Sensitivity experiments of impacts of large-scale urbanization in East China on East Asian winter monsoon

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By using the global atmospheric general circulation model CAM4.0 including an urban canopy parameterization scheme, the possible impacts of large-scale urbanization in East China on East Asian winter monsoon was investigated via idealized numerical experiments. Results suggest that large-scale urbanization can cause a significant warming effect in both surface temperature and air temperature near the surface over most areas of East China. Meanwhile, large-scale urbanization also alters the surface energy balance, causing evident increases in net surface long-wave radiation and sensible heat flux as well as intensified surface thermal heating to the atmosphere. Forced by the surface thermal heating anomalies induced by the large-scale urban expansion, East Asian winter monsoon circulation exhibits distinct changes. Overall, the extensive urbanization over East China will weaken East Asian winter monsoon, but intensify winter monsoon in northeast China.

large-scale urbanization, East Asian winter monsoon, sensitivity experiment

Land use/land cover change (LULCC) as well as its impacts on climate have received more and more attention during past decades. IPCC AR4 report [1] states that LULCC can affect climate not only at local/regional scales but also at large scales through adjustments in atmospheric general circulation. Studies demonstrated that large-scale LULCC can produce noticeable impacts on the monsoon circulation [2–5]. Several other studies suggest that changes of vegetation coverage can also exert great impacts on climate in China [6–10].

As an extreme case of LULCC, urbanization can affect both the atmospheric circulation and climate at local to regional scales [11–14]. The climatic effect of urbanization attributes to dramatic changes in land surface boundary conditions from natural surfaces to manmade urban areas, which tend to produce the so-called "urban heat island (UHI)" phenomenon as proposed by Howard [15]. In general, UHI is most visible in winter [16], and several recent studies pointed out that the anthropogenic heating plays an important role on the formation of UHI in winter [17–19]. Studies further indicated that the UHI intensity tends to be enhanced under the control of anti-cyclonic circulation [20–25].

Zhou et al. [26] reported a significant urbanization effect in southeast China based on the observational analysis. Previous studies have been focused primarily on the local and regional impacts of urbanization, while impacts of large-scale urbanization have received very limited attention. It is generally agreed that urban effects are mainly local and thus have a negligible impact on climate at the global scale. However, the rapid expansion of urban areas in East China is unprecedented in spatial extent and intensity and is expected to modify regional land surface properties dramatically, especially the surface thermal forcing to the atmos-

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phere, at much larger spatial scales than any regions in the world. The question is, will such changes affect the regional general circulation and climate? Answering this scientific question is of great importance with significant societal and economic implications in China. It is well known that China is located in the East Asian monsoon area and the land-sea thermal contrast is a key factor in the formation of the monsoon system. To what extent can the large-scale urbanization over this region alter the land surface thermal forcing, and thus influence the monsoon system? As there are no robust methods to address this question using observations, this study aims to explore the potential impacts of large-scale urbanization on the monsoon system based on idealized numerical sensitivity experiments. As winter usually has stronger UHI than other seasons and the global climate models demonstrate better performance in simulating winter climate [27,28], only the impacts of large-scale urbanization on winter monsoon and climate are investigated in this study.

1 Model and experiment design

1.1 Model

The global atmospheric general circulation model of the National Center of Atmospheric Research (NCAR) Community Atmosphere Model Version 4.0 (CAM4.0) [29] was used in the current study. CAM4.0 is a component model of the Community Earth System Model (CESM) and can be run in two modes. First, it can be run together with the land surface model (Community Land Model Version 4.0, CLM4.0), the Ocean model (POP2) and the Sea Ice model (CICE4). Second, it can be also run with the land surface model, the sea ice thermal-dynamic model (CICE) and the data ocean model (DOCN) with observational sea surface temperature (SST) and sea ice prescribed as the lower boundary conditions. The second mode is selected in our study.

