

# Impacts of urbanization on future climate in China

Liang Chen<sup>1,2</sup> · Oliver W. Frauenfeld<sup>1</sup>

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**Abstract** Urbanization plays an important role in human-induced climate change at the regional scale through altered land-atmosphere interactions over urban areas. In this study, the impacts of future urbanization in China on climate are investigated. The Weather Research and Forecasting model is used to downscale future projections using Representative Concentration Pathways (RCP) 4.5 simulations from the Community Earth System Model. Results for 2050 show decreased latent and increased sensible heat fluxes over the urban area, therefore leading to higher surface temperatures and less humidity. Future climate projections reveal that urbanization produces strong warming effects, up to 1.9 °C at regional and local/urban scales, which is comparable to the magnitude of greenhouse gas forcing under the RCP 4.5 scenario. Greater urban warming effects are projected during night and summer, which can be attributed to the high heat capacity of built-up areas. The impacts of urbanization on precipitation show varying effects primarily in summer—both increases and decreases depending on spatial scale—related to both local moisture deficits and large-scale circulation changes. Urbanization could strengthen the East Asian summer monsoon in southern China in summer, and slightly weaken it in eastern China in winter. Due to these significant impacts, we

suggest that urbanization should be included in model projections to provide a more realistic and complete depiction of future climate.

**Keywords** Urbanization · Future climate · WRF · China

## 1 Introduction

Human-induced land cover changes exert significant impacts on climate at regional and global scales by modifying the energy, water, and momentum exchanges between the land surface and atmosphere. Urbanization, one of most extreme and increasing land cover changes, is considered to play an important role in local weather and regional climate because of its effects on both temperature (Oke 1982) and precipitation (Shepherd 2005). Urban areas are warmer, like an “island” of heat surrounded by cooler rural areas (Shastri et al. 2015). This is known as urban heat island effect because of the low albedo, large heat-storage capacity of urban surfaces (Kalnay and Cai 2003), and anthropogenic heat emission (Grimm et al. 2008; Ichinose et al. 1999). Also, it has been reported that urbanization can influence precipitation patterns. The impervious surface of urban areas can largely reduce the moisture available for evaporation. The urban heat island effect may influence the development of clouds, convection, and rainfall patterns over the urban areas (Shepherd 2005). Furthermore, surface winds can be affected; buildings in urban areas may increase surface roughness, thus decreasing surface wind speed. The urban-induced sensible heat fluxes can modify vertical momentum fluxes through boundary layer convection (Vautard et al. 2010).

China is a fast growing country with rapid urbanization. Its gross domestic product grew at an average rate of 9.5 %

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✉ Liang Chen  
lchen15@gmu.edu

<sup>1</sup> Department of Geography, Texas A&M University, College Station, TX, USA

<sup>2</sup> Present Address: Center for Ocean-Land-Atmosphere Studies, George Mason University, Fairfax, VA, USA

from 1978 to 2000, compared with 5 % in developing countries and 2.5 % in developed countries (Zhou et al. 2004). Urban population in China increased from 191 million in 1980 to 622 million in 2009, which was largely driven by rural-to-urban migration (Gong et al. 2012). In the future, China is projected to have the second-largest (after India) urban population growth by 2050 (United Nations 2014). Therefore, not only has urbanization in China become a critical socio-economic topic, but it also has crucial implications for the climate system.

Previous studies have demonstrated the possible effects of urbanization on both temperature and precipitation in China. Jones et al. (2008) found a minor urbanization-related warming of about 0.1 °C per decade over China for the period 1951–2004. A similar small urban-related warming trend (0.11 °C per decade) was also found over northern China for the period 1961–2000 (Ren et al. 2008). Moreover, cities in southern China show a stronger urbanization effect than those in the north (Hua et al. 2008). Based on in-situ observations from 1979 to 1998, Zhou et al. (2004) suggested that the rapid urbanization in southeastern China has increased mean surface temperature at a rate of 0.05 °C per decade. In addition to this observational evidence, climate models have also been used for urbanization-related climate studies at different scales and regions, such as in Beijing (Miao et al. 2009; Zhang et al. 2014), the Yangtze River Delta (Liao et al. 2014; Wang et al. 2015), the Pearl River Delta (Wang et al. 2013; Zhao et al. 2013), and China as a whole (Chen and Zhang 2013; Feng et al. 2012, 2013, 2014; Shao et al. 2013; Wang et al. 2012). For instance, Wang et al. (2012) found that urban expansion can lead to increased surface air temperature, enhanced convergence, decreased cloud fraction, and changes in regional precipitation. Furthermore, urbanization is also able to influence the East Asian monsoon system (Feng et al. 2013).

Despite the well-documented significant impacts of urbanization on climate at both local and regional scales, projections of future climate have rarely considered the possible increases of urban area in their land cover change scenarios. In Coupled Model Intercomparison Project Phase 5 (CMIP5), even though land cover changes have been included in the climatic forcings of some modeling groups, usually urban fraction still remains constant over time (Di Vittorio et al. 2014). Mahmood et al. (2014) suggest that urban forcing should be included in future climate modeling systems because of its impacts on atmospheric dynamics, thermodynamics, energy exchanges, cloud microphysics, and composition.

Therefore, in this study, a regional climate model is used to investigate the impacts of urbanization in China on future climate. We use the WRF model to dynamically downscale future climate projections from CESM. Impacts

of urbanization were detected based on two land cover scenarios. The unique contributions of this study are that it is the first to estimate how possible future urbanization affects climate in China, and also the first to examine whether future urbanization has a comparable impact on climate as greenhouse gas forcing.

## 2 Model description and experimental design

### 2.1 WRF model

The WRF model version 3.5 is used for regional climate simulations. A regional climate model is used here because the coarse resolution of GCMs precludes an accurate depiction of urbanization and cannot adequately resolve the scale of urban areas or mesoscale physical processes. Therefore, regional climate modeling is better suited because it provides a higher spatial resolution and a better representation of physical processes and feedbacks occurring at regional scales, especially in areas with complex land surface conditions, such as heterogeneous land cover and terrain. Furthermore, a number of studies have successfully used WRF to examine the influence of urbanization on climate in China (Feng et al. 2012, 2014; Miao et al. 2009; Wang et al. 2012). Therefore, the WRF model seems able to capture the land-atmosphere interactions such as those related to urbanization over China.

The model domain of this study covers the entire region of China at a horizontal resolution of 30 km (Figure S1). The domain is centered at 35°N and 103°E, with dimensions of 240 grid cells west–east × 180 grid cells south–north, and the top model level is at 50 hPa. In this study, the resolution might still not be adequate to describe some cities. However, this spatial resolution has been adopted in previous studies employing WRF climate downscaling over China (Feng et al. 2013; Gao et al. 2015; Liu et al. 2013) and should also be effective for capturing land-atmosphere interactions in our study.

