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Temporal upscaling of surface urban heat island by incorporating an annual temperature cycle model: A tale of two cities

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ABSTRACT

Satellite thermal remote sensing potentially provides a new way to monitor local climate change due to urbanization, especially changes in surface temperatures that result in the surface urban heat island (SUHI). However, this technique is restricted to clear-sky conditions. Because of this limitation, satellite-derived land surface temperature (LST) records are frequently interrupted, sometimes even becoming temporally sparse and, accordingly, climatically less representative. Given this challenge, we propose a strategy that incorporates an annual temperature cycle (ATC) model to perform temporal upscaling of the SUHI from a climatic perspective. Using two megacities (Beijing and Shanghai) as case studies, our major findings include: (1) urbanization tends to enlarge the amplitude of annual daytime LST series for both cities; (2) urbanization in Beijing narrows the diurnal LST range on annual average but broadens it in Shanghai; (3) within an annual cycle, the daytime SUHI intensity (SUHII) reaches its maximum one month later than the daytime LST maximum for Beijing, whereas this time difference is negligible for Shanghai; and (4) compared with the observation-based and moving-window-based temporal aggregations, the ATC-based temporal aggregation allows to produce a clear-sky SUHI climatology that is more representative and becomes potentially valuable for prediction or application purposes. From a climatic perspective, the temporal upscaling of the SUHI, therefore, provides insights into the impacts on local thermal environments that are induced by urbanization.

1. Introduction

Urban areas usually experience higher temperatures than their rural surroundings (Oke, 1982); this difference in temperature is typically termed an urban heat island (UHI). The thermal stress imposed by the UHI on local climate significantly affects the environment and the quality of life of urban residents (Patz et al., 2005; Clinton and Gong, 2013). As one of the four types of UHI (boundary layer, canopy or surface air, surface, and subsurface) (Yow, 2007), the surface UHI (SUHI) represents a modification of the land surface temperature (LST) due to urbanization (Voogt and Oke, 2003).

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1.1. Background

Investigation of the SUHI was difficult until the advent of thermal remote sensing, which provides spatially continuous LST measurements over a large area. Previous SUHI studies can be divided into three categories: examination of spatial patterns, characterization of temporal dynamics, and analysis of control factors and processes. Spatial patterns of SUHIs have been recognized at different spatial scales (Chen et al., 2006; Gluch et al., 2006). Control factors include vegetation abundance and impervious surface (Small, 2006; Wang et al., 2007; Yuan and Bauer, 2007; Zhang et al., 2012), surface structures (Oke, 1981), thermal properties (Oke et al., 1991), social-statistical indicators such as population density and energy consumption (Zhang and Wang, 2008), and meteorological elements (Oke et al., 1991; Zhou et al., 2011).

Temporal dynamics refer to the diurnal, seasonal, annual, and interannual variations of urban climate. SUHI dynamics at multiple time scales are more difficult to detect remotely, partly because high-spatial-resolution LST data have infrequent temporal sampling owing to the trade-off between their spatial and temporal resolutions (Zhan et al., 2013). In addition, cloud cover also frequently interrupts satellite thermal remote sensing. Some studies, nevertheless, have attempted to quantify the temporal patterns in SUHIs solely using thermal datasets collected within the space of one or more years (i.e., *purely data-driven studies*), as well as using a combination of satellite data and temporal dynamic models at multiple time-scales (i.e., data-model-driven studies).

1.1.1. Purely data-driven studies

Two categories of research employ large amounts of remotely sensed LST data to conduct SUHI analysis. Case studies of individual cities stress the associated thermal details of that city. Such studies use high-frequency geostationary LSTs to focus on the hourly and even sub-hourly dynamics of the SUHI. However, the coarse spatial resolution of these LSTs necessitates disaggregation of LSTs to characterize urban scales adequately (Stathopoulou and Cartalis, 2009; Zakšek and Oštir, 2012; Keramitsoglou et al., 2013). Studies may also focus on the SUHI's day-night, daily, monthly, or seasonal dynamics, or the dynamics over a period of years, largely based on LSTs obtained by polar-orbiting satellites (e.g., AVHRR and MODIS LSTs) (Streutker, 2003; Wang et al., 2007; Lazzarini et al., 2013; Anniballe et al., 2014). Studies in the second category have examined a great number of cities across different continents and emphasized the common statistical regimes of SUHIs across different climates. Recent investigations have begun to stress both the diurnal and annual aspects of SUHI as well as their driving mechanisms for cities spread across different bioclimatic zones at national, continental, or global scales (Imhoff et al., 2010; Peng et al., 2012; Schwarz et al., 2011; Clinton and Gong, 2013; Zhou et al., 2014; Wang et al., 2015).

1.1.2. Data-model-driven studies

Another effective approach to analyzing the temporal patterns of SUHI is to incorporate temporal dynamic models. These models provide a statistical fit to the expected LST time series based on available discrete remotely sensed LST observations at irregular time intervals. Diurnal temperature cycle models represent the temporal LST variation using a piecewise function with parameters extracted from remotely sensed LSTs. The extracted parameters summarize the LST dynamics and are thus more informative than the LST pattern itself (Göttsche and Olesen, 2001; Zhou et al., 2013).

