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ORIGINAL PAPER

Impacts of urbanization and agricultural development on observed changes in surface air temperature over mainland China from 1961 to 2006

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Abstract

A large proportion of meteorological stations in mainland China are located in or near either urban or agricultural lands that were established throughout the period of rapid urbanization and agricultural development (1961–2006). The extent of the impacts of urbanization and agricultural development on observed air temperature changes across different climate regions remains elusive. This study evaluates the surface air temperature trends observed by 598 meteorological stations in relation to the urbanization and agricultural development over the arid northwest, semi-arid intermediate, and humid southeast regions of mainland China based on linear regressions of temperature trends on the fractions of urban and cultivated land within a 3-km radius of the stations. In all three regions, the stations surrounded by large urban land tend to experience rapid warming, especially at minimum temperature. This dependence is particularly significant in the southeast region, which experiences the most intense urbanization. In the northwest and intermediate regions, stations surrounded by large cultivated land encounter less warming during the main growing season, especially at the maximum temperature changes. These findings suggest that the observed surface warming has been affected by urbanization and agricultural development represented by urban and cultivated land fractions around stations in with land cover changes in their proximity and should thus be considered when analyzing regional temperature changes in mainland China.

Keywords Surface air temperature · Climate change · Urbanization · Agricultural development · Land cover changes

1 Introduction

Land use and land cover (LULC) changes, such as urbanization and agricultural development, are important anthropogenic factors that influence climate aside from greenhouse gas emission (Kalnay and Cai 2003). Urbanization can alter the radiation budget and modify the surface energy balance, thus increasing near-surface air temperature (Stewart and Oke 2012). Reduction of evaporative cooling by replacing vegetation with impervious surface and buildings is one of the main reasons for this urban heat island (UHI) effect (Arnfield 2003; Oke 1982; Zhao et al. 2014). Anthropogenic heat release is another main aspect that changes the surface energy balance, which also affects surface temperature (Li et al. 2013). The release of the daytime stored energy from nearby buildings and other artificial materials at night contributes to nighttime UHI, resulting to a more apparent UHI effect on minimum temperature (Peng et al. 2013). Nevertheless, urbanization may also lead to a decreased temperature in arid regions (Georgescu et al. 2011; Zhao et al. 2014). Meanwhile, agricultural development, including the enhancement of irrigation and fertilization, may increase evapotranspiration through increasing vegetation growth/productivity. Thus, agricultural development increases evaporative cooling and lowers the near-surface air temperature during the growing season (Bonfils and Lobell 2007; Govindasamy et al. 2001; Han and Yang 2013; Zhang et al. 2013). The agricultural cooling

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effect is more obvious on the daytime maximum temperature, and a weaker or even a warming effect on nighttime minimum temperature was found in irrigation regions (Bonfils and Lobell 2007).

The warming or cooling effects due to urbanization or agricultural development are usually estimated by comparing the observed temperature in urban or agricultural locations with that in the reference locations with minimal influences of human activities. These results largely depend on the classifications of urban (or agricultural) versus reference stations (Lowry 1977). Different methods have been used to identify the type of stations on the bases of various data, such as population (Easterling et al. 1997; Ren et al. 2008), satellite-measured nighttime light (Hansen et al. 2001), satellite-derived normalized difference vegetation-index data (Gallo et al. 1993), energy consumption (Li et al. 2013), and land use (Rim 2009). The agricultural and reference stations are usually identified using land use/land cover data (Bonfils and Lobell 2007; Han and Yang 2013; Mahmood et al. 2008). Therefore, the land use/land cover data can be in turn used to identify the urban, agricultural, and reference stations simultaneously, with the urban or cultivated land fractions around stations as indices. For example, the land use/land cover of the area within a certain radius of the site (Rim 2009), or the grid cell where the meteorological station is located (Zhu et al. 2012) is adopted. However, the results depend on the spatial scale of the land being used surrounding the stations. In order to minimize the unpredictability of the scale length, the land use fractions within the radii of 1–10, 15, and 30 km, centered at each station, were tested (Han et al. 2012; Han and Yang 2013). The role of urbanization on observed temperature changes can be derived based on the positive correlations between the temperature trends and urbanization indices (Li et al. 2013), and the impacts of agricultural development can be derived from the negative correlations between these trends and the cultivated (or irrigated) land fractions (Han and Yang 2013; Lobell and Bonfils 2008).

Although urban and agricultural areas only constitute a small fraction of the Earth's surface area (Small 2005; Vitousek et al. 1997), most meteorological stations are located in or near either urban or agricultural areas (Das et al. 2011; Montandon et al. 2011). Global croplands and urban areas have expanded recently (Foley et al. 2005), especially in countries such as China that experience rapid economic growth. The corresponding changes in land use/land cover may superimpose any regional or global trends in these areas (Fall et al. 2010; Gallo et al. 1999; Li et al. 2009a). The warming or cooling effects on observed temperature changes have drawn considerable attention (Bonfils and Lobell 2007; Kalnay and Cai 2003).

The climate in China has warmed considerably since 1960 (Ding 2006; Piao et al. 2010; Ren et al. 2005). During the same period, the country experienced remarkable agricultural development since the 1960s and rapid urbanization since the 1980s. Previous studies have determined that surface warming in China is more significant over urban lands than over cultivated lands (Hu et al. 2010; Yang et al. 2009). These findings suggest that urbanization enhances surface warming, but agricultural development may suppress this phenomenon in some regions (Han and Yang 2013; Shi et al. 2013; Zhu et al. 2012), which is seldom considered when evaluating the regional variations in air temperature (Ren et al. 2005; Yang et al. 2015). However, most studies to date have been limited either to the impact of urbanization or the impact of agricultural development.

In addition, although the impressions regarding urbanization and agricultural development having influences on observed air temperature have been acknowledged, the extent of their contributions over different regions of China, such as the northwest and southeast regions, remains elusive. As the responses of air temperature to urbanization and agricultural activity vary across regions (Li et al. 2013; Lobell et al. 2009), and the rates of urbanization and agricultural development differ across different regions of China, the impacts of agricultural development or urbanization on temperature can be expected to vary by region. However, most studies to date have been limited to certain regions of China. The impacts of agricultural development were mainly conducted over Northwest China (Han and Yang 2013), or the North China Plain (Shi et al. 2013), the Loess Plateau (Xu et al. 2016), as well as northeast (Zhao et al. 2016; Zhu et al. 2012) and southwest China (Zhang et al. 2002). The studies about the warming effects of urbanization were often conducted in east or south China (Wang et al. 2015; Yang et al. 2011), where the most rapid urbanization was experienced. Therefore, how the remarkable agricultural development and rapid urbanization together affect observed changes in surface air temperature, especially their different contributions over different regions of China, remains elusive. The present study aims to quantitatively investigate the combined impacts of urbanization and agricultural development on observed temperature changes from the northwest to the southeast regions of mainland China.

2 Study area, data, and methods

2.1 Study area

Mainland China can be approximately divided into arid/semi-arid, semi-humid, and humid regions with corresponding agriculture zones according to the 400- and 1000-mm precipitation isohyets (Compiler Group of Physical Geography of China 1993; Feng 2005; Han et al. 2012). In this study, this division was done with a consideration of provincial-level administration divisions, in order to match with the census data (Fig. 1): the northwest region (including Xinjiang Autonomous Region, Qinghai Province, Gansu Province, Ningxia Autonomous Region, and Inner Mongolia Autonomous Region), the southeast region (including Guizhou Province, Guangxi Province, Guangdong Province, Hainan Province, Fujian Province, Zhejiang Province, Jiangxi Province, Hunan Province, Hubei Province, Shanghai Municipality, Chongqing Municipality, Anhui Province, and Jiangshu Province), and the intermediate region (covers the remaining 13 provinces of mainland China). Urbanization levels and cropping systems differ considerably across the three regions (Feng 2005; Piao et al. 2010; Wang et al. 2012). The northwest region includes the main underdeveloped areas of China, and agriculture is the most important industry. The cultivated lands in the hyper-arid area in Northwest China rely heavily on perennial irrigation (Feng 2005). The intermediate region includes the main agricultural and densely populated areas of China and has a collectively rapid urbanization and agricultural development. The southeast region includes the main economical developed areas, with vast cultivated lands converted into urban land (Wang et al. 2012).

