A New Estimation of Urbanization's Contribution to the Warming Trend in China

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ABSTRACT

The extent to which an urbanization effect has contributed to climate warming is under debate in China. Some previous studies have shown that the urban heat island (UHI) contribution to national warming was substantial (10%–40%). However, by considering the spatial scale of urbanization effects, this study indicates that the UHI contribution is negligible (less than 1%). Urban areas constitute only 0.7% of the whole of China. According to the proportions of urban and rural areas used in this study, the weighted urban and rural temperature averages reduced the estimated total warming trend and also reduced the estimated urban effects. Conversely, if all stations were arithmetically averaged, that is, without weighting, the total warming trend and urban effects will be overestimated as in previous studies because there are more urban stations than rural stations in China. Moreover, the urban station proportion (68%) is much higher than the urban area proportion (0.7%).

1. Introduction

How much urbanization has contributed to climate warming is still being debated (Trenberth et al. 2007; Peterson 2003; Craig and Singer 2009; Goodridge 1996), particularly in China (Jones et al. 2008; Yang et al. 2011; Li et al. 2004b, 2010b, 2014; Zhao et al. 2014; Zhang et al.

2010; Zhou et al. 2004; Ren et al. 2008; Yan et al. 2010; Du et al. 2007; Chu and Ren 2005). As the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report mentioned, most recent attention on urban heat island (UHI) effects has focused upon China (Hartmann et al. 2013).

Some studies have indicated that the UHI contribution was large, while some have showed a smaller contribution (Table 1). Some studies looked at individual sites and estimated the UHI effects based on cities of different sizes. For example, Chu and Ren (2005) estimated an urbanization contribution to Beijing's temperature change to be 71% during 1961–2000 and 49% during 1979–2000 by comparing the temperature trends of urban and rural stations in the Beijing region; Hua et al. (2008), Yang et al. (2011), Tang et al. (2008), and Wang and Ge (2012) showed urbanization contributions for different city sizes during 1961–2009 of 35%–58%

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TABLE 1. Studies of the UHI effect in China.

Reference	Period	Study area	No. of stations	Percentage of urban stations	Homogenization method	Station classification method	Gridding method	UHI effect [$^{\circ}\text{C} (10\text{ yr})^{-1}$]	UHI contribution (%)
This study	1951–2010	China; different station types	607	68	Easterling et al. (1996); Li et al. (2004a)	Land index; the reference station has minimum urbanization surrounding the station	$2.5^{\circ} \times 2.5^{\circ}$; land-weighted method	<0.001 for China 0.074 for C1 0.058 for C2	<1 24 21
Chu and Ren (2005)	1961–2000	Beijing	20	70	Easterling et al. (1996)	EOF	—	0.16 for Beijing	71
Hua et al. (2008)	1961–2000	Different city sizes in China	290	66	—	Pop index; the reference station has $\text{Pop}_{2000} < 100\,000$	—	0.05 for large cities 0.03 for medium and small cities	—
Yang et al. (2011)	1981–2007	Different city sizes in eastern China	463	71	—	OMR and night lighting	OMR	0.285 for metropolises 0.207 for large cities 0.135 for medium cities	44 35 32
Tang et al. (2008)	1961–2004	Different city sizes in southwestern China	322	63	—	Pop index; the reference station has $\text{Pop}_{2002} < 30\,000\text{--}40\,000$	—	0.077 for small cities 0.086 for large and medium cities 0.016 for small cities	27 58 20
Wang and Ge (2012)	1980–2009	Different city sizes in China	149	80	—	Land index; the reference station has minimum urbanization surrounding the station	—	0.258 for large cities 0.099 for medium and small cities	41 21
Du et al. (2007)	1961–2005	Yangtze River delta	99	20	—	Night lighting index	—	0.069	27
Zhou et al. (2004)	1979–98	Southeastern China	—	—	—	OMR	OMR	0.05	11
Li et al. (2010b)	1954–2005	Northeastern China	—	31	Li et al. (2004a)	Pop index; the reference station has $\text{Pop} < 50\,000$, or $\text{Pop} = 50\,000\text{--}500\,000$ and the station sites may be rural or suburban	Five subregions by using principal components as weighting factors	0.027	8.2
Tang et al. (2008)	1961–2004	Southwestern China	322	63	—	Pop index; the reference station has $\text{Pop}_{2002} < 30\,000\text{--}40\,000$	—	0.052	45
Yang et al. (2011)	1981–2007	Eastern China	463	71	—	OMR and night lighting	OMR	0.14	24

TABLE 1. (Continued)

