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Seasonal Variation in Air Temperature and Relative Humidity on Building Areas and in Green Spaces in Beijing, China

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Abstract: The cooling and humidifying effects of urban parks are an essential component of city ecosystems in terms of regulating microclimates or mitigating urban heat islands (UHIs). Air temperature and relative humidity are two main factors of thermal environmental comfort and have a critical impact on the urban environmental quality of human settlements. We measured the 2-m height air temperature and relative humidity at the Beijing Olympic Park and a nearby building roof for more than 1 year to elucidate seasonal variations in air temperature and relative humidity, as well as to investigate the outdoor thermal comfort. The results showed that the lawn of the park could, on average, reduce the air temperature by (0.80±0.19)℃, and increase the relative humidity by (5.24±2.91)% relative to the values measured at the building roof during daytime. During the nighttime, the lawn of the park reduced the air temperature by (2.64±0.64)℃ and increased the relative humidity by (10.77±5.20)%. The park was cooler and more humid than surrounding building area, especially in night period (more pronounced cooling with 1.84 ℃). Additionally, the lawn of the park could improve outdoor thermal comfort through its cooling and humidifying effects. The level of thermal comfort in the park was higher than that around the building roof for a total of 11 days annually in which it was above one or more thermal comfort levels (average reduced human comfort index of 0.92) except during the winter.

Keywords: air temperature; relative humidity; outdoor thermal comfort; urban park planning

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1 Introduction

Climate change and urbanization are global phenomena in the 21st century (Kalnay and Cai, 2003). More than half of the world's population lives in urban areas now, and this value will increase to nearly 70% by 2050 (United Nations, 2014). A large amount of the population is migrating to settle down in cities, and this practice results in changing natural land surfaces into impervious surfaces and reducing the amount of urban green space (Oke, 1982; Kuang et al., 2015, 2016, 2017, 2019b; Dong et al., 2017). Meanwhile, global climate change has manifested itself in the rise of near-surface temperatures over the past several decades, and this trend is expected to continue (IPCC, 2015). Higher urban temperatures may affect the inhabitability of cities, worsen air pollution, increase the risk of heat-related mortality and increase the amount of energy consumption used for cooling (Oke, 1982; Voogt and Oke, 2003; Kolokotroni et al., 2006; Sarrat et al., 2006; Medina-Ramón and Schwartz, 2007; Tan et al., 2010; Oleson et al., 2015; Chen et al., 2016). In addition, the impervious surfaces absorb higher solar energy than does the natural vegetation surface, causing changes in the

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relative humidity, affecting the air temperature and reducing human comfort (Solecki et al., 2005; Tan et al., 2015; Kong et al., 2016).

As an important part of urban planning, urban parks have a cooling effect and provide various ecosystem services and benefits (Oke, 1989; Niemelä et al., 2010). On the one hand, urban parks cool the ambient environment by evapotranspiration (ET) processes, which consume solar energy through transpiration in vegetation and water evaporation (Hathway and Sharples, 2012). The cooling effect in urban park areas makes an important contribution to saving energy and reducing emissions, and the trees provide shade areas by intercepting solar radiation with leaves and branches (Zhang et al., 2014; Kong et al., 2016). Peng et al. (2014) confirmed that afforestation cools the local land surface temperature in China (Peng et al., 2014). In urban areas, a common adaptation measure to improve thermal comfort is to produce an increase of what is called 'blue and green infrastructure', which can reduce air temperature and increase humidity (Gill et al., 2007; Allen III, 2012). On the other hand, the vegetation can further decrease turbulent and convective heat transport, thus reducing thermal discomfort (Spronken-Smith and Oke, 1999; Shashua-Bar et al., 2011). In addition, the cooling effect of vegetation varies in different seasons due to changes in the vegetation coverage rate. Sugawara et al. (2016) and Doick et al. (2014) found that urban parks usually cool by 0.5℃–4℃ in summer, which was determined based on extensive field measurements (Doick et al., 2014; Sugawara et al., 2016). Therefore, there is a pressing need for urban researchers to further mitigate temperature increases in urban areas.

Outdoor human comfort is influenced by multifaceted factors, which depend on air temperature, wind speed, relative humidity and solar radiation (de Freitas and Grigorieva, 2015). It was found that humans feel comfortable within the temperature range of 21℃–27.5℃; additionally, humans felt comfortable within a relative humidity range of 30%–65% and when wind speed values were greater than 5 m/s during the experiments (de Freitas and Grigorieva, 2015), but comfort ranges are expected to vary according to local climate features because of the human adaptation to local climate or long-term acclimatization. De Freitas and Grigorieva (2015) classified human thermal indices by computational models, including the proxy thermal stress index, energy balance stress index, and proxy energy balance strain index (De Freitas and Grigorieva, 2015). Outdoor human comfort depends on the energy balance and human senses between the humans and their surroundings, which is an important factor in the evaluation of the livability of a city (Coccolo et al., 2016; 2018). Several models have also quantified outdoor human comfort using the physiological equivalent temperature (PET), the standard effective temperature and the index of thermal stress, others are some models in mechanism including predicted mean vote (PMV) and standard effective temperature (SET) (Höppe, 1999; Spagnolo and de Dear, 2003; Pearlmutter et al., 2006).

Near-surface air temperature and relative humidity are the two main factors in the thermal environment, which is defined as the observation value of 2.0 m above the ground and is monitored by static meteorological instruments; the thermal environment is significantly affected by microclimate, air quality, anthropogenic heat sources and human thermal comfort (Fang et al., 1998; Harvell et al., 2002; Koken et al., 2003; Willett et al., 2007; Grimm et al., 2008; Sherwood et al., 2010; Frankel et al., 2012; Zhao et al., 2014; Li and Zha, 2018). Because it is difficult to apply the same data and standards to urban regions around the world, it is easier to obtain observational data (Lazzarini et al., 2013; Yan et al., 2018). Meanwhile, the retrieval of quantitative and spatially explicit remotely sensed data remains a challenge (Kuang et al., 2019). Thus, the existing research on macroscopic urban climate change mostly focuses on cities and regions in different national and regional areas using field observations (Hamada and Ohta, 2010; Lazzarini et al., 2013; Chapman et al., 2017; Yan et al., 2018). Compared to the land surface temperature (LST), the air temperature is closely related to human health and human comfort, and carrying out observations can compensate for the shortcomings involved in retrieving LST from remote sensing (Zakšek and Oštir, 2012; Zhou et al., 2013). Previous studies have focused on the LST differences inside a city and compared the values to those of rural areas or park cooling effects of thermal environments in different seasons (Zhou et al., 2013; Kikon et al., 2016; Sugawara et al., 2016; Chapman et al., 2017; Coccolo et al., 2018; Li and Zha, 2018). However, few studies have concentrated on the seasonal variance in air temperature and humidity, as well as human thermal comfort. Therefore, the results of this study significantly help city managers and planners improve the microclimate behavior of cities.

This study analyzed field measurements performed atop a dense building and in a large green park in Beijing, with the main purpose of investigating the seasonal variation in air temperature, humidity and thermal comfort. First, we present data to illustrate the near-surface air temperature differences between the urban park and building area as well as variations within the respective environments. Then, we attempt to compare the near-surface relative humidity in both the building area and the park. Finally, we analyze the thermal comfort in the outdoor environment under two conditions.

2 Materials and Methods

2.1 Observation experiment

The land use cover in Metropolitan Beijing is changing dramatically with rapid urbanization. The built-up area was 1268 km^2 in 2015, with 72.6% impervious surface, 24.0% green space and 3.4% other land cover types (e.g., water body, bare soil) (Fig. 1). The building areas account for 43.1% of the impervious surface areas, and other areas are covered by roads and parking lots.

