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

Linear changing rates of the LST with UDI

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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<UDI≤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).

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 been experiencing 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.gsccloud.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 < 0.05) and four urban zones [exurban (0.05 < UDI ≤ 0.25), suburban (0.25 < UDI ≤ 0.5), urban (0.5 < UDI ≤ 0.75), and urban core (0.75 < UDI ≤ 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,
respectively. The dynamic urban coverage maps were used to delineate rural and urban areas for each city in order to reflect the actual UHI trends along the UDI gradient impacted by rapid urban expansion. For example, the urban areas for the 32 cities increased by 44% on average between 2005 and 2010 (data not shown). We hypothesized that there was no UHI effect in rural areas that can be considered as the reference. The UHI effect was then estimated as the temperature differences relative to rural areas ($\Delta T$). The annual and seasonal (summer and winter) $\Delta T$ in the day (13:30) and night (1:30) were calculated over the period 2003–2012 for each city individually. Summer and winter were defined as the periods from June to August, and from December to February, respectively. Linear regression analysis was performed to examine the increasing rate of the $\Delta T$ with a rising UDI for each city.

To investigate the spatial variability of the $\Delta T$ trends across cities in China, we estimated the linear rates of the $\Delta T$ along the UDI gradients in all six sub-regions of China. Significance tests ($p = 0.05$) were conducted to determine if there were differences across regions.

We explored the climatic effects on the spatial variability of the $\Delta T$ increasing rates across cities. Annual climate data of precipitation and temperature from 2003 to 2012 for each city were obtained from China Meteorological Observation (downloaded free from http://cdc.cma.gov.cn/). The impacts of background vegetation conditions, reflected by rural enhanced vegetation index (EVI), were also assessed with the hypothesis that the city with a larger EVI should have a greater $\Delta T$ increasing rate (Peng et al., 2012; Zhou et al., 2014b). The version-5 Terra MODIS EVI (MOD13A2) between 2003 and 2012 was used in this study.
analysis (1 km spatial resolution and 16-day interval). Noises caused by cloud contamination, atmospheric variability, and bi-directional effects were further removed using an adaptive Savitzky–Golay filtering method (Chen et al., 2004; Jönsson and Eklundh, 2004; Zhou et al., 2014a). The Pearson’s correlation analyses were performed in SPSS PASW Statistics 18 (SPSS Inc.).

2.3. Temporal trends of UHI effect in different urban zones

In order to examine the UHI trends over time induced by rapid urbanization, the annual mean \( \Delta T \) rates were estimated for the period 2003–2012 using the static UDI zones of the year 2005. The UHI effect in an urban zone was assumed constant if an insignificant \( \Delta T \) trend over time was observed. Linear regression models were used to test for temporal patterns of the \( \Delta T \) for each city separately. We also evaluated the temporal trends of rural LST using linear regression to examine the possible temperature changes induced by climate variability and human activities (e.g., tree planting or deforestation, and cropland management). The Pearson’s correlation coefficients between climatic factors (annual mean temperature and annual precipitation) and \( \Delta T \) in urban zones were calculated for each city in order to investigate the responses of the \( \Delta T \) to climate variability.