Reference	Period	Study area	No. of stations	Percentage of urban stations	Homogenization method	Station classification method	Gridding method	UHI effect [$^{\circ}\text{C} (10 \text{ yr})^{-1}$]	UHI contribution (%)
Jones et al. (1990)	1954–83	Eastern China	84	50	—	Pop index; the reference station has $\text{Pop}_{1984} < 100\,000$	—	<0.05	<10
Jones et al. (2008)	1951–2004	Eastern China	—	—	Li et al. (2004a)	Comparing the temperature trends on land and marine sea surface temperatures	Land–ocean	0.1	40
Zhao et al. (2014)	1951–2010	Eastern China	245	Five groups	Cao et al. (2013)	Pop index; five groups of different city sizes	—	0.044	9–24
Ren et al. (2008)	1961–2000	North China	282	78	Li et al. (2004a)	Pop index; the reference station has $\text{Pop}_{2002} \leq 50\,000$	$2^{\circ} \times 3^{\circ}$; unweighted average of all stations	0.11	38
Li et al. (2004b)	1954–2001	China	373	32	Li et al. (2004a)	As in Li et al. (2010b)	As in Li et al. (2010b)	<0.01	<10
Zhang et al. (2010)	1961–2004	China	614	78	Zhang et al. (2010)	Reference station has $\text{Pop}_{2000} < 20\,000$ for western China and $\text{Pop}_{2000} < 70\,000$ for eastern China; fewer than two station moves; and construction area around the station is less than 40%	$2.5^{\circ} \times 2.5^{\circ}$; unweighted average of all stations	0.076	27
Shao et al. (2011)	1970–2007	China	756	20	—	Remotely sensed land images	Australian National University spline (ANUSPLIN) method	0.01	0.6

for large cities and 20%–32% for medium and small cities, based on approaches that use a population (pop) index, land index, night-lighting index, or observation minus reanalysis (OMR) method (Wang et al. 2013). Some studies have looked at larger regions like south-eastern, eastern, or northern China. Zhou et al. (2004) found an urbanization contribution of 11% for south-eastern China during 1979–98 by using the OMR method. Yang et al. (2011), Jones et al. (1990, 2008), and Zhao et al. (2014) estimated the UHI contribution for eastern China was from less than 10% to 40% for different periods during 1951–2010, by using population indices, the OMR method, or by comparing temperature trends on land with marine sea surface temperatures. Ren et al. (2008) found an urbanization contribution of 38% for northern China during 1961–2000 based on a population index. Other studies looked at the all of China. Zhang et al. (2010) estimated the UHI contribution for the whole of China to be 27% during 1961–2004 based on a population index. Li et al. (2004b) suggested an UHI contribution of less than 10% for the whole of China from 1954 to 2001 based on a population index and principal component analysis. Shao et al. (2011) concluded that the UHI contribution to China is only 0.6% during 1970–2007 based on a station classification according to remotely sensed land images. Zhao et al. (2014) indicated that any urbanization contribution to Chinese warming compared with the atmospheric circulation contribution is very small. Summarizing, it seems that single sites and smaller regions tend to provide a larger contribution of UHI than those found in the studies that consider much larger regions. The IPCC assessment of the urbanization effects concluded that they are negligible overall at the global land scale (Trenberth et al. 2007; Hartmann et al. 2013; Hansen et al. 2010).

In addition, the UHI results will be divergent as a result of different study periods, different methods for estimating the UHI effect, different standards for defining reference stations, different procedures for constructing regional series, and different regional natural background conditions of climate change. For example, the study period covering 1950–80 gives a smaller value for any urbanization effect because this period, just prior to rapid development of urbanization, experienced little warming; different methods for estimating the UHI effect also give different results. The definition of what the UHI is and the type of data used also differs between studies. For example, using atmospheric reanalysis (the OMR method), station comparison of urban warming to rural warming, or comparison of land warming to ocean warming reveals that a less strict standard for defining reference stations can reduce the UHI intensity because some urban stations may be regarded as reference stations

and the reference temperature is comparatively warmer; regional climates are often different (some are warming, some are cooling), and the regions where warming is occurring will likely yield larger UHI effect, while the cooling regions are usually considered to have little UHI effect.

In recent decades, China has experienced substantial urbanization. However, the area of urbanization remains limited to a relatively small proportion of China. Land data indicate that the urban land area represents only 0.7% of the total land in China (69 264 km², as estimated in this study). There are many land-based meteorological stations in China; however, they are unevenly distributed. Most of these stations (68%; 413 out of 607; see section 3a for station classification) are located in urbanized regions and only a smaller fraction of the stations (32%; 194 out of 607) are located in nonurbanized regions. Therefore, the percentage of urban stations is much higher than the percentage of the urban land area (i.e., 68% versus 0.7%, respectively). Moreover, the percentage of rural stations is lower than the percentage of the rural land area (i.e., 32% versus 99.3%, respectively). Certain areas without urbanization (such as high mountains, deserts, or large lakes) often contain hardly any meteorological stations. Therefore, based on the recent station observations, the estimated warming trend has been overestimated. For example, if we assume that there are five stations in a region composed of two urban and three rural stations, then the two urban stations represent 40% of this region if the data from all stations are arithmetically averaged (Smith et al. 2008; Jones et al. 2012; Tang and Ding 2007). However, the actual scale of the urbanization effect is much less than 40%.

In this study, the spatial scale of the urbanization effect is considered. Moreover, we attempt to reestimate the national warming trend based on weighted urban and rural records. The weights are obtained according to satellite-derived urban–rural land data (Vogelmann et al. 2001; Liu et al. 2005). Additionally, the UHI contribution to national-scale warming is estimated. Sections 2 and 3 introduce the data sources and methods, respectively. Section 4 discusses the results and section 5 provides a summary and outlook.