China has experienced rapid urbanization since the early 1980s when it began to carry out reformations and open policy, as reflected in the time series of the population residing in urban areas (based on data regarding provincial population from the National Bureau of Statistics of China (2010)). The urban population of mainland China increased from 1.27×10^8 in 1961 to 5.77×10^8 in 2006. Among the three regions, urban population increased the most rapidly in the southeast region (from 0.70×10^8 in 1961 to 322×10^8 in 2006, Fig. 2a), reflecting the urbanization rate is the largest in that region.

Based on data regarding provincial agricultural development from the National Bureau of Statistics of China (2010), China having benefited from the increased use of fertilizers (consumption of chemical fertilizers increased from 0.4×10^6 t in 1961 to 49.3×10^6 t in 2006), expanded irrigation (irrigated area in China increased from 32.1×10^6 ha in 1961 to 55.8×10^6 ha in 2006), and an improved management, the nation conducted rapid agricultural development during the study period. The irrigated area increased the most rapidly in the intermediate region, from 12.5×10^6 ha in 1961 to 27.2×10^6 ha in 2006, followed by the northwest region (Fig. 2b). However, the irrigated area in the southeast region increased more slowly to 1975, and kept stable thereafter. As a result, grain production of China increased from 136.5×10^6 t in 1961 to 498.0×10^6 t with a decreased grain crop sown area in 2006. The different agricultural development rates among the three regions can be roughly identified from the changes of grain production (Fig. 2c). The grain production increased the most rapidly in the intermediate region, from 59.3×10^6 t in 1961 to 274.8×10^6 ton in 2006. By contrast, a slowdown of the increasing rate occurred in the middle 1980s, and even a decrease occurred in the end 1990s in the southeast region. The differences in the changes of grain production among the three regions are corresponding to the differences in changes of irrigated area.

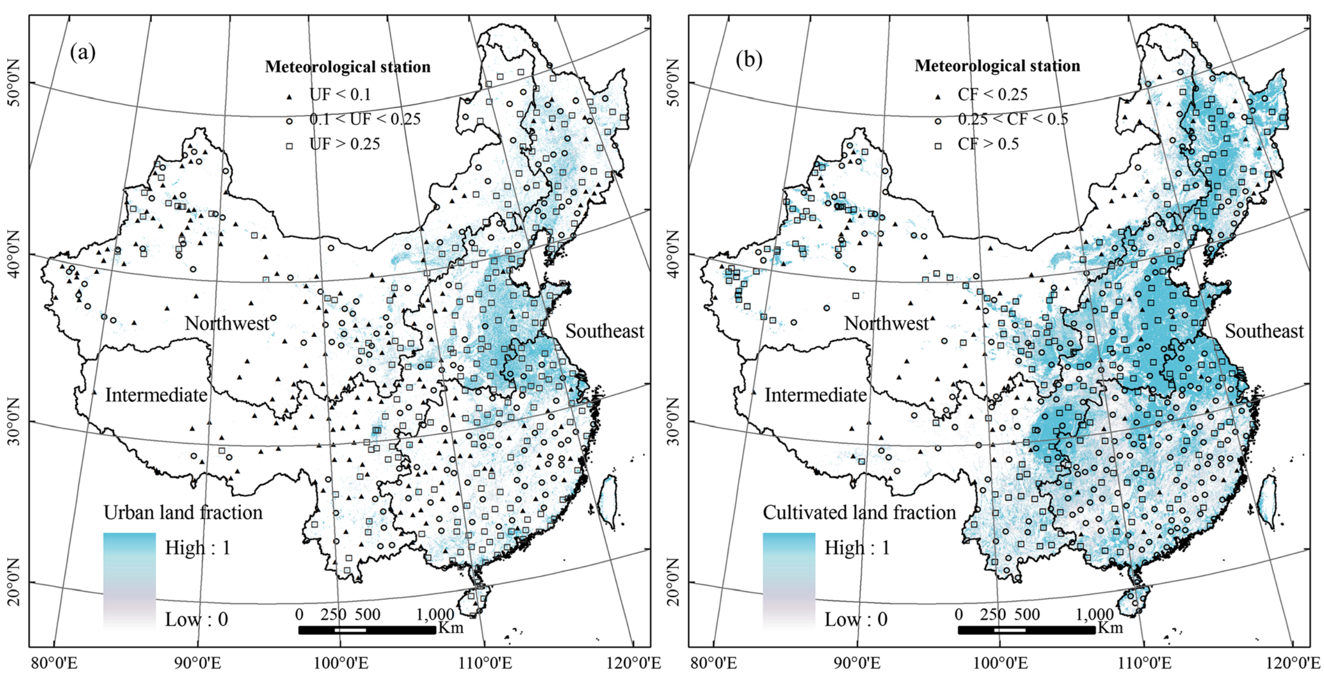


Fig. 1 The meteorological stations and the **a** urban land and **b** cultivated land fractions in each 1-km grid over mainland China at year 2000. The size of the circles represents the UF in panel (**a**) and CF in panel (**b**) of the stations. The Northwest, intermediate, and southeast regions are delineated in the map

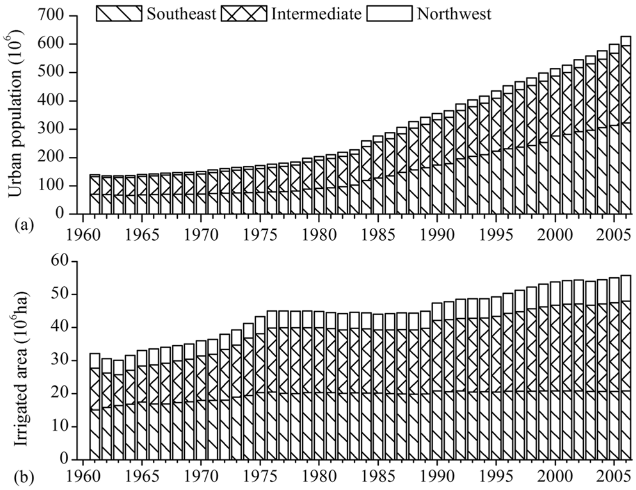


Fig. 2 Time series of **a** urban population and **b** irrigated area of the three regions over mainland China from 1961 to 2006

2.2 Surface air temperature data and trends analysis

The surface air temperature dataset includes the monthly average temperature (T_a), maximum temperature (T_{max}), and minimum temperature (T_{min}) as obtained by 756 and 45 meteorological stations across mainland China [the National Meteorological Information Center of CMA (http://cdc.cma.gov.cn)] and Xinjiang Province (the Climatic Center of Xinjiang) from 1961 to 2006. A total of 649 stations were obtained upon stations neither fell into the sea nor were located at small islands along the coast, and with more than 40 years' worth of records. Relocations and changes in the environmental conditions around stations have resulted temporal inhomogeneity in China's surface air temperature data (Li et al. 2004b). Although researchers have adjusted the corresponding inhomogeneous temperature series to generate homogenized historical temperature datasets (Li et al. 2004b; Li and Yan 2009), unadjusted temperature time series have been used to evaluate urbanization or irrigation effects (He et al. 2007; Shi et al. 2013; Zhang et al. 2005; Zhu et al. 2012) because the adjustment may inadvertently weaken the land use effect (Zhou et al. 2004). The current study uses an unadjusted air temperature dataset. However, the trends of annual mean T_a, T_{max}, and T_{min} at these stations were compared with a corresponding homogenized dataset (a homogenized historical temperature dataset for the period of 1951 to 2004 was collated from 731 stations (Li et al. 2004a; Li et al. 2009b) [http://data.cma.gov.cn]). If a particular station was not included in the homogenized dataset, a nearby station was used instead. Fifty-one stations (7.9% of all stations) that deviated significantly from their corresponding homogenized data were eliminated (the differences of trends in annual T_a, T_{max}, and T_{min} were greater than 0.3, 0.3, and 0.45 K/decade, respectively, which displayed about 3% maximum trend differences) to minimize the effects of inhomogeneous data. The remaining 598 stations (Fig. 1) were analyzed. A total of 186, 231, and 181 stations were examined in the northwest, intermediate, and southeast regions.

