

## Urbanization and heterogeneous surface warming in eastern China

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With the homogeneity-adjusted surface air temperature (SAT) data at 312 stations in eastern China for 1979–2008 and the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) nighttime light data, the spatial heterogeneities of the SAT trends on different scales are detected with a spatial filtering (i.e. moving spatial anomaly) method, and the impact of urbanization in eastern China on surface warming is analyzed. Results show that the urbanization can induce a remarkable summer warming in Yangtze River Delta (YRD) city cluster region and a winter warming in Beijing-Tianjin-Hebei (BTH) city cluster region. The YRD warming in summer primarily results from the significant increasing of maximum temperature, with an estimated urban warming rate at 0.132–0.250°C per decade, accounting for 36%–68% of the total regional warming. The BTH warming in winter is primarily due to the remarkable increasing of minimum temperature, with an estimated urban warming rate at 0.102–0.214°C per decade, accounting for 12%–24% of the total regional warming. The temporal-spatial differences of urban warming effect may be attributed to the variation of regional climatic background and the change of anthropogenic heat release.

**heterogeneous surface warming, urbanization, surface air temperature, maximum temperature, minimum temperature, eastern China**

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Surface warming over recent five decades is attributed to natural climate change and anthropogenic forcing. The anthropogenic forcing mainly includes the emissions of greenhouse gases (GHG) and aerosols, as well as the land use/cover change (LUCC) [1]. Relative to the enhanced greenhouse effect, however, the climatic effect of LUCC has not been drawn sufficient attention. The urbanization is one of the extreme processes in LUCC [2]. It can alter surface vegetation distribution, induce regional climate change and increase uncertainty in future climate projection [3]. Moreover, large-scale urbanization can affect regional surface energy and water balance [4], and thus may intensify the frequency of extreme weather/climate events. Since both GHG and urbanization tend to increase the surface air temperature (SAT), it is quite difficult to estimate the relative contribution of either effect to the surface warming [5].

A variety of methods have been adopted to detect the climatic effect of urbanization. The most conventional and

direct method is the so-called urban-minus-rural (UMR) method in which the SAT at urban and rural sites is contrasted. The key of this method depends on whether or not those sites or stations can be objectively classified. In general, such a classification utilizes either population data [6–17] or satellite data (such as nighttime light imagery and land cover dataset) [18–23] as well as the geographic location of the stations. In addition, Empirical Orthogonal Function (EOF) [24,25], Principal Component Analysis (PCA) [26,27] and station metadata [28] can also be applied to define reference or rural stations. By comparing the difference between urban and reference (rural) stations, the impact of urbanization on SAT can be estimated.

Although the UMR method can directly detect the climatic effect of urbanization, it is sensitively dependent of classification of stations and sampling, which would increase the uncertainty of results [5]. Kalnay and Cai [5] proposed a new method to assess the impact of urbanization and LUCC on climate by computing the difference of SAT trends between observation and reanalysis, i.e. the so-called

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observation-minus-reanalysis (OMR) method. The OMR method is based on the fact that the reanalysis data did not assimilate observed surface information. This method does provide some signatures consistent with the distribution of underlying surface properties [22,29–36]. However, whether or not the OMR fully represents the impact of LUCC is still controversial [37,38].

China has been experiencing rapid economic growth and intensive urbanization since the 1980s. Due to close ties in social and economic aspects, single cities have expanded to form distinctive city clusters in eastern China, such as the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) city clusters. Meanwhile, the climatic effect of urbanization has drawn more and more attention. Some previous studies indicated that urbanization has little impact on regional warming [7,13,26,27]. However, recent investigations have suggested that the urbanization process can not only increase the local daily temperature, but also play an essential role in regional climate change [6,9,12,14–17,20–24,28–30,35,36]. Using the OMR method, Zhou et al. [29] and Zhang et al. [30] found that the urbanization exerts a significant influence on temperature trends in eastern China. Their results also revealed that the urbanization process is likely to enhance the increasing trend of the minimum temperature while imposing a relatively small influence on the maximum temperature, thus decreasing the diurnal temperature range. On the basis of the UMR method, Du et al. [20] indicated that the warming rate brought about by the urbanization in the YRD region is  $0.069^{\circ}\text{C}$  per decade and the effect of urban heat island is more significant in summer than winter. Zhang et al. [39] performed a series of numerical simulations to show that the urban heat island effect in the YRD region features obvious diurnal variation, thus affects the structure and development of urban boundary layer. With records at 282 stations in northern China, Ren et al. [15] determined that the urban warming rate is  $0.11^{\circ}\text{C}$  per decade, which accounts for 37.9% of the overall regional warming in northern China. However, they found that the urban heat island effect is more remarkable in winter than summer, unlike that in the YRD region [20]. Ding and Dai [40] and Ren et al. [14,15] argued that urbanization is one of major sources for uncertainties in climate change analysis. Yang et al. [22] showed that the contribution of urbanization to the surface warming appears to be comparable to that of GHG in the YRD region.

There are numerous studies to have focused on the impact of urbanization on the SAT change in China (Table 1). However, there are considerable inconsistencies that still exist in the aforementioned results. Such inconsistencies may be attributed to the differences of time period, regional span and analysis method. Another important issue in the analysis of station observations is the homogeneity of data. Homogeneity-adjusted data can mitigate the influence of subjective factors on temperature records and objectively reflect climate change [41–44]. Besides, the inconsistent

conclusions in the seasonal and diurnal variations of urbanization effect still exist. With a homogeneity-adjusted dataset, the objective of this work is to estimate the effect of urbanization on the SAT change in eastern China, detect the seasonal variation of urban warming in different regions, and analyze the impact of urbanization on maximum and minimum temperatures. Therefore, to assess the climatic effect of urbanization is of great significance for further understanding the relationship between urban development and extreme climate change.

## 1 Data sources and homogeneity adjustment

Surface climate/weather observation network in China consists of three levels: 160 National Reference Climate Stations (RCS, hourly observation), 600 National Basic Weather Stations (BWS, four times a day) and 1800 Ordinary Weather Stations (OWS, daily observation). The RCS and BWS are referred to as national stations, totally 760 sites. As indicated by Wu [45], 70%–80% of the national stations have been migrated for several times since the 1950s. Therefore, it is necessary to perform the homogeneity adjustment of station records before analyzing those records [45–47].

