RESEARCH ARTICLE

Key Points:
- Long-term modeling was conducted over three extensive urban agglomerations in China
- The effects of urbanization on temperature trends were quantified
- Urbanization contributes to ~10% of overall warming in urban agglomerations

Modeling the contribution of long-term urbanization to temperature increase in three extensive urban agglomerations in China

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Abstract This study simulated the effects of changes in the underlying surface induced by long-term urbanization on trends in surface air temperature (SAT) over three extensive urban agglomerations (Beijing-Tianjin-Hebei, BTH; the Yangtze River Delta, YRD; and the Pearl River Delta, PRD) in China during 1980–2009. To isolate the effects of continuous urban expansion on SAT with the least computation cost, we employed the Community Land Model (CLM4.5) in an off-line mode for a relatively long period. Based on a high-quality land use data set dating back to the 1980s, two scenarios were designed to represent the distributions of both nonurban and historically urban land use. By comparing the results of two numerical experiments, urban-induced warming in daily mean SAT (T_{mean}) over the three urban agglomerations, BTH, YRD, and PRD, were found to be 0.13°C/30 yrs, 0.12°C/30 yrs, and 0.09°C/30 yrs, contributing about 9.70%, 10.3%, and 9.68% to the mean long-term SAT trends, respectively. In addition, a higher contribution of urban-related warming was found in winter for BTH and in summer for the other two regions. However, urban-related warming had no significant effect on the trends of daily maximum SAT (T_{max}) when compared with daily minimum SAT (T_{min}). Specifically, at a local scale, the contributions of urban warming to the background warming in three representative cities, Beijing, Shanghai, and Guangzhou, were 12.7%, 29.0%, and 23.6%, respectively.

1. Introduction

The effects of urbanization on temperatures have been found to be negligible when compared with the global or regional trends in average temperature [*Hansen et al.*, 2010; *Jones et al.*, 1990; *Li et al.*, 2004; *Parker*, 2004; *Peterson et al.*, 1999]. In contrast, some studies have indicated that urbanization may induce a large warming bias in regional or local temperature time series [*Balling and Idso*, 1989; *Ren et al.*, 2007]. Aside from the differences in spatial scales, study regions, and periods, the data sets and methods themselves are also responsible for controversy related to the rates of urban warming or the contributions of urban warming within the observed temperature trends.

One issue that arises is that heterogeneity in temperature time series may be caused by nonclimatic effects, such as changes in observation time and location. These factors could bias any estimate of the effects of urbanization. *Peterson* [2003] used homogenized data set to study the effects of urbanization across the contiguous United States and found that no significant difference existed in the nationwide averaged temperature trends between urban and rural stations. *Wang et al.* [2013a] applied homogenized temperature records to reexamine the effects of urbanization and suggested that the contribution of urbanization to the recorded warming trend in Beijing was only 10.9%. However, earlier studies estimated this value to be much larger, based on the original or partly homogenized temperature observations [*Ren et al.*, 2007; *Yan et al.*, 2010]

Another problem leading to considerable discussion on this topic was the methods used to assess the effects of urbanization on temperature trends. Some studies classified weather stations into different types and calculated the difference in temperature trends between urban and rural stations as effects of urbanization. However, the indices used to classify stations (e.g., population, satellite-observed nighttime light intensity, and land cover data) were often determined subjectively. The results of the estimation of the effects of urbanization were sensitive to

these methods. *Gallo et al.* [1999] found that the trends of the range of diurnal temperatures in rural areas differed with inconsistent methods that were used in different studies to define land use type, causing diurnal temperatures to vary from −0.41 to −0.67°C/100 yrs. Some studies also have looked at reanalyzed output data (almost always derived from the National Centers for Environmental Prediction) and found quite large differences in the temperature trends between reanalyzed and observational data [*Kalnay and Cai*, 2003; *Kalnay et al.*, 2006; *Zhou et al.*, 2004]. Because reanalyzed data reflect large-scale climate change but may not assimilate surface observations, they attributed this difference to urbanization or other land use effects [*Kalnay and Cai*, 2003]. However, *Wang et al.* [2013b] found that the multidecadal variability of temperature in the reanalyzed data is generally weaker than that in the analysis of raw data from the station observations. This systematic discrepancy leads to inconsistent estimates of the effect of urbanization. Therefore, the results of the effects of urbanization based on the traditional observational analysis methods still contain uncertainties.

Numerical modeling enables researchers to estimate the effects of urbanization based on the observed temperature trends from a new perspective. Some earlier studies selected several Januarys and Julys to simulate the influence of urbanization on surface air temperatures in winter and summer [*Trusilova et al.*, 2008; *Zhang et al.*, 2010]. *Feng et al.* [2012] performed numerical experiments from December 2006 to December 2008 to quantify the regional effects of underlying surface changes caused by urbanization on the surface air temperature in China. *Wang et al.* [2012] conducted a 3 year high-resolution modeling study over three extensive urban agglomerations in China and estimated the changes of surface air temperature caused by urbanization. *Feng et al.* [2013] carried out a 10 year model simulation to investigate the long-term effects of urbanization on regional climate in China, particularly the effects on the East Asia monsoon. Many efforts have used modeling approaches to quantify the influence of urbanization on temperature, but most of them integrated a model with only two land cover patterns (preurbanization and posturbanization). Actually, the changes in impervious surface caused by urbanization reflect continuous processes, rather than two separate and unique urban land use patterns. In addition, their simulations were integrated with identical initial and boundary conditions in several representative years. Thus, the effects of urban growth in the long-term changes of near-surface temperature can only be poorly derived using these modeling results.

We needed to integrate our model continuously over decades to assess the degree to which the trends in surface air temperature are affected by urban expansion and produce results that were closer to reality. However, high-resolution long-term simulations with all-coupled climate models are restricted given the limitation of computational resources. Therefore, this study applied a land surface model in a stand-alone mode as a compromise to attempt to isolate the local effects of historical urbanization on surface air temperatures from large-scale climatic warming.

In this paper, section 2 introduces the methods (model and experimental setup) and data (gridded temperature observations, land use, and atmospheric forcing data). Section 3 presents the main results and section 4 provides the conclusions and discussion.

2. Model and Data

2.1. Model Description

This study employed a newly developed land surface model, the Community Land Model version 4.5, (CLM4.5) [*Oleson et al.*, 2013]. CLM4.5 can simulate interactions among the land surface, soil, and canopy processes and has been widely used in global, regional, and single-point simulations. The spatial heterogeneity of land cover within CLM4.5 is represented by dividing each grid cell into five land units: glacier, lake, wetland, vegetated, and urban. An urban parameterization (CLMU) that is to represent the differences between urban and rural areas has been incorporated into the model since the introduction of CLM4.0 [*Lawrence et al.*, 2011]. CLMU adopts an urban canyon configuration that reduced the complexity of the urban surfaces into a single urban canyon. The canyon system is composed of roofs, sunlit areas, shaded walls, as well as impervious (e.g., buildings and roads) and pervious (e.g., parks, lawns, and forests) canyon floor [*Oleson et al.*, 2010]. The absorption and reflection of solar radiation and the trapping of longwave radiation caused by multiple reflections from canyon surfaces are considered by CLMU [*Oleson et al.*, 2008]. A one-dimensional heat conduction equation is solved numerically for a five-layer column to determine conduction fluxes into and out of canyon surfaces. The explicit time-stepping integration of the surface flux solution is used. In this study, we ran the CLM4.5 in an off-line mode with a 30 min time step, forced by the atmospheric conditions above the urban canopy layer.

2.2. Experimental Setup

To elucidate the effects of urban warming during the past three decades (1980–2009), we designed two sets of numerical experiments employing two urban land use scenarios, which corresponded to different paths of urbanization. The control run (NOURB) removed the urban surface fractions in all model grids. The coverage of the other four land units (vegetated, glacier, wetland, and lake) increased proportionally. A sensitivity run (URB) updated the urban surface fractions to represent continuous urbanization processes in China for the period of 1980–2009 based on the Model Land Cover Datasets version 2.0 (MLCD2.0). Section 2.4 presents the details related to this land use data set. Because CLM4.5 does not support dynamic changes in the characteristics of the underlying surface, we performed some experiments with the "subsection" method. Specifically, the entire simulation period was divided into six equal subperiods: 1980–1984, 1985–1989, 1990–1994, 1995–1999, 2000–2004, and 2005–2009. Both the control and sensitivity runs were integrated over these subperiods but with different urban land cover patterns. In the control run, the urban fractions of all the model grids were held to zero during the entire simulation period. In the sensitivity run, the urban fractions in each subperiod were updated with the land cover data of corresponding time nodes. Specifically, the land cover information in 1980, 1985, 1990, 1995, 2000, and 2005 that had been derived from MLCD2.0 was used to represent the land use condition during the simulation subperiods of 1980–1984, 1985–1989, 1990–1994, 1995–1999, 2000–2004, and 2005–2009, respectively. This treatment mirrors the continuous urbanization process in China during the past 30 years as realistically as possible.

