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ORIGINAL PAPER

Impact of urbanization on summer rainfall in Beijing–Tianjin–Hebei metropolis under different climate backgrounds

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Abstract The Beijing–Tianjin–Hebei region experienced the most rainfall in 1994 and the least rainfall in 1997 during the last 20 years. Utilizing the Weather Research and Forecasting (WRF) model coupled with a single-layer urban canopy model (UCM), we investigate the possible effects of urbanization on summer precipitation under different climate backgrounds using the two extreme years. By comparing the results of control and sensitivity runs, we find totally different effects in the 2 years. In 1994, the rainfall and rainfall frequency decrease in most areas due to urbanization, and decreases in the rainfall intensity occur in urban areas of Beijing, Tangshan, and Shijiazhuang. In 1997, the rainfall, rainfall frequency, and intensity are reduced in southwest of Beijing–Tianjin–Hebei, while the change is opposite in northeast. Urbanization alters the diurnal distribution of rainfall, the energy budget, and the water vapor content in the atmosphere. Due to the decrease in city evaporation and transpiration, the surface latent heat flux is reduced. The water vapor mixing ratio in urban area decreases apparently from surface to 850 hPa, while it increases from 850 to 600 hPa. Overall, the reduction of water vapor mixing ratio in 1994 is more than that in 1997, which implies that the "dry island effect" caused by urbanization is stronger in the wet year than that in the dry year. Results also show that the inhibition (enhancement) of deep convection may explain the modification of precipitation.

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1 Introduction

The urban population has grown at a rate of 1.7% in the past 20 years (Angel et al. 2005). It is expected that the population would be 70% higher in 2050 (Nations United 2007). In comparison with rural areas, urban areas have a larger heat-storage capacity, Bowen ratio, and surface roughness (Oke 1982); these differences lead to the modification of dynamic processes in the atmospheric boundary layer and the surface energy budget, which ultimately affects the regional climate in and around urban areas (Bornstein and Lin 2000; Liu et al. 2006).

Both observational data and numerical models were used to study the impact of urbanization on climate. Horton found that heavy rain is more likely to occur in big cities in 1982. Changnon (1979) and Huff and Changnon (1972) indicated that, by urbanization, the precipitation increased by 9–17% in Saint Louis and its leeward region of 50–75 km in warm season. With the development of modern observation technology and the use of numerical models, studies have found that the urbanization can affect the regional climate. Utilizing long time station data, Hideo (2003) pointed out that the increasing trend of precipitation was clearer in the densely populated area of Tokyo. Chen et al. (2007) showed that the frequency of thunderstorms in Taipei increased by 67% in the afternoon due to urbanization. A case study conducted

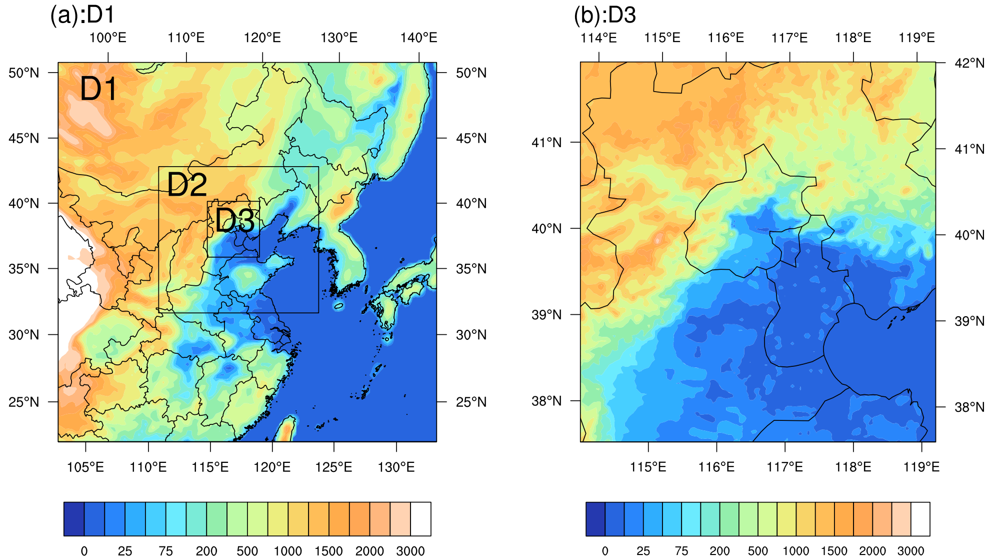

Fig. 1 The simulated domain and terrain distribution (unit: m). **a** Nested configuration of D1, D2, and D3. **b** D3 (Beijing–Tianjin–Hebei) region

