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Does quality control matter? Surface urban heat island intensity variations estimated by satellite-derived land surface temperature products

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A B S T R A C T

The temporally regular and spatially comprehensive monitoring of surface urban heat islands (SUHIs) have been extremely difficult, until the advent of satellite-based land surface temperature (LST) products. However, these LST products have relatively higher errors compared to *in situ* measurements. This has resulted in comparatively inaccurate estimations of SUHI indicators and, consequently, may have distorted interpretations of SUHIs. Although reports have shown that LST qualities are important for SUHI interpretations, systematic investigations of the response of SUHI indicators to LST qualities across cities with dissimilar bioclimates are rare. To address this issue, we chose eighty-six major cities across mainland China and analyzed SUHI intensity (SUHII) derived from Moderate Resolution Imaging Spectroradiometer (MODIS) LST data. The LST-based SUHII differences due to inclusion or exclusion of MODIS quality control (QC) flags (i.e., ΔSUHII) were evaluated. Our major findings included, but are not limited to, the following four aspects: (1) SUHIIs can be significantly impacted by MODIS QC flags, and the associated QC-induced ΔSUHIIs generally accounted for 24.3% (29.9%) of the total SUHII value during the day (night); (2) the ΔSUHIIs differed between seasons, with considerable differences between transitional (spring and autumn) and extreme (summer and winter) seasons; (3) significant discrepancies also appeared among cities located in northern and southern regions, with northern cities often possessing higher annual mean ΔSUHIIs. The internal variations of ΔSUHIIs within individual cities also showed high heterogeneity, with ΔSUHII variations that generally exceeded 5.0 K (3.0 K) in northern (southern) cities; (4) ΔSUHIIs were negatively related to SUHIIs and cloud cover percentages (mostly in transitional seasons). No significant relationship was found in the extreme seasons. Our findings highlight the need to be extremely cautious when using LST product-based SUHIIs to interpret SUHIs.
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1. Introduction

More than half of the world's population lives in cities, wherein natural surfaces have been replaced with urban surfaces (WHO, 2010). One consequence of this alteration is the occurrence of urban heat islands (UHIs), a phenomenon where urban areas have higher temperatures than their surrounding rural areas (Oke, 1982; Stewart and Oke, 2012). UHIs can decrease biodiversity (Knapp et al., 2010; Reid, 1998), increase the consumption of energy to cool buildings during the summer (Akbari and Konopacki, 2005), deteriorate water and air quality (Grimm et al., 2008; Sarrat et al., 2006), and result in health problems (Gong et al., 2012; Lafortezza et al., 2009; Taha, 1997).

UHIs have been studied using surface air temperatures obtained from ground-based stations for a long period (Arnfield, 2003). Such ground-based measurements, however, are unable to represent

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highly heterogeneous urban surfaces accurately because of the low density and uneven distribution of weather stations. The development of thermal remote sensing provides periodically and spatially comprehensive coverages of land surface temperatures (LSTs). It has greatly improved our understanding of surface urban heat islands (SUHIs) (Hu et al., 2016; Imhoff et al., 2010; Keramitsoglou et al., 2011; Peng et al., 2012; Rajasekar and Weng, 2009a; Tran et al., 2006; Wang et al., 2017; Ward et al., 2016; Weng and Larson, 2005; Weng, 2009; Wu et al., 2013; Zhou et al., 2014).

To depict the satellite-derived SUHI of a city, scalar indicators are often designed and used to understand the overall features of an SUHI. Such indicators are usually defined by researchers for specific purposes, such as SUHI intensity (SUHII) (Jin, 2012), heat island area (Zhang and Wang, 2008), and magnitude of the UHI (Rajasekar and Weng, 2009b). Among these indicators, the SUHII, often defined as LST differences between urban and rural areas, is the most widely used (Voogt and Oke, 2003). During the delineation of SUHIs, uncertainties appear in the following two aspects as a result of the deficiencies in satellite-derived LSTs.

First, satellite remote sensing cannot pass through clouds, which produces frequent data gaps in the time series of LSTs (Jin and Dickinson, 2010; Li et al., 2013). Some studies simply choose cloud-free images at one or more time points to describe the SUHIIs, while others used temporally aggregated data (Gallo and Owen, 1999; Zhou et al., 2014). Both the selection of time points and temporally aggregated data have been shown to induce uncertainties in the estimated magnitudes and spatial patterns of SUHIIs (Huang et al., 2016; Hu and Brunsell, 2013).

