Hindawi Publishing Corporation
Advances in Meteorology
Volume 2015, Article ID 352360, 12 pages
http://dx.doi.org/10.1155/2015/352360

Research Article

A Comparison of Two Methods on the Climatic Effects of Urbanization in the Beijing-Tianjin-Hebei Metropolitan Area

Mingna Wang[1,2] and Xiaodong Yan[3]

[1] *Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing 100049, China*
[2] *College of Earth Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China*

Correspondence should be addressed to Mingna Wang; wangmn@ucas.ac.cn

Received 28 September 2014; Revised 25 March 2015; Accepted 8 April 2015

Academic Editor: Charles Jones

Both the "urban minus rural" (UMR) and the "observation minus reanalysis" (OMR) methods were used to quantify the potential impacts of urbanization on regional temperature changes in the Beijing-Tianjin-Hebei metropolitan area in China. DMSP/OLS nighttime light imagery and population census data were used to classify stations into four classes: rural, small city, medium city, and large city groups. The regional average annual mean temperature was estimated to increase by 0.12°C decade^{-1} derived from urban warming, accounting for 40% of total climate warming from 1960 to 2009 using the UMR method. The OMR method also indicates that rapid urbanization has a significant influence on surface warming trend although the urban warming intensity is dependent on reanalysis dataset. The seasonal cycle patterns from all three datasets are consistent with each other, which is contrary to the UMR result owing to the cooling effect of agriculture activity in the rural stations confusing the UMR result. So in this paper we found a deficiency of the UMR method where it would underestimate the effects of urbanization in summer. In this regard, the results from the OMR method are relatively more convincing although we admit it still has many other problems.

1. Introduction

In addition to the climate change contributions from greenhouse gas concentrations and aerosol loading, anthropogenic changes in the large-scale character of land use/land cover change (LUCC) can also significantly influence climate change [1].

In terms of LUCC, urbanization has received much attention in climatic research. However, two divergent views on influence of urbanization on regional and global mean temperature trends currently exist. Many researchers support that urban heat island effects are real but local and have no biased large-scale trends; the second one holds the other view that urban heat island (UHI) effects contaminate the global and regional temperature time series, and urbanization is an important contribution to climate change by human activities. Both of these two views have many supporters.

IPCC proposed that the effects of urbanization on the land-based temperature record are negligible (0.006°C decade^{-1}); the release of heat from anthropogenic energy production can be significant over urban areas, but it is not globally significant [1]. Peterson et al. identified that well-known global temperature time series from in situ stations were not significantly impacted by urban warming (0.005°C decade^{-1}) [2], and no statistically significant impact of urbanization could be found in annual temperature in the contiguous United States [3]. Jones et al. studied station data from the Soviet Union, eastern Australia, and eastern China and then showed that urbanization influences have relatively minor contributions to regional warming trends [4]. Many papers also agreed with the viewpoint that the UHI effect in China during the last 50 years was minor compared to the background trend of increasing temperature [5, 6].

Nevertheless, some studies have employed the "urban minus rural" method (UMR) to indicate that urbanization may play a more significant role with regard to temperature trends on multiple geographic scales. Such results should be given more consideration for the mitigation of climate change [7]. Oke showed that even a city of 1000 people could have an UHI effect, and the magnitudes of UHI effects were linearly

Table 1: Results of recent studies of the urban heat island effects in China at regional and national scales.

Study area	Method	Time period	UHI warming (°C decade^{-1})	References
Mainland China	UMR	1954–2004	<0.012	[5]
Yangtze River Delta	UMR	1961–2005	0.069	[37]
North China	UMR	1961–2000	0.11	[10]
China	Comparison with SST	1951–2004	0.1	[38]
Northeast China	UMR	1954–2005	0.027	[6]
Southeast China	OMR	1979–1998	0.05	[26]
East of 110°E over China	OMR	1960–1999	0.12	[39]
China	OMR	1960–1999	0.14	[40]
East China	OMR and UMR	1981–2007	OMR: 0.398, 0.260, 0.214, 0.167 UMR: 0.285, 0.207, 0.135, 0.077 for stations from metropolises, large cities, medium cities, and small cities	[36]

correlated with the logarithm of the population [8]. Wang et al. chose 42 pairs of eastern China urban and rural stations to study UHI effects and revealed that the magnitude of UHI effects was 0.08°C decade^{-1} from 1954 to 1983 which must be carefully considered when attributing causes to observed trends [9]. Ren et al. found that the annual mean temperature of the national basic/reference stations in north China was significantly impacted by urban warming (0.11°C decade^{-1}) [10]. Therefore, they suggested that the urban warming bias for the regional average temperature anomaly series should be corrected.

A new method to estimate the effect of LUCC on air temperature changes that subtracts surface temperatures that are derived from the NCEP-NCAR reanalysis data from the trends that are observed at surface stations (observation minus reanalysis (OMR)) was proposed [11]. The rationale for the OMR method is that the reanalysis data represent large-scale climate changes due to greenhouse gases and atmospheric circulation but are insensitive to regional surface processes because little or no surface data or information (surface observations of temperature, moisture, and wind over land) about land surface changes has been utilized in the data assimilation process. Thus, Lim et al. studied the sensitivity of surface climate change to land types by the OMR method to reveal that warming over barren and urban areas is larger than most other land types [12]. The study of Fall et al. confirmed the robustness of the OMR method for detecting nonclimatic changes at the station level and provided robust results regarding the impact of LUCC on the temperature trends over the conterminous United States [13]. The results indicated that the regions converted into urban areas show a positive OMR trend which agreed well with those obtained by Lim et al. [12]. Hu et al. used the OMR method to estimate the impact of land surface forcing on mean and extreme temperatures in eastern China and found that LUCC impacts could explain one-third of the observed increase of the annual warm nights and nearly half of the observed decrease of the cold nights [14].

China has been experiencing a dramatic growth in urban areas and population since implementing the reform and open policy. All regions in China had more than a 20% expansion in urban areas during 1980–2005, and the Eastern Plain had the largest increase in urban area (2.5 million ha) [15], which could significantly change the land surface physical processes and surface heat flux. There could have been substantial impacts on local and regional climates as a result of the rapid urbanization. Therefore, determining how to estimate urban and land use contributions to the warming trends is a hot research topic currently.

Table 1 illustrates some results of recent studies on UHI effects in China at regional or national scales. Overall, the contribution of urban warming on temperature change, which was determined from the OMR method, has been more significant than the effect determined from the UMR approach. However, no papers explain that in detail, regardless of annual or seasonal changes.