The initial conditions of some slowly changing variables (e.g., soil moisture and deep ground temperature) affect model performance. Biases in these model state variables may lead to incorrect partitioning of water and surface energy balances over a long period of time. To reduce the effects of initial conditions on subsequent model simulations, we initialized CLM4.5 using a spin-up procedure to generate physically consistent initial conditions. Specifically, we ran the model repeatedly using Climatic Research Unit, National Centers for Environmental Prediction (CRUNCEP) atmospheric forcing data of a certain year until the slowly varying variables each reached a state of equilibrium. For each subcase, the CLM4.5 was integrated for 50 years using the atmospheric forcing data of the initial year. This procedure was considered as the model spin-up. Then, based on physically consistent initial conditions, a 5 year integration forced by atmospheric data of corresponding years was conducted.

Figure 1 displays the model domain and the classification results of cities in China based on their respective urbanized areas. Brown patches represent the urban regions discussed in this study; from north to south they are the urban agglomerations of Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta (BTH, YRD, and PRD, respectively). The spatial resolution of the simulation domain was $0.2° \times 0.2°$.

2.3. Gridded Temperature Observations

The gridded daily temperature observations, provided by the National Climate Center of China Meteorological Administration, was the data set used for model validation. This data set was developed through the interpolation of surface air temperature time series data from 751 observation stations scattered across mainland China and had a spatial resolution of $0.5° \times 0.5°$. Quality control, homogeneity testing, and correction for the original temperature series of this data set were carefully conducted. Its construction aims to meet the accelerating demand of the validation of a high-resolution climate model [*Xu et al.*, 2009].

We also used Global Land Data Assimilation System Version 2 (GLDAS-2) to validate our simulation of surface heat flux. This monthly 1.0° data set generated through temporal averaging of the 3-hourly data, which contains a series of land surface parameters simulated from the Noah Model 3.3 (ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/GLDAS/GLDAS_NOAH10_M.020/).

2.4. Land Use Data Set

The Earth Observation of Climate Change research group provided the land use data from the MLCD 2.0 in this study [*Hu et al.*, 2015]. The MLCD2.0 was developed to provide long-term land cover data for climate models with the goal of improving the effectiveness of their surface parameterizations and simulation performance. The accuracy of the land cover classification of this remote sensing data set has been investigated through the comparison with other multisource land cover products, including the United States Geological Survey and Moderate Resolution Imaging Spectroradiometer land cover data sets as well as the China land use data sets. The International Geosphere-Biosphere Programme land cover classification scheme was adopted by this data set. Four representative years (1980, 1990, 2000, and 2009) were considered as important nodes for human-induced land surface changes during the past several decades in China. Spatial resolution of 10 km was used to provide land use information throughout China and its three extensive urban agglomerations.
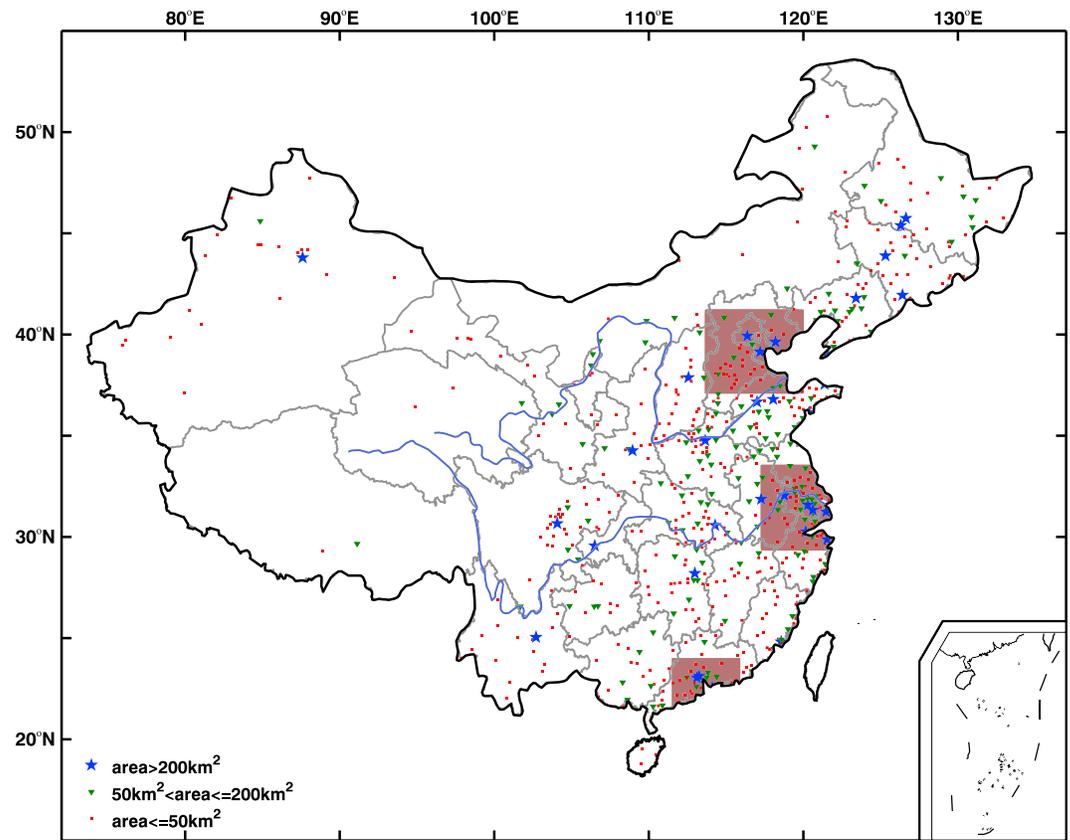
Figure 1. Model domain and the classification result of cities in China according to build-up area. Brown patches stand for the focused urban regions of this study: Shown from top to bottom are BTH, YRD, and PRD urban agglomerations.

Figures 2a and 2b show the spatial distribution of urban fractions over each model grid in 1980 and 2009. The percentages of urbanized areas in China were less than 15% in 1980, which is consistent with the low level of urbanization known to exist at the beginning of China's "reform and opening up" policy that was initiated in 1978. However, the fractions of urban land cover increased dramatically by 2009, especially over the three extensive urban agglomerations in China. Figure 2c shows the changes of averaged urban land use fractions for the BTH, YRD, PRD areas, and the whole of China. Obviously, the cities have expanded steadily during the first two decades of the present study period. Dramatic growth of the urban areas occurred in the YRD and PRD during 2000–2009, surpassing the averaged urban fraction of BTH. The PRD experienced the highest rate of urbanization (15.2%), followed by the YRD (14.5%) and BTH (12.7%).

2.5. Atmospheric Forcing Data

Atmospheric forcing data is required when we run the CLM4.5 in an off-line mode. In this study, the data set used to force the CLM4.5 is CRUNCEP atmospheric forcing data (http://dods.extra.cea.fr/data/p529viov/cruncep/), which include various physical variables, such as temperature, specific humidity, wind speed, pressure at the lowest atmospheric level, precipitation, and incoming shortwave and longwave radiation. This data set was created by combining two existing data sets: the monthly Climate Research Unit Time Series data set version 3.2, with the spatial resolution of $0.5 \times 0.5°$ and covering period of 1901–2002, and the 6-hourly 2.5×2.5 National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data set, covering 1948–2010. The CRUNCEP data set has a spatial resolution of 0.5×0.5, and spans from 1901 to 2010.

