JGR Atmospheres

RESEARCH ARTICLE
10.1029/2019JD030948

Key Points:
- A new method to determine urbanization level around stations is presented, which shows the applicability to classify stations for assessing urbanization effect
- Also provided is the further evidence that the urbanization has significantly contributed to the observed warming trendsover the last decades in mainland China
- Urbanization effect shows notable difference for different data sets of national stations and for different timeperiods of 1960–2015 and 1980–2015

Supporting Information:
- Supporting Information S1

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Citation:
Tysa, S. K., Ren, G., Qin, Y., Zhang, P., Ren, Y., Jia, W., & Wen, K. (2019). Urbanization effect in regional temperature series based on a remote sensing classification scheme of stations. *Journal of Geophysical Research: Atmospheres*, *124*, 10,646–10,661. https://doi.org/10.1029/2019JD030948

Received 4 MAY 2019
Accepted 30 AUG 2019
Accepted article online 11 OCT 2019
Published online 21 OCT 2019

Urbanization Effect in Regional Temperature Series Based on a Remote Sensing Classification Scheme of Stations

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Abstract Quantifying the urbanization effect on station and regional surface air temperature (SAT) trends is a prerequisite for monitoring and detecting long-term climate change. Based on the data set of satellite visible spectral remote sensing, a new method is developed to determine the urbanization level around observational sites on varied spatial scales and to classify the sites into different categories of stations (U1, U2, ..., U6) with U1 the least and U6 the largest affected by urbanization. Urbanization effect on SAT anomaly series of urban and national stations are then evaluated for the periods of 1980–2015 and 1960–2015. Results show that the percentage of built-up area in different circumferences of the observational sites can be considered as a good indicator of comprehensive urbanization level of station and can be used to classify stations and to determine reference stations; the largest increase in annual mean SAT (T_{mean}) during 1980–2015 occurred at U6 stations, and U1 stations registered the weakest annual mean warming. The urbanization level is significantly positively correlated to the linear trends of annual mean T_{mean} and minimum SAT (T_{min}) and significantly negatively correlated to the diurnal temperature range (DTR) change. The data sets of the national reference climate station network and basic meteorological station network show large urbanization effect and contribution, with the annual mean urbanization contributions reaching 28.7% and 25.8% for the periods 1960–2015 and 1980–2015, respectively. For all the national stations (2,286 in total), the urbanization contributions are 17.1% and 14.6% for the two same periods, respectively.

1. Introduction

Urbanization can alter local environments via a series of physical processes, resulting in local environmental stresses (Cardelino & Chameides, 1990; Intergovernmental Panel on Climate Change, 2013) and, at the same time, affecting the trends of surface climate observations of urban stations (Rai et al., 2012; Ren et al., 2007, 2015). In mainland China, for example, the climate warmed significantly over the past half century (Committee of Chinese National Assessment, 2016), but the increasing temperature trends have been overestimated due to the effect of urbanization, which is probably one of the most important systematic biases in surface air temperature (SAT) series of urban stations with different urbanization levels.

In the previous studies, long-term trends of SAT in local and regional scales have been found to be associated with the urbanization level in a large extent in mainland China (He et al., 2007; Hua et al., 2008; Li et al., 2018; Ren et al., 2005, 2008; Yang et al., 2013; Zhang et al., 2010; Zhou et al., 2004). It is necessary to evaluate the bias of urbanization effect to the data sets, because the data had been extensively used by researchers in their analyses of regional (Ren et al., 2005, 2012) and global (Hansen et al., 2010; Jones et al., 2008; Lawrimore et al., 2011) climate change. Sun et al. (2016) reported that the linear trend in the observed annual mean temperature of all the national stations in mainland China is 1.44 °C over the period 1961–2013, of which 0.49 °C (0.12–0.86 °C) or about one third can be attributed to urbanization. Ren et al. (2015) showed that the contribution of the urbanization effect to the SAT warming is at least 24.9% for the national stations of mainland China during the period 1961–2004, approximately consistent with that reported by Zhang et al. (2010).

Most of the related researches have estimated the urban warming in a large-scale temperature series based on the comparison of urban and rural/reference (Hinkel & Nelson, 2007; Mete et al., 1997; Ren & Ren, 2011; Wen et al., 2019), which is a widely used method and generally regarded as the most robust way to examine the urban biases (Brohan et al., 2006; Hartmann et al., 2013). Different urbanization indicators have been adopted to classify stations with different urbanization levels and to select representative reference stations as benchmark. The most frequently applied indicators include population (total population, urban resident population, and population density) in the urban areas where the stations are located (Chu & Ren, 2005; Jones et al., 1990; Portman, 1993; Zhou & Ren, 2005), remote sensing nighttime light level (Hansen et al., 1999; Owen et al., 1998; Peterson et al., 1999), satellite remote sensing surface temperature (Gallo et al., 1993; Ren & Ren, 2011), and satellite remote sensing visible spectral data (Gallo et al., 1999; Gallo et al., 2002; Hansen et al., 2001; Kalnay & Cai, 2003; Yang et al., 2013). The difference in the methods and data set used by the various researchers is one of the main causes of the different estimates obtained for urbanization effects and contributions.

Land use/land cover (LULC) derived from the satellite remote sensing visible spectral data could be used to reflect the urbanization process around the observational stations intuitively. The LULC data have higher spatial resolution and wide coverage and thus have a good potential to be applied in classifying stations and selecting reference stations. Previous researches have separated different categories of stations based on urban land use around the observational sites to evaluate SAT trends due to urbanization in mainland China (He et al., 2013; Wang & Ge, 2012; X. Yang et al., 2011; Yang, Shi, et al., 2011; Yang, Wu, et al., 2013).

X. Yang et al. (2011), Yang, Shi, et al. (2011) used satellite remote sensing visible spectral data to evaluate the observational environment of six meteorological stations in Anhui Province, China, and the method showed a good applicability to surveying and selecting of representative meteorological stations. They also applied the data to classify the observational sites of Hefei City, China, into urban and rural stations according to the percentage of urban land use area in a buffer area around the stations, showing a good relationship between the annual mean temperature (annual mean minimum temperature) and the percentage urban land use area in the buffer areas. They further analyzed the urbanization effects on SAT changes for the urban stations and all national stations during 1970–2008, showing a large and significant urbanization-induced warming at the urban stations as well as the national stations during the period (X. Yang et al., 2011; Yang, Shi, et al., 2011).

Wang and Ge (2012) applied the satellite remote sensing data set but took the urbanization rate around the stations into consideration. They classified the national stations of China into three categories with different urbanization levels according to urban land use change around the stations, taking the stations with weak urbanization process as reference stations to evaluate the urbanization effect on temperature trends of other categories of urban stations. The analysis showed large urbanization contribution of 41% for the stations with high urbanization rate and an urbanization contribution of 20% for all the national stations in mainland China during 1980–2009.