Previous studies have predominantly focused on the UHI effect over a single large city [16, 17], and the study of urbanization in Beijing has attracted the most attention [18, 19]. Ren et al. showed that, with regard to the annual mean surface air temperature (SAT) at Beijing Station, the UHI contribution reached 80.4% during 1961–2000 and 61.3% during 1981–2000 [20]. However, with the increasing development and growth of the small and medium cities in Beijing-Tianjin-Hebei metropolitan area, the regional influence of urbanization should not be underestimated. The accurate detection and estimation of surface warming caused by urbanization in the Beijing-Tianjin-Hebei area may contribute significantly to the sustainable development and planning of orderly human activities in the region. Therefore, in the current study, we attempt to use both the UMR and the OMR methods to quantitatively determine the potential magnitude of UHI contributions to regional annual or seasonal temperature trends during a rapid urbanization period in the Beijing-Tianjin-Hebei metropolitan area. As far as the OMR is concerned, previous studies usually used one reanalysis dataset, but we know that each reanalysis may have some deficiencies in its model physics or assimilation process. So we conduct comparative studies with three independent reanalyses (NCEP/NCAR, NCEP/DOE, and ERA-interim) in order to show a fair and reasonable urban effect.

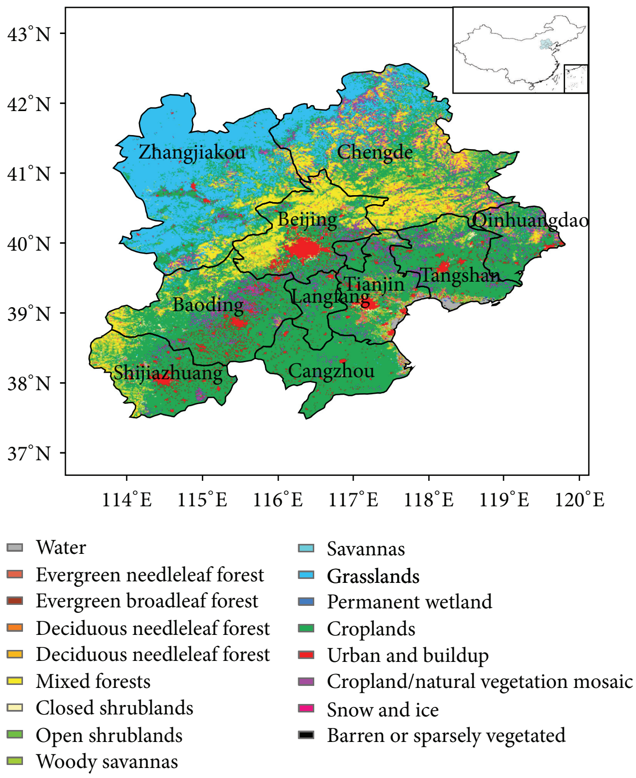


Figure 1: Study area and land cover types based on MODIS land cover product.

2. Region Definition, Data, and Analysis Methods

2.1. Study Area. The Beijing-Tianjin-Hebei metropolitan area refers to the center of Beijing and Tianjin and includes Shijiazhuang, Baoding, Qinhuangdao, Langfang, Cangzhou, Chengde, Tangshan, and Zhangjiakou, eight large cities in Hebei Province. The geographical location of these cities and land cover type are shown in Figure 1. The urban types are displayed in red in Figure 1. Hebei Province is named Ji for short in China, so the Beijing-Tianjin-Hebei metropolitan area is usually referred to as JING-JIN-JI area (JJJ area for short below). This region is defined as the political, cultural, and economic center of China. The JJJ regional plan is an important regional planning of the national Twelfth Five-Year Plan. Because of the rapid economic development, this region has been identified as the economic center of northern China.

According to the China City Statistical Yearbook (1985–2009), the total nonagricultural population in urban districts of the JJJ area doubled in about 20 years from 1984 to 2008. Undoubtedly, the large increase in the urban population due to the rapid urban expansion could considerably impact the local and regional climate and environment of the JJJ area.

2.2. Data. The meteorological data that were used in this study include the daily mean surface air temperature from 79 weather and climate observation stations in JJJ area, all covering 50 years from 1960 to 2009. The dataset included observations from all of the national reference climate stations and national basic weather stations in the study area as well as from some ordinary weather stations in Hebei Province. The inhomogeneity of the national reference climate stations and national basic weather stations that was caused by site relocation was adjusted [18, 21]. The data were also of good quality and were relatively evenly spatially distributed. All climate and weather stations in China are maintained by professional workers.

The U.S. Air Force Defense Meteorological Satellite Program's Operational Linescan System (DMSP/OLS) has provided a capable method for obtaining urban information at coarse spatial scales through its unique low-light imaging capability to detect persistent lights, even from small human settlements, gas fires, and vehicles in the dark background at night. The Version 4 stable nighttime light products (1992–2009) with 1 km spatial resolution were used to classify the stations. They are downloaded from the National Geophysical Data Center (http://www.ngdc.noaa.gov/eog/re_direct.html).

In addition, three widely used reanalysis datasets were used in our study. These included the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (NNR) [22], the National Centers for Environmental Prediction/Department of Energy (NCEP/DOE) Atmospheric Model Intercomparison Project- (AMIP-) II reanalysis data (NDR) [23], and the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data (ERA) [24]. The NNR and NDR datasets covered the period from 1948 and 1979 to the present, respectively, with the spatial resolution of the Global T62 Gaussian grid (192×94). There were some deficiencies in the model physics of the NNR; for example, the description of cloudiness and soil moisture is poor, which could bias the estimation of surface temperature [25]. Although based on the widely used NNR, the NDR has improved this quality by featuring newer physics and observed soil moisture forcing as well as fixing known errors of the NNR [23]. Consequently, the OMR for the NDR data should more accurately characterize near-surface temperature over land [26]. The latest extension reanalysis ERA-interim was also used in our analysis. It covers the period from 1979 to the present with a spatial resolution of $1.5^{\circ} \times 1.5^{\circ}$. In this work, we selected the same reference period that is used for comparison from 1979 to 2009. The ERA is somewhat more sensitive to land surface forcing than the NNR or NDR. However, results derived from the ERA would contain a portion of surface temperature variation due to land surface forcing [12, 27], and these results would strengthen our conclusions. Furthermore, an integrated study using a few types of reanalysis datasets may help to decrease the uncertainties brought about by data deficiencies, and a comparative analysis of three reanalyses may perhaps be helpful to confirm the results of the OMR. Following the same techniques put forward by Kalnay and Cai [11], we also interpolated the gridded reanalysis data to observational sites with bilinear interpolation.

