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Long-term and fine-scale satellite monitoring of the urban heat island effect by the fusion of multi-temporal and multi-sensor remote sensed data: A 26-year case study of the city of Wuhan in China

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ABSTRACT

The trade-off between the temporal and spatial resolutions, and/or the influence of cloud cover, makes it difficult to obtain continuous fine-scale satellite data for surface urban heat island (SUHI) analysis. To relieve these difficulties, this study employs multi-temporal and multi-sensor fusion methods for a long-term and fine-scale summer SUHI analysis of the city of Wuhan in China. By integrating several series of satellite images, we generated 26-year (1988 to 2013) high spatial resolution (Landsat-like) summer land surface temperature (LST) data. This series of data was then used for a qualitative and quantitative analysis of the SUHI patterns, evolution characteristics, and mechanisms. This study not only provides a generalized research framework for the long-term and fine-scale analysis of the SUHI effect, but also reveals several findings about the heat distribution and SUHI characteristics in Wuhan. Firstly, our results show that the high temperature and sub-high temperature areas were continuously concentrated from rural to urban areas, but the high temperature area within the old city zones showed an obvious decreasing tendency. Secondly, a more important finding is that the SUHI intensity first increased and then decreased over the 26 years. The maximum temperature difference between the city zone and the rural area was in 2003 (7.19 K for the old city zone, and 4.65 K for the area within the third ring road). Finally, we confirm that the relationships between heat distribution and land cover (especially vegetation and impervious surfaces) were interannually stable, and that the influences of industry, businesses, and residential districts on the SUHI effect were in descending order in Wuhan.

1. Introduction

More than 50% of the human population lives in cities, and this proportion is projected to increase to 60% by 2030 (DESA, 2002; Zhou, Huang, & Cadenasso, 2011). Rapid urbanization results in increasing replacement of natural landscapes by impervious surfaces, which can alter the surface radiation, thermal properties, and humidity over urban areas (Wang et al., 2007). One of the environmental consequences of urbanization is the urban heat island (UHI) effect. This describes the phenomenon of higher temperatures occurring in urban areas than in the surrounding suburban/rural areas (Oke, 1982). The UHI effect can alter biodiversity (Knapp, Kühn, Stolle, & Klotz, 2010), climate (Dixon & Mote, 2003; Kalnay & Cai, 2003; Mackey, Lee, & Smith, 2012), and even air conditions (Grimm et al., 2008; Lo & Quattrochi, 2003); therefore, it can have a great influence on the quality of life and human well-being in urban areas (Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Lafortezza, Carrus, Sanesi, & Davies, 2009; Steeneveld, Koopmans, Heusinkveld, Van Hove, & Holtslag, 2011).

The UHI effect can be evaluated by both air temperature measurements and satellite LST measurements. The measurement of air temperature is performed either on a traverse through a city or by comparing temperatures from point measurements (Schwarz, Lautenbach, & Seppelt, 2011). In general, air temperature UHI measurements have a high temporal resolution with extensive time coverage, and can effectively describe the temporal variation of the UHI effect (Li, Zhou, & Ouyang, 2013). However, because of the sparse distribution of observation stations, a spatially continuous analysis is often difficult. To solve these problems, many studies of the UHI effect have been based on land surface temperature (LST) measurements from remote sensors. The remotely sensed UHI has been termed the surface urban heat island (SUHI) effect (Streutker, 2002; Voogt & Oke, 2003). One important advantage of using remotely sensed data is the wall-to-wall continuous coverage of the urban area (Li et al., 2011). Therefore, LST derived from thermal infrared remote sensors has become one of the most commonly used indicators for heat island analysis.

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Numerous studies of the SUHI effect have been carried out using large-scale satellite LST data sets, such as the AVHRR data of the NOAA satellites (Dousset & Gourmelon, 2003; Streutker, 2002, 2003) and the MODIS data of the Terra/Aqua satellites (Imhoff, Zhang, Wolfe, & Bounoua, 2010; Rajasekar & Weng, 2009b). Using MODIS data, a comparative SUHI analysis can also be implemented between daytime and nighttime (Cui & De Foy, 2012; Quan et al., 2014). However, these data are only suitable for coarse-scale urban temperature mapping with about a 1-km spatial resolution, and it has been proved that a spatial resolution of about 50 m is needed to properly estimate the SUHI effect at a district level (Sobrino, Oltra-Carrió, Sòria, Bianchi, & Paganini, 2012). Fortunately, a number of satellite systems can retrieve thermal infrared LST information with a relatively fine spatial resolution. For example, the spatial resolution of the TM/ETM+/TIRS sensors onboard the Landsat-5–8 satellites is 60 m to 120 m. Spatially fine analyses have been achieved by the use of this type of data, such as the spatio-temporal evolution of the SUHI effect (Cai, Du, & Xue, 2011; Li, Wang, Wang, Ma, & Zhang, 2009; Li, Zhang, & Kainz, 2012), as well as its relationship with vegetation (Chen, Zhao, Li, & Yin, 2006; Weng, Lu, & Schubring, 2004), impervious surfaces (Li et al., 2011; Yuan & Bauer, 2007), and other factors (Mackey et al., 2012; Zhang & Wang, 2008). Some researchers have also studied how urbanization and land use and land cover (LULC) affect the SUHI effect (Aniello, Morgan, Busbey, & Newland, 1995; Rajasekar & Weng, 2009a; Weng, 2003). In recent years, the Landsat series of satellites has been the foremost data source for fine-scale SUHI analysis, although the Landsat satellites do not acquire nighttime images.