The parameterization of physical processes (Table 1) was chosen based on previous studies (Feng et al. 2012; Wang et al. 2012). For land surface processes, the Noah land surface model (Chen and Dudhia 2001) was coupled with the Urban Canopy Model (UCM) (Kusaka and Kimura 2004; Kusaka et al. 2001). The UCM is a single-layer model that simulates energy and momentum exchange between an urban surface and the atmosphere (Kusaka et al. 2001). Over urban areas, surface temperatures and heat fluxes are estimated from three surface types: roof, wall, and road. The Noah model then calculates surface temperatures and heat fluxes for a given grid cell based on the fractional coverage of urban and vegetated area (Chen et al. 2011).

**Table 1** Parameterization of the physical processes in the WRF model configuration

Physical processes	Parameterization
Microphysics	WRF single-moment 3-class scheme (Hong et al. 2004)
Longwave radiation	RRTM scheme (Mlawer et al. 1997)
Shortwave radiation	Dudhia scheme (Dudhia 1989)
Planetary boundary layer	Yonsei University scheme (Hong et al. 2006)
Cumulus parameterization	Kain–Fritsch scheme (Kain 2004)
Land surface	Noah land surface model (Tewari et al. 2004)
Urban surface	Single-layer UCM (Kusaka and Kimura 2004)

## 2.2 Lateral boundary and initial conditions

For the WRF downscaling of future climate projections, the “Global 6-hourly Bias-corrected CMIP5 CESM” (Monaghan et al. 2014) dataset is used as the lateral boundary and initial conditions. This dataset is generated based on the output from the simulation of Community Climate System Model version 4 (CCSM4)<sup>1</sup> ensemble member #6 for each scenario in the CMIP5 archive. This dataset was chosen because CESM ranks as the best of the CMIP5 GCMs in terms of simulating observed temperature and precipitation at the global scale (Knutti and Sedlacek 2013). It also performs well in simulating climate (especially temperature) variability in China (Chen and Frauenfeld 2014a). Therefore, it likely provides relatively robust boundary conditions for WRF, compared to other GCMs. Furthermore, the CESM output has been bias corrected. GCMs contain biases at the regional scale due to both their coarse resolution, and their limited representation of certain physical processes (Chen and Frauenfeld 2014a, b). These biases will also affect the quality of the downscaling. In the Monaghan et al. (2014) dataset, the European Centre for Medium-Range Weather Forecasts (ECMWF)’s Interim Reanalysis (ERA-Interim; (Dee et al. 2011) was used for bias correction, where the bias-corrected CESM output is generated by summing the 1981–2005 average 6-hourly annual cycle from ERA-Interim with a 6-hourly perturbation term from CESM (Bruyère et al. 2014).

From the bias-corrected CESM output, 11-year historical (1995–2005) and RCP4.5 (2050–2060) simulations are used as lateral boundary and initial conditions in WRF. The RCP4.5 scenario represents a moderate

future climate warming pathway. The first year is considered as spin-up period and only 10-year results are analyzed. The sea surface temperature (SST) and deep soil temperature are actively updated during the simulations.

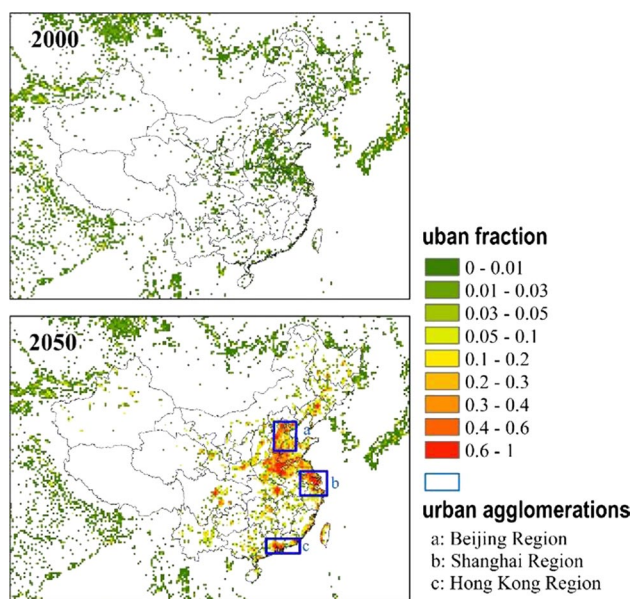
## 2.3 Experimental design

We conduct three experiments to investigate the climatic impacts of future urbanization in China. (1) *HIST*: A historical run (1995–2005) forced with current land cover conditions, which is prescribed using the USGS 24-category land use data (Figure S2). (2) *RCP45*: An RCP4.5 scenario run (2050–2060) forced with current land cover conditions. (3) *URB*: An RCP4.5 scenario run (2050–2060) forced with future urbanized land cover conditions. The *RCP45–HIST* difference shows future climate change due to greenhouse gas forcing in RCP 4.5, while the *URB–RCP45* difference shows the impacts of urbanization on future climate. Following the experimental design of Argüeso et al. (2014), all urban types are set to the default high-density residential category.

Future urban area was derived from global forecasts of urban expansion (Seto et al. 2012). The probability of urbanization in 2030 was estimated based on global urban extent circa 2000, urban population, population density, and country-level gross domestic product projections in 2030. From the 2030 urban forecast data, grid cells with urbanization probability higher than 75 % (Güneralp et al. 2015a) were considered as urban area in 2050. This is based on the assumption that, if a pixel has a high probability of urbanization in 2030, it will likely have a similar or higher probability of becoming urban in 2050. Figure 1 shows the urban fractions in 2000 and 2050 specified in the WRF model. Extensive urbanization is evident in eastern and southeastern China, which correspond to the most developed and populated areas in this country.

In the future urbanized land cover scenario, urban fraction in each grid cell was increased based on the urban projection from Seto et al. (2012). Vegetated land cover categories were proportionally replaced by urban area. Only grid cells in China were modified for future urbanization, while other grid cells were kept the same as current land cover conditions. Figure 2 shows the four land cover types with the largest changes in 2050 after the projected urbanization has occurred. Cropland is the major land cover type that will be encroached upon by urban area in the future. The total increase in urban area will be 2.6 % in China. Consequently, cropland will decrease by 2.2 % in 2050 due to urbanization, with the remaining 0.4 % accounted for by decreases in grassland and forest.

<sup>1</sup> The CCSM4 is a subset of CESM1, hereafter referred to as CESM.



