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Spatiotemporal trends of urban heat island effect along the urban development intensity gradient in China

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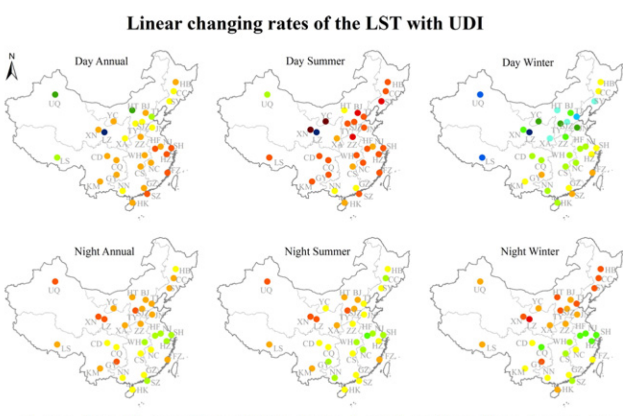
HIGHLIGHTS

- Spatiotemporal trends of the UHI effect (ΔT) were analyzed in China.
- ΔT varied greatly across cities, UDI zones, and time periods.
- ΔT–UDI patterns were mostly in linear form except few convex or concave ones.
- ΔT increased or remained stable from 2003 to 2012 for most cities.
- Caution should be paid to the methods to quantify UHI intensity over large areas.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban heat island (UHI) represents a major anthropogenic modification to the Earth system and its relationship with urban development is poorly understood at a regional scale. Using Aqua MODIS data and Landsat TM/ETM + images, we examined the spatiotemporal trends of the UHI effect (ΔT, relative to the rural reference) along the urban development intensity (UDI) gradient in 32 major Chinese cities from 2003 to 2012. We found that the daytime and nighttime ΔT increased significantly ($p < 0.05$, mostly in linear form) along a rising UDI for 27 and 30 out of 32 cities, respectively. More rapid increases were observed in the southeastern and northwestern parts of China in the day and night, respectively. Moreover, the ΔT trends differed greatly by season and during daytime in particular. The ΔT increased more rapidly in summer than in winter during the day and the reverse occurred at night for most cities. Inter-annually, the ΔT increased significantly in about one-third of the cities during both the day and night times from 2003 to 2012, especially in suburban areas ($0.25 < \text{UDI} \leq 0.5$), with insignificant trends being observed for most of the remaining cities. We also found that the ΔT patterns along the UDI gradient were largely controlled by local climate-vegetation conditions, while that across years were dominated by human activities. Our results highlight the strong and highly diverse urbanization effects on local climate cross China and offer limitations on how these certain methods should be used to quantify UHI intensity over large areas. Furthermore, the impacts of urbanization on climate are complex, thus future research efforts should focus more toward direct observation and physical-based modeling to make credible predictions of the effects.

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1. Introduction

Urbanization is accelerating in the world. More than half of world's population live in urban areas now, and this number is projected to be 66% by 2050 (United Nations, 2014). At the same time, the amount of global urban land is expanding at twice the population growth rate (Angel et al., 2011) and is expected to nearly triple by 2030 if current trends in population density continues (Seto et al., 2012). Urban heat island (UHI) phenomenon, referred as the temperature rise in urban relative to surrounding areas (Oke, 1973; Arnfield, 2003), is one of the most important urbanization-induced impacts. It cannot only alters environmental conditions such as net primary production (Imhoff et al., 2004; Zhou et al., 2014a), biodiversity (Reid, 1998), water and air quality (Grimm et al., 2008), and climate (Arnfield, 2003; Dixon and Mote, 2003; IPCC, 2014; Jin et al., 2005; Shepherd, 2005) but also can affect human health and comfort (Gong et al., 2012; Patz et al., 2005). These effects are expected to be more serious when interacting with global climate changes (IPCC, 2014; Patz et al., 2005). Thus a better understanding of the UHI effects is important to support future climate change mitigation and human adaptive strategies (Arnfield, 2003; Imhoff et al., 2010; Zhou et al., 2014b).

The UHI effect could undergo changes during urban development mainly in two opposite ways. On one hand, an increase in the proportion of impervious surface (built-up land) reduces the vegetated areas and can elevate the UHI effect due to the resultant decrease in latent heat flux and the increase in heat storage (Arnfield, 2003). On the other hand, several approaches or conditions have been reported to able to mitigate or alleviate the UHI effect. For example, the management of urban green spaces (e.g., fertilization, irrigation, and green space creation) has been shown to largely offset the negative effects associated with land cover change from rural to urban conditions (Gregg et al., 2003; Searle et al., 2012). In addition, a reduction in incoming solar radiation has been reported due to heavy smoke over urban areas (Oke, 1982; Sang et al., 2000).

