Urbanization Effects on Observed Surface Air Temperature Trends in North China

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ABSTRACT

A dataset of 282 meteorological stations including all of the ordinary and national basic/reference surface stations of north China is used to analyze the urbanization effect on surface air temperature trends. These stations are classified into rural, small city, medium city, large city, and metropolis based on the updated information of total population and specific station locations. The significance of urban warming effects on regional average temperature trends is estimated using monthly mean temperature series of the station group datasets, which undergo inhomogeneity adjustment. The authors found that the largest effect of urbanization on annual mean surface air temperature trends occurs for the large-city station group, with the urban warming being 0.16°C $(10\ \mathrm{yr})^{-1}$, and the effect is the smallest for the small-city station group with urban warming being only 0.07°C $(10\ \mathrm{yr})^{-1}$. A similar assessment is made for the dataset of national basic/reference stations, which has been widely used in regional climate change analyses in China. The results indicate that the regional average annual mean temperature series, as calculated using the data from the national basic/reference stations, is significantly impacted by urban warming, and the trend of urban warming is estimated to be 0.11°C $(10\ \mathrm{yr})^{-1}$. The contribution of urban warming to total annual mean surface air temperature change as estimated with the national basic/reference station dataset reaches 37.9%. It is therefore obvious that, in the current regional average surface air temperature series in north China, or probably in the country as a whole, there still remain large effects from urban warming. The urban warming bias for the regional average temperature anomaly series is corrected. After that, the increasing rate of the regional annual mean temperature is brought down from 0.29°C $(10\ \mathrm{yr})^{-1}$ to 0.18°C $(10\ \mathrm{yr})^{-1}$, and the total change in temperature approaches 0.72°C for the period analyzed.

1. Introduction

Detection and attribution of global and regional climate change, especially of the nature and possible causes for climate warming over the past century, are a central issue in current climate change research. Detection and attribution are mainly based on the instrumental data of the past century in addition to the simulation using climate models. Due to the replacement of observation instruments, relocation of observation sites, changes in observation times, changes in the time system, and the urbanization effect, inhomogeneities have occurred in the data series to varying degrees. The urbanization effect is especially important in that it directly affects the trend of surface air temperature (SAT). Thus there is a need to check and to eliminate the urbanization effect in studying regional or global average SAT change (Karl et al. 1988; Jones et al. 1990; IPCC 2001; Hansen et al. 2001; Zhou et al. 2004).

At present, a major divergence of views exists in the international climatological community on whether the urbanization effect still remains in the current global and regional average SAT series. The Intergovernmental Panel on Climate Change (IPCC) third assessment report pointed out that the urban heat island effect is of secondary importance, and it had not surpassed 0.05°C (as of 1990) in the past 100 years on a global average as compared to the optimal estimation of the global average SAT change of 0.6°C (IPCC 2001). Nevertheless, some research efforts have shown that the urban heat

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island (UHI) effect might have played a larger role in the temperature trend estimated to date, which should be given more consideration and should be emended (Karl et al. 1988; Wang et al. 1990; Zhao 1991; Portman 1993; Hansen et al. 2001; Ren 2003; Zhou et al. 2004).

Karl et al. (1988) made a systematic comparative analysis of stations in American urban and rural areas, finding that during 1901–84 cities, and even small towns with a population of more than 1000, experienced evident influence of urbanization on the SAT trend. Karl and Jones (1989) concluded that, during the 1901–84 period, the bias caused by urbanization in the American annual mean SAT series is +0.1° to +0.4°C, which is almost equivalent to the overall climate warming trend (+0.16°C) in the same time period. Balling and Idso (1989) calculated the SAT change over eastern American areas during 1920–84 and found that the SAT increases by 0.39°C over the 64 years, but it only rises by 0.02°C after the urbanization effect was deducted. Goodridge (1992) found that annual mean SAT rose by 1.44°C in the past 100 years over cities with a population of 0.64~8.71 million in California, while the temperature increased only 0.28°C in the same period for small cities and towns with a population of 4000~99 000. Hughes and Balling (1996) showed that the SAT change trend over big cities in South Africa was 0.15°C $(10\ \text{yr})^{-1}$, significantly higher than that over small cities and towns. Through a comparative analysis of the observed SAT data of the stations and of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) SAT reanalysis data, Kalnay and Cai (2003) came to the conclusion that, in nearly one century, the annual mean SAT increased by 0.27°C over the United States, owing to land-use changes and the urbanization process. If the inhomogeneity-adjusted surface observation data were used, the influences of land-use change and urbanization would be even larger (Cai and Kalnay 2004).

On the other hand, Jones et al. (1990) made a comparative analysis of the mean SAT changes from urban and rural stations in the former Soviet Union, east China, east Australia, and America, showing that urbanization has had little effect upon the mean SAT change over those regions, and annual mean SAT temperature increase recorded at the rural stations is even larger than the warming observed at the urban stations in east China. According to the night-light intensity information from satellite pictures and American aeronautical charts, Peterson et al. (1999) divided the 7280 stations of the Global Historical Climate Network (GHCN) into rural stations, suburban stations, and urban stations and, by separately calculating the global mean SAT anomalies based on all of these stations and the 2712 rural stations, they found that the warming at the rural stations during 1880–98 was 0.7°C $(100\ \text{yr})^{-1}$ and the warming for all stations was 0.65°C $(100\ \text{yr})^{-1}$. At the same time, they showed that, during the 1951–89 period when coverage of rural stations became the most complete, the warming at rural stations was 0.8°C $(100\ \text{yr})^{-1}$ and the temperature rise for all stations was 0.92°C $(100\ \text{yr})^{-1}$. They concluded that the global mean SAT series constructed with the GHCN dataset was not significantly influenced by urbanization.

However, analyses for several regions of China showed that increase in UHI intensity with time exerted a significant influence upon the SAT trends over the past decades (Wang et al. 1990; Zhao 1991; Portman 1993; Ren 2003; Zhou et al. 2004; Lin and Yu 2005; Zhang et al. 2005; Chu and Ren 2005). By dividing China into six parts, Wang et al. (1990) compared 42 pairs of urban and rural SAT data for 1954–83 and found that the UHI produced a comparatively evident effect on SAT trends at urban stations. In a study of the urbanization effect on Chinese surface temperature over a period of 39 years, Zhao (1991) concluded that the urbanization effect in China could not be neglected. Lin and Yu (2005) studied the decadal temperature change and the heat island effect over the Beijing region and found that the influence of the UHI effect was very obvious in the SAT observations from the Beijing station. By using the surface observation data and the reanalyzed data, Zhou et al. (2004) determined that the rate of temperature warming brought about by urbanization in southeast China was 0.05°C $(10\ \text{yr})^{-1}$, much larger than the former estimates for other areas and periods. Using similar data and methods, Zhang et al. (2005) calculated the rate of temperature warming caused by urbanization and land-use change in China to be 0.12°C $(10\ \text{yr})^{-1}$. Chu and Ren (2005) showed that, in the annual mean SAT warming estimated from the national Reference Climate Station (RCS) and the national Basic Weather Station (BWS) in the Beijing region over the past 40 years, the contribution of the urbanization effect reached 71%. If only the Beijing station is considered, the contribution of urban warming to the overall warming is as large as 80% (Ren et al. 2007). However, Li et al. (2004) indicated a much weaker urban warming in some regions and the country as a whole by comparing SAT trends between rural and urban stations.