The trends of mean T_a, T_{max}, and T_{min} during the period from May to September, from October to April, and throughout the year in the period of 1961 to 2006 were analyzed for all the 598 stations. The magnitude of the trend in surface air temperature is given by

$$\beta = \text{median}\left[\frac{(X_j - X_i)}{(j-i)}\right], \forall i < j, \tag{1}$$

where i and j refer to the year, X_i and X_j denote the annual mean temperature in years i and j, and β is the change trend magnitude. The average temperature trends in different seasons of stations in the three regions are shown in Table 1. The trends' significance was assessed by the non-parametric Mann–Kendall test with a trend-free, pre-whitening method (Yue et al. 2002).

2.3 Land use data and linear regression method

The proportions of urban land (as a sum of the residential, industrial, and traffic lands) and cultivated land (including dryland and paddy croplands) for 2000 at grid intervals of 1 km, based on the 1:100,000 land use map (Liu et al. 2003), were used to identify the land uses around stations. The area fractions of the urban land (including residential, industrial, and traffic lands) and cultivated land in 2000 are shown in Fig. 1. The urban land fractions (UF) and cultivated land fraction (CF) within a certain radius were calculated as the indices denoting the urban and agricultural land use surrounding each station. Then, the linear regressions of temperature trends on the UFs and CFs were calculated, and a t test was used to evaluate the statistical significance of the linear regression.

The dependence of observed surface air temperature trends to UFs and CFs was then evaluated on the basis of linear regression slopes (k), following Bonfils and Lobell (2007). Different radii (1–10, 15, and 30 km) were tested to calculate the UFs and CFs, and a certain radius of each station generating the most significant correlations is regarded as optimal. The T_a trends of the 598 stations are significantly correlated with the UFs, and the correlations are less significant during the main growing season (May–September) (Table 2). Among the correlations of UFs within different radii, the correlation is the most significant at 3-km radii. The T_a trends during the main growing season of the 598 stations are also significantly correlated with the CFs; and the correlation is the most significant at 3-km radii. Therefore, the land use fractions within a 3-km radius are chosen as the indices representing urbanization and agricultural development and used thereafter. The UFs within a 3-km radius of 598 stations range from 0 to 93.9%, with a mean value of 22.8%, and the CFs range from 0 to 97.9%, with a mean value of 38.3% (Table 1).

Table 1 Average temperature trends (K/decade) in different seasons of stations in the three regions of China

Region	Number of stations	UF (%)	CF (%)	Annual			May–Sep.			Oct.–Apr.		
				T_a	T_{max}	T_{min}	T_a	T_{max}	T_{min}	T_a	T_{max}	T_{min}
China	598	22.8	38.2	0.270	0.192	0.371	0.157	0.101	0.254	0.347	0.250	0.455
Northwest	186	16.3	35.8	0.346	0.255	0.476	0.234	0.177	0.370	0.422	0.305	0.551
Intermediate	231	24.0	41.5	0.271	0.188	0.384	0.149	0.084	0.254	0.352	0.250	0.477
Southeast	181	27.7	36.5	0.189	0.133	0.246	0.089	0.045	0.133	0.262	0.195	0.330

3 Results

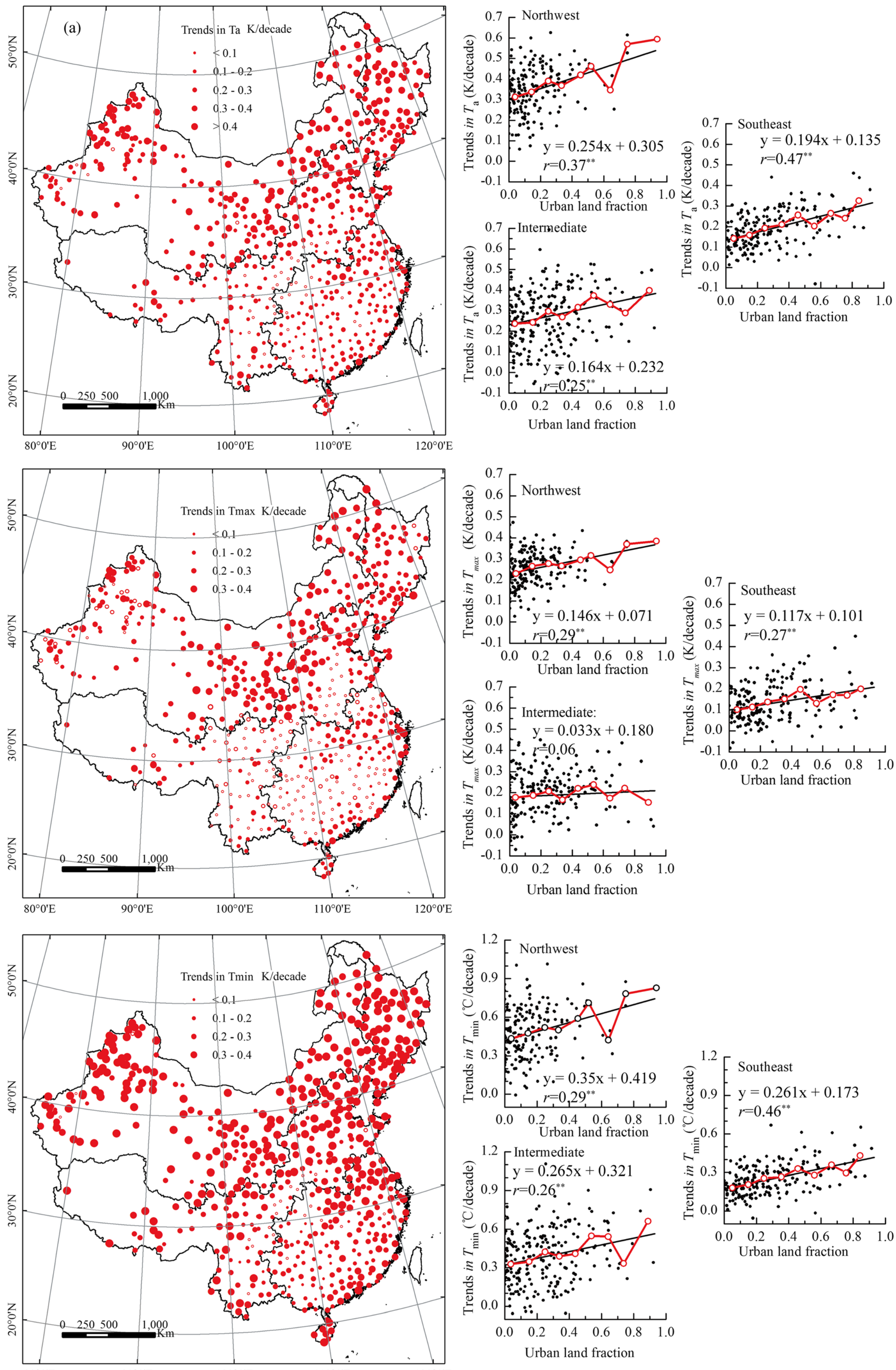
3.1 Dependence of temperature trends on urban land fractions

Of the 598 stations, 555, 421, and 571 exhibited a significant increasing trend in T_a, T_{max}, and T_{min} at $P < 0.05$, respectively (Fig. 3). The average trends of T_a, T_{max}, and T_{min} of the 598 stations are 0.270, 0.192, and 0.371 K/decade, respectively (Table 1). T_a trends are generally higher than T_{max} trends, but lower than T_{min} trends. Meanwhile, the average trends of T_a, T_{max}, and T_{min} in the period of October to April are 0.347, 0.250, and 0.455 K/decade, respectively, whereas these trends are only 0.157, 0.101, and 0.254 K/decade in the main growing season. Among the three regions, the northwest region exhibits the highest warming (the average trend of T_a of the 186 stations is 0.346 K/decade), followed by the intermediate region (the average trend of T_a of the 231 stations is 0.271 K/decade).