by Shepherd et al. (2010) indicated that simulations without urban produced less cumulative rainfall in the area to the west-northwest of Houston than simulations with the urban represented. Wang et al. (2012) conducted a simulation of 5 years using WRF to detect the urbanization effects. Their results showed that urban expansion led to increase in surface air temperature of about 1 °C, and this climatic forcing of urbanization on temperature is more pronounced in summer and nighttime than in other seasons and daytime.

In recent years, the process of urbanization in China is very rapid, particularly in the three vast urban agglomerations: the Pearl River Delta, the Yangtze River Delta, and the Beijing–Tianjin–Hebei metropolis. The impact of urbanization on regional climate change may occur at larger spatial-temporal scales (Feng et al. 2014). Such urban expansion may result in increased heat wave, more city water-logging, enhanced urban pollution, and more thunderstorm days. In order to understand urban precipitation, improve air quality, and ensure a pleasant and healthy environment for urban dwellers, understanding the impacts of urbanization becomes more and more important.

The Beijing–Tianjin–Hebei metropolis is located in the East Asian monsoon region. In general, there is more precipitation in northern part of eastern China when the summer monsoon is stronger, and vice versa (Yu 2001; Guo et al. 2003; Lü et al. 2006; Ding et al. 2007; Hao et al. 2016). Especially, the East Asian summer monsoon was strong in 1994 (Yu 2001; Lü et al. 2006), but weak in 1997 (Yu 2001; Sun and Ding 2002). Zhang et al. (2015) have investigated the impact of urbanization on summer rainfall in Beijing–Tianjin–Hebei area using WRF coupled with UCM. They found that due to urbanization, the rainfall and rainfall frequency in the urban area of Beijing, Tianjin, and Tang Shan decreased, while they increased in the downwind area. However, the impact of urbanization process under different climate backgrounds is still unclear. Moreover, few studies have compared the urbanization effects under the dry and wet climate situation, respectively.

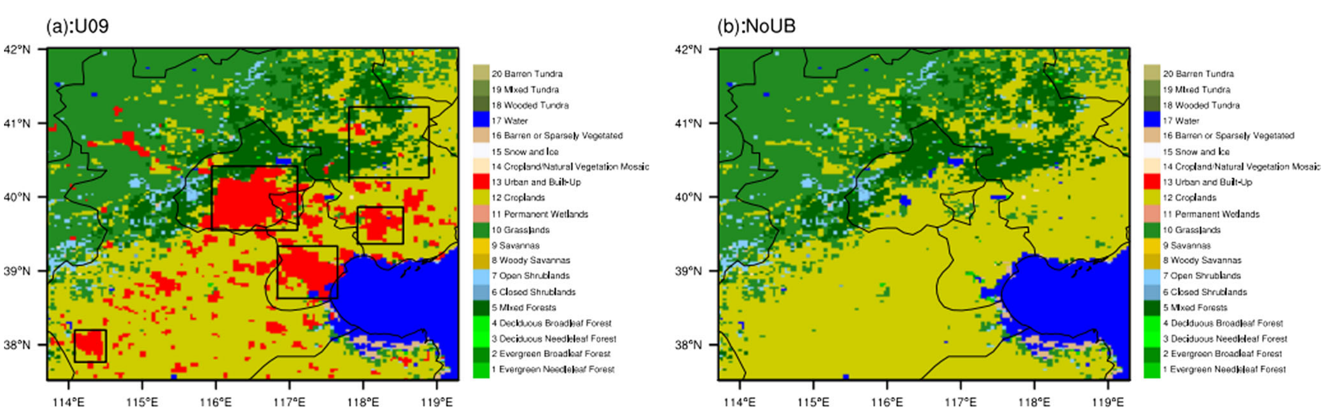

Fig. 2 The land use classifications used in WRF/UCM simulations. **a** With the urban land use fraction updated based on the 2009 remote sensing data products. **b** With the urban land use removed

