Geography

May 2012 Vol.57 No.14: 1708–1715
doi: 10.1007/s11434-012-4999-0

Estimation of urbanization bias in observed surface temperature change in China from 1980 to 2009 using satellite land-use data

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Received December 9, 2011; accepted January 11, 2012; published online March 8, 2012

Since the 1980s, China has undergone rapid urbanization. Meanwhile, the climate has been warming substantially. In this paper, the urbanization effect on observed temperatures from 1980 to 2009 in China is estimated, based on analysis of urban land use from satellite observation. Urban land-use expansion (ΔU) during 1980–2005 is applied as an urbanization index. According to these ΔU values, stations are divided into three categories: (C1) intense urbanization around the stations; (C2) moderate urbanization around the stations; and (C3) minimal urbanization around the stations. Most C1 stations are in municipalities or provincial capitals, while C2 stations tend to be in prefecture-level cities. C3 stations are mostly in counties. The urban heat island (UHI) effect can be estimated if the urban effect on C3 is negligible. The warming of C1 or C2 relative to that of C3 represents their urbanization effects, assuming that the same larger-scale natural warming has affected each category. For C1, the local urbanization effect is 0.258°C/10 a over 1980–2009, accounting for 41% of the total warming; the trend at C2 is 0.099°C/10 a, or 21%. For all China, the urbanization effect is 0.09°C/10a, accounting for 20% of the total national warming. Winter urban warming is greater than in summer. The assumption of negligible urbanization effect on C3 is debatable, and so the true urbanization effect may equal or slightly exceed estimates. Further, the ΔU index may have some uncertainties, for it is only one of the urbanization indices. However, it provides a new and direct estimation of environmental change, in contrast to indirect indices.

urbanization, urban land-use change, UHI effect

Citation: 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, doi: 10.1007/s11434-012-4999-0

Urbanization may have affected the trend of surface air temperature (SAT), which has become a central issue in current climate change research. In general, there are two goals in the study of the urbanization effect: (1) to estimate the urban heat island (UHI) effect on observed SAT, especially on SAT increase over the last 100 years; and (2) to evaluate the contribution of the greenhouse effect (over and above the UHI effect) on temperature. Since the last century, most land areas have experienced considerable urbanization, which has affected the energy budget and urban SAT change. Urban land-use expansion is the salient feature of urbanization, and it directly reflects environmental change from urbanization. Therefore, studying the relationship between urban land-use expansion and observed temperature change aids estimation of the UHI effect.

There has been much research into the urbanization effect on climate change. The first method from the literature [1–4] involves comparison of temperatures in urban and rural areas to evaluate the urbanization effect, which is suitable for assessing the local UHI effect. The second method [5–14] relies on an urban development (social environment) index to estimate that effect, based on factors such as population, night lighting, and vegetation index. It offers the advantage of extensive spatial coverage, but limited temporal coverage [15]. The third method [16] is to estimate the UHI effect by comparing land SAT with sea surface temperature (SST). However, it may be difficult to ascribe resultant differences to the UHI effect alone, because other factors may cause the land-ocean difference [17–19]. The fourth method [20–22] estimates the impact of

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urbanization and other land use through comparing SAT trends observed by surface stations with those derived from atmospheric reanalyses (called NNR or REA). However, the REA method has some uncertainties, such as non-homogenization of the observed data and inherent model biases (especially in the analysis of anthropogenic aerosol), among others [16,23–26]. The fifth method [27,28] for evaluating the UHI effect is based on analysis of temperature differences at night between windy and calm conditions. In China, the above methods have been used to estimate the urbanization effect (Table 1). For example, Wang et al. [29], Jones et al. [30], Portman [31], Li et al. [32,33], Hua et al. [34], Ren et al. [35] and Tang et al. [36] used the second method and the population index to estimate the UHI effect in China. However, there is great divergence in the population standards for defining rural or reference stations (Table 1). Yang et al. [37] and Du et al. [38] also used the second method and a night-light index to calculate the urbanization effect in eastern China. Jones et al. [16] adopted the third method to estimate the effect, also in eastern China. Zhou et al. [20], Zhang et al. [39] and Yang et al. [37,40] used the fourth method to calculate UHI intensity in the same region. This method was not applied to the whole of China, because of an altitude limitation (less than 500 m above mean sea level). The UHI results from these studies vary considerably (Table 1), and the UHI contribution to climate warming is still debatable.