**Fig. 1** Urban fractions in 2000 and 2050 specified in the WRF model, with the three subregions (*bottom*) considered as urban agglomerations

### 3 Results

#### 3.1 Evaluation of WRF downscaling

To first assess the performance of the WRF downscaling, results from *HIST* are compared with CRU temperature and precipitation observations (Harris et al. 2014). Figure S3 shows that WRF exhibits a good spatial agreement with the observed climatology of seasonal surface air temperature, with a spatial correlation coefficient of 0.96 ( $p < 0.01$ ) in both summer and winter. In summer, WRF well captures the hot regions, such as the Tarim Basin in the Xinjiang Province, Sichuan Basin, Hubei, and Hunan provinces. In winter, a systematic cold bias exists in simulated temperature. This cold bias is large over the Tibetan Plateau, which can be attributed to cold biases in the original GCMs (Chen and Frauenfeld 2014b) and the high elevation and complex terrain in this region (Gao et al. 2015).

Figure S4 shows the comparison between observed seasonal precipitation and the *HIST* WRF simulation. Similar to previous studies applying dynamically downscaled precipitation over China (Gao et al. 2011, 2012; Liu et al. 2013), WRF only simulates precipitation fairly over China, with a spatial correlation coefficient of 0.77 ( $p < 0.01$ ) in summer and 0.54 ( $p < 0.01$ ) in winter (Figure S4). In summer, the CRU observations show low precipitation in northern China, and high precipitation in the southeast with the largest precipitation amounts in southern China as a result of the East Asian summer monsoon. WRF well reproduces the basic spatial pattern of precipitation distribution,

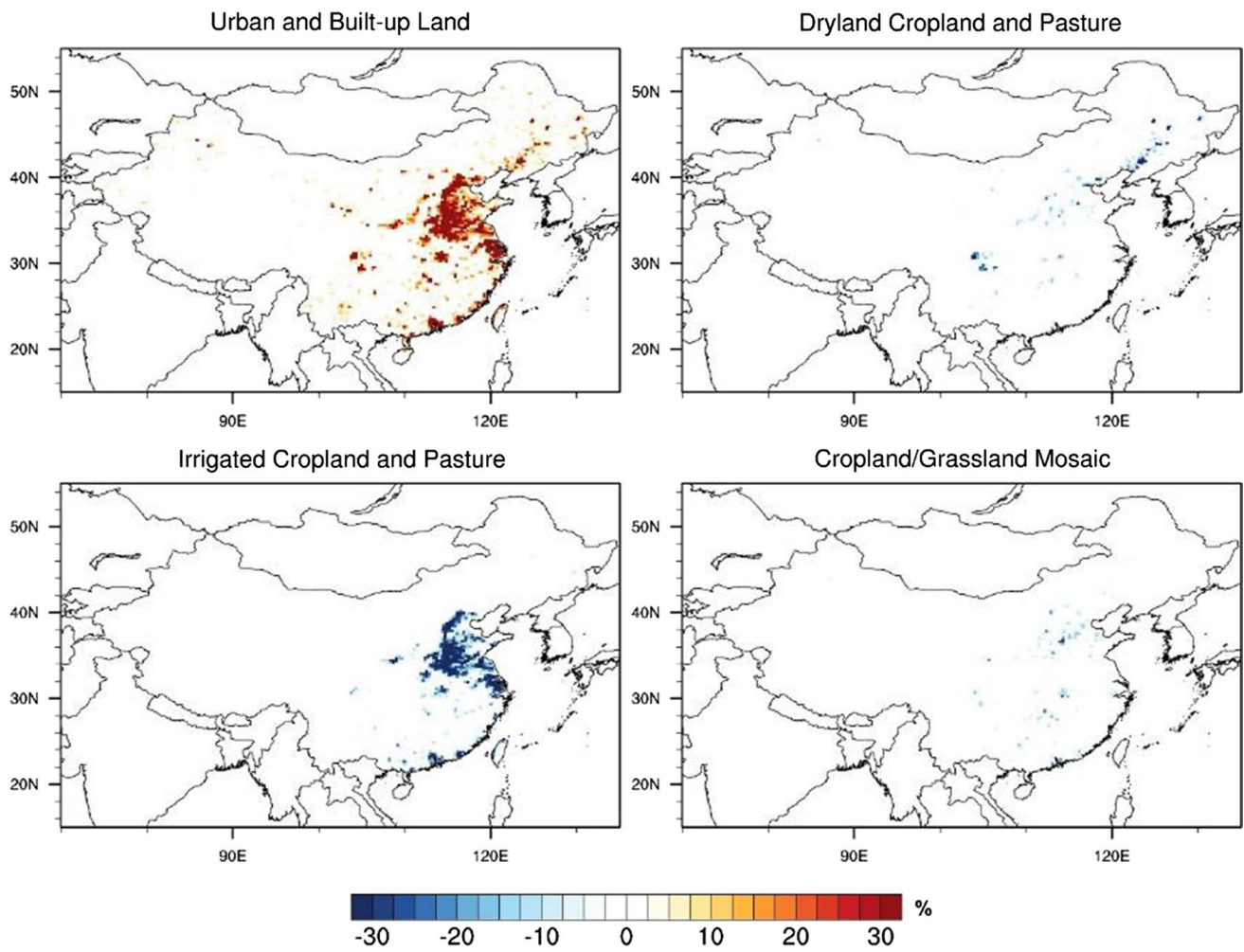
however, it overestimates the precipitation in southwestern China and the Yangtze River delta regions. The wet bias in southwestern China can result from the overestimated precipitation in the GCMs (Chen and Frauenfeld 2014b) and the influence of the Tibetan Plateau. However, the wet bias over the Yangtze River delta region may be attributed to the uncertainties of the observational data. Feng et al. (2012) presented observed precipitation over China based on Tropical Rainfall Measuring Mission (TRMM) data, which show high precipitation over the Yangtze River delta region. During winter, the observed precipitation decreases from the southeast to the northwest. However, WRF largely underestimated precipitation in the southeast and overestimated precipitation in the southwest. Yuan et al. (2012) also found such a winter dry bias over southeastern China, which might be attributed to the selection of land surface schemes. They suggested that the Rapid Update Cycle (RUC) land surface scheme can produce better climatology of winter precipitation in southern China than the Noah land surface scheme. However, the RUC land surface scheme does not support the urban model in WRF, which is only available for the Noah model. Based on the above assessment and previous studies, WRF seems capable of providing reasonable dynamically downscaled high-resolution climate simulations for this study. However, due to the large bias evident over the Tibetan Plateau, this region will be excluded from our analyses.

