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Remote sensing of the urban heat island effect in a highly populated urban agglomeration area in East China

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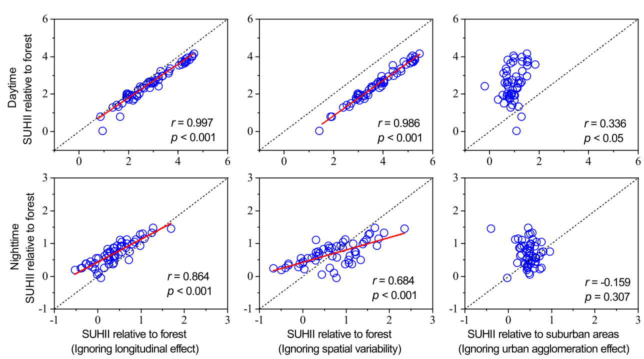
HIGHLIGHTS

- Surface urban heat island intensity (SUHII) was studied in an urban agglomeration.
- Four methods were used to predict the reference temperature of urban areas.
- Ignoring urban agglomeration effect would lead to large biases of SUHII estimates.
- The SUHII was evident in spite of urban size with large spatiotemporal variability.
- The climate, vegetation, surface albedo, and population density control the SUHII.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasingly urban agglomeration, representing a group of cities with a compact spatial organization and close economic links, can rise surface temperature in a continuous area due to decreasing distance between cities. Significant progress has been made in elucidating surface urban heat island intensity (SUHII) of a single city or a few big cities, but the SUHII's patterns remain poorly understood in urban agglomeration regions. Using Aqua/Terra MODIS data over 2010–2015, we examined the SUHII variations and their drivers in Yangtze River Delta Urban Agglomeration (YRDUA) of east China. Instead of using the widely-used suburban/rural areas as references, this study predicted the unaffected reference temperature wall-to-wall from natural forests by a simple planar surface model. Results indicated that urbanization warmed the land surface regardless of urban area size in YRDUA, with the SUHII clearly larger in the day (2.6 ± 0.9 °C) than night (0.7 ± 0.4 °C). The SUHII varied markedly by cities, yet the largest did not happen in the presumed core cities. Also, the SUHII differed greatly in a seasonal cycle, with summer-winter difference of 4.2 ± 0.9 °C and 2.0 ± 0.5 °C in the day and night, respectively. Particularly, cooling effects of urban areas were observed in winter for the majority of cities at night. These spatiotemporal patterns depend strongly on the background climate (precipitation and air temperature), vegetation activity, surface albedo, and population density, with contrast mechanisms during the day and night. Further, we showed that ignoring urban agglomeration effect (using suburban/rural areas as the unaffected references) would lead to large biases of SUHII estimates in terms of magnitude and spatial distribution. Our results emphasize the necessity of considering cities altogether when assessing the urbanization effects on climate in an urban agglomeration area.

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1. Introduction

The urban heat island (UHI) effect, referred to the temperature increases in urban than surrounding areas (Howard, 1833; Oke, 1973), represents one major anthropogenic modification to the Earth system in parallel with increasingly urban growth. UHI can seriously impact water and air quality (Grimm et al., 2008), local climate (Arnfield, 2003; Shepherd, 2005; Yang et al., 2017), vegetation (Zhou et al., 2014a; Zhou et al., 2016c), and energy consumption (Santamouris et al., 2015). It can also affect human health by increasing morbidity and mortality (Patz et al., 2005). These influences are expected to be more severely under a warming climate (Ward et al., 2016; Zhao et al., 2014) and a rapidly urbanizing world (Seto et al., 2012; UN, 2015). Therefore, a thorough understanding of the UHI's patterns and driving forces is critical for formulating effective mitigation and adaptation strategies.

The UHI effect has gained strong interests from scientists and urban planners in recent decades and the studies in general can be grouped into two broad types (Shepherd, 2005; Voogt and Oke, 2003). The first is the air UHI obtained from urban and rural weather stations (Huang and Lu, 2015; Oke, 1973; Peterson, 2003), which cannot provide sufficient detail for urban climate research and planning due to the limited monitoring stations (Anniballe et al., 2014; Jin and Dickinson, 2010; Wang et al., 2017). Comparatively, the second is the surface UHI calculated from remote sensing data, which has emerged as a major tool towards understanding the UHI variability owing to easy access and rich spatial coverage of satellite products (Li et al., 2017; Santamouris, 2015; Wang et al., 2017). The surface UHI intensity (SUHII), normally defined as the land surface temperature (LST) difference in urban relative to suburban or rural areas, therefore has been widely studied at local (Anniballe et al., 2014; Kong et al., 2014; Li et al., 2014, 2018; Peng et al., 2016; Wang et al., 2017; W. Zhou et al., 2017), regional (Du et al., 2016; Imhoff et al., 2010; Li et al., 2017; Santamouris, 2015; Ward et al., 2016; Zhao et al., 2014; Zhou et al., 2016a; Zhou et al., 2016b), and global (Clinton and Gong, 2013; Peng et al., 2012) scales.