Accurate time series data are very important for the monitoring of SUHI growth (Streutker, 2003). Long-term remotely sensed data can help us to more intuitively understand the evolution mechanism of the SUHI effect and its relationship with LULC and/or climate change (Li et al., 2012), and can therefore help decision-makers develop and execute rational land-use policies (Zhang et al., 2013). However, due to the limited spatial coverage, poor temporal resolution, and the influence of cloud cover, it is often difficult to obtain a long-term data sequence at a finer scale. For instance, although the Landsat satellites have a revisit cycle of 16 days, the effects of clouds, as well as stripe gaps (Landsat-7), can lead to there being no available data over a period of several months. It is also well known that the difference in the SUHI patterns of different seasons can be quite obvious (Li et al., 2012). Therefore, an LST data sequence for long-term SUHI analysis should be obtained in the same season, which further increases the difficulties of image acquisition. This contradiction between supply and demand for satellite data is a very common problem in SUHI research. As a result, most of the existing studies of long-term SUHI patterns have had to use only a few representative remotely sensed images (Li et al., 2012; Zhang et al., 2013). The use of discontinuous data can result in great uncertainty when drawing conclusions. How to realize a temporally continuous fine-scale view of the SUHI effect is therefore an open and significant issue.

The main objectives of this paper are: 1) to solve the spatio-temporal discontinuity of remotely sensed LST for a summer SUHI analysis; and 2) to provide a long-term (26-year) and fine-scale (Landsat-like) case study of the city of Wuhan in China. Multi-temporal and multi-sensor fusion methods were employed to obtain spatially continuous summer LST data from 1988 to 2013 by integrating the observations of NOAA-AVHRR, Terra-MODIS, Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI/TIRS. Based on the long-term and fine-scale data, a SUHI evolution analysis of Wuhan was carried out, and a number of important findings were revealed.

2. Methods

2.1. Study area

The Wuhan metropolis was chosen as the study area in this research. Wuhan is located between 113°41′–115°05′ E and 29°58′–31°22′ N, having a total area of 8494.41 km^2 and a population of about 10.02 million. Since China's "Open and Reform Policy" started at the end of the 1970s, Wuhan has experienced rapid urbanization over the last three decades. As the capital of Hubei province, it has been recognized as the economic, educational, and transportation center of central China (as shown in Fig. 1 (a) and (b)). The confluence of the middle reaches of the Yangtze River and Han River divides the metropolitan area into three parts, namely Wuchang, Hankou, and Hanyang (as shown in Fig. 1 (c)). In order to avoid image mosaicing and the associated problems, a single standard scene of Landsat data covering about 80% of Wuhan was used in this research. From Fig. 1 (c), it can be seen that the Wuhan metropolis is located at the center of this study area. The study area can therefore be considered as being representative of the whole of the city of Wuhan.

Wuhan has a subtropical monsoon climate, with the mean annual temperature ranging from 288.95 K to 290.65 K. It is noteworthy that Wuhan is regarded as one of the hottest "stove cities" in China (Han, Li, & Zheng, 2009; Qian et al., 2007; Su, Gu, & Yang, 2010), especially in summer, and the temperature at night is the highest of all the large cities in China. Research into the summer SUHI mechanism is therefore of special significance. In this study, we obtained daily highest air temperatures from 2001 to 2010 from meteorological data, and then calculated the 10-year average highest temperatures of each day (see Fig. 2). After analyzing these data, and considering the data availability, we considered the 100 hottest days to be the "ideal date range", which was from the middle of June to the middle of September (between the thick lines in Fig. 2). All the observed or fused LST data used for the SUHI analysis were from this ideal range, with the exception of three LSTs which were observed close to this range in September, as illustrated in Fig. 2 by the thin lines. It should be noted that although these three exceptions were out of the ideal summer period, the air temperatures were still quite high (301.35 K, 303.95 K, and 308.85 K); therefore, they had little effect on the subsequent analysis.

2.2. The satellite data

We first collected the available Landsat-5, Landsat-7, and Landsat-8 images, which were acquired in the date range of Fig. 2 in the years from 1988 to 2013. Due to the effects of clouds and gaps, the Landsat images were only available for a total of 10 years. To make up for the data deficiency and to obtain continuous 26-year data, some Landsat (out of the date range), MODIS, and AVHRR data (within the date range and/or out of the date range) were collected for the multi-temporal and multi-sensor fusion. By the data fusion, continuous fine-scale LSTs within the ideal data range could be obtained. In summary, the data used in this study are listed in Table 1.

For MODIS, the MOD11A1 LST product was directly used. For the other sensor data, the LSTs were retrieved using the existing standard algorithms described in the next section. The thermal infrared bands of Landsat-5 TM, Landsat-7 ETM+, Landsat-8 TIRS, MODIS, and AVHRR have spatial resolutions of 120 m, 60 m, 100 m, 1 km, and 1.1 km, respectively. Since the downloaded Landsat data had been resampled to a 30-m resolution, the analysis was performed at this scale. In addition to the thermal infrared bands and the LST products, the reflective bands were also needed to compute the normalized difference vegetation index (NDVI), the impervious surface fraction (ISF), and the vegetation fraction (VF) for the correlation analysis. All the satellite data were rectified to the Universal Transverse Mercator (UTM) projection system (Spheroid WGS84, Datum WGS84, and Zone 49).

2.3. LST retrieval methods

2.3.1. LST retrieval from Landsat images

There have been several algorithms developed for the retrieval of LST from Landsat images, including the mono-window algorithm (Qin, Karnieli, & Berliner, 2001), the single-channel algorithm (Jiménez-