Methods for detecting and adjusting homogeneity in temperature series have been studied [41–43]. Li et al. [41] used two-phase regression homogeneity test approach to correct the SAT records in China and released the first China Homogenized Historical Temperature (CHHT, version 1.0) dataset. Afterward, Li and Yan [43] applied Multiple Analysis of Series for Homogenization (MASH) to adjust the daily temperature series (1960–2008) at 549 stations in China. The MASH method has a rigorous mathematical foundation and has been developed into mature software program. Compared with the aforementioned method [41], The MASH method can objectively correct the inhomogeneity without station metadata, and especially can detect deviation arising from the alteration from manual to automatic observation systems [48].

The homogeneity-adjusted daily mean SAT data [43] is used in this study. Besides, nighttime light data obtained from the Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) is applied to classify stations into different types. The version 4 stable nighttime light products with 1 km spatial resolution were downloaded from the National Geophysical Data Center (<http://www.ngdc.noaa.gov/dmsp/downloadV4composites.html>). For its unique low-light imaging capacity, the nighttime light imagery can not only be used as the characteristic index in the analysis of urbanization effect, but also meet the needs of detection in human activities [49,50]. In terms of Zhou et al. [29] and Hu et al. [35], the urbanization process in China primarily started around 1979. Therefore, observed data during the period from 1979 to 2008 in eastern China

**Table 1** Results of studies on the climatic effect of urbanization in China

Authors	Study area (Number of stations)	Time period	Method (Classification index)	Urban warming (°C per decade)	Seasonal variation of urban warming	Spatial variation of urban warming <sup>a)</sup>	Impact on maximum and minimum temperatures
Wang et al. [6]	China (84)	1954–1983	UMR (Population)	0.08	North: Winter>Summer Others: Summer>Winter	North>YHR>Northeast>Southeast	
Jones et al. [7]	East China (84)	1954–1983	UMR (Population)	0.05			
Zhao [8]	China (160)	1951–1989	UMR (Population)	0.02–0.06	Winter>Spring>Autumn>Summer		
Portman [9]	North China (41)	1954–1983	UMR (Population)	0.06	Spring>Winter>Summer>Autumn		
Li et al. [26]	China (390)	1954–2001	PCA (Population)	<0.012		YHR>South>Northwest	
Zhou et al. [29]	Southeast China (194)	1979–1998	OMR	0.05			$T_{\min}>T_{\max}$
Zhang et al. [30]	East China (431)	1960–1999	OMR	0.12		Northeast>South	$T_{\min}>T_{\max}$
Zhou & Ren [12]	North China (282)	1961–2000	UMR (Population)	0.11	Winter>Spring, Autumn>Summer		
Chu & Ren [24]	Beijing (20)	1961–2000	EOF	0.16	Autumn>Spring>Winter>Summer		
Du et al. [20]	YRD (99)	1961–2005	UMR (Nighttime light)	0.069	Summer>Autumn>Spring>Winter		$T_{\max}>T_{\min}$
He et al. [21]	China (673)	1991–2000	UMR (NLCD)	0.11	Winter>Autumn>Spring>Summer	Northeast>South>YHR	
Fang et al. [13]	Northwest China (92)	1961–2000	UMR (Population)	0.01–0.07			
Ren et al. [15]	North China (282)	1961–2000	UMR (Population)	0.11	Winter>Summer		
Hua et al. [16]	China (382)	1961–2000	UMR (Population)	0.03–0.05	Winter>Summer	North>YHR>South	$T_{\min}>T_{\max}$
Tang et al. [17]	Southwest China (322)	1961–2004	UMR (Population)	0.05–0.09	Autumn>Spring, Winter>Summer		Reduce cold night
Hu et al. [35]	East China (322)	1979–2008	OMR				$T_{\min}>T_{\max}$
Li et al. [27]	Northeast China (187)	1954–2005	PCA (Population)	0.027	Spring>Winter>Autumn>Summer		
Zhang et al. [28]	China (752)	1961–2004	UMR (Metadata)	0.076	Winter>Spring>Summer>Autumn	YHR>Northeast>South	
Yang et al. [22]	YRD (463)	1981–2007	OMR (Population)	0.17–0.40	OMR: Winter>Summer		
Sun et al. [36]	YRD (130)	1979–2003	UMR (Nighttime light)	0.08–0.29	UMR: Summer>Winter		$T_{\min}>T_{\max}$
Wang & Ge [23]	China (160)	1980–2009	UMR (LUDC)	0.099–0.258	Summer>Winter		

a) YHR: Yangtze-Huaihe River basins.

(15°–54°N, 110°–136°E) is used in the following analysis.

## 2 Methods

### 2.1 Time series and linear trends

The homogeneity-adjusted SAT data at 312 stations located in eastern China with continuous observation during the analysis period are selected from 549 stations. Four seasonal mean temperatures are defined by calculating the average of each three-month: December-to-February (winter), March-to-May (spring), June-to-August (summer) and September-to-November (autumn). Seasonal mean, maximum and minimum temperatures for each season are computed for the period from 1979 to 2008. Their linear trends can be estimated by using ordinary least squares. Meanwhile, the  $t$ -test is applied to examine the statistical significance of the linear trends.

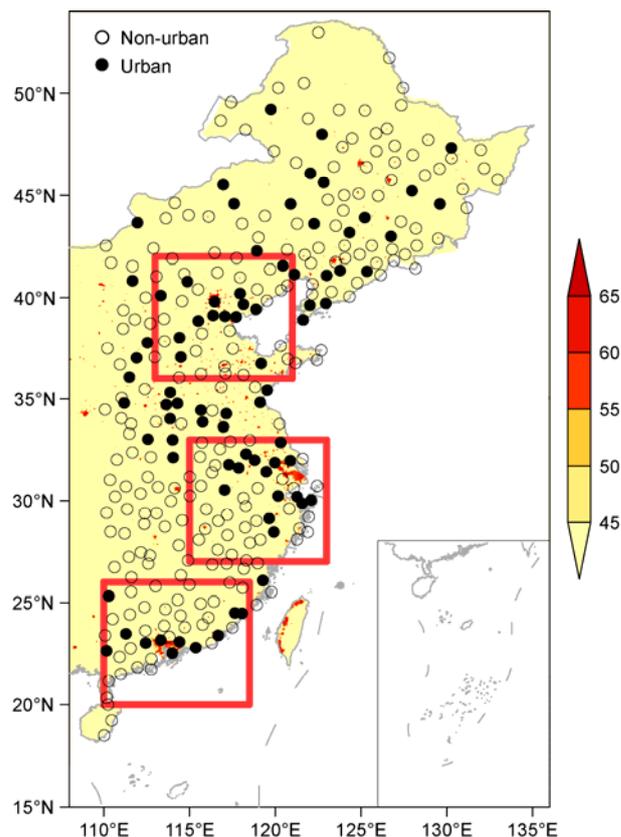
### 2.2 Spatial filtering and moving spatial anomaly

A spatial filtering method in this study is proposed to identify the impact of climatic forcing with different spatial scales on the SAT change. Concretely, for each station a moving spatial anomaly (MSA) is defined as the departure from an average over a region with center at the station. Then, the moving spatial anomalies for all the stations are calculated when the region is slid. Since such a region is moving, it acts as a filtering window, and thus the MSA is a spatially-filtered component. By altering the size of the filtering window, the spatial heterogeneities on different spatial scales are detected.