Our observation experiments were carried out in two sites. One was in the Olympic Forest Park, Chaoyang District (116°24′E, 40°01′N); this site was used to represent parks and had a total area of 6.80 km^2 and a greening ratio of 95.6% (Fig. 1, a1). The park was composed of lawn with densely planted grass interspersed with trees approximately 5 m tall, and the observational instrument was placed in the park lawn plot. Another site that was used to represent building surfaces was selected in the residential area of Southern Kexue Yard (116°22′E, 39°59′N), and it was located a straight distance of 4.1 km from the Olympic Forest Park site (Fig. 1, a2). The selected building roof was composed of cement concrete with a gray color and was 18 m from the ground surface, with a total area of 321.3 m^2. The observation instruments were placed approximately 5.3 m from the northern edge and 5.2 m from the southern edge of the building.

Both sites were equipped with an EC150 CO_2/H_2O analyzer and an HMP155 air temperature and humidity sensor at a height of 2.0 m. The relative humidity and air temperature (T_a) were observed. The collected data were stored in a CR3000 data logger (Campbell Scientific Inc., USA) at a sampling frequency of 10 Hz.

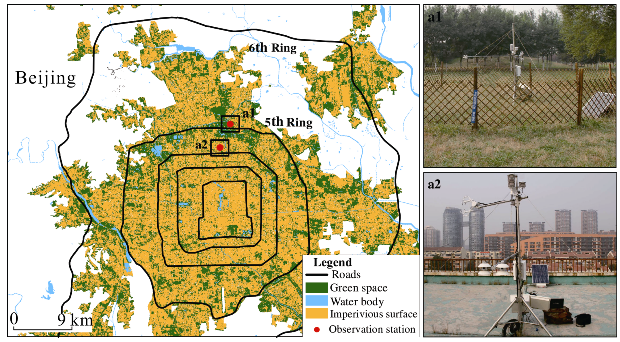

Fig. 1 Observation sites (a1: Olympic Forest Park; a2: Southern Kexue Yard)

2.2 Methods

The period analyzed was from December 1, 2011 to November 30, 2012. We selected 321 days and calculated the mean diurnal cycles of 30-min near-surface air temperature and relative humidity (measured at 2.0 m above the surface) in winter (averaged in December 2011 and January and February 2012), spring (averaged in March, April, and May 2012), summer (averaged in June 2012, July and August 2012), and autumn (averaged in September, October, and November 2012). The selected valid days were 75, 85, 85 and 80 days, respectively. We excluded rainy days and incomplete measurements data. The monthly and seasonal differences in the near-surface air temperature and relative humidity during the daytime and nighttime were analyzed between the building and the park in Beijing. Daytime and nighttime were defined by sunrise (6:00 in summer and spring, 7:30 in autumn and winter) and sunset (18:30 in summer and spring, 17:00 in autumn and winter).

We selected the comfort index (CI) to represent the comfort of human body in atmospheric environment, which suggests that people adjust physiology status, adapt to the environment and guard against sudden changes of cold and heat according to meteorological factor (including air temperature, relatively humidity, and wind speed) (Xu et al., 2013). CI was calculated as has been recommended by the Beijing Meteorological Bureau. The CI empirical model predicts the thermal comfort degree mainly through air temperature, relative humidity and wind speed. As the CI increases, the thermal comfortable level decreases (Xu et al., 2013; Amani-Beni et al., 2018). The formula is as follows:

$$CI = 1.8\times T + 0.55\times(1-RH) - 3.2\times V^{0.5} + 32$$
$$= 1.8\times T + 0.55\times RH - 3.2\times V^{0.5} + 32.55 \quad (9)$$

where *CI* represents the thermal comfort degree, and *T* represents the near-surface air temperature (℃). *RH* represents the relative humidity (%). *V* represents the wind speed (m/s). The classification of CI as an indicator of the thermal non-moderate index was in accordance with the uniform standards set by the China Meteorological Administration, and it was divided into nine comfort levels as followed (Table 1) (Terjung, 1966; Wu, 2003). We divided them into three parts, thermal environment, moderate environment and cold environment.

3 Results and Analysis

3.1 Comparison of air temperature on building and park area

The air temperature of the lawn in Olympic Park was, on average, 0.61℃ to 1.06℃ cooler than that of the building in one year (Table 2). The differences in air temperature between the building and the park in the four seasons were all larger during nighttime than during daytime by an average of 1.84℃ (Table 2). Meanwhile, the statistical results also showed that the difference was the largest during the nighttime in autumn, which was as high as 1.06℃ in daytime and 3.59℃ at nighttime. In contrast, the minimum difference in air temperature between buildings and parks was found during the daytime in spring, at 0.61℃ (Table 2).

The results also showed that the most obvious difference in air temperature between buildings and parks occurred in October (Fig. 2), with a gap of 4.07 ℃ during the nighttime and 1.24℃ during the daytime. In winter, the air temperature difference was approximately 0.75℃ during the daytime and 2.45℃ during the nighttime (Table 2). With seasonal warming, the gap between the two increases. The temperature gap values were 0.46℃ (in March), 0.51℃ (in April), and 0.65℃ (in May), mainly due to the beginning of vegetation growth, which led the evaporation of trees and meadows in the park to begin to increase; this increase led to the rapid cooling of the surface, resulting in an increased temperature gap between parks and buildings. The average temperature difference was 0.8℃ during the daytime in summer. However, during the nighttime, the difference continued to increase until it peaked in October (autumn).

The air temperature difference of the building between daytime and nighttime was lower than that of the park (Fig. 3). The diurnal temperature variation in the building area was greatest in summer, while the park diurnal temperature difference was largest in autumn. Additionally, the building had the largest diurnal temperature difference of 1.92℃ in May (spring). The temperature difference between daytime and nighttime was minimal in February (winter), and the temperature decreased by only 0.34 ℃ in the evening (Fig. 2).

3.2 Comparison of relative humidity of building area and green space

There were obvious differences in the relative humidity between the park and building roof during nighttime and daytime, and the difference was largest in autumn

Table 1 Levels of comfort degrees

CI	Level	Feeling	Comfortable degree	
> 85	H I	Heat, thermal regulation dysfunction, body feeling is not adapted	Great discomfort	Thermal
81–85	H II	Hot, uncomfortable and prone to excessive sweating	Discomfort	
76–80	H III	Warm, uncomfortable and prone to sweating	Mild discomfort	
71–75	H IV	Warm, comfortable and slightly sweaty	Mild comfort	
56–70	V	Comfortable	Comfort	Moderate
51–55	C IV	Cool, the human body feels more comfortable	Mild comfort	Cold
41–50	C III	Cold, the human body feels uncomfortable	Mild discomfort	
20–40	C II	Very cold, the human body feels very uncomfortable, the temperature has dropped	Discomfort	
< 20	C I	Extreme cold, the human body feel very uncomfortable, cold shiver	Great discomfort	

Notes: H represents heat; C represents cold

Table 2 Air temperature differences between the building and park

Areas	Air temperature (℃)			
	Winter	Spring	Summer	Autumn
Building (day)	–0.74	17.03	27.38	15.95
Building (night)	–1.2	15.63	25.71	14.43
Park (day)	–1.51	16.42	26.61	14.89
Park (night)	–3.64	13.37	23.44	10.84
Difference (day)	0.77	0.61	0.77	1.06
Difference (night)	2.44	2.26	2.27	3.59

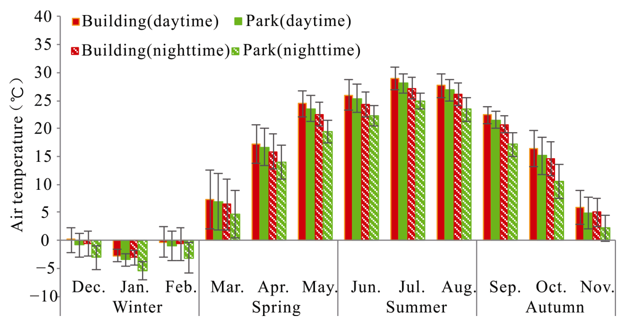

Fig. 2 Monthly air temperature of green space and dense building during daytime and nighttime