#### 3.2 Changes in land surface characteristics after urbanization

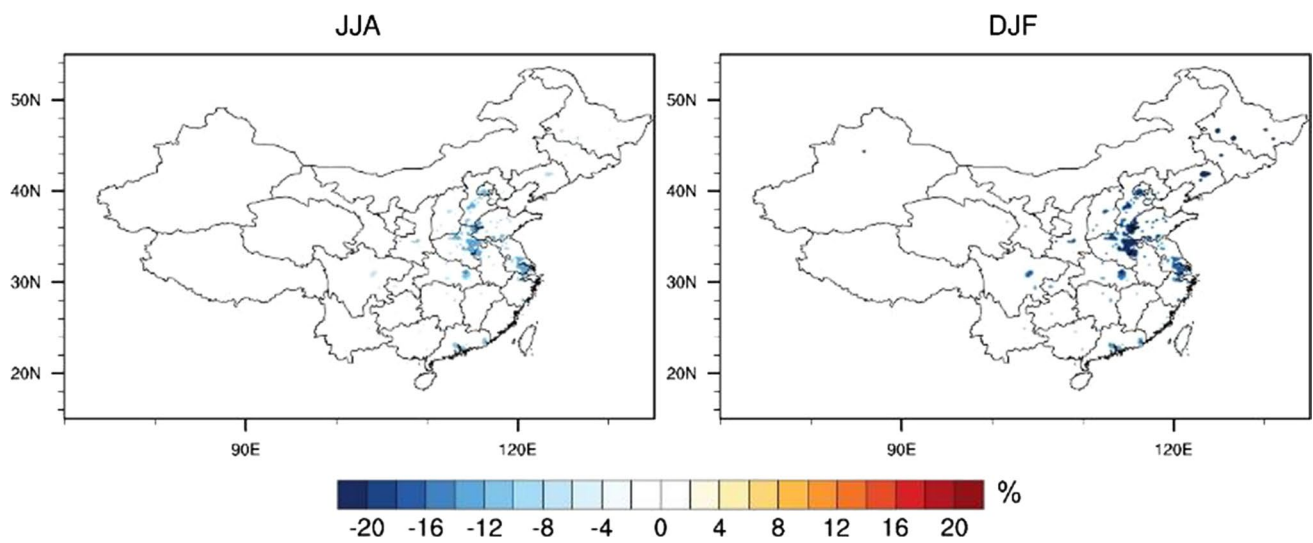
Urbanization can modify the surface characteristics and influence the land surface energy balance. Figure 3 shows surface albedo changes after urbanization in 2050. After urbanization, albedo decreased mainly over the urbanized area. In the Noah model, the surface albedo is calculated based on vegetation fractions for each grid cell. Compared with vegetated areas (e.g., cropland), urban surfaces have a lower albedo. Also, it is found that the albedo decrease in winter is larger than in summer. This is because cropland has a low albedo in summer during the growing season, and a high albedo in winter after harvest.

Due to the unique thermal properties of urban surfaces, we also examine the changes in surface sensible and latent heat fluxes after urbanization (Fig. 4). Generally, urbanization tends to increase the surface sensible heat but decrease the latent heat flux over the urban area. The decrease in vegetation, which is replaced with urban area, combined with the impervious surface of urban area, may reduce evapotranspiration and thus decrease the latent heat flux. For the sensible heat flux, its increase can also be attributed to the albedo decrease and the thermal properties of urban surfaces. Seasonally, larger heat flux changes are found