He et al. (2013) applied the change in proportion of urban area as an indicator of urbanization rate around the stations and related the urbanization rate to annual mean SAT trends observed at the national stations in the Beijing-Tianjin-Hebei area, North China. They found a significant positive correlation between the urbanization rates and the SAT trends at all stations and an increase of 10% in urban area around the stations approximately contributed to the 0.13 °C rise in annual mean SAT in addition to regional warming. They showed an urbanization contribution of 44.1% to the overall warming trend as observed at the national stations during 1978–2008.

Urbanization effect on SAT series can be related to the influences of human activity on different spatial scales (Gallo & Xian, 2016; Ren et al., 2015; Stewart & Oke, 2012). At least three spatial scales would be important: the mesoscale from the whole city, the local scale of the size of a park and functional district, and the microscale of buildings nearby a station (Peterson, 2003; Ren et al., 2015). Gallo et al. (1996) noted that the effect of LULC is more significant at 10-km radius around the stations by examining the impact of urbanization on observed diurnal temperature range (DTR). The above-mentioned studies applied remote sensing visible spectral data generally considered the influence of local or microscale LULC but did not consider the possible simultaneous influence at microscale and mesoscale.

The works of Wang and Ge (2012) and He et al. (2013) have an advantage over the earlier remote sensing data based studies in taking the rate of urbanization around the stations into consideration in classifying stations or selecting reference stations, but at the same time, the methods also limit the analysis period to the shorter aft-satellite era, which only lasts three to four decades. On the other hand, it is unnecessary to address the rate of urbanization around the observational site for selecting rural or reference station if only the present observational environment of a station is good enough because the observational environments around almost all of the "bad" stations have been gradually worsened since their establishments (Ren et al., 2015). A "good" station which is good at present must also be good in the past, given that the station experienced no relocation.

In this study, a new methodology is developed based on the satellite remote sensing visible spectral data, and the percentage/relative area of urban land use on multispatial scales around an observational site at present was used as an indicator of urbanization level to classify the observational stations in mainland China. Six different urbanization levels including the weakest degree of urbanization are identified for the national stations. Urbanization effects on, and contributions to, the overall trends of annual and seasonal mean SAT series of urban stations for the period 1980–2015, and of two different national station networks for the periods 1980–2015 and 1960–2015, are quantitatively assessed.

2. Data and Methods

2.1. Data

The monthly SAT data set of "China National Surface Meteorological Station Homogenization Temperature Monthly Dataset (V1.0)," which includes 2,419 stations with a record length of 66 years (i.e., 1950–2015), has been homogenized in the National Meteorological Information Center, China Meteorological Administration (Cao et al., 2016). The data set includes the records of monthly mean SAT, monthly mean maximum SAT, and monthly mean minimum SAT. It can be divided into three sub–data sets: the national Reference Climate Network (RCN), the national Basic Meteorological Network (BMN), and the national Ordinary Meteorological Network (OMN). The RCN and BMN (RCN + BMN), about 825 stations totally, have been most frequently applied in analyses and monitoring of climate change in China, but recently, a few of groups have also begun to use all the stations from the three sub–data sets (RCN + BMN + OMN).

In this study, 2,286 stations from the RCN + BMN + OMN are used, considering the problem of missing data by discarding the temperature series with missing monthly records of more than 3 months in any year of the period 1960–2015. A total of four types of temperature indicators are analyzed, including mean SAT (T_{mean}), maximum SAT (T_{max}), minimum SAT (T_{min}), and DTR.

The LULC data set of mainland China in 2015 was provided by the Resources and Environmental Sciences Data Center, Chinese Academy of Sciences (Xu et al., 2018). The spatial resolution of the data set is 1.0 km × 1.0 km, which is based on the Landsat 8 remote sensing images and generated by artificial visual interpretation. The Resources and Environmental Sciences Data Center data have undergone a unified quality control and an integrated check. Compositions of land use classes in the data set include cultivated land, forestry land, grass land, water area, urban, rural and residential land, and unused land. The numbers 51 and 53 in classification system are used as urban land use in this paper, including the built-up areas of large, medium and small cities, the county capitals and towns, and other construction land (factories and mines, large industrial areas, oil fields, salt fields, quarries, as well as traffic roads, airports, and special land use; Xu et al., 2018).

2.2. Methods

2.2.1. Selection of Urbanization Indicator

In order to estimate the effects of urbanization of different levels on temperature trends at varied spatial scales from microscale (0–10 km) to mesoscale (more than 10 km but less than 100 km), the percentage of urban land use area around the observational sites is calculated in different buffer circles with the stations as the centers of them. This is done with an assumption that the larger proportion of built-up areas around the observational sites at any spatial scales within a maximum circumference will exert an impact on SAT records.

First, we determine study extent of urban land use around stations, that is, the maximum spatial scale for the urban land use impact on SAT records of stations. For each of the stations, 20 circles with radius of 1, 2, 3, ..., 20 km (1-km increment) and stations as the centers are determined, which are defined as buffer circles. Second, the urban land use categories are extracted, and the percentages of urban land use (PULU) in 2015 are calculated for each of the buffer circles, and a total 20 PULU values are produced for each station.

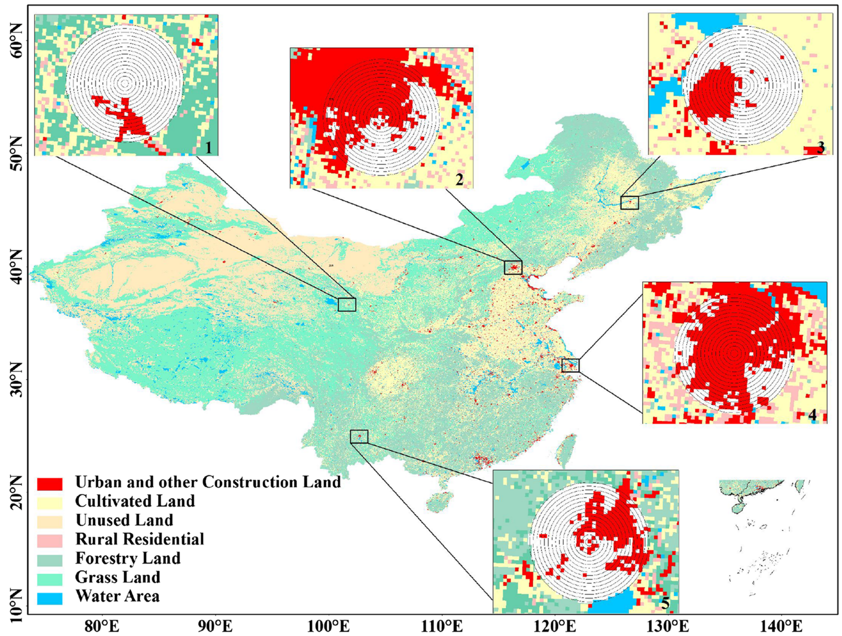

Figure 1. Visualization of land use/land cover in mainland China in 2015 and urban land use in 16 buffer circles around five representative meteorological sites (only the urban land use in buffer circles is shown; 1: Xining; 2: Peking; 3: Harbin; 4: Shanghai; 5: Kunming).

Finally, the Pearson's correlation coefficients between the annual T_{mean} trend series and 20 PULU values in all buffer circles of the total 2,286 stations are calculated (Supporting Information, Figure S1).