3. Results

3.1. Model Validation

The ability of CLM4.5 to simulate effectively has been evaluated when reproducing the features of urban climate [*Demuzere et al.*, 2013]. Because we ran the CLM4.5 in an off-line mode and focused on the effects
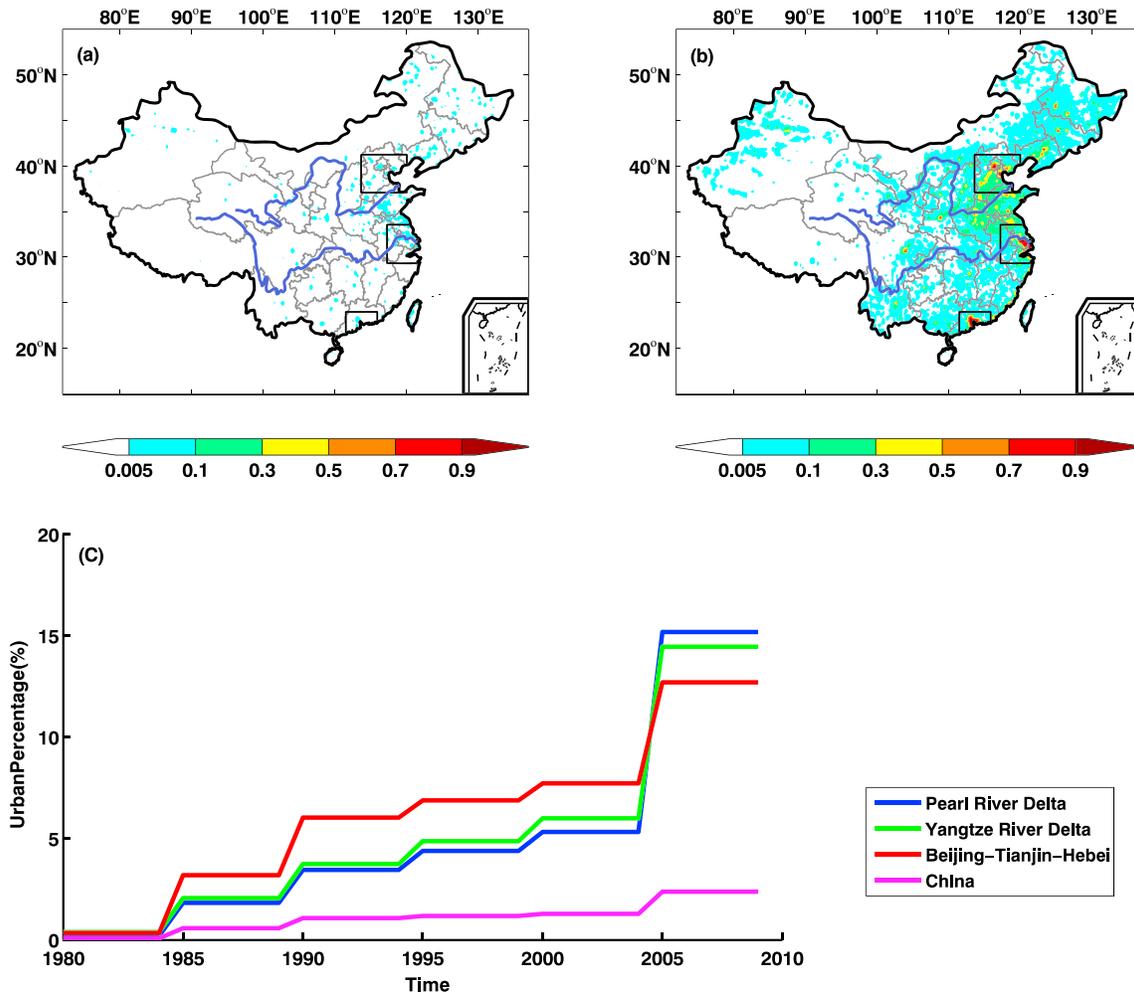
Figure 2. (a) Spatial distributions of urban fractions (units: %) over each model grid in 1980 in China. (b) Same as Figure 2a, but in 2009. (c) Changes of averaged urban land use fractions over BTH, YRD, PRD, and the whole China for the year of 1980–2009.

of urbanization on temperature, we compared the observed and CLM4.5 simulated annual average 2 m air temperature.

Figures 3a and 3b show the spatial patterns of the observed annual mean 2 m air temperature and the difference between URB simulated and observed temperatures. The simulated temperature was found to agree well with the observed data in most areas of China, although overestimates were found in the temperatures over some western areas. Figure 3c shows the spatial patterns of correlation coefficients between observed and URB simulated temperatures. The correlation coefficient indicates the direction and strength of the linear relationship between the observed and simulated temperatures. The simulated temperature in most regions had a high correlation coefficient with observed data. Table 1 shows the mean error and root-mean-square error about the simulated and observed surface air temperatures in the three urban agglomerations analyzed here. Compared with the observational data, the simulated temperature has a relatively low bias in all three urban domains. The largest bias with a value of −0.5°C occurred in BTH. The value of the mean error was about 0.03°C and −0.06°C in the YRD and PRD, respectively. BTH also had a larger root-mean-square error (1.67°C) when compared with the other two urban domains where the values were about 0.55°C. Considering this bias is a system error of the model, it could not prevent us to study the urban warming effect through the numerical experiments.

3.2. Effects of Urbanization on Mean Temperatures and Surface Heat Flux

Figure 4 shows the spatial patterns of urban-induced warming during the six study periods used here, based on the differences in the annual mean temperature between URB and NOURB model runs. Surface air temperature
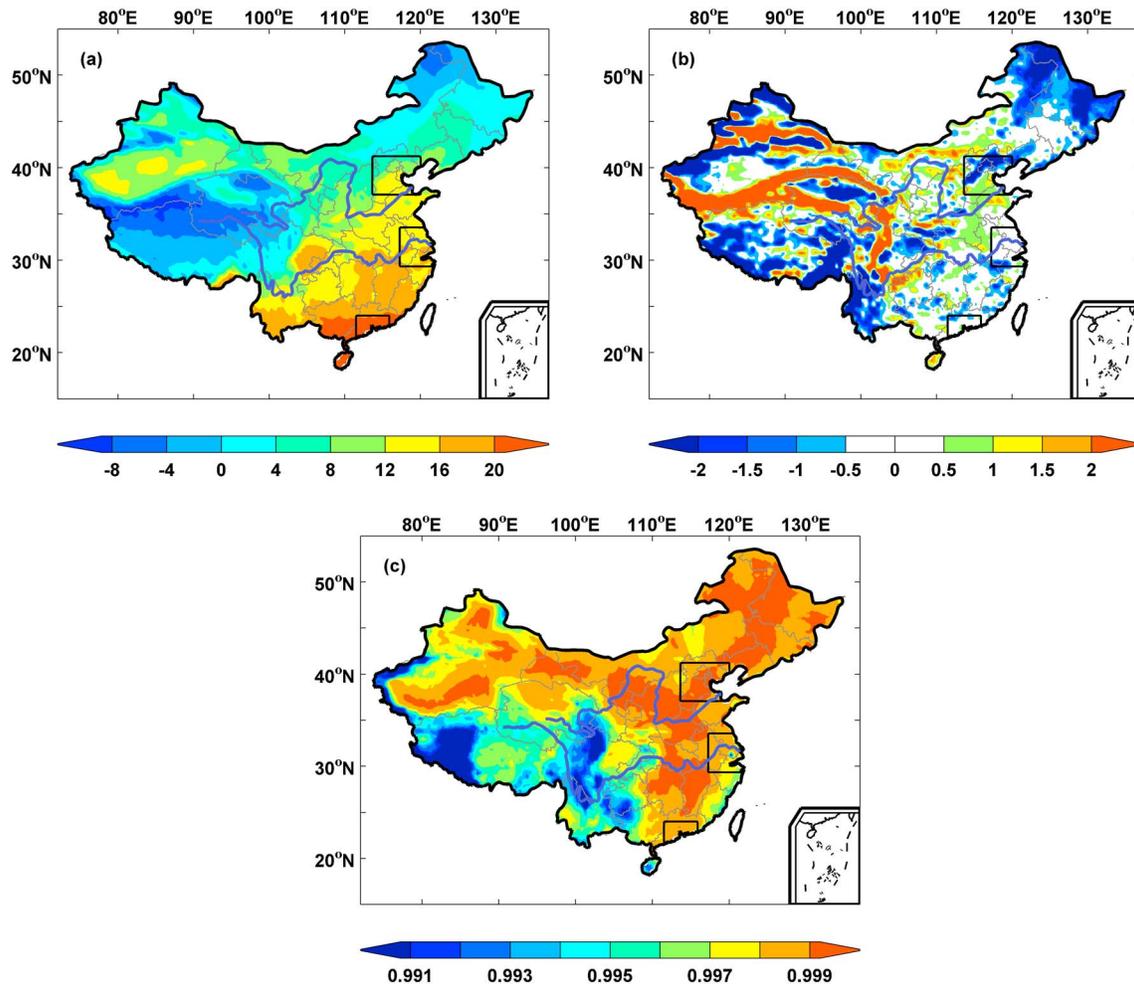
Figure 3. (a) Spatial patterns of the observed annual mean surface air temperature (unit: °C). (b) The difference between URB simulated and observed temperatures (units: °C). (c) The correlation coefficients between observed and URB simulated temperatures.

has been enhanced significantly by urbanization, particularly in the three extensive urban agglomerations in East China. In addition, North China has experienced more profound urban warming than South China.