However, a systematic evaluation on the spatiotemporal trends of the UHI effects along an urban development intensity (UDI) gradient across multiple cities is still lacking. Relatively limited studies focused on the spatial trends or site-specific observations. For example, Yuan and Bauer (2007) found a strong linear relationship between land surface temperature (LST) and percent impervious surface (can be considered as a surrogate for UDI) in the Twin Cities of Minnesota. Imhoff et al. (2010) examined the general relationship between UHI and UDI for 38 most populous cities in the continental United States, but paid little attention to the spatiotemporal variability of the correlations. Since the UHI intensity (Clinton and Gong, 2013; Peng et al., 2012; Zhou et al., 2014b) and the vegetation dynamics (one major driver for the UHI effect) (Zhou et al., 2014a) varied substantially across space and time, there is a strong impetus to systematically understand the UHI spatiotemporal patterns in parallel with rapid urbanization.

In this study, we analyzed the UHI effects from 2003 to 2012 for 32 major cities across various climatic regions of China using Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature (LST) products in conjunction with Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM +) images. Unlike our previous efforts that focused on UHI intensity (urban–suburban LST differences) (Zhou et al., 2014b) and the footprint of the UHI effects (Zhou et al., 2015), the purposes of this study were to (1) investigate the relationship between UHI and UDI and (2) examine the temporal trends of the UHI effect in parallel with rapid urbanization of those cities. China is ideal to investigate the climatic effects induced by urbanization at a regional scale, since it has being experienced the fastest urbanization in the world in the past three decades (United Nations, 2014; Seto et al., 2012) and has a climate ranging from tropical to subarctic/alpine and from rain forest to desert. Analyzing UHI effects in China can not only help enhance understanding the physical characteristics and driving forces of UHI in general, but can also be essential for formulating climate mitigation strategies and long-term ecosystem management plans in the country.

2. Materials and methods

2.1. Remotely sensed land surface temperature (LST) and urban development intensity (UDI)

All 32 cities are municipalities or provincial capitals except Shenzhen, which is China's first special economic zone and was established in 1978. It is now considered as one of the fastest growing cities in the world (Fig. 1). Most cities are mainly surrounded by cultivated land and the rest by forests (e.g., Hangzhou and Fuzhou) or grassland (Lhasa). The maximal research areas of these cities were defined by China's official administrative areas (i.e., city, *shi*) (Chan, 2010). Water body pixels within the administrative boundaries or those with an elevation more than 50 m above the highest point in urban and urban core zones (see definition below) were excluded from this analysis (Figs. 1 and 2) because these pixels may overshadow the urbanization effects on temperature (Imhoff et al., 2010; Zhou et al., 2015).

LST was obtained from Aqua MODIS 8-days composite products (version 5) with a spatial resolution of 1 km (MYD11A2) from 2003 to 2012. The LST data, including temperature observations that were monitored at 13:30 h (daytime) and 1:30 h (nighttime) local solar time, were estimated using a generalized split-window algorithm (Wan and Dozier, 1996). The retrieval of LST was further improved by correcting noise resulting from cloud contamination, topographic differences, and zenith angle changes, with the absolute bias generally less than 1 K and less than 0.5 K in most cases (Wan, 2008).

Land cover maps of each city were derived from the cloud-free Landsat TM images (downloaded free from http://www.usgs.gov/) with a spatial resolution of 30 m. The gap-filled Landsat ETM + Scan Line Corrector (SLC)-off products (obtained free from http://www.gscloud.cn/) were used instead for few cases provided without the TM data. The scan gaps were filled using a local linear histogram matching technique (Storey et al., 2005). Around 170 scenes of images were used to extract the extent of urban land for all the cities in this study (Table S1). The acquisition time of these images spanned 2004–2006 and 2009–2011 and represented two time periods of circa 2005 and 2010, respectively. The land covers were classified into four broad types (i.e., built-up land, water body, cultivated land, and other land) using the maximum likelihood classification approach (Strahler, 1980). The accuracies of the classified products were assessed by using the high-resolution images and pictures incorporated in Google Earth Pro®. The accuracies, measured by Kappa coefficients (Foody, 2002), were generally larger than 0.80 for all those cities. Details on land use classification can be found in Zhao et al. (2015).

UDI was defined as the proportion of built-up areas in each MODIS LST pixel in this analysis. It was mapped using 33 × 33 moving window based on the 30 m urban land cover maps for the year 2005 and 2010 for each city individually. The resultant UDI map has a spatial resolution of 990 m and was resampled to 1 km in order to keep accordance with the size of LST data. We further stratified the landscape into five zones based on the UDI. Emanating inward from the lowest to the highest UDI in a city (Fig. 2), these five zones were rural ($UDI \leq 0.05$) and four urban zones [exurban ($0.05 < UDI \leq 0.25$), suburban ($0.25 < UDI \leq 0.5$), urban ($0.5 < UDI \leq 0.75$), and urban core ($0.75 < UDI \leq 1$)]. The rural area was usually covered by both cultivated and natural vegetation, while the exurban and suburban areas were mainly covered by cultivated vegetation besides built-up land (Fig. 1).

2.2. Trends of UHI effect along the UDI gradients

The mean LST in the five UDI zones were calculated over the period 2003–2012. For the years without UDI maps, we assumed that the UDI maps in 2005 and 2010 can be applied to 2003–2007 and 2008–2012,