It is clear that the issue of the possible influence of UHI effects on the present available global and regional mean SAT series has not yet been solved. Chinese researchers have used different datasets to establish the national average SAT series for the last 50–100 yr (Tao et al. 1991; Chen et al. 1991; Chen and Zhu 1998; Ding and Dai 1994; Lin et al. 1995; Shi et al. 1995; Wang et al. 1998; Zhai and Ren 1999; Qian and Zhu 2001; Liu et al. 2004; Ren et al. 2005), but almost all of these datasets come from the records of the RCSs and BWSs. Although some researchers (Ren and Zhou 1994; Zhai and Ren 1999) did take the growing UHI effect upon the regional average SAT series into preliminary account when constructing regional average SAT series, most researchers did not pay attention to this issue. Recent studies have shown that the annual mean SAT over China increased by about 1.3°C during the time period of 1951–2004 with the rate of temperature warming being close to 0.25°C $(10\ \text{yr})^{-1}$ (Ren et al. 2005), significantly higher than the averaged global land area warming of about 0.14°C $(10\ \text{yr})^{-1}$ over the same period (Jones and Moberg 2003). However, no adjustment for the urbanization effect on SAT observations was made in the latest studies of China. The intensified UHI effect might have been the major error source in the estimation of the regional average SAT trend in China.

Applying the data from the RCSs, the BWSs, and the ordinary weather stations (OWS) in north China, and on the basis of examination and adjustment of the inhomogeneity of the temperature data, the present paper analyzes the differences between the rates of SAT change in 1961–2000 obtained from the stations in urban areas of varied sizes and the change in rural areas, and estimates the relative contribution of the UHI effect to the overall mean SAT trends of the various types of urban stations and of the RCSs and BWSs within the study region.

2. Region definition, data, and methods

North China in the present paper refers to the central northern part of China (Fig. 2), mainly including central and southern Inner Mongolia, Beijing, Tianjin, Hebei, Shanxi, eastern Shaanxi, northern Henan, central and western Shandong, and northern Anhui and Jiangsu, within the region 33°–43°N, 108°–120°E. This region has diverse topography with the southeast being lowlands consisting mainly of the North China Plain. The Inner Mongolian Plateau and the Loess Plateau are located in the northwest of the region. The southwestern part of the study region consists of the Guanzhong Plain and the Qinling Mountains.

The climate data used are the monthly mean surface air temperature during 1961–2000 from all of the weather and climate observation stations, including the RCSs, BWSs, and OWSs in this region. Year 1961 is taken as the beginning year because almost all of the RCSs and BWSs and a majority of the OWSs were established by that time; temperature records after the year 2000 are not used because the traditional surface observation network in China was being replaced with automatic weather stations during the time period 2000–05 and this changeover might have led to more inhomogeneity of the data.

The RCSs total 143 in mainland China. Being relatively evenly distributed across the country, they are designated to observe as many climatic variables as possible, including hourly surface air pressure, surface air temperature, wind, precipitation, and so on. The climatic variables observed at the 530 BWSs in the country are similar to those of the RCSs, but are only measured eight times a day. China's 1736 OWSs are generally monitored by provincial meteorological administrations and measure fewer climatic variables only three or four times a day. The RCSs and BWSs are taken together as a single group in this paper, and henceforth are called the National Stations (NSs); the OWSs are called the ordinary stations. The numbers of the RCSs, BWSs, and OWSs in the study region are 29, 73, and 213, respectively.

All of the data from these stations are stored and managed in the Climate Data Center of the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA); missing values from 102 months, which account for 0.75% of the total records, are replaced by climatological averages for 1971–2000 if they are for 12 months running or less within a year. If the missing records are more than 12 months in succession, the stations are excluded. In total, 33 stations were thus discarded. By checking the SAT data quality using statistics for all of the stations, some of the possible erroneous records are also ruled out and a dataset from 282 stations for the study is ultimately used. The station density reaches about two stations per 10 000 km^2, comparable to station density in the United States and Europe. The data are also of good quality and are relatively evenly spatially distributed. All climate and weather stations in China are maintained by professional workers.

An average of four recordings daily at 0200, 0800, 1400, and 2000 Beijing Time (1800, 0000, 0600, and 1200 UTC) is generally used as the daily mean temperature in China, and the monthly mean temperature is calculated based on the daily mean temperature. The NSs keep a round-the-clock watch or eight measurements per day, and the records at the four times are all of the observed synoptic data. However, the ordinary stations do not take measurements during nighttime. The temperature values at two for these stations are calculated through a calibration method using parallel records by automatic thermometers. In this case, the monthly and annual mean temperatures of the ordinary stations are comparable with those of the NSs. This study, therefore, does not adopt the daily average of the maximum and minimum temperatures to obtain monthly and yearly averages, as researchers usually do for global climate change analyses.

We examine and adjust the inhomogeneity of the data. A prodigious amount of work has been performed to examine and adjust the inhomogeneity of SAT data around the globe, and methods for the homogenization have been formulated (e.g., Easterling and Peterson 1995; Peterson et al. 1998; Jones and Moberg 2003). Similar works have also been conducted for Chinese climate data in recent years (e.g., Yan et al. 2001; Li et al. 2003; Feng et al. 2004). Inhomogeneity of the Chinese climate data is mainly caused by relocation of stations, changes in observation times, changes in the time system used, and the replacement and modification of instruments. Station relocation is expected to result in the most obvious discontinuous points in the station temperature series. Li et al. (2003) adopted the Peterson and Easterling method to conduct the examination and adjustment of inhomogeneity of the monthly mean SAT series of the 731 NSs (including a few of the OWSs) across China, and through comparison with the preadjustment series, they found that the method is comparatively effective for examining the inhomogeneity of the Chinese SAT series. Hu et al. (2003) also conducted an examination and made adjustments to the inhomogeneity of the data from the Chinese NSs, acquiring a relatively homogeneous SAT data series.

With reference to the method used by Easterling and Peterson (1995) and Li et al. (2003), inhomogeneity examination and adjustment are conducted on the monthly SAT data from all 282 stations in north China for 1961–2000. This requires setting up a reference station series for each station examined. On the basis of calculating the correlation coefficient between the station series to be examined and the other station series, we select five stations with the highest correlation coefficients as reference stations, and adopt the square of the correlation coefficients as weights to average the five station series into a reference temperature series. In finding out the apparent breakpoints, subjective judgments are made according to the metadata of the stations. If station relocation occurs near the breakpoint, the breakpoint is considered to be artificially imposed, rather than caused by the climate variation itself, and it needs to be further adjusted; otherwise, the breakpoint is retained as is.

For all of the stations, 208 observation sites have been changed at least once during 1961–2000, and only 74 stations have not been relocated at all. A check of the metadata indicates that the breakpoints in the SAT series for 145 stations are due to station relocation, accounting for about half of the total stations used. The SAT data of these stations are adjusted based on the reference temperature series. The number of stations adjusted for the inhomogeneity of data for the various station groups is shown in Table 1.

Figure 1 gives examples of the Beijing and Wutaishan stations, and shows that the difference of the annual mean SAT series between the pre- and postadjustment periods of inhomogeneity is quite obvious. During 1961–2000, the Beijing station was relocated five times, in 1965, 1969, 1970, 1981, and 1997. In 1997, the station was moved to its present-day site in a nearby suburb; therefore, the temperature before 1997 is evidently biased on the high side. The temperature series are adjusted to reflect the present location. After the adjustment, therefore, the temperature values before the breakpoint are lower than the original ones. The Wutaishan station was moved from the top to the foot of the Wutaishan Mountains in 1998. The original time series shows that SAT undergoes an evident jump in 1998. The SAT anomaly series after the adjustment, however, becomes more continuous and homogeneous.