Figure 5 illustrates the changes in regional average surface air temperatures (T_{mean}, T_{max}, and T_{min}) because of urbanization over the three extensive urban agglomerations analyzed here (BTH, YRD, and PRD) for 1980–2009. Sharp increases in urban heat islands appeared in the late 1990s, which coincide with the rapid urbanization occurring during those years. Table 2 shows the linear trends of annual and seasonal urban warming with the F test of regression showing that all of them were significant ($P < 0.01$) for the period of 1980–2009 in the three urban agglomerations. Urbanization enhanced the trends of T_{mean} over the three metropolitan regions, with the magnitudes of 0.13°C/30 yrs, 0.12°C/30 yrs, and 0.09°C/30 yrs (Table 2).

Jones et al. [2008] used a homogenized weather station-based data set and sea surface temperature data sets to assess the possible urban influence in the eastern part of the Chinese mainland. They found that urban-related warming over eastern China was about 0.1°C per decade for the period of 1951–2004 which is larger than our result. The reasons relevant to the difference may include the following: (1) their study period 1951–2004 is a longer period when compared with 1980–2009; and (2) they estimated the

Table 1. Mean Error and Root-Mean-Square Error Between Simulated Surface Air Temperature and Observed Values

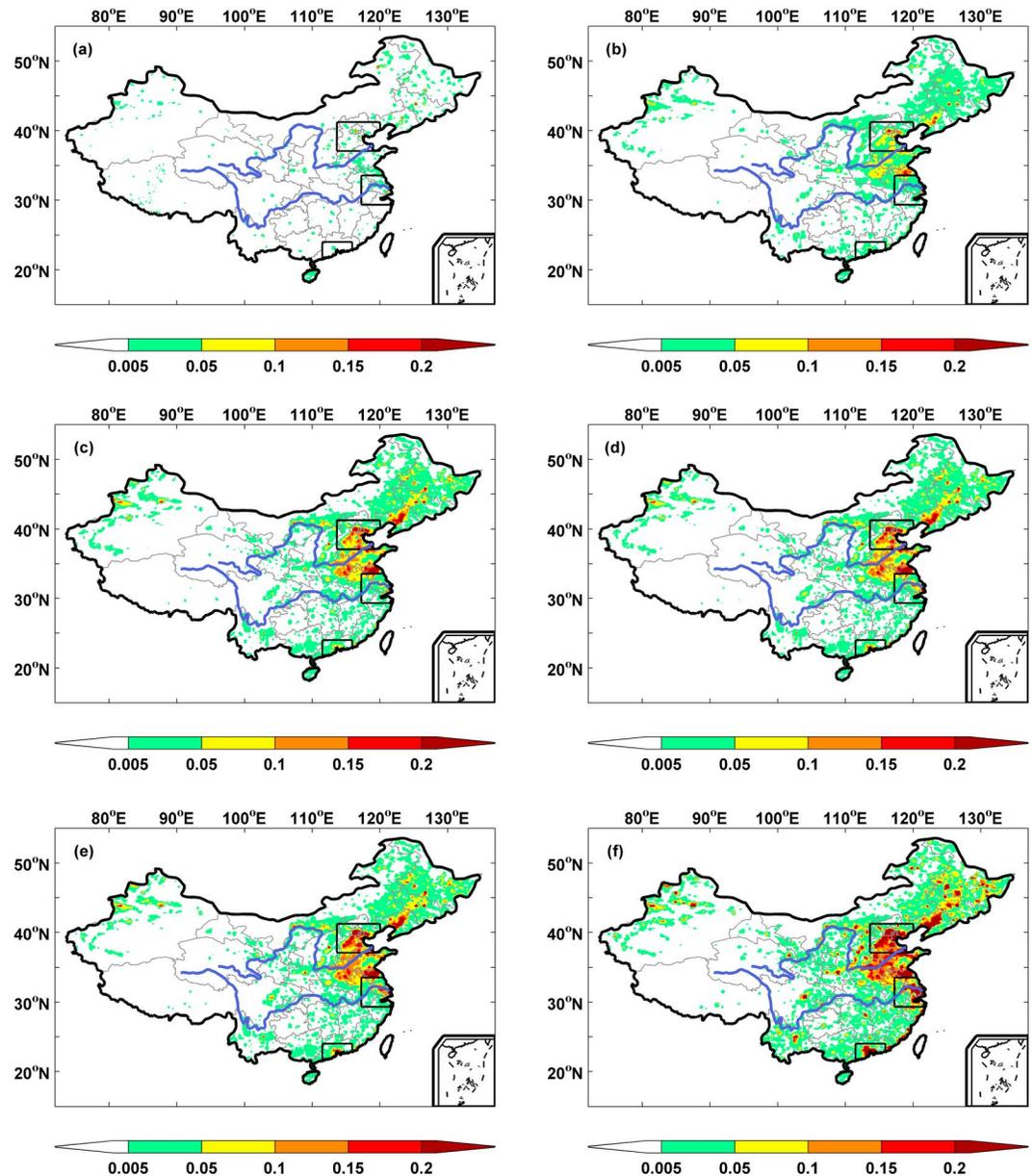|	Mean Error (°C)	Root-Mean-Square Error (°C)
BTH	−0.52	1.67
YRD	0.03	0.55
PRD	−0.06	0.57

Figure 4. Spatial distributions of annual mean temperature changes (units: °C) due to urbanization for the periods of (a) 1980–1984, (b) 1985–1989, (c) 1990–1994, (d) 1995–1999, (e) 2000–2004, and (f) 2005–2009.