The results showed that all the correlation coefficients are above the 99.9% confidence level in each buffer circle with radii less than 20 km. The largest correlation coefficient is found when the radius of buffer circle is 4 km, and then the correlations gradually decrease with an increase of the radius. However, a slight upward trend is observed when the radius is larger than 16 km. The possible reason for this is that, when the radius of buffer circle is larger than 16 km, it may have already reached the distance to the neighboring city/town, especially in case that a denser observational network of 2,286 stations are utilized.

However, the largest spatial scale affected by urbanization is just within the mesoscale extent, which is approximately comparable to those found by applying change rate of urban land areas rather than PULU in the buffer circles (He et al., 2013; Wang & Ge, 2012). In this study, therefore, urban land use information in 16-km buffer circles around the station can be extracted to analyze the urban impact on SAT series. Different from all previous studies (He et al., 2013; Wang & Ge, 2012; Yang, Hou, et al., 2011; Yang, Shi, et al., 2011; Yang et al., 2013), however, we consider PULU values themselves, rather than the change rate of urban land areas, in each of 1- to 16-km radius buffer circles (Figure 1), which means that the possible impact of urban land use on SAT series of observation sites in varied spatial extents from microscale to mesoscale are all examined.

2.2.2. Classification of Urbanization Level

Based on the maximum of PULU values (MPULU) in all 16 buffer circles around stations, the 2,286 national stations are divided into 11 groups. The first group is defined as the MPULU ranges from 0% to 5% in all of the 1–16 km radius buffer circles, indicating that PULU in all buffer circles are less than 5%, or within the range of 0–5% for the stations in this group. The second group of stations has a MPULU value between 5% and 15% in the 16 buffer circles, and the 11th group of stations registers a MPULU value between 95% and 100%.

The MPULU usually appears in the fourth buffer circle (3–4 km) for all the 11 groups of stations (Figure S2), which can explain the above-mentioned finding that PULU has the highest correlation with the annual T_{mean} trends series in the 4-km radius buffer circle (Figure S1). This is also consistent with the fact that most of the stations are located within or near the medium-sized and small cities of the country, and the level of urbanization effect on the temperature change at the observational sites will be closely related to their distance from the urban centers (Ren et al., 2015).

In addition to the MPULU around station, the average of each PULU value at all spatial scales also needs to be considered. Therefore, the second step of classification of urbanization level for the above stations of 11 groups is to calculate the area-weighted average of the PULU (APULU) in the 16 buffer circles around stations for each of the groups, by using the inverse function distance weighting method:

$$APULU = \frac{\sum_{r=1}^{16} \frac{1}{r+c} \cdot PULU(r)}{\sum_{r=1}^{16} \frac{1}{r+c}}, \tag{1}$$

where r stands for the radius of buffer circle, $PULU(r)$ for the percentage of urban land use in r-km radius buffer circle, and c for a constant. The purpose of adding the constant c is to avoid the distance of the sample being too small as to infinite of the inverse function. Here, c is set to 5.

Though the urbanization level should have a positive correlation with the annual mean T_{mean} trend, the annual mean T_{mean} trends of the 11 groups do not increase linearly (Figure S3). The annual mean T_{mean} trends of the stations in the fourth, sixth, and ninth groups are somehow lower than the neighboring groups (as showed by the orange area in Figure S3), for example, but these lower trend values well correspond to the similarly lower APULU, indicating a good correspondence between the two variables. The classification of urbanization level thus not only calculates the MPULU in the 16 buffer circles as conducted in the first step but also considers the mean state of PULU values in all scales around the station. Around such stations as those in the fourth, sixth, and ninth groups, the PULU only has an abnormally large value in 1-km radius of buffer circle (Figure S2).

Therefore, certain groups as classified only by the range of the MPULU values have obviously lower APULU values and also the corresponding smaller temperature trends. Based on the APULU values, the 11 groups are regrouped into six categories (units), including U1, U2, U3, U4, U5, and U6, in order of increasing urbanization levels (Figure S4). The stations in ninth group are thus classified as U4 stations (yellow bar as shown in Figure S4) due to mean APULU values in all scales around these stations are close to the values around the stations of fifth and sixth groups (19.17%). The six categories of stations will be used to analyze the effects of varied urbanization levels on long-term trends of temperature.

Table S1 shows the six categories of stations differently affected by urbanization processes. It is assumed that the first category of stations (U1) with APULU less than 1% is hardly affected by urbanization, and they can be taken as reference stations. The relative warming of stations in other categories to that of reference stations can generally represent the urbanization effect. The stations in other categories have been affected by low (U2), lower (U3), medium (U4), higher (U5), and high (U6) urbanization levels, respectively, and they are termed as urban stations. It is very likely that the actual temperature anomaly series of the stations in U1 have still been affected by urbanization though in a much less extent.

2.2.3. Selection of Reference Stations

The specific criteria for selecting reference station in the RCN + BMN + OMN data set in mainland China are used in previous studies (Ren et al., 2015; Zhang et al., 2010), which had to be of sufficient length in data series and good continuity in the observations, higher stability and less relocation of observational sites, and, most importantly, an immunity to the urbanization influences. These criteria have been referred to determine the reference stations in this study.

The following specific steps are set for selecting reference stations: First, we choose stations in U1 with the beginning of record no later than 1960, the number of relocation less than three times after 1960 and horizontal distance of relocation less than 5 km, the difference between the elevation of the candidate reference station and the arithmetic mean elevation of other stations in same grid box is less than 40 m. A total of 128 U1 stations are selected, and this category of reference stations is regarded as U1 reference stations (green points as shown in Figure 2a; green grids in Figures 2b and 2c), and each green grid box has a maximum of two U1 reference stations. It can be seen, however, that there is no U1 reference station in some of the grid boxes of eastern region, in particular, in North China Plain and Northeast China Plain, due to the highly urbanization around the stations.