Here, we use a different method to estimate the urbanization effect on Chinese climate since 1980. Urban land-use expansion (ΔU) is used as an index of urbanization, because urban area expansion is the salient feature of urbanization. It provides direct estimation of environmental change as compared to other indirect indices, such as population and night light. The ΔU data are retrieved from satellite images with high spatial resolution. Values of ΔU are defined between two points in time, and this variation directly represents environmental change over that period. This change can be compared to the temporally correspondent SAT change. The ΔU data are obtained for the area surrounding a given weather station, which furnishes the temperature records for our analysis.

1 Data

1.1 Temperature data

Temperature data are obtained from the "Monthly Surface Climate Dataset in China" of China Meteorological Administration (CMA). We use mean monthly SAT, acquired from data of 160 National Reference Climate Stations (NRCS) from the Chinese National Climate Center (NCC), CMA. These stations are selected based on several criteria, including long observation period, good temporal continuity, and few errors from data transmission. This 160-station dataset has been used in many works on climate variation and prediction in China [41–50].

Table 1 Studies on the urbanization effect in China

Period	Study area	Urbanization effect (°C/10 a)	Method	Reference
1954–1983	China	0.08	Pop index, the reference station: Pop_{1985} <147000	[29]
1954–1983	East China	< 0.05	Pop index, the reference station: Pop_{1984} <100000	[30]
1954–1983	North China	0.09 large city 0.05 small city	Pop index, the reference station: Pop_{1982} <1000/km^{-2}	[31]
1951–2001	China	< 0.01	Pop index, the reference station: Pop < 50000, or Pop=50000–500000 and the station sites being rural or suburban	[32]
1954–2005	Northeast China	0.027	Same as above	[33]
1961–2000	China	0.05 large city 0.03 medium and small city	Pop index, the reference station: Pop_{2000} <100000	[34]
1961–2000	North China	0.11	Pop index, the reference station: Pop_{2002} ⩽50000	[35]
1961–2004	Southwest China	0.086 large and medium city 0.016 small city 0.052 southwest China	Pop index, the reference station: Pop_{2002} <30000~40000	[36]
1961–2005	Yangtze River Delta	0.069	Night-lighting index	[38]
1981–2007	East China	0.398_1, 0.285_2 metropolis 0.26_1, 0.207_2 large city 0.214_1, 0.135_2 medium city 0.167_1, 0.077_2 small city	1, REA; 2, night lighting and population	[37]
1981–2004	East China	0.1	Comparing the temperature trends on land and in the ocean	[16]
1979–1998	Southeast China	0.05	REA	[20]
1960–1999	East of 110°E over China	0.12	REA	[39]
1960–1999	China	0.14	REA	[40]

We select the 30-a period from 1980 to 2009, following the international convention in climate variability studies (at least 30 years). This is also the period of dramatic warming (Figure 1) and rapid urban development in China, and therefore the optimal period for UHI research. The past 30 years have witnessed rapid industrial development throughout the country, whose gross domestic product (GDP) increased from \$$2\times10^{11}$ in 1980 to \$$4.3\times10^{12}$ in 2009 (data from National Bureau of Statistics of China). As a result, urbanization has progressed rapidly and the UHI effect on climate change during this period is expected to be more significant than those of any other period (if the UHI has affected the climate in China at all). Observed temperatures show that this same 30-a period has had the most rapid warming since 1880 in China. Figure 1 shows mean temperature series since 1880 [51]. In this series, China is divided into 10 subregions covering most territories. The dotted line at 1980 in the figure marks the 30 years of most rapid warming since 1880, although there are temperature fluctuations at intervals of 5–7 years.

Missing values at some stations account for 1.4% of total records. Among them, eleven sites with missing records over more than five consecutive years (accounting for about 1% of total records) are excluded. Other missing values are estimated using linear interpolation of data from adjacent years. In addition, considering the large spatial extent (60° longitude by 40° latitude) and complex terrain of China, temperatures from all stations are analyzed as anomalies relative to a base period 1971–2000 to reduce noise induced by microclimates in each city.

