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# Surface urban heat island in China's 32 major cities: Spatial patterns and drivers

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## ABSTRACT

Urban heat island (UHI) is a major anthropogenic alteration on Earth environments and its geospatial pattern remains poorly understood over large areas. Using MODIS data from 2003 to 2011, we quantified the diurnal and seasonal surface UHI intensity (SUHII, urban–suburban temperature difference) in China's 32 major cities, and analyzed their spatial variations and possible underlying mechanisms. Results show that the annual mean SUHII varied markedly from 0.01 to 1.87 °C in the day and 0.35 to 1.95 °C at night, with a great deal of spatial heterogeneities. Higher SUHIIs for the day and night were observed in the southeastern and northern regions, respectively. Moreover, the SUHII differed greatly by season, characterized by a higher intensity in summer than in winter during the day, and the opposite during the night for most cities. Consequently, whether the daytime SUHII was higher or lower than the nighttime SUHII for a city depends strongly on the geographic location and research period. The SUHII's distribution in the day related closely to vegetation activity and anthropogenic heat releases in summer, and to climate (temperature and precipitation) in winter, while that at night linked tightly to albedo, anthropogenic heat releases, built-up intensity, and climate in both seasons. Overall, we found the overwhelming control of climate on the SUHII's spatial variability, yet the factors included in this study explained a much smaller fraction of the SUHII variations in the day compared to night and in summer relative to winter (day vs. night: 57% vs. 72% in summer, and 61% vs. 90% in winter, respectively), indicating more complicated mechanisms underlying the distribution of daytime SUHII, particularly in summer. Our results highlight the different diurnal (day and night) and seasonal (summer and winter) SUHII's spatial patterns and driving forces, suggesting various strategies are needed for an effective UHI effect mitigation.

## 1. Introduction

Urbanization, a major human activity, poses increasingly strong impacts on Earth environments (Grimm et al., 2008; Vitousek, Mooney, Lubchenco, & Melillo, 1997). Among these effects, the resultant urban heat island (UHI), refers to the phenomenon that urban areas tend to have higher atmospheric or surface temperatures than the surroundings, is one of the most well-documented example of anthropogenic modification on Earth system (Arnfield, 2003; IPCC, 2007; Oke, 1973; Voogt & Oke, 2003). UHI can not only alter the eco-environments such as net primary production (Imhoff et al., 2004), biodiversity (Reid, 1998), water and air quality (Grimm et al., 2008), and climate (Arnfield, 2003; Dixon & Mote, 2003; IPCC, 2007; Jin, Dickinson, & Zhang, 2005; Jin, Shepherd, & King, 2005; Shepherd, 2005) but also affect human health and well-beings like an increase in morbidity, mortality, and risk of violence (Gong et al., 2012; O'Loughlin et al., 2012; Patz, Campbell-Lendrum, Holloway, & Foley, 2005). These impacts were expected to be more serious when interacting with global climate changes (IPCC, 2007; McCarthy, Best, & Betts, 2010; Patz et al., 2005). Thus, a better understanding of the UHI effects is critically important to support future climate mitigation actions and human adaptive strategies (Arnfield, 2003; Imhoff, Zhang, Wolfe, & Bounoua, 2010; Oke, 1973).

UHI has two broad types. The first is the atmospheric UHI calculated from weather station networks (Chow & Roth, 2006; Fast, Torcolini, & Redman, 2005; Karl & Quayle, 1988; Peterson, 2003) and the second is the surface UHI estimated from thermal infrared remote sensing techniques (Imhoff et al., 2010; Jin, Dickinson, et al., 2005; Peng et al., 2012; Voogt & Oke, 2003). Because of easy access and wall-to-wall coverage of satellite products, the surface UHI has gained rising attention in recent decades (Clinton & Gong, 2013; Imhoff et al., 2010; Jin, Dickinson, et al., 2005; Peng et al., 2012; Tran, Uchihama, & Yasuoka, 2006; Zhang, Imhoff, Wolfe, & Bounoua, 2010). We will deal with the surface UHI intensity (SUHII) in this study.

Surface UHI remains poorly understood over large areas. Most of the previous studies were conducted in a particular or several contrasting

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cities regarding the magnitude of surface UHI rather than geospatial patterns (e.g., Li et al., 2011; Tran et al., 2006; Yuan & Bauer, 2007). A few recent efforts had been made to understand the regional and global distributions of SUHII, yet they concentrated on big cities that are mostly situated in coastal areas and/or have different driving variables, therefore leading to highly diverse conclusions (Clinton & Gong, 2013; Imhoff et al., 2010; Jin, Dickinson, et al., 2005; Peng et al., 2012; Zhang et al., 2010). For instance, Jin, Dickinson, and Zhang (2005) suggested that the SUHII were pronounced at both daytime and nighttime globally but did not explore their drivers. Zhang et al. (2010) only focused on the daytime SUHII and the ecological control on global variations. Imhoff et al. (2010) demonstrated that the SUHII was more intense in the day than at night, and was mainly controlled by ecological context across 38 metropolises in the conterminous United States. Peng et al. (2012) also concluded that the SUHII was significantly higher in the day than at night across 419 global big cities and their spatial variability was attributed to the urban–suburban differences in vegetation activity during the daytime and in albedo and anthropogenic heat releases at night. The most recent global report (Clinton & Gong, 2013) indicated a similar magnitude for annual mean SUHII in the day and at night averaged across cities with large geographical heterogeneity that was mainly determined by the development intensity, vegetation amount, and the size of the urban metropolis. Apparently, a more detailed assessment on the spatial patterns of SUHII and underlying mechanisms is needed for a better understanding of the UHI effects over large areas.