effects of urbanization using the method of comparing land surface temperature with sea surface temperature. In addition to effects of urbanization, many factors may induce land-ocean differences, so the results deriving from the above method may be difficult to represent when analyzing the effects of urbanization alone. *Ren et al.* [2008] analyzed the effects of urbanization on surface air temperature trends using a data set of 282 meteorological stations in north China during 1961–2000; they found that urban warming is about 0.11°C per decade. *Wang et al.* [2013a] analyzed a homogenized data set of temperature observations in Greater Beijing to quantify the urbanization effect on changes in observed surface air temperature. They found that during 1978–2008, urban warming in Greater Beijing was 0.066°C per decade. Their value is larger than ours because their study region is Greater Beijing, an area that experienced one of the most rapid urbanization processes in China. *Zhou et al.* [2004] analyzed the effects of urbanization in southeast China and found that warming of the mean surface temperature by 0.05°C per decade could be attributed to urbanization. *Wu and Yang* [2013] analyzed the effects of urbanization on surface warming with homogeneity-
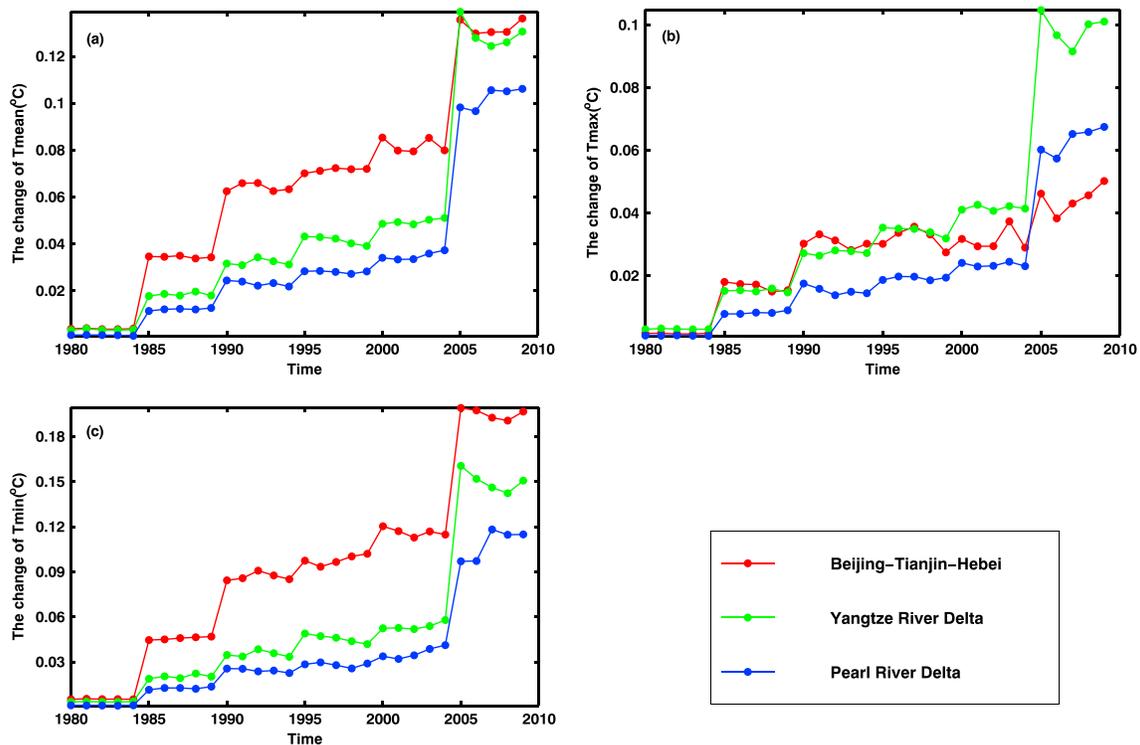
Figure 5. Changes in regional averaged annual mean surface air temperatures (unit: °C) due to urbanization over three vast urban agglomerations for the years of 1980–2009: (a) T_{mean}, (b) T_{max}, and (c) T_{min}.

adjusted surface air temperature data from eastern China. They estimated that the urbanization-induced annual mean temperature change was 0.057°C per decade in all of eastern China, a finding that was a little higher than our result. *Li et al.* [2004] used a homogenized annual mean surface air temperature data set to analyze the urban heat island effect on warming and found that the urban heat island effect enhanced the warming trends by about 0.011°C per decade in the Yangtze River Valley and South China during 1951–2001; this finding was lower when compared with our data, perhaps because of the different study periods and areas.

Studying the changes of T_{max} and T_{min} can help us understand the diurnal variation of the effects of urbanization. For all the three regions, urban-induced warming trends in T_{max} were evident but with much smaller magnitude than those of T_{mean} (Figure 5b). The largest urban warming trend in T_{max} occurred over the YRD (0.09°C/30 yrs), while this kind of trend over BTH was the smallest (0.04°C/30 yrs). The characteristics of interannual variations of urban-induced warming in T_{min} are similar to T_{mean} but with much larger magnitudes. Temperature trends enhanced by the urban warming over BTH, YRD, and PRD are 0.19°C/30 yrs, 0.14°C/30 yrs, and 0.10°C/30 yrs, respectively.

Table 2. Linear Trends of Annual and Seasonal Urban Warming for the Period of 1980–2009 (Unit: °C/30 yrs)

		BTH	YRD	PRD
T_{mean}	Annual	0.13	0.12	0.09
	Summer	0.11	0.11	0.05
	Winter	0.20	0.14	0.11
T_{max}	Annual	0.04	0.09	0.06
	Summer	0.08	0.11	0.05
	Winter	0.07	0.08	0.04
T_{min}	Annual	0.19	0.14	0.10
	Summer	0.14	0.11	0.04
	Winter	0.25	0.14	0.11

Table 3. Contributions of Urban Warming to Overall Warming for the Period of 1980–2009 (Unit: %)

		BTH	YRD	PRD
Warming contribution (T_{mean})	Annual	9.70	10.3	9.68
	Summer	12.1	18.0	31.3
	Winter	15.3	9.86	6.36

Hua et al. [2008] found that urban warming at large city stations in China for T_{min} during 1960–2000 was about 0.08°C/decade. *Wang et al.* [2013a] showed that urbanization-related warming at Greater Beijing for annual mean T_{min} was 0.105°C/decade during 1978–2008, which is a little higher than our results.

To evaluate the contribution of urbanization, we calculated the difference of the linear trends of temperature change between the URB and NOURB simulations and obtained the rate of warming (ΔT_{urb}) induced by urbanization. Meanwhile, a regional total warming rate (ΔT_{tot}) is obtained by calculating the linear trend of change in URB-simulated temperature. Thus, the ratio of ΔT_{urb} and ΔT_{tot} indicates the contribution of urbanization to the regional overall warming. Table 3 shows the contribution of urbanization to the overall
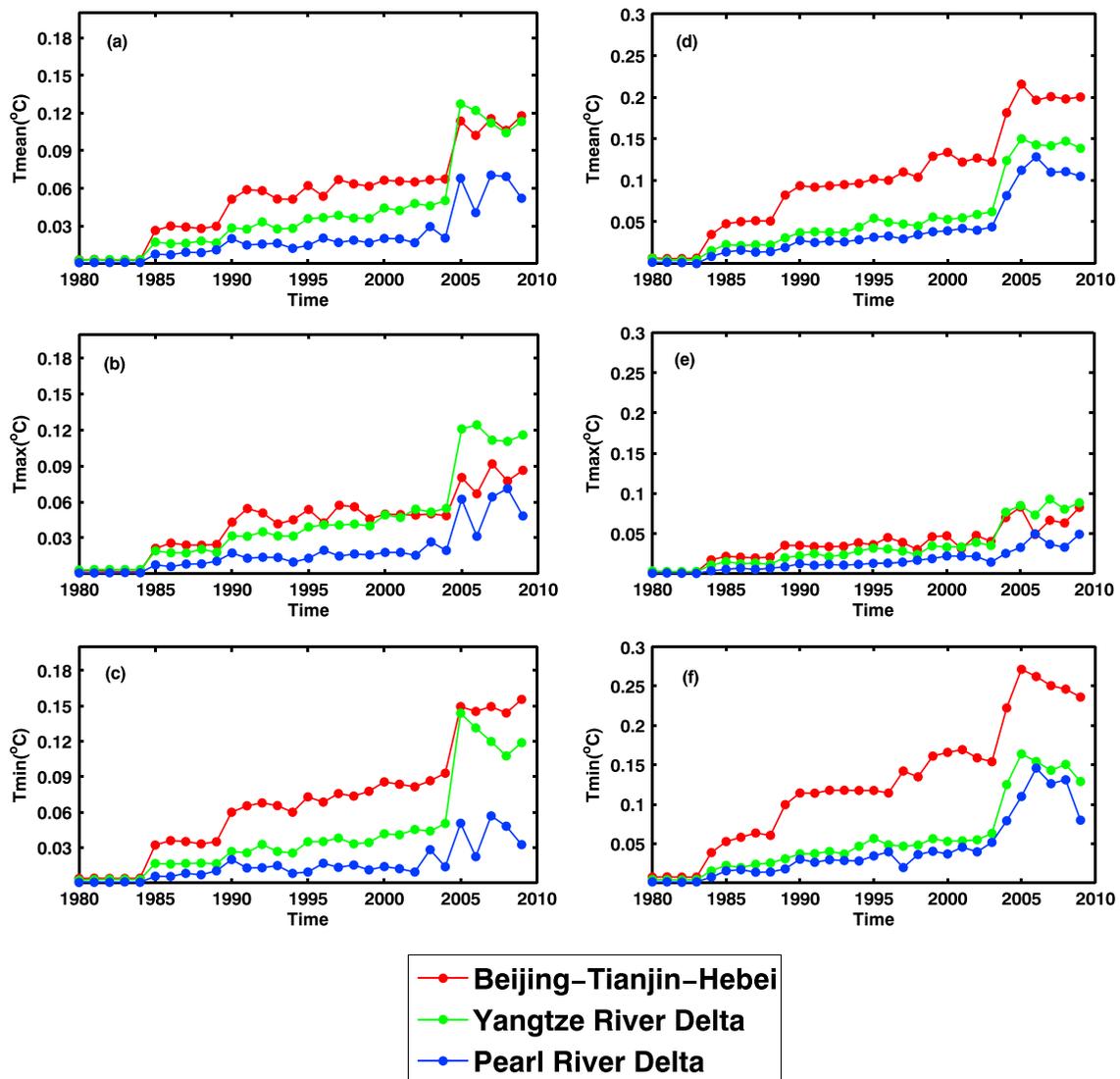

Figure 6. Changes in (left) summer and (right) winter regional averaged surface air temperatures (unit: °C) due to urbanization over three vast urban agglomerations for the years of 1980–2009: (a, d) for T_{mean}; (b, e) for T_{max}; and (c, f) for T_{min}.