1.2 Land use data

Land use data were procured from the "1:100000 Land Use Dataset in China" of the China Data Sharing Infrastructure of Earth System Science. The database was first developed by the Chinese Academy of Sciences (CAS) in the early 1980s, and has been repeatedly updated. The original data are USA Landsat Thematic Mapper/Enhanced Thematic Mapper (TM/ETM) images, which have a spatial resolution of 30 m by 30 m. Pixels of the final product were aggregated into 100 m by 100 m resolution. The selected period was 1980–2005, with data updates every five years. Urban land-use types include urban built-up land and other industrial land uses (e.g. large industrial areas, factories, oil fields, salt works, quarries, transport roads, and airports) in large, medium and small cities and towns. Figure 2(a) shows ΔU data for the selected period, with each cell representing a 100 m by 100 m pixel of increased urban land area (over the 1980 level). Overall, urban land use has increased significantly, especially in eastern China.

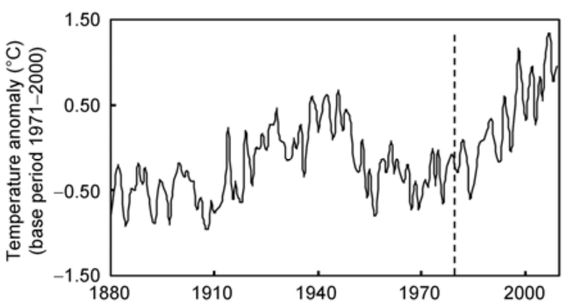

Figure 1 Change in annual mean surface air temperature in China from 1980 to 2009.

2 Selection of urbanization index

Commonly-used urbanization indices include population, night lighting, and vegetation index. Among these, population and night lighting can be used to classify weather stations into urban or rural types, but both represent environmental change only indirectly. Furthermore, night light as an urbanization index in China may not be consistent across the nation, since levels of infrastructure development vary. For example, cities of similar physical dimensions may have different night-light signatures. We use urban land-expansion as the index of urbanization, because it directly

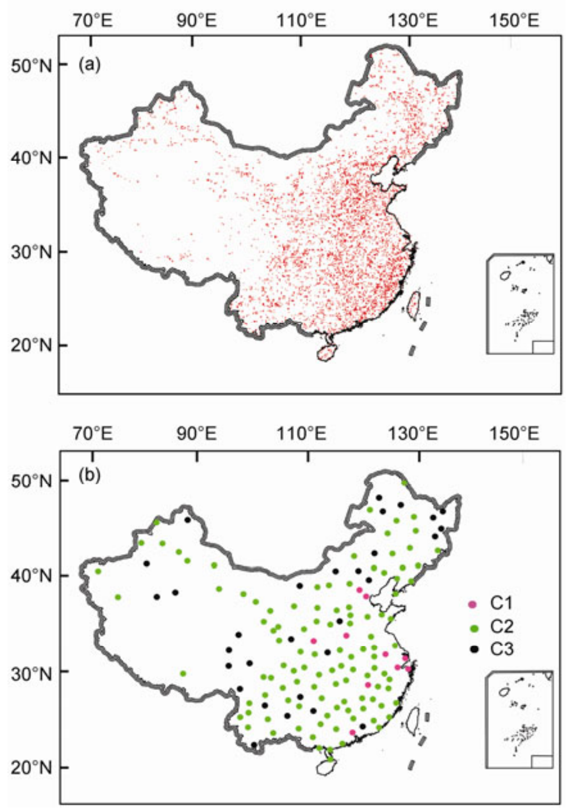

Figure 2 Urban land-use expansion (a), and station distribution in China (b). (a) Processed image of urban land-use expansion (ΔU) from satellite observation between 1980 and 2005. Resolution is 100m by 100 m (one pixel). Every red pixel represents ΔU increase over the 1980 level in the area. (b) Station distribution of each category in China. C1, Intense urbanization surrounding the station; C2, moderate urbanization; C3, minimal urbanization.

represents urban environmental change and the land dataset has high spatial resolution and wide coverage. We extract ΔU data from the area immediately surrounding a given weather station, rather than from an entire city, to estimate the influence of urbanization around each station on observed temperatures. Various distances around the weather stations are selected, for determining the radius of the area surrounding a station with greatest correlation between temperature trends and urban land-expansion.