2. Data

a. Temperature data

Temperature data were obtained from the monthly surface climate dataset provided by the China Meteorological Administration (CMA; Li et al. 2009). Originally, 728 meteorological stations were selected, including

FIG. 1. Distribution of meteorological stations in China used for this study: C1 (red, intense urbanization surrounding the station); C2 (green, moderate urbanization); and C3 (black, minimal urbanization). The classification method is described in [section 3](#).

the national reference climate stations and basic meteorological stations. Owing to instrument changes and station relocations, certain stations were discarded from the dataset and some were added. A total of 670 stations are currently in operation. Of these stations, 63 were eliminated because of a lack of data for more than 10 years. Overall, 607 stations were selected for obtaining temperature data ([Fig. 1](#)).

Quality control assessment of the temperature data was performed by the National Meteorological Information Center (NMIC) of the CMA. The quality control methods included synoptic cross validations and validations of climatological characteristics (e.g., annual spatial distribution, seasonal spatial distribution, annual trend distribution, seasonal trend distribution, interannual mean temperature contrast, and correlations).

The homogenization was performed by the NMIC team and the methods were introduced in [Li et al. \(2004a, 2009\)](#) based on approaches developed by [Easterling et al. \(1996\)](#). Since changes in instruments, station moves, or different observing practices can cause step changes, a technique was used for detecting a change in the trend of a time series by identifying the changepoint in a two-phase regression. The obvious discontinuous points are homogenized after they are assessed together with the station metadata. The homogenized dataset has been used in many works on climate variation and urbanization effects in China ([Li et al. 2010a,b, 2014](#); [Ren et al. 2005, 2008](#); [Jones et al. 2008](#); [Ge et al. 2013](#); [Wang et al. 2014](#)).

Missing monthly station data account for 6% of the total records (based on the 1951–2010 period) and generally occur in the earlier years. Missing values were

estimated using linear interpolation of data from neighboring stations. To evaluate the statistical fidelity of the regression models, split-sample calibration-verification tests ([Meko and Graybill 1995](#)) were used. [Ge et al. \(2013\)](#) summarizes the details of the results. The test results show the validation of the regression models. The differences between two annual-mean temperature time series before and after the imputed missing data were compared ([Fig. 2](#)). In general, the data imputation did not significantly affect the temperature trend. The standard deviation (SD) of the difference between the average of the 607 stations with and without the imputed data was calculated. The annual SD of this series is 0.012°C.

b. Land data

The Chinese land-use database has been developed by the Chinese Academy of Sciences (CAS). The original data were derived from remotely sensed satellite data

FIG. 2. Annual mean temperature anomaly before and after missing data imputation for China. The reference period is 1951–80.

provided by U.S. *Landsat 5* Thematic Mapper (TM) and *Landsat 7* Enhanced Thematic Mapper (ETM) images that have a spatial resolution of $30\text{ m} \times 30\text{ m}$ (Vogelmann et al. 2001). These images were then aggregated by CAS into $100\text{ m} \times 100\text{ m}$ elements (Liu et al. 2002, 2005). We selected the period from 1980 onward. The urban land-use area was extracted from the dataset for all land types. The urban land-use types include urban land and other industrial land uses in large, medium, and small cities and towns. The urban land is composed of areas of intensive use in which structures cover most of the land area. The industrial land includes large industrial areas, factories, oil fields, salt works, quarries, transport roads, and airports. The calculated urban land accounts for only 0.73% of the total land surface of China. To evaluate the fidelity of the satellite data, we compared it with the statistical data from China's National Bureau of Statistics (NBS; National Bureau of Statistics of the People's Republic of China 2010). The percentage of urban land area in China is also calculated based on the national urban area and industrial area in NBS data. The result is 0.8%, close to the satellite-observed result (0.73%). So the satellite-observed data can be considered to be reliable for estimating urbanization as an area percentage.

The global urban land-use data were obtained from the History Database of the Global Environment (HYDE) of the Netherlands Environmental Assessment Agency. The HYDE (gridded) dataset provides past and current time series of land use with a grid resolution of $0.075^\circ \times 0.075^\circ$ (Goldewijk 2001; Goldewijk et al. 2010). The current land cover data were based on satellite data from version 2 of the land cover product using the IGBP classification map (DISCover; Loveland et al. 2000) and global land cover (GLC) based on the Global Land Cover 2000 project dataset using the Vegetation Data for the Millennium Ecosystem Assessment (VEGA2000) (Bartholome et al. 2002), which were combined with national land-use statistics.

3. Method

a. Station classification

To divide the stations into either urban or rural types, the land classification data are extracted from the area that immediately surrounds a given station, which indicates that most stations have experienced recent and pronounced urban land-use expansion. Therefore, it is difficult to select an adequate set of reference stations that are free from urbanization effects for the period since 1951 across all of China.