In this study, the spatial filtering (i.e. MSA) method is applied to the linear trend of the SAT change. In order to isolate the heterogeneous climatic effect of the urbanization, the size of filtering window is empirically taken as  $8^\circ \times 8^\circ$ ,  $12^\circ \times 12^\circ$  and  $16^\circ \times 16^\circ$ , respectively, combined with nighttime light imagery and station distribution (Figure 1). Assume that the SAT change on the spatial scales larger than the size of the filtering window is attributed to large scale climatic forcing. Then the spatial heterogeneity of the SAT trends indicated with the MSA calculated above reflects the impact of regional climatic forcing such as urbanization, LUCC and anthropogenic heat release on the SAT change.

### 2.3 Classification of stations and definition of urban warming

Figure 1 shows the DMSP/OLS nighttime light imagery in 2008 and the distribution of stations. With the nighttime light data, the location of stations and the related study results [51–53], an urban station is defined when the nighttime light value is no less than 55 and a non-urban station is defined when the value is less than 55. In terms of such a classification of stations, an urban warming rate can be estimated for



**Figure 1** DMSP/OLS nighttime light imagery in 2008 (shaded) and distribution of stations for two categories (urban versus non-urban) (circles). Red boxes indicate three representative regions associated with the Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) city clusters in China, respectively.

three major city clusters (red boxes in Figure 1) in eastern China, respectively. For each city cluster region, the urban warming rate ( $U_n$ ) can be expressed as

$$U_n = \frac{1}{n} \sum_{i=1}^n a_i, \quad (1)$$

where  $a_i$  represents the MSA of the SAT trend and  $n$  is the number of urban stations within the region. Meanwhile, a regional total warming rate ( $R_m$ ) is defined as

$$R_m = \frac{1}{m} \sum_{i=1}^m b_i, \quad (2)$$

where  $b_i$  represents the total SAT trend and  $m$  is the number of all the stations (including urban and non-urban stations) within the region. Thus, the contribution rate ( $U_r$ ) of urbanization to the regional total warming is calculated as

$$U_r = \frac{U_n}{R_m} \times 100\%. \quad (3)$$

By analyzing  $U_n$  and  $U_r$  in the three city cluster regions, the impact of urbanization on regional climate change in eastern China can be estimated.

### 3 Results

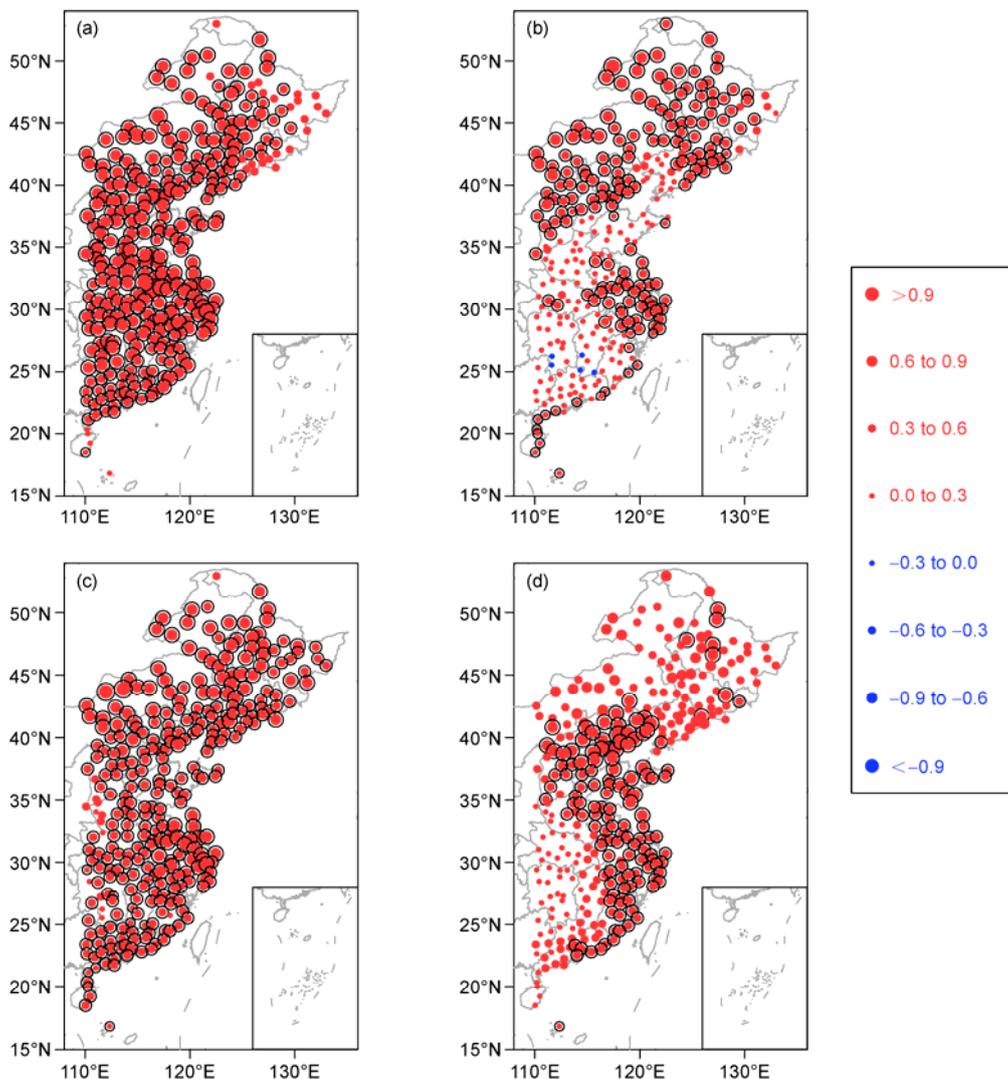
#### 3.1 Temporal-spatial variations of SAT trends