Buffers out to a radius of 50 km were developed around every station, and we calculated the correlation coefficient (r) between ΔT and ΔU at every 5 km increment (i.e. 1 km, 5 km, 10 km,$\cdots$, 50 km). Figure 3 presents r values for the various radii around the stations. High values were found at 10–20 km; beyond that, correlation decreased gradually. At radii from 10–20 km, r was calculated again at every 1 km increment, finding the highest value at radius 16 km, with $r = 0.20$ ($n = 149$) statistically significant at the 95% level ($r = 0.20 > t_{0.05,150} = 0.15$). Therefore, we chose urban land-use change data within a 16 km circle surrounding each station to estimate the urbanization effect on temperature.

The result indicates that 95% of all stations have experienced significant urban land-use expansion in their surroundings. Therefore, it is difficult to select adequate numbers of reference stations that are free from urbanization effects in all of China. Therefore, stations with the least urban land-use expansion are regarded as such reference stations, for estimating the UHI effect. Stations were divided into three categories, according to ΔU values surrounding the station: (C1) intense urbanization (ΔU >10000 ha); (C2) moderate urbanization (ΔU=100–10000 ha); and (C3) minimal urbanization (ΔU <100 ha). The C3 are regarded as the reference stations because of their small ΔU values. The purpose of station classification is to assess whether urban land-use change of variable extent (classified into three rough intervals) induced distinct temperature trends. Spatial distributions of stations in each category are shown in Figure 2(b). Red circles represent category C1 (n = 10), with most stations in eastern China. Blue circles show C2 stations (n = 110), which are distributed evenly across the country. Black circles designate C3 stations (n = 29). Our results indicate that the C1 stations are in large metropolitan areas experiencing rapid urbanization, mostly municipalities and provincial capitals (90%). Most C2 stations are in prefecture-level cities (65%), whereas C3 stations tend to be in counties (76%). We compared mean annual temperature trends for these three types using a single factor variance analysis; pairwise comparison is made with the least significant difference (LSD) method (Table 2). Results of the single factor variance analysis show that differences between the three categories are statistically significant (F = 7.503, P = 0.001).

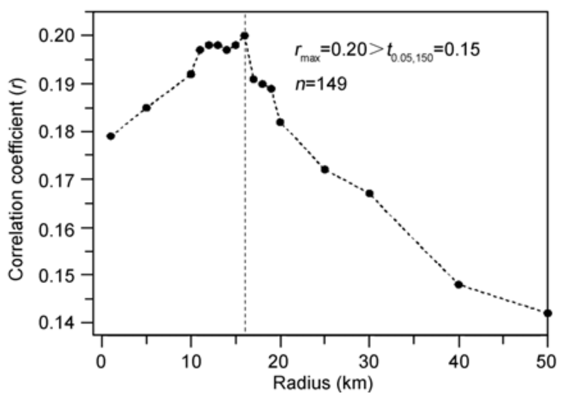

Figure 3 Correlation of temperature trend and urban land-use change at variable distances around sites.

The urbanization influence can be estimated if the effect of UHI on ΔT at the C3 stations is assumed negligible (because their ΔU values are very small). The difference in warming between the C1 or C2 and C3 stations represents urbanization warming, assuming that the larger-scale natural warming has affected each category equally. In reality, the assumption of negligible urbanization effect at the C3 stations is debatable. Thus, the urbanization warming estimated based on the difference between the C1 or C2 and C3 stations should be considered minimum values; the actual urbanization effect may be equal to or greater than the values shown here.

3 Results

3.1 Temperature trends without removing urbanization effect

Figure 4(a) indicates mean annual temperature anomalies of stations from each category, between 1980 and 2009. It shows that mean annual temperatures in all three categories have largely risen since 1980, although there are 5–7-a fluctuations. Table 2 lists mean temperature trends of the three types. The warming rates of C1, C2 and C3 are 0.629°C/10 a, 0.470°C/10 a and 0.371°C/10 a, respectively.

Table 2 Statistics of mean annual temperature trends of different station types in China

Category	n	Temperature trend (°C/10 a)	Item	df	Mean square deviation (°C/10 a)	F	Sig.
C1 (ΔU>10000 ha)	10	0.629**	Between groups	2	0.251	7.503	0.001
C2 (ΔU=100–10000 ha)	110	0.470**	Within groups	146	0.033		
C3 (ΔU<100 ha)	29	0.371**	Total	148			

** Statistically significant at the 0.01 level by using t-test.

t-tests for each category were done to evaluate the significance of temperature trends. These trends are significant for all three types (C1: $t = 9.77$ ($P = 0.000$); C2: $t = 7.712$ ($P = 0.000$); C3: $t = 6.163$ ($P = 0.000$)). The mean warming rates are positively correlated with ΔU, i.e. C1 > C2 > C3, or that of municipalities or provincial capitals > that of other prefecture-level cities > that of counties. The differences between the three categories are statistically significant, based on the single factor variance analysis.