3. Results

3.1. Spatial trends of UHI effects with rising UDI

The area-weighted annual mean UHI effect (\( \Delta T \)) averaged from 2003 to 2012 increased significantly \((p < 0.05)\) with rising UDI for 27 out of 32 cities during the daytime (Figs. 3 and 4). The \( \Delta T \)–UDI trends in five arid/semi-arid cities (Urumqi, Lhasa, Lanzhou, Hohhot, and Taiyuan) were not statistically significant (Fig. 4A). In particular, an evident decay trend happened in Lanzhou, while a slight decrease after an increase occurred in Taiyuan (Fig. 3). The significant \( \Delta T \) increasing rates (reflected by the linear regression slope between \( \Delta T \) and UDI) varied greatly with geographic locations from 1.7 in Tianjin to 5.1 in Fuzhou (Fig. 4A). Overall, the cities located in the southeastern parts of China (East, Central-south, and Southwest China) experienced more rapid increase compared to northwestern counterparts (Northwest, North, and Northeast China) (Figs. 4A and 5A). Comparatively, the annual mean nighttime \( \Delta T \) increased significantly \((p < 0.05)\) with UDI for 30 out of 32 cities except two humid hot cities (Nanjing and Hefei) (Figs. 4D and 5D). Cold island effects (i.e., negative \( \Delta T \)) were observed in exurban and suburban areas relative to rural reference for Nanjing and Hefei (Fig. 6). The significant \( \Delta T \) increasing rates varied substantially from 1.1 °C (per 100% UDI, hereafter) in Shanghai to 5.4 °C in Lanzhou, with the largest in Northwest China (4.3 ± 1.0 °C, mean ± standard deviation) and the least in East China (2.0 ± 0.7 °C) (Figs. 4D and 5D). For all cities combined, the annual mean rate was 2.9 ± 0.8 °C in the day and 3.1 ± 0.5 °C at night (Fig. 5A and D).

The \( \Delta T \)–UDI trends differed greatly by season. The daytime \( \Delta T \) increased more rapidly in summer than in winter for nearly all the cities (Figs. 3, 4B, and C). All cities except for Lanzhou (insignificant decrease) and Hohhot (insignificant increase with cold island effect in exurban and suburban areas) exhibited evident increases in summer, whereas about half of the cities had insignificant trends (mostly decrease) in winter. On average, the increasing rate reached up to 4.7 ± 0.7 °C in summer, over four times that in winter (1.1 ± 0.6 °C). The northern parts of China witnessed more obvious seasonal changes compared to southeastern neighbors (Fig. 5B and C). Interestingly, the \( \Delta T \) declined after an increase with a rising UDI in Urumqi in summer, whereas the opposite happened in winter. The \( \Delta T \) increased linearly from exurban to urban core in summer, and the reverse occurred in winter for Hohhot. By contrast, the nighttime \( \Delta T \)–UDI trends differed slightly by season, characterized by the average rates of 2.7 ± 0.6 °C and 3.1 ± 0.7 °C across cities in summer and winter, respectively. Cities in Northeast and North China presented more evident trends in winter than summer, while that in other regions varied slightly by season.

Notably, a clear concave or convex increase was observed in few cities. Specifically, the concave increases occurred in Changchun, Jinan, Shenyang, Shijiazhuang, and Tianjin in the day during summer, and in Changchun, Harbin, Jinan, Shenyang, Shijiazhuang, and Xi’an at night in both summers and winters. By contrast, the convex increases were found in Kunming and Shenzhen in the day, and in Lanzhou and Lhasa at night in both seasons.

The daytime \( \Delta T \) increasing rates were positively and significantly \((p < 0.01)\) related to mean annual temperature and precipitation in winters, but were negatively (statistically insignificant) linked to both

![Fig. 3. Trends of daytime urban heat island effect (\( \Delta T \), defined as the LST differences relative to rural areas) with UDI for China’s 32 major cities averaged over 2003–2012. Summer and winter were defined as the periods from June to August, and from December to February, respectively.](image-url)
variables in summers (Table 1). In contrast, the nighttime ΔT increasing rates were negatively \((p < 0.01)\) related to mean annual temperature and precipitation in both summer and winter seasons. Moreover, the background vegetation condition, as reflected by rural EVI, was positively and negatively related to daytime and nighttime ΔTi increasing rates in both seasons \((p < 0.05)\), respectively.

### 3.2. Temporal trends of UHI effects in different urban zones

The temporal trends of the ΔT differed greatly across urban zones and cities from 2003 to 2012 (Table 2). Relative to the rural base condition, the annual mean daytime ΔT increased significantly \((p < 0.05)\) over 8, 12, 5, and 2 out of 32 cities in exurban, suburban, urban, and urban core areas, respectively. Comparatively, the ΔT elevated significantly over 6, 12, 10, and 8 cities in exurban, suburban, urban, and urban core areas at night, respectively. Concurrently, evident decline trends were observed in three cities of urban (Hohhot, Lhasa, and Shanghai) and urban core zones (Hohhot, Shanghai, and Xining), and one city of exurban (Changchun) and suburban (Hohhot) areas during the day. By contrast, only the exurban of Yinchuan showed apparent \((p < 0.05)\) decay trends during the night. Interestingly, the reference rural LST reduced significantly in about 10 out of 32 cities during both the day and night time periods.