Currently, a medium-complexity urban canopy model (UCM) [30,31] has been incorporated into CLM4.0. Model parameters of UCM can be categorized into urban spatial parameters, urban morphological parameters and thermal and radiative properties of roofs/walls/roads. The basic features of the urban canopy can be described by 28 model parameters and the relevant processes within the urban canopy are also described by UCM, which make CLM4.0 suitable for the urban related studies. According to population, culture as well as social morphology, the global land has been divided into 33 sub-areas, and the same model parameters are used specifically in each individual urban area. The model has been successfully used in previous studies For example, Oleson [32] used the model to investigate the future responses of the urban and rural climate to different climate change scenarios in the Coupled Model Inter-comparison Project Phase 5 (CMIP5), and Oleson et al.

[33] suggested that the model provides an effective tool to simulate the urban effect.

1.2 Experimental design

Two 25-year integration experiments are carried out to explore the possible impacts of large-scale urban expansion in East China on East Asian winter monsoon and the climate in China. The Eulian dynamical core was selected in our experiments and the model was run with T42 horizontal resolution and 26 levels in the vertical direction.

(1) Control run (CTL): Default land cover type and parameters are used. The climatology of monthly SST is prescribed. The model runs from January 1st and continuously is integrated for 25 model years.

(2) Sensitivity experiment (PCT50): Same as CTL run except that the percentage of the urban area in each model grid box in our target area has been increased to 50% while the default vegetation coverage has been decreased proportionally for each vegetation type. At the same time, the anthropogenic heating has been taken into consideration in this experiment. Figure 1 shows the target domain where the model parameters have been modified.

The last 20-year model results simulated by the two experiments are compared to quantify the possible impacts of large-scale urbanization. All results discussed below represent the differences between PCT50 and CTL (PCT50 minus CTL) in the 20-year averaged meteorological variables in winter.

2 Results

2.1 Control run

Firstly, simulation results of CTL run are compared with NCEP/NCAR reanalysis to evaluate the model performance
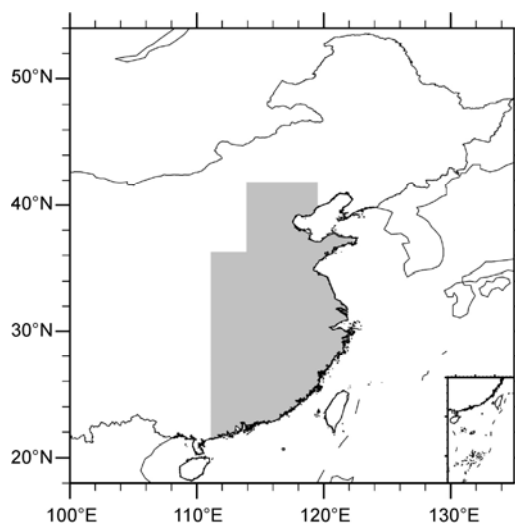

Figure 1 Target domain (shaded area) where the model parameters have been modified in PCT50 run.

in simulating climate over East Asia. Figure 2(a1)–(a2) shows the 2 m air temperature. On the whole, the model results agree very well with the reanalysis in the mid-low latitudes over this region, but underestimate the temperatures in the high latitude areas, where cold biases are found in the model simulated 2 m air temperature. The spatial correlation coefficient between the simulated 2 m temperature and the reanalysis is 0.993 (statistically significant at the 1% level) and the root-mean-squared error (RMSE) is 3.067°C. Figure 2(b1)–(b2) shows that the model successfully reproduces the observational features of the atmospheric general circulation (wind field and geopotential height) at 850 hPa over East Asia; the spatial correlation coefficient between the simulated 850 hPa geopotential height and the reanalysis is 0.989 (statistically significant at the 1% level) and the root-mean-square error is 21.91 gpm. Overall, CAM3.1 is able to capture the basic features of winter atmospheric general circulation and temperature over East Asia, which provides the basis for the sensitivity study.

2.2 Sensitivity run

As the focus of this study is the possible effects of large-scale urbanization on climate and the monsoon circulation over East Asia, the East Asian monsoon area is selected as our study region and possible responses of temperature, surface energy flux, geopotentail height and wind field are discussed in this section.