Figure 4(b)–(e) shows seasonal temperature anomalies of the three station types. Table 3 gives the seasonal temperature trends in each category, which are statistically significant at the 95% confidence level using the *t*-test. The warming rates in all seasons for all station types appear to agree with C1 > C2 > C3. Differences of temperature trends between the three station types are more significant in spring and winter than in summer and autumn, according to the single factor variance method (spring: $F = 7.975$, $P = 0.001$; winter: $F = 3.228$, $P = 0.043$; summer: $F = 2.655$, $P = 0.074$; autumn: $F = 2.166$, $P = 0.118$).

3.2 Effect of urban land use on temperature trends

Urbanization effects on local and national-scale temperature trends were calculated using the method of section 2. Table 4 presents the results. At the local scale, the urbanization effect of C1 is 0.258°C/10 a, accounting for 41% of the total local warming while that of C2 is 0.099°C/10 a, accounting for 21% of that warming. Seasonally, the urbanization effect of C1 or C2 generates greater urban-warming in spring and winter than in autumn and summer.

At the national scale, the total urbanization effect in China from 1980 to 2009 was 0.09°C/10 a, accounting for 20% of the total national warming (0.46°C/10 a). Seasonally,

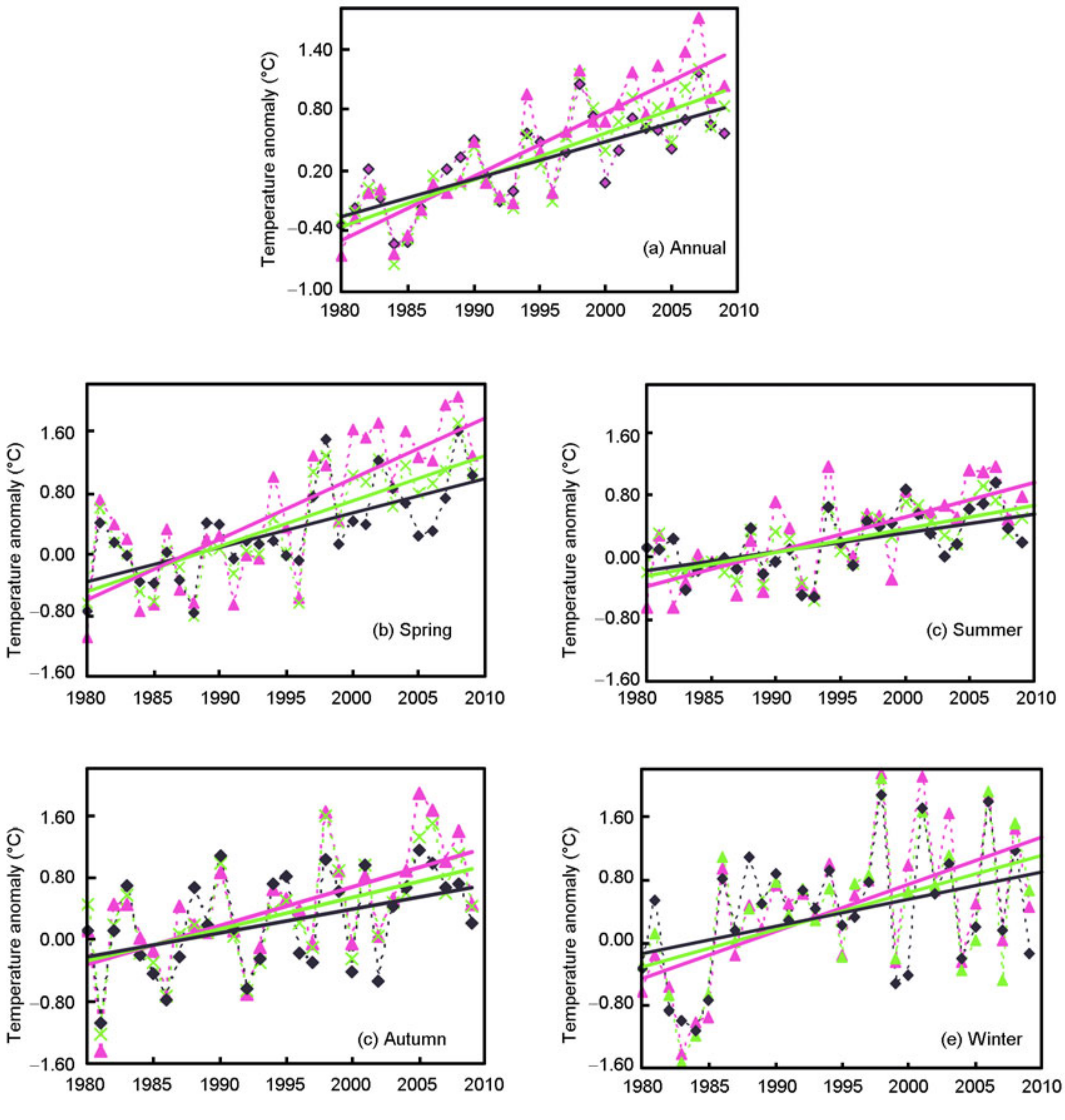

Figure 4 Annual and seasonal mean temperature change for C1, C2 and C3 in China from 1980 to 2009.

Table 3 Mean seasonal temperature trend for each station category (°C/10 a)

Station	Spring	Summer	Autumn	Winter
C1	0.794**	0.440**	0.498**	0.596**
C2	0.591**	0.295**	0.405**	0.477**
C3	0.449**	0.239**	0.307*	0.346**

* Statistically significant at the 0.05 level; ** statistically significant at the 0.01 level.

the urbanization effect for all China in spring and winter surpasses those in autumn and summer. The seasonal contribution of urban warming to overall national warming is greatest in winter (25%) and lowest in summer (20%).

After removal of the urbanization effect, the remaining national warming was 1.11°C/30 a or 0.37°C/10 a (1980–2009), still higher than the global warming trend over the same period (0.18°C/10 a [26]). Seasonal warming weakens significantly after removal of the urbanization effect. Spring warming ranged from 0.577 to 0.448°C/10 a; in winter it was from 0.458 to 0.346°C/10 a, autumn from 0.392 to 0.307°C/10 a, and summer from 0.297 to 0.239°C/10 a. The remaining warming in spring and winter was still higher than in autumn and summer.