Stations with the smallest urban land-use expansion are treated as reference stations (C3). A reference station is defined such that the urban area (S_{urban}) in the unit distance (11 km) (Ge et al. 2013) that surrounds the station is less than 1%; otherwise, the station is designated as an urban station. In certain highly urbanized areas (e.g., eastern China), several regions may have no reference stations. For these regions, a less strict reference station criterion is applied, where the urban area can be larger than 1% but must be less than 10%, and the urban land-use area over the past several decades must have exhibited only minimum changes (e.g., Baofeng, Fujin, Shouxian, Yebaishou, Dongshan, and Xuyi). Subsequently, the urban stations are divided into stations with intense urbanization in the surrounding area (C1, $S_{\text{urban}} > 30\%$) and those with moderate urbanization in the surrounding area (C2, $1\% < S_{\text{urban}} < 30\%$). The distribution for each category can be found in Fig. 1. There are 194 reference stations and 413 urban stations. In the east (dividing line: 107.5°E), the number of urban and rural stations are 305 and 65, respectively; in the west, the numbers are 108 and 129. To designate reference stations for every C1 or C2 station, the following criteria are adopted: a similar elevation and land surface configuration and the nearest rural station. The distance between urban and reference stations is on average 145 km. In the east the average is 155 km and in the west the average is 119 km. For some urban sites in eastern China, the distance between the urban and reference stations is somewhat larger because there are fewer rural stations. Eastern urban stations include Jinan, Yanzhou, Weifang, Dongying, Yiyuan, Huimin, and Mohe, where the rural stations are more than 300 km away.

To evaluate the reliability of the urban land index for station classification, the correlation coefficients are calculated between the urban land index and the other classification indices (population and night lighting). The data for population and night lighting are from the GHCN dataset. The population data were typically old and the station threshold criterion for a rural station is a population of $<10\,000$. The night-light data were from 1995 and the threshold criterion for a rural station is $<32\ \mu\text{W m}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$ brightness. The 366 common stations found between this study and the GHCN dataset are analyzed. The results indicate that the spatial correlations are statistically significant at the 95% level ($r = 0.64_{\text{population_and_land}}$ or $0.69_{\text{night_light_and_land}} > t_{0.05,366} = 0.10$). The ratios of station classifications (urban:rural) for the three indices are 258:108, 150:216, and 240:126 for land, population, and night lighting, respectively. We compare the land classifications with

the other two classifications separately. The results show that 54% of urban stations and 77% of rural stations from the land classification agree with that from the population classification, and 84% of urban stations and 79% of rural stations agree with that from the night-lighting classification. The latter seems to be better than the former. But both the population and night-lighting indices only represent environment changes indirectly.

b. Estimating the large-scale warming trend

A weighted averaging method is used to calculate the average regional warming trend in this study. First, the total land area of China is divided into regular latitude–longitude grid boxes ($2.5^\circ \times 2.5^\circ$). For each grid box, the percentage of urban and rural land is calculated according to their respective areas at different times. The percentage of urban land is used as the weight for the urban temperature, and the percentage of rural land is used as the weight for the rural temperature in each grid box in each year. Second, according to the homogenized temperature data from 607 stations, the monthly, seasonal, and annual temperature anomalies are calculated for each station over the period 1951–2010. The reference period used is 1951–80. Third, the station data are converted into a gridded dataset. In a grid box that contains two or more urban (or rural) stations, the average temperature of all available urban (or rural) stations is used to represent the specific grid box. In grids without stations, the data are interpolated from the nearest station. There are 6% grid boxes that need to be interpolated (this percentage does not change over time). The interpolation errors are estimated based on a distance decay rule and by modeling the relationship of temperature standard deviations and distances among stations (see Ge et al. 2013 for details). Fourth, the gridbox temperatures are obtained by using a weighted averaging method (based on the weighted urban and rural records). Finally, the national mean temperature is calculated using the area-weighted average, which is additionally weighted based on the cosine of the central latitude.

Smaller-sized grids (e.g., $1^\circ \times 1^\circ$ and $0.5^\circ \times 0.5^\circ$) for China result in too much missing data because of the unequal distribution of the stations; therefore, we chose a $2.5^\circ \times 2.5^\circ$ latitude–longitude grid. The number of grid boxes is 203 (within 17.5° – 55° N, 72.5° – 135° E).

The uncertainty errors are estimated according to the calculation method of Brohan et al. (2006), including station error (Folland et al. 2001), bias error, imputation error, sampling error (Smith et al. 1994; Jones et al. 1997), and interpolation error. Additional details of this method are described in section 5 of the supplementary material of Ge et al. (2013).

c. Estimating the UHI contribution to warming

At the local site-based scale, the difference in warming between every urban station (C1 or C2) and its reference station (C3) represents urbanization-induced warming. At the grid scale, the warming difference between each grid box's average temperature (based on true grid – land distribution) and its rural temperature represents the urbanization-induced warming of the grid. At the national scale, the warming difference between the national average temperature and the national rural temperature represents urbanization's contribution to the national warming.

4. Results

a. Urbanization's contribution to warming

An urbanization effect is detected in the total warming trend, but the UHI contributions differ according to the spatial scale. Figure 3 shows the UHI effect at the station (Fig. 3a), grid (Figs. 3b,f), eastern (Fig. 3d), western (Fig. 3e), and national (Fig. 3c) levels. The station level means the local site-based observation, with a small spatial scale. The grid level represents a slightly larger spatial scale, and the UHI value is an average over the land distribution within a grid. The national-level value is the mean of all grid-based values for the whole China.