The inter-annual variations of rural LST were positively related to annual mean air temperature for majority of cities in both the day (significant for 19 of 32) and night (significant for 18 of 32) (Table S2). At the same time, the rural LST was negatively linked with annual precipitation for most cities, whereas significantly for only eight and one city during the day and night, respectively. Comparatively, both the positive and negative relations were observed between the inter-annual variations of the ΔT in urban zones (exurban, suburban, urban, and urban core) and annual mean air temperature or precipitation, although the correlations were significant for few cities only (Table S2). For example, the ΔT related positively and significantly \((p < 0.05)\) to annual precipitation in some urban zones of five cities (e.g., Beijing, Shijiazhuang, Hangzhou, Lanzhou, and Lhasa) during the day, and two cities (Beijing and Hefei) at night. Concurrently, the significant negative correlations were observed in three cities (Changchun, Urumqi, and Shenzhen) during the day, and five cities (Xi’an, Fuzhou, Nanchang, Guangzhou, and Lhasa) at night. Similar
phenomenon happened for the relationships with annual mean air temperature (Table S2).

4. Discussion

4.1. Spatial relationship between UHI and UDI in China and their drivers

Our results showed that the UHI effect (i.e., ΔΤ) increased significantly with rising UDI for most of the cities in the day and night (Figs. 3–6), which is consistent with findings in the United States (Imhoff et al., 2010) and other synthesis reports (Arnfield, 2003). The ΔΤ increasing rate was apparently weaker (even insignificant for few cities) in arid–cold regions (i.e., the northern parts of China) during the day, mostly owing to the low vegetation activity in these dry areas compared to the other regions. For example, the background vegetation conditions (as reflected by rural EVI) in Central-south China was over 1.7 times that in Northwest China (0.36 vs. 0.21). This phenomenon can be further verified by the strong positive correlation between ΔΤ increasing rates and rural EVI across cities in the daytime (Table 1).

In contrast, low ΔΤ increasing rates were found in humid–hot cities at night, which can be explained by their high soil moisture and the low surface albedo in these dry areas. For example, the stronger evaporative cooling effects produced by vegetated surface in summer than in winter (Imhoff et al., 2010; Jin, 2012; Zhou et al., 2014b) in the northern parts of China witnessed larger seasonal changes, which can be attributed to the greater seasonal change of the vegetation activity in the regions (caused by intensive agricultural practices in summer and defoliation in winter) (Piao et al., 2003). Conversely, the ΔΤ trend was much weaker in summer than in winter for the cities in North and Northeast China during the night (Figs. 4–6). Three factors might contribute to this phenomenon. First, the albedo differences between urban and rural areas were more pronounced during winter than summer because of defoliation and/or snow and ice coverage for most cities, particularly for the high-latitude cities (Zhou et al., 2014b), which turned the ΔΤ in winter. Second, lower soil moisture in winter than in summer, influenced by the monsoon climate (Wu et al., 2005), could drive more rapid increase of ΔΤ with UDI in winter than in summer by reducing heat storage and subsequently releasing heat at night in the rural zones. Finally, the heating-created anthropogenic heat flux in urban areas during winter, especially for the high-latitude cities where central heating systems are used extensively, could indirectly strengthen the ΔΤ trends (Zhou et al., 2014b).