Figure 2 shows the spatial distribution of seasonal mean SAT trends in eastern China. Warming signals can be observed obviously in each season, and the annual mean warming rate is about  $0.5^{\circ}\text{C}$  per decade. This value is higher than that estimated by Ding et al. [54], which may be due to the increased warming during last three decades in eastern China. Moreover, the large-scale warming exhibits considerable temporal-spatial variations. The warming is more spatially heterogeneous in summer (Figure 2(b)) and winter (Figure 2(d)), while relatively homogeneous in spring (Figure 2(a)) and autumn (Figure 2(c)). Overall, the warming rates are larger in spring and autumn than winter and summer (Table 2). The difference of warming rate between urban and non-urban stations (Table 2) may reflect the cli-

matic effect of urbanization. It is found that the urban warming also features an obvious seasonal variation. The urbanization effect appears considerably remarkable in winter and spring, but relatively weak in autumn and summer. With the difference, the annual mean temperature change caused by urbanization is estimated to be  $0.057^{\circ}\text{C}$  per decade, accounting for 11.4% of total averaged warming in whole eastern China.

#### 3.2 Spatial heterogeneities of SAT trends on different scales

Since the SAT trends are characterized by obvious spatial heterogeneity in summer and winter, the spatial filtering (i.e., MSA) method described in section 2 is employed to extract the effect of regional climatic forcing on seasonal mean SAT change in these two seasons. Figure 3 demonstrates the spatial distributions of the MSA for seasonal

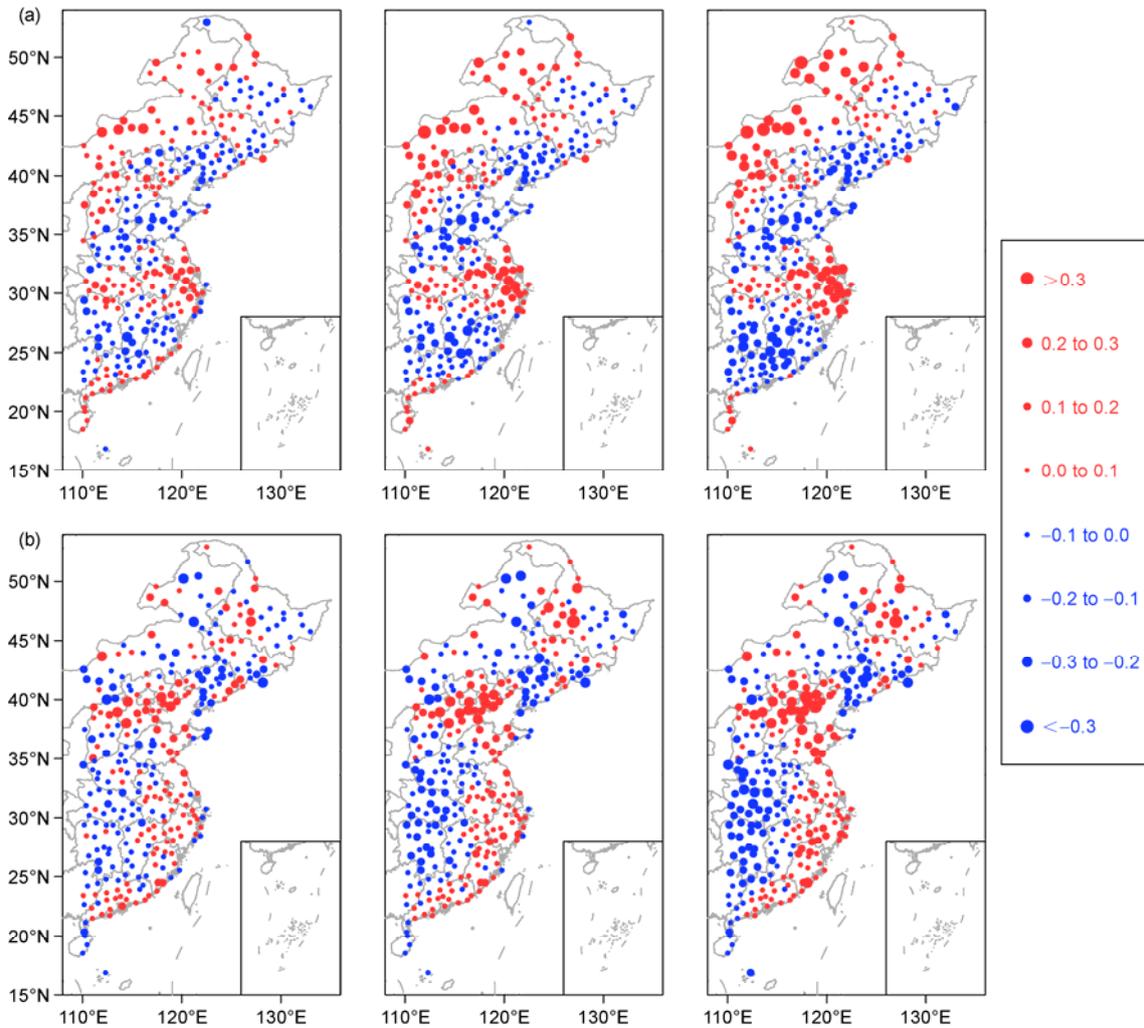


**Figure 2** Seasonal mean surface air temperature trends for (a) spring, (b) summer, (c) autumn and (d) winter during 1979–2008. The red solid circles denote the value of the trends, while the black open circles denote that trend is significant at 95% confidence level (Unit:  $^{\circ}\text{C}$  per decade).

**Table 2** Regional average of seasonal and annual mean surface air temperature trends during 1979–2008<sup>a)</sup> (Unit: °C per decade)

	Annual	Spring	Summer	Autumn	Winter
All stations	0.500	0.644	0.324	0.519	0.492
Urban	0.542	0.696	0.355	0.551	0.547
Non-urban	0.485	0.625	0.313	0.508	0.472
Difference	0.057 <sup>**</sup>	0.071 <sup>**</sup>	0.042	0.043 <sup>*</sup>	0.075 <sup>**</sup>

a) Statistical significance at 0.05 (\*) and 0.01 (\*\*) levels.