Table 4. Linear Trends of Annual and Seasonal Warming of Regional Climate Background for the Period of 1980–2009 in Three Urban Agglomerations (Unit: °C/30 yrs)

		BTH	YRD	PRD
T_{mean}	Annual	1.34	1.16	0.94
	Summer	0.91	0.60	0.17
	Winter	1.31	1.41	1.73

temperature trends. In terms of annual mean, the highest contribution of urbanization was found in the YRD, reaching 10.3%. The ones over BTH and PRD share nearly the same magnitude (9.7%).

Wang et al. [2013a] estimated that the contribution of urbanization to the overall temperature trend in Greater Beijing was about 10.9%. *Wu and Yang* [2013] showed that urbanization-induced temperature change accounted for 11.4% of the total averaged warming in the region of eastern China. Their results are close to our estimate. *Ren et al*. [2008] estimated that the contribution of urban warming to the total temperature trend in north China reached 37.9% for the period of 1961–2000. Their value is larger than our result, perhaps for two reasons. One is the difference in study regions and study period. Another is the method used to classify the stations. However, defining rural or reference stations using different population standards may result in a large difference in the final result.

Urbanization-related warming also has strong seasonal variation. The changes in the summer and winter regional average surface air temperatures (T_{mean}, T_{max}, and T_{min}) were caused by urbanization over three extensive urban agglomerations during 1980–2009 (Figure 6). In terms of T_{mean}, the strongest effect of urbanization on the overall warming trend was in winter in BTH, reaching 0.20°C/30 yrs. The smallest urban warming trend occurred in summer in PRD. Overall, the urbanization effect on the changes in T_{mean} was more profound in winter. However, for T_{max}, the trends in summer T_{mean} related to urbanization were slightly larger than those in winter. As to T_{min}, the urban-induced warming was more remarkable in winter than in summer (Table 2). For T_{mean}, the largest urbanization contribution occurred in summer in the PRD (31.3%). The smallest urbanization contribution occurred in winter in the PRD (6.36%). BTH experienced a higher contribution in wintertime than summer. However, a higher contribution was also found in summer for the YRD and PRD (Table 3). This temporal-spatial difference of contribution of urban-related warming may be associated with the following reasons: First, the net
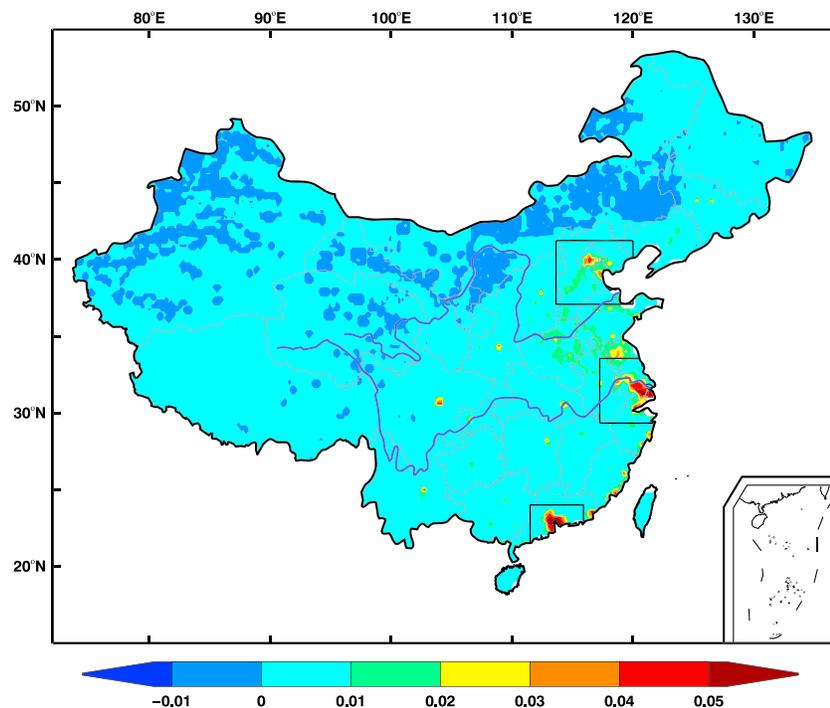

Figure 7. Spatial distribution of annual mean albedo change due to urbanization for the period of 2005–2009.
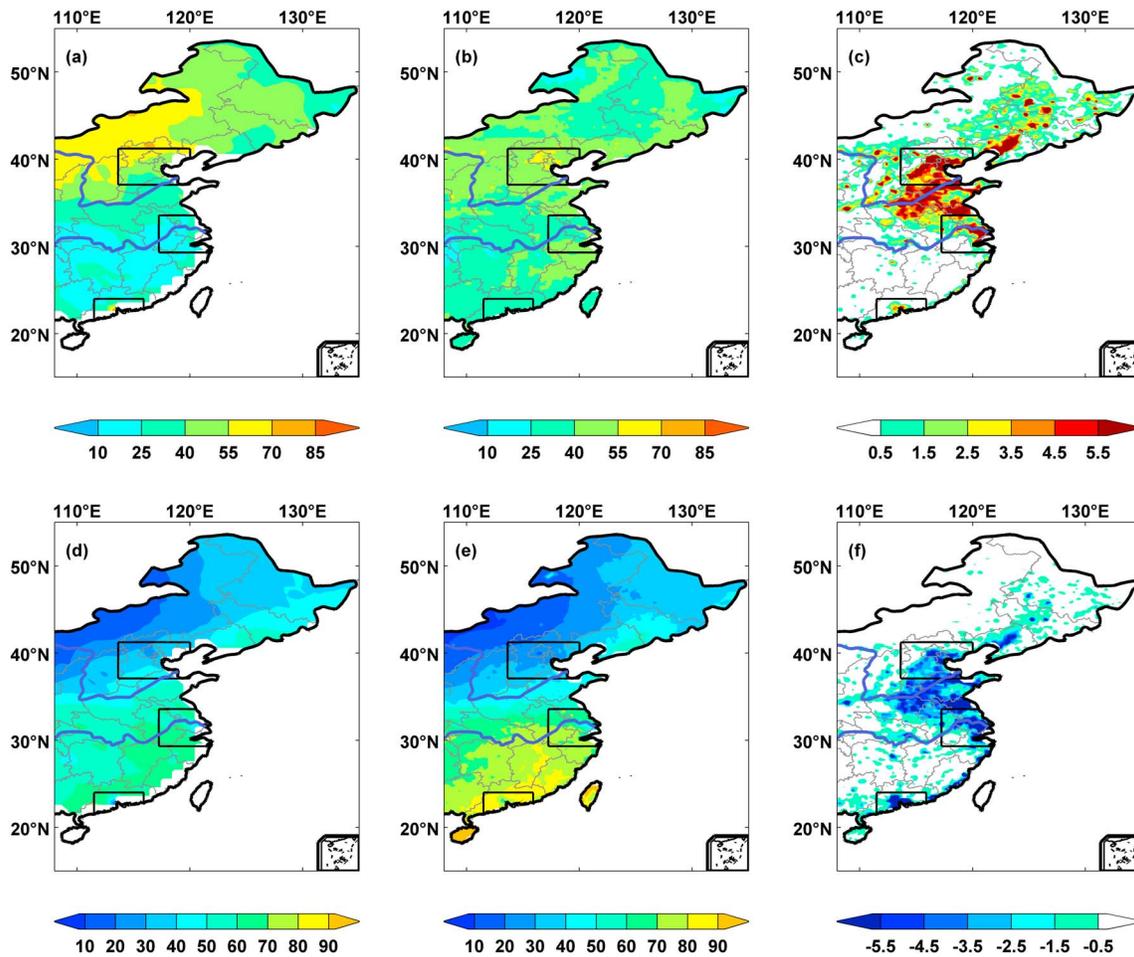
Figure 8. Spatial distributions of annual mean: (a) observed sensible heat flux; (b) simulated sensible heat flux; (c) changes of sensible heat flux due to urbanization; (d) observed latent heat flux; (e) simulated latent heat flux; (f) changes of latent heat flux due to urbanization for the period of 2005–2009 (unit: W m^{-2}).