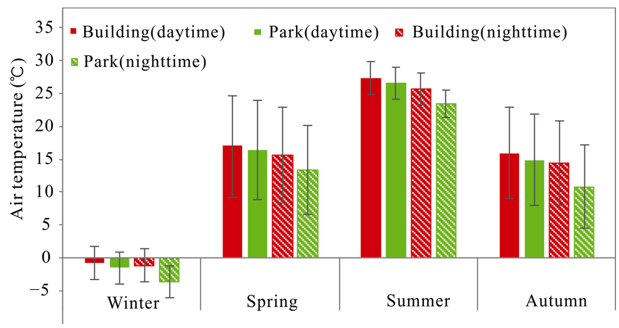

Fig. 3 Seasonal air temperature of green space and building during daytime and nighttime

(Fig. 4). Compared with the relative humidity between the building area and the lawn of the park, the seasonal difference during nighttime was higher than that during daytime. Meanwhile, the seasonal difference in relative humidity in the park was higher than that in the building area. The difference was the largest in autumn, with a difference of 8.55% during the day and 18.08% at night. In summer, it was 6.42% in the daytime and 10.48% at night. In spring, it was 4.24% in the daytime and 8.49% at night. In winter, the difference was the smallest, at only 1.76% in the daytime and 6.04% at night.

The relative humidity of parks and buildings during the daytime and nighttime are presented in Fig. 5. In October (autumn), the difference was the largest for the year, with a gap of 10.36% in daytime. In January (winter), the difference was 1.13% during the day and 4.52% at night. The gap became smaller after winter until it reached its lowest, and then it reached its peak in autumn. The greatest gap of day and night, which was 7.43%, occurred in summer on the building. The green park area was greatest in autumn, at 15.48%.

3.3 Wind speed on building area and Olympic park

When the local air temperature was affected by horizontal advection, the cooling effect of the park is not obvious, because the wind speed is opposed to aerodynamic impedance. It was also found the higher the wind speed, the smaller the temperature difference between the park and the building (Fig. 6). The difference in wind speed between the two observation points was mainly distributed in spring and summer and autumn. There was little difference between the two in winter. During the year, the roof of the building had 54 days of wind speeds smaller than the roof, including 25 days in winter, 23 days in spring, 2 days in summer and 4 days in autumn.

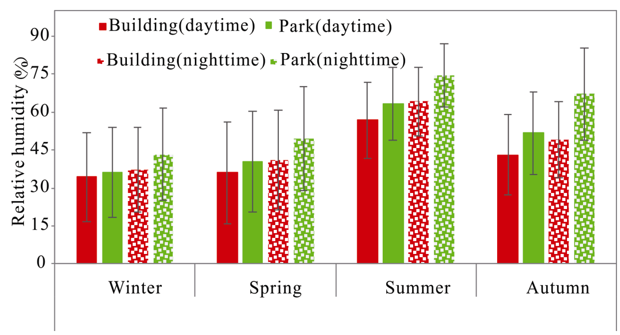

Fig. 4 Seasonal relative humidity of green space and dense building during daytime and nighttime

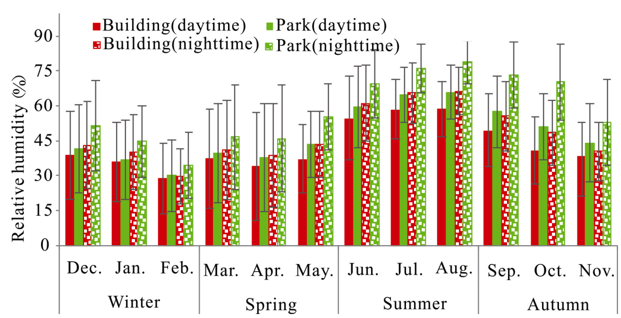

Fig. 5 Monthly relative humidity of green space and dense building during daytime and nighttime

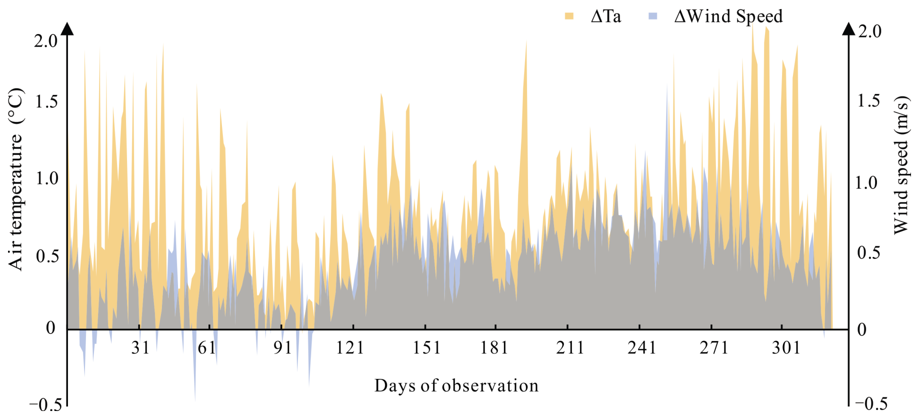

Fig. 6 The daily difference between temperature and wind speed (Δ Ta is the temperature gap between the building roof and the park, Δ Wind speed is wind speed difference of the two sites)

3.4 Comfort degree on building area and Olympic park

According to the comfort index distribution calculated by Equation (9) (Fig. 7), the daily comfort index fluctuated up and down with changes in air temperature, relative humidity and wind speed. According to the classification criteria (empirical value) of the China Meteorological Administration (Table 2), CI index was divided into thermal environment (CI ⩾ 70) and cold environment (55 < CI < 70) and the highest comfort level as moderate (CI ⩽ 55) (Fig. 7). In a cold environment, the comfort level lowered as temperature lowered, humidity increased, and wind speed increased. In contrast, in a thermal environment, the comfort level (Table 1) lowered as the temperature increased, the humidity declined, and the wind speed declined (according to the Equation 9).

According to the CI classification criteria (Table 1), we divided the values into three parts (Fig. 7). One was the thermal environment, including HIII mild discomfort, HII discomfort, and HI great comfort. The second was the moderate environment, including HIV mild comfort, V comfort, and CIV mild comfort. The third was the cold environment, including CIII mild discomfort, CII discomfort, and CI great comfort. According to the calendar of comfort level, the results indicated that the comfort levels of the park and building in spring and autumn were both higher than those in summer and winter (Fig. 8). The level of comfort in the park was, on average, higher than that of the building, except during the winter, when the number of days above one or more comfort days was 11 (Table 3). However, the negative effects sometimes occurred in the cold environment. The park reduced the human comfort index by an average of 0.92 during the year. The effect of the park comfort optimization was most obvious and was mainly affected by the wind speed and humidity under low temperature conditions.