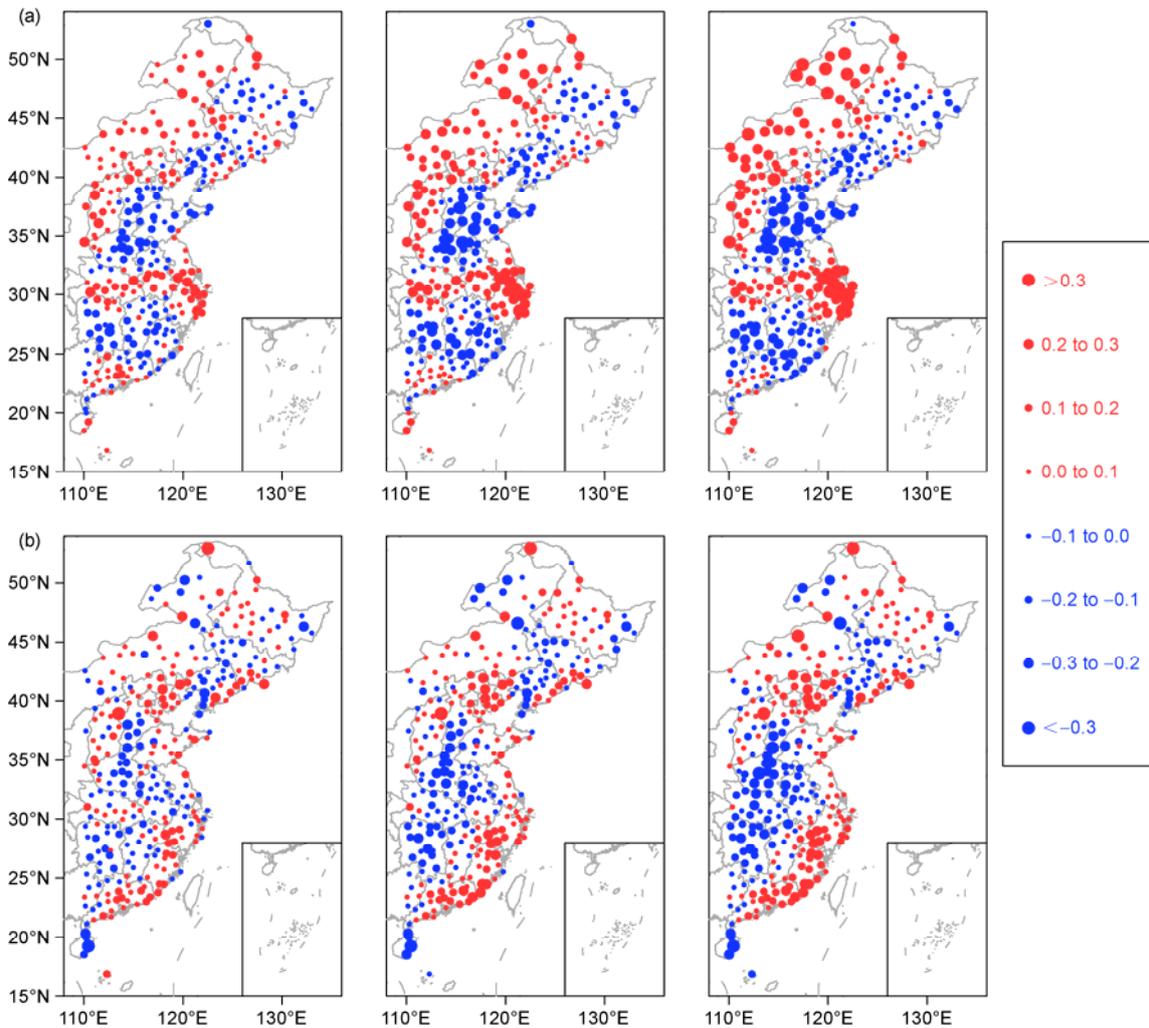


**Figure 3** Moving spatial anomalies of seasonal mean surface air temperature trends for three types of filtering window sizes (I: 8°×8°, II: 12°×12°, III: 16°×16°) for (a) summer and (b) winter (Unit: °C per decade).

mean SAT trends on three sizes of filtering windows. It is evident that although warming signal becomes more obvious with the expansion of filtering window, the spatial patterns roughly keep unchanged. In summer (Figure 3(a)), the remarkable warming primarily confines to the YRD and eastern Inner-Mongolian regions. In winter (Figure 3(b)), the significant warming mainly locates in the BTH region. The increasing of seasonal mean temperatures in YRD and BTH regions may result from the continuing urbanization process, and that in eastern Inner-Mongolia may be due to

the desertification occurred over recent decades [35]. Temporal-spatial variations of urbanization effect in the YRD and BTH regions examined in this study are consistent with those in Du et al. [20] and Ren et al. [15].

In comparison with the MSA for seasonal mean SAT trends in Figure 3, Figures 4 and 5 illustrate the spatial distributions of the MSA for maximum and minimum temperature trends, respectively. It can be found that the urban warming in the YRD region in summer is primarily determined by the significant increasing of maximum temperature



