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Assessing the effects of landscape design parameters on intra-urban air temperature variability: The case of Beijing, China

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A B S T R A C T

Understanding the causes of the intra-urban air temperature variability is a first step in improving urban landscape design to ameliorate urban thermal environment. Here we investigated the spatial and temporal variations of air temperature at a local scale in Beijing, and their relationships with three categories of landscape design parameters, including the land cover features, site geometry, and spatial location. Air temperature measurements were conducted during the winter of 2012 and the summer of 2013 by mobile traverses. The results showed that spatial temperature difference between the maximum and minimum observed temperature in the study area ranged from 1.2 to 7.0 °C, and varied depending on season and time of the day. The magnitude and spatial characteristic of the air temperature variations depend strongly on the landscape parameters characterizing the immediate environment of the measurement sites. Increasing the percentage vegetation cover could significantly decrease air temperature, while the increase of building area would significantly increase it. In addition, the observed air temperature increased as the sky view factor (SVF) increased during daytime, while a contrary tendency was observed during nighttime. However, the impacts of SVF on air temperature were context-dependent. Furthermore, the air temperature increased with increasing distance from the park and water body boundary. Our findings also indicated that the relative importance of these landscape parameters in explaining air temperature differences varied among different times and seasons. Therefore, if appropriately combined, all investigated landscape parameters can effectively improve urban thermal environment on a yearly basis.

1. Introduction

Growing urban populations and urban expansion, with increasing built-up areas and human activities, results in significant modifications in the underlying surface properties and energy balance, and thus alters the urban climate [1]. A distinct feature of urban climate is the urban heat island (UHI) effect, which is directly related to the conversion of land cover from rural to urban covers [2–4]. Also, intra-urban surface cover variations result in the preferred spatial clustering of urban canopy layer (UCL) scale surfaces and surface units. This results in distinctive surface energy balance and microclimatic characteristics at a local scale [5]. Given the vast array of surface that forms the urban mosaic-like structure, it is not surprising that the microclimate within the urban environment varies significantly within the micro to local scale [6,7]. Urban microclimate both influences and is influenced by human behavior and decision-making, due to the complex interactions between air temperature and microscale landscape parameters [8]. Therefore, better understanding the causes of this intra-urban air temperature variability is critical in improving landscape design strategies to ameliorate urban thermal environment [9–11].

The first category of landscape parameters that influence urban microclimate is the land cover features. As urban areas develop and density increases, impervious urban surface covers replace permeable natural vegetation covers. Finally, impervious surface change the reflectivity and energy balance of surfaces resulting in locally higher air temperature. For this reason, vegetated areas play a critical role in moderating and dampening the warming effects of impervious land covers in urban environments [12–14]. Many field-based measurements have found that urban green areas are generally cooler than their surrounding built-up areas, and can produce air temperature differences up to 1–7 °C, a phenomenon referred to as a "park cool island" [15–21]. Furthermore, a few

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qualitative associations between air temperature and its surrounding land cover features have been reported [22–24]. Sun [23], for example, showed that air temperature significantly correlated with green ratio and building ratio at night in Taichung City, Taiwan. Yokobori and Ohta [24] investigated the effect of land cover on ambient air temperatures and found that air temperatures varied significantly according to ambient land cover types, and air temperatures decreased as the amount of vegetated area around the sites increased.

Site geometry is another crucial landscape parameter because of its importance in determining the receipt and loss of radiation. An important measure of surface geometry of a given site is the sky view factor (SVF), i.e. the fraction of the overlying hemisphere occupied by the sky [25]. During the day, the lower SVF at the canyon will result in less incoming solar radiation, and thus has an important effect on the ground surface temperature as well as the air temperature directly above it. The "urban cool island" phenomenon documented in many previous studies is mainly related to the low SVF [26,27]. During nighttime, the decreased SVF below roof level reduces the loss of long-wave radiation to the sky and also reduced turbulent heat transfer in the often calm canyon air. Therefore, theoretically it is considered to be a major factor of the nocturnal UHI phenomenon [28–31]. However, some studies have also found that SVF does not have a large importance on city temperature, especially not air temperature, and that it should not be assigned to much importance [32–34]. From past research it remains somewhat unclear the role that site geometry plays in its effects on urban air temperature.