On the basis of our examination and adjustment of the inhomogeneity of data, an analysis is made of the features of the regional climate change and of the influence of urbanization upon the SAT trend. The key to the examination of the urbanization effect on temperature trend lies in the choice of reference or baseline stations, which should be able to reflect macroscale background climate change. Suppose that stations located in rural areas have not been affected by urbanization and the warming or cooling recorded there represents large-scale actual change in surface air temperature. The rural stations can thus be regarded as baseline stations for checking the urbanization effect. To examine the UHI effect of different types of urban stations, the present paper uses demographics on the population at the places where the stations are located and of station location description to classify the stations. The population data is the number of permanent residents provided by the China Statistics Bureau (2002). The station location descriptions are taken from the annual surface meteorological observation reports of the NMIC/CMA. Location descriptions are generally rough and are usually divided into "cities" (including such descriptions as urban district, city proper, and city area, etc.), "suburbs" (including such descriptions as nearby suburbs, outer suburbs, outskirts, and suburbs, etc.) and "rural areas" (including such descriptions as

TABLE 1. Numbers of stations for each station group and for those undergoing inhomogeneity adjustment in north China.

	Rural	Small city	Medium city	Large city	Metropolis	National
Population criteria (million)	<0.05 (<0.10 for Shandong Province)	0.01–0.10 (excluding rural)	0.10–0.50 (excluding rural)	0.50–1.00 (excluding rural)	>1.00 (excluding rural)	
Number of stations	63	133	37	17	22	95
Percentage	22	47	13	6	8	34
Number of stations adjusted	24	51	20	8	11	37

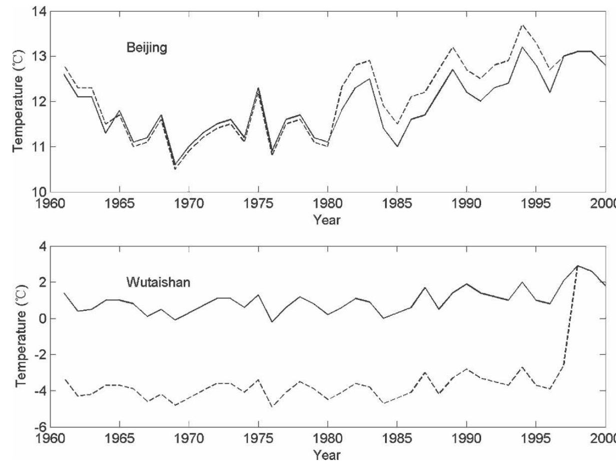

FIG. 1. Comparison of the annual mean surface air temperature before (dashed lines) and after (solid lines) inhomogeneity adjustment for the Beijing and Wutaishan stations.

villages and rural area”). There are also some special descriptions for those remote stations, such as “grassland,” “desert,” “sea island,” and “mountaintop,” etc. which are all considered to be rural areas in the present study.

We prescribed that a station at a rural area with a population of no more than 0.05 million is regarded as a rural station, but the population limit for rural stations in Shandong Province is prescribed to be 0.1 million or less because of the scarcity of stations with a population of 0.05 million or less. Such a criterion for choosing rural stations is not very satisfactory, but we simply have no more ideal way to identify real rural stations in this densely populated region. To avoid, as much as possible, the influence of urbanization on station records near these towns or small cities, we set another criterion that stations with populations less than 0.05 million (0.1 million in Shandong Province) in the nearby residential areas must be located in villages, rural areas, grassland, desert, sea island, and mountaintop, as documented in the metadata. Therefore, all of the rural stations chosen are located in rural areas or outside towns and small cities, and this could minimize the possible influence of the UHI effect on air temperature records, though the effect might still exist to some extent.

Stations not located in rural areas and stations near residential areas with a population of more than 0.01 million are regarded as city stations and they are divided into four categories based on population of nearby residential areas: small city stations (with a population of 0.01–0.1 million), medium city stations (with a population of 0.1–0.5 million), large city stations (with a population of 0.5–1.0 million), and metropolis stations (with a population of 1.0 million or more). As climate change studies for the past 100 years in China were conducted based generally on the dataset of the NSs, the present paper specially takes the NSs as a category for examining the influence of the growing UHI effect on regional average SAT series as obtained using the dataset of these stations. Nearby city or town population and the specific location description are no longer taken into consideration for this category. Definitions for various categories of stations and the quantity statistics are listed in Table 1, which shows that the number of small city stations (133) is the largest, followed by the NSs, rural stations, medium city stations, and metropolis stations in order. There are only 17 large city stations in the study region.

Figure 2 shows the locations of stations of various categories in north China. There is a denser and more even distribution of the rural stations, small city stations, and the NSs. Medium city stations, large city stations, and metropolis stations, however, are relatively sparsely and unevenly distributed in the study region. Medium city stations and metropolis stations are mainly scattered in the southeast and the center, while large city stations are mainly located in the central area of the study region.

Based on the dataset mentioned above, regional average monthly and annual mean SAT anomalies of north China for the period 1961–2000 are calculated for each of the station groups, and regional average temperature change trends are obtained for the station groups. The regional average SAT anomaly series for the city station groups and the NSs are compared with the series of the rural stations to estimate the influence of the growing UHI effect on temperature trends. By analyzing the difference of rates of the temperature change between the city station groups and the rural station groups, we can obtain the rate of warming induced by urbanization and calculate the relative contribution of the urban warming to the overall temperature change as estimated from the different regional average SAT series.

In calculating the SAT anomalies of a single station, 1971–2000 is used as the climate reference period. Monthly, seasonal, and annual mean SAT anomalies are obtained by calculating the SAT difference of a certain year from the reference period. The four seasonal mean SAT is the averages of each three-month season—winter (DJF), spring (MAM), summer (JJA), and autumn (SON), respectively—while the annual mean SAT is the average of the 12 months of the year. Furthermore, with reference to the method of Jones and Hulme (1996), the study region is divided into 20 grids of $2° \times 3°$ (latitude $\times$ longitude), and the yearly SAT anomalies of the stations within each grid are simply averaged to obtain the average SAT anomalies of the grid for each of the years. The average SAT anomalies are weighted with regard to the area of each grid to obtain the average SAT anomaly series of the entire region.

The statistical significance of the urban warming trend is checked using the t test. Given x_i, the time variable, and $y_i (y_i = T_i - t_i)$, the SAT difference between urban and rural stations for year i,

$$y_i' = a + bx_i + e, \quad i = 1, 2, 3, \ldots, n,$$

where y_i' is the expected value of the SAT difference between urban and rural stations for year i, a and b are regression coefficients, and e is the regression error. Here y_i' could be checked for the significance level against a T distribution with $n - 2$ degrees of freedom. If the value exceeds the $p < 0.05$ or <0.01 threshold, then the urban warming trend for any urban station group is considered statistically significant. Table 2 lists the values of t-test statistics for the station groups.

On the basis of analyzing the influence of urbanization on SAT series of various categories of stations, we further adjust the influence of the UHI effect on the temperature series of the NSs in the region studied. The method of adjustment is to subtract the linear trends of the regional average SAT anomalies of the rural stations from the linear trends of the regional average SAT anomalies of the urban station groups. The trend differences are taken as the adjusting coefficients. The adjusted annual mean SAT anomaly series of the city station groups and the NSs are obtained by eliminating the trend differences from the original year-on-year SAT anomalies of the station groups.