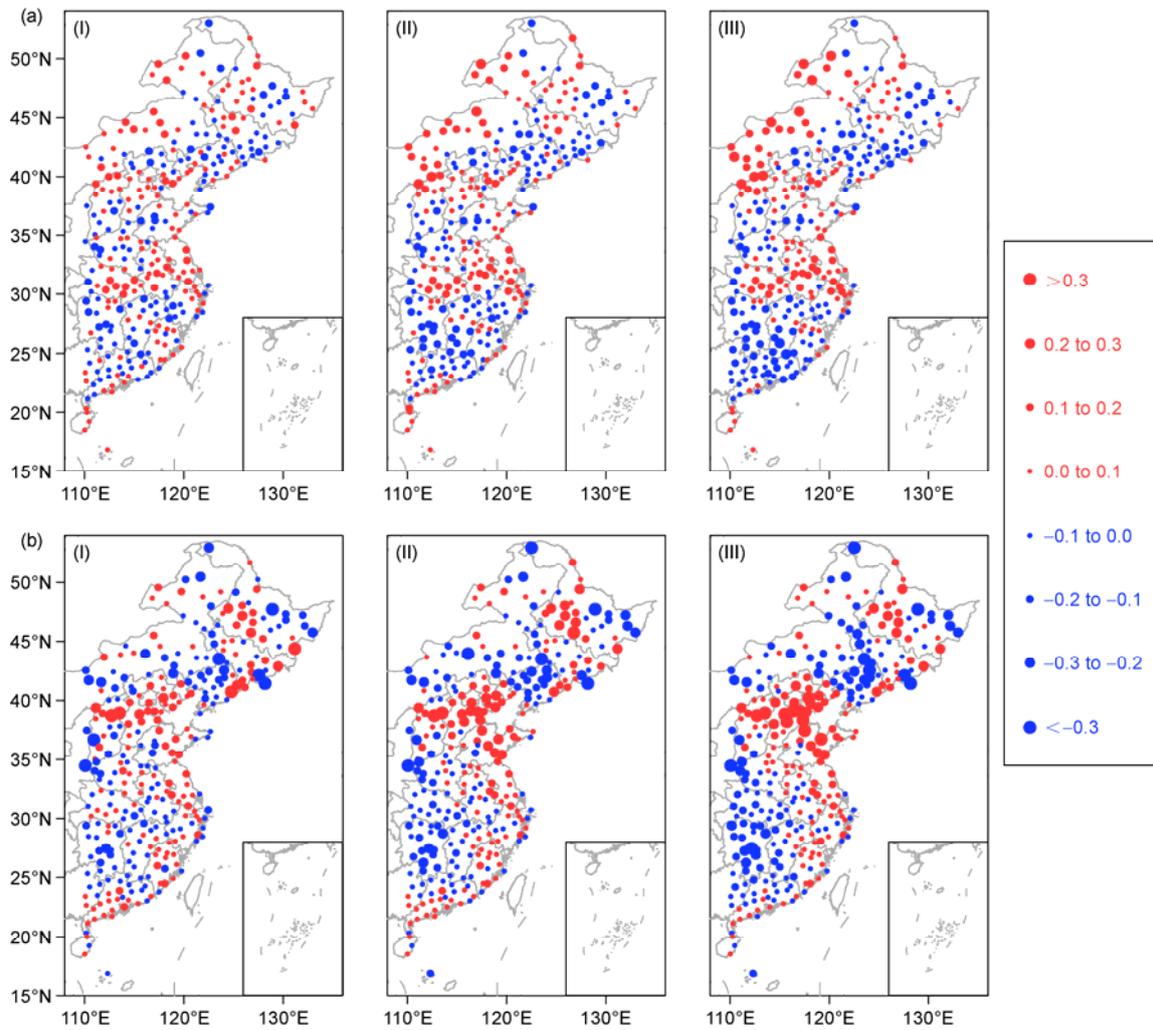
**Figure 4** Same as Figure 3, but for the seasonal mean maximum temperature.

(Figure 4(a)), while that in the BTH region in winter is primarily due to the remarkable increasing of minimum temperature (Figure 5(b)). The temporal-spatial differences of urbanization effect may be related to the anthropogenic heat release [55]. Several studies have indicated that anthropogenic heat in the YRD region is mainly caused by the air conditioning refrigeration, which is more intensive during daytime than night and eventually can increase the daily maximum temperature in summer [56,57]. Conversely, anthropogenic heat in the BTH region is primarily caused by winter heating that is more intensive during night, which favors the increasing of daily minimum temperature in winter [58–60]. Additionally, winter maximum temperature also has increased in some other regions of northern and south-eastern China (Figure 4(b)). The reason for such occurrences requires further investigation.

### 3.3 Urban warming and contribution rates

In terms of eqs. (1)–(3), the urban warming rates together

with their contribution to the total regional warming are computed for three filtering windows and for three city cluster regions in eastern China. Table 3 lists the maximal urban warming rate and its corresponding season for each filtering window and for each city cluster. With the expansion of the filtering window size, the maximal urban warming rate is increased. However, the corresponding season substantially keeps unchanged. Specifically, the urbanization in the BTH region has significant impact on the increasing of winter minimum temperature with an estimated urban warming rate at 0.102–0.214°C per decade, while the urbanization in the YRD region primarily affects the summer maximum temperature with an urban warming rate at 0.132–0.250°C per decade. Winter maximum temperature in the PRD region is also increased at a rate of 0.076–0.125°C per decade that may be attributed to the urbanization process. Among the three city cluster regions, the urbanization causes the most significant warming in the YRD region, while the PRD region undergoes the smallest urban warming. Table 4 lists the contribution rate of urbanization



**Figure 5** Same as in Figure 3, but for the seasonal mean minimum temperature.

**Table 3** The maximal urban warming rate and its corresponding season (Unit: °C per decade)

	8°×8°	12°×12°	16°×16°
BTH	0.102 Winter minimum temperature	0.165 Winter minimum temperature	0.214 Winter minimum temperature
YRD	0.132 Summer maximum temperature	0.220 Summer maximum temperature	0.250 Summer maximum temperature
PRD	0.076 Winter maximum temperature	0.106 Winter maximum temperature	0.125 Winter maximum temperature

**Table 4** The contribution rate of urban warming and its corresponding season (Unit: %)

	8°×8°	12°×12°	16°×16°
BTH	12 Winter minimum temperature	19 Winter minimum temperature	24 Winter minimum temperature
YRD	36 Summer maximum temperature	60 Summer maximum temperature	68 Summer maximum temperature
PRD	20 Winter maximum temperature	28 Winter maximum temperature	32 Winter maximum temperature

to the total regional warming. It can be seen from the table that the urban warming accounts for 12%–24%, 36%–68% and 20%–32% of the total regional warming, respectively, in the BTH, YRD and PRD regions. Most strikingly, the contribution rate of urban warming in the YRD region is the largest and explains around half of the total regional warming. This suggests that the urbanization process does impose an essential impact on the regional climate change, especially in the YRD, a rapid urbanized region.

#### 4 Conclusions and discussion

With homogeneity-adjusted SAT data at 312 stations in eastern China for 1979–2008, this study investigates spatial heterogeneities of the SAT trends and their association with the urbanization. Main conclusions are as follows.

(1) The SAT is characterized by a significant large-scale increasing trend from 1979 to 2008 in eastern China. The annual mean warming rate is estimated to be 0.5°C per decade. This large-scale warming features an obvious seasonal variation. The warming is more remarkable in spring and autumn than winter and summer. Meanwhile, the spatial pattern of the warming is more heterogeneous in summer and winter.

(2) The difference between urban and non-urban stations indicates that the warming rate of urbanization effect on annual mean temperature is 0.057°C per decade, accounting for 11.4% of total averaged warming in whole eastern China. Overall, the urbanization effect has obvious seasonal variation, which appears to be more significant in winter and spring, and relatively weak in autumn and summer.

(3) A spatial filtering (i.e. the MSA) method is proposed to detect the spatial heterogeneity of the SAT trends. The MSA distribution exhibits a significant summer urban warming in the YRD region and a significant winter urban warming in the BTH region. The YRD warming in summer primarily results from the increasing of maximum temperature while the BTH warming in winter is due to the increasing of minimum temperature.