Table 2 Parameters of linear regression (the slope k, and correlation coefficient r) of T_a trends (K/decade) of stations upon the UFs and CFs, with a certain radius centered of the stations

Land use index	Radius (km)	Annual		May–Sep.		Oct.–Apr.	
		k	r	k	r	k	r
UFs	1	0.06	0.14**	0.033	0.08*	0.07	0.15**
	2	0.095	0.17**	0.051	0.10*	0.114	0.19**
	3	0.116	0.18**	0.063	0.10*	0.141	0.19**
	4	0.127	0.17**	0.067	0.09*	0.156	0.19**
	5	0.141	0.17**	0.072	0.09*	0.176	0.19**
	6	0.153	0.16**	0.076	0.09*	0.192	0.18**
	7	0.159	0.15**	0.076	0.08	0.203	0.18**
	8	0.166	0.15**	0.076	0.07	0.213	0.17**
	9	0.171	0.14**	0.074	0.07	0.223	0.17**
	10	0.178	0.14**	0.073	0.06	0.236	0.17**
	15	0.219	0.13**	0.064	0.04	0.307	0.16**
	30	0.281	0.11**	0.007	0	0.437	0.15**
CFs	1	−0.038	−0.09*	−0.058	−0.14**	−0.025	−0.05
	2	−0.058	−0.12**	−0.083	−0.18**	−0.04	−0.07
	3	−0.058	−0.11**	−0.092	−0.19**	−0.035	−0.06
	4	−0.047	−0.09*	−0.087	−0.18**	−0.02	−0.03
	5	−0.037	−0.07	−0.082	−0.17**	−0.008	−0.01
	6	−0.031	−0.06	−0.079	−0.16**	0	0
	7	−0.027	−0.05	−0.077	−0.16**	0.003	0.01
	8	−0.023	−0.04	−0.074	−0.15**	0.007	0.01
	9	−0.021	−0.04	−0.072	−0.15**	0.009	0.01
	10	−0.019	−0.04	−0.07	−0.14**	0.01	0.02
	15	−0.017	−0.03	−0.067	−0.14**	0.008	0.01
	30	−0.029	−0.05	−0.072	−0.14**	−0.01	−0.02

**Significant at $P < 0.01$, *significant at $P < 0.05$


(a)
Trends in Ta K/decade
< 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
> 0.4
0 250 500 1,000
Km
50°0'N
40°0'N
30°0'N
20°0'N
80°0'E
90°0'E
100°0'E
110°0'E
120°0'E
Northwest
y = 0.254x + 0.305
r=0.37**
Trends in T_a (K/decade)
Urban land fraction
Southeast
y = 0.194x + 0.135
r=0.47**
Intermediate
y = 0.164x + 0.232
r=0.25**
Trends in Tmax K/decade
< 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
Northwest
y = 0.146x + 0.071
r=0.29**
Trends in T_{max} (K/decade)
Southeast
y = 0.117x + 0.101
r=0.27**
Intermediate:
y = 0.033x + 0.180
r=0.06
Trends in Tmin K/decade
< 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
Northwest
y = 0.35x + 0.419
r=0.29**
Trends in T_{min} (℃/decade)
Southeast
y = 0.261x + 0.173
r=0.46**
Intermediate
y = 0.265x + 0.321
r=0.26**

◀ **Fig. 3** The trends in annual mean **a** T_a, **b** T_{max}, and **c** T_{min} in 1961–2006 over mainland China (The solid marks show that the trends are significant at $P < 0.05$, and unfilled marks show that the trends are not significant), and their plots against UFs at the stations in the northwest, intermediate, and southeast regions. The linear regression lines (solid black lines), equations, and correlation coefficient (r, significant at $P < 0.01$, *significant at $P < 0.05$), and the average trends partitioned by CF classes (red lines with circles) are shown in the panels

The temperature trends are positively correlated with the UFs within a 3-km radius from the stations (Table 3 and Fig. 3), and these correlations are most significant in the southeast region ($P < 0.01$). Moreover, the T_{max} correlations are weaker than those of T_a and T_{min}, even though no statistical correlation is detected between T_{max} trends and the UFs in the intermediate region. In the northwest and intermediate regions, the correlations are weaker in the period of May to September than in the period of October to April. But no obvious difference of the correlations is observed in the two periods over the southeast region. This result suggests that the spatial extent of urban land has an obvious influence on observed temperature trends, and the stations surrounded by a large fraction of urban land experience greater warming than the stations surrounded by a small fraction of urban land. The slopes of the linear regression of T_a trends upon UFs are 0.254, 0.164, and 0.194 K/decade in the northwest, intermediate, and southeast regions, respectively. The relative magnitude of the slopes (the ratio of the regression slope to the average trend for all the stations) are 73.4, 60.4, and 102.9% of the average trend for all the stations (0.346, 0.271, 0.189 K/decade, in Table 1 in the corresponding regions). The result indicates that the dependence of temperature trends on the UFs is the most significant in the southeast region, followed by the northwest region, which is consistent with the most rapid urbanization in the southeast region.

3.2 Dependence of temperature trends on cultivated land fractions

The temperature trends are negatively correlated with CFs within a 3-km radius from the stations (Table 4 and Fig. 4), but these correlations are considerably weaker than the correlations with the UFs. In the northwest and intermediate regions, the correlations are statistically significant ($P < 0.01$) during the main growing season, but not significant ($P > 0.05$) during the period of October to April. In the southeast region, the correlations are not statistically significant ($P > 0.05$) during both the two periods. The significant negative linear correlations during the period of May to September suggest that, in the northwest and intermediate regions, the spatial extent of cultivated land has an obvious influence on observed temperature trends during the main growing season, and the stations with large CFs generally experience less warming during this season than those with small CFs do. The dependence of T_{max} on the CFs is more significant than that of T_{min}. The slopes of the linear regression of main growing season T_{max} trends upon CFs are 0.059 and 0.077 K/decade in association with fully covered crop land use (i.e., 100%) in the northwest and intermediate regions, respectively. The relative magnitudes of the slopes are 33.3 and 91.7% of the average trends for the stations located in the two regions. The result indicates that the dependence of temperature trends on the CFs of stations is more significant in the intermediate region.

Table 3 Parameters of linear regression of the trends in T_a, T_{max}, and T_{min} (K/decade) during 1961–2006 upon the UFs

Regions		Annual		May–Sep.		Oct.–Apr.	
		k	r	k	r	k	r
China	T_a	0.116 ± 0.052	0.18**	0.063 ± 0.049	0.10*	0.141 ± 0.057	0.19**
	T_{max}	0.030 ± 0.043	0.06	0.005 ± 0.047	0.01	0.037 ± 0.046	0.07
	T_{min}	0.170 ± 0.081	0.17**	0.109 ± 0.075	0.12**	0.208 ± 0.089	0.19**
Northwest	T_a	0.254 ± 0.093	0.37**	0.167 ± 0.103	0.23**	0.268 ± 0.103	0.35**
	T_{max}	0.146 ± 0.071	0.29**	0.110 ± 0.088	0.18*	0.131 ± 0.083	0.22**
	T_{min}	0.350 ± 0.170	0.29**	0.254 ± 0.171	0.21**	0.388 ± 0.187	0.29**
Intermediate	T_a	0.164 ± 0.084	0.25**	0.084 ± 0.074	0.15*	0.208 ± 0.097	0.27**
	T_{max}	0.033 ± 0.070	0.06	0.001 ± 0.069	0	0.042 ± 0.076	0.07
	T_{min}	0.265 ± 0.129	0.26**	0.187 ± 0.106	0.22**	0.309 ± 0.151	0.26**
Southeast	T_a	0.194 ± 0.054	0.47**	0.175 ± 0.053	0.44**	0.206 ± 0.060	0.45**
	T_{max}	0.117 ± 0.063	0.27**	0.122 ± 0.068	0.25**	0.118 ± 0.064	0.26**
	T_{min}	0.261 ± 0.075	0.46**	0.246 ± 0.069	0.46**	0.282 ± 0.082	0.45**

**Significant at $P < 0.01$, *significant at $P < 0.05$

Table 4 Parameters of linear regression of the trends in T_a, T_{max}, and T_{min} (K/decade) during 1961–2006 upon the CFs