2.3. Methods of Defining Types of Stations. The key issue of estimating the effect of urbanization on temperature trends is to define the reference or baseline stations. The stations located in rural areas could be assumed to be reference

Table 2: Numbers of stations for each station group in the JJJ area.

Station group name	Population criteria (million)	Number of stations
Large city station	≥0.5	11
Medium city station	0.1–0.5	31
Small city station	0.05–0.1	26
Rural station	≤0.05	11

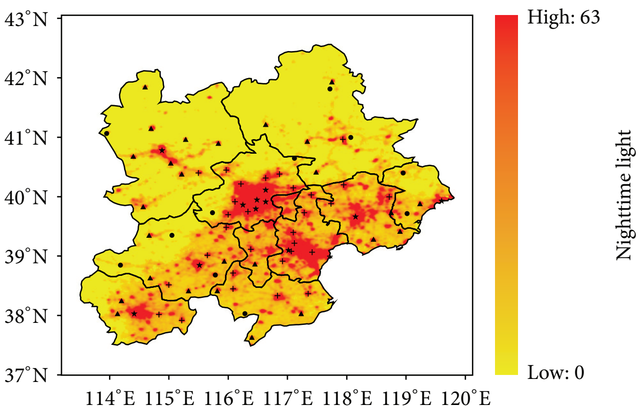


Figure 2: The distribution of the four types of stations in the JJJ area. The background is DMSP/OLS nighttime light data from 2009 (⋆ large city station; + medium city station; ▲ small city station; • rural station).

stations that have not been affected by urbanization and the temperature trends recorded at the rural stations would actually represent large-scale changes.

The stations were firstly classified into four types according to the population data provided by China City Statistical Yearbook (2009): large city stations with nonagricultural populations over 0.5 million; medium-sized city stations with nonagricultural populations of 0.1–0.5 million; small city stations with nonagricultural populations of 0.05–0.1 million; and rural stations with nonagricultural populations less than 0.05 million. This is consistent with Easterling et al. who considered a population of 0.05 million as the critical value between "urban" and "nonurban" stations [28].

Additionally, the DMSP/OLS nighttime light imagery was also applied to define the rural stations. The total number of stations with nonagricultural populations less than 50,000 was 17. Then the nighttime light data of these sites were analyzed. Among these 17 stations, the nighttime light values of six stations increased significantly, which indicated that these stations experienced a process of urbanization. These six sites were then classified as small city stations. Therefore, in the present study, a total of 11 rural stations were chosen. The definitions for the various categories of stations and the numbers of each station are listed in Table 2, which shows that the number of medium city stations was the largest, followed by the small city stations.

2.4. Calculation of Temperature Anomalies. Figure 2 illustrates the locations of all stations we analyzed in the JJJ area. Many factors, such as topography and altitude, could bias the research results when using average temperatures; therefore, we adopted temperature anomalies of the station observations and the reanalysis data to denote the interannual variation of the regional temperature for each station category. All trends were calculated using a simple linear regression, and the statistical significance of the linear trend was assessed using a t-test. The Mann-Kendall trend test [29, 30] was used to determine abrupt changes and the significance of urban warming [31, 32].

3. Results

3.1. Surface Air Temperature (SAT) Trends. The observed trends in the surface air temperature for the different station groups in the JJJ area are listed in Table 3. From 1960 to 2009, the trends in the annual mean temperature were all positive for the four station groups, with the largest increase occurring at the large city stations (0.43°C decade^{-1}), followed by the medium city stations (0.30°C decade^{-1}) and then the small city stations (0.28°C decade^{-1}). The weakest warming trend, only 0.19°C decade^{-1}, occurred at the rural stations, indicating that urbanization might have exerted a significant influence upon the observed temperature warming in the JJJ area. The annual mean temperature trends from 1979 to 2009 were even larger. The values for the seasonal trends are shown along with the annual means for each station group. The seasonal mean SAT trends for the various station groups all appeared to be largest in winter, followed by the spring. Relatively weak warming was observed during the autumn and summer. The rural stations even witnessed a slight cooling trend in the summertime. For the JJJ area as a whole, the annual mean SAT trend was 0.30°C decade^{-1}, which is similar to the results from northern China, 0.29°C decade^{-1} from 1961 to 2000 [10]. The regional averaged SAT warming trends during the winter, spring, summer, and autumn were 0.54, 0.46, 0.1, and 0.1°C decade^{-1}, respectively.

Figure 3 reveals the spatial distribution of the annual mean SAT trends from the observed station records and the reanalysis data in the JJJ area during 1979–2009. The station observations (Figure 3(a)) indicated that the spatial distribution of the warming trend was closely related to the intensity of the nighttime lights. The urban stations with relatively intense nighttime lights exhibited rapid increases in the temperature. Conversely, stations with weak warming trends were mainly rural or small city stations. A broad range of spatial difference existed in the observed SAT in the study area, with a minimum of 0.081 and a maximum of 1.012°C decade^{-1}. In contrast, the ERA (Figure 3(b)), NNR (Figure 3(c)), and NDR (Figure 3(d)) reanalysis data all showed the strongest warming trends from 1979 to 2009. However, the trend values did not reach the amplitude of the observed station records. The spatial difference ranged from 0.399 to 0.630°C decade^{-1} for the ERA, 0.284 to 0.510°C decade^{-1} for the NNR, and 0.227 to 0.346°C decade^{-1} for the NDR. The spatial differences of the reanalysis data were substantially less than that of the station observations, because the reanalysis data only reflected the atmospheric