On an annual time scale, the sinusoidal function is adopted as the most representative model to fit the annual LST time series at the satellite overpass time. Bechtel (2011, 2012) used this approach to characterize urban thermal landscapes with multi-temporal Landsat data. This fitting strategy was also implemented to analyze decadal-scale SUHI patterns obtained from Landsat data (Weng and Fu, 2014). Quan et al. (2016) recently combined the sinusoidal models and the piecewise linear trend model to decompose the trend, seasonal, and noise components of LSTs. Here we refer to the fitting of sinusoidal or other functions to represent annual LST temperature cycles as annual temperature cycle (ATC) models.

1.2. Objectives

The combination of remotely observed LST time series with their corresponding temporal dynamic models provides a new opportunity to examine the spatiotemporal patterns of SUHI. However, the following challenges remain. (1) The performance of simple models to fit temperature cycles when applied to LSTs obtained times other than mid-morning or to temporally dense LST observations from satellite sensors with shorter sampling intervals (e.g., MODIS LSTs) remains uncertain. More importantly, the spatiotemporal characteristics of the SUHI encoded in the ATC parameters have not been sufficiently examined. (2) Can methods be found to overcome the limitation of irregular and sometimes infrequent satellite LST viewing conditions due to cloud cover that may limit the representability of the derived SUHI estimates? The climatological availability of suitable remote sensing viewing conditions will depend on the location of a city and its particular climate zone and there are large variations in these conditions. The frequency of suitable viewing conditions may also vary seasonally.

Given these challenges, this study first evaluates the ATC model based on annual MODIS LSTs obtained at four overpass times per diurnal cycle. From a climatic perspective, we next propose a temporal upscaling concept for the remote sensing of SUHIs to address the problem of irregularly sampled LSTs with long temporal gaps. We choose two megacities (Beijing and Shanghai) that have different climates to illustrate and intercompare the spatiotemporal details of SUHI derived from the method.

2. Study area and data

2.1. Study area

The study area includes the two largest megacities in China, Beijing and Shanghai. These two cities are separated by a distance of more than 1000 km (see Fig. 1a). Beijing and Shanghai had populations of about 21.1 million and 24.2 million, respectively, in 2013. Beijing is bordered by mountains ranging from 1000 m to 1500 m in altitude to the north and west and by plains with an average altitude of 44 m to the south and east. Shanghai is located on a flat plain with an average elevation of 4 m. Beijing is located in a semi-humid temperate zone characterized by hot and humid summers and cold and dry winters (Huo, 1989). Shanghai is located in a humid subtropical zone and has damp and chilly winters and hot and humid summers (Djen, 1992). Like many other megacities around the world, literature surveys show that these two cities are characterized by significant SUHIs (Wang et al., 2007; Zhou et al., 2013; Zhang et al., 2013; Quan et al., 2014; Zhan et al., 2014a,b).

2.2. MODIS data

Three MODIS Collection-5 products collected during 2012 were used in this study. These included the daily LST products MOD11A1 and MYD11A1 and the yearly land cover product MCD12Q1 provided by the National Aeronautics and Space Administration (NASA) at Level1 via the Atmosphere Archive and Distribution System (LAADS) [https://ladsweb.nascom.nasa.gov/]. The two LST products in total provide four instantaneous scenes per day at about 10:50 (Terra-day) and 22:10 (Terra-night), and 13:10 (Aqua-day) and 01:50 (Aqua-night) local time at a spatial resolution of 1000 m. The retrieval errors of MODIS LST products have been validated to within 1 K at multiple validation sites for a relatively wide range of surface and atmospheric conditions (Wan et al., 2002, 2004; Wan, 2008, 2014; Wang and Liang, 2009). The land cover product describes land cover types at 500 m spatial resolution and incorporates five different classification schemes; in this study, the IGBP scheme was adopted. For each city, the pixels within the city border identified as urban and built-up land in the IGBP scheme were designated as urban areas, and those identified as cropland were designated as rural areas (i.e., water pixels were excluded). As shown in Fig. 1b and c, the urban and built-up land is concentrated mainly within the urban cores marked by the blue municipal boundaries.

As surface longwave radiation is unable to penetrate through clouds, satellite thermal remote sensing can only capture LSTs under clear-sky conditions. Fig. 2 shows the average percentage of the urban and rural pixels of both cities that experienced clear-sky conditions for each month in 2012. For both cities, spring (March, April, and May) and autumn (September, October, and November) were the periods during which clear skies were most prevalent. For Beijing, clear-sky pixels were more frequent at night than during the day, except during summer (June, July, and August). For Shanghai, there were only a few clear-sky pixels during summer daytime (June, July, and August) owing to the summer convective activity (known locally as the 'plum