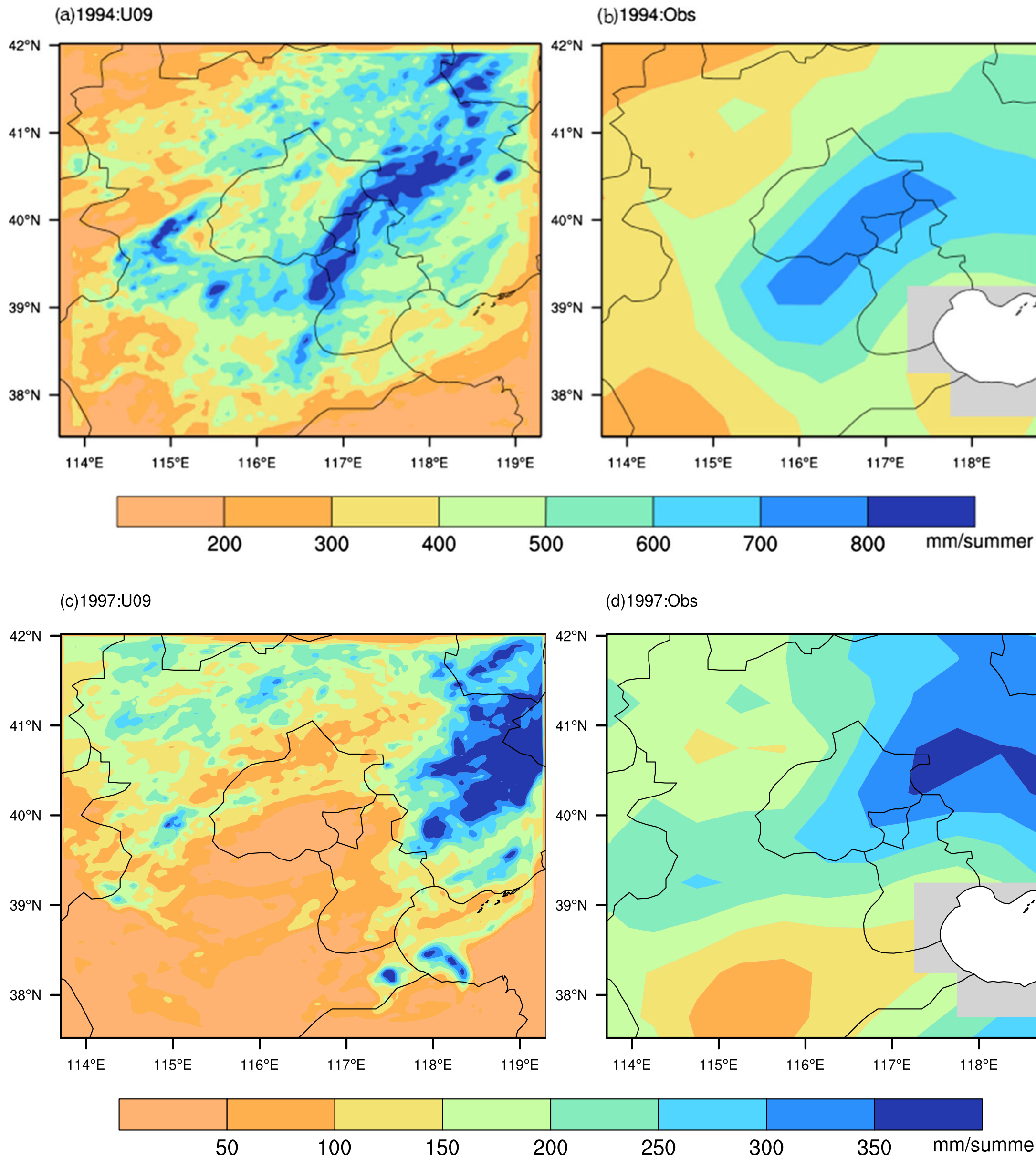

Fig. 3 Spatial pattern of 1994 and 1997 summer rainfall (unit: mm) in Beijing–Tianjin–Hebei: U09 (**a**, **c**), observation(**b**, **d**)

In this paper, we selected the extreme dry and wet years (1994 and 1997) to compare the impact of urbanization on summer rainfall in Beijing–Tianjin–Hebei metropolis.

The motivations for this study are summarized as follows: (1) to explore whether the urbanization has different influence on summer rainfall in the dry and wet year, (2) to determine quantitatively the difference, and (3) to explore the potential mechanism.