At the local station scale, Fig. 3a shows the site-based observation of three station types (C1, C2, and C3). In these three rows of plots, every series is an average for all stations of each category. The three graphs in the first row show annual and seasonal temperature anomalies for C1, C2, and C3. The Student's *t* tests for each category were calculated to evaluate the significance of temperature trends. These trends are significant for all three types at the 0.01 level. The annual warming rates for all station types appear to agree with $C1 > C2 > C3$. The differences between the three categories are statistically significant, based on the single-factor variance analysis ($F = 14.945$, $P = 0.000$). Differences in temperature trends between the three station types are more significant in winter ($F = 6.243$, $P = 0.002$) than in summer ($F = 1.562$, $P = 0.211$). The graphs in the second (or third) row show temperature anomalies of C1 (or C2) stations against their reference stations (C1/ref or C2/ref). The mean warming rates of C1 (or C2) stations are significantly higher than their reference stations (C1 and C1/ref: $F = 10.388$, $P = 0.002$ and C2 and C2/ref: $F = 44.088$, $P = 0.000$).

Urbanization effects on local temperature trends were calculated using the method described in section 3. Table 2 presents the results. At the local scale for analysis category I, the urbanization effect on category

a. site-based observation (point)

FIG. 3. Urbanization effect on mean temperature at different spatial scales in China. (a) The top row shows site-based observations of C1 (intense urbanization around stations), C2 (moderate urbanization), and C3 (minimal urbanization). In the second and third rows of (a) C1/ref represents the reference stations for C1, C2/ref represents the reference stations for C2, and both C1/ref and C2/ref are part of the C3 stations. In the bottom row of (a), the average UHI values of urban stations in different zones, divided according to China's climate division scheme, are shown (Ge et al. 2013). In (a) every series is an average for all stations of each category (at a station level). (b) Grid-based samples, every series is an average over a grid box in the domain (at a grid level). The green lines (rural) represent the rural grid-scale warming without urbanization effects, calculated based on all rural stations, and the red lines (grid average) represent the grid-scale warming with urbanization effects, calculated based on the weighted average of all rural and urban stations. In (b), three grids series are shown because their urbanization areas are larger than for other grids. (c) Grid-based average for the whole of China for the entire year, winter, and summer. (d) As in (c), but for the eastern part of China (dividing line: 107.5°E). (e) As in (c), but for the western part. (f) UHI values for all grid boxes.

C1 is $0.074^{\circ} \pm 0.008^{\circ}\text{C} (10\text{ yr})^{-1}$, accounting for $23.9\% \pm 2.5\%$ of the total local warming, whereas on C2 is $0.058^{\circ} \pm 0.002^{\circ}\text{C} (10\text{ yr})^{-1}$, accounting for $21.4\% \pm 0.7\%$ of that warming. In different climate zones (the bottom row of Fig. 3a), the UHI effect on station-level warming is shown to be more pronounced in the north (zones I and II in the bottom row of Fig. 3a) than in the south (zone III in the bottom row of Fig. 3a). This is consistent with other studies (Hua et al. 2008; Zhang et al. 2010).

At the gridbox scale, Fig. 3b shows the grid-based samples for gridded rural series (green) and grid-average series (red). The gridded rural lines represent the rural grid warming without urbanization effects, calculated based on all rural stations. The grid-average lines represent the grid-scale warming with urbanization effects, calculated based on the weighted average of all rural and urban stations. The warming difference between each grid average temperature and its rural

FIG. 3. (Continued)

TABLE 2. Effects of urbanization on local and national temperature trends in China [$^{\circ}\text{C} (10 \text{ yr})^{-1}$]. Analysis I uses all national grid boxes and all national (urban and rural) stations, analysis II uses 23 grid boxes and urban–rural stations pairings of 1:1 in each grid, and analysis III uses 23 grid boxes and all urban–rural stations from these grids. All values are statistically significant at the 0.01 level using a Student's t test.

Analysis	Scale		Annual	Winter	Summer
I	Station-level C1	Temp trend	0.309 ± 0.029	0.384 ± 0.066	0.202 ± 0.031
		Urbanization effect	0.074 ± 0.008	0.063 ± 0.012	0.047 ± 0.011
	Station-level C2	Temp trend	0.269 ± 0.025	0.368 ± 0.063	0.163 ± 0.026
		Urbanization effect	0.058 ± 0.002	0.055 ± 0.005	0.036 ± 0.003
	National level	Temp trend	0.227 ± 0.021	0.316 ± 0.053	0.160 ± 0.024
II	Station-level C2	Urbanization effect	0.0008 ± 0.0001	0.0017 ± 0.0008	0.0013 ± 0.0002
		Temp trend	0.233 ± 0.024	0.324 ± 0.058	0.150 ± 0.027
	Regional level	Urbanization effect	0.058 ± 0.003	0.059 ± 0.005	0.044 ± 0.004
		Temp trend	0.163 ± 0.023	0.254 ± 0.057	0.096 ± 0.026
		Urbanization effect	0.0004 ± 0.00004	0.0003 ± 0.00004	0.0004 ± 0.00004
III	Station-level C2	Temp trend	0.222 ± 0.024	0.311 ± 0.059	0.141 ± 0.027
		Urbanization effect	0.052 ± 0.003	0.054 ± 0.004	0.041 ± 0.003
	Regional level	Temp trend	0.164 ± 0.023	0.255 ± 0.057	0.098 ± 0.026
		Urbanization effect	0.0003 ± 0.00003	0.0003 ± 0.00003	0.0002 ± 0.00002

temperature represents the UHI effect in the gridded data. Figure 3f gives the UHI values for each grid box. The figure indicates that the urbanization effects throughout most of China are less than $0.1^{\circ}\text{C} (60 \text{ yr})^{-1}$, and the urbanization contribution is generally quite small.

