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Identification of typical diurnal patterns for clear-sky climatology of surface urban heat islands

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ABSTRACT

Understanding the diurnal dynamics of surface urban heat islands (SUHIs) is an indispensable step towards their full interpretation at multiple time scales. However, because of the tradeoff between the spatial and temporal resolutions of satellite-derived land surface temperature (LST) data, the climatology, variety, and taxonomy of diurnal SUHI (DSUHI) patterns remain largely unknown for numerous cities with different bioclimates. By combining daily MODIS LST data with a newly developed four-parameter diurnal temperature cycle (DTC) model, we selected 354 Chinese megacities located in different bioclimatic zones to examine the characteristics of the DSUHI descriptors and systematically investigate the prevalent DSUHI temporal patterns.

The DSUHI variations demonstrate that both the daily maximum and minimum SUHI intensity (SUHII) can occur during most periods of the day, although these intensities are more likely to occur in the early morning and noon/afternoon. Our results also reveal that both strong SUHIs (SUHII > 3 K) and surface urban cool islands (SUCIs) (SUHII < 0 K) are more prevalent than those identified directly through the four MODIS transits. According to the SUHI dynamics, five typical DSUHI temporal patterns are identified: standard-spoon, weak-spoon, quasi-spoon, inverse-spoon, and straight-line patterns. A gradient was found with spoon-like patterns (DSUHI dynamics typically with a daytime valley and a roughly constant trend or a small peak at night) in North China and inverse-spoon (DSUHI dynamics with a typical daytime peak and a constant trend at night) or straight-line patterns (DSUHI dynamics virtually unchanged all day) in South China. The DSUHI shapes were found to be greatly controlled by the urban-rural contrast in the normalized difference vegetation index (NDVI) and urban geometry. Our results not only advance our understanding of the diurnal climatology of SUHIs but also provide a basis for urban surface heat mitigation by identifying the possible timing of the mitigation requirement.

1. Introduction

The rapid urbanization of the past few decades has continuously converted natural habitats into urban surfaces and it has also had a large impact on the urban climate, environment and ecology (Kalnay and Cai, 2003). One of the most distinctive urbanization-induced

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Abbreviations: CUHI, canopy layer urban heat island; CUHII, canopy layer urban heat island intensity; DCUHI, diurnal canopy layer urban heat island; DSUHI, diurnal surface urban heat island; DTC, diurnal temperature cycle; GST, ground surface temperature; LST, land surface temperature; NDVI, normalized difference vegetation index; SAT, surface air temperature; SUCI, surface urban cool island; SUHI, surface urban heat island; SUHII, surface urban heat island intensity; UHI, urban heat island

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outcomes is the urban heat island (UHI), a phenomenon in which urban temperatures tend to be higher than that of the surrounding area (Oke, 1982). The UHI has been reported in numerous cities worldwide (Stewart and Oke, 2012) and it profoundly affects people's lives (Akbari and Konopacki, 2005; Gong et al., 2012; Patz et al., 2005). Typically, the UHI denotes the elevated urban temperatures measured in the canopy layer and/or at the skin-surface. They are referred to as the canopy layer UHI (CUHI) and the surface UHI (SUHI), respectively, both of which have been documented extensively (Clinton and Gong, 2013; Flores et al., 2016; Hu and Brunsell, 2015; Nichol, 2005; Oke, 1982; Pichierri et al., 2012; Stewart and Oke, 2012; Wang et al., 2017).

The CUHI and SUHI have dissimilar temporal patterns on different time scales, and the exploration of these different patterns has been a major focus of previous UHI studies (Anniballe et al., 2014; Lazzarini et al., 2013; Wang et al., 2017). CUHI dynamics from very small (e.g., hourly) to very large (e.g., inter-annual) time scales can be observed directly through high-frequency in-situ surface air temperature (SAT) measurements (Chow and Roth, 2006; de Faria Peres et al., 2018; Ren et al., 2007; Runnalls and Oke, 2000). Similarly, high-frequency in-situ ground surface temperatures (GSTs) can be used to characterize the multi-temporal development of the SUHI (Wang et al., 2017). Nevertheless, GSTs obtained from stations, when compared with in-situ SATs, are highly sensitive to the local surface type and are therefore characterized by a high spatial heterogeneity, making such point-based GSTs far less capable of representing the overall thermal differences between urban and nonurban areas. Satellite-derived land surface temperatures (LSTs) overcome this shortcoming by providing spatially continuous data of the surface thermal status at a large scale (Voogt and Oke, 2003; Weng, 2009), and such data have been widely used in SUHI investigations under clear-sky conditions (e.g., Li et al., 2012; Imhoff et al., 2010; Keramitsoglou et al., 2011; Meng et al., 2018; Quan et al., 2014; Schwarz et al., 2011; Shen et al., 2016; Stathopoulou and Cartalis, 2009; Zhou et al., 2014).