Located in the East Asian monsoon region, China covers a wide temperature gradient decreasing from south to north and a large precipitation gradient decreasing from southeast to northwest (Wu, Yin, Zheng, & Yang, 2005), suggesting China should be an ideal place to examine the impacts of UHI at regional scale. Various studies have documented the SUHII in selected cities in China (Cai, Du, & Xue, 2011; Ding & Shi, 2013; Li et al., 2011; Tran et al., 2006; Xu & Chen, 2004). However, to our knowledge, no studies have systematically analyzed the SUHII of all major cities in China. Quantifying and analyzing the magnitude and spatial pattern of SUHII in China can not only help enhance understanding the physical characteristics, driving forces, and consequences of UHI in general, but also be essential for formulating climate mitigation strategies and plans in the country.

The purpose of this study was to investigate the geographic variations of the diurnal and seasonal SUHII in China's 32 major cities, and to explore their possible driving forces. The latest version 5 of Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature (LST) data were used to evaluate the surface temperature differences between urban and surrounding suburban areas over these 32 major cities that are distributed across China. Measurements of SUHII were related to both biophysical and anthropogenic factors to explore the possible causes for their spatial variabilities.

## 2. Data and methods

### 2.1. Datasets

We focused on 32 major cities in China (Fig. 1). All of them are municipalities or provincial capitals except Shenzhen, which is China's first special economic zone established in 1978 and is now considered as one of the fastest-growing cities around the world. To investigate the geographic variations of SUHII, these cities were grouped into six regions according to the geography of China (Fang, Chen, Peng, Zhao, & Ci, 2001): North China (Beijing, Hohhot, Shijiazhuang, Taiyuan, and Tianjin), Northeast China (Changchun, Harbin, and Shenyang), East China (Fuzhou, Hangzhou, Hefei, Jinan, Nanchang, Nanjing, and Shanghai), Central-south China (Changsha, Guangzhou, Haikou, Nanning, Shenzhen, Wuhan, and Zhengzhou), Southwest China (Chengdu, Chongqing, Guiyang, Kunming, and Lhasa), and Northwest China (Lanzhou, Urumqi, Xi'an, Xining, and Yinchuan) (Fig. 1). The east, central-south, and southwest parts of China have typical humid-hot climate. Northeast China, North China, and Northwest China have typical humid-cold, subhumid/semiarid-temperate, and arid climates, respectively (Wu et al., 2005).

Land surface temperature (i.e., LST) was obtained from Aqua MODIS 8-days composite products (version 5) with a spatial resolution of 1 km × 1 km (MYD11A2) from 2003 to 2011 for each city. The Aqua MODIS LST data was retrieved from clear-sky (99% confidence) observations that monitored at 1:30 and 13:30 local solar time using a generalized split-window algorithm (Wan & Dozier, 1996). Wan (2008) reported that the accuracy of MODIS V5 LST is better than 1 K for most tested cases (39 out of 47), and Rigo, Parlow, and Oesch (2006) found less than 5% differences between MODIS LSTs and in-situ measurements in urban areas.

Urban coverage map of each city was derived from the cloud-free Landsat TM/ETM + images (http://www.usgs.gov/ and http://datamirror.csdb.cn/) with a high spatial resolution of 30 m × 30 m in circa 2000, 2005, and 2010. First, the Landsat images were preprocessed (e.g., re-projection, mosaic, histogram equalization) using ERDAS Imagine version 9.2. Second, the land covers were grouped into three types (i.e., built-up land, water body, and other land) using the maximum likelihood classification approach (Strahler, 1980). Built-up land consisted of the impervious surfaces of cities, towns (lands used for townships and settlement), and industrial and mining lands. Water body represents the reservoirs, ponds, and rivers. Other land represents all the other kinds of land covers including cropland, forest, shrub, grass, and unused land. Finally, the accuracies of the classified products were assessed using Google Earth Pro® (GE) following the approach of Zhou, Zhao, and Zhu (2012), and the Kappa coefficients measuring classification accuracy (Foody, 2002) were calculated. Kappa coefficients for the 32 cities ranged from 0.77 to 0.93, with most of them were larger than 0.80, which meets the accuracy requirements of this analysis.

The following datasets were assembled to examine their relations with the SUHII:

a) The MODIS Enhanced Vegetation Index (EVI) (16-day composites) and Bidirectional Reflectance Distribution Function (BRDF) albedo (8-day composites) from 2003–2011: the albedo products consisted of shortwave black sky albedo (BSA, directional hemispherical reflectance at local solar noon) and white sky albedo (WSA, bihemispherical reflectance). Because the BSA was linearly correlated with WSA and showed a similar relationship with SUHII to WSA (Peng et al., 2012), only WSA was utilized in this analysis.
b) Digital Elevation Model (DEM): digital elevation data at a 3 arc-second (approximately 90 m) spatial resolution from the Space Shuttle Radar and Topography Mission (SRTM) was used (http://earthexplorer.usgs.gov/).
c) Built-up Intensity (BI): the BI, defined as the percentage of landscape taken by built-up land, was derived from urban coverage maps. Methods to derive BI will be described in 2.2. Analysis.
d) Climate information on temperature and precipitation: monthly climate data from 2003 to 2011 for each city was obtained from Chinese Meteorological Observations (http://cdc.cma.gov.cn/). The meteorological station for each city was located within its suburban or urban area to reflect the climatic background for each city (Fig. 1).
e) Nighttime lights: the remotely sensed nighttime light signals derived from the Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) (version 4 and downloaded from http://ngdc.noaa.gov/eog/dmsp/ downloadV4composites.html) were used to as a proxy of anthropogenic heat releases in both urban and suburbs following previous studies (Elvidge et al., 2001; Ghosh et al., 2010; Peng et al., 2012). The annual DMSP data were compiled for 2003–2010 with a nominal spatial resolution of 2.7 km.