. H. Chen, and Y. Y. Ren. 2007. “Implications of Temporal Change in Urban Heat Island Intensity Observed at Beijing and Wuhan Stations.” Geophysical Research Letters 34: L05711.
Ren, Y. Y., and G. Y. Ren. 2011. “A Remote-Sensing Method of Selecting Reference Stations for Evaluating Urbanization Effect on Surface Air Temperature Trends.” Journal of Climate 24: 3179–3189.
Sakakibara, Y., and K. Owa. 2005. “Urban–Rural Temperature Differences in Coastal Cities: Influence of Rural Sites.” International Journal of Climatology 25: 811–820.
Sandra, O., A. Henrique, and V. Teresa. 2011. “The Cooling Effect of Green Spaces as a Contribution to the Mitigation of Urban Heat: A Case Study in Lisbon.” Building and Environment 46: 2186–2194.
Wang, X. L., X. R. Li, and Z. K. Feng. 2010. “Research on Urban Extension Based on Shannon Entropy.” [In Chinese.] China Population Resource and Environment 20 (3): 88–92.
Yang, P., W. D. Liu, J. Q. Zhong, and J. Yang. 2011. “Evaluating the Quality of Temperature Measured at Automatic Weather Stations in Beijing.” Journal of Applied Meteorological Science 22 (6): 706–715.
Yang, P., G. Y. Ren, and W. D. Liu. 2013. “Spatial and Temporal Characteristics of Beijing Urban Heat Island Intensity.” Journal of Applied Meteorology and Climatology 52 (8): 1803–1816.
Yang, P., Z. N. Xiao, and W. D. Liu. 2013. “Comparison of Diurnal Temperature Variation in Urban and Rural Areas in Beijing and Its Seasonal Change.” [In Chinese.] Journal of Atmospheric Sciences 37 (1): 101–112.
Yokohari, M., R. D. Brown, Y. Kato, and S. Yamamoto. 1997. “The Cooling Effect of Paddy Fields on Summertime Air Temperature in Residential Tokyo, Japan.” Landscape Urban Plan 53: 17–27.