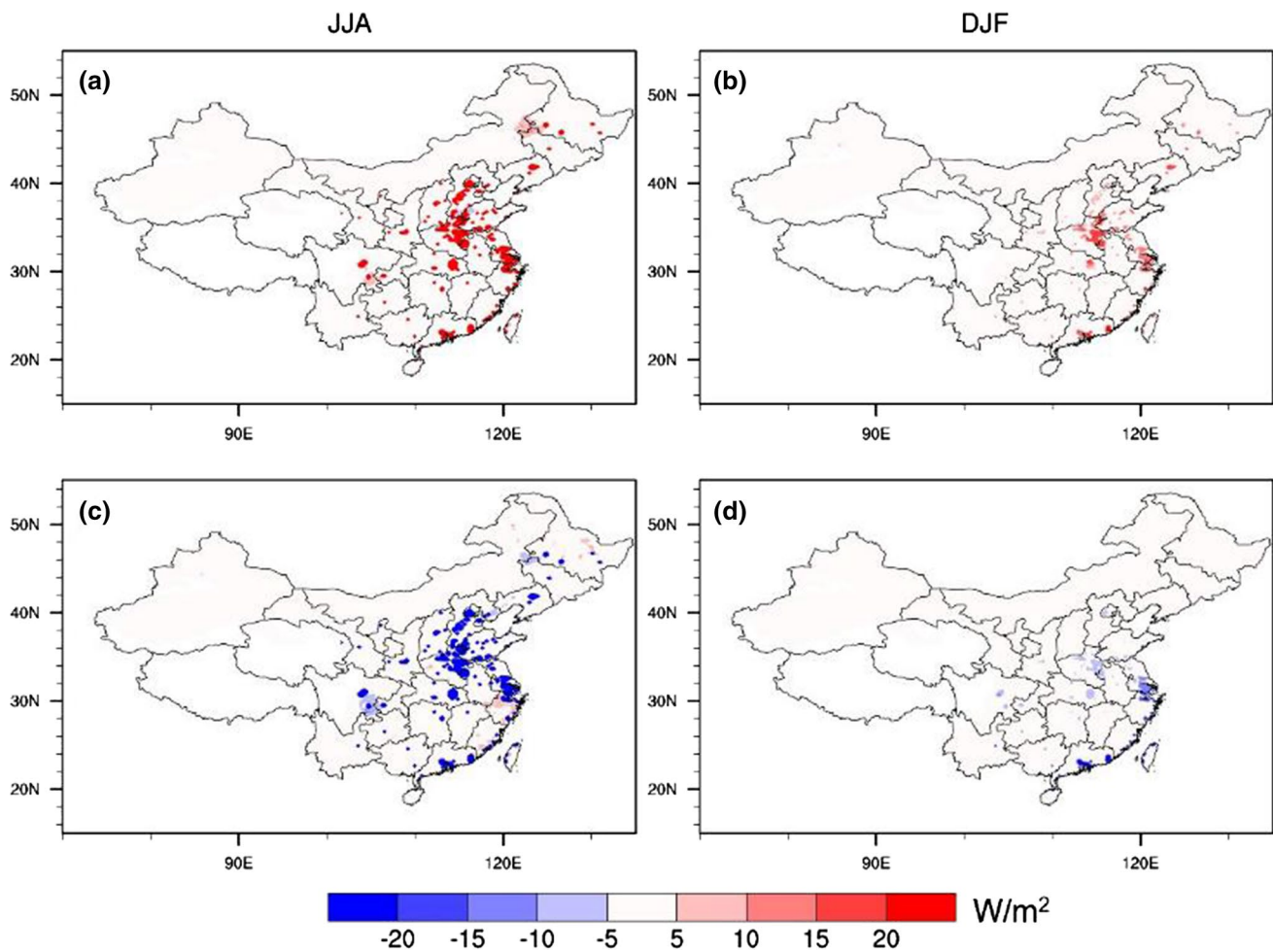




**Fig. 2** Four land cover types with the largest changes in 2050 after urbanization has occurred



**Fig. 3** Albedo changes (%) in summer and winter after urbanization



**Fig. 4** Same as Fig. 3 but for sensible heat (a, b) and latent heat (c, d) fluxes ( $\text{W/m}^2$ )

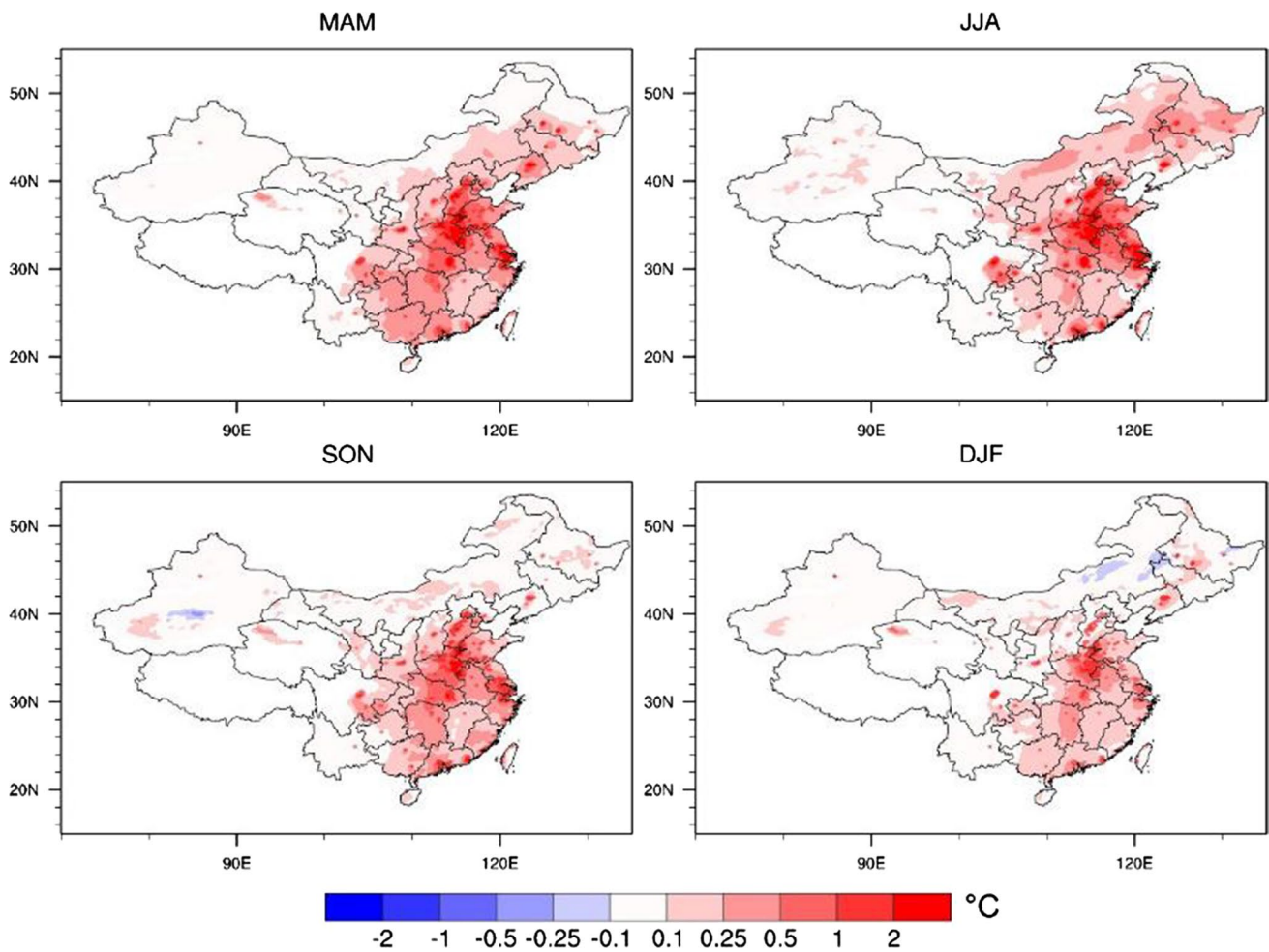
in summer. This can be explained in terms of the surface receiving the highest insolation in summer, which exerts the strongest influence on the surface energy budget. Also, evapotranspiration is the strongest in summer, therefore the latent heat flux would be decreased the most during this season as a consequence of urbanization.

### 3.3 Impacts on surface temperature

With the decreased surface albedo and increased sensible heat flux, urbanization exhibits a significant impact on future temperature (Fig. 5). Statistical significance was also determined for the temperature changes, which are statistically significant only over the extensively urbanized regions. Warming effects are found in eastern China, with the greatest temperature increase over the urban agglomerations. The small urban areas, especially in the northwest (such as Lanzhou, Gansu Province and Urumqi, Xinjiang Province), also show warming after urbanization. The increase in temperature is the greatest and most extensive

during summer, followed by spring and autumn, while winter undergoes the smallest projected warming. The seasonal pattern of temperature change can be explained by the surface heat flux changes.

We also focus on three important urban agglomerations in China: the Beijing region, Shanghai region, and Hong Kong region (Fig. 1). These regions are defined based on Feng et al. (2013), and allow us to further assess the temperature impacts of urbanization at local and regional scales. The three urban agglomerations are chosen because they exhibit the greatest increases in urban development nationwide (Feng et al. 2013). Table 2 compares the warming effects of greenhouse gas forcing and urbanization for China, and for three urban agglomerations. The grid cells with urban fractions higher than 50 % are considered as metropolitan areas and are calculated separately, so that the impacts of urbanization at local and broader (regional) scales can be discerned. Under the RCP 4.5 scenario, surface air temperature increases significantly throughout the year. Mean annual temperature is projected to be 1.8 °C



**Fig. 5** Seasonal temperature changes (°C) in 2050 after urbanization

**Table 2** Temperature changes for the three subregions and China in the RCP (*RCP45–HIST*) and URB (*URB–RCP45*) experiments