Consequently, investigations of SUHI temporal variations on seasonal/monthly and inner-annual timescales have benefited greatly from the accumulation of thermal remote sensing data, particularly those from polar-orbiting satellites with relatively fine spatial resolutions (i.e., Landsat/TM, ETM+, and TIRS, NOAA/AVHRR, Terra & Aqua/MODIS, along with others) (Bechtel, 2015; Clinton and Gong, 2013; Streutker, 2003; Tran et al., 2006; Zhou B. et al., 2013). Polar-orbiting satellites, however, only sample LSTs at a comparatively low frequency (only two to four times per day at most) primarily because of the tradeoff between the spatial and temporal resolution of satellite observations (Sobrino et al., 2012; Zhan et al., 2013). This temporal discontinuity in the LST records from polar orbiting satellites limits SUHI studies to discrete times during a diurnal cycle when the satellite transits (Clinton and Gong, 2013; Nichol and To, 2012; Peng et al., 2012; Shastri et al., 2017), while the true and continuous SUHI temporal pattern during a diurnal cycle (hereafter termed the DSUHI temporal pattern) has been less investigated.

To better understand true DSUHI temporal patterns, two strategies have been devised. The first uses spatially downscaled high-frequency LSTs obtained from geostationary satellites (e.g., the GOES satellite operated by the National Oceanic and Atmospheric Administration, the FY satellite by the China Meteorological Administration and the MSG satellite by the European Organization for the Exploitation of Meteorological Satellites). This approach is termed the *spatial downscaling strategy*. It can generate hourly or sub-hourly LST data with a spatial resolution of 1 km or finer, which are suitable for DSUHI investigations (Bechtel et al., 2012; Sismanidis et al., 2015a, b; Zakšek and Oštir, 2012; Zhou J. et al., 2013). The other strategy combines LST observations from polar-orbiting satellites and the diurnal temperature cycle (DTC) models (hereafter termed the *DTC modeling strategy*) to reconstruct temporally continuous LST dynamics, from which DSUHI temporal patterns can be explored (Fang et al., 2017).

Using these two strategies, DSUHI temporal patterns have been investigated in a very limited number of case cities, and they appear to exhibit a greater variety than diurnal CUHI (DCUHI) patterns. Specifically, the DCUHI usually exhibits a higher intensity at nighttime compared to daytime (Oke, 1982), while the DSUHI exhibits no general patterns but rather varies among different cities/seasons. For example, on typical days in spring, autumn, and winter in Beijing, as well as for summer in Athens, studies have reported that DSUHI and DCUHI patterns are similar (Sismanidis et al., 2015b; Zhou et al., 2013a). The CUHI and SUHI intensities (CUHIIs and SUHIIs) in these two cities generally decrease after sunrise, reach a minimum around solar noon, and then increase until the evening, after which stable and significant nighttime SUHIIs (CUHIIs) persist until the following sunrise. The summer seasons of some other cities (Rome, Beijing, and most of the cities in China within the Yangtze River Delta urban agglomeration) exhibit a different DSUHI temporal pattern: The SUHIIs after sunrise increase quickly, generally reach a peak within 2 h after the solar noon, and then decrease until sunset and remain relatively constant throughout the night (Fang et al., 2017; Sismanidis et al., 2015b; Zhou et al., 2013a). Yet another DSUHI temporal pattern was found for typical summer days in Paris and Istanbul: The SUHIIs first exhibit a four-hour downward trend after sunrise; they then increase to a diurnal maximum mostly in the afternoon, followed by a slow downward trend until sunset, and a quasi-stationary trend until the next sunrise (Sismanidis et al., 2015b; Zakšek and Oštir, 2012).

DSUHI temporal patterns have been recognized preliminarily using the *spatial downscaling* and *DTC modeling* strategies as summarized above; however, we have identified two issues requiring further investigation. First, previously acknowledged DSUHI temporal patterns were mostly obtained on a single or few days across a yearly cycle, and thus the climatological DSUHI temporal patterns remain largely unknown. Second, previous reports of DSUHI temporal patterns focused on a single or few cities located in a small number of bioclimatic zones; such case studies are unable to provide a full insight into the DSUHI temporal patterns that exhibit great variations among different cities. Therefore, our current understanding of the variety and taxonomy of the prevalent DSUHI temporal patterns for numerous cities with very different bioclimates on a large (e.g., continental) scale remains preliminary.

To address these limitations and derive a full understanding of the true diurnal dynamics of the large-scale climatological SUHI, in the present study we selected > 300 cities within different bioclimatic zones across China. By incorporating a newly developed four-parameter DTC model, the *DTC modeling* strategy was used for deriving the temporally continuous DSUHI dynamics. We choose *DTC modeling* over the *spatial downscaling* strategy because of the advantages of the former strategy in terms of its data and the convenience in its methodology (further explanations are given in Section 3.2). The characteristic descriptors and the prevalent patterns of the DSUHI were investigated over the full annual cycle of months/seasons from the climatological perspective. This study provides a simple yet efficient methodology for studying DSUHI temporal patterns. The identified DSUHI temporal patterns deliver, to the best of our knowledge, a first insight into the taxonomy of the SUHI diurnal dynamics, as well as how DSUHI temporal patterns may vary among different bioclimatic zones. These provide for an improved interpretation of the SUHI on multiple spatiotemporal scales.

2. Study area

The past three to four decades have witnessed a very rapid urbanization of cities in China, wherein significant UHIs have been reported (Wang et al., 2015; Zhou et al., 2014). In this study, we chose 354 megacities with urban areas exceeding 10 km^2 (the delineation of urban areas is given in Section 3.2.3) as the study area (Fig. 1). These cities are mostly distributed in seven bioclimatic zones according to Zheng et al. (2010): Southern Subtropical (SS), Mid Subtropical (MS),