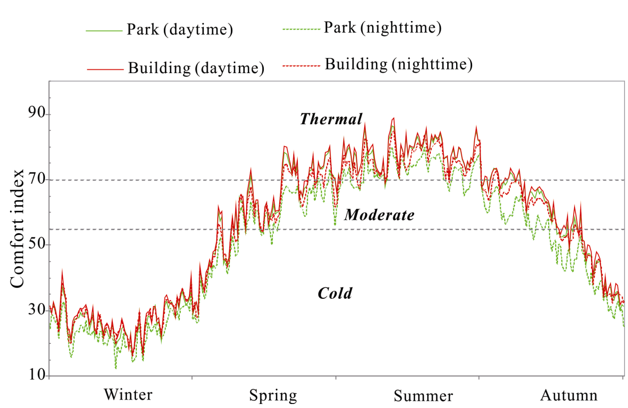

Fig. 7 The thermal comfort index in the four seasons

More precisely, both the park and the building had a discomfort level (CII) with low air temperature for a long time in winter (Fig. 8 and Table 3). Spring was mostly classified by comfort (V) and mild comfort (HIV, CIV) degrees. The difference in the comfort levels between parks and dense buildings was most pronounced in summer. The number of days (7 days) categorized by a degree of very uncomfortable (HI) was caused by extreme heat on buildings and was higher than the number of days in the park (4 days). Meanwhile, a total of 22 comfortable days (including V and HIV) occurred in the park, while only 19 days occurred on the building. In autumn, there was no significant difference between the

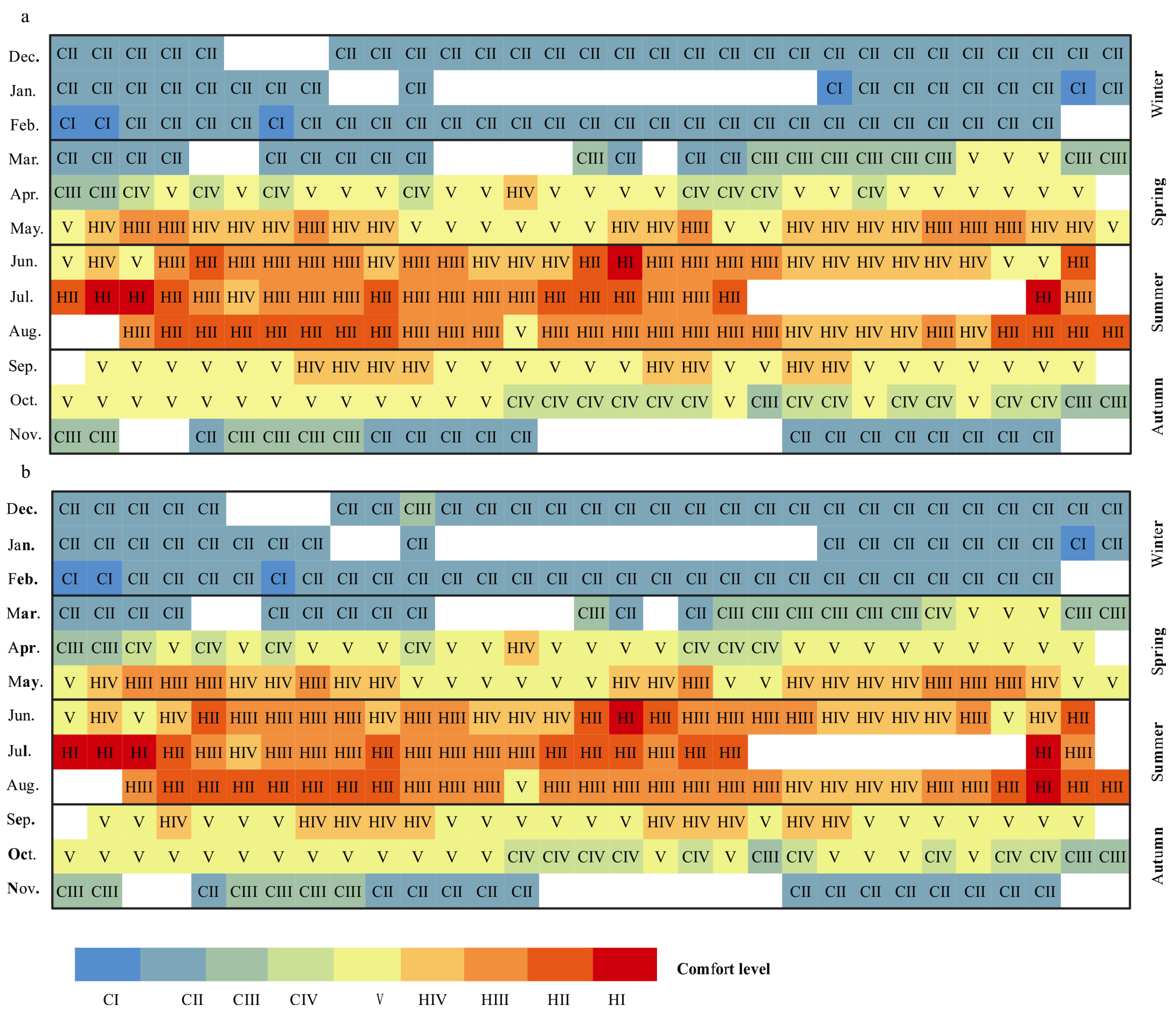

Fig. 8 The comfort level distributions in Beijing (a: comfort level in the park; b: comfort level on the building)

park and building regarding mild discomfort (CIII) and discomfort (CII), but there were two days that the building was more comfortable (V) than the park. By comparing the CI values of the two, we found that the relative humidity of the park increased significantly, and there were excessive relative humidity differences.

Daily variations in the park and building in each season presented obvious differences (Table 3). In winter, the park and building had days that were uncomfortable and accounted for 93% of all days (70 days). In spring, both the park and the building were comfortable, with 33 and 34 days, respectively, as well as having 22 and 20 days of mild comfort, respectively. In summer, the difference in comfort level between the park and building was most obvious. In the park, 6% (5 days) of the days were classified as comfort, 21% (17 days) were classified as mild comfort, 42% (34 days) were classified as mild discomfort, 26% (21 days) were classified as discomfort, and 5% (4 days) were classified as highly discomfort. On the building roof, 5% (3 days) of the days were classified as comfort, 20% (16 days) were classified as mild comfort, 42% (34 days) were classified as mild discomfort, 26% (21 days) were classified as discomfort, and 7% (7 days) were classified as highly discomfort. The gap between the two was reflected in the number of highly uncomfortable daytimes, with more days observed on the building than in the park. It is worth noting that there were four days when the building was more comfortable than the park in autumn. By observing the weather conditions on the days (Table 4), we found that this phenomenon was caused by the larger relative humidity difference between the two in a cold environment. When the relative humidity was higher, the evaporation of water vapor would remove the heat and cause a cold sensation to the human body.

Table 3 Number of days with each comfort degree level

	Winter		Spring		Summer		Autumn	
	Park	Building	Park	Building	Park	Building	Park	Building
H I	–	–	–	–	4	7	–	–
H II	–	–	–	–	21	21	–	–
H III	–	–	7	9	34	34	–	–
H IV	–	–	15	13	17	16	8	10
V	–	–	33	34	5	3	39	41
C IV	–	–	7	7	–	–	10	6
C III	–	1	11	11	–	–	9	9
C II	70	70	12	11	–	–	14	14
C I	5	4	–	–	–	–	–	–

Table 4 The climate parameters of special levels of comfort difference days

Date	Park			Building		
	Ta (℃)	*RH* (%)	Wind speed (m/s)	*Ta* (℃)	*RH* (%)	Wind speed (m/s)
2012-10-14	12.83	34.49	0.41	14.59	19.29	0.83
2012-10-18	12.83	48.15	0.48	14.84	31.13	0.93
2012-10-19	12.31	61.53	0.30	14.11	46.13	0.67
2012-10-23	13.12	57.04	0.26	14.98	41.85	0.44

4 Discussion

4.1 More pronounced cooling effect of Olympic Park in summer and nighttime

Urban parks have a significant cooling effect, which has been widely studied and verified in different regions and cities (Spronken-Smith and Oke, 1999; Chang et al., 2007; Chow et al., 2011; Chen et al., 2012, 2016; Amani-Beni et al., 2018). We compared the seasonal variation in air temperature and relative humidity in the Olympic Park and a building area. Overall, the analytical results indicated that the cooling and humidification effect of the park was more obvious in summer and autumn than that of the building, followed by spring and winter. The Olympic Park reduced the air temperature from 0.61℃ to 1.06℃ during the daytime and from 2.26℃ to 3.59 ℃ during the nighttime. Thus, we found that the cooling effect at night was more obvious with 1.65℃–2.53℃ according our observation data. Previous studies have focused on the discussion of the cooling effect of daytime parks, ignoring the contrast within a day and night (Sun et al., 2017; Amani-Beni et al., 2018; Dai et al., 2018). Our results are consistent with a previous study showing that urban green spaces reduced the temperature by a mean of 2℃ in Beijing (Sun et al., 2017). The variance of air temperature between parks and buildings is directly related to the structure, property difference and human activity of the underlying surface (Shahmohamadi et al., 2011). The heat reduction performance of a green space also depends on the vegetation coverage of the surroundings, vegetation type, and sky view factor (SVF) (Fahmy et al., 2010; Xi et al., 2012; Middel et al., 2014; Song and Wang, 2015).