Regions		Annual		May–Sep.		Oct.–Apr.	
		k	r	k	r	k	r
China	T_a	− 0.058 ± 0.041	− 0.11**	− 0.092 ± 0.038	− 0.19**	− 0.035 ± 0.045	− 0.06
	T_{max}	− 0.022 ± 0.034	− 0.05	− 0.064 ± 0.036	− 0.14**	− 0.004 ± 0.036	− 0.01
	T_{min}	− 0.075 ± 0.064	− 0.09*	− 0.087 ± 0.059	− 0.12**	− 0.067 ± 0.071	− 0.08
Northwest	T_a	− 0.069 ± 0.054	− 0.18*	− 0.111 ± 0.056	− 0.28**	− 0.029 ± 0.060	− 0.07
	T_{max}	− 0.022 ± 0.040	− 0.08	− 0.059 ± 0.049	− 0.17*	0.012 ± 0.047	0.04
	T_{min}	− 0.081 ± 0.097	− 0.12	− 0.104 ± 0.095	− 0.16*	− 0.069 ± 0.107	− 0.09
Intermediate	T_a	− 0.059 ± 0.072	− 0.11	− 0.087 ± 0.061	− 0.18**	− 0.046 ± 0.083	− 0.07
	T_{max}	− 0.030 ± 0.058	− 0.07	− 0.077 ± 0.057	− 0.17**	− 0.014 ± 0.063	− 0.03
	T_{min}	− 0.103 ± 0.110	− 0.12	− 0.091 ± 0.089	− 0.13*	− 0.108 ± 0.128	− 0.11
Southeast	T_a	− 0.030 ± 0.060	− 0.07	− 0.044 ± 0.058	− 0.11	− 0.025 ± 0.066	− 0.06
	T_{max}	0.007 ± 0.064	0.02	− 0.021 ± 0.070	− 0.05	− 0.008 ± 0.066	− 0.02
	T_{min}	− 0.026 ± 0.083	− 0.05	− 0.033 ± 0.077	− 0.06	− 0.014 ± 0.091	− 0.02

**Significant at $P < 0.01$, *significant at $P < 0.05$

The dependence of main growing season temperature trends on UFs and CFs over the northwest and intermediate regions are analyzed collectively through a stepwise linear regression method (Draper and Smith 2014) (Table 5). In the northwest region, the impact of UFs on T_a, T_{max}, and T_{min} trends are all much larger than that of CFs. In the intermediate region, the effects of UFs and CFs on T_a trends are comparative, but the impacts of UFs are much larger on T_{min}, whereas the effects of CFs are much larger on T_{max}.

3.3 Different temperature changes at stations over urban and cultivated lands

To distinguish potential impacts of UFs and CFs further, all the stations were categorized into four groups as follows: reference (UF < 10% and CF < 25%, 110 stations), urban (UF > 25% but CF < 25%, 64 stations), agricultural (CF > 50% but UF < 10%, 59 stations), and other stations. The average temperature time series for "urban" group show higher warming trend than the reference station group, but those for the "agricultural" group show lower trends than reference station group (Table 6). When the northwest region is taken as an example, the growing season T_{max} trends of the reference (53 stations), urban (14 stations), and agricultural (28 stations) groups are 0.188, 0.209, and 0.134 K/decade, respectively. The trends of the group with UF < 10% and CF < 25% are thought to be presumably attributed to reference climate variability (Li et al. 2012). The time series of the average T_a, T_{max}, and T_{min} for the reference, urban, and agricultural groups over each region were compared in Fig. 5. The "urban" and "agricultural" groups depart from the reference group in the opposite directions.

4 Discussions and conclusions

The factors affecting surface temperature trends, such as changes in solar radiation at Earth's surface (Wild et al. 2007), atmospheric CO_2 (Hansen et al. 1981), and aerosol (Huang et al. 2006), may be related to the geographical locations. These effects could be spatially inhomogeneous at much larger scale far beyond the distance between the meteorological stations. Although the correlations between the observed temperature trends and the latitude of the stations (0.61 for annual T_a) over mainland China are significant at $P < 0.01$, no significant correlations were detected between the UFs (and CFs) and station latitude at $P < 0.01$ (Table 7). On the other hand, although the UFs (and CFs) are significant correlated with the longitude and altitude of stations, observed temperature trends were not correlated with the longitude and altitude of the stations at $P < 0.01$. These results eliminate the possibility that the dependence of air temperature trends on UFs (and CFs) originates from station latitude.

The dependences of temperature trends on UFs and CFs imply urbanization warming effects due to urbanization and cooling effects due to agricultural development on stations. The more significant dependence of T_{min} trends on UFs than that of T_{max} is consistent with the fact that the urban heating effect is intense at night because buildings and streets release the solar heat absorbed during the day (Kalnay and Cai, 2003; Liu et al. 2007; Peng et al. 2011). On the other hand, the more significant dependence of T_{max} trends on CFs than that of T_{min} trends during the main growing season is consistent with the fact that agricultural development reduces sensible heat flux during daytime (Bonfils and Lobell 2007). It should be noted that the rate at which urbanization (or agricultural development) rather than the presence of urban or cultivated lands is

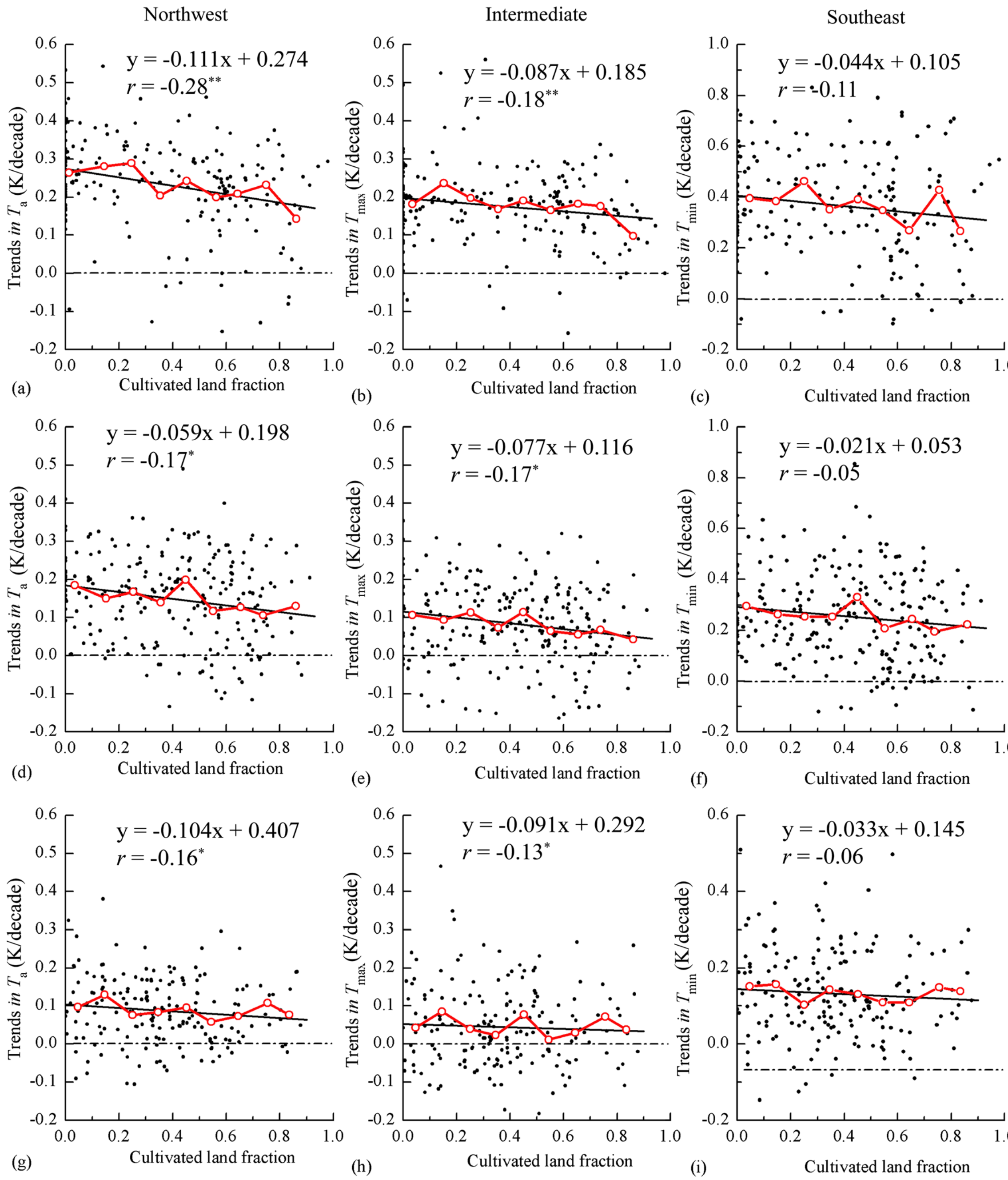


Fig. 4 Trends in main growing season T_a (**a**), T_{max} (**b**), and T_{min} (**c**) in the northwest region; T_a (**d**), T_{max} (**e**), and T_{min} (**f**) in the intermediate region; and T_a (**g**), T_{max} (**h**), and T_{min} (**i**) in the southeast region of mainland China against the CFs at the stations. The linear regression lines (solid black lines), equations, and correlation coefficient (r, significant at $P < 0.01$, *significant at $P < 0.05$), and the average trends partitioned by CF classes (red lines with circles) are shown in the panels