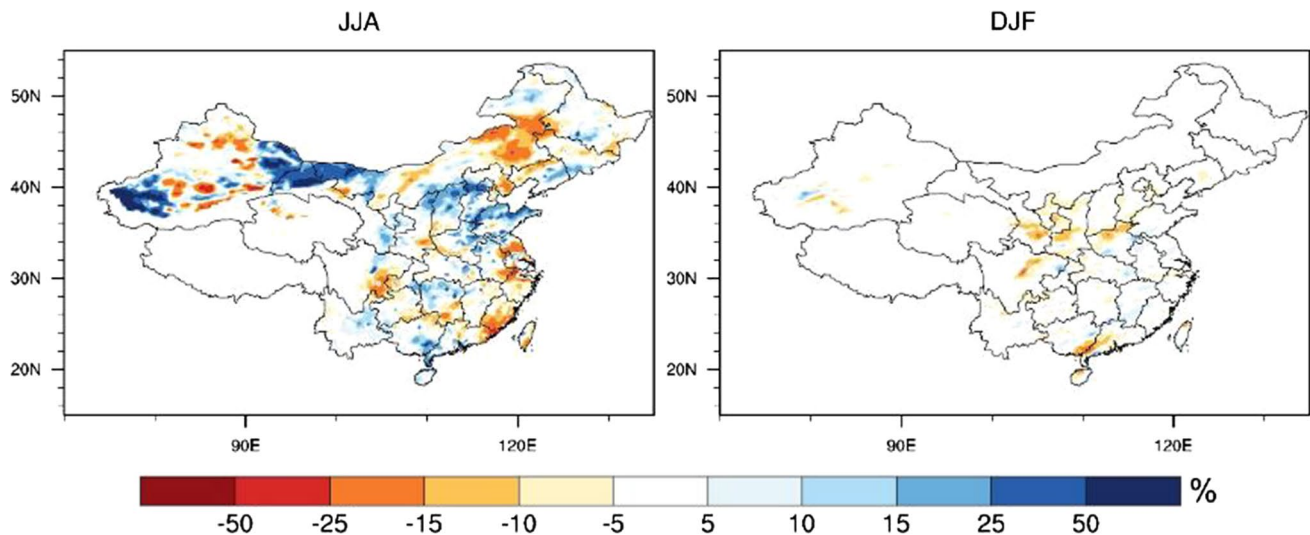
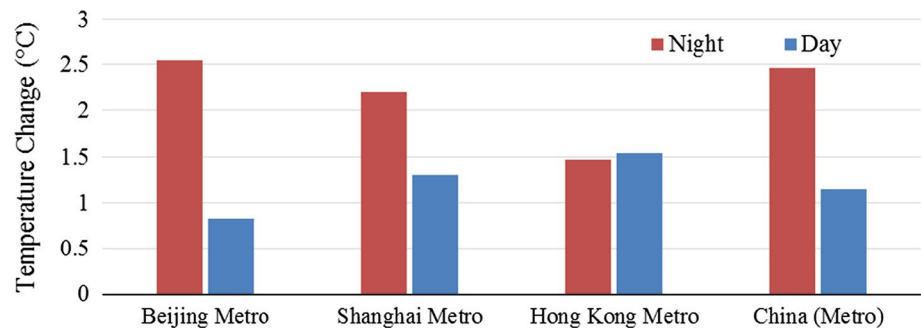
Regions	RCP (°C)			URB (°C)		
	Annual	Summer	Winter	Annual	Summer	Winter
Beijing region	1.9*	1.3*	3.0*	0.6*	1.0*	0.3
Shanghai region	1.4*	1.2*	1.1*	0.8*	1.3*	0.3
Hong Kong region	1.2*	0.5*	1.4*	0.6*	0.8*	0.3
China	1.8*	1.0*	2.3*	0.2	0.2	0.1
Beijing metro	1.9*	1.2*	3.0*	1.8*	2.6*	1.0
Shanghai metro	1.3*	1.3*	0.9*	1.8*	2.7*	0.7
Hong Kong metro	1.9*	0.5*	0.9*	1.4*	1.9*	0.7
China metro	1.6*	1.0*	2.0*	1.9*	2.4*	1.1*

Statistically significant differences (95 % level) are shown with asterisks. Metro indicates that only urban areas (urban fraction >50 %) were considered

higher than present over China, with a larger warming in winter than in summer. The temperature increase is larger in the north (Beijing) than the southeast (Shanghai and Hong Kong). Similar warming is found in the metropolitan and surrounding areas, because urbanization is not included

in the RCP experiments for future climate projections in CMIP5. At the regional (country-wide) scale, urbanization increases the mean annual temperature by only 0.2 °C over all of China, with a larger warming in summer. However, urbanization has much stronger impacts on temperature at

**Fig. 6** Daytime and nighttime 2-m air temperature changes (°C) over urban areas in three subregions and China after urbanization



**Fig. 7** Same as Fig. 3 but for precipitation (%)

local scales, such as metropolitan areas. Temperature can increase as much as 1.9 °C in urban areas, which is comparable to and has even exceeded the warming effects resulting from greenhouse gases.

The impacts of urbanization on temperature during day versus night were also examined (Fig. 6). Generally, the warming effects of urbanization are stronger during night than day (except in Hong Kong). The larger warming effect during night was also found in previous studies (Kalnay and Cai 2003; Wang et al. 2012), and can be explained by the high heat capacity in urban areas. During day, urban surfaces with low albedo absorb and store energy, but less evapotranspiration limits surface-to-atmosphere energy release, which persists into the night and thereby increases nighttime temperatures. Similar diurnal temperature patterns of urbanization effects were also found in observationally based studies (Hua et al. 2008; Ren and Zhou 2014). These studies show the strongest urbanization effect on minimum temperature in winter, but Wu and Yang (2013) and Ren et al. (2008) found a larger urban warming during daytime in summer for southern China. This

discrepancy may be attributed to the parameterization of anthropogenic heating in the WRF, which will be discussed in Sect. 4.

### 3.4 Impacts on precipitation

The impacts of urbanization on precipitation do not have uniform patterns, like those on temperature changes. The spatial distribution of seasonal precipitation changes is shown in Fig. 7. Significant precipitation changes are only found over the extensive urbanized areas during summer. It should be noted that there are significant changes in precipitation and wind over northeastern China during summer, even though no significant urbanization effects are found over this region. In summer, precipitation decreases in southeastern China, especially over the Shanghai region, and increases over southern China (Hong Kong region) and Beijing region. These results agree with the conclusions of Feng et al. (2012), who also found an increase in precipitation in the Beijing-Tianjin-Hebei region and a decrease in the Yangtze River delta region. Using two