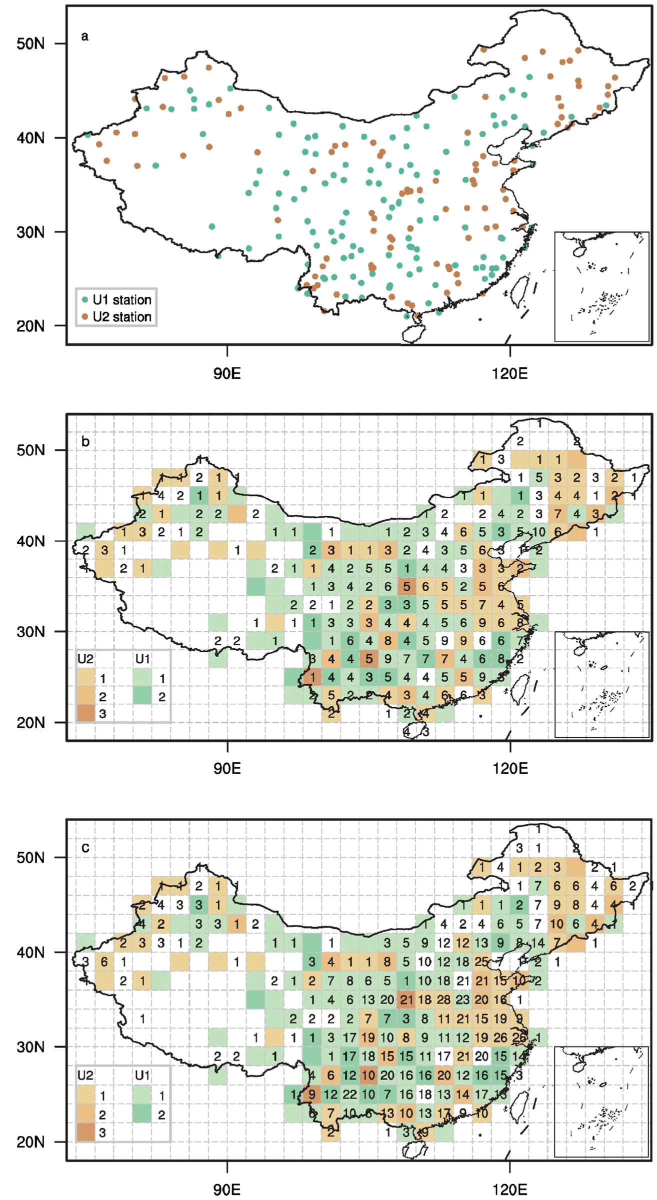

Figure 2. (a) Distribution of reference stations (green marks stand for U1 reference station; brown marks for U2 reference station), and number of reference and urban stations in grid boxes at a spatial resolution of 2° × 2° in mainland China (b: RCN + BMN data set; c: RCN + BMN + OMN data set; color grid boxes stand for the number of reference station in the grid, number for the number of urban station in the grid).

Based on the fact that the MPULU range 5–15% and the APULU is 3.36% around the U2 stations, respectively, stations in U2 category have potential applicability as reference stations in highly urbanization area of the plains. Therefore, in order to obtain enough reference stations to fill the blank boxes in eastern China, we use the same selecting criteria to filter the U2 stations for the remaining empty grids. This category of reference stations is regarded as U2 reference stations (brown points as shown in Figure 2a; brown grids in Figures 2b and 2c). The number of U2 stations and boxes are 101 and 72, respectively. The total reference stations (U1 + U2) are thus 228, and the total boxes with reference stations are 175. The reference station network including two categories of reference stations is utilized in this study to estimate urbanization effect and contribution in the SAT series of "urban stations" with different urbanization levels from 1980 to 2015, and of the national stations of the RCN + BMN + OMN and RCN + BMN data sets during different periods.

The "urban stations," which are all the stations in addition to the reference stations in the data set, will be assessed for the urbanization effect contained in their temperature series for period 1980–2015. Therefore, the target stations have excluded the reference stations for the assessment of urban stations. Also assessed for urbanization effect are the two complete data sets of the national stations (RCN + BMN + OMN and RCN + BMN) for periods 1980–2015 and 1960–2015. In this later assessment, however, the reference stations have not been excluded from the target stations so that the actual effects of urbanization on the usually used temperature data series can be determined, as practiced in the previous studies (Ren et al., 2008; Ren & Zhou 2014).

In order to ensure comparability between different urbanization effects, all results with different urbanization levels were based on the grids that have U3–U6 stations referring to the common practice as done in estimating regional averaged temperature series.

2.2.4. Statistical Methods

In this study, annual mean values are the average of 12 monthly mean values, and seasonal mean values are the average of 3 months in any of the seasons, which are divided according to climatological seasons of spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February).

The whole study area is divided into grid boxes with a spatial resolution of 2° × 2°, and at least one station is selected in each grid so that the reference series and "urban station" series of the grid can be established. Arithmetic average series of each of the reference and target stations are made to obtain the respective mean temperature anomaly series for the grid box. Temperature anomaly is calculated relative to the average of climatological reference period 1981–2010. The linear trend of difference of the urban station (national station) and reference station mean temperature series for the grid is defined as urbanization effect. If the urbanization effect is significant statistically on the grid, the urbanization contribution, which is defined as percent proportion of urbanization effect to the overall trend, will be calculated. The calculation method of the urbanization effect can be expressed as

$$\Delta T_{U-R} = T_U - T_R, \tag{2}$$

where is the linear trend of SAT series of urban station (national station) and is the linear trend of SAT series of reference station. Urbanization contribution is expressed as

$$C_U = \left| {}^{\Delta T_{U-R}}\!/_{T_U} \right| \cdot 100\%. \tag{3}$$

The detailed introduction about the calculation of urbanization effect and contribution for individual stations and grid boxes could be found in Chu and Ren et al. (2005), Ren et al. (2008), and Ren & Zhou (2014).

The linear trend of the temperature anomaly series is estimated using the ordinary least squares method. The serial correlation of the monthly mean SAT should not significantly affect the trend estimate, and it is not processed before the calculation of the trends (Von Storch & Navarra, 1999). The statistical significance of the linear trend of the temperature anomaly series is judged using the Student's *t*-test. The trend of temperature (temperature difference) series is considered statistically significant when a confidence level is equal to or higher than 99%.

3. Results

3.1. Distribution of Stations and Their Temperature Trends

The stations with the urbanization above median level (U4) are mainly distributed in East and North China (Figure 3), with the U6 stations totally distributed in North China and the coastal zone, and U5 stations dominantly located in eastern parts of the country. However, middle and western parts of China own more stations with lower urbanization levels. As the urbanization level increases, the average trends of annual mean T_{mean} of various categories at different latitudes gradually shift to the right of the *x*-axis (right panels of Figure 3), ranging from 0.298 to 0.425 °C per decade (−0.28 to 0.79 °C per decade for extreme value), which confirm the simultaneous variation of the urbanization levels and the trends of annual mean SAT series.