The observed temperature variation law and difference was because the park, as a natural space, had less influence on human activities all year round, and the change in temperature and relative humidity were mainly determined by the park's own characteristics. Various factors mainly affect the absorption of solar radiation through the coverage of vegetation and the albedo of coverage types. When the vegetation coverage was high in summer, the area of shade increased, and the cooling effect was significant. This finding has also been supported by related studies; for instance, Potchter et al. (2006) found that an urban park with more trees was cooler than a park with fewer trees during the day (Potchter et al., 2006). Tan et al. (2015) noted that shade was the main factor providing the cooling effect of trees (Tan et al., 2015). Wu and Chen (2017) certified that trees had effects on the interception of shortwave radiation and reasonable heat abatement (Wu and Chen, 2017). Furthermore, the cooling effect of the park might be due to evapotranspiration and the higher albedo of green vegetation, which retains less solar heat and lower ambient temperatures than do impervious surfaces (Shahmohamadi et al., 2011). Vegetation coverage affects calorie consumption through transpiration. As the vegetation coverage increases, the transpiration consumes more energy, causing the redistribution of surface energy, and the Bowen ratio is continuously reduced to reduce the surface temperature, after the snow melted, the ratio of daytime latent heat flux decreased because vegetation was not yet active during the snow-free periods and the Bowen ratio increased (Shui et al., 2019). The results confirmed the park's potential contribution to the urban microclimate and mitigation of the heat island effect. Conclusively, these differences we discussed mainly depend on the land cover of the observed site surrounding the environment. However, it was not limited to the land use cover due to the three main causes of temperature change, including solar radiation, atmospheric circulation and underlying surface. A lack of space forbids further discussion at this point.

Meanwhile, we found that Beijing Olympic Park could increase its relative humidity by 1.76%–8.55% during the daytime and 7.23%–15.48% during the nighttime. Potchter et al. (2006) also found that urban parks could increase the relative humidity values and that an urban park covered with grass could be more humid than the built-up area during the day (Potchter et al., 2006). Amani-Beni et al. (2018) observed different types of vegetation in Olympic park and found that the air humidity of grass increased by 2.44, the relative humidity of irrigated grass increased by 3.37%–5.16%, the dry grasses increased by only 0.23%–0.56%, and the trees increased by 2.39 (Amani-Beni et al., 2018). The lower relative humidity of the building was due to the internal characteristics of the building area, i.e., concrete building, pavement and skyscraper. The area is usually poor in temperature and humidity conditions, and it is a hot and dry gathering area in the city. In spring, summer and autumn, the humidification effect of the park was strong. The humidification effect began to decline, which was related to the yellowing and shedding of leaves in late autumn and the weakening of transpiration.

4.2 Difference in comfort degree on building area and in Olympic Park

Human thermal comfort mainly depends on air temperature, wind speed, solar radiation, humidity, and human activity (Givoni, 1991). The arrangement of land use also substantially affects outdoor human comfort (Chen et al., 2016). In this study, appropriate temperature, humidity and wind speed improve the degree of comfort in the park. Based on the daily average temperature, humidity and wind speed values, the specific statistics of the two sites showed that the difference between the park and the building roof was even more disparate during the day, specifically by comparing the daily average temperature, the park (amount of 321 days of statistical results) had 320 days the average daily temperature was greater than the roof of the building. And the temperature of the park was lower than the roof of the building during all nights of monitoring at night. Observations of relative humidity showed that the roof of the building was larger than the park during the day, with 21 days in a year, 19 days in the winter and 2 day in the spring. The nighttime relative humidity building roof was higher than the park for 11 days, both were in winter. From the perspective of energy distribution, the higher the temperature, the more energy the water molecules get, and it is easy to leave the water and evaporate into the air. However, in the winter, the air temperature in the park is lowered, the vapor phase pressure tends to be stable, and the roof of the building is affected by human heat (the winter heating is discharged upwards), and the evaporation of water vapor is more obvious than that of the park (Wouters et al., 2015; Shui et al., 2019).

We found that high discomfort often occurred in winter and summer. The feeling of the surrounding environment was mainly extremely cold with high wind speeds and extreme heat with high humidity. In the thermal environment, the discomfort was reflected by the comprehensive influence of the external temperature and humidity. People directly feel heat and tend to sweat. In summer, discomfort mainly occurs on extreme heat days, and the duration is not long, i.e., approximately 2–4 days. This type of event is considered a heatwave, which can be thought of as an extreme weather phenomenon and is actually a rare random event. Extreme heat waves occur mainly in summer in urban areas (Fig. 8). Some factors that affect the urban microclimate include anthropogenic heat production (such as artificial lighting, quantity of cooking heat, and traffic load energy), the building height, the high residential density and the wind speed reduction that results in slower heat dissipation (Giannopoulou et al., 2014; Vellei et al., 2017).

It is worth noting that there were more mild discomfort and less comfort days in the park than on the building in autumn, which was mainly due to the increase in the relative humidity difference in October (Fig. 5), which caused cooling. According to Equation (9), the change in the CI index was determined by 1.8 T, 0.55 RH, and $3.2V^{0.5}$, which were critical values (Table 5). In the cold environment, when the temperature difference between the park and the building exceeded 5.56℃, when the difference in relative humidity exceeded 18.18%, or when the wind speed exceeded 9.77 m/s, the comfort levels differed. In the thermal environment, when the difference in air temperature was greater than 2.78℃, the difference in relative humidity was greater

Table 5 Critical value of changing comfort degree

	Cold environment		Thermal environment	
	Determinative term	Critical value	Determinative term	Critical value
Air temperature (℃)	1.8 T=10	5.56	1.8 T=5	2.78
Relative humidity (%)	0.55 RH=10	18.18	0.55 RH=5	9.09
Wind speed (m/s)	3.2 $V^{0.5}$=10	9.77	3.2 $V^{0.5}$=5	2.44

than 9.09%, or the difference in wind speed was 2.44 m/s, the comfort levels differed. This result also means that the CI index is lower when the park humidity is higher than the building on some days.

4.3 The implication of green space and building planning in a megacity

Urban parks have a high potential for climate regulation, and they can relieve heat stress and optimize human comfort by cooling the air temperature (Takács et al., 2016). The cooling effect that occurs in park areas is known as the park cool island (PCI), with affecting factors including the green area ratio, park shape index, and park elevation, among others (Oliveira et al., 2011). Our findings were consistent with previous results. In addition, we suggest that the park's shape, composition and type should be taken into account to make full use of the park and its cooling function. Previous research has indicated that there are also differences in the effect of tree species on cooling effects (Liu et al., 2008; Xu et al., 2017; Dai et al., 2018). For example, trees usually serve as the backbone of park trees, and their transpiration helps cool the surrounding environment, while their dense leaves can absorb solar radiation to provide shade and open space (Liu et al., 2008). The shrubs do not have trunks, so they can not provide the same cooling shade area as trees; however, they have strong resistance and wide adaptability characteristics. Meanwhile, Liu et al. (2008) found that the temperature of green space decreased with increasing coverage, and when the coverage reached or was above 60%, the green space had obvious cooling and humidification effects (Liu et al., 2008). Therefore, we encourage more mixed plantings to increase the richness of the urban park.