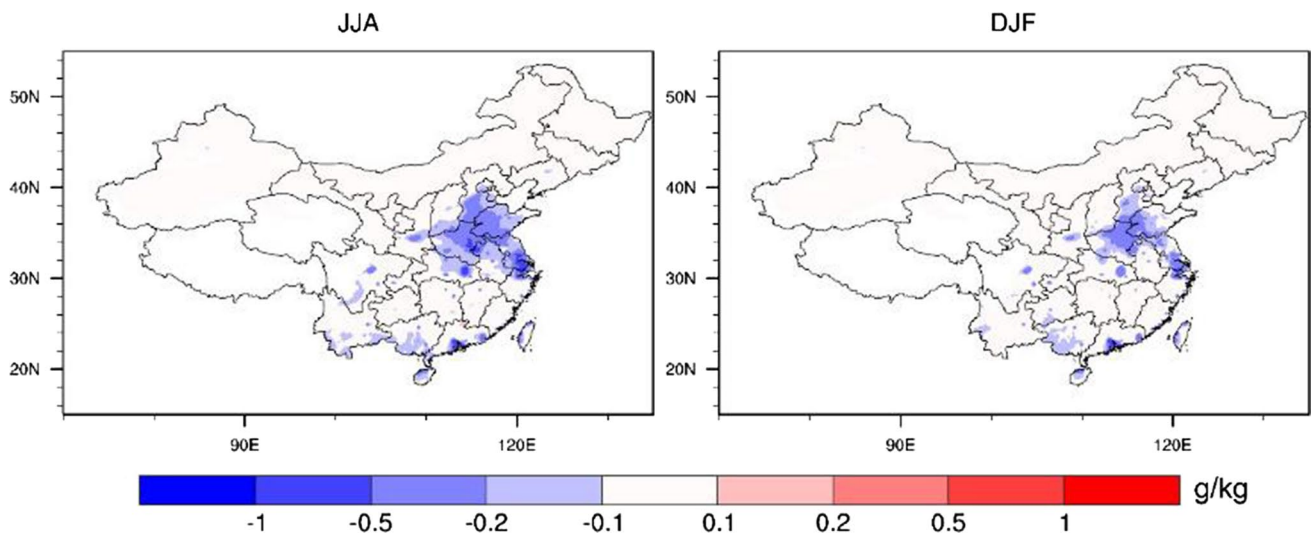


Fig. 8 Same as Fig. 3 but for 2-m specific humidity (g/kg)

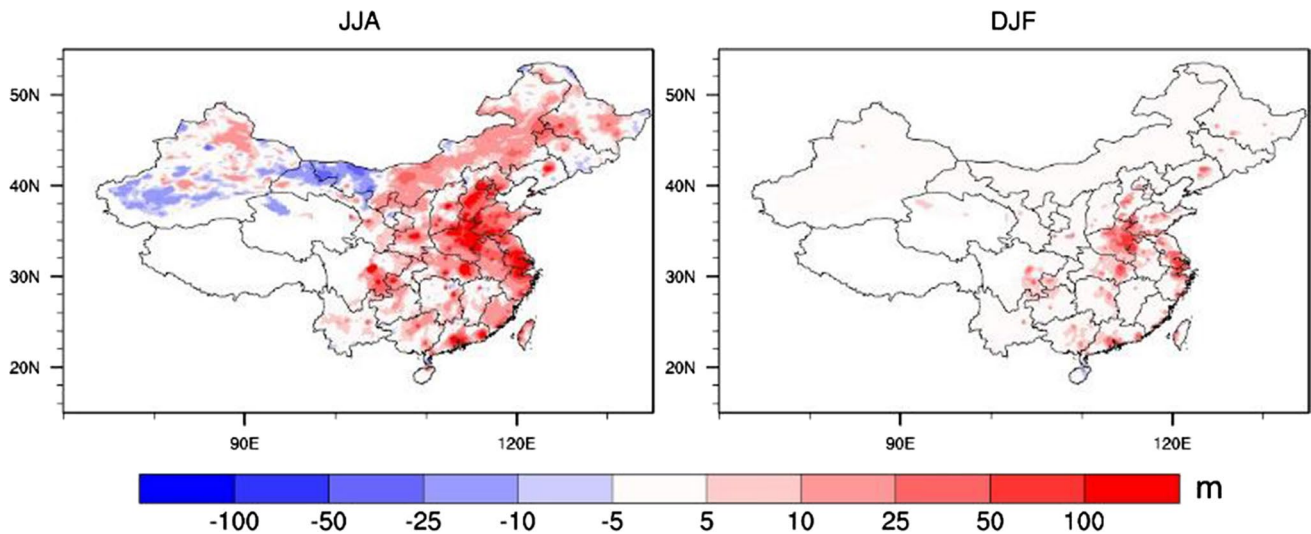
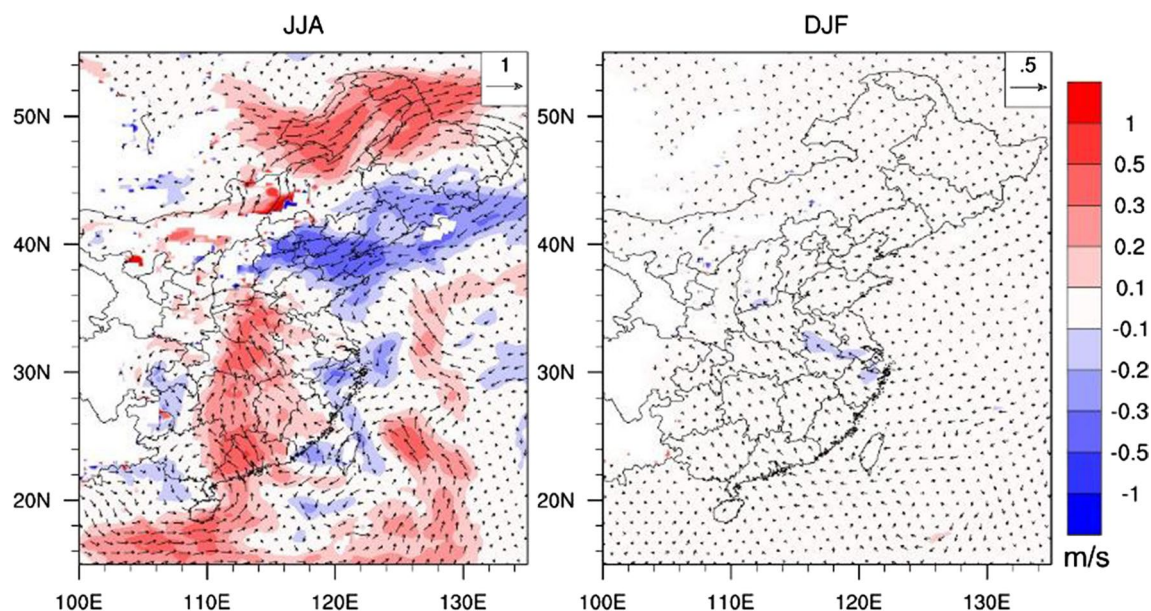


Fig. 9 Same as Fig. 3 but for planetary boundary layer height (m)

nested domains in the WRF model, Wang et al. (2013) suggested urbanization in the Pearl River Delta (Hong Kong region) may increase annual total precipitation due to an increase in heavy and extreme rain events. In winter, the impacts of urbanization on precipitation are very small. This is because the precipitation in most areas of China is controlled by the East Asian monsoon system, in which precipitation is dominant in summer whereas there is little winter precipitation.