Previous studies show that albedo is usually lower in urban areas, which causes the land surface to absorb more solar radiation. Meanwhile, urban has larger heat storage capacity than the natural land surface. The anthropogenic heating tends to warm the urban areas significantly, resulting in evident UHI effects and hence completely different thermal states from the natural land surface. Figure 3 shows the difference (PCT50 minus CTL) in surface temperature and air temperature near the surface, which can be used to quantify the possible climatic impacts of large-scale urbanization. Large-scale urbanization increases the surface temperature significantly, especially over those regions with
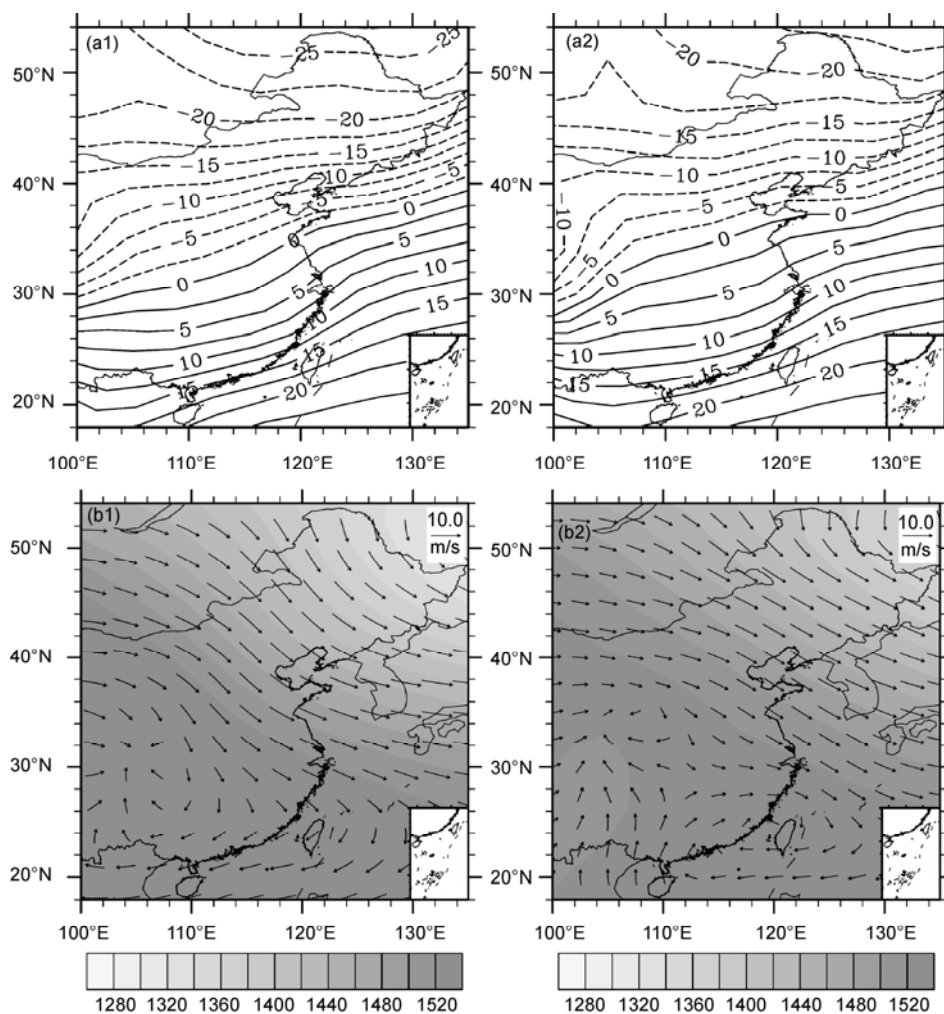
Figure 2 Comparison of simulated results in CTL run and NCEP reanalysis: (a1) and (a2) 2 m air temperature (°C); (b1) and (b2) 850 hPa geopotential height and wind field (the shaded area represents the geopotential height in gpm, and the vector is wind field in m/s). "1" represents the control run and "2" the NCEP reanalysis.
