Journal of Environmental Management 222 (2018) 86–94

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Interannual variations in surface urban heat island intensity and associated drivers in China

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ARTICLE INFO

Keywords:
Surface urban heat island
Climate variability
Urbanization
Interannual
China

ABSTRACT

The spatial, diurnal and seasonal variations of surface urban heat islands (SUHIs) have been investigated in many places, but we still have limited understanding of the interannual variations of SUHIs and associated drivers. In this study, the interannual variations in SUHI intensity (SUHII, derived from MODIS land surface temperature (LST) data (8-day composites of twice-daily observations), urban LST minus rural) and their relationships with climate variability and urbanization were analyzed in 31 cities in China for the period 2001–2015. Significant increasing trends of SUHII were observed in 71.0%, 58.1%, 25.8% and 54.8% the cities in summer days (SDs), summer nights (SNs), winter days (WDs) and winter nights (WNs), respectively. Pearson's correlation analyses were first performed from a temporal perspective, which were different from a spatial perspective as previous studies. The results showed that the SUHII in SDs and WDs was negatively correlated with the background LST and mean air temperature in most of the cities. The nighttime SUHII in most cities was negatively and positively correlated with total precipitation and total sunshine duration, respectively. Average wind speed has little effect on SUHII. Decreasing vegetation and increased population were the main factors that contributed to the increased SUHII in SDs and SNs, while albedo only influenced the SUHII in WDs. In addition, Pearson's correlation analyses across cities showed that cities with higher decreasing rates of vegetation exhibited higher increasing rates of the SUHII in SDs and WDs. Cities with larger population growth rates do not necessarily have higher increasing rates of SUHII.

1. Introduction

Urbanization is accelerating worldwide, especially in developing countries (United Nations, 2014). Urban heat islands (UHIs) (Zhou et al., 2014), air pollution (Tao et al., 2016) and other problems due to urbanization are becoming increasingly serious and generating increasing attentions globally. Comprehensive analyses of urbanization effects on the environment are needed.

UHI, a major harmful consequence of urbanization, refers to higher temperatures in urban areas than in nonurban areas (Zhou et al., 2014; Giorgio et al., 2017). UHIs have a series of adverse impacts on ecosystems (e.g. net primary production (Imhoff et al., 2004)), human health (e.g. aggravating respiratory disease and even leading to death (Curriero et al., 2002)) and the environment (e.g. air and water pollution (Grimm et al., 2008)). UHIs estimated via remote sensing are called surface UHI (SUHI), which is different from weather station based air UHI in terms of conception, magnitude and application (Voogt and Oke, 2003). SUHI has attracted considerable attentions in recent decades due to the easy access, wide and full coverage of remote sensing (Zhou et al., 2014; Liu and Zhang, 2011). Moderate Resolution Imaging Spectroradiometer (MODIS) Land surface temperature (LST) data have 1 km spatial resolution with (at best) twice daily temporal resolution and wide coverage, and have been used to study the spatial, diurnal and seasonal variations of SUHI throughout world (Han and Xu, 2013; Hung et al., 2006; Zhang et al., 2004; Zhou et al., 2013, 2016b; Imhoff et al., 2010; Clinton and Gong, 2013; Peng et al., 2012; Yao et al., 2017a). In China, the daytime SUHI intensity (SUHII, the LST in urban area minus in rural area) exhibited great spatial and seasonal heterogeneity: a) it differed largely by cities, ranging from −1 K in Lanzhou to more than 7 K in Kunming (Wang et al., 2015b), b) it

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https://doi.org/10.1016/j.jenvman.2018.05.024
Received 8 January 2018; Received in revised form 5 April 2018; Accepted 9 May 2018
0301-4797/

differed greatly in seasons, the highest and lowest SUHII were normally in summer and winter, respectively (Wang et al., 2015b; Zhou et al., 2014, 2016a; 2016b; Yao et al., 2017c). The nighttime SUHII did not change substantially across cities and seasons (Wang et al., 2015b; Zhou et al., 2014, 2016a; 2016b; Yao et al., 2017c). The air UHI intensity also varied spatially and seasonally in China, though it was much lower than SUHII (Wang et al., 1990; Hua et al., 2008).

However, with rapid urbanization, few studies have analyzed the interannual variations of SUHIs at a national scale due to short time series of the MODIS LST data (available from 2000 to present). Zhou et al. (2016a) showed that the SUHII increased in about one-third of the 32 cities in China during 2003–2012; Yao et al. (2017c) showed that the SUHII increased in approximately half of the 31 cities in China during 2001–2015, yet no more information about the SUHII variability is available. Therefore, more studies focusing on the interannual variations in SUHII in China were needed.

The relationships between diurnal, seasonal, spatial variations of SUHIs and the associated factors have been studied thoroughly, and the daytime and nighttime SUHII were strongly linked to vegetation activity (in growing seasons) and albedo (Peng et al., 2012; Xian and Crane, 2006; Wang et al., 2017). Anthropogenic heat release, air temperature, precipitation and wind speed also influence the SUHII, while population density contribute less (Du et al., 2016; Peng et al., 2012). However, the relationships between interannual variations in SUHII and its associated factors may not necessarily be consistent with the relationships between spatial variations in SUHII and related drivers. Previous studies only analyzed the interannual variations in SUHII and its relationships with no more than three factors, for example, Zhou et al. (2016a) showed that the interannual variations in SUHII were generally invariant with mean air temperature and precipitation; Yao et al. (2017a) showed that decreased vegetation was an important for the increasing SUHII in China's Yangtze River Basin; Yao et al. (2017c) showed that increasing anthropogenic heat release and decreased vegetation were the main factors for the increasing SUHII in China, and the daytime SUHII was negatively correlated with background LST. Thus, ignoring other factors (e.g. sunshine duration, wind speed, albedo and population) may miss important drivers. Much more detailed analysis should be conducted for clear understanding.