3. Results

a. Regional average temperature series without adjusting the urbanization effect

Figure 3 gives regional average annual mean SAT anomalies for north China obtained using the data from different station groups for the period 1961–2000, which do not undergo UHI effect adjustment, but have already been quality controlled and processed for inhomogeneity. The changes in annual mean SAT for the six station groups are fairly consistent and the trends in temperature change for the 40 yr are all positive. Along with the warming trend, there exist remarkable interannual and interdecadal SAT variations. The regional average annual SAT cools gradually during 1961–69, but it climbs again after 1969 and increases rapidly after 1984, in particular. The highest annual mean SAT oc-

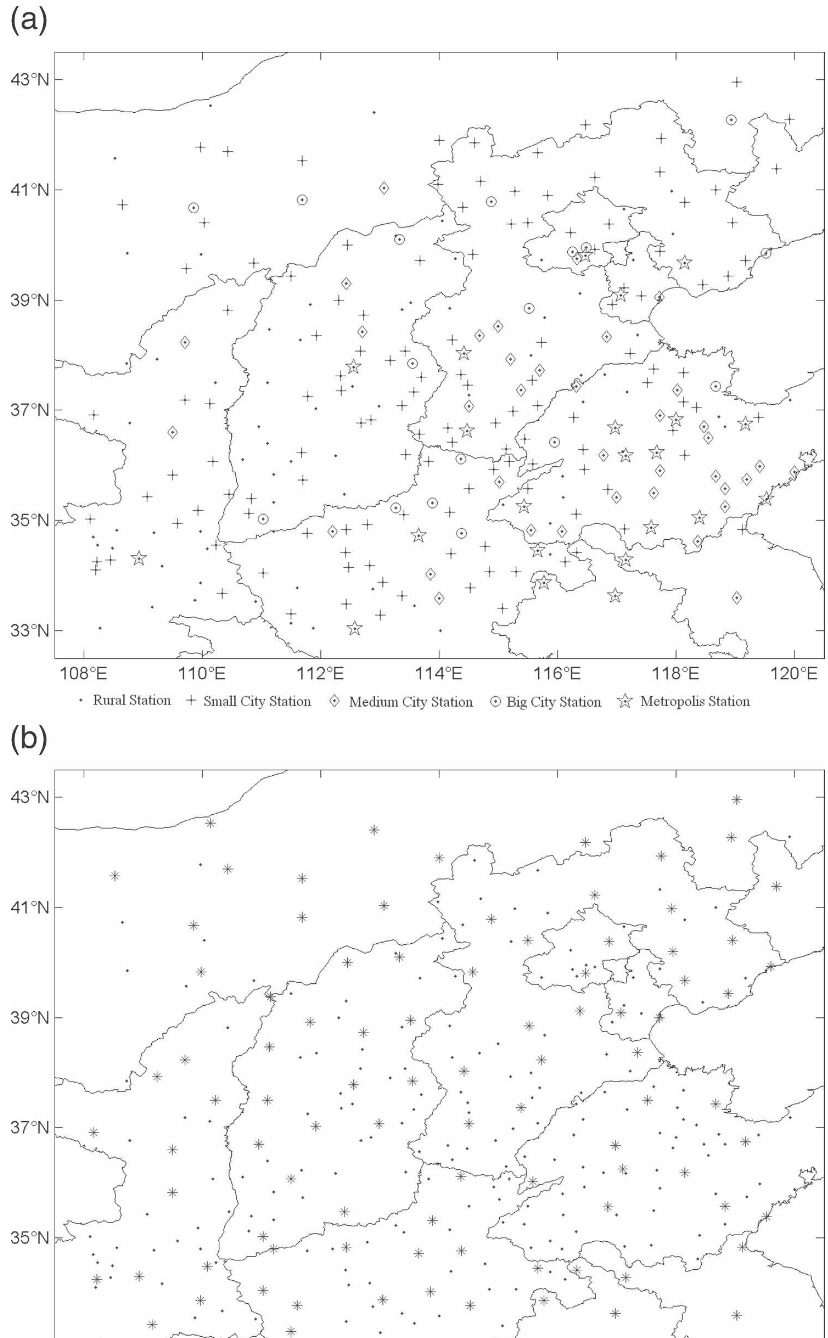

FIG. 2. Distribution of stations for various categories in north China: (a) rural and various city stations and (b) national and ordinary stations.

curs in 1998. These features, and the interannual and interdecadal variations of the annual mean SAT over North China, are very similar to those recognized for the country as a whole (Chen and Zhou 1998; Wang et al. 1998; Ren et al. 2005).

Table 3 shows the annual and seasonal mean SAT trends for each station group. In terms of the annual mean SAT change, the largest increase occurs at the large city stations, with a linear trend reaching 0.34°C $(10\ \mathrm{yr})^{-1}$, though the warming for all groups is statisti-

TABLE 2. Values of statistics for the station groups calculated using the t test: $t_{0.05} = 2.03$ and $t_{0.01} = 2.72$.

	Annual	Spring	Summer	Autumn	Winter
Small city	8.25	4.46	4.44	7.68	6.94
Medium city	7.55	5.69	5.15	6.79	3.89
Large city	8.64	4.64	6.47	6.6	5.34
Metropolis	3.69	2.65	1.86	5.34	1.1
National	13.73	8.69	11.12	10.46	8.09

cally significant at the 0.01 confidence level; Next comes to the medium-size cities, metropolises, and small-sized cities, with the linear trends ranging between ~0.25 and 0.28 [°C (10 yr)$^{-1}$]; The smallest temperature increase, which is only 0.18°C (10 yr)$^{-1}$, occurs at rural stations. With a linear trend of 0.29°C (10 yr)$^{-1}$, the increase in SAT at the NSs ranks as the second largest change. Warming trends for various city station groups and for the NSs turn out to be evidently larger than for rural stations, indicating that urbanization processes might have exerted a significant influence upon the SAT warming in the period analyzed.

Change in seasonal mean SAT for various station groups all appear to be most significant in wintertime, followed by springtime and autumn, with an insignificant warming seen in summertime (Table 3). Rural stations even witness a slight cooling trend in the warm season. In the four seasons, the largest warming trends all occur at large city stations, while rural stations show the smallest changes in SAT. Urban station groups experience different warming trends in the four seasons, however, with the largest warming occurring in wintertime for large city stations, and the least warming appearing in summertime for small city stations (Table 3). The NSs experience a fairly remarkable warming in all seasons, with the wintertime mean SAT increase being significant at the 0.01 confidence level, followed by the warming in springtime and autumn, statistically significant at the 0.05 confidence level. The warming in summertime at the NSs is statistically insignificant.

In comparison to the country as a whole, the warming trend over north China is generally larger. A recent study applying an inhomogeneity-adjusted dataset of the NSs shows that the annual mean SAT increase for China during 1951–2001 is 0.22°C (10 yr)$^{-1}$ (Ren et al. 2005). The annual mean SAT warming of the NSs in north China during 1961–2000 reaches 0.29°C (10 yr)$^{-1}$. Wintertime warming over the whole country dur-