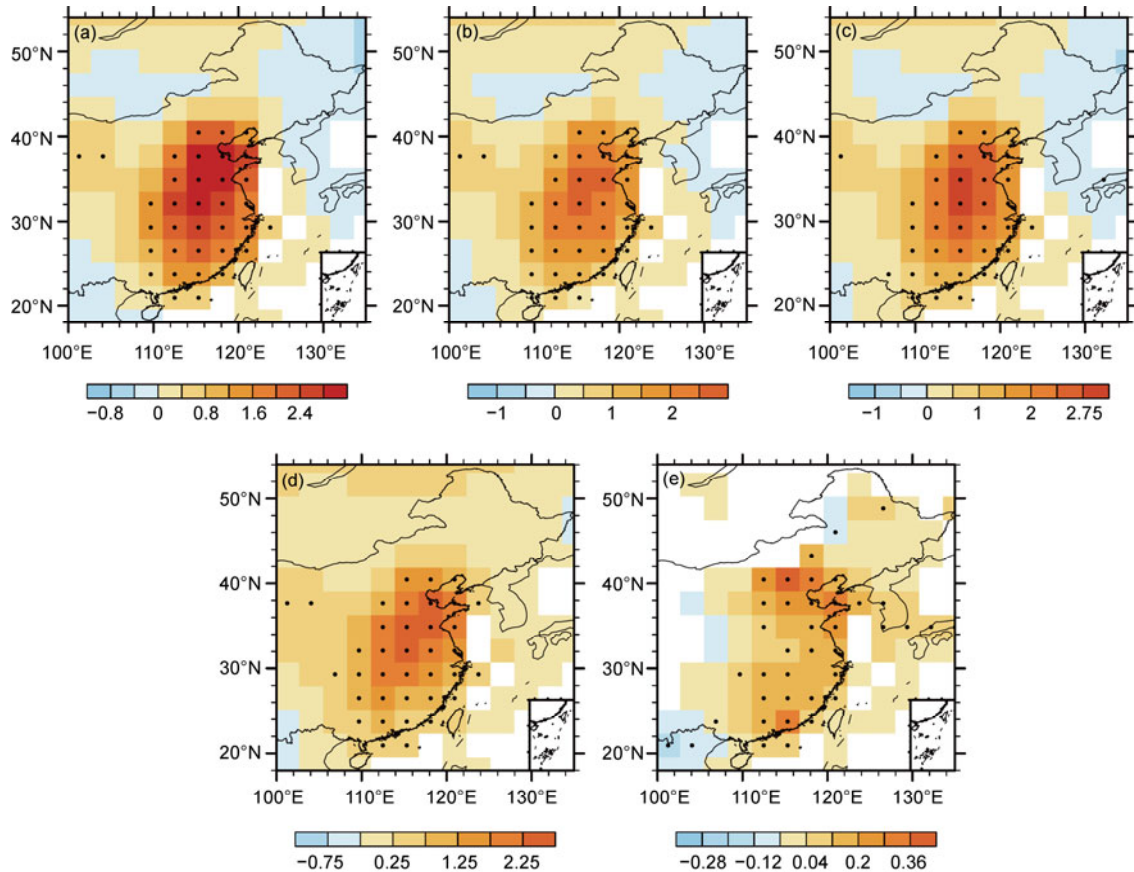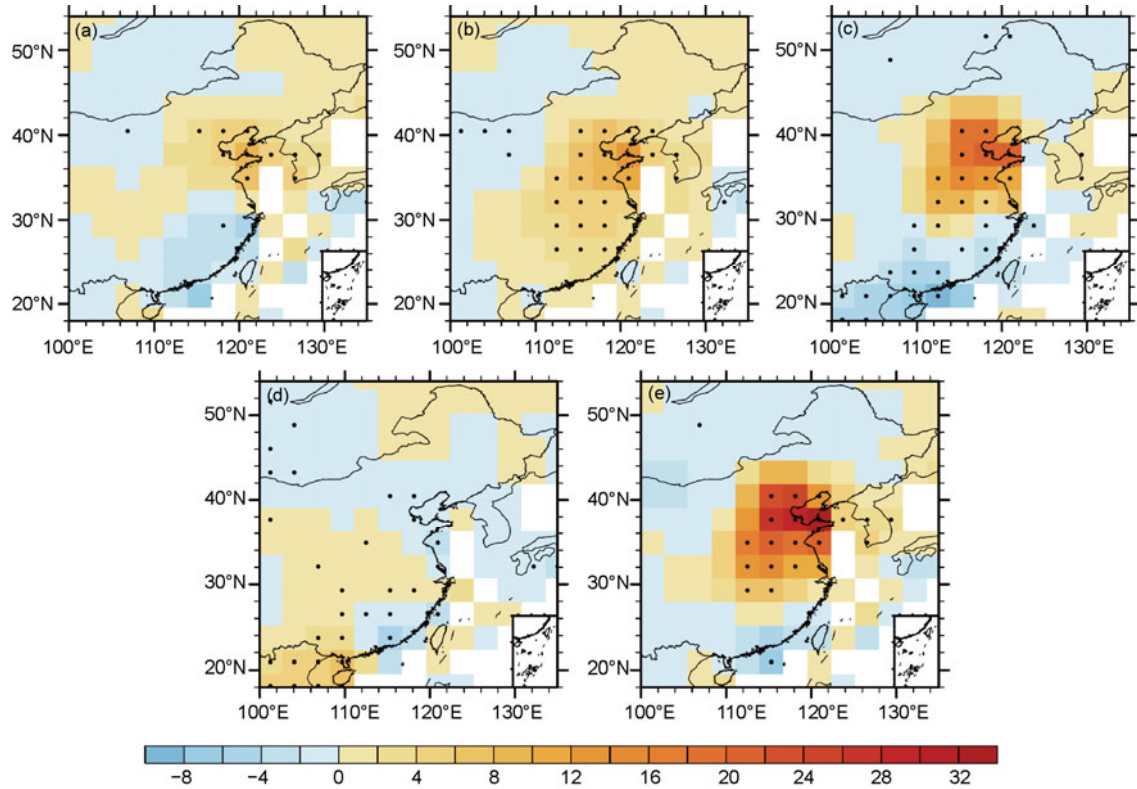
Figure 3 Geographic distribution of differences (PCT50 minus CTL run) in winter (a) surface temperature, (b) 2 m air temperature, (c) daily minimum 2 m air temperature, (d) daily maximum 2 m air temperature and (e) urban heat island intensity in °C. The dot-shaded areas indicate that the differences are statistically significant at the 10% level.