At the national scale, Fig. 3c shows the rural series (green) and the average of all series (red) for the whole of China for the annual average and the two extreme seasons. Every series is the grid-based average. The warming difference between the national weighted average temperature and the national rural temperature represents the urbanization contribution to the national warming in this dataset. The urbanization contribution is approximately $0.0048^{\circ} \pm 0.0006^{\circ}\text{C} (60 \text{ yr})^{-1}$ [or $0.0008^{\circ} \pm 0.0001^{\circ}\text{C} (10 \text{ yr})^{-1}$], which accounts for less than 1% of the total climate warming in China and represents a negligible contribution to the national average. This result is principally due to the weighting of the temperature data according to our land-use definitions. Let us look at eastern China separately from the whole of China because eastern China is more industrial and less rural (i.e., natural) than western China. Figure 3d shows that the UHI effects on eastern warming are very small; it is difficult to see the difference between the curves without urbanization and with urbanization. Only in areas surrounding Beijing–Tianjin is the UHI effect slightly more pronounced than in other regions (Fig. 3f).

To examine the robustness of the urban–rural pairing, we have made further analyses. First, the grid boxes with at least two urban–rural station pairs are selected and there are 23 such grid boxes. This generates a reduced analysis with a smaller geographical area than for the

original. Second, two sets of analyses are added. One uses 23 grids and the same number of urban and rural stations in each grid (Table 2, analysis category II); another uses 23 grids and all urban–rural stations within these grids (Table 2, analysis category III). In the two sets of analyses, both the warming trend and the urbanization contributions at the local and regional scales are calculated. The results can be seen in analysis categories II and III in Table 2. The comparison of two

FIG. 4. Annual mean temperature series (relative to the period 1951–80) for China. The colored lines represent different series (area-weighted average and unweighted average). The gray area gives the 95% uncertainty range of the New series as a result of all errors. The bar graph shows the linear warming trend for the periods 1951–2007 and 1955–2006 for each series (the Li and Wangfif series were finished in 2006).

FIG. 5. Urban land area and meteorological station locations in each $2.5^{\circ} \times 2.5^{\circ}$ grid box. The eight examples shown were randomly selected, and their locations are given in the center map of China. In example 1, there are two stations: a and b. Here, L_1 is the distance between a and the midway point, while L_2 is the distance between b and the midway point. The graph for example 1 shows that the areas around each station are mostly affected by urbanization, but the areas between stations (covering L_1 and L_2) are not affected by urbanization.

analyses shows that whether a reference station is used as a reference for any other station or not (urban–rural pairing of 1:1 or $n:1$) does not significantly influence the results of temperature trend and UHI effect.

b. Comparison with other studies

Table 1 compares results from several studies that have looked at urbanization effects on individual sites and larger regions. Single sites will likely give larger UHI values than the studies for much larger regions. Upon examining the local UHI effect at individual sites, Chu and Ren (2005) showed that the urbanization contribution to Beijing warming to be 71% during 1961–2000 by comparing the temperature trends of urban and

rural stations in the Beijing region. Hua et al. (2008) showed urbanization effects during 1961–2000 of $0.05^{\circ}\text{C} (10\text{ yr})^{-1}$ for stations in large cities and $0.03^{\circ}\text{C} (10\text{ yr})^{-1}$ for stations in medium cities and small towns based on the population index. Their values are slightly lower than ours. Yang et al. (2011) used the OMR method and night-lighting index and estimate the urbanization effects on station temperatures in metropolitan areas and large cities to be 0.285° and $0.207^{\circ}\text{C} (10\text{ yr})^{-1}$, respectively, accounting for 44% and 35% of the total local warming; those in medium and small cities are, respectively, 0.135° and $0.077^{\circ}\text{C} (10\text{ yr})^{-1}$, or 32% and 27%. Their values are larger than ours because their study period of 1981–2007 is just within the period of the

FIG. 6. Urban areas in China and around the world. (a) Urban area in 2010 for China. Data are from satellite observation and the CAS database. (b) The global urban area in 2010. Data from satellite observations and the HYDE database (Goldewijk 2001; Goldewijk et al. 2010) are shown. (c) Urban area percentage for each grid box in China ($2.5^{\circ} \times 2.5^{\circ}$). (d) Urban area percentage for each grid box ($5^{\circ} \times 5^{\circ}$) around the world.

rapid increase in urbanization and also the UHI sizes are likely larger when there is more warming. Tang et al. (2008) used the population index to calculate urbanization effects of $0.016^{\circ}\text{C} (10\text{ yr})^{-1}$ for stations in small cities (20%) and $0.086^{\circ}\text{C} (10\text{ yr})^{-1}$ for stations in large and medium cities (58%) in southwestern China during 1961–2004, close to our C1 and C2 results.