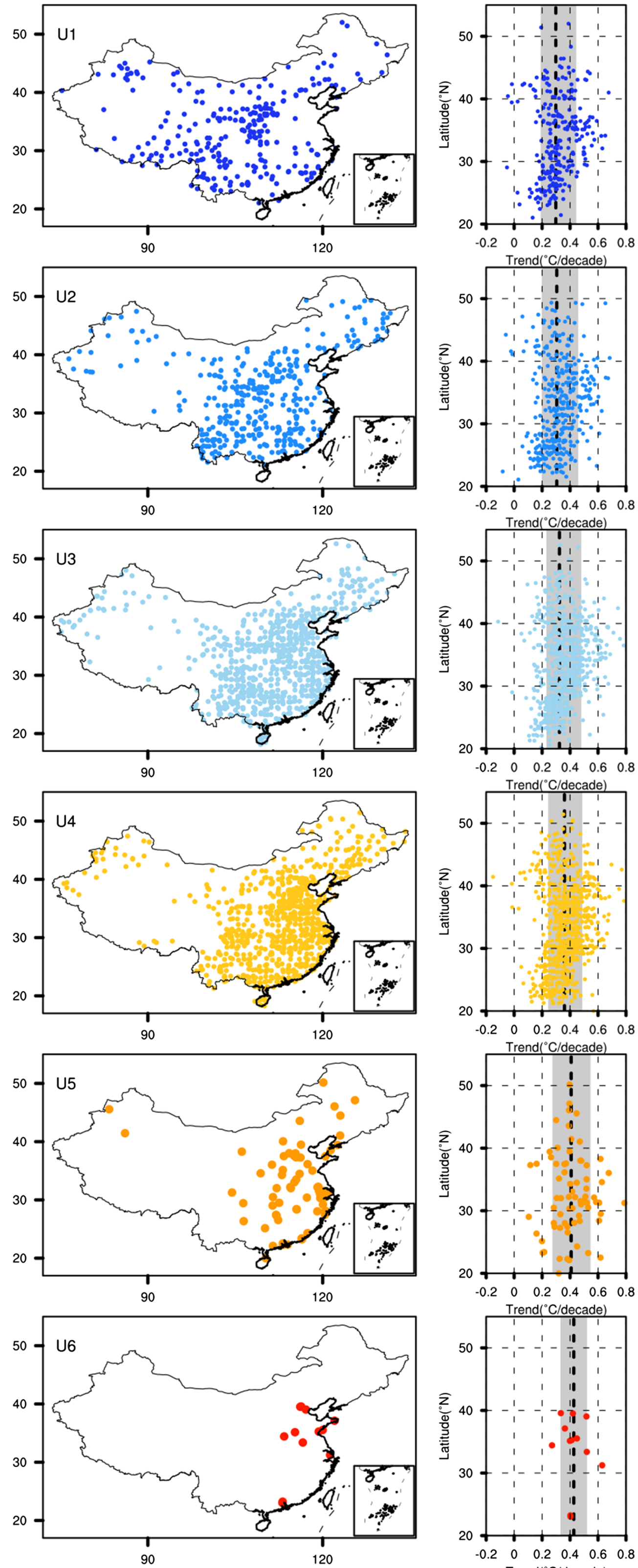

Figure 3. Spatial distribution of stations and average annual mean T_{mean} trends of various categories (U1–U6) during the period 1980–2015 (black dashed lines on the right panels stand for the average values of the temperature trends, and the width of the gray areas for a standard deviation).

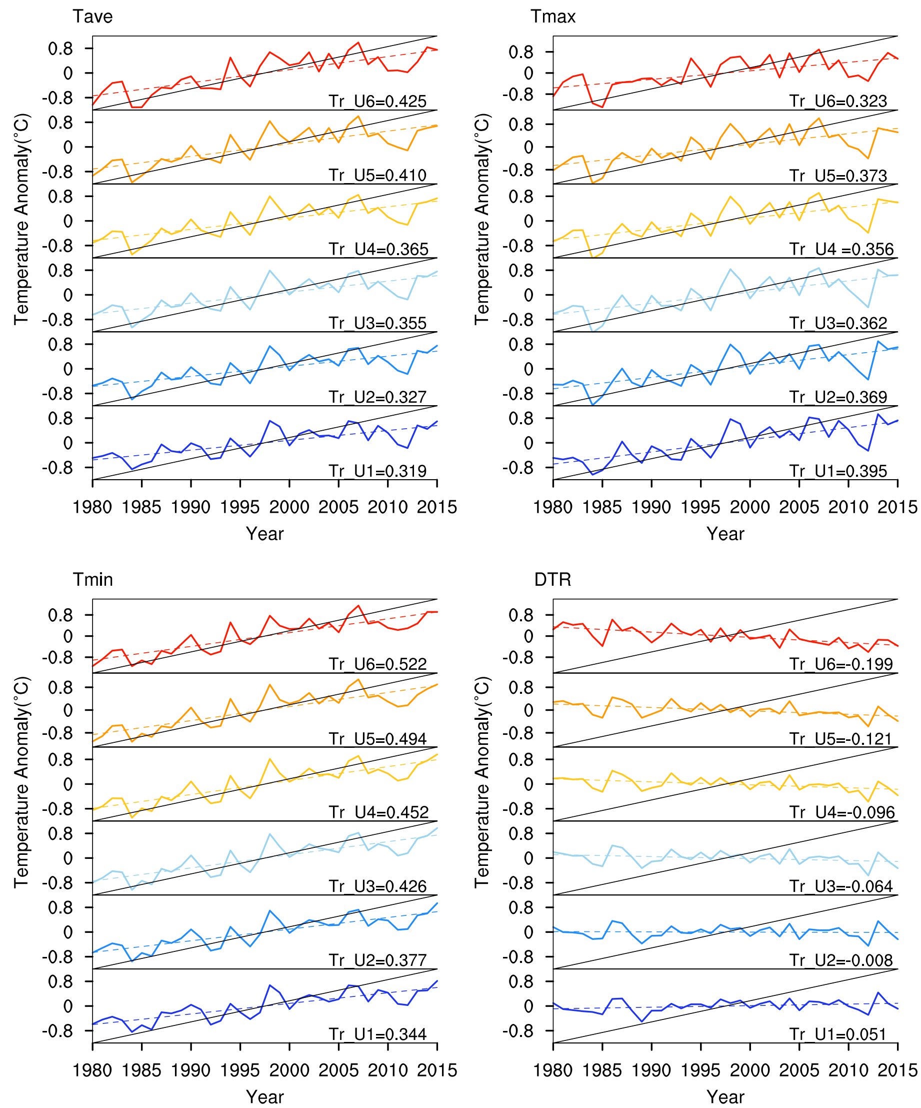

Figure 4. Regional average annual mean surface air temperature (DTR) anomalies for different categories of stations in mainland China during 1980–2015 (the values stand for average linear trend of series [unit: °C per decade]). DTR = diurnal temperature range.

3.2. Temperature Trends for Stations with Different Urbanization Levels

Changes in regional average annual mean SAT of the different categories of stations in the past 36 years are all positive (Figure 4). Annual mean T_{min} and T_{mean} increases are large and highly significant, and the increase rates are proportional to the urbanization levels. The maximum trend in annual mean T_{mean} occurs at the stations affected by the highest urbanization level (U6) in mainland China, which has an annual mean linear trend of 0.425 °C per decade during the period 1980–2015. As the urbanization level increases, annual mean T_{min} trends at stations in each category change from 0.344 °C per decade for U1 stations to 0.522 °C per decade for U6 stations. Though annual mean T_{max} trend is negatively correlated with the urbanization level probably due to the increased effect of aerosols at the higher urbanization level stations during daytime (e.g., Wang & Dickinson, 2013; Zhang et al., 2012), the trend differences between the stations in each category are very small.