The type of park should be considered as one of the primary considerations. Numerous studies have proven that the cooling effects of different landscape patterns on the park are different (Yang et al., 2017). The cooling effects of various park types are different, such as community parks in general urban areas, neighborhood parks in central urban areas, and district gardens in urban core areas (Fahmy et al., 2010). The building landscape patterns and vegetation (as forest, grassland, and cultivated land) classes have a significant influence on the surface urban heat island (Yang et al., 2017). Xu et al (2017) carried out field measurements, and the results indicated that the shading device and trees showed the best effects among all the selected devices (Xu et al., 2017). These results provided policymakers and landscape architects with practical information about the benefits of urban green space. Urban green space has been proven to bring environmental benefits from the unique effects of various landscapes.

Urban parks can also be appropriately increased to increase their cooling effect. Bowler et al. (2010) found that a park cooled by an average temperature of 0.94℃ and claimed that, through comparison, a larger park with more trees could be cooler by comparing 16 study areas ranging from 0.1 ha to 120 ha (Bowler et al., 2010). The average cooling effect is 1.5℃–3.0℃. For a mid-sized urban park (0.5×10^6 m^2) and a larger urban green space (more than or equal to 1.5×10^6 m^2), the PCI intensity is even higher (Oke, 1989; Bowler et al., 2010). Moreover, Spronken-Smith (1999) found that the PCI was inversely correlated with wind speed. Li and Zha (2018) found that the temperature around different types of parks in a certain range showed different trends with increasing distance from the park, which was similar to three polynomial functions (Li and Zha, 2018). When the park area was between 50.56–52.69 km^2, the cooling effect of a community park was obvious; when the area was between 124.23–126.92 km^2, the cooling effect of an ecological park was the most significant (Li and Zha, 2018). Overall, the cooling effect of different types of parks varies with different area ranges, and it increases with the increase of the area within a certain range.

The planning of Beijing's green space system indicates that urban planning should construct an ecological green space system according to the standard of an 'ecological garden city'. The system will be perfected by realizing a reasonable layout that meets the requirements of an 'ecological garden city' and achieves a given green space index. Therefore, urban park planning is guided by policies and regulations, such as the 'Classification Standard of Urban Green Space (CJJ/T85-2002)', which proposed that park green space should possess multifunctional attributes, such as economic function, ecological function and social function. The 'Park Design Code (GB51192–2016)' clearly states that park green space with recreation functions should be open to the public, especially when there are better facilities, in terms of both ecology and beautification. Currently, the green space system is gradually changing from ecological function to ecological and recreational functions and will enter a new stage of being upgraded to meet the needs of diversification in the future in Beijing. However, there are some problems during the construction stage: the total amount of green space in the park is still insufficient; the ecological spatial pattern is not perfect, the urban development and construction crowds out the green construction land, and there is a lack of function of the park's green features.

An urban park is a 'cooling system' composed of different types, shapes and areas, which can reduce the overall temperature level of the megacity and improve the ecologically livable environment. And our observation experiment also confirmed this point, the park's cooling and humidifying effect will bring people a more comfortable environment, especially at night. Therefore, we recommend and encourage urban park designers and managers to pay attention to park area and shape, landscape patterns, vegetation form and layout design. In particular, the planning of large parks plays an important role in urban microclimate regulation. The concrete approach can improve the green quantity of green space and improve the greening ecological benefits under the conditions of urban land use tension. According to the principle of ecology, the complex communities of trees, shrubs and lawn are constructed as the greenbelt structure unit. We can take measures of rational allocation by taking plant species, quantity, and plant community level into consideration to increase the humidity, regulate the climate, and alleviate the city's thermal environment. In addition, vegetation coverage should be taken into account by making full use of the local natural environmental conditions to take advantage of the cooling effects of parks (Amani-Beni et al., 2018).

5 Conclusions

The study investigated the seasonally different effects of near-surface air temperature, relative humidity and thermal comfort between a park and a building area. Our results indicated that the Olympic park site could reduce the air temperature by (0.80±0.19)℃ with a range of 0.61℃–1.06℃ and increase the relative humidity by (5.24±2.91) %, with a range of 1.76%–8.55%, relative to the building roof site during the daytime for one year. During the nighttime, the Olympic park site reduced the air temperature by an average of (2.64±0.64)℃ with a range of (2.26–3.59)℃ and increased the relative humidity by an average of (10.77±5.20) %, with a range of 7.23%–15.48%. Our observational results indicated that the significantly cooling and humidification effects occurred in park, which in the four seasons of the year, summer is the most obvious, and throughout the day, night period is especially (1.67℃ cooler in winter, 1.65℃ cooler in spring, 1.5℃ cooler in summer and 2.53℃ cooler in autumn). Thus, the more pronounced cooling and humidifying effects in the thermal environment optimized thermally comfortable and attractive human settlement. The park improved the comfort index by an average of 0.93. Our results clearly indicated that the spatial arrangements of green spaces must be considered in cities. In general, Beijing Olympic park plays an effective role in cooling and humidifying, and this effect was more pronounced in summer and during the nighttime. Therefore, quantifying the cooling effect of parks in a megacity would benefit making preferable greening infrastructure that is related to helping urban planning decisions.

Further empirical studies are needed in which all the different factors that explain the influence of the park green areas around the surrounding environment are considered. This information would help planners provide the feedback necessary to improve the characteristics and spatial settlement of urban parks, according to the specific features of each city. We encourage urban planning to reasonably and appropriately improve vegetation coverage. An appropriate amount of green space is conducive to adjusting the urban microclimate and improving the comfort degree level of human settlements.

References

Allen III W L, 2012. Environmental reviews and case studies: advancing green infrastructure at all scales: from landscape to site. *Environmental Practice*, 14(1): 17–25. doi: 10.1017/S1466046611000469

Amani-Beni M, Zhang B, Xie G D et al., 2018. Impact of urban park's tree, grass and waterbody on microclimate in hot summer days: a case study of Olympic Park in Beijing, China. *Urban Forestry & Urban Greening*, 32: 1–6. doi: 10.1016/j.ufug.2018.03.016

Bowler D E, Buyung-Ali L, Knight T M et al., 2010. Urban greening to cool towns and cities: a systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3): 147–155. doi: 10.1016/j.landurbplan.2010.05.006

Chang C R, Li M H, Chang S D, 2007. A preliminary study on the local cool-island intensity of Taipei city parks. *Landscape and Urban Planning*, 80(4): 386–395. doi: 10.1016/j.landurbplan.2006.09.005

Chapman S, Watson J E M, Salazar A et al., 2017. The impact of urbanization and climate change on urban temperatures: a systematic review. *Landscape Ecology*, 32(10): 1921–1935. doi: 10.1007/s10980-017-0561-4

Chen K, Zhou L, Chen X D et al., 2016. Urbanization level and vulnerability to heat-related mortality in Jiangsu province, China. *Environ Health Perspect*, 124(12): 1863–1869. doi: 10.1289/EHP204

Chen P Y, Tung C P, Lin W C et al., 2016. Spatial optimization procedure for land-use arrangement in a community based on a human comfort perspective. *Paddy and Water Environment*, 14(1): 71–83. doi: 10.1007/s10333-015-0479-x

Chen X Z, Su Y X, Li D et al., 2012. Study on the cooling effects of urban parks on surrounding environments using Landsat TM data: a case study in Guangzhou, southern China. *International Journal of Remote Sensing*, 33(18): 5889–5914. doi: 10.1080/01431161.2012.676743

Chow W T L, Pope R L, Martin C A et al., 2011. Observing and modeling the nocturnal park cool island of an arid city: horizontal and vertical impacts. *Theoretical and Applied Climatology*, 103(1–2): 197–211. doi: 10.1007/s00704-010-0293-8

Coccolo S, Kämpf J, Scartezzini J L et al., 2016. Outdoor human comfort and thermal stress: a comprehensive review on models and standards. *Urban Climate*, 18: 33–57. doi: 10.1016/j.uclim.2016.08.004