modified land surface parameters in the model, with a warming effect generally above 1°C and the maximum of about 3°C (Figure 3(a)). It also increases the air temperature near the surface. For example, 2 m average air temperature, maximum air temperature and minimum air temperature all rise to some extent. It is noted that the spatial patterns of the differences in those variables are similar to those of the surface temperature (Figure 3(b)–(d)). Overall, the increases in daily minimum temperatures over urban areas are evidently larger than those of daily maximum temperatures. To further quantify the UHI effect, the urban-rural temperature difference is estimated and its difference (PCT50 minus CTL) is shown in Figure 3(e). Clearly, winter UHI over East China intensifies significantly under the large-scale urbanization case, and the amplitude of UHI has reached up to 0.36°C.

Large-scale urbanization alters not only the surface temperature but also the surface energy balance (Figure 4). Compared to the natural land surface, the different components of the surface energy budget as well as the thermal forcing to the atmosphere have been significantly changed under the urbanization case. On the whole, urban expansion tends to increase net short-wave radiation absorbed by the land surface, the net long-wave radiation to the atmosphere

(positive toward the atmosphere) and surface sensible heat, but decrease the surface latent heat slightly. Among all the components of the surface energy budget, the changes in sensible heat are most significant while the changes in net long-wave radiation, short-wave radiation and latent heat are relatively small. Pronounced increases in net long-wave radiation and surface sensible heat flux over urban areas are the dominant features. The maximum increase of sensible heat reaches 20 W/m^2, and the maximum increase in net long-wave radiation is also more than 10 W/m^2 (Figure 4(b), (c)). In contrast, no apparent changes are found in the surface net short-wave radiation and latent heat flux. It is noted that the surface heating to the atmosphere enchances significantly with a maximum of 30 W/m^2 (Figure 4(e)). In summary, large-scale urbanization leads to increased surface sensible heat and net long-wave radiation, resulting in enhanced surface thermal heating to the atmosphere. The thermal forcing induced by large-scale urbanization may be responsible for the anomalous general circulation.

Figure 5 show the differences (PCT50 minus CTL) in the geopotential heights at various pressure levels, reflecting the main features of the response of winter atmospheric general circulation to the anomalous thermal forcing induced by large-scale urbanization. Large-scale urbanization evidently

Figure 4 Geographic distribution of simulated differences (PCT50 run minus CTL run) in winter (a) surface net short-wave radiation, (b) net long-wave radiation from the surface to the atmosphere, (c) surface sensible heat flux, (d) latent heat flux and surface heating to the atmosphere in W/m^2. The dot-shaded areas indicate that the differences are statistically significant at the 10% level.
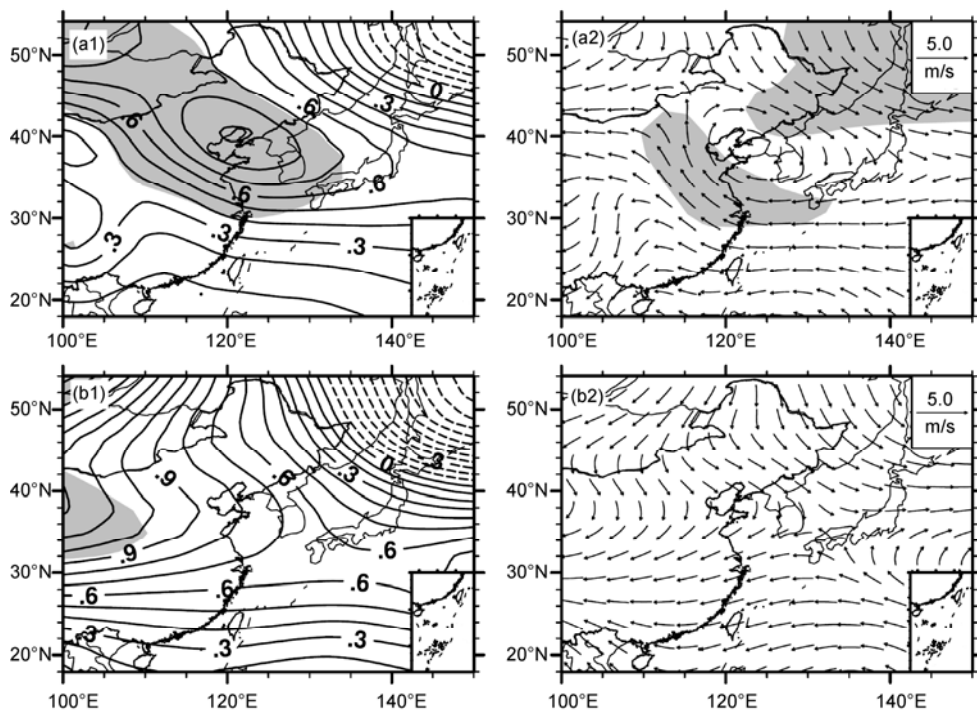
Figure 5 Differences (PCT50 minus CTL) in DJF (a1) 850 hPa, (a2) 500 hPa geopotential height in dagpm and (a2) 850 hPa, (b2) 500 hPa wind field in m/s. The shaded areas indicate that the differences are statistically significant at the 1% level.