For U1 stations, annual mean T_{max} increases faster than other categories of stations, and annual mean T_{min} rises more slowly, but the difference between the two trends is small so that annual mean DTR only slightly increases (Figure 4). As the urbanization level increases, annual mean T_{min} increase more obvious than

Table 1
Urbanization Effect (Unit: °C per decade) on, and Urbanization Contribution (Unit: %) to, the Annual Mean Surface Air Temperature (DTR) Trends for Varied Categories of Urban Stations (U3–U6) in Mainland China During 1980–2015

SAT		U3	U4	U5	U6
T_{mean}	A	0.036*	0.046*	0.091*	0.106*
	B	10.3	12.8	22.2	25.0
T_{min}	A	0.082*	0.108*	0.151*	0.178*
	B	19.3	24.0	30.5	34.2
T_{max}	A	−0.033	−0.039	−0.021	−0.072*
	B	N/A	N/A	N/A	22.1
DTR	A	−0.115*	−0.147*	−0.172*	−0.250*
	B	100	100	100	100

Note. "A" denotes urbanization effect (°C per decade); "B" denotes urbanization contribution (%); "N/A" indicates that the urbanization effect did not pass significance of the confidence level 99%. DTR = diurnal temperature range.
*Significance at the confidence level 99%.

annual mean T_{max}, and the annual mean DTR is significantly reduced. It shows that the annual mean T_{max} and T_{min} increases at the urban stations (U2–U6 stations) are becoming asymmetry, and urbanization level is negatively correlated to the DTR trend.

Of the four seasons, seasonal mean SAT increases most in spring, followed by winter and autumn, and summer temperature change is the smallest. With the increase of urbanization level, the amplified warming occurs most obviously in winter, spring, and autumn (Figure S5). In particular, the difference of average (median) trends between U1 and U6 is large for seasonal mean T_{min}, reaching more than 0.200 °C per decade.

The seasonal mean DTR trends for U1 stations are positive in all seasons (Figure S5). However, the average (median) DTR trends for urban stations are negative except for U2–U5 for spring. Although the increase of DTR happens in most categories of stations with the decrease of urbanization level, the U6 stations with the highest level of urbanization witnesses a negative trend of DTR in spring, due to the largest increase in T_{min} and the almost same change of T_{max} to that of U1 in this season. The seasonal mean DTR are more sensitive to urbanization level in cold season. From U1 to U6, not only the DTR trends change from positive to negative gradually, but the absolute values of the differences between the urban stations and U1 stations also increase, and the maximum difference of average (median) trends even reaches more than 0.400 °C per decade for autumn, with the trend of U6 stations far below those other categories of stations, probably due to the much lower increasing rate of seasonal mean T_{max} than other categories of stations (Figure S5).

3.3. Urbanization Effect for Urban Stations

The urbanization effects on, and contributions to, annual/seasonal mean SAT and DTR change during 1980–2015 gradually strengthen for different groups of urban stations (U3–U6) with the increase of urbanization levels (Table 1; Figure S6). U2 stations are not included in the figure and the table because they have already been taken as reference stations for some of the grid boxes.

Urbanization effects are positive for annual mean T_{min} and T_{mean} for all categories of urban stations during 1980–2015. For annual mean T_{min}, which witnesses a maximum urbanization effect of 0.178 °C per decade for the urban stations with the highest urbanization level (U6), average urbanization contribution is 34.2% (Table 1). The average contributions of annual mean T_{mean} range from 10.3% to 25.0% for urban stations with different urbanization levels. The decrease of annual mean T_{max} difference series is much less than that on the increase of annual T_{min} difference series for urban stations, with effects of urbanization on T_{max} trends range from −0.033 °C per decade for U3 stations to −0.072 °C per decade for U6 stations (Table 1). Therefore, the annual mean DTR difference series have highly significant decline trend. As the urbanization level increases, the urbanization effect on the DTR trends of the urban stations gradually increases, with a maximum urbanization effect of −0.250 °C per decade for U6 stations. Urbanization contributions to the annual and seasonal mean DTR trends reach 100% for all of the urban stations.

The annual mean T_{mean} and T_{min} are more affected by urbanization as mentioned above. On the seasonal scale, the average (median) urbanization effects are more significant on winter, spring, and autumn for urban stations, all reaching more than 0.150 °C per decade for T_{min} (Figure S6). Urbanization contributions to seasonal mean T_{min} trends for U6 are all above 36.0% in cold seasons, and the urbanization contribution to seasonal mean T_{mean} trend for U6 stations also reaches 30.4% in winter (Table S2). The urbanization contributions to seasonal mean T_{max} trends are mainly reflected in the winter, with winter maximum value at 30.8%.

As urbanization level increases, the significant decrease of seasonal mean DTR difference series happens, especially in cold seasons. For example, the average (median) urbanization effects in autumn mean DTR change are −0.100 °C per decade for U3 stations and −0.348 °C per decade for U6 stations (Figure S6). However, though the U3 stations have a low urbanization level, while the contributions in each of the seasons are close or equal to 100%, it may relate to the study region, the grids with U3–U6 were selected to

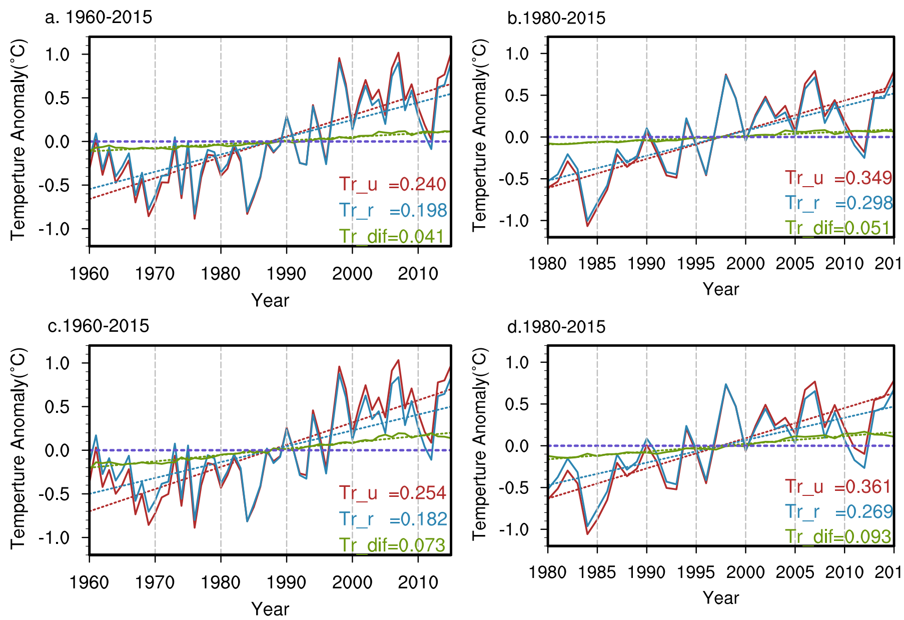

Figure 5. Annual mean T_{mean} anomalies of the stations of RCN + BMN + OMN (a, b) and RCN + BMN (c, d), reference stations, and the differences between national stations and reference stations, during 1960–2015 (a, c) and 1980–2015 (b, d) in mainland China (red lines stand for national stations series, blue lines for reference stations series, and green lines for the difference series; values are the linear trends of the series [unit: °C per decade]).

calculate urbanization effect and contribution, which are mainly distributed in the east of China, the most developed region.