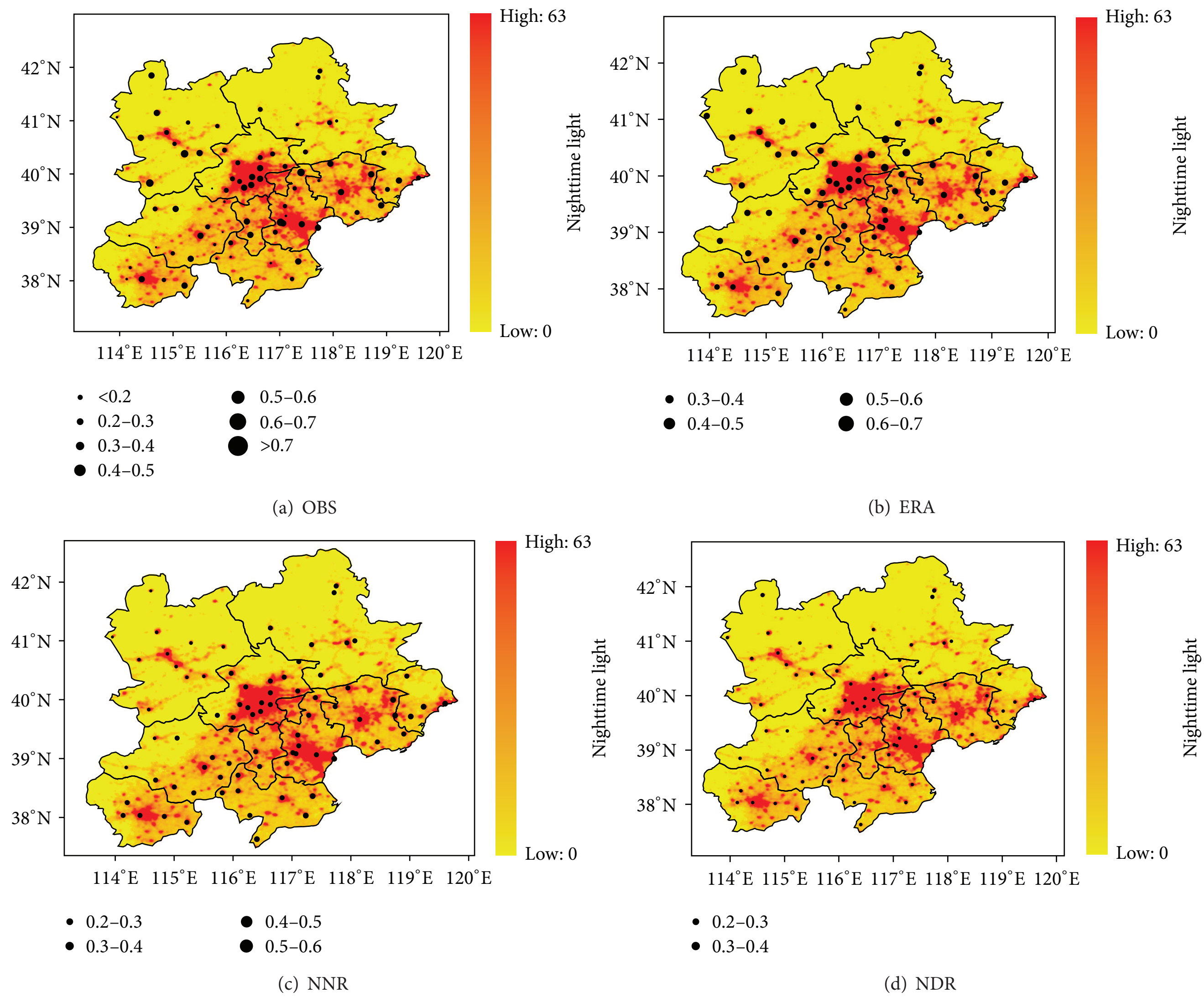


FIGURE 3: Annual mean SAT trends from (a) station observations (OBS), (b) ECMWF ERA-interim reanalysis data (ERA), (c) NCEP/NCAR reanalysis data (NNR), and (d) NCEP/DOE reanalysis data (NDR) during 1979–2009 (unit: $^{\circ}$C decade^{-1}). Also shown is the DMSP/OLS nighttime light imagery from 2009.

circulation and greenhouse gas concentrations but were insensitive to regional surface processes associated with different land types.

3.2. Effect of Urbanization on SAT Trends. Table 3 shows trends for the annual and seasonal mean SAT related to urbanization for various city station groups. The values in the parentheses are the SAT trend differences between the urban station groups and rural sites. From the difference in the observational temperature trends between the urban and rural stations (Table 3), the annual mean UMR trend was 0.24°C decade^{-1} for the large city station, 0.11°C decade^{-1} for the medium city station, and 0.09°C decade^{-1} for the small city station (statistically significant at the 0.01 confidence level for each city station group). The average annual urban warming in the JJJ area was 0.12°C decade^{-1} (statistically significant at the 0.01 confidence level). The effect of urbanization on the SAT trend for each city group after 1979 appeared to be slightly larger than that of 1960–2009. Among the four seasons, the urban warming in the summer was the largest (0.13°C decade^{-1}), followed by spring (0.11°C decade^{-1}) and autumn (0.10°C decade^{-1}). The annual SAT trend in winter was hardly affected by urbanization (0.04°C decade^{-1}). The contribution of urban warming to the total warming was largest in the summer, reaching 100% for all of the city station groups, whereas winter witnessed the lowest contribution. One reason may be attributed to the fact that the wind velocities during the summer are weaker than in winter in northern China, as many studies have reported that urban heat island intensity increases with decreasing wind speed [33–35]. The effects of UHI in the JJJ area did not significantly contribute to the observed rapid warming during the wintertime; therefore, the large-scale climate changes due to greenhouse gases and atmospheric circulation were likely