Coccolo S, Pearlmutter D, Kaempf J et al., 2018. Thermal comfort maps to estimate the impact of urban greening on the outdoor human comfort. *Urban Forestry & Urban Greening*, 35: 91–105. doi: 10.1016/j.ufug.2018.08.007

Dai Z W, Wu S T, Cheng H S et al., 2018. Effect of vegetation on summer microclimate in suburban forest park: a case study of Fuzhou National Forest Park. *Journal of Chinese Urban Forestry*, 16(6): 1–5. (in Chinese)

De Freitas C R, Grigorieva E A, 2015. A comprehensive catalogue and classification of human thermal climate indices. *International Journal of Biometeorology*, 59(1): 109–120. doi: 10. 1007/s00484-014-0819-3

Doick K J, Peace A, Hutchings T R, 2014. The role of one large greenspace in mitigating London's nocturnal urban heat island. *Science of the Total Environment*, 493: 662–671. doi: 10.1016/j.scitotenv.2014.06.048

Dong J W, Kuang W H, Liu J Y, 2017. Continuous land cover change monitoring in the remote sensing big data era. *Science China Earth Sciences*, 60(12): 2223–2224. doi: 10.1007/s11430-017-9143-3

Fahmy M, Sharples S, Yahiya M, 2010. LAI based trees selection for mid latitude urban developments: a microclimatic study in Cairo, Egypt. *Building and Environment*, 45(2): 345–357. doi: 10.1016/j.buildenv.2009.06.014

Fang L, Clausen G, Fanger P O, 1998. Impact of temperature and humidity on perception of indoor air quality during immediate and longer whole-body exposures. *Indoor Air*, 8(4): 276–284. doi: 10.1111/j.1600-0668.1998.00008.x

Frankel M, Bekö G, Timm M et al., 2012. Seasonal variations of indoor microbial exposures and their relation to temperature, relative humidity, and air exchange rate. *Applied and Environmental Microbiology*, 78(23): 8289–8297. doi: 10.1128/AEM.02069-12

Giannopoulou K, Livada I, Santamouris M et al., 2014. The influence of air temperature and humidity on human thermal comfort over the greater Athens area. *Sustainable Cities and Society*, 10: 184–194. doi: 10.1016/j.scs.2013.09.004

Gill S E, Handley J F, Ennos A R et al., 2007. Adapting cities for climate change: the role of the green infrastructure. *Built Environment*, 33(1): 115–133. doi: 10.2148/benv.33.1.115

Givoni B, 1991. Impact of planted areas on urban environmental quality: a review. *Atmospheric Environment*. *Part B*. *Urban Atmosphere*, 25(3): 289–299. doi: 10.1016/0957-1272(91)90001-U

Grimm N B, Faeth S H, Golubiewski N E et al., 2008. Global change and the ecology of cities. *Science*, 319(5864): 756–760. doi: 10.1126/science.1150195

Hamada S, Ohta T, 2010. Seasonal variations in the cooling effect of urban green areas on surrounding urban areas. *Urban Forestry & Urban Greening*, 9(1): 15–24. doi: 10.1016/j.ufug.2009.10.002

Harvell C D, Mitchell C E, Ward J R et al., 2002. Climate warming and disease risks for terrestrial and marine biota. *Science*, 296(5576): 2158–2162. doi: 10.1126/science.1063699

Hathway E A, Sharples S, 2012. The interaction of rivers and urban form in mitigating the Urban Heat Island effect: a UK case study. *Building and Environment*, 58: 14–22. doi: 10.1016/j.buildenv.2012.06.013

Höppe P, 1999. The physiological equivalent temperature: a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43(2): 71–75. doi: 10.1007/s004840050118

IPCC Intergovernmental Panel on Climate Change. 2015. *Climate Change 2014*: Mitigation of Climate Change: Working Group

III Contribution to the IPCC Fifth Assessment Report. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781107415416.

Kalnay E, Cai M, 2003. Impact of urbanization and land-use change on climate. *Nature*, 423(6939): 528–531. doi: 10.1038/nature01675

Kikon N, Singh P, Singh S K et al., 2016. Assessment of urban heat islands (UHI) of Noida City, India using multi-temporal satellite data. *Sustainable Cities and Society*, 22: 19–28. doi: 10.1016/j.scs.2016.01.005

Koken P J M, Piver W T, Ye F et al., 2003. Temperature, air pollution, and hospitalization for cardiovascular diseases among elderly people in Denver. *Environmental Health Perspectives*, 111(10): 1312–1317. doi: 10.1289/ehp.5957

Kolokotroni M, Giannitsaris I, Watkins R, 2006. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. *Solar Energy*, 80(4): 383–392. doi: 10.1016/j.solener.2005.03.010

Kong F H, Yan W J, Zheng G et al., 2016. Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation. *Agricultural and Forest Meteorology*, 217: 22–34. doi: 10.1016/j.agrformet.2015.11.005

Kuang W H, 2019a. New evidences on anomalous phenomenon of buildings in regulating urban climate from observations in Beijing, China. *Earth and Space Science*, 6(5): 861–872. doi: 10.1029/2018ea000542

Kuang W H, Liu A L, Dou Y Y et al., 2019. Examining the impacts of urbanization on surface radiation using Landsat imagery. *GIScience & Remote Sensing*, 56(3): 462–484. doi: 10.1080/15481603.2018.1508931

Kuang W H, Liu Y, Dou Y Y et al., 2015. What are hot and what are not in an urban landscape: quantifying and explaining the land surface temperature pattern in Beijing, China. *Landscape Ecology*, 30(2): 357–373. doi: 10.1007/s10980-014-0128-6

Kuang W H, 2019b. Mapping global impervious surface area and green space within urban environments. *Science China Earth Sciences*, 62, 1591 (2019). doi: 10.1007/s11430-018- 9342-3

Kuang W H, Chen L J, Liu J Y et al., 2016. Remote sensing-based artificial surface cover classification in Asia and spatial pattern analysis. *Science China Earth Sciences*, 59(9): 1720–1737. doi: 10.1007/s11430-016-5295-7

Kuang W H, Yang T R, Liu A L et al., 2017. An EcoCity model for regulating urban land cover structure and thermal environment: taking Beijing as an example. *Science China Earth Sciences*, 60(6): 1098–1109. doi: 10.1007/s11430-016- 9032-9

Lazzarini M, Marpu P R, Ghedira H, 2013. Temperature-land cover interactions: the inversion of urban heat island phenomenon in desert city areas. *Remote Sensing of Environment*, 130: 136–152. doi: 10.1016/j.rse.2012.11.007

Li L, Zha Y, 2018. Mapping relative humidity, average and extreme temperature in hot summer over China. *Science of the Total Environment*, 615: 875–881. doi: 10.1016/j.scitotenv.2017.10.022

Liu J M, Li S H, Yang Z F, 2008. Temperature and humidity effect of urban green spaces in Beijing in summer. *Chinese Journal of Ecology*, 27(11): 1972–1978. (in Chinese)

Medina-Ramón M, Schwartz J, 2007. Temperature, temperature extremes, and mortality: a study of acclimatisation and effect modification in 50 US cities. *Occupational and Environmental Medicine*, 64(12): 827–833. doi: 10.1136/oem.2007.033175

Middel A, Häb K, Brazel A J et al., 2014. Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, 122: 16–28. doi: 10.1016/j.landurbplan.2013.11.004

Niemelä J, Saarela S R, Söderman T et al., 2010. Using the ecosystem services approach for better planning and conservation of urban green spaces: a Finland case study. *Biodiversity and Conservation*, 19(11): 3225–3243. doi: 10.1007/s10531-010-9888-8

Oke T R, 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455): 1–24. doi: 10.1002/qj.49710845502

Oke T R, 1989. The micrometeorology of the urban forest. *Philosophical Transactions of the Royal Society B*: *Biological Sciences*, 324(1223): 335–349. doi: 10.1098/rstb.1989.0051

Oleson K W, Monaghan A, Wilhelmi O, et al., 2015. Interactions between urbanization, heat stress, and climate change. *Climatic Change*, 129(3–4): 525–541. doi: 10.1007/s10584-013-0936-8

Oliveira S, Andrade H, Vaz T, 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(11): 2186–2194. doi: 10.1016/j.buildenv.2011.04.034

Pearlmutter D, Berliner P, Shaviv E, 2006. Physical modeling of pedestrian energy exchange within the urban canopy. *Building and Environment*, 41(6): 783–795. doi: 10.1016/j.buildenv.2005.03.017

Peng S S, Piao S L, Zeng Z Z et al., 2014. Afforestation in China cools local land surface temperature. *Proceedings of the National Academy of Sciences of the United States of America*, 111(8): 2915–2919.