Upon examining the UHI effects on larger regions like southeastern, eastern, or northern China, Zhou et al. (2004) used the OMR approach to estimate an urbanization effect of $0.05^{\circ}\text{C} (10\text{ yr})^{-1}$ in the southeast (11%) during 1979–98. Yang et al. (2011) used the same method to estimate the UHI effect for eastern China to be 24% during 1981–2007. Jones et al. (2008) compared the temperature trends on land and in marine temperatures to the east of China and estimated the urbanization effect to be $0.1^{\circ}\text{C} (10\text{ yr})^{-1}$ in the east (40%) during 1951–2004. Zhao et al. (2014) showed that any urbanization contribution compared with the atmospheric circulation contribution to eastern China warming was very small. Ren et al. (2008) estimated an urbanization effect of $0.11^{\circ}\text{C} (10\text{ yr})^{-1}$ in the north (38%) during 1961–2000 based on the population index.

Regarding the national UHI effect on total warming, Zhang et al. (2010) estimated larger UHI values of $0.08^{\circ}\text{C} (10\text{ yr})^{-1}$ between 1961 and 2004 (27%) based on the population index. Li et al. (2004b) suggested an average UHI effect for all of China from 1954 to 2001 to be less than $0.01^{\circ}\text{C} (10\text{ yr})^{-1}$, lower than other results because they used a principal component analysis (PCA) based on a weighting method used to construct the regional average series. Shao et al. (2011) showed an UHI warming of $0.01^{\circ}\text{C} (10\text{ yr})^{-1}$ for the whole of China during 1970–2007, accounting for 0.6% of the total warming in China, which is close to our result.

Compared with other studies, our findings suggest that the UHI contribution [less than 1%, $0.0008^{\circ}\text{C} (10\text{ yr})^{-1}$] at the national scale is small because the scale of the urban effect is considered in this current study by weighting according to the station urbanization classification. The unweighted average, as in other studies, potentially overestimates the scale of the urban effect.

Figure 4 shows the national average series from the weighted method (New series) and unweighted methods [e.g., the Ref, NMIC, CRU TS3.21-China (Harris et al. 2014; Ge et al. 2013), Tang (Tang and Ding 2007), Li (Li

TABLE A1. Information on the selected temperature series for the whole of China.

Series	Time period	No. of stations	Data summary	Resolution	Gridding method	Source
Ref	1951–2010	607	Quality controlled; homogenized using the Peterson–Easterling (P–E) method	Gridded; $2.5^{\circ} \times 2.5^{\circ}$	For grids with stations, the arithmetic (unweighted) average temp is derived from all stations and for grids without stations, the nearest station data are interpolated.	This study
NMIC	1951–2007	731	Quality controlled; homogenized using the P–E method	Gridded; $1^{\circ} \times 1^{\circ}$	For grids with stations, the unweighted average temp from all stations is derived and for grids without stations, the modified kriging method is used for interpolation.	NMIC data from CMA (http://www.cma.gov.cn/2011qx fw/2011qs jgx/)
Tang	1951–2007	616	Quality controlled	Gridded; $5^{\circ} \times 5^{\circ}$	The mean of the highest and lowest mean temps is used and the gridding method uses the unweighted average temp from all stations.	Tang and Ding (2007)
CRU-China	1951–2009	109	Quality controlled; homogenized	Gridded; $0.5^{\circ} \times 0.5^{\circ}$	Station combination method uses the climate anomaly method (CAM; Jones 1994) and the gridding method uses triangulation.	CRU TS3.21 data (http://badc.nerc.ac.uk/data/); see Harris et al. (2014)
Li	1951–2006	728	Quality controlled; homogenized using the P–E method	Gridded; $5^{\circ} \times 5^{\circ}$	Station combination uses CAM method and gridding method uses the unweighted average temp from all stations.	Li et al. (2010a)
Wangjf	1951–2006	666	Quality controlled; homogenized using the P–E method	Gridded	Station combination uses MSN method and the gridding method uses the average temp from all stations.	Wang et al. (2014)

[et al. 2010a](#)), and Wangjf ([Wang et al. 2014](#)) series; see the [appendix](#) for information on these series]. The bar graph in [Fig. 4](#) displays the linear-trend values of each series for the periods 1951–2007 and 1955–2007 and demonstrates that the unweighted warming estimates always exceed the weighted estimates. That is, previous studies have overestimated the urban warming effect. The warming differences between the weighted and unweighted measures are 0.046° , 0.050° , 0.026° , and $0.030^{\circ}\text{C} (10\text{ yr})^{-1}$ (linear trend) for the Ref-New, NMIC-New, CRU-New, and Tang-New series, respectively,

during the period 1955–2007, and 0.006° and $0.040^{\circ}\text{C} (10\text{ yr})^{-1}$ for the Li-New and Wangjf-New series during the period 1955–2006. For the period 1951–54, the temperature curves diverge because of the different datasets and methods used to calculate the mean temperature, so we perform calculations over 1955–2007 as well as during 1951–2007.