at the origin of net warming or cooling on observed temperature changes (Lobell et al. 2009). With the rapid urbanization and agricultural development since the 1960s, a station with a large UF (or CF) would be affected by the accelerated urbanization (or agricultural development). However, because the data of detailed land use change is not available, only the land use in 2000 is applicable. In China, the expansion of urban land cover (Wang et al. 2012) and increased energy consumption (Li et al. 2013) are more evident in big cities with large UFs. Four of the five most urbanized provinces (Guangdong, Shandong, Jiangsu, and Zhejiang) in 2010 experienced the most fasted urban expansion from 1990 to 2010 (Wang et al. 2012). The number of stations located in urban land cover rapidly increased from 21 in the 1980s to 146 in 2003, indicating that the stations identified as “urbanized” in the 2000s would be experiencing more rapid urbanization than

Table 5 Stepwise regression parameters between the temperature trends (K/decade) in summer and the UFs and CFs in the northwest and intermediate regions

Region	Northwest			Intermediate		
Parameters	Regression slope k		r	Regression slope k		r
	UF	CF		UF	CF	
T_a	0.181 ± 0.099**	− 0.118 ± 0.054**	0.37	0.084 ± 0.072*	− 0.087 ± 0.060**	0.24
T_{max}	0.118 ± 0.087**	− 0.063 ± 0.048**	0.26	0.001 ± 0.068	− 0.077 ± 0.057**	0.17
T_{min}	0.268 ± 0.169**	− 0.115 ± 0.093*	0.27	0.187 ± 0.105**	− 0.091 ± 0.087*	0.26

**Included at $P < 0.01$, *included at $P < 0.05$

those identified as "non-urbanized" (Li et al. 2013). On the other hand, NDVI experienced marked increases in agricultural regions with large CFs (Fang et al. 2004). Therefore, stations with a large urban (or cultivated) land fraction would receive a higher and increasing urban impact (or agricultural impact) on air temperature observation. It is one of the reasons why the temperature trends are significantly dependent on the UFs (or CFs).

The magnitude of urbanization warming and agricultural cooling effects on stations vary by regions. The southeast region experienced the most rapid urbanization (which can be detected from the most rapid increase in urban population). Accordingly, the impact of urbanization on observed temperature trends is the most significant in the southeast region. The slope of the linear regression of T_a trends upon UFs is 0.194 K/decade in the southeast region, with the maximum relative magnitude of the slope (the ratio of the regression slope to the average trend for all the stations) among the three subregions. On the other hand, there is no obvious agricultural cooling effect on observed temperature trends, which corresponds to the fact that a slowdown of agricultural development occurred associated with the rapid urbanization rate since the middle 1980s.

In the northwest and intermediate regions, both the impacts of urbanization and agricultural development on observed changes in surface air temperature were discovered. The impacts of urbanization are more significant in the northwest region than those in the intermediate region (which can be detected from Tables 3 and 5). The slope of the linear regression of T_a trends upon UFs is 0.254 and 0.164 K/decade in the northwest and intermediate regions. On the other hand, agricultural development has had cooling effects on observed main growing season temperature changes at stations with large CFs in the northwest

Table 6 Trends in stations averaged air temperature time series from 1961 to 2006 (K/decade) for different station groups over the three regions of China

Regions and groups[a]		No.[b]	Fractions		Annual			May–Sep.			Oct.–Apr.		
			UF	CF	T_a	T_{max}	T_{min}	T_a	T_{max}	T_{min}	T_a	T_{max}	T_{min}
China	N	110	0.03	0.08	0.262	0.165	0.388	0.186	0.118	0.277	0.314	0.198	0.449
	U	64	0.58	0.10	0.307	0.223	0.418	0.196	0.130	0.296	0.383	0.282	0.512
	A	59	0.06	0.71	0.233	0.193	0.303	0.121	0.089	0.198	0.299	0.228	0.372
Northwest	N	53	0.03	0.05	0.316	0.222	0.434	0.252	0.188	0.349	0.369	0.242	0.480
	U	14	0.52	0.11	0.466	0.339	0.635	0.323	0.209	0.501	0.554	0.380	0.734
	A	28	0.07	0.73	0.319	0.223	0.420	0.174	0.134	0.315	0.416	0.293	0.510
Intermediate	N	43	0.02	0.09	0.257	0.149	0.401	0.151	0.082	0.258	0.335	0.209	0.493
	U	18	0.63	0.11	0.330	0.229	0.460	0.188	0.109	0.331	0.414	0.304	0.542
	A	19	0.06	0.68	0.191	0.179	0.234	0.096	0.062	0.138	0.245	0.230	0.275
Southeast	N	14	0.04	0.13	0.176	0.136	0.196	0.075	0.044*	0.084	0.249	0.211	0.270
	U	32	0.58	0.10	0.213	0.145	0.290	0.127	0.077	0.168	0.306	0.216	0.392
	A	12	0.06	0.68	0.124	0.093	0.171	0.040*	0.021*	0.061*	0.173	0.123*	0.243