Potchter O, Cohen P, Bitan A, 2006. Climatic behavior of various urban parks during hot and humid summer in the mediterranean city of Tel Aviv, Israel. *International Journal of Climatology*, 26(12): 1695–1711. doi: 10.1002/joc.1330

Sarrat C, Lemonsu A, Masson V et al., 2006. Impact of urban heat island on regional atmospheric pollution. *Atmospheric Environment*, 40(10): 1743–1758. doi: 10.1016/j.atmosenv.2005.11.037

Shahmohamadi P, Che-Ani A I, Maulud K N A et al., 2011. The impact of anthropogenic heat on formation of urban heat island and energy consumption balance. *Urban Studies Research*, 2011: 497524. doi: 10.1155/2011/497524

Shashua-Bar L, Pearlmutter D, Erell E, 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology*, 31(10): 1498–1506. doi: 10.1002/joc.2177

Sherwood S C, Ingram W, Tsushima Y et al., 2010. Relative humidity changes in a warmer climate. *Journal of Geophysical*

Research, 115(D9): D09104. doi: 10.1029/2009jd012585

Shui T T, Liu J, Xiao Y, et al., 2019. Effects of snow cover on urban surface energy exchange: observations in Harbin, China during the winter season. *International Journal of Climatology*, 39(3): 1230–1242. doi: 10.1002/joc.5873

Solecki W D, Rosenzweig C, Parshall L et al., 2005. Mitigation of the heat island effect in urban New Jersey. *Global Environmental Change Part B: Environmental Hazards*, 6(1): 39–49.

Song J Y, Wang Z H, 2015. Impacts of mesic and xeric urban vegetation on outdoor thermal comfort and microclimate in Phoenix, AZ. *Building and Environment*, 94: 558–568. doi: 10.1016/j.buildenv.2015.10.016

Spagnolo J C, de Dear R J, 2003. A human thermal climatology of subtropical Sydney. *International Journal of Climatology*, 23(11): 1383–1395. doi: 10.1002/joc.939

Spronken-Smith R A, Oke T R, 1999. Scale modelling of nocturnal cooling in urban parks. *Boundary-Layer Meteorology*, 93(2): 287–312. doi: 10.1023/a:1002001408973

Sugawara H, Shimizu S, Takahashi H et al., 2016. Thermal influence of a large green space on a hot urban environment. *Journal of Environmental Quality*, 45(1): 125–133. doi: 10.2134/jeq2015.01.0049

Sun S B, Xu X Y, Lao Z M et al., 2017. Evaluating the impact of urban green space and landscape design parameters on thermal comfort in hot summer by numerical simulation. *Building and Environment*, 123: 277–288. doi: 10.1016/j.buildenv.2017.07.010

Takács Á, Kiss M, Hof A et al., 2016. Microclimate modification by urban shade trees-an integrated approach to aid ecosystem service based decision-making. *Procedia Environmental Sciences*, 32: 97–109. doi: 10.1016/j.proenv.2016.03.015

Tan C L, Wong N H, Tan P Y et al., 2015. Impact of plant evapotranspiration rate and shrub albedo on temperature reduction in the tropical outdoor environment. *Building and Environment*, 94: 206–217. doi: 10.1016/j.buildenv.2015.08.001

Tan J G, Zheng Y F, Tang X et al., 2010. The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology*, 54(1): 75–84. doi: 10.1007/s00484-009-0256-x

Terjung W H, 1966. Physiologic climates of the conterminous United States: a bioclimatic classification based on man. *Annals of the Association of American Geographers*, 56(1): 141–179. doi: 10.1111/j.1467-8306.1966.tb00549.x

United Nations. 2014. *World Urbanization Prospects:* The 2014 Revision, New York: UN. https://www.un.org/development/desa/publications/2014-revision-world-urbanization-prospects.html

Vellei M, Herrera M, Fosas D et al., 2017. The influence of relative humidity on adaptive thermal comfort. *Building and Environment*, 124: 171–185. doi: 10.1016/j.buildenv.2017.08.005

Voogt J A, Oke T R, 2003. Thermal remote sensing of urban climates. *Remote Sensing of Environment*, 86(3): 370–384. doi: 10.1016/s0034-4257(03)00079-8

Willett K M, Gillett N P, Jones P D, et al., 2007. Attribution of observed surface humidity changes to human influence. *Nature*, 449(7163): 710–712. doi: 10.1038/nature06207

Wouters H, Demuzere M, de Ridder K, et al., 2015. The impact of impervious water-storage parametrization on urban climate modelling. *Urban Climate*, 11: 24–50. doi: 10.1016/j.uclim.2014.11.005

Wu Dui, 2003. Discussion on various formulas for forecasting human comfort index. *Meteorological Science and Technology*, 31(6): 370–372. (in Chinese)

Wu Z F, Chen L D, 2017. Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: integrating modeling with in-situ measurements. *Landscape and Urban Planning*, 167: 463–472. doi: 10.1016/j.landurbplan.2017.07.015

Xi T Y, Li Q, Mochida A et al., 2012. Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas. *Building and Environment*, 52: 162–170. doi: 10.1016/j.buildenv.2011.11.006

Xu X Y, Sun S B, Liu W et al., 2017. The cooling and energy saving effect of landscape design parameters of urban park in summer: a case of Beijing, China. *Energy and Buildings*, 149: 91–100. doi: 10.1016/j.enbuild.2017.05.052

Xu X X, Li X J, Meng D D, 2013. Impacts of Beijing different underlying surfaces on Urban Heat Islard Effect and human comfort. *Journal of Capital Normal University (Natural Sciences Edition)*, 34(3): 47–52, 76. (in Chinese)

Yan H, Wu F, Dong L, 2018. Influence of a large urban park on the local urban thermal environment. *Science of the Total Environment*, 622–623: 882–891. doi: 10.1016/j.scitotenv.2017.11.327

Yang Q Q, Huang X, Li J Y, 2017. Assessing the relationship between surface urban heat islands and landscape patterns across climatic zones in China. *Scientific Reports*, 7(1): 9337. doi: 10.1038/s41598-017-09628-w

Zakšek K, Oštir K, 2012. Downscaling land surface temperature for urban heat island diurnal cycle analysis. *Remote Sensing of Environment*, 117: 114–124. doi: 10.1016/j.rse.2011.05.027

Zhang B, Xie G D, Gao J X et al., 2014. The cooling effect of urban green spaces as a contribution to energy-saving and emission-reduction: a case study in Beijing, China. *Building and Environment*, 76: 37–43. doi: 10.1016/j.buildenv.2014.03.003

Zhao L, Lee X, Smith R B et al., 2014. Strong contributions of local background climate to urban heat islands. *Nature*, 511(7508): 216–219. doi: 10.1038/nature13462

Zhou J, Chen Y C, Zhang X et al., 2013. Modelling the diurnal variations of urban heat islands with multi-source satellite data. *International Journal of Remote Sensing*, 34(21): 7568–7588. doi: 10.1080/01431161.2013.821576