Large seasonal changes of the ΔΤ–UDI trends with evident spatial distributions were observed for the 32 cities. In the daytime, the ΔΤ increased more rapidly in summer than in winter for nearly all the cities (Figs. 3, 4B, and C), mainly because of the stronger evaporative cooling effects produced by vegetated surface in summer than in winter (Imhoff et al., 2010; Jin, 2012; Zhou et al., 2014b). The northern parts of China witnessed larger seasonal changes, which can be attributed to the greater seasonal change of the vegetation activity in the regions (caused by intensive agricultural practices in summer and defoliation in winter) (Piao et al., 2003). Conversely, the ΔΤ trend was much weaker in summer than in winter for the cities in North and Northeast China during the night (Figs. 4–6). Three factors might contribute to this phenomenon. First, the albedo differences between urban and rural areas were more pronounced during winter than summer because of defoliation and/or snow and ice coverage for most cities, particularly for the high-latitude cities (Zhou et al., 2014b), which turned the ΔΤ in winter. Second, lower soil moisture in winter than in summer, influenced by the monsoon climate (Wu et al., 2005), could drive more rapid increase of ΔΤ with UDI in winter than in summer by reducing heat storage and subsequently releasing heat at night in the rural zones. Finally, the heating-created anthropogenic heat flux in urban areas during winter, especially for the high-latitude cities where central heating systems are used extensively, could indirectly strengthen the ΔΤ trends (Zhou et al., 2014b).

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Table 1
Pearson’s correlation coefficients between the linear changing rates of urban heat island effect (ΔΤ) along the Urban Development Intensity (UDI) gradients and the climatic (precipitation and temperature) or background vegetation (as reflected by rural Enhanced Vegetation Index [EVI]) factors across cities.

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Precipitation</th>
<th>Background EVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>0.46c</td>
<td>0.57b</td>
<td>0.59b</td>
</tr>
<tr>
<td>Summer</td>
<td>−0.17</td>
<td>−0.34</td>
<td>0.37b</td>
</tr>
<tr>
<td>Winter</td>
<td>0.65c</td>
<td>0.57b</td>
<td>0.51b</td>
</tr>
<tr>
<td>Night</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
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<td>−0.70c</td>
<td>−0.43c</td>
</tr>
<tr>
<td>Summer</td>
<td>−0.60d</td>
<td>−0.42b</td>
<td>−0.48c</td>
</tr>
<tr>
<td>Winter</td>
<td>−0.61d</td>
<td>−0.71c</td>
<td>−0.50b</td>
</tr>
</tbody>
</table>

a Significant at 0.01 level.
bb Significant at 0.05 level.
effects of plant evapotranspiration induced by the relatively higher vegetation activity and soil moisture (by irrigation) in urban zones compared to rural areas. In addition, two arid cities (Lanzhou and Urumqi) presented cold island effects during the day in winter. This might be related to the air pollution (Zhou et al., 2014b) and vegetation activity in this season. Heavy air pollution in winter for the northern cities resulted from large amount of coal burned for heating (He et al., 2002) can decrease incoming solar radiation in the urban area compared to the rural area (Sang et al., 2000), which in turn might artificially reduce urban temperature and even result in cold island effect. Low vegetation activity in winter exerted little cooling effects on rural surface, where usually there is more available energy than its urban counterpart during the day (Li and Bou-Zeid, 2013). This could result in urban cold island in those cities as well. Moreover, two humid–hot cities (Nanjing and Hefei) showed cold island effect in exurban and suburban areas compared to rural references, likely due to the abundance of surface water in the rice paddy fields or other wetlands in these rural areas (Hao et al., 2015).

We also found that the ΔT trends were not always in linear forms. Convex and concave patterns were formed under certain natural and anthropogenic influences. For example, some northern cities presented a concave trend in the daytime during summer mainly because of the higher evapotranspiration (cooling effects) per vegetated surface in exurban and/or suburban areas compared to rural counterparts induced by intensive land use activities (e.g., agricultural practices and urban green land management) (Piao et al., 2003; Zhou et al., 2014a). The concave trend was also found at night for some northern cities. The reason for this phenomenon was not clear. It might be related to the lower heat storage and releasing per impervious surface in exurban and/or suburban areas (mostly residential area) compared to urban core zones (mainly commercial area) (Oke, 1982). In contrast, two southern cities (Kunming and Shenzhen) showed a convex increase in the day primarily due to the higher evapotranspiration per vegetated pixels in urban and urban core areas caused by intensive urban greening practices (Zhou et al., 2014a). At the same time, two arid cities (Lanzhou and Lhasa) exhibited convex increase at night, possibly because the influence of water body in the cities. There were rivers cross exurban and suburban zones of the two cities. This could increase heat storage during the day and thus might promote the ΔT in the areas (i.e., exurban and suburban) close to the river (e.g., Oke, 1982).