*$P > 0.05$, the others are significant at $P < 0.01$

[a] N, U, and A: "reference," "urban," and "agricultural" station groups

[b] The number of stations

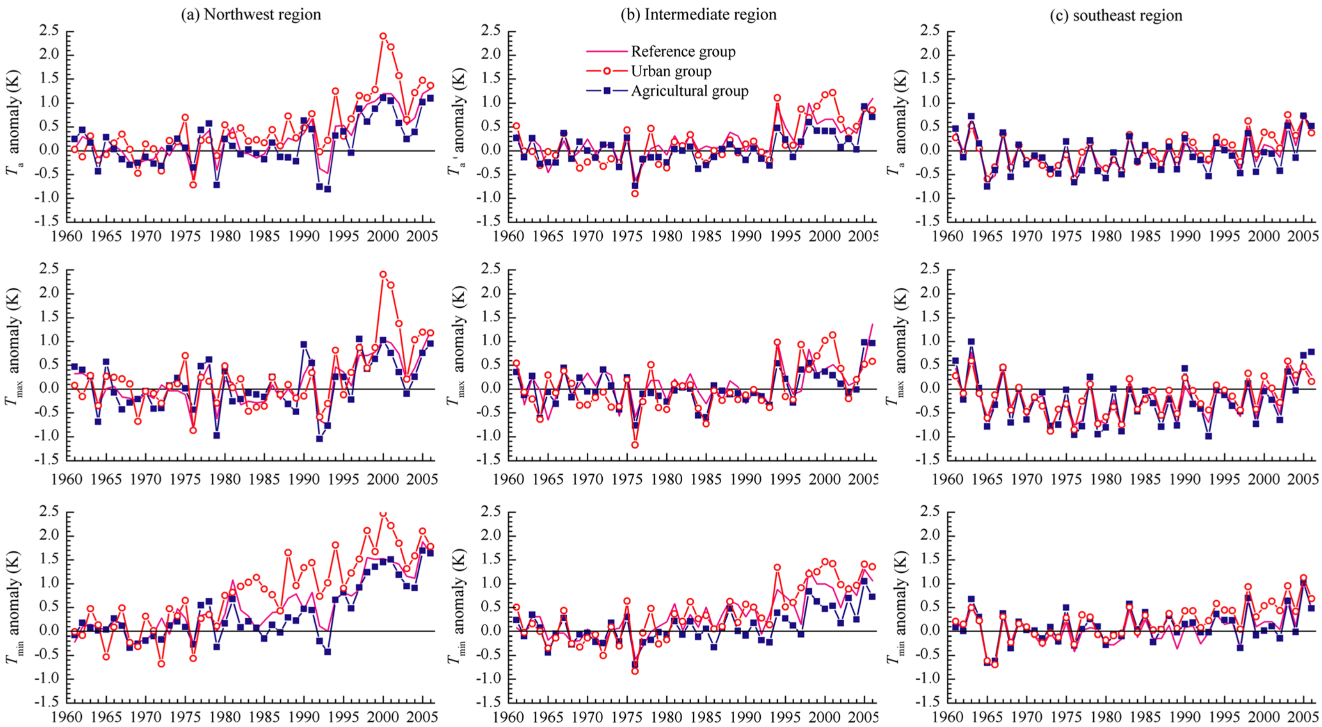


Fig. 5 Time series of the deviations of average main growing season T_a, T_{max}, and T_{min} from the means of 1961–1975 in the northwest (**a**), the intermediate (**b**), and the southeast (**c**) regions of mainland China for the reference, urban, and agricultural station groups

and intermediate regions of China, and the impacts are more significant in the intermediate region, which is consistent with the fact that agriculture developed most rapidly in the intermediate region. The average mean annual precipitations of corresponding stations in the northwest, intermediate, and southeast regions are 252, 709, and 1442 mm, respectively. Irrigation amount per unit area is largest in the northwest region, followed by the intermediate region. Because of the arid climate, irrigation plays an important role in agriculture in the northwest region (with larger irrigation amount per unit area), followed by the intermediate region. In 2006, irrigated land accounts for 61.9, 60.7, and 46.2% of the cultivated land in the northwest, intermediate, and southeast regions, respectively. Irrigation plays a big role in agricultural cooling in the northwest region (Han and Yang 2013), and contributes to the cooling in the intermediate region (Shi et al. 2013).

Table 7 Correlation coefficients between the geographic locations (longitude, latitude, and altitude) and the UFs, CFs, and annual temperature trends (K/decade) of stations

	UF	CF	T_a	T_{max}	T_{min}
Longitude	0.34**	0.02	0.05	0.07	−0.01
Latitude	−0.05	0.05	0.61**	0.51**	0.59**
Altitude	−0.43**	−0.28**	0.06	0.10	0.05

**Significant at $P < 0.01$

The average UFs and CFs within 3 km of the 598 meteorological stations in 2000 were 22.7 and 38.3%, respectively. However, the urban and cultivated land covered only 3.29 and 12.7% of the area of mainland China (Shi et al. 2006), respectively. Urbanization has caused additional warming in addition to background regional/global warming in the northwest, intermediate, and southeast regions of China, while agricultural development has caused lower warming/cooling during the main growing season in addition to background regional/global warming in the northwest and intermediate regions of China. Therefore, the changes of agricultural and urban land uses surrounding the meteorological stations should be paid attention when evaluating or calculating the overall temperature trends by observations if the actual local warming is of relevance (e.g., in urban or agricultural climatology). For example, the agricultural cooling effects should be seriously considered when evaluating the UHI effects using the "urban" minus "rural" method (Lowry 1977). UHI effect depends on both temperatures in the urban and in rural/reference stations. Rural temperature would be affected by land covers (Imhoff et al. 2010) and differs among water, wetland, crop, and forest. Therefore, agricultural development in crop lands leads to higher UHI as rural temperature is "cooler." UHI calculated from the difference of urban minus rural area temperatures would be higher when rural areas receive extensive irrigation; however, it would be reduced when the rural area is located in the desert (Georgescu et al. 2011; Zhao et al. 2014). Besides, the effects of urbanization and agricultural development on temperature changes should be considered when evaluating observed temperature changes, such as recent warming hiatus (Li et al. 2015). If the UHI effects are restrained, an excessive "hiatus" signal would be sent to the temperature observations. However, a restrained "hiatus" signal would be sent if the UHI effects are heightened. On the other hand, an excessive "hiatus" signal would be sent to the temperature observations if the agricultural cooling effects are heightened, and a restrained "hiatus" signal would be sent if the agricultural cooling effects are lowered.

Several uncertainties associated with this study must be noted. First, although stations reporting obvious discrepancies between the temperature trends of the original and homogenized adjusted time series are eliminated, uncertainties from the inhomogeneities of the temperature time series remain. Second, land use/land cover changes not considered in this study may result in significant uncertainties (Han et al. 2016). Third, most stations are surrounded by both urban and cultivated lands, making the numbers of stations that can be treated as "reference," "urban,"and "agricultural" limited.

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References

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int J Climatol 23:1–26

Bonfils C, Lobell D (2007) Empirical evidence for a recent slowdown in irrigation-induced cooling. Proc Natl Acad Sci U S A 104:13582–13587

Compiler Group of Physical Geography of China (1993) Physical geography of China (in Chinese). Higher Education Press, Beijing

Das L, Annan JD, Hargreaves JC, Emori S (2011) Centennial scale warming over Japan: are the rural stations really rural? Atmos Sci Lett 12:362–367. https://doi.org/10.1002/asl.350

Ding Y (2006) National Assessment Report of Climate Change (I): climate change in China and its future trend. Adv Clim Chang Res 2:3–8

Draper NR, Smith H (2014) Applied regression analysis. Wiley

Easterling DR et al (1997) Maximum and minimum temperature trends for the globe. Science 277:364–367

Fall S, Niyogi D, Gluhovsky A, Pielke RA, Kalnay E, Rochon G (2010) Impacts of land use land cover on temperature trends over the continental United States: assessment using the North American Regional Reanalysis. Int J Climatol 30:1980–1993

Fang J, Piao S, He J, Ma W (2004) Increasing terrestrial vegetation activity in China, 1982–1999, vol 47. Springer, Berlin

Feng G (ed) (2005) Irrigation and drainage in China. China Water Power Press, Beijing

Foley JA, Defries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574

Gallo K, McNab A, Karl T, Brown J, Hood J, Tarpley J (1993) The use of NOAA AVHRR data for assessment of the urban heat island effect. J Appl Meteorol 32:899–908

Gallo KP, Owen TW, Easterling DR, Jamason PF (1999) Temperature trends of the US Historical Climatology Network based on satellite-designated land use/land cover. J Clim 12:1344–1348

Georgescu M, Moustaoui M, Mahalov A, Dudhia J (2011) An alternative explanation of the semiarid urban area "oasis effect". J Geophys Res Atmos 116

Govindasamy B, Duffy PB, Caldeira K (2001) Land use changes and Northern Hemisphere cooling. Geophys Res Lett 28:291–294

Han S, Yang Z (2013) Cooling effect of agricultural irrigation over Xinjiang, Northwest China from 1959 to 2006. Environ Res Lett 8:024039

Han S, Xu D, Wang S (2012) Decreasing potential evaporation trends in China from 1956 to 2005: accelerated in regions with significant agricultural influence? Agric For Meteorol 154:44–54

Han S, Tang Q, Xu D, Wang S, Yang Z (2016) Observed near-surface atmospheric moisture content changes affected by irrigation development in Xinjiang, Northwest China. Theor Appl Climatol. https://doi.org/10.1007/s00704-00016-01899-00702

Hansen J, Johnson D, Lacis A, Lebedeff S, Lee P, Rind D, Russell G (1981) Climate impact of increasing atmospheric carbon dioxide. Science 213:957–966

Hansen J et al (2001) A closer look at United States and global surface temperature change. J Geophys Res 106:23,947–923,963

He JF, Liu JY, Zhuang DF, Zhang W, Liu ML (2007) Assessing the effect of land use/land cover change on the change of urban heat island intensity. Theor Appl Climatol 90:217–226. https://doi.org/10.1007/s00704-006-0273-1

Hu Y, Dong W, He Y (2010) Impact of land surface forcings on mean and extreme temperature in eastern China. J Geophys Res 115. https://doi.org/10.1029/2009jd013368