Second, satellite-derived LSTs are far less accurate than temperatures measured at ground-based stations. This is mostly due to the difficulties in determining surface emissivity and atmospheric thermal radiance (Li et al., 2013). To address this issue, satellite-derived LST products, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) LST, have generated quality control (QC) flags to denote retrieval errors using specific labels (Wan, 2008). To obtain climatically representative SUHIIs, some studies disregarded the QC flags and used the averages of all available clear-sky LSTs over a certain period (Zhou et al., 2014). Others additionally performed a temporal aggregation of LSTs by considering the QC flags; they might use only LSTs labeled 'good quality' (corresponding to the quality assurance (QA) flag '00′ from the MODIS LST product) (Bechtel, 2015) or LSTs labeled with an LST error less than 1.0 K (Clinton and Peng, 2013), 2.0 K (Zhao et al., 2014) or 1.0 K for rural pixels and 2.0 K for urban pixels, respectively (Zhao et al, 2017). A temporal aggregation of the weighted LST time series according to associated QC flags has also been used (Zhou et al., 2013). However, these different weighting strategies have recently been clarified to make noteworthy differences to the resultant SUHII values. In other words, the consideration of the QC flags or not is able to introduce biases in SUHIIs for individual cities (Gawuc and Struzewska, 2016). Such biases, therefore, may mislead the interpretation of an SUHI (e.g., whether a heat island or a cool island appears), thereby distorting the comparisons of SUHIIs for different cities.

Though QC-induced SUHII variations have been preliminarily investigated, issues persist in the following two aspects. First, SUHII variations induced by the consideration of QC flags have only been explored in a single city, while the spatiotemporal characteristics of such variations over cities within dissimilar bioclimates remain largely unknown. Second, it is still unclear what the primary factors might be that influence QC-induced SUHII variations. To address these issues, this study aims to investigate spatiotemporal QC-induced variations of SUHIIs for major cities across mainland China. We will further explore the possible factors related to these associated variations. Through elaborating examinations at a relatively large scale, this study will advance the understanding of potential errors from satellite LSTs to assess SUHIIs.

2. Study area

Located in East Asia and covering a vast territory, mainland China spans a considerable variety of climate zones, including tropical, subtropical, temperate, mid-temperate, and cold climate zones, from south to north. Associated air temperatures and precipitation amounts generally decrease across these climate zones (Wu et al., 2005). Significant UHIs have been observed for most cities across mainland China (Li et al., 2004), where a dramatic growth in population and urbanization have been witnessed over the past four decades (Seto et al., 2011; United Nations, 2014). The cities within various climates increase significant regional dependences on their associated SUHI features (e.g., intensity). This makes mainland China an ideal place to investigate the statistical features of SUHIs at the regional and continental scales.

In this study, 86 'big' cities are selected within seven geographical regions. This selection is based on a combination of factors, including the size of the urban area, the urban population, and the administrative significance of the urban area (to make sure that a least one city was chosen per province) (see Fig. 1). Due to the terrain and climate, a considerable portion of the chosen cities are located in the northeastern, northern, eastern, central, and southern regions. Only a small portion of cities are located in the northwestern and southwestern regions. The delineation of urban and rural areas is conducted based on annual land cover product from the Climate Change Initiative (CCI) program of the European Space Agency (ESA) (Bontemps et al., 2012; ESA, 2015). The 2012 map is used with a resolution of 300 m, and urban areas are delineated as the built-up pixels and aggregated with a distance of 2 km following Zhou et al. (2014). The definition of a rural background as a fixed buffer zone outside urban area has been widely accepted in previous SUHI investigations (Bechtel, 2015; Clinton and Peng, 2013; Cheval and Dumitrescu, 2009; Debbage and Shepherd, 2015). The width of the buffer used in this study is set to 15 km, so that (1) the rural buffer is able to cover rural lands instead of suburban lands and meanwhile (2) the computational efficiency is kept acceptable.

To better investigate the internal variations of QC-induced SUHII variations within a city, we selected seven main megacities within the seven geographical regions (Fig. 1). These megacities are characterized by their large urban sizes, populations (ranging from approximately 8.0 and 24.2 million), economic volumes, and representativeness of their associated geographical regions. These megacities are Harbin in northeastern China, Beijing in northern China, Xi'an in northwestern China, Shanghai in eastern China, Wuhan in central China, Chengdu in southwestern China, and the Guangzhou-Shenzhen-Dongguan-Foshan (GSDF) agglomeration in southern China. GSDF denotes a metropolitan agglomeration with no clear urban boundaries between its sub-cities.

3. Data and methods

3.1. Data

This study principally employed 1-km resolution LST products retrieved from the MODIS onboard the Terra and Aqua satellites. The LST products used were the daily L3 products MOD11A1 and MYD11A1 (collection 5) from 2012. They were taken at approximately 10:30 (Terra day), 13:30 (Aqua day), 22:30 (Terra night), and 01:30 (Aqua night) local time each day. The MODIS LSTs were retrieved using the generalized split-window LST algorithm, and the associated retrieval LST errors were mostly lower than 1.0 K (Wan, 2008; Wan and Li, 2008). Nevertheless, the retrieval errors may increase for a number of reasons, such as uncertainties in land

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