4.2. Temporal trends of the UHI effects from 2003 to 2012 in China

We found that the background temperature (as reflected by rural land surface temperature) decreased from 2003 to 2012 for most cities (Table 2), closely related to the trends of air temperature (Table S2). The ΔT, however, increased significantly in about one-third of the cities, especially in the suburban areas during both the day and night times (Table 2). These can be attributed to a) more built-up land expansion occurred in the suburban area over time (Fig. 7), and b) more intensive management of urban green space in the urban and urban core areas (Zhou et al., 2014a). Conversely, few cities showed apparent decline trends of daytime ΔT in urban or urban core zones (Table 2) even though they experienced simultaneous urbanization intensification (Fig. 7). The improved management and maintenance of urban green spaces likely drove part of this relationship. Chinese municipal governments have created new green areas or preserved existing green spaces in conjunction with rapid urbanization in recent years (Yu and Padua, 2007; Zhao et al., 2013).

We found that the inter–annual variations of the ΔT were generally invariant with climate factors (Table S2). Nevertheless, few cities with significant correlations indicated that more intensive ΔT was likely to
happen in wet years during the day (i.e., positive relationship) and in dry years for the night (i.e., negative relationship) (Table S2). This phenomenon can be explained by the better vegetation condition and the higher soil moisture content during the wet years that can result in larger daytime $\Delta T$ and lower nighttime $\Delta T$ compared to the dry years. Surprisingly, weaker surface UHI effects were more likely to occur in hot years during both the day and night times (Table S2), contrary to the previous understanding that heat waves could accelerate UHI effects due to the associated decrease of surface moisture and wind speed in urban areas (Li and Bou-Zeid, 2013). The discrepancy might be attributed to 1) the satellite data available is not long enough to reflect the relationship between UHI and climate variability (Zhao et al., 2014), and 2) the collinearity problem of the climatic impacts with that induced by other factors (Zhou et al., 2014b). Long-term observations and physical-based models are urgently needed to investigate the responses of UHI effects to climate extremes in future.

4.3. Caution to the methods to quantify UHI intensity over large areas

The varying $\Delta T$ trends along UDI gradients across space and time suggests that caution should be paid to the methods to quantify UHI intensity over large areas. For example, the annual mean UHI intensity, if defined as temperature differences in urban and urban core (UDI > 0.5) relative to rural (UDI < 0.05) areas in current research, reached up to 2.20 °C in the day and 2.17 °C at night for those 32 major cities (Fig. 8). These two values are nearly two times as large as our previous estimates (1.11 and 1.13 °C for the day and night, respectively) that were loosely defined as the temperature differences between urban (UDI > 0.5) and nearby equal-area buffer zones (Zhou et al., 2014b). The direction of the UHI estimates might be reversed when using different methods. For example, two arid cities (Lanzhou and Urumqi) exhibited cold island effect in this analysis but had weak heat island effect if compared to suburban during the day on an annual mean scale. The relative magnitudes of the UHI effect across regions might also differ if the quantification method is used. For example, the greatest daytime and nighttime UHI intensity happened in East and Northwest China, respectively, yet both occurred in Northeast China if compared to suburban areas. It is therefore necessary to realize the empirical nature of the estimated UHI intensities because of their dependence on the definitions. However, UHI estimates under the two definitions were positively and significantly related, especially for the diurnal changes (Table 3). For example, the UHI intensity was higher in summer than winter for most cities during the day, with the opposite for the night (Fig. 8), which was highly consistent with our previous

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<th>Fig. 7. Changes of the mean UDI in different UDI zones from 2005 to 2010.</th>
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<td>Fig. 8. Spatial distributions of surface urban heat island intensity (°C) in China’s 32 major cities averaged over the period 2003–2012. The diurnal and seasonal ranges were defined as the intensity differences between daytime and nighttime and between summer and winter, respectively.</td>
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findings (Zhou et al., 2014b). This phenomenon can be attributed to the fact that the large-scale UHI distribution was largely controlled by the background climate (Imhoff et al., 2010; Zhou et al., 2014b, Zhao et al., 2014).