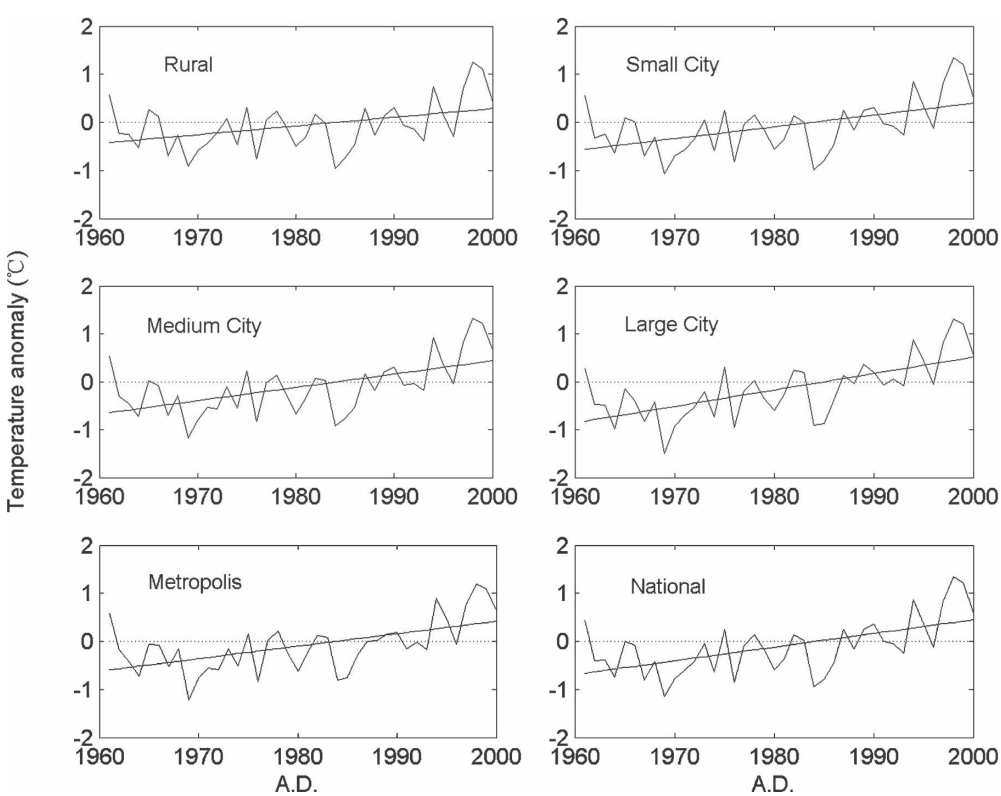

FIG. 3. Region-averaged annual mean surface air temperature anomalies and the linear trends of various station groups for 1961–2000 in north China.

TABLE 3. Trends in surface air temperature [unit: °C $(10\ yr)^{-1}$] for each of the station groups in north China during 1961–2000 statistically significant at (asterisk) the 0.05 level and (double asterisk) at the 0.01 level when using a t test.

Station group	Annual	Spring	Summer	Autumn	Winter
Rural	0.18**	0.14	−0.01	0.11	0.50**
Small city	0.25**	0.20	0.04	0.18	0.61**
Medium city	0.28**	0.27**	0.10	0.20*	0.60**
Large city	0.34**	0.31**	0.14	0.25*	0.72**
Metropolis	0.26**	0.25*	0.05	0.21*	0.56**
National	0.29**	0.24*	0.09	0.21*	0.62**

ing 1951–2001 is 0.36°C $(10\ yr)^{-1}$, while that for north China for 1961–2000 is as large as 0.62°C $(10\ yr)^{-1}$. The warming in spring, summer, and autumn for the country as a whole is more similar to that for north China. Of course, the comparison of temperature trends could only be made roughly because the time periods investigated in the two studies are not identical, in spite of the fact that the long-term temperature trends in China are generally not very sensitive to the choice of beginning years of the time periods (M. Xu 2002, personal communication).

b. *Spatial characteristics of the temperature trends without adjusting for the urbanization effect*

Figure 4 shows the spatial distribution of annual-mean SAT change trends over north China during 1961–2000 with no adjustment of the urbanization effect for the data at city stations. Figure 4 shows that,

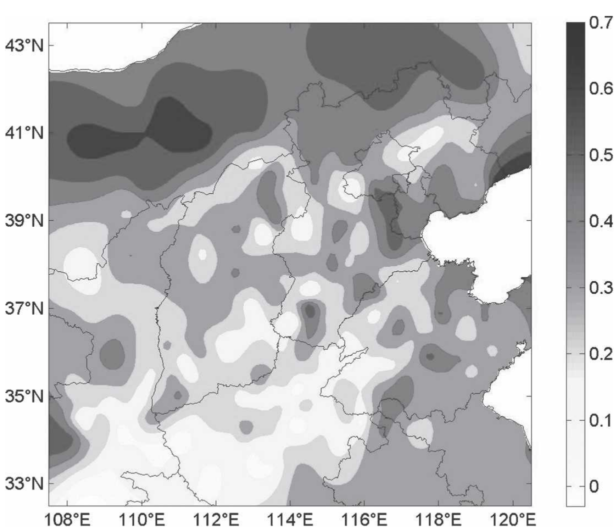

FIG. 4. Spatial distribution of annual mean temperature trends in north China during 1961–2000 [unit: °C $(10\ yr)^{-1}$]. The data used are inhomogeneity adjusted, but the urbanization effect on temperature trends is not adjusted.

TABLE 4. As in Table 3 but for urban warming.

Station group	Annual	Spring	Summer	Autumn	Winter
Small city	0.07**	0.06**	0.04**	0.07**	0.11**
Medium city	0.10**	0.13**	0.10**	0.09**	0.10**
Large city	0.16**	0.16**	0.14**	0.14**	0.22**
Metropolis	0.08**	0.11*	0.05	0.10**	0.06
National	0.11**	0.10**	0.09**	0.10**	0.12**

except for the weak cooling over a few sites in the southwestern part of the region, all areas generally experience a warming trend, with the trend over central and southern Inner Mongolia being the strongest, reaching 0.5°C $(10\ yr)^{-1}$. The annual mean temperature warming for most parts of Henan and southern Shaanxi is generally less than 0.15°C $(10\ yr)^{-1}$. The reason for regional differences in the temperature warming need to be further investigated. Stations in the southwestern part of the study region with relatively small warming trends, however, are mostly situated in the mountainous areas of the Qinling Mountains, adjacent to the well-known cooling area of southwest China (Chen and Zhou 1998; Ren et al. 2005). The obvious warming over Inner Mongolia may have much to do with the weakening influence of the wintertime Siberian high and the winter monsoon (Gong and Wang 1999), but the largest SAT trends spotted in central Inner Mongolia may have been caused by the influence of more rapid urbanization in the area of Hohhot and Baotou.

Some local-scale temperature trend centers can also be seen in Fig. 4. High centers, such as those around Qinhuangdao, Zibo, Xingtai, Langfang, and Beijing, are all near economically developed, densely populated large and medium cities—places where the influence of urbanization on SAT change is more apparent. On the other hand, some sites with relatively small warming are sparsely populated places where rural or small city stations are located, with economic development lagging behind and where the UHI effect exerts a weaker influence on SAT records. The basis for this inference is that the spatial consistency for baseline SAT change is comparatively high and the small high- and low-trend centers mainly reflect the influence of local factors. Therefore, the existence of the "cow eyes" of the trend distribution in Fig. 4 requires further examination and adjustment for the influence of the UHI effect on SAT records at city stations and the NSs.

c. *UHI effect*

Table 4 and Fig. 5 show the urban warming rates for various city station groups and the NSs, as well as the contribution of the urban warming to the overall warm-

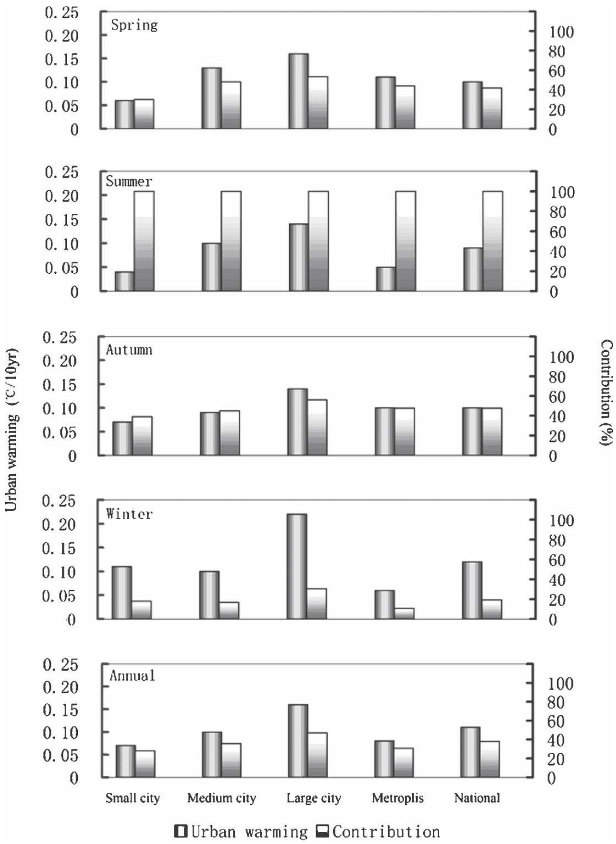

FIG. 5. Effects of urbanization on annual and seasonal mean temperature trends for city station groups and the national stations. Left bars indicate the urban warming [°C (10 yr)$^{-1}$] and right bars show the percentage contribution of the urban warming to the overall warming.