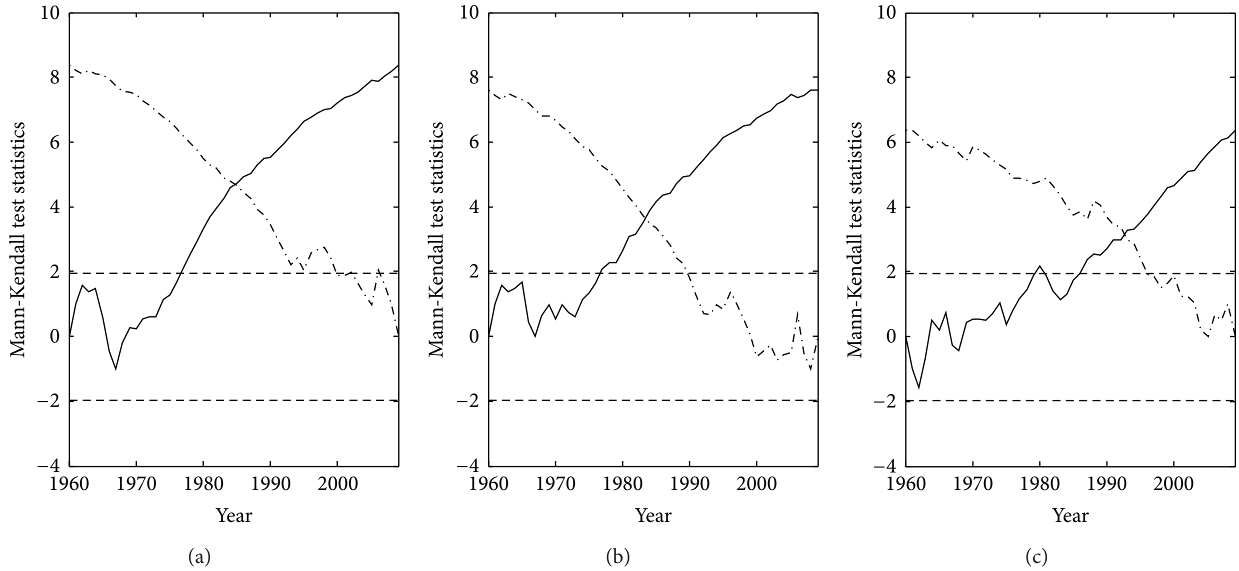


Figure 4: Sequential Mann-Kendall test applied to the observed annual mean temperature for the UMR of large city groups (a), medium city groups (b), and small city groups (c). The value ±1.96 (the 95% confidence level) is represented with horizontal dashed lines. The solid lines represent the MK trend for the time series, and the dash dotted lines represent the MK trend for the backward series.

Table 3: Observed trends of the annual and seasonal mean surface air temperature for different station groups in the JJJ area. The values in parentheses are the results of different urban station groups minus the rural station. Statistical significance is 0.05 (single asterisk) and 0.01 (double asterisk). The units for the values are $^{\circ}$C decade^{-1}.

Station group name	Winter	Spring	Summer	Autumn	Annual (1960–2009)	Annual (1979–2009)
Large city station	0.75^{**} (0.24^{**})	0.68^{**} (0.31^{**})	0.21^{**} (0.22^{**})	0.11^{**} (0.09^{**})	0.43^{**} (0.24^{**})	0.66^{**} (0.27^{**})
Medium city station	0.54^{**} (0.03)	0.49^{**} (0.12^{*})	0.12^{**} (0.13^{**})	0.06 (0.04)	0.30^{**} (0.11^{**})	0.50^{**} (0.11^{**})
Small city station	0.47^{**} (−0.04)	0.34^{**} (−0.03)	0.12^{*} (0.13^{**})	0.24^{**} (0.22^{**})	0.28^{**} (0.09^{**})	0.51^{**} (0.13^{**})
Urban station	0.55^{**}	0.47^{**}	0.12^{**}	0.12	0.31^{**}	0.53^{**}
Rural station	0.51^{**}	0.37^{**}	−0.01	0.02	0.19^{**}	0.39^{**}
UMR	0.04	0.11^{*}	0.13^{**}	0.10^{**}	0.12^{**}	0.14^{**}

Table 4: Linear trends of regional average annual, rural, and UMR temperature ($^{\circ}$C decade^{-1}) and the contribution of urban warming to the total warming for different time periods. Statistical significance is 0.05 (single asterisk) and 0.01 (double asterisk).

	Total	Rural	UMR	UHI contribution
1960–1969	-1.10^{*}	−1.13	0.03	0.30%
1970–1979	0.39	0.25	0.16^{*}	41.03%
1980–1989	0.46	0.33	0.15^{*}	32.61%
1990–1999	1.28^{**}	1.14^{*}	0.16^{*}	12.50%
2000–2009	0.26	0.21	0.09	34.62%
1960–2009	0.30^{**}	0.19^{**}	0.12^{**}	40.00%

the dominant contributors. This seasonal conclusion agrees with the results of Ren et al. for northern China [10] and Yang et al. in eastern China [36].

Table 4 shows the contribution of urban warming at different time periods. The contribution of urban warming to the overall warming was 40% for the 50 years from 1960 to 2009. The warming trends of the background (rural station) and urban stations were the strongest during the 1990s, followed by the 1980s and 1970s. The UMR trends in the 1970s, 1980s, and 1990s were the largest (all statistically significant at the 0.05 confidence level). This indicated that urbanization in the JJJ area was consistent with the Chinese progress of the reform and open policy since 1978. We know that the study area experienced rapid urban development after the Tangshan earthquake in 1976. Although the UMR in the 1990s was the largest, the contribution of urban warming to the overall warming was the largest in the 1970s (41.03%) because the background warming trend in the 1990s was so large.

Figure 4 shows the results of the sequential Mann-Kendall methods applied to the time series of the annual mean SAT for the UMR of different city groups. The sequential Mann-Kendall analysis indicated that the time series of the annual mean temperature differences between the city and rural sites all had very significant positive trends that exceeded the 99% confidence level. The abrupt changes in the trends of the time series of the annual mean SAT began in the early 1980s for the large city and medium city station groups (Figures 4(a) and 4(b)) and the early 1990s

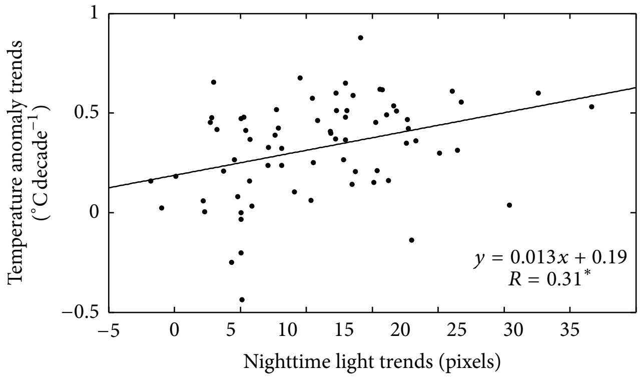


Figure 5: Correlation between the trends of the annual mean SAT and the intensity of the nighttime lights from 1992 to 2009.

for the small city groups (Figure 4(c)). The positive trends of the large city and medium city stations began to pass the 95% confidence level during the 1970s, while the small city stations passed the 95% confidence level during the late 1980s. Therefore, the small city stations clearly experienced weaker and slower urbanization progress than the large and medium city stations.

Figure 5 shows the trend of the annual mean SAT related to the intensity of the nighttime lights, and the correlation coefficient was 0.31, which is statistically significant at the 0.05 confidence level. It is notable that the observed SAT was somewhat affected by the urbanization in the JJJ area. Therefore, the increasing UHI effect amplified the trend of the observed SAT. Only when the urbanization effect is removed can these records be considered accurate and better represent the baseline temperature. The warming trend of the regional average annual SAT in the JJJ area decreased from 0.30°C decade^{-1} to 0.19°C decade^{-1} after the adjustment.