Therefore, the present study aims at filling the existing research gaps and improving our understanding of the relationships between interannual variations in SUHII and related drivers. We performed systematic analyses of a) the interannual variations of SUHII, b) its relationships with climate factors (mean air temperature, background LST, total precipitation, total sunshine duration and average wind speed (see section 2)), c) its relationships with urbanization related factors (albedo, decreasing vegetation and increasing population) for the period 2001–2015 in this study. China was chosen as the study area because of its rapid urbanization in recent decades, large area of approximately 9.6 million km^2 and large variations in climate and altitude (Kuang et al., 2016).

2. Data and methods

2.1. Study area

In this study, the SUHI was studied in 31 municipalities (directly governed by the central government) or provincial capitals (Administrative center of a province) (Fig. 1). The 31 cities were divided into 15 southern cities, 15 northern cities and a plateau city (Lhasa). The Qinling Mountain-Huaihe River Line (at about 33°N) was used as dividing line in the present study for two main reasons: a) it is a traditional North-South dividing line in China, and b) the north of this line is different from the south of this line in terms of climate, tree species, agricultural production and people's living customs (Bi et al., 2007; Shi et al., 2013a, 2013b; Wang et al., 2015b; Yao et al., 2017c). Southern China was mainly characterized by humid climate, which was different from the semi-humid, semi-arid and arid climate in Northern China.

2.2. Data

Urban and nonurban areas were extracted from China's Land Use/Cover Datasets (CLUDs, 30 m spatial resolution, 25 land cover types, in the year 2000, 2005, 2010 and 2015), which were generated from Landsat TM/ETM+ and HJ-1A/1B imagery. The dataset is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The overall accuracy was over 90% for the 25 land cover types according to previous studies (Kuang et al., 2016; Liu et al., 2010, 2014). More information can be found in Kuang et al. (2016), Liu et al. (2014) and Liu et al. (2010).

LST was derived from the MODIS LST data (MOD11A2, version 6, Terra satellite, monitored at 10:30 a.m. and 10:30 p.m., 8-day composite, 1 km spatial resolution, 2001–2015), the accuracy of the LST data was better than 1 K in 39 of 47 cases according to a previous study (Wan, 2008). We used the MOD11A2 product rather than MYD11A2 product since it has longer time series (MOD11A2: February 2000 to present, MYD11A2: July 2002 to present) (He et al., 2017; Yao et al., 2017c, 2018a; 2018b). Vegetation and albedo information was extracted from MODIS enhanced vegetation index (EVI) data (MOD13A2, version 6, Terra satellite, 16-day composite, 1 km spatial resolution, 2001–2015) and MODIS albedo data (MCD43B3, version 5, combined Terra and Aqua satellites, 8-day composite, 1 km spatial resolution, shortwave white sky albedo (WSA), 2001–2015), respectively (Huete et al., 2002; Liang et al., 2002; Peng et al., 2012; Zhou et al., 2014).

Daily climate data from the China Meteorological Administration for the period 2001–2015 was used in this study, including mean air temperature (24-hour mean), total precipitation (24-hour in total), total sunshine duration (24-hour in total) and wind speed (24-hour mean). Weather stations in and around the city were chosen to represent the climate of the city (Fig. 1) (Du et al., 2016; Zhou et al., 2014, 2016a; 2016b). Detailed information about weather stations can be found in Table S1. In addition, non-agriculture population was derived from the statistical yearbook in each city (only available for 23 of the 31 cities). In China, the non-agricultural population refers to the working population engaged in non-agricultural production and the dependent population of their families.

2.3. Extracting urban and rural areas

Twenty-five land cover types of CLUDs were first combined into four major types (urban areas, rural settlements, water bodies and other types) since we only need to distinguish these 4 major land cover types in this study. Next, we generated two types of land cover maps: a) resampled maps, in which CLUDs were resampled to 1 km spatial resolution (matching the MODIS data), and b) proportion maps, where we calculated the proportions of each of the 4 land cover types for each 1 km spatial resolution pixel. Urban areas were then classified into two stationary areas: city center (CC, pixels composed of 100% urban area) and the whole urban area (WUA, total urban area of the four resampled maps) (Fig. 2). In addition, we generated a 20–25 km buffer based on the WUA (Yao et al., 2017b, 2017c; Zhou et al., 2016c), excluding the pixels with a) proportions of urban area plus rural settlements higher than 5% (Imhoff et al., 2010; Zhou et al., 2016a) and b) proportions of water bodies higher than 0%. The resultant areas were then defined as rural areas in this study. The rural areas were set far from the urban areas (20–25 km buffer) because previous studies showed that the extent of SUHIs is much larger than the size of the urban area (Han and Xu, 2013; Zhang et al., 2004; Zhou et al., 2015). In this study, we did not exclude the altitude effects, the reasons can be found in supplementary material 1 (Yao et al., 2018a).