ing recorded. In view of the regional average annual-mean SAT, the largest influence of the UHI effect on temperature increase is found for large city stations, with the urban warming rate being 0.16°C (10 yr)$^{-1}$, accounting for 47.1% of the overall warming as estimated from the unadjusted data of this station group. The influence of the UHI effect upon medium cities, metropolitan cities, and small cities is slightly smaller, with the contribution of urban warming to the overall warming being around 30%.

The urban warming trends as measured by annual and seasonal mean SATs are mostly statistically significant at the 0.01 confidence level for each of the city station groups. Exceptions are from metropolis stations for which the urban warming during summertime and wintertime is statistically insignificant, and the UHI effect during springtime is significant at the 0.05 confidence level. The average annual urban warming at the NSs is 0.11°C (10 yr)$^{-1}$, statistically significant at the 0.01 confidence level. The contribution of urban warming to the overall warming for the station group is 37.9%, surpassed only by large city stations. In the 40-yr period of study, the annual mean SAT warming trends caused by the enhanced UHI effect in north China are, respectively, 0.28°C for small cities, 0.40°C for medium cities, 0.64°C for large cities, 0.32°C for metropolitan cities, and 0.44°C for the NSs.

Why the influence of the UHI effect on metropolis stations is weaker than on other city stations needs further investigation. However, it may be attributable to the longer distance between station locations and the city centers or built-up areas. It may also be related to the comparatively slower urbanization process of the metropolitan cities than that of medium and large cities. It is also worth noting that the metropolis stations and the large city stations are the smallest in number and are distributed unevenly. Thus, they do not represent the regional average SAT trends as well as the other city station groups. The failure of the urban warming trend of the metropolis stations to pass the significance test is also related to the smaller number of stations.

Among the four seasons, the UHI effect causes the largest warming in winter, followed by spring and autumn, while summer undergoes the smallest urban warming (Fig. 5). However, the contribution of urban warming to the overall warming is largest in summer, reaching 100% for all city station groups. With the UHI effect omitted, the summertime baseline SAT over north China actually shows a slightly downward trend rather than a warming. The contributions of urban warming to the overall warming for national stations are also larger in autumn and spring, reaching 48% and 42%, respectively. Wintertime UHI warming makes up a relatively smaller proportion in the overall warming, which is only 19.4%, indicating that the growing UHI effect in north China does not contribute significantly to the rapid wintertime warming as recorded by the NSs. It is likely that variations in large-scale atmospheric circulation and the enhanced greenhouse effect or changes in other factors might have played a more dominant role.

Analyses from the Beijing, Tianjin, and Wuhan areas indicate that the contribution of UHI warming to the overall warming has obviously decreased in 1979–2000 as compared to the earlier time period or the period of 1961–2000, though the last 20 years has witnessed more significant absolute warming as a result of the UHI effect (Chu and Ren 2005; Ren et al. 2007). The UHI contribution to the overall warming in terms of annual mean SAT of the NSs in the Beijing area, for example, is 48.5% for the period 1979–2000, but it reaches as high as 71.1% for 1961–2000 (Chu and Ren 2005). Therefore, much of the climate warming in the most recent 20 years over north China can be regarded as a baseline change, which may have been caused mainly by natural factors or by anthropogenic global climate change.

d. Adjustment of the UHI effect

The growing UHI effect on station SAT trends over north China has significantly increased the regional average SAT trends. Only when this effect is removed can we better analyze the changing trends of the regional baseline temperature, and detect further regional climate change and attribute it to any large-scale influential factors. Currently, as the data used in the majority of the analyses of regional climate change in the country including north China originate from the records of the NSs, the present paper makes an attempt to adjust the UHI effect on annual mean SATs of the NSs in the study region.

The regional average annual and seasonal mean SAT anomaly series of north China after the adjustment for the UHI effect are obtained. It is notable that the increase of the annual mean SAT over north China during 1961–2000 is still significant after the influence of the UHI effect is adjusted, but the warming trend decreases from the original 0.29° to 0.18°C (10 yr)$^{-1}$. Quite a lot of warming over north China is caused by the UHI effect, therefore, and the baseline annual mean SAT warming is merely 0.72°C over the 40 years.

Warming in all seasons after the UHI adjustment weakens significantly, with winter warming decreasing from 0.62° to 0.5°C (10 yr)$^{-1}$, spring and autumn from 0.24° and 0.21° to 0.14° and 0.11°C (10 yr)$^{-1}$, respectively, and the trend for summer from 0.09°C (10 yr)$^{-1}$ to an insignificant negative trend. The postadjustment temperature trend indicates that the regional baseline warming magnitudes over north China in the 40-yr study are 0.56°C for springtime, 0.44°C for autumn, and 2.00°C for wintertime, and the seasonal mean SAT decreases slightly in summertime.

Figure 6 shows the spatial features of the annual mean SAT trends over north China after adjustment for the UHI effect, while Fig. 7 presents the differences in the annual mean SAT trends between the pre- and posturbanization effect adjustments. It is obvious from the figures that annual mean SAT warming is generally reduced after the adjustment, with the decrease being particularly evident over central and southern Inner Mongolia and some city areas. Warming rates for most of the NSs now range from 0° to 0.3°C (10 yr)$^{-1}$, and the stations at which the annual mean SAT abnormally increases obviously drops in number compared to the distribution of temperature trends obtained from the preurbanization effect adjustment data (Figs. 6 and 4). The decrease in annual mean SAT trends after the adjustment ranges generally from 0.08° to 0.12°C (10 yr)$^{-1}$ (Fig. 7). In addition, some closed warming centers encircling the city stations (cow eyes) in Fig. 4 have now disappeared. The cooling phenomena becomes more conspicuous in the southwestern part of the study region, but the spatial gradient of the annual mean SAT change over the whole of north China is not significantly changed (Fig. 6).

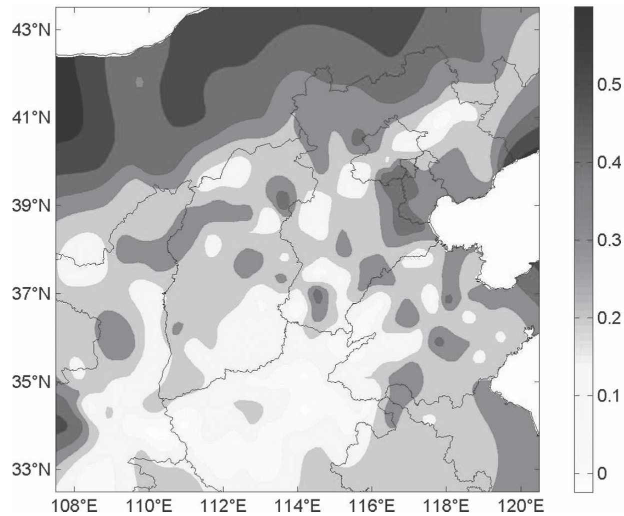

FIG. 6. Spatial distribution of annual mean temperature trends in north China in 1961–2000 [unit: °C (10 yr)$^{-1}$] after adjustment for the urbanization effect.