4 Discussion

Ideally, reference stations should be those without surrounding urbanization. However, such stations rarely exist in China, and it is difficult to obtain information from an adequate number of reference stations at national scale. Therefore, the stations (C3) with minimal surrounding urbanization were admitted as reference stations for assessing the UHI effect. Thus, the warming from urbanization estimated by the differences between the C1 or C2 and C3 stations are considered minimum values, and the true urbanization effect may equal or slightly exceed these values.

Observed temperature trends are nearly unrelated to geographic factors like altitude and latitude (Figure 5). Altitude is not significantly correlated with ΔT, and latitude only weakly positively correlated. This is because C1 and C2 stations have high mean warming rates and low mean latitudes (C1: ΔT = 0.629°C/10 a, Lat. = 32.3°, σ = 4.9°; C2: ΔT = 0.470°C/10 a, Lat. = 33.5°, σ = 7.4°), whereas C3 stations have a low mean warming rate and high mean latitude (ΔT = 0.371°C/10 a, Lat. = 37.4°, σ = 8.6°). These contrasts between categories counter the observed positive correlation between large-scale temperature trends and latitude. The positive correlation of latitude with ΔT may be related to heating in winter at high latitude, and is also consistent with greenhouse effect theory.

Table 1 compares results from several studies. Upon examining the local UHI effect in different classes of cities, Hua et al. [34] showed urbanization effects of 0.05°C/10 a in large cities and 0.03°C/10 a in medium cities and small towns, during 1961–2000. Their values are less than ours because their study period was 1961–1980, when the urbanization effect was much less than that after 1980. Yang et al. [37] estimated urbanization effects over 1981–2007 of 0.285°C/10 a for metropolises, and 0.207°C/10 a for large cities. The latter is near our C1 result. They further estimated 0.135°C/10 a for medium cities and 0.077°C/10 a for