3.3. Observation Minus Reanalysis (OMR) Analysis. Compared with the progress of urbanization, the conversions of land use types caused by other human activities, such as agriculture, overgrazing, and deforestation, have been even more intense. China is one of the most obvious land use change regions, but the climatic effects from land use/cover changes and greenhouse gas emissions are difficult to distinguish. However, neglecting the role of land use changes could lead to the wrong assessment of human activities on contributions to surface warming. It is very important to reveal the contributions of urbanization and other land use changes to climate change. In this paper, we used the OMR method to analyze the contribution of urbanization and other land use changes to surface warming.

Figure 6 shows the observation and reanalysis time series of temperature anomalies for the four station groups from 1979 to 2009. Both the observed and the reanalysis annual mean temperatures showed increasing trends. The reanalysis dataset agreed best with the station observation from rural stations (Figure 6(a)), indicating that the rural stations were less affected by urbanization and that the background temperature changes were captured in both the observations and the reanalysis data. The warming trends of the station observations were stronger than the reanalysis data, with the strongest in the large city groups (Figure 6(d)), followed by the medium city groups (Figure 6(c)), small city groups (Figure 6(b)), and then the rural stations (Figure 6(a)).

The OMR values of the NDR were the largest (Figure 6). The ERA-interim [24] indirectly assimilated near-surface temperature observations [41], so the ERA was similar to the observed counterparts in China [42, 43]. This is shown in Figure 6, and the OMR of the ERA was the smallest (Figure 6). The most substantial increase in the OMR values occurred in the early 2000s in the small and medium city groups (Figures 6(b)-6(c)), indicating a significant effect of rapid urbanization on the SAT in the early 2000s. The largest increase of the OMR in the large city groups occurred during the late 1980s, implying that rapid urbanization developed during this period (Figure 6(d)), which is relatively consistent with the UMR abrupt changes tested by the Mann-Kendall method.

Table 5 presents the annual mean temperature trends from the station observation and three reanalysis datasets, along with the OMR and UMR values for each station group. The most significant increase in the station observed annual mean SAT occurred at the largest stations with an annual linear trend of 0.66°C decade^{-1}, and the weakest occurred at the rural stations with a trend of 0.39°C decade^{-1}. The trends of the reanalysis datasets among the various station groups were nearly uniform with a low range of 0.52 to 0.54°C decade^{-1} for the ERA, 0.43 to 0.50°C decade^{-1} for the NNR, and 0.24 to 0.26°C decade^{-1} for the NDR. This predominantly reflected changes in circulation and greenhouse warming. The annual OMR trends indicated strong warming in the large cities with 0.12, 0.19, and 0.42°C decade^{-1} for the ERA, NNR, and NDR, contributing 18.18%, 28.79%, and 63.64%, respectively. The annual OMR trends were weakest for the rural stations at 0.11, −0.06, and −0.15°C decade^{-1} for the ERA, NNR, and NDR, respectively. If these rural values were added to the UMR, the results would be consistent with those of the OMR. Accordingly, both methods showed that urbanization has imposed significant effects on the SAT in the JJJ area.

The seasonal mean temperature trends from three reanalysis datasets all present significant increasing trends, strongest in the winter and spring. In the four seasons, the trends of all the three reanalysis datasets among various station groups show little differences. In addition, the seasonal OMR values show strongest warming trends in the large city stations, followed by the medium and small city station groups. The OMR trends in the winter and spring are stronger than those in summer and autumn (Table 5), which agrees with the result obtained by Yang et al. [40] and Hu et al. [14] by the same method for eastern China, but no one had pointed out why it appeared contrary to the UMR result. The reason why it is contrary to the UMR result is difficult to explain.

The OMR values (Figure 7) exhibited a spatial pattern similar to the trends of the observational temperature (Figure 3(a)). On average, the OMR magnitudes for the NDR were largest, and those for the NNR and ERA were relatively small. The geographical distribution of both the OMR and