3.4. Urbanization Effect for National Stations

Figure 5 shows annual mean T_{mean} anomalies of the stations of RCN + BMN + OMN (a, b) and RCN + BMN (c, d), the reference stations, and the national stations minus reference stations differences during 1960–2015 (a, c) and 1980–2015 (b, d). The four annual mean T_{mean} difference series all exhibit a statistically significant positive trend, the urbanization effect on the annual mean T_{mean} trend reaches 0.041 °C per decade, and the urbanization contribution is 17.1% in the data series of RCN + BMN + OMN but is 0.073 °C per decade and 28.7% in the data series of RCN + BMN, respectively, during the period 1960–2015 (Figures 5a, 5c, and 6a). In the last three decades, the annual mean urbanization effect reaches 0.051 °C per decade, and the urbanization contribution is 14.6% in RCN + BMN + OMN, but 0.093 °C per decade and 25.8% in RCN + BMN, respectively (Figures 5b, 5d, and 6b). The results of evaluation using the same reference station network show that the urbanization contributions to the annual mean T_{mean} trends in the two data sets differs by 11.6% and 11.2% for the different time periods 1960–2015 and 1980–2015, respectively.

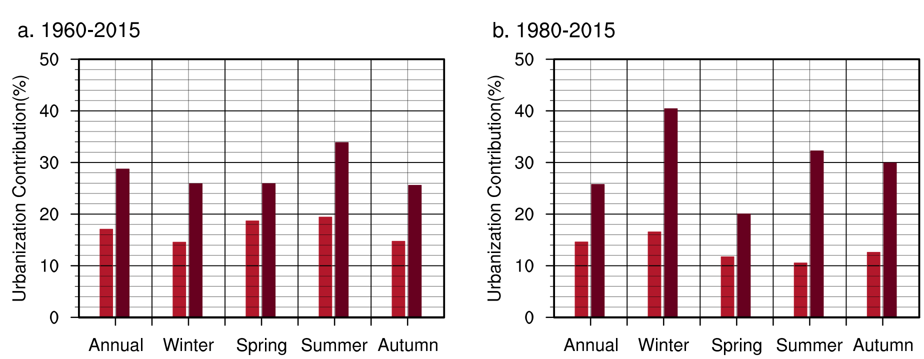

Figure 6. Urbanization contribution to the annual and seasonal mean T_{mean} trends of the national stations of RCN + BMN + OMN (red) and RCN + BMN (purple) for the periods 1960–2015 (a) and 1980–2015 (b).

The urbanization effects on the seasonal mean T_{mean} trends in the data set of RCN + BMN are also larger than those in the data set of RCN + BMN + OMN for the two periods (Figure S7 and Table S3). The range of urbanization effects in the two data sets is 0.032 to 0.087 °C per decade on the seasonal scale during the period 1960–2015. Urbanization effects are largest in winter for both of the RCN + BMN + OMN and RCN + BMN stations for the past 56 years, reaching 0.044 and 0.087 °C per decade, respectively. The smaller seasonal mean urbanization effects occur in summer and autumn (Figure S7). The seasonal characteristic of urbanization effects on the seasonal mean T_{mean} trends is identical in the two time period, but the values are lager for the past 36 years (Figure S7 and Table S3). However, the seasonal characteristic of urbanization contributions to the overall T_{mean} trends shows the difference in two time periods. The highest contribution occurs in warm season for the period 1960–2015, being 19.4% for RCN + BMN + OMN and 33.9% for RCN + BMN in summer; but the largest seasonal mean urbanization contributions, 16.6% and 40.4% for the two data sets, respectively, occur in winter in the period 1980–2015 (Figure 6).

The difference of urbanization effects and contributions in the same temperature data set between the two study periods is notable. After 1980, urbanization is developing more rapidly in mainland China, which has been reflected in the different urbanization effects of the T_{mean} series. At the same time the background change and natural variability of the annual mean T_{mean} series during the last three decades are also larger than those in the longer time period, so the annual mean urbanization contributions in both of the two data sets are generally reduced after 1980 (Figure 6). However, the urbanization contribution just increase greatly in winter, and it may be related to climate warming hiatus.

On the other hand, the different results also appear in two data sets over the same period. The main reason why urbanization effect and contribution are larger in the data series of RCN + BMN than RCN + BMN + OMN is obvious. The stations of RCN + BMN are mostly located in urban areas or margin of big and medium-sized cities because of the historical and unique socioeconomic conditions, which require the weather and climate observations to be near the urban areas as much as possible (Ren et al., 2008, 2015). In case of OMN stations, which accounts for more than two third of the RCN + BMN + OMN stations, the observations are generally made in or near the county capitals which are mostly small cities or towns. In addition, most of the stations in RCN + BMN have been moved for at least one time from urban to suburban areas due to the rapid urbanization process, as compared to the stations of OMN, and the adjustment to the breakpoints of the temperature series or the data inhomogeneity mainly due to relocations would in certain extent recover the urbanization effect that was ever weakened in its original data series (Hansen et al., 1999; Ren et al., 2015; Zhang et al., 2014).

4. Discussion

4.1. Classification Method of Urbanization Level

Compared with the previous studies which used the change of urban land use around the stations to analyze the effect of urbanization on temperature series (Yang, Hou, et al., 2011; Yang, Shi, et al., 2011; Wang & Ge, 2012; He et al., 2007), the method to determine the urbanization level around observational sites developed in this study has taken a comprehensive consideration of both microscale and mesoscale effects of urban land use around the observational sites and also has solved the problem of limited analysis period due to the shorter aft-satellite era for usage of change rate of urban land coverage. We also applied a bigger data set, which is almost three times of the previous data sets in terms of observational stations, for the classification of land use around each of the stations.

Based on the analysis of correlation between the annual mean SAT trends and 20 PULU data in all buffer circles of 2,286 stations, we selected urban land use within buffer less than 16-km radius to assess the effect of urbanization on SAT changes. However, the areas of urban land use around these stations are sometimes larger than 16-km radius buffer circle, for example, in case of Beijing or Shanghai cities (Figure 1). We only considered the average status of area of the urban land use around all stations in mainland China, but for stations that still have urban land use in a buffer circle radius greater than 16 km, this may influence the classification results of these stations. Additionally, the selected reference stations (U1) may have been affected in certain extent by the urbanization, though the effect would be substantially small compared to those of the urban stations. At the same time, not all grid boxes have U1 stations as reference, and about 41% grids used

U2 as the reference stations when estimating urbanization effect in the data sets. Therefore, the evaluation results of urbanization effect with U2 as the reference stations would be underestimated compared with those with U1 as the reference stations. As a result, the urbanization effect and contribution as shown in this paper should be regarded as conservative. Another potential source of uncertainties would be the homogenization of the data. Because the stations moved usually from the urban areas to the suburban areas, the urbanization effect on the data series will be restored after homogenization by using the generally applied methodologies (Ren et al., 2015; Zhang et al., 2014). However, the land use data are still for the current observational sites, leading to a mismatch sometimes between the urban warming rates and the PULU around the observational grounds. Although this would have a small impact on the determination of their correlations, reference stations, and urban stations, the urban indicator should be further completed to consider the exact positions of the historical observational sites. This issue should be emphasized especially when the samples (stations) for use are insufficient. However, the above uncertainties can be reduced when the method is applied in less developed regions or in regions where enough stations are available for selecting reference observational data series.