changes the atmospheric circulation over most areas in East Asia. Similar responses of winter geopotential height over East Asia to the surface thermal forcing have also been found in both lower level (850 hPa) and upper level (200 hPa, Figure not given) of the atmosphere. Corresponding to the urban thermal forcing, geopotential heights uplift over most areas of East China. Significant positive anomalies of the geopotential height appear over a belt region extending from the Bohai Bay, across North China, to Mongolia. Notable negative anomalies appear in the downstream area. Similar patterns of the anomalous general circulation are also found at lower (850 hPa), middle (500 hPa) and high (200 hPa, figure not given) levels of the atmosphere. An evidently closed center of the geopotential height anomalies at lower levels is found near the Bohai Bay, which is located to the north-east of the anomalous heating region. It is also noted that the structure of atmospheric response to the anomalous surface thermal forcing has a weak baroclinicity, and significant anomalies of the geopotential height over East Asia become weaker and slanted westward with increasing height. The uplifted geopotential height over most areas of the East Asia can be explained as the direct response to the surface thermal forcing induced by the urbanization, and as a result of the atmospheric adjustment, the geopotential height drops in the downstream area.

To further understand the response of the winter monsoon circulation to the urbanization, the differences of wind fields at various levels between PCT50 and CTL experiments are examined. Corresponding to the spatial patterns of the geopotential height anomalies, lower level wind at 850 hPa has significantly changed in the case of urbanization. Southerly wind anomalies are clearly seen over east China (110°–120°E), with apparent anti-cyclonic (cyclonic) circulation anomalies located in its northeast (southwestern) areas. Accompanied with the southerly wind anomalies over most areas of East China, northerly wind anomalies appear over Northeast China. In contrast, upper level wind anomalies are characterized by the anomalous northerly wind over an extensive region north of 35°N but the anomalous easterly wind in southern areas of 35°N , both of them, however, are relatively weak. In summary, large-scale urbanization over East China tends to weaken the winter monsoon on the whole, but intensify the winter monsoon in Northeast China with clearly enchanced northerly wind. It is also noted that the urban effects on winter atmospheric general circulation mainly happens in the mid to lower levels of the atmosphere.

3   Conclusion and discussion

Based on idealized numerical experiments with NCAR CAM4.0, possible impacts of large-scale urbanization in East China on East Asian winter Monsoon are investigated in this study. Results show:

(1) In the large-scale urbanization case, significant warming happens over most urban expansion areas with an increase up to 3°C in surface temperature and around 2.5°C in surface air temperature. Both winter averaged daily minimum and maximum air temperatures increase significantly over those regions, with a much larger magnitude in the minimum temperature than the maximum temperature. Meanwhile, the average urban-rural temperature difference also rises to by 0.36°C.

(2) The surface energy balance is altered significantly under the influence of large-scale urbanization. The surface sensible heat flux and net long-wave radiation from the surface to the atmosphere are both increased while increase in the net short-wave radiation and decrease in the latent heat flux are relatively small. Such changes modify the surface energy budget and lead to a thermal heating forcing from the surface to the atmosphere.

(3) Changes in the surface energy budget and the abnormal surface thermal heating can produce evident influence on East Asian winter monsoon. The large-scale urbanization in East China tends to weaken winter monsoon on the whole, but intensify the winter monsoon in the Northeast China accompanied by evidently enchanced northerly wind anomalies. It is also noted that the urban effects on winter atmospheric general circulation mainly happens in the mid to lower levels of the atmosphere.

we explored the possible impacts of large-scale urbanization on the atmospheric general circulation and climate in China and found significant responses of the atmosphere to the urbanization, which can provide some clues for better understanding of the urbanization effect on climate and related physical mechanisms. However, it is difficult to quantify the impacts of realistic urbanization via idealized numerical experiments with an extreme urban expansion scenario. So it is still not clear that to what extent that large-scale urbanization will affect large-scale atmospheric general circulation and climate. Therefore, it is necessary to perform further investigation using more realistic urbanization scenarios with high-resolution regional climate models. In addition, we only focus on the impacts due to the changes in surface physical conditions related to urbanization but ignore the likely impacts related to the urban aerosol emission. Both should be considered in the future research in order to better understand the complete impacts of the large-scale urbanization.

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