radiation in north China is smaller than that in south China especially in winter, which induces the proportion of surface heat flux change due to urbanization corresponding to net radiation in BTH, which is larger than that in YRD and PRD, so the amplitude of the urban warming in BTH is larger in winter. Second, the change of regional climate background should be considered. Table 4 shows the linear trends of annual and seasonal warming of regional climate background for the period of 1980–2009 in three urban agglomerations. The mean surface temperature increase for BTH (0.91°C/30 yrs) is highly larger than that for YRD (0.60°C/30 yrs) and PRD (0.17°C/30 yrs) in summer; however, the condition in winter is converse that the mean surface temperature increase for BTH (1.31°C/30 yrs) is smaller compared with YRD (1.41°C/30 yrs) and PRD (1.73°C/30 yrs); the regional overall warming rate relatively smaller in BTH in winter and comparatively smaller in YRD and PRD in summer is another reason that makes higher contribution in winter for BTH and in summer for the other two regions.

Changes in land use patterns from natural land cover to urban may result in a change in surface parameters such as albedo and may also alter the surface energy balance. Figure 7 shows the change in the spatial distribution of annual mean albedo that was caused by urbanization for the period of 2005–2009. Urbanization resulted in an increased in albedo over the three agglomerations analyzed here; however, our findings were different from previous studies that showed that urbanization resulted in a decrease in albedo. We found that causes for the differences in albedo were mainly related to the urbanization parameter we used in CLM4.5. CLM4.5 allows for multiple urban density classes in the urban land unit, rather than a single-domain urban density class used in CLM4.0. Three urban classes [tall building district (TBD), and high density (HD) and medium density (MD)] were used in CLM4.5 and urban properties including radiation (e.g., emissivity and albedo) and morphological (e.g., height to width ratio, roof fraction, and average building height) parameters were defined uniquely for the three
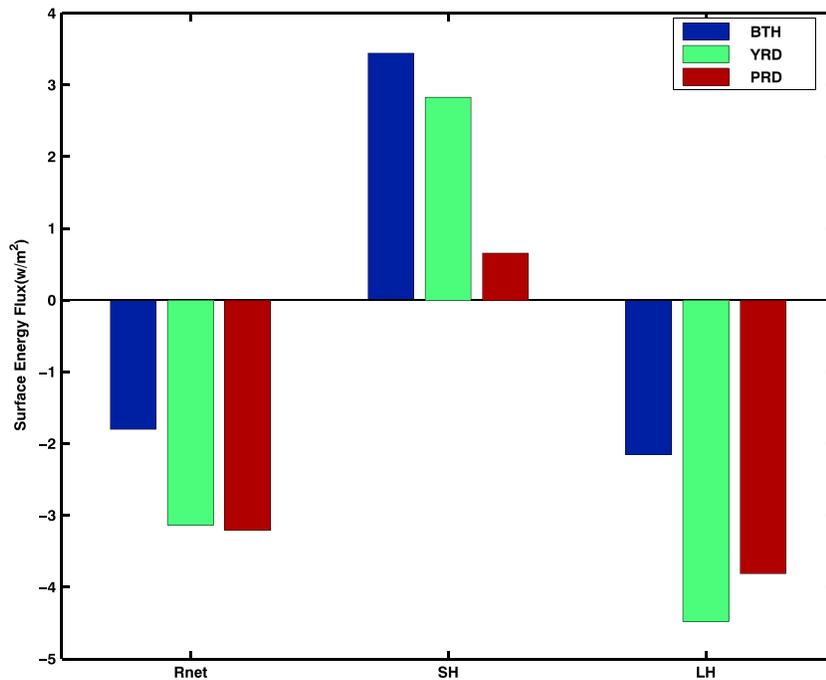
Figure 9. Changes in the surface energy fluxes (URB minus NOURB) in the three urban domains. R_{net}, net surface radiation; SH, sensible heat flux; LH, latent heat flux (unit: $W\,m^{-2}$).

classes. Because the high-quality land use data set (MLCD2.0) that included real land surface changes during the past several decades in China had only one urban class, we use all of these urban data as the fraction of HD in CLM4.5 and set the fraction of TBD and MD to zero in our experiments because we do not have other enough data to support the reclassification of urban data; meanwhile, HD is considered as a moderate class. Thus, in fact, the used urban parameters in the experiments are the relevant parameters of HD.

However, we found that the roof fraction in HD was the largest with the value of about 0.6 when compared with TBD (0.5) and MD (0.3) in CLM4.5; this was even larger than the roof fraction in CLM4.0 (MD in CLM4.5 is comparative to CLM4.0). In addition, roof albedo in HD was also the largest in three classes and also larger than CLM4.0. As we know, the mechanism of urbanization decreasing the albedo is the multiabsorption and multireflection of solar radiation by urban canyon (pervious and impervious road) and the relative lower albedo of the wall and the road. In our experiments, the use of HD class, the high roof fraction, and high roof albedo of HD in CLM4.5 make the simulated urban albedo higher compared to most past studies and also higher than in no-urban areas. Most of the previous studies showed that the decrease of albedo and latent heat flux and the increase of sensible heat flux in urbanized area are the main factors of urban warming. Our simulation result indicated that urbanization does not always decrease the albedo, and the change of albedo does not play the dominant role in the urban heat island effect. Likely, some results of numerical simulation could be affected by the setup of the parameters, but the essence and main characteristics of urban heat island effect would not be changed.

Surface heat flux such as latent heat flux and sensible heat flux may strongly influence surface air temperatures. Therefore, understanding how the process of urbanization modified the surface heat flux is helpful. Figures 8a and 8b (8d and 8e) show the spatial distribution of observed and simulated annual mean sensible (and latent) heat flux in eastern China, respectively. The CLM4.5 model generally reproduced the spatial distribution of observed annual mean surface heat flux quite well although a little overestimation occurred in some areas of southeast China. Figures 8c and 8f show the changes of sensible flux and latent heat flux caused by urbanization for 2005–2009, respectively. The sensible heat flux has obviously been enhanced by urbanization, especially in the three extensive urban agglomerations in East China. Urbanization led to a significant decrease in latent heat flux in the three extensive urban agglomerations in East China.