4.4. Uncertainties

Uncertainties remain in this analysis. First, large area differences existed among UDI zones for a particular city and across cities, which may affect the area-weighted mean LST. Second, we used the empirical value of the rural LST to represent city's climatic background, and assumed that there were no urbanization effects in rural areas. Our results did show that the UDI in the rural zone increased slightly over time for all the cities (Fig. 7), which suggest that the UHI effect (difference relative to rural areas) might be underestimated. Third, we did not conduct a detailed attribution analysis on the phenomenon that both the convex and concave ΔΤ–UDI trends have been observed in few cities. It might be related to the intensified vegetation management (e.g., irrigation, fertilization, choice of species) and the existence of water body. However, other factors such as landscape configuration (Arnfield, 2003; Li et al., 2011; Oke, 1982), atmospheric environment (Jauregui and Luyando, 1999), and land use (Jin et al., 2005; Oke, 1982) may play important roles in forming these trends. Fourth, cold island effect happened in a few cities, especially during the daytime in the winter. The actual reason for this phenomenon remains unclear. Fifth, although urbanization intensified through time, more than half of the cities demonstrated insignificant trends of the ΔΤ, likely because our research period was not long enough to adequately reflect the temporal trends. Moreover, we used the static land coverage maps in 2005 and 2010 (Zhao et al., 2015) to delineate the UDI maps for the periods of 2003–2007 and 2008–2012, respectively. This would introduce some biases on the UDI distribution, especially for cities that experienced rapid urbanization. In future projects, consecutive land-cover maps would likely result in a more effective evaluation of the ΔΤ trends over time.

5. Conclusions

This study examined the spatiotemporal trends of surface UHI effects (i.e., ΔΤ) along the UDI gradient in 32 major cities across different regions of China. Since China has complex zonal variations and experienced the world's most intensive urbanization in recent decades, this analysis provides valuable information on predicting the UHI effects and the associated consequences in the context of future urban development over large areas.

Our results indicated that both the daytime and nighttime ΔΤ increased dramatically with a rising UDI for majority of cities, with a great deal of spatial heterogeneities. Larger intensifying rates were observed in the southeastern and northwestern portion of China for the day and night, respectively. At the same time, the ΔΤ–UDI relationships were not always linear, convex and concave patterns can be formed under certain natural and anthropogenic influences. In addition, we indicated that the ΔΤ trends differed greatly by season, characterized by the higher increasing rates in summer during the day and in winter at night across most cities. The background climate-vegetation regimes were found mainly responsible for the ΔΤ–UDI trends across cities, while human activities and the agricultural practices in particular also matters. Inter-annually, we showed that the ΔΤ increased significantly in about one-third of the cities in the past decade (especially in suburban areas) and decreased in few cases. These patterns, however, were mainly controlled by human activities such as the urban development and urban green space management, and were overall invariant with local climate variability.

This research highlights the strong and highly diverse urbanization effects on local climate, stressing the necessity of the site-specific mitigation actions for sustainable urban development. Also, we emphasize that caution should be paid to the methods to quantify UHI effects over large areas, since the UHI estimate may vary substantially by the definitions and the direction can even be reversed. Nevertheless, the impacts of urbanization on climate are complex and uncertainties remained in this study. While remote sensing is helpful in quantifying the UHI effects over large areas, the combination use of direct observations and earth system models are needed for a better understanding of the physical characteristics, driving forces, and consequences of UHI, and therefore help formulating the climate mitigation strategies and plans.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2015.11.168.

References