In addition, there can be no doubt about the important role of heat advection between contrasting surfaces at the microscale in the UCL [35]. Hence, the air temperature at a site is also affected by dispersion through turbulence and advection from its surroundings. In particular, vegetated areas or water bodies within the urban environment are moist and cool compared to their surrounding built areas [36], and thus the cooling effects of vegetation or water could extend into its surrounding area. For example, Ca et al. [37] investigated the influence of a park on the urban summer climate in the nearby areas, and found at noon, the park can reduce by up to 1.5 °C the air temperature in a busy commercial area 1 km downwind. Observations made by other researches also show an extension of the cooling effect [16,34,38–40].

As this brief overview shows, the landscape design parameters of land cover, urban geometry, and the spatial location (proximity to the park or water) have been found to influence the local air temperature. The problem, however, is that different researchers look at the problem form a different angle using different landscape parameters, and it is very difficult to conclude which particular landscape factors would be more important in effecting the air temperature within the urban context. In addition, urban climate is also affected by external influences such as the topographic features, season and prevailing weather. Therefore, it is important to control geographical, seasonal and meteorological (i.e. wind speed and cloud cover) variables as much as possible to understand the location specific impacts on changes in urban air temperature.

In this study, we investigate the spatial and temporal differences of air temperature at a local scale in Beijing, and to gain insights on its linkage to the landscape parameters including percentage of building area, percentage vegetation cover, SVF, distance to park, and distance to water body. Specifically, this study tried to answer the following two questions: (1) how do the different landscape parameters differentially contribute to explaining the variance of local air temperatures, and (2) if the relative importance of these landscape parameters in explaining local air temperature varies by season and time of day?

2. Methodology

2.1. Study area and measurement sites

Beijing (39°56′ N, 116°20′ E), the capital of China, is located in the northern part of the North China Plain. It is the second largest city in China with a total population of 19.6 million by the end of 2010. It has a monsoon influenced humid continental climate characterized by hot and humid summers and generally cold, windy and dry winters. According to the climatological normals (1971–2000), January is the coldest month with an average temperature of −3.7 °C, while July is the hottest month with an average temperature of 26.2 °C. The highest temperature in 1971–2000 was 41.9 °C, and the coldest temperature was −18.3 °C. The main wind direction is from southeast to northeast in summer and in reverse during winter. Since 1978, Beijing's urban population and yearly construction area have been gradually increasing. This urbanization process, with its increasing built-up areas and anthropogenic activities, results in significant modifications in the underlying surface properties and the quick increase in the intensification of the UHI effect [41].

The measurements took place at the Beijing Olympic Park and its surrounding built-up areas in the Beijing city (Fig. 1). The study area is rectangular, 3.2 × 2.1 km in size and situated at the northern part of the city. It can be regarded as a typical area in the process of urbanization in Beijing. This area is very flat, and thus temperature difference due to topographic influence can be ignored. In addition, this district has a perfectly orthogonal urban geometry and the streets are oriented E–W and N–S, with an average width of 25 m. Therefore, it is a good study area to explore the relationship between air temperature and landscape design factors. In this study area, 26 measurement sites were chosen with the intention to investigate the quantitative relationship between air temperature and landscape variables (Fig. 1). A description of the measurement sites is given in Table 1. These measurement sites located sufficiently close to one another to be affected by uniform meso-scale climate conditions, and yet, also affected by distinctly different micro-scale landscape characteristics. The nature of the adjacent underlying surface greatly affects air temperature. Thus, to standardize temperature, all air temperature measurements were made over a common surface: paved road, as shown in Fig. 2(a).

2.2. Air temperature measurements

Mobile traverses were used to conduct air temperature measurements on 8 days during the winter of 2012 (December 2012 to February 2013) and the summer of 2013 (June to August). Survey times were early afternoon (14:00–15:00) and midnight (23:00–00:00). All observations were carried out during clear and windless days, i.e. when the UHI effects could be expected to be most pronounced. Avoidance of windy and cloudy conditions also minimizes the influence of meteorological variables.

Measurements of air temperature were taken using a mobile station with a thermistor temperature sensor connected to a data logger with a precision of 0.1 °C along the measurement route. The temperature sensor was fitted within a radiation shield, which mounted onto the front of a bicycle at 1.5 m above ground level. A GPS travel recorder was used to note geographical coordinates of latitude, longitude, and altitude synchronized to observations. Three fixed weather stations were installed in different regions within the study area for recording of the daily trend of air temperature. These data were used to correct the values taken with the mobile station because the measurements at different sites were not instantaneous. Each traverse took about 1 h to complete, and all data were adjusted to the beginning time of each transect by