Urban agglomeration (also known as city clusters), representing a group of cities having a compact spatial organization and close economic connections (Fang, 2015), has become the most salient feature of global urbanization in recent decade (Wu, 2014). It consists of at least one mega-city at the core of three or more other large cities in a specific geographical area. In contrast to individual cities, urban agglomeration can alter the thermal environment substantially in a continuous area due to decreasing or disappearing distance between cities (Du et al., 2016; Zhou et al., 2016a). However, the SUHII's patterns remained poorly understood in urban agglomerations, since most previous efforts a) focused on a single city or a few big cities, and b) assumed no UHI effect in their surrounding suburban or rural areas (Du et al., 2016; Li et al., 2017). This may not only underestimate the SUHIIs of the core cities (D. Zhou et al., 2015), but also fail to reveal the detailed patterns of SUHIIs in an urban agglomeration region. There is a clear need to better understand the UHI effects in urban agglomerations via new research protocols to help scientists and city planners make more informed decisions about the future of urban environments.

The purpose of this study was to examine the SUHII variations in Yangtze River Delta Urban Agglomeration (YRDUA) of eastern China and to explore their possible driving forces. The YRDUA is one of the most highly populated and developed regions of China and one of the six megalopolitan regions in the world (Xu et al., 2016). There are total 14 cities above the prefecture-level in YRDUA and each has a series of city-administered districts (*Shixiaqu*) and counties (*Shixiaxian*) under their jurisdiction regardless of their population size and economic strengthen. Numerous UHI studies have been conducted in the region, but they mainly focused on the core cities (Shanghai, Nanjing, and Hangzhou) and the city-administered districts (Kong et al., 2014; Li et al., 2011; Li et al., 2014; Li et al., 2012). A recent effort assessed the surface UHI effect in the entire YRDUA (Du et al., 2016), but they defined suburban areas as the unaffected references that would most likely underestimate the SUHII (D. Zhou et al., 2015). These together make the YRDUA ideal for a case study of UHI effect in an urban agglomeration area. The cloud-free Landsat Operational Land Imager (OLI) images together with the latest version 6 of Moderate Resolution Imaging Spectroradiometer (MODIS) LST data were used. Unlike previous studies using loosely defined suburban/rural areas as the unaffected references (Du et al., 2016; Imhoff et al., 2010; Zhou et al., 2014b), this study estimated the reference temperature from natural forest LSTs using a simple planar surface model (Anniballe et al., 2014). The model was proved effective in predicting reference LST in a spatially-explicit manner at a regional level (Zhou et al., 2016a). We also calculated the SUHII in a traditional way in order to investigate the possible bias of SUHII estimates without considering urban agglomeration effect (assuming no UHI effect in suburban or rural areas). Finally, measurements of SUHII were correlated with a range of the background climate and urbanization factors to investigate the causes for their spatiotemporal variations.

2. Materials and methods

2.1. Study area

The boundaries of what constitutes the YRDUA vary by the perspectives of economy, culture and geography. In this study, the YRDUA (29.0–33.5° N, 118.3–122.6° E) refers to the area consisting of one core city (Shanghai), two sub-core cities (Nanjing and Hangzhou), 11 other prefecture-level cities, and 42 city-administered counties (for the convenience, the county was hereafter referred to as the city) in the southeastern part of Jiangsu Province, the northern part of Zhejiang Province, and Shanghai City, with highly diverse urbanization levels (Fig. 1). It is located in east China and has an area of about 1.03 $\times 10^5$ km^2. Most of its area is plain (with the elevation <100 m), except for the southwestern part, which is dominated by hilly lands with the maximum elevation of 1548 m. Under a typical marine monsoon subtropical climate, the mean annual precipitation and temperature in YRDUA range from 804 to 2057 mm and 9.3 to 17.3 °C, respectively. The region lies in a well-established infrastructure network containing both high-speed roads and harbor areas. In addition to the pleasant climate, the YRDUA becomes one of the most developed economic belts in China and maintains a rapid growth rate. Occupying <2.2% of China's land area, the YRDUA contributes almost a quarter of China's gross domestic product (GDP). In 2015, the GDP reached up to 10,877 billion Yuan. At the same time, the region is one of the most densely populated regions on the Earth, home to over 82.3 million people in 2015, of which approximately 53.6 million are urban dwellers. The population and GDP for each city were presented in Table 1. Evidences showed that the rapid urbanization contributed significantly to surface warming in YRDUA (Du et al., 2016; Yang et al., 2011).

2.2. Land use classification

The research team derived a 30-m land use map for year 2015 from the Landsat OLI data. The data are free to public at the U.S. Geological Survey's EROS Data Center (http://eros.usgs.gov/). Since cloud-free images are not available for the entire study area in 2015, eleven scenes of images spanning 2013–2016 were used in this study (Table 2). The Spectral Angle Mapper (SAM) algorithm (Kruse et al., 1993) was used to classify the land uses into five broad types including cropland, built-up land, forest, water, and unused land. The SAM method is based on the calculation of the spectral angle, which performed better than the traditional Maximum Likelihood supervised classification for multi- or hypo-spectral images (Yonezawa, 2007). The cropland refers to the lands used for crop or vegetable planting. Built-up land consists of all the impervious surfaces of cities and counties. Forest contains natural and planted forests. Water body includes reservoirs, ponds, lakes,