[Figure 5](#) presents the urban land area and meteorological stations in randomly selected grid boxes. The national urban land area is shown in [Figs. 6a,c](#). [Figure 5](#) shows that the areas closely surrounding each station are

most affected by urbanization, but the areas between stations (covering lengths L_1 and L_2) are not usually affected by urbanization. The urban land proportion is small, whereas the urban station proportion is large. Therefore, we assign a land weight to each urban or rural station in each grid box to account for this imbalance (see section 3b for information on estimating the large-scale warming trend), which reduces the urban effect on the estimated national average temperatures. In addition, from Fig. 5, it can be seen that if data from the urban stations and rural stations are arithmetically averaged without weighting, the urban stations represent additional areas (station a and L_1 , station b and L_2) that are far away from urbanization areas and may have not been affected significantly by urbanization.

Furthermore, the weighted estimation technique for urbanization contributions to warming can also be applied globally. Land classification data indicate that the global urban area is small (Figs. 6b,d). Although certain regions have experienced substantial urbanization over the last century, urban land accounts for only 0.4% of the total land surface. The urban land percentage is lower than the urban station percentage [Global Historical Climatology Network (GHCN v.3): 45.8% and GISS: 45.9%; estimated according to the 7364-station dataset from GHCN and the 6026-station dataset from GISS]. Therefore, the unweighted average of urban and rural stations data may estimate a larger UHI effect because of the station locations in urban areas (Wickham et al. 2013; Montandon et al. 2011). Conversely, the weighted averages can demonstrate a lower urbanization effect and reduce the estimated UHI contribution.

5. Summary and outlook

This study estimates urban land-use (urbanization) effects on the temperature trend in China based on weighted urban and rural records. At the local level, the effect of urbanization on the station-level warming is obvious, accounting for 24% and 21% of the local warming of C1 and C2 stations. At the national level, the urbanization contribution is about $0.001^{\circ}\text{C} (10\text{yr})^{-1}$ and less than 1% of the total climate warming in China.

Previous studies that used the unweighted average of all records (urban and rural) overestimated the spatial scale of urban stations because the urban area is only a small part of the land area of China. This study provides new evidence that the urbanization effect on large-scale warming is negligible although there is a significant local UHI effect in small parts of China. Other factors like atmospheric circulation have likely played a leading role

in climate warming (Zhao et al. 2014). Moreover, this study suggests that it is important to consider the spatial scale of urban areas to better understand the surface warming trend and urban effects.

This study still includes some uncorrected problems that could be addressed in future studies.

- (i) The UHI effect is considered to be small scale by assuming that the nonurbanization area is not affected by UHI. This assumption has brought some uncertainties to the results. Some studies showed that upstream urbanization may exacerbate the UHI effect over downstream areas through advective processes (Zhang et al. 2009). In this study, the impact of upstream urbanization has not been considered and this will be further addressed in the future.
- (ii) Some stations were located in the suburbs near the edge of a city. So the measured air temperature at those stations may not fully reflect the air temperature of the urban area, especially for a city with only one station. In this study, the effect of site location in a city on urban temperature has not been considered.

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APPENDIX

Information on the Average-Unweighted Series

The average-unweighted series refer to the series that use a simple arithmetic average of the data from urban and rural stations in each grid box. This study includes the Ref, NMIC, CRU-China, Tang, Li, and Wangj series. Table A1 provides detailed information on these series.

The Ref series has been developed in this study in order to be compared with the New series. The homogenized data from 607 stations are the same as those of the New series. The gridding method, however, is different compared to the New series. The Ref grid data are obtained by using the arithmetic average temperature from all stations in each grid and the interpolation using the nearest station data in grids

without stations. The NMIC grid series was produced and published in 2007 by China's national meteorological service from the National Meteorological Information Center of the CMA. The series data (<http://www.cma.gov.cn/2011qxw/2011qsjgx/>) are representative of the temperature in China because those data have been prepared by national meteorological services. The homogenized station data in the NMIC series are the same as those in this study. The NMIC grid data are obtained by using the arithmetic average temperature from all stations in each grid and the interpolation using the modified kriging method in grids without stations. In the Tang series, 616 stations are included and the temperature data are quality controlled but not homogenized (Tang and Ding 2007). The grid data are calculated through the arithmetic average temperature from all stations using the mean values of the maximum and minimum temperatures of each station. The CRU series are from CRU TS3.21 data (which can be found online at <http://badc.nerc.ac.uk/data>; Harris et al. 2014). A total of 109 stations are included in the CRU-China series and the temperature data were adjusted through a homogenization method (Jones et al. 1985). The grid data are obtained by the triangulation method. In the Li series, 728 stations are used and the temperature data are homogenized (Li et al. 2009). The station data are combined by using the climate anomaly method, and the grid data are obtained by the arithmetic average over all stations. In the Wang series, the homogenized data from 666 stations are the same as in this study. The station data are combined by using the mean of stratified non-homogeneous surface (MSN) method (Wang et al. 2014), and the grid data are obtained by the average from all stations.

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