4. Discussion

It is worth explaining why there is such a large urbanization effect on the city stations and NSs SAT trends in north China. Due to the large difference between cities and rural areas in every aspect of economic development and social well-being, meteorological stations in China were mostly set up near cities or towns. The observers at these stations generally graduated from meteorological schools, and they were approved to become city and town dwellers so that they could enjoy better social well-being than countryside dwellers could. There are some remote stations, which are usually called arduous stations, in western China, but these are mostly located in small towns or some sites with better traffic conditions. The lead observers at the "arduous stations" are city or town dwellers, and their families settle in cities. They work at the stations for one year or a number of months, earning higher salaries

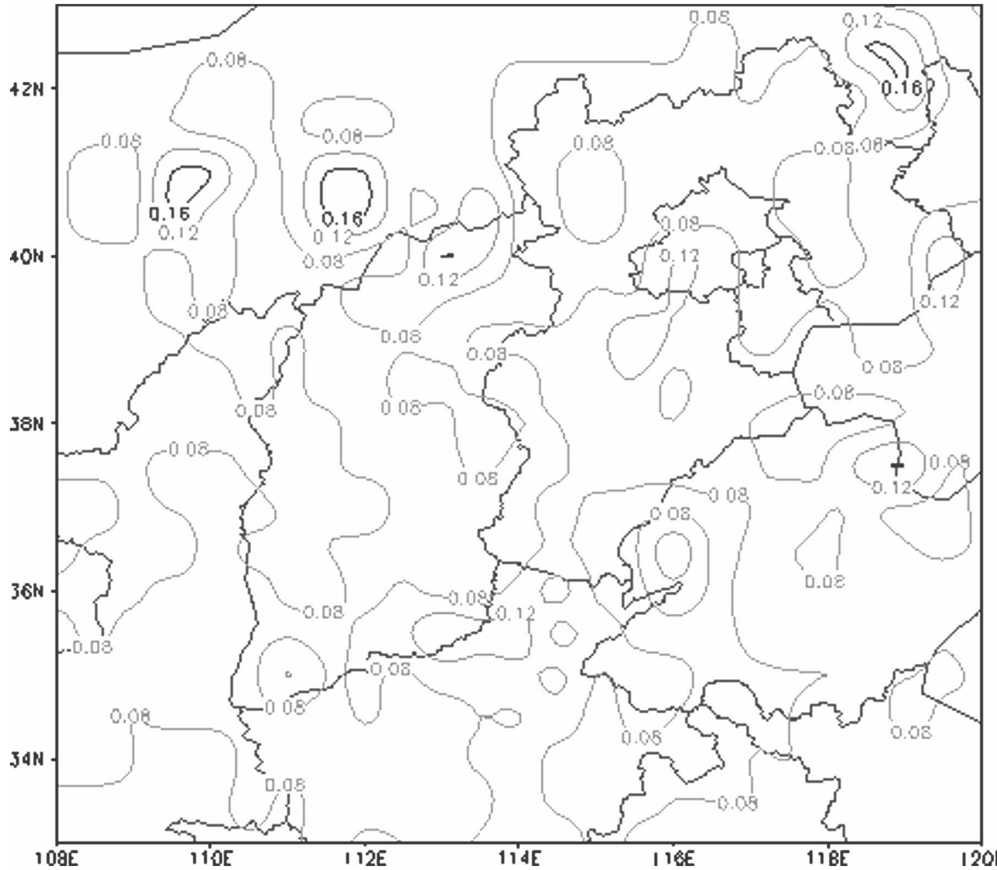

FIG. 7. Difference in annual mean surface air temperature trends between pre- and posturbanization effect adjustments.

than those staying at city stations, and then they are replaced by their colleagues from cities. The large difference in development between cities and rural areas does not encourage the establishment and operation of rural observational stations in the country, which may be the main reason why the majority of the stations have been set up near cities or towns.

The past half-century, and especially the past 30 years, has witnessed a rapid urbanization process throughout the country. The urbanization rate of China in 1950 was only 10.6%, for example, but was as high as 43.9% in 2006 (China Statistics Bureau 2007). Much of the increase occured after 1978. From 1978 to 2006, the urbanization rate of the country increases from 17.9% to 43.9%, with the growth rate being more than two times the world average during the same period. From 1950 to 2002, the number of cities in the country increased from 130 to 668 according to the annual reports of the Ministry of Construction of China. This unprecedented urbanization process resulted in the observational stations being frequently surrounded by built-up areas and forced the stations to be moved outward from within cities to the suburbs in order to comply with the observational regulations of the CMA. As a rule, however, these stations have been relocated not far from the built-up areas of the cities. Therefore, even if the stations are moved to suburbs, or the so-called countryside, they can hardly escape from the influence of urbanization, in particular in the big cities, due to the extended "heat dome" over the built-up area and nearby suburbs. Certainly, a larger heat island effect would be felt before the stations are moved. Relocation of the stations thus results in the inhomogeneitys found in the SAT records, but they do not eliminate the UHI effect. When the inhomogeneity due to site relocation is adjusted, the UHI effect will be recovered to some extent in the SAT series.

It is therefore obvious that the closure of observational sites to built-up areas in and around cities and towns and the rapid expansion of the cities and towns, in particular during the last 30 years, is the main reason for the increasing UHI effects recorded in the SAT series of the city stations and national stations in north China.

In a previous study, Wang et al. (1990) found that, during the 1954–83 period, the annual mean SAT warming recorded in north China was 0.21°C (10 yr)$^{-1}$ for urban stations and 0.12°C (10 yr)$^{-1}$ for rural stations. Portman (1993) also analyzed the UHI effect over north China. They adopted the mean SAT data of 21 urban stations and 8 rural stations within the area 32° ~42°N, 110° ~125°E for the period 1954–83. The 21 urban stations were divided into 7 big-city stations (with an average population of more than 2.3 million) and 14 small-city stations (with an average population of more than 0.4 million). They showed that the UHI warming trend is 0.09°C (10 yr)$^{-1}$ for the 7 big-city stations and 0.05°C (10 yr)$^{-1}$ for the 14 small-city stations. Recently, Zhou et al. (2004) used observed surface data and the reanalyzed data to calculate the temperature change rate caused by urbanization and land-use changes in southeast China to be 0.05°C (10 yr)$^{-1}$, which was considered to be much greater than previous estimates for other areas and periods.

North China, as defined in the present paper, includes the study region of Wang et al. (1990) and is roughly the same as the study region of Portman (1993). However, our investigation adopts much denser data sites than did the previous investigations. The present SAT series includes the most remarkable warming period from the early 1980s onward, and it also undergoes the inhomogeneity examination and adjustment, which are believed to lead to a larger increase in the regional average SAT than if the data were not homogeneity adjusted (Hansen et al. 2001; Ren et al. 2005). There is no overlap for the regions analyzed in the present paper and in Zhou et al. (2004), and the data and methods used are different as well. As the study regions are not completely the same, the data and methods used vary and, above all, there is an obvious difference in the time periods analyzed, it is difficult to accurately compare the present analytical results with the previous works by other researchers. However, these studies are generally consistent with each other in finding that the growing UHI effect has a significant influence on regional average SAT series as obtained from the NSs in north China, though the urban warming of large city, medium city, and national station groups given in this paper is larger than those of the previous studies. Our analysis results are also generally consistent with those of Zhao (1991), Zhang et al. (2005), Chu and Ren (2005), and Ren et al. (2007).