To investigate the possible reasons for precipitation changes, impacts on 2 m specific humidity, the height of the planetary boundary layer (PBL), and the East Asian monsoon are also examined. Figure 8 shows the changes in surface specific humidity after urbanization. During

summer, there is a significant decrease in specific humidity over urban areas (by up to  $-1.0$  g/kg over Shanghai and Hong Kong). The change in specific humidity in winter shows a similar pattern, but with a smaller decrease. Decreasing specific humidity can be attributed to the decrease in evapotranspiration after urbanization. This may reduce atmospheric moisture and therefore decrease precipitation in these regions. Many studies indicate that precipitation over urban areas is strongly related to the structure of the urban boundary layer (Huszar et al. 2014; Niyogi et al. 2010; Wang et al. 2012). The impacts of urbanization on the PBL height are presented in Fig. 9. Generally, the PBL height increases over the urban area, with a stronger and more extensive increase in summer (up to 100 m) than in



**Fig. 10** Same as Fig. 3 but for wind field at 850 hPa (m/s)

winter, as a result of the increased sensible heat fluxes. As also found in previous studies (Shimadera et al. 2015), the increased PBL height indicates that the atmosphere over the urban area is likely more unstable and tends to develop more convective clouds, causing more precipitation from afternoon to evening. However, the deficit of atmospheric moisture over the urban area may offset the impacts from the elevated PBL.

Finally, urbanization likely influences the East Asian monsoon system. To investigate this potential effect, we quantify the changes in the 850 hPa wind field in summer and winter (Fig. 10). In summer, the strong warming effects of urbanization can increase the temperature gradient between the ocean and the land, thus strengthening the summer monsoon in the south. Indeed, easterly wind anomalies are evident in the 850 hPa fields, advecting moisture over the Beijing region. This potentially accounts for the precipitation increases over this region. However, because urban heating in winter is not as strong as in summer, the influence of urbanization on the winter monsoon is very small, and is only evident over the Yangtze River delta region. That likely also explains why the winter precipitation changes are negligible in response to urbanization.

#### 4 Discussion and conclusions

Urbanization in China impacts future climate through changes in the energy, water, and momentum exchanges between the urban surface and the lower atmosphere. In

terms of temperature, urbanization shows strong warming effects during summer and at night. Over the three urban agglomeration regions, we find a possible warming of 0.6–0.8 °C in annual mean temperature by the 2050s caused by urbanization. Ren et al. (2008) estimated the trend of urban warming to be 0.11 °C (10 year)<sup>-1</sup> in northern China based on 1960–2000 temperature observations. The magnitude of warming is slightly higher in our study because we focused on urban agglomeration regions. For the entire area of China, the annual mean surface air temperature will increase by 0.2 °C by 2050. This temperature increase agrees with previously suggested urbanization-contributed warming rates (Zhou et al. 2004).

As mentioned in the introduction section, land cover changes have been considered in future climate projections in CMIP5. For future climate, vegetation changes are projected to induce a significant annual surface temperature increase of 0.4 °C in east Eurasia (Jiang et al. 2011). Vegetation conversion from grassland to forestland in southeastern China may decrease annual mean temperatures by 0.11 °C (Yu et al. 2013). In other regions in the world, Trail et al. (2013) found that reforestation of cropland in the southeastern US tends to increase surface air temperature by 0.5 °C, while deforestation tends to decrease surface air temperature by 0.5 °C. The reported grassland degradation in Mongolia may lead to a warming (0.1–0.4 °C) of annual mean temperature in the future (Zhang et al. 2013). In terms of the magnitude of future regional temperature changes, we find the effects of urbanization to be on par with those from vegetation changes. Therefore, urban forcing should be included in future climate simulations.

At local scales, future urbanization tends to increase summer temperature by as much as 2.7 °C over urban areas. Previous studies have shown intensified heat stress—a leading cause of weather-related human mortality—as a result of urbanization and future climate change (Oleson et al. 2015). Therefore, the vulnerability and adaptation of urban populations need to be considered in future climate projection.

Precipitation changes show a more complex pattern than temperature. Urbanization tends to decrease atmospheric moisture as a result of decreased evapotranspiration, but increases PBL height by increasing the sensible heat flux. Feng et al. (2014) also found strengthened vertical motion due to urbanization. However, it did not result in increased precipitation because of the decreased surface moisture in urban areas. We did not see a consistent change in precipitation over China's three main urban agglomerations. Kaufmann et al. (2007) suggests that there is no causal relationship between urbanization and precipitation, because the East Asian monsoon plays a dominant effect in this region. We did indeed find that urbanization may strengthen the summer monsoon, and slightly weaken the winter monsoon. Therefore, the impacts of urbanization on precipitation are due to the combined effects of both local moisture changes and large-scale circulation features.

However, limitations still exist in this study, such as the future urbanization extent and parameterization of urban-atmosphere interactions in the WRF model. There are uncertainties in urban land expansion because of its underlying drivers, including urban population and economic growth (Güneralp and Seto 2013). The dataset of urban land expansion in this paper has been applied to several studies related to urbanization in China (Güneralp et al. 2015a, b), indicating its value in predicting future urbanization. This study is dedicated to the best estimation of the possible impacts of future urbanization in China based on these sensitivity experiments. Also, the spatial resolution (30 km) of the WRF model may undermine the robustness of future urban area. Nested high-resolution modeling should be adopted in the future studies.

Discrepancies still exist between observations and model simulations in terms of the seasonality of temperature changes. Ren et al. (2008) found that the urbanization effects cause the largest warming in winter over northern China. Yang et al. (2011) found a similar seasonal pattern of temperature change over eastern China based on an observation-minus-reanalysis method; however, this same study found a larger warming in most of the urban areas during summer when applying an urban-minus-rural method (Yang et al. 2011). Most other model-based studies suggest a stronger summer warming from urbanization (Georgescu et al. 2012; Huszar et al. 2014; Wang et al. 2012, 2013; Zhang et al. 2010), aligning with the results

in our study. This discrepancy may be due to the parameterization of anthropogenic heating in the urban model, in which only the diurnal anthropogenic heating is considered for the urban canopy layer, but its seasonality has not been included. Sailor and Lu (2004) found greater energy expenditures associated with heating during winter in higher-latitude cities. This can explain why the model does not capture the larger observed winter warming over northern China. Moreover, Flanner (2009) projected that there will be a large increase in annual mean anthropogenic heat flux in China from 2005 to 2040. Therefore, both temporal and spatial variation of anthropogenic heating should be considered in future studies.

Additionally, urban aerosol effects are another factor that can influence the regional climate during urbanization (Kaufmann et al. 2007). However, in this study we only focused on the biogeophysical effects of urbanization. Future work will also consider the aerosol impact of urbanization.

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