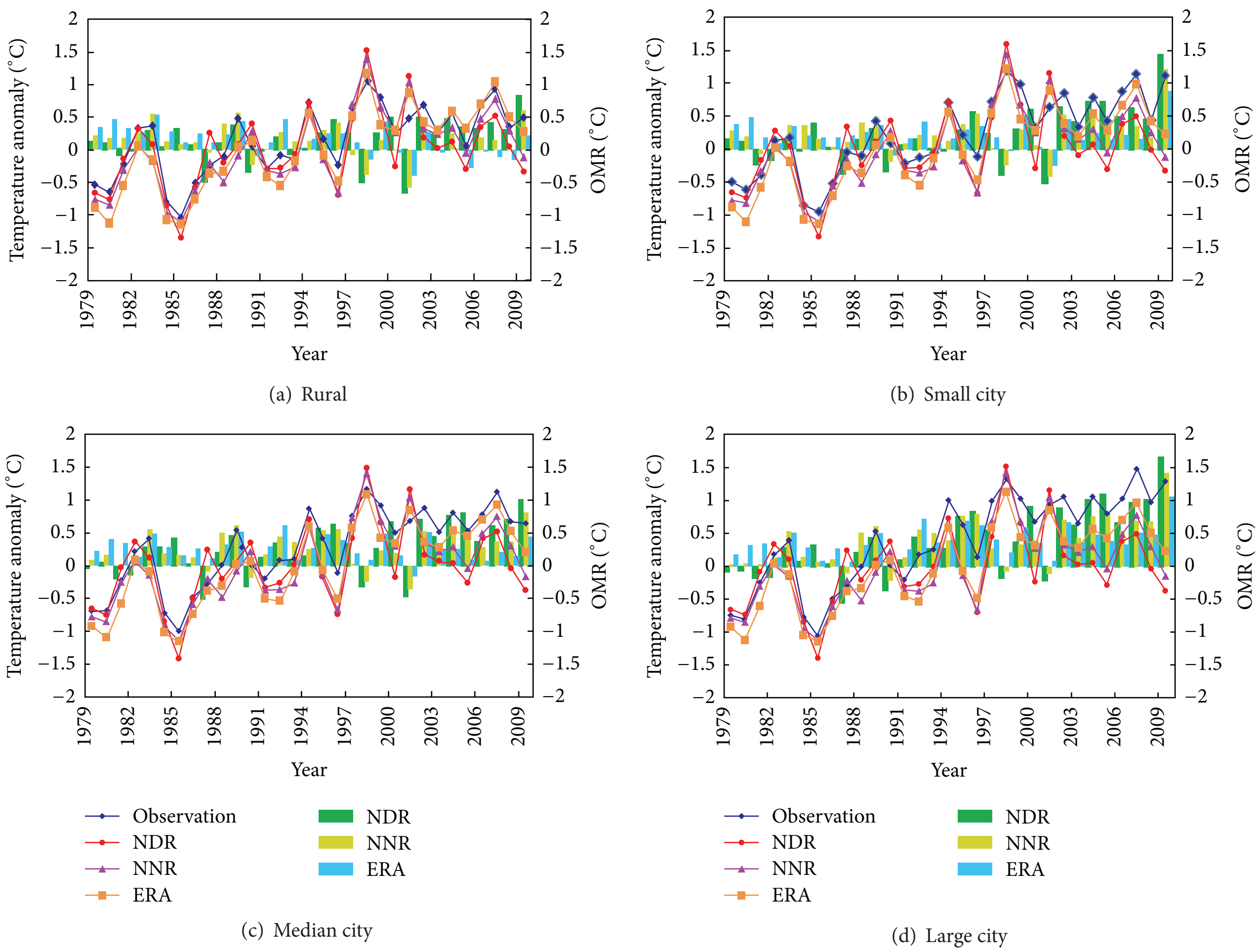
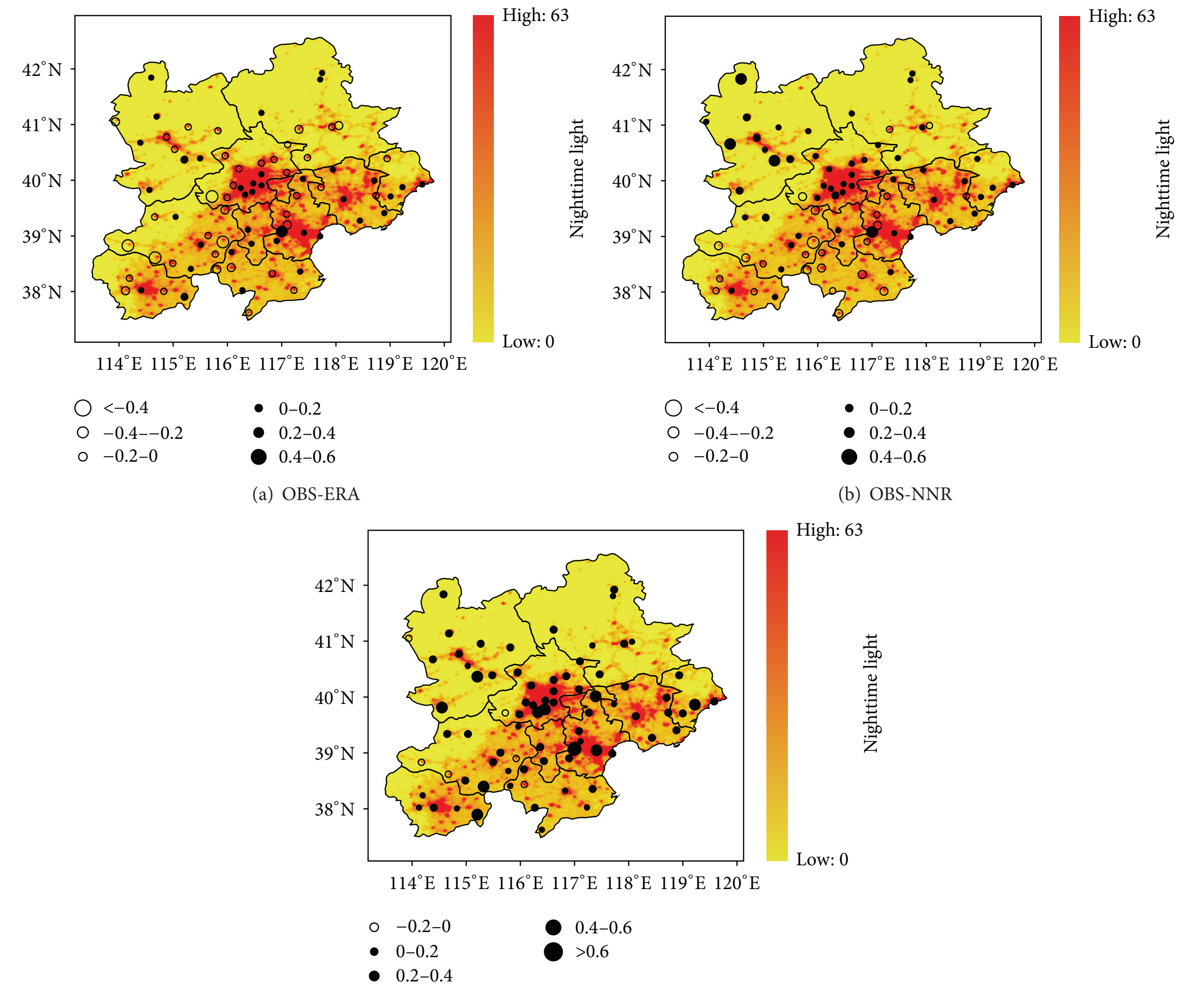


Figure 6: Observation and reanalysis time series of temperature anomalies (line graph) and OMR values (bar chart) for (a) rural, (b) small city, (c) medium city, and (d) large city groups from 1979 to 2009.

the observational temperature trends revealed that land surface change most likely affected the observed temperature and that the significant warming was affected by urbanization in the JJJ area, especially in Beijing, Tianjin, and other large cities with the most intense nighttime lighting and strongest UHI effects. We know that the OMR results reflect changes in land use rather than simply urbanization, so the negative OMR trends that were predominant found at the rural stations (Table 5 and Figure 7) could be caused by agricultural irrigation and increasing vegetation activity [44], especially in the summer and autumn season (Table 5) which reflected the climatic effects of both urbanization and increased agricultural planting around the cities. In terms of seasonal differences in Table 5, the urban warming effect from the OMR method in winter is the largest, but the contribution of urban warming is the largest in summer from the UMR result. This can be attributed to the fact that the rural stations were affected by agricultural irrigation and increasing vegetation activity in summer, so the cooling effects that we can see in Table 5 and Figure 7 enlarged the result of urban minus rural method.