Overall, the method took relative area of urban land use around the meteorological observational site at varied spatial scales as indicator of urbanization to analyze urbanization effect on, and contribution to, the trend of temperature data series at urban and national stations, showing analysis results comparable to those by using other sophisticated procedures as described below. Therefore, it has a good potential to be applied in the future for the studies of urbanization effect in the long-term SAT data series in regional and global land scales.

4.2. Compared with Other Analyses in Mainland China

Compared with the results of Sun et al. (2016) based on the RCN + BMN + OMN data set, the conclusion in this study is slightly smaller than theirs that showed a one-third urbanization contribution to the linear trend of annual mean SAT in the past 50 years (Table S4). This may be related to the different methods used to attribute the locally anthropogenic forcing to SAT change. Sun et al. (2016) applied the optimal fingerprinting approach to evaluate anthropogenic influences including urban warming by examining if an observed SAT change is significantly larger than that expected from internal variability and if the observed SAT trend is consistent with that simulated by climate models, while this study used the urban minus rural method to directly assess the urbanization effect. The two procedures have their own advantages and disadvantages, and the results derived from them would be different. However, our analysis might have produced an underestimate of the urbanization effect because the selected reference stations might have been affected by urbanization in a less extent, and the result in our analysis should be regarded as a conservative estimate.

It is therefore noteworthy that, due to the remnants of urbanization effect in the data series of the reference stations used in this study, the urbanization effect and contribution at the stations other than reference stations given in this paper should be regarded as the lowest estimates, and the real values would be higher than the results.

For the analyzing results by using the RCN + BMN data set, no result based on the optimal fingerprinting approach is available for time being. As for the studies by using the urban minus rural method, the selected reference stations are various due to the varied procedures used for determining the rural observational sites, and the inconsistency of study period may also lead to slightly different results. However, the result in this study is approximately consistent with the previous ones when the homogenized RCN + BMN data set were used (Table S4). Majority of the results stayed between 20% and 30% in the past 50 years or so, but all the estimates should be lower than the true values. As there was no any previous study which had used the same method to analyze urbanization effect and contribution in the SAT series of the different data sets in mainland China, however, there is no analysis result available to be strictly compared with here.

Figure S8 presents the growing condition of the urban land use in the buffer circle of 16-km radius around two meteorological stations without any relocation during 1980–2015, which are located in the typical medium-sized cities of Beijing-Tianjin-Hebei region and the Pearl River Delta, respectively. There were significant urban land expansions around the two stations since early 1990s, and PULU in 16-km radius buffer circles are close to or exceeded 50% in 2015, which shows that the impacts of urbanization on the observational environment are evident at the observational sites. Other urban stations in mainland China also experience similar change in land cover around the observational grounds during the past decades in varied extents.

Figure S9 shows the averaged PULU within 8-km radius buffer circle around the 2,419 observational stations during 1980–2015. The 8-km buffer radius is selected to show some consideration for the majority of small cities in the data set. The PULU at a local scale around all stations in RCN + BMN + OMN data set for each of the buffer circles in 1980, 1990, 1995, 2000, 2005, 2010, and 2015 were calculated. The annual average values of all the stations for all buffer circles show the remarkable increase of PULU around stations since the early 1980s, from 4% in 1980 to 10% in 2015 (Figure S9). However, the results also show that the urbanization process around the observational sites was nonlinear during the period 1980–2015, with the more strong urbanization processes found during 2000–2005 and 2010–2015, respectively. After 2010, the increase of the average PULU becomes very strong.

Therefore, on one hand, under the background of the large-scale climate change and variability, urbanization development in the whole time periods of 1980–2015 and 1960–2015 may have strengthened the urban heat intensity around the observational stations, leading to a consistent SAT rising in addition to the global and regional warming. On the other hand, the urbanization effect in different periods may have been different for individual and regional SAT series due to the nonlinear characteristics of urban land use variation. Moreover, we should give attention not only to the regional average SAT series caused by urbanization in the different data set and periods but also to the unbalanced spatial pattern of the urbanization effect in the country.

5. Conclusions

This study presented a new satellite-based methodology to classify the observational stations in mainland China and shows the analysis results of urbanization effect and contribution in the annual and seasonal mean SAT series of urban stations and different categories of national stations for varied periods over mainland China, based on the new methodology. The following conclusions can be drawn:

The percentage of built-up area in different buffer circles around the observational sites can be considered as a good indicator for the comprehensive urbanization level of a station and can be used to classify stations and also to select reference temperature stations for assessing the urbanization effect on the SAT data series of urban and national stations.

Correlation coefficients between the annual mean SAT trends of 1980–2015 and the PULU in each of the buffer circles with radius from 1 to 16 km are all highly significant (≥99.9% confidence level) for the 2,286 stations in mainland China. The highest correlation was found when the radius of buffer circle was 4 km. The urbanization indicator in this study considers the effect of urban land use around the observational sites at both microscale and mesoscale.

All stations are classified as six categories, or U1, U2, U3, U4, U5, and U6, respectively, in order of increasing urbanization levels. The largest increase in annual mean SAT occurred at the stations affected by urbanization of the highest level (U6) during 1980–2015, and the U1 stations registered the smallest annual mean SAT trends. Winter, spring, and autumn mean SAT had a larger warming rate and are more sensitive to the urbanization level.

During the period of 1980–2015, urbanization contribution to annual mean surface SAT trends ranges from 10.3% to 25.0% for urban stations (U3–U6); urbanization effect and contribution are larger and more significant in the annual mean minimum SAT series, with a maximum urbanization effect and contribution of 0.178 °C per decade and 34.2% for U6 stations; urbanization led to a nonsignificant negative impact on annual mean maximum SAT trends, and a highly significant decline of annual mean DTR trends. The urbanization contribution to the downward trends of annual mean DTR reaches 100% for all urbanization level of stations (U3–U6).

The assessment of national stations using U1 and U2 stations as reference shows significant but different urbanization effects in the annual mean SAT trends. Larger urbanization effect and contribution for the national reference climate and basic meteorological station networks (RCN + BMN) than those on all the national stations (RCN + BMN + OMN) for both 1960–2015 and 1980–2015 are found. During the two periods, the urbanization contributions are 28.7% and 25.8%, respectively, for annual mean SAT trends of RCN + BMN, and they are 17.1% and 14.6% for all the national stations.

Acknowledgments
The land use/land cover data set of mainland China is provided by the Resources and Environmental Sciences Data Center (RESDC), Chinese Academy of Sciences (CAS) (www.resdc.cn/data.aspx?DATAID=184). The monthly surface air temperature data set is provided by the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA) (http://data.cma.cn/data/detail/dataCode/A.0029.0004.html). This work is supported by the National Key R&D Program (2018YFA0605603) and the Natural Science Foundation of China (NSFC; 41575003).

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