(4) The urbanization in the BTH region has significant impact on the increasing of winter minimum temperature with an estimated urban warming rate at 0.102–0.214°C per decade, while the urbanization in the YRD region primarily affects the summer maximum temperature with an urban warming rate at 0.132–0.250°C per decade. Winter maximum temperature in the PRD region is also increased by urbanization at a rate of 0.076–0.125°C per decade.

(5) The urban warming accounts for 12%–24%, 36%–68% and 20%–32% of the total regional warming, respectively, in the BTH, YRD and PRD regions. Most strikingly, the contribution rate of urban warming in the YRD region is the largest and explains around half of the total regional warming.

As most meteorological stations have been migrated for

several times, the homogeneity-adjusted dataset, which could mitigate the impact of subjective factors in observed records, is taken to analyze the SAT change in eastern China in this study. Despite there are a few controversies about the method of homogeneity adjustment, the adjusted data reflects temperature series more objectively. Furthermore, Peterson [19] argued that there was no significant impact of urbanization in observed records once the temperature series were adjusted for homogeneities. However, this study confirmed that an urban warming effect is still remarkable in the homogeneity-adjusted data.

Although the spatial filtering (i.e. MSA) method proposed in this study can detect the spatial heterogeneities of temperature trends on different scales, whether or not the filtered spatial patterns could fully reflect the impact of LUCC on temperature trends still needs to be further examined. Meanwhile, the results can be altered with the expansion of filtering windows, so which scale should be selected to appropriately detect the impact of urbanization also needs to be investigated. Although three scales that are empirically chosen to analyze the spatial heterogeneities of the SAT trends in this study, the spatial patterns displayed for the three scales are substantially consistent, which confirms the effectiveness of the MSA method in identifying the impact of urbanization and other LUCC processes on the SAT change.

Despite a small contribution to the SAT trends in entire eastern China, the urbanization still has considerable influence on the regional climate change. Therefore, a more reasonable urban planning should be considered in order to mitigate regional climate warming. This study also found that the climatic effect of urbanization features obvious temporal-spatial differences, which may be associated with the variation of regional climatic background and the change of anthropogenic heat release. The mechanism responsible for those impacts needs to be further explored in future studies.

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- 1 Intergovernmental Panel on Climate Change. IPCC AR4 Report. Cambridge: Cambridge University Press, 2007
- 2 Pielke R A. Land use and climate change. *Science*, 2005, 310: 1625–1626
- 3 Jiang D B, Zhang Y, Lang X M. Vegetation feedback under future global warming. *Theor Appl Climatol*, 2011, 106: 211–227
- 4 Li X, Yang X Q, Tang J P, et al. Multiple urban heat islands and surface energy balance during summer in Yangtze River Delta city cluster region simulated with WRF/NCAR (in Chinese). *J Meteorol Sci*, 2011, 31: 441–450
- 5 Kalnay E, Cai M. Impact of urbanization and land-use change on climate. *Nature*, 2003, 423: 528–531
- 6 Wang W C, Zeng Z, Karl T R. Urban heat islands in China. *Geophys Res Lett*, 1990, 17: 2377–2380