Table 4 Effect of urbanization on temperature trends in China

Scale		Annual	Spring	Summer	Autumn	Winter
Whole China	Urbanization effect (°C/10 a)	0.090	0.128	0.058	0.085	0.112
	National contribution (%)	19.5	22.2	19.5	21.7	24.5
C1	Urbanization effect (°C/10 a)	0.258	0.345	0.201	0.191	0.25
	Local contribution (%)	41.0	43.5	45.7	38.4	41.9
C2	Urbanization effect (°C/10 a)	0.099	0.142	0.056	0.098	0.131
	Local contribution (%)	21.1	24.0	19.0	24.2	27.5

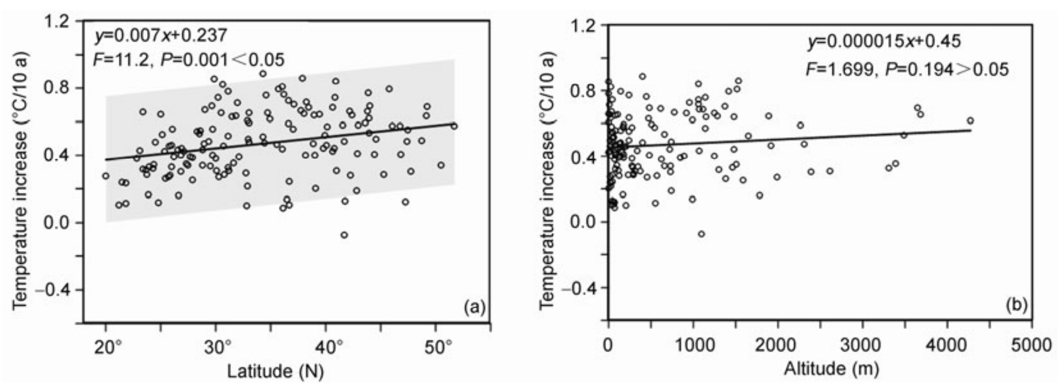

Figure 5 Temperature change with latitude (a)/altitude (b) in China, from 1980 to 2009. Gray shade in (a) represents the 95% confidence interval.

small cities, close to our C2 result. Regarding the national UHI effect on total warming, Jones et al. [16] estimated the urbanization effect in the east during 1981–2004. Their estimation of 0.1°C/10 a agrees with our result (0.09°C/10 a). Wang et al. [29] estimated a UHI intensity of 0.08°C/10 a between 1954 and 1983 in China, a little lower than our result. Li et al. [33] suggested an average UHI effect for all China from 1951 to 2001 at less than 0.01°C/10 a, an order of magnitude smaller than the total warming. Their result is much lower than in other studies, because their reference temperature was comparatively warmer; their reference stations included suburban and rural stations, whereas other studies only considered rural stations because suburban temperatures are still affected by the UHI. Jones et al. [30] addressed the urbanization effect in China by selecting the period between 1954 and 1983, just prior to the rapid increase in urbanization. At that time, urban development and the urbanization effect were minimal, and there was little change in urban land use. Moreover, since land-use satellite data are unavailable, we did not select the period before 1980 for study.

5 Conclusions

(1) Our results suggest that urban land use (urbanization) in China has had a significant impact on observed temperature trends since 1980. At the local level, the effect of urbanization on category C1 (mostly municipalities or provincial capitals) was 0.258°C/10 a, accounting for 41% of the total local warming, while that on C2 (mostly prefecture-level cities) was 0.099°C/10 a, accounting for 21% of that warming.

(2) At the national level, the urbanization contribution is at least 0.09°C/10 a and 20% of the total climate warming in China. Seasonally, the urbanization effect in winter and spring is more pronounced than in summer and autumn. We stress that the magnitude of urbanization effect for the 30 years (1980–2009) in this article cannot be directly translated to a longer period (e.g. 100 a), because urbanization has increased more rapidly since 1980 than ever before.

(3) After removal of the urbanization effect, national warming was 0.37°C/10 a (1980–2009), still higher than the global warming trend (0.18°C/10 a).

(4) The index of urban land-use change may have some uncertainties, for it is only one of the urbanization indices. However, it provides a new and direct estimation of environmental change, in contrast to indirect indices.

The authors thank the anonymous reviewers for their good suggestions. The authors also thank Profs. Wang Shaowu, Li Qinxiang, Deng Xiangzheng and Xu Xinliang for their valuable comments and data support. This work was supported by the National Natural Science Foundation of China (41101083).

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