Huang Y, Dickinson RE, Chameides WL (2006) Impact of aerosol indirect effect on surface temperature over East Asia. Proc Natl Acad Sci 103:4371–4376

Imhoff ML, Zhang P, Wolfe RE, Bounoua L (2010) Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sens Environ 114:504–513

Kalnay E, Cai M (2003) Impact of urbanization and land-use change on climate. Nature 423:528–531

Li Z, Yan Z (2009) Homogenized daily mean/maximum/minimum temperature series for China from 1960-2008. Atmos Oceanic Sci Lett 2:237–243

Li Q, Liu X, Zhang H (2004a) Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. Adv Atmos Sci 21:260–268

Li Q, Zhang H, Liu X, Huang J (2004b) Urban heat island effect on annual mean temperature during the last 50 years in China. Theor Appl Climatol 79:165–174. https://doi.org/10.1007/s00704-004-0065-4

Li Q, Li W, Si P, Xiaorong G, Dong W, Jones P, Huang J, Cao L (2009a) Assessment of surface air warming in Northeast China, with emphasis on the impacts of urbanization. Theor Appl Climatol 99:469–478. https://doi.org/10.1007/s00704-009-0155-4

Li Q, Zhang H, Liu X, Chen J, Li W, Jones P (2009b) A mainland China homogenized historical temperature dataset of 1951-2004. B Am Meteorol Soc 90:1062–1065

Li B, Chen Y, Shi X (2012) Why does the temperature rise faster in the arid region of Northwest China? J Geophys Res 117:D16115

Li Y, Zhu L, Zhao X, Li S, Yan Y (2013) Urbanization impact on temperature change in China with emphasis on land cover change and human activity. J Clim 26:8765–8780

Li Q, Yang S, Xu W, Wang XL, Jones P, Parker D, Zhou L, Feng Y, Gao Y (2015) China experiencing the recent warming hiatus. Geophys Res Lett 42:889–898. https://doi.org/10.1002/2014gl062773

Liu J, Liu M, Zhuang D, Zhang Z, Deng X (2003) Study on spatial pattern of land-use change in China during 1995–2000. Sci China Ser D Earth Sci 46:373–384

Liu W, Ji C, Zhong J, Jiang X, Zheng Z (2007) Temporal characteristics of the Beijing urban heat island. Theor Appl Climatol 87(1–4):213–221

Lobell DB, Bonfils C (2008) The effect of irrigation on regional temperatures: a spatial and temporal analysis of trends in California, 1934-2002. J Clim 21:2063–2071

Lobell DB, Bala G, Mirin A, Phillips T, Maxwell R, Rotman D (2009) Regional differences in the influence of irrigation on climate. J Clim 22:2248–2255

Lowry WP (1977) Empirical estimation of urban effects on climate: a problem analysis. J Appl Meteorol 16:129–135

Mahmood R, Hubbard KG, Leeper RD, Foster SA (2008) Increase in near-surface atmospheric moisture content due to land use changes: evidence from the observed dewpoint temperature data. Mon Weather Rev 136:1554–1561. https://doi.org/10.1175/2007mwr2040.1

Montandon LM, Fall S, Pielke Sr RA, Niyogi D (2011) Distribution of landscape types in the Global Historical Climatology Network. Earth Interact 15:1–24

National Bureau of Statistics of China (2010) China Compendium of Statistics 1949-2008. China Statistics Press, Beijing

Oke TR (1982) The energetic basis of the urban heat island. Q J Roy Meteor Soc 108:1–24

Peng S, Piao S, Ciais P, Friedlingstein P, Ottle C, Bréon F-M, Nan H, Zhou L, Myneni RB (2011) Surface urban heat island across 419 global big cities. Environ Sci Technol 46(2):696–703

Peng S, Piao S, Ciais P, Myneni RB, Chen A, Chevallier F, Dolman AJ, Janssens IA, Peñuelas J, Zhang G, Vicca S, Wan S, Wang S, Zeng H (2013) Asymmetric effects of daytime and night-time warming on Northern Hemisphere vegetation. Nature 501:88–92

Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, Zhou L, Liu H, Ma Y, Ding Y, Friedlingstein P, Liu C, Tan K, Yu Y, Zhang T, Fang J (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–51. https://doi.org/10.1038/nature09364

Ren G et al (2005) Climate changes of China's mainland over the past half century. Acta Meteorol Sin 63:942–956

Ren G, Zhou Y, Chu Z, Zhou J, Zhang A, Guo J, Liu X (2008) Urbanization effects on observed surface air temperature trends in North China. J Clim 21:1333–1348

Rim C-S (2009) The effects of urbanization, geographical and topographical conditions on reference evapotranspiration. Clim Chang 97: 483–514. https://doi.org/10.1007/s10584-009-9618-y

Shi P, Wang J, Feng W, Ye T, Ge Y (2006) Respons of eco-environmental security to land use/cover changes and adjustment of land use policy and pattern in China. Adv Earth Sci 21:111–119

Shi W, Tao F, Liu J (2013) Regional temperature change over the Huang-Huai-Hai Plain of China: the roles of irrigation versus urbanization. Int J Climatol 34:1181–1195. https://doi.org/10.1002/joc.3755

Small C (2005) A global analysis of urban reflectance. Int J Remote Sens 26:661–681

Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. B Am Meteorol Soc 93:1879–1900

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science 277:494–499

Wang L, Li CC, Ying Q, Cheng X, Wang XY, Li XY, Hu LY, Liang L, Yu L, Huang HB, Gong P (2012) China's urban expansion from 1990 to 2010 determined with satellite remote sensing. Chin Sci Bull 57: 2802–2812

Wang X, Sun X, Tang J, Yang X (2015) Urbanization-induced regional warming in Yangtze River Delta: potential role of anthropogenic heat release. Int J Climatol 35:4417–4430

Wild M, Ohmura A, Makowski K (2007) Impact of global dimming and brightening on global warming. Geophys Res Lett 34. https://doi.org/10.1029/2006gl028031

Xu L et al (2016) Agricultural irrigation-induced climatic effects: a case study in the middle and southern Loess Plateau area, China. Int J Climatol. https://doi.org/10.1002/joc.4869

Yang X, Zhang Y, Liu L, Zhang W, Ding M, Wang Z (2009) Sensitivity of surface air temperature change to land use/cover types in China. Sci China Ser D Earth Sci 52:1207–1215. https://doi.org/10.1007/s11430-009-0085-0

Yang X, Hou Y, Chen B (2011) Observed surface warming induced by urbanization in east China. J Geophys Res 116:D14113. https://doi.org/10.1029/2010jd015452

Yang H, Yang D, Hu Q, Lv H (2015) Spatial variability of the trends in climatic variables across China during 1961–2010. Theor Appl Climatol 120:773–783. https://doi.org/10.1007/s00704-014-1208-x

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol Process 16:1807–1829

Zhang J, Yang Z, Wang D, Zhang X (2002) Climate change and causes in the Yuanmou dry-hot valley of Yunnan, China. J Arid Environ 51: 153–162

Zhang J, Dong W, Wu L, WEI J, CHEN P, Dong-Kyou L (2005) Impact of land use changes on surface warming in China. Adv Atmos Sci 22:343–348

Zhang X, Tang Q, Zheng J, Ge Q (2013) Warming/cooling effects of cropland greenness changes during 1982–2006 in the North China Plain. Environ Res Lett 8:024038

Zhao L, Lee X, Smith RB, Oleson K (2014) Strong contributions of local background climate to urban heat islands. Nature 511:216–219

Zhao N, Han S, Xu D, Wang J, Yu H (2016) Cooling and wetting effects of agricultural development on near-surface atmosphere over Northeast China. Adv Meteorol (in press)

Zhou L, Dickinson RE, Tian Y, Fang J, Li Q, Kaufmann RK, Tucker CJ, Myneni RB (2004) Evidence for a significant urbanization effect on climate in China. Proc Natl Acad Sci U S A 101:9540–9544

Zhu X, Liang S, Pan Y (2012) Observational evidence of the cooling effect of agricultural irrigation in Jilin, China. Clim Chang 114: 799–811. https://doi.org/10.1007/s10584-012-0435-3