Figure 9 shows the changes in surface energy fluxes caused by urbanization in the three urban domains analyzed here. The underlying surface changes from other land use types to urban lead an increase in sensible heat flux
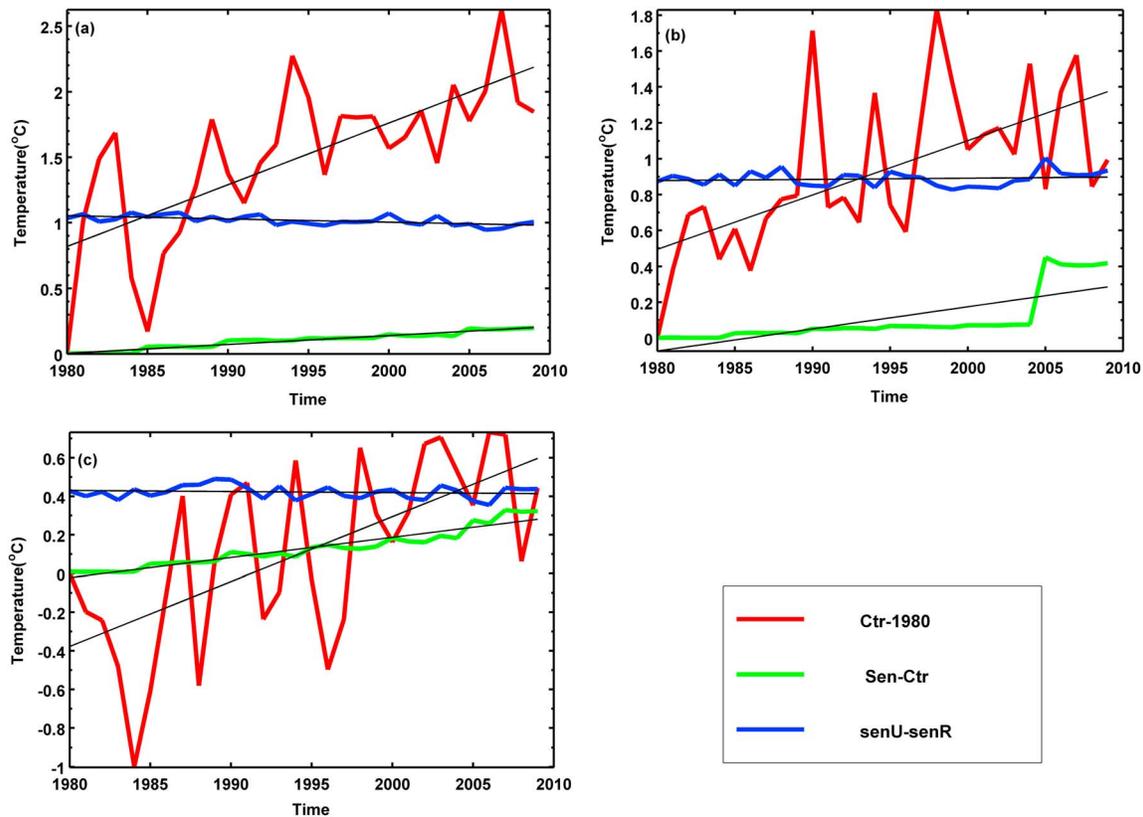
Figure 10. Temporal variations of annual mean temperature (unit: °C) in (a) Beijing, (b) Shanghai, and (c) Guangzhou. The red line represents the temperature anomalies simulated by NOURB run, the green line stands for the temperature differences between URB and NOURB runs, the blue line represents the temperature difference between urban and its corresponding rural patches in the grid cells of URB run, and the black line denotes its corresponding linear trend for 1980–2009.

and a decrease in latent heat flux. In our study, the urbanization also made the net surface radiation decrease. Previous studies showed that the albedo decrease in urbanized area is a cause for urban warming. However, the urban parameter including high roof fraction and high roof albedo used for HD urban class in CLM4.5 made our simulation of albedo increase in urbanized area, which indicated that the decrease of albedo does not play the dominant role in urban heat island effect. In fact, the processes of urbanization make the underlying surface change from the vegetation to waterproof surface which is mostly made up of cement. Therefore, urbanization processes make the available surface soil moisture low, and this impacts the heat flux partitions in urbanized areas, inducing an increase in sensible heat flux and a decrease in latent heat flux. The urbanized areas become drier with the partitioning of sensible heat flux and latent heat flux, which play a dominant role in daytime urban heat island effect. Meanwhile, urban areas have larger heat storage capacity and greater heat transport to build interiors or deep soil, which can be released at night to heat the surface atmosphere. It is an important cause of the nocturnal urban heat island effect.

3.3. Urbanization Effect on Temperature Trends in Representative Cities

To further calculate the contributions of local urban warming to changes in temperature in some representative cities of the three urban agglomerations analyzed here, we selected the temperature time series over the model grids that included cities of Beijing, Shanghai, and Guangzhou. Figure 10 displays the temporal variations of

Table 5. Contributions of Urban Warming to Overall Warming in Representative Cities for the Period of 1980–2009 (Unit: %)

		Beijing	Shanghai	Guangzhou
Warming contribution (T_{mean})	Annual	12.7	29.0	23.6
	Summer	13.4	41.1	10.3
	Winter	22.1	27.2	19.8

annual mean temperature simulated by NOURB, between the URB and NOURB runs, and between the urban and rural areas over the grid in the URB run. Temperature differences between URB and NOURB runs show increasing trends for the period of 1980–2009. However, a slightly decreasing trend can be found in temperature differences between the urban and rural areas over the grid in the URB run, which may be related to more significant changes in evaporation in rural areas that are caused by global warming.

Temperature trends enhanced by urbanization were about 0.2°C/30 yrs, 0.36°C/30 yrs, and 0.30°C/30 yrs in Beijing, Shanghai, and Guangzhou, respectively. *Hua et al.* [2008] investigated the warming effect caused by urbanization based on a daily temperature data set in China and found that significant urban warming at large city stations was about 0.05°C/decade. The present urban warming values for the three cities analyzed here were greater; this may be related to the period of 1980–2009 in our study, a period that witnessed more significant urbanization than the period of 1961–2000 and their method of defining urban and rural sites. Table 5 gives the contribution of urbanization to overall warming in Beijing, Shanghai, and Guangzhou for 1980–2009. In terms of T_{mean}, the contribution of urban warming reached 12.7%, 29.0%, and 23.6% for Beijing, Shanghai, and Guangzhou, respectively. *Wang et al.* [2013a] applied the homogenized SAT data set to quantify the effects of urbanization on observed temperature trends and extremes in Greater Beijing for 1978–2008. They suggested that the contribution of urbanization to overall warming in Greater Beijing was 10.9%, which is consistent with our results.

4. Conclusion and Discussion

In this study, a CLM4.5 model in an off-line mode was employed to quantify the degree to which historical urbanization has imposed effects by changing regional temperatures. Based on the simulation results from two cases with typical urbanization patterns as observed in China, we investigated the urbanization-induced temperature trends and their contribution to the overall warming in three areas of extensive urban agglomeration in China.

The simulated effect of urbanization on the annual mean trends in T_{mean} was 0.09–0.13°C/30 yrs and accounted for about 10% of the overall warming in the three metropolitan regions analyzed here. Urbanization had a smaller effect on the trends of T_{max} (0.04–0.09°C/30 yrs) than those of T_{min} (0.10–0.19°C/30 yrs). Urbanization had a larger effect on trends of T_{mean} and T_{min} in winter than in summer. However, the situation was reversed for T_{max}. The greater contribution of urbanization-induced T_{mean} warming was found in winter for BTH and in summer for PRD or YRD. Specifically, in terms of the annual mean surface air temperature, the contributions of urbanization to overall warming in Beijing, Shanghai, and Guangzhou were 12.7%, 29.0%, and 23.6%, respectively. Many researchers have used traditional observational analysis methods to investigate the effects of urbanization. *Wang et al.* [2013a] estimated the urban-related warming in Greater Beijing at about 0.105°C/decade for T_{min} and 0.066°C/decade for T_{mean} which accounted for about 10.9% to the overall warming trend for the period of 1978–2008. As discussed above, the criteria for defining urban and rural stations, station network density, the regional extent, and so on could affect the final results when using traditional observational analysis methods to analyze the effect of urbanization. In addition, causes for the differences found between these previous studies and our results are likely to be related to variations in the analytical methods, study time periods, and analytical regional extent employed.

The estimation of the effects of urbanization on the changes in local temperatures continues to be a complex topic. Aside from urban land use, anthropogenic heat and aerosols released into the urban canopy may also contribute to the effects of urbanization.

Our study focuses on temperature differences between urban and nonurban scenarios. As both NOURB and URB experiments are forced by the same atmospheric data, that is, when there is no two-way coupling between the atmosphere and land surface, it is likely that the simulated results underestimated urban warming. Meanwhile, the urban signal has been somewhat contained in the actual atmospheric forcing data. Actually, estimating the urban warming trends with the CLM4.5 model in a stand-alone mode is a compromising way, since high-resolution long-term simulations with fully coupled model are seriously restricted by the limitation of computation resources. We have compared our simulation results with some observational results and demonstrated that maybe the urban warming was underestimated by the simulated result; but, likely, the amplitude of underestimation is not very large. In addition, some studies have also employed the land model in the off-line way to estimate the effects of historical urbanization. *Hamdi et al.* [2009] studied the effects of historical urbanization in

Brussels Capital Region; they also selected to run the land surface model in a stand-alone mode forced by ECMWF reanalysis data to be able to run the model over a very long period without any computational cost restrictions. In fact, the regional climate model, which is one-way driven by GCM or Reanalysis data (no feedback from RCM to GCM), also has a similar circumstance. Therefore, although some limitations exist in our simulation, the present results for three extensive urban agglomerations still have the important value and will provide some basic findings, which may serve as a reference for future studies using relevant methods.

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