Causes for the differences between our result and those found by other researchers are likely to be related to station network density, the criteria for defining urban and rural stations, analytical methods, time periods, and the regional extent analyzed. A more evident UHI effect on the SAT trends obtained in this paper compared to the previous works can be attributed to the availability of more "rural" observational sites and the extended time period analyzed. The extended time period includes a rapid urbanization phase after the Chinese economic reform policy initiated in 1978. The use of inhomogeneity-adjusted data in this study also contributes to the higher estimate of the urban warming, as reported in Ren et al. (2005) and evidenced below.

However, there are still some issues that need to be further resolved in the future. The present paper classifies the city stations mainly based on population of the cities where the stations are located. Although descriptions of the specific locations of the stations is taken into consideration, no attention is given to the distances between the station sites and the city centers or the rim of the built-up areas nor is it given to the city functions. Another key issue is related to the determination of rural stations. As rural stations completely free from urbanization effects can hardly be found, the rural stations selected in this study are only the currently available stations that are relatively less affected by the growing UHI effects. Some urbanization effects, therefore, would more or less exist in the regional average SAT series as obtained from the data of the rural station group. As a result, UHI warming trends and their contributions to the overall warming as given in this paper for the city station groups and the national stations could be conservative.

Li et al. (2004) evaluated the UHI effect on the observed surface warming of the past 50 years over China, and they concluded that the average UHI effect for the entire country during the time period investigated is less than 0.06°C and urbanization-induced warming has much less effect on the observed regional warming in the country. They also presented analytical results for subregions of north, northeast, and northwest China, showing no significant urbanization-induced warming, though a weak UHI effect of about 0.01°C (10 yr)$^{-1}$ could be detected for subregions of the Yangtze River and south China. These results are consistent with the analyses for the four regions including eastern China by Jones et al. (1990). Obviously, the estimate of the UHI effect on regional average SAT trends by Li et al. (2004) is much lower than that given in this paper. The major cause for the divergence lies in the fact that they used only the dataset of the NSs, and the present paper also uses the dataset of the OWSs in addition to the NSs. The NSs are primarily located near cities, and have already been affected by the increased UHI effect as indicated above, resulting in the difficult task of determining a baseline for "rural" stations. Many ordi-

TABLE 5. Difference in regional average annual mean urban warming trends between post- and preinhomogeneity adjustments [unit: °C $(10\ yr)^{-1}$].

	Annual	Spring	Summer	Autumn	Winter
Small city	0.02	0.02	0.0	0.01	0.02
Medium city	0.04	0.04	0.05	0.04	0.04
Large city	0.02	0.02	0.02	0.03	0.02
Metropolis	0.01	0.01	0.0	0.0	0.01
National	0.02	0.01	0.0	0.01	0.02

nary stations, on the other hand, are still in rural areas or near small towns, making the selection of "rural stations" from them more practical and reasonable. The number of ordinary stations is almost three times the national stations in most parts of the country.

To learn the possible effect of inhomogeneity adjustment on the analysis results, we calculated the regional average urban warming trend and urban warming contribution using the pre-inhomogeneity-adjusted data, and compared them with results obtained using the post-inhomogeneity-adjusted data. Table 5 gives the differences of annual and seasonal-mean urban warming trends between them. The urban warming obtained with the inhomogeneity-adjusted data is larger in varying degrees. The annual mean urban warming rate for the NSs after the inhomogeneity adjustment increases by 0.02°C $(10\ yr)^{-1}$, but the summertime urban warming trend remains unchanged. An increase of 0.01°–0.02°C $(10\ yr)^{-1}$ is found for spring, autumn, and winter. This result supports the previous finding by Hansen et al. (2001) that the inhomogeneity adjustment for SAT series serves to regain the UHI warming trends to a certain extent.

This result, however, is different from the analysis of Peterson (2003) for the United States. He studied the influence of inhomogeneities of SAT series on the estimation of American UHI effects and found that the mean SAT difference between city and rural stations based on pre-inhomogeneity-adjusted data is 0.31°C, while the temperature difference based on post-inhomogeneity-adjusted data is only 0.04°C. He concluded that the inhomogeneity of the SAT series led to a higher estimation of the UHI effect on the SAT records. When the inhomogeneities are adjusted, no significant urbanization effect could be detected in the regional average annual mean SAT series.

As regions and time periods analyzed are different, comparisons cannot be made in a simple way between the analysis results for north China and the United States. However, the present paper is focused on eliminating the station relocation effect on the inhomogeneity adjustment because the relocations of stations are identified as the main cause for the data inhomogeneities. Nevertheless, the most serious inhomogeneity errors in the American historical temperature dataset are caused by a change in observation time. As a result, the main causes for the inhomogeneity of the data series between two regions are different, which may partly explain the differences in analytical results. In addition, Peterson (2003) uses only three years of pre- and postadjusted data to make the comparison, whereas we use the data of the 40-yr period to conduct the comparison. The differences in analytical methods might also contribute to the disparity of the results.

5. Conclusions

In this paper the SAT change trends over north China for 1961–2000 and the effects of the urbanization process on regional average annual- and seasonal-mean SAT trends are analyzed. The following conclusions can be drawn from the analysis:

1) Based on the inhomogeneity-adjusted data of the national stations, which is not adjusted for urbanization effects, the regional average annual mean SAT over north China increased by 1.16° or 0.29°C $(10\ yr)^{-1}$ in the 40-yr period 1961–2000 with the mean seasonal SAT in spring, summer, autumn, and winter rising 0.96°, 0.36°, 0.84°, and 2.48°C, respectively. Compared to the change over the whole country, climate warming in the study region is more remarkable.
2) The influence of the growing UHI effect on regional average annual- and seasonal-mean SAT trends in north China is generally significant. In the regional average annual mean SAT series obtained from the dataset of the NSs, the urban warming reaches 0.11°C $(10\ yr)^{-1}$, accounting for 37.9% of the overall warming. The regional average annual mean SAT increase induced by the UHI effect in the 40 yr is 0.44°C, with winter registering the highest value, spring and autumn ranking second, and summer the lowest. However, the contribution of summer urban warming to the overall warming ranks at the top. For various city station groups and the NSs, summer warming is completely caused by the growing UHI effect. Urban warming in autumn and spring contributes considerably to the overall warming, usually ranging from 30% to 55%. Winter urban warming, however, contributes the least to the overall warming, ranging from 10% to 30%.
3) Among the city station groups, large city stations witness the largest increase in annual and seasonal mean SATs and the influence of the UHI effect on

the mean temperature trends. The annual mean urban warming reaches 0.16°C $(10\text{ yr})^{-1}$ for the station group. However, annual mean urban warming recorded for medium city, metropolitan, and small city station groups are also significant, reaching 0.10°, 0.08°, and 0.07°C $(10\text{ yr})^{-1}$, respectively. The seasonal differences in urban warming among various city station groups are similar to those recorded by the national stations.

4) After adjustments for the influence of the UHI effect, annual and seasonal mean SAT warming over north China for 1961–2000 largely weakens. The regional average annual mean SAT increase drops from 0.29°C $(10\text{ yr})^{-1}$ for the preadjustment data to 0.18°C $(10\text{ yr})^{-1}$ after adjustment. The seasonal-mean temperature trends after the UHI adjustment drop from 0.62° to 0.5°C $(10\text{ yr})^{-1}$ for winter; from 0.24° and 0.21° to 0.14° and 0.11°C $(10\text{ yr})^{-1}$ for spring and autumn, respectively; and the summer SAT undergoes a change from the originally evident warming [0.09°C $(10\text{ yr})^{-1}$] to an insignificant cooling trend.
5) Although there still exist some uncertainty and further studies are needed, the results presented in this paper suggest that a large portion of the current surface climate warming over north China is caused by the increased UHI effect.

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