- 7 Jones P D, Groisman P Y, Coughlan M, et al. Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, 1990, 347: 169–172
- 8 Zhao Z C. The changes of temperature and the effects of the urbanization in China in the last 39 years (in Chinese). *Meteor Mon*, 1991, 17: 14–17
- 9 Portman D A. Identifying and correcting urban bias in regional time series: Surface temperature in China's northern plains. *J Clim*, 1993, 6: 2298–2308
- 10 Zhou S Z, Shu J. *Urban Climatology* (in Chinese). Beijing: Chinese Meteorological Press, 1994. 244–339
- 11 Easterling D R, Horton B, Jones P D, et al. Maximum and minimum temperature trends for the globe. *Science*, 1997, 277: 364–367
- 12 Zhou Y Q, Ren G Y. Identifying and correcting urban bias for regional surface air temperature series of north China over period of 1961–2000 (in Chinese). *Climatic Environ Res*, 2005, 10: 743–753
- 13 Fang F, Bai H Z, Zhao H Y, et al. The urbanization effect in northwestern China and its contribution to temperature warming (in Chinese). *Plateau Meteorol*, 2007, 26: 579–585
- 14 Ren G Y, Chu Z Y, Chen Z H, et al. Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. *Geophys Res Lett*, 2007, 34: L05711
- 15 Ren G Y, Zhou Y Q, Chu Z Y, et al. Urbanization effects on observed surface air temperature trends in North China. *J Clim*, 2008, 21: 1333–1348
- 16 Hua L J, Ma Z G, Guo W D. The impact of urbanization on air temperature across China. *Theor Appl Climatol*, 2008, 93: 179–194
- 17 Tang G L, Ren G Y, Zhou J X. Change of urban heat island intensity and its effect on surface mean air temperature records in southwest China (in Chinese). *J Appl Meteor Sci*, 2008, 17: 722–730
- 18 Hansen J, Ruedy R, Sato M, et al. A closer look at United States and global surface temperature change. *J Geophys Res*, 2001, 106: 23947–23963
- 19 Peterson T C. Assessment of urban versus rural *in situ* surface temperatures in the contiguous United States: No difference found. *J Clim*, 2003, 16: 2941–2959
- 20 Du Y, Xie Z Q, Zeng Y, et al. Impact of urban expansion on regional temperature change in the Yangtze River Delta. *J Geogr Sci*, 2007, 17: 387–398
- 21 He J F, Liu J Y, Zhuang D F, et al. Assessing the effect of land use/land cover change on the change of urban heat island intensity. *Theor Appl Climatol*, 2007, 90: 217–226
- 22 Yang X C, Hou Y L, Chen B D. Observed surface warming induced by urbanization in east China. *J Geophys Res*, 2011, 116: D14113
- 23 Wang F, Ge Q S. Estimation of urbanization bias in observed surface temperature change in China from 1980 to 2009 using satellite land-use data. *Chin Sci Bull*, 2012, 57: 1708–1715
- 24 Chu Z Y, Ren G Y. Effect of enhanced urban heat island magnitude on average surface air temperature series in Beijing region (in Chinese). *Acta Meteorol Sin*, 2005, 63: 534–540
- 25 Kim M K, Kim S. Quantitative estimates of warming by urbanization in South Korea over the past 55 years (1954–2008). *Atmos Environ*, 2011, 45: 5778–5783
- 26 Li Q, Zhang H, Liu X, et al. Urban heat island effect on annual mean temperature during the last 50 years in China. *Theor Appl Climatol*, 2004, 79: 165–174
- 27 Li Q X, Li W, Si P, et al. Assessment of surface air warming in northeast China, with emphasis on the impacts of urbanization. *Theor Appl Climatol*, 2010, 99: 469–478
- 28 Zhang A Y, Ren G Y, Zhou J X, et al. On the urbanization effect on surface air temperature trends over China (in Chinese). *Acta Meteorol Sin*, 2010, 68: 957–966
- 29 Zhou L M, Dickinson R E, Tian Y H, et al. Evidence for a significant urbanization effect on climate in China. *Proc Natl Acad Sci USA*, 2004, 101: 9540–9544
- 30 Zhang J Y, Dong W J, Wu L Y, et al. Impact of land use changes on surface warming in China. *Adv Atmos Sci*, 2005, 22: 343–348
- 31 Lim Y K, Cai M, Kalnay E, et al. Observational evidence of sensitivity of surface climate changes to land types and urbanization. *Geophys Res Lett*, 2005, 32: L2271222
- 32 Nuñez M N, Ciapessoni H H, Rolla A, et al. Impact of land use and precipitation changes on surface temperature trends in Argentina. *J Geophys Res*, 2008, 113: D06111
- 33 Yang X C, Zhang Y L, Liu L S, et al. Sensitivity of surface air temperature change to land use/cover types in China. *Sci China Ser D: Earth Sci*, 2009, 52: 1207–1215
- 34 Fall S, Niyogi D, Gluhovsky A, et al. Impacts of land use land cover on temperature trends over the continental United States: Assessment using the North American Regional Reanalysis. *Int J Climatol*, 2010, 30: 1980–1993
- 35 Hu Y C, Dong W J, He Y. Impact of land surface forcings on mean and extreme temperature in eastern China. *J Geophys Res*, 2010, 115: D19117
- 36 Sun M, Tang J P, Xu C Y. Impact of urbanization and land-use change on regional temperature in eastern China (in Chinese). *J Nanjing Univ Nat Sci*, 2011, 47: 679–691
- 37 Trenberth K E. Climatology (communication arising): Rural land-use change and climate. *Nature*, 2004, 427: 213
- 38 Vose R S, Karl T R, Easterling D R, et al. Climate (communication arising): Impact of land-use change on climate. *Nature*, 2004, 427: 213–214
- 39 Zhang L, Yang X Q, Tang J P, et al. Simulation of urban heat island effect and its impact on atmospheric boundary layer structure over Yangtze River Delta region in summer (in Chinese). *J Meteorol Sci*, 2011, 31: 431–440
- 40 Ding Y H, Dai X S. Temperature change during the recent 100 years over China (in Chinese). *Meteorol Mon*, 1994, 20: 19–26
- 41 Li Q X, Liu X N, Zhang H Z, et al. Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. *Adv Atmos Sci*, 2004, 21: 260–268
- 42 Li Q X, Dong W J. Detection and adjustment of undocumented discontinuities in Chinese temperature series using a composite approach. *Adv Atmos Sci*, 2009, 26: 143–153
- 43 Li Z, Yan Z W. Homogenized daily mean/maximum/minimum temperature series for China from 1960–2008. *Atmos Oceanic Sci Lett*, 2009, 2: 236–242
- 44 Li Z, Yan Z W. Application of multiple analysis of series for homogenization to Beijing daily temperature series (1960–2006). *Adv Atmos Sci*, 2010, 27: 777–787
- 45 Wu Z X. Preliminary analysis of the information on meteorological station historical evolution and its impacts on homogeneity of observational records (in Chinese). *J Appl Meteorol Sci*, 2005, 16: 461–467
- 46 Li Q X, Liu X N, Zhang H Z, et al. Homogeneity study of *in situ* observational climate series (in Chinese). *Meteorol Sci Technol*, 2003, 31: 3–10
- 47 Wu L H, Kang L L, Chen H Y, et al. Effect of meteorological observation environment variability on homogeneity of temperature series in Zhejiang Province (in Chinese). *Meteorol Sci Technol*, 2007, 35: 152–156
- 48 Cao L J, Yan Z W. Progresses in research of homogenization of climate data (in Chinese). *Adv Clim Change Res*, 2011, 7: 129–135
- 49 He C Y, Shi P J, Li J G, et al. Restoring urbanization process in China in the 1990s by using non-radiance-calibrated DMSP/OLS nighttime light imagery and statistical data. *Chin Sci Bull*, 2006, 51: 1614–1620
- 50 Wang H R, Zheng X Q, Yuan T. Overview of researches based on DMSP/OLS nighttime light data (in Chinese). *Progr Geogr*, 2012, 31: 11–19
- 51 He C Y, Li J G, Chen J, et al. The urbanization model and process in Bohai sea surrounding area in the 1990s by using DMSP/OLS data (in Chinese). *Acta Geogr Sin*, 2005, 60: 409–417
- 52 Shu S, Yu B L, Wu J P, et al. Methods for deriving urban built-up area using night-light data: Assessment and application (in Chinese). *Remote Sens Technol Appl*, 2011, 26: 169–176
- 53 Xu M J, Chen L, Liu H J, et al. Pattern and process of urbanization in the Yangtze Delta based on DMSP/OLS data (in Chinese). *Remote Sens Land Resour*, 2011, 3: 106–112
- 54 Ding Y H, Ren G Y, Zhao Z C, et al. Detection, causes and projection of climate change over China: An overview of recent progress.

- Adv Atmos Sci, 2007, 24: 954–971
- 55 Chen B, Shi G Y, Dai T, et al. Climate forcing due to anthropogenic heat release over China (in Chinese). *Clim Environ Res*, 2011, 16: 717–722
- 56 Zhang C, Shu J, Chen S S. Urban anthropogenic heat categorizing and its effects on urban temperature (in Chinese). *Resour Environ Yangtze Basin*, 2011, 20: 232–238
- 57 Zhang Y, Bao W J, Yu Q, et al. Study on seasonal variations of the urban-heat island and its interannual changes in a typical Chinese megacity (in Chinese). *Chin J Geophys*, 2012, 55: 1121–1128
- 58 Hua L J. An analysis of the temperature range and the warming effect of urbanization in China regions (in Chinese). Dissertation for the Doctoral Degree. Qingdao: Ocean University of China, 2004. 22–43
- 59 Ji C P, Liu W D, Xuan C Y. Impact of urban growth on the heat island in Beijing (in Chinese). *Chin J Geophys*, 2006, 49: 69–77
- 60 Zhang J H, Meng Q W, Li X, et al. Urban heat island variations in Beijing region in multi spatial and temporal scales (in Chinese). *Sci Geogr Sin*, 2011, 31: 1349–1354

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