4. Conclusion and Discussion

The above findings demonstrate that urbanization effects essentially exert positive promotions on the regional climate warming in the Beijing-Tianjin-Hebei metropolitan area. Using the UMR method, the urban warming of approximate $0.12^{\circ}\mathrm{C\,decade}^{-1}$ accounting for 40% of regional total climate warming ($0.30^{\circ}\mathrm{C\,decade}^{-1}$) from 1960 to 2009 and accounting for 25.69% of regional total climate warming from 1979 to 2009 could be found. Using the OMR method, the urban warming intensity is dependent on reanalysis dataset. A very slight UHI could be detected from the ERA, while the urban warming of $0.10^{\circ}\mathrm{C\,decade}^{-1}$ and $0.26^{\circ}\mathrm{C\,decade}^{-1}$ accounting for 18.77% and 51.19% of regional total warming from 1979 to 2009 could be calculated from the NNR and NDR, respectively. The differences might have partly resulted from diversities of assimilation systems and input datasets. For instance, ERA indirectly assimilated near-surface temperature observations [41], so a very slight UHI could be detected. Thus the ERA dataset is somewhat not optimal for the OMR method in the study area.



(a) OBS-ERA

(b) OBS-NNR

(c) OBS-NDR

Figure 7: Annual mean temperature trends from the observation minus reanalysis method (°C decade^{-1}) for the (a) ERA, (b) NNR, and (c) NDR. The DMSP/OLS nighttime lights imagery from 2009 is also shown.

Although there are differences among the annual urban warming from ERA, NNR, and NDR, the seasonal cycle patterns from all three datasets are consistent with each other. A stronger UHI occurs in winter and it is weaker in summer from the OMR results, which may reflect strong anthropogenic heating effect in winter. However, the findings from the UMR method demonstrate that the urban warming contributes the largest in summer and smallest in winter. The reverse seasonal cycle pattern of urban warming from the UMR and OMR method implicates that our understanding of the seasonal cycle of urban effects has some uncertainties. As we know that the UMR used the observations entirely. The urban sites are influenced by UHI. Meanwhile, the rural sites are also influenced by other factors, such as vegetation transpiration and moisture evaporation from soil. Vegetation greening enhanced the transpiration and thus cooling of the climate [45]. This cooling effect of agriculture activities can also be found as suggested for the USA [13]. In our study area, vegetation has strong activities in summer. So the strongest urban warming effect in summer from the UMR method might be larger than actual UHI effect. Winter witnessed the lowest contribution from the UMR method that may be attributed to the stronger wind speed in winter in northern China, as UHI intensity decreases with increasing wind speed [33–35].

Therefore, we found some deficiencies of the UMR method that the results from the UMR overestimate the urban warming effect in winter and underestimate it in summer. On the other hand, the results from the OMR method are relatively more convincing although we admit its accuracy depends on the quality of reanalysis dataset.

We used nighttime light data to classify the station groups, but nighttime light can only provide objective urban development information, not details on the physical features

Table 5: Annual and seasonal mean temperature trends from station observation and three reanalysis datasets. Shown are the differences between the observations and the reanalysis datasets (OMR) as well as the differences between the urban and rural sites (UMR) for the different station groups from 1979 to 2009 (°C decade^{-1}). Statistical significance is 0.05 (single asterisk) and 0.01 (double asterisk).

Station group name	Datasets	Winter	Spring	Summer	Autumn	Annual
Large city station	OBS	1.06**	1.00**	0.37**	−0.09*	0.66**
	NDR	0.22**	0.32**	0.21**	0.25**	0.24**
	NNR	0.68**	0.39**	0.34**	0.32**	0.47**
	ERA	0.72**	0.50**	0.49**	0.36**	0.54**
	OMR (NDR)	0.84**	0.68**	0.16**	−0.44**	0.42**
	OMR (NNR)	0.38**	0.61**	0.03	−0.51**	0.19**
	OMR (ERA)	0.34**	0.50**	−0.12**	−0.55**	0.12**
	UMR	0.17**	0.26**	0.42**	−0.02	0.29**
Medium city station	OBS	0.83**	0.86**	0.27**	0.08	0.50**
	NDR	0.24**	0.33**	0.19**	0.24**	0.24**
	NNR	0.68**	0.39**	0.33**	0.30**	0.50**
	ERA	0.73**	0.48**	0.45**	0.36**	0.53**
	OMR (NDR)	0.59**	0.53**	0.08	−0.16**	0.26**
	OMR (NNR)	0.15**	0.47**	−0.06	−0.22**	0.00
	OMR (ERA)	0.10*	0.38**	−0.18**	−0.28**	−0.03
	UMR	−0.06	0.12**	0.32**	0.15**	0.13**
Small city station	OBS	0.64**	0.64**	0.36**	0.43**	0.51**
	NDR	0.21**	0.33**	0.22**	0.26**	0.25**
	NNR	0.64**	0.40**	0.33**	0.32**	0.43**
	ERA	0.65**	0.51**	0.51**	0.32**	0.52**
	OMR (NDR)	0.43**	0.31**	0.14**	0.17**	0.26**
	OMR (NNR)	0.00	0.24**	0.03	0.11**	0.08
	OMR (ERA)	−0.01	0.13**	−0.15**	0.11**	−0.01
	UMR	−0.25**	−0.10*	0.41**	0.50**	0.14**
Rural station	OBS	0.89**	0.74**	−0.05	−0.07	0.37**
	NDR	0.44**	0.33**	0.23**	0.25**	0.26**
	NNR	0.65**	0.41**	0.34**	0.32**	0.43**
	ERA	0.71**	0.51**	0.51**	0.34**	0.52**
	OMR (NDR)	0.45**	0.41**	−0.28**	−0.32**	0.11*
	OMR (NNR)	0.24**	0.33**	−0.39**	−0.39**	−0.06
	OMR (ERA)	0.18**	0.23**	−0.56**	−0.41**	−0.15**

of the sites and surroundings. Urban meteorological observations are more likely to be made within park cool islands than in industrial regions [3]. Therefore, more detailed information of the station locations and their surroundings or extensive remote sensing observation of the stations is needed in future works. Obviously, a more realistic treatment of the land surface and vegetation-climate interaction in models would be helpful for improving our understanding of the effects of LUCC on the climate [46]. Moreover, the surface observed data did not give any information about how high urbanization affects the overlying atmosphere [31]. To seek answers to these issues, the impact of UHI effect on the observed regional climate change needs more in-depth research, so integrated application of the observation analysis and numerical simulation methods will make the conclusions more convincing.

Although there still exist some uncertainties, the results presented in this paper suggest that a large portion of the current surface climate warming over the Beijing-Tianjin-Hebei metropolitan area is caused by urbanization. The results presented in this work suggest that the climatic effects of LUCC should be considered in climate change mitigation strategies during the rapid urbanization of China.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research was sponsored by the Major State Basic Research Development Program of China (973 Program, no. 2010CB950900) and the National Natural Science Foundation of China (41405072).

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