2 Data and methodology

In this study, WRF (version 3.5) coupled with a single-layer urban canopy model (SLUCM) is used. SLUCM takes the urban building geometry and the associated radiative, thermal, and moisture effects into account in its surface energy budgets and wind shear calculations (Miao et al. 2009, 2010). This model includes shadows from buildings, canyon orientation, diurnal variation of azimuth angle, reflection of short and long wave radiation, wind profiler in the canopy layer and multi-layer heat transfer equation for roof, wall, and road surfaces (Kusaka and Kimuro 2004; Lin et al. 2008). WRF/SLUCM improves the characteristics of urban thermodynamic and dynamic influences, which accurately reproduces the diurnal range and spatial distribution of the urban heat island, diurnal variation of wind speed and wind direction, the mountain breeze circulation and heat island circulation, and atmospheric turbulence of boundary layer (Miao et al. 2009; Kusaka et al.

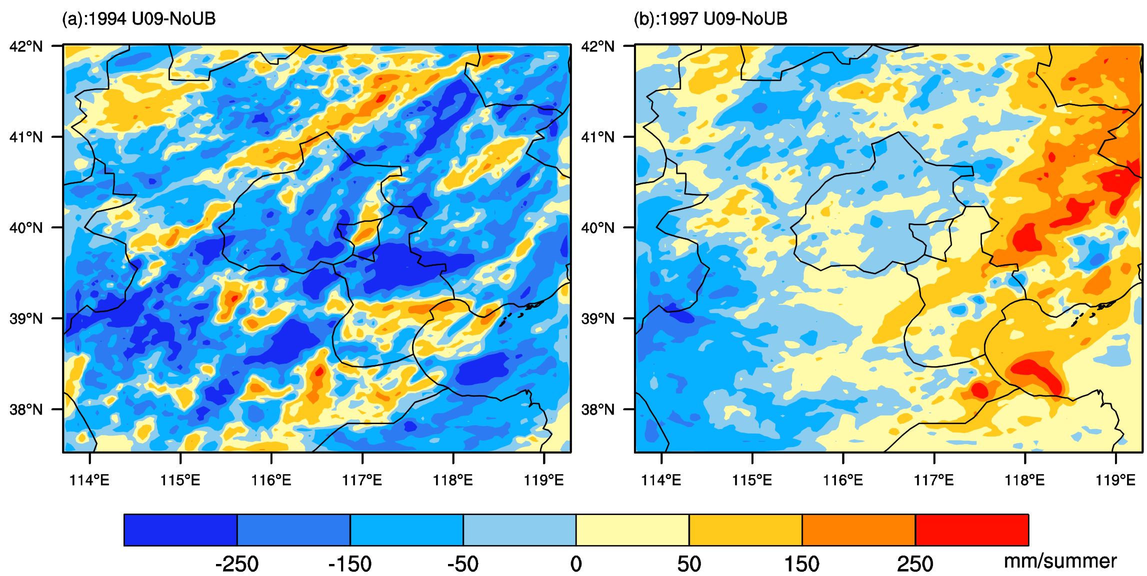

Fig. 4 Spatial pattern of the difference in 1994 (**a**) and 1997 (**b**): summer precipitation between control run and sensitivity run (unit: mm)

2009; Wang et al. 2012). It can also well describe the variation of meteorological elements and the distribution of precipitation in severe convective weather process (Zhang et al. 2007; Wu and Tang 2011; Zheng et al. 2013). Such coupled mesoscale atmospheric–urban modeling system enables us to study urban effects.

Three one-way nested model domains with spatial resolutions of 30, 10, and 3.3 km are configured for the current study. The Lambert conformal map projection is used for the model horizontal coordinates with the central point at 38°N, 118°E. In the vertical, the grid contained 35 terrain-following eta levels from the surface up to 50 hPa. As shown in Fig. 1, the innermost domain provides a full coverage of the Beijing–Tianjin–Hebei metropolitan region. The main physical parameterizations include the rapid radiative transfer model (RRTMG) (Iacono et al. 2008), the WRF single-moment five-class scheme microphysical parameterization (WSM5) (Hong et al. 2004), the Kain–Fritsch convective parameterization (K-F) (Kain 2004), the Yonsei University (YSU) planetary boundary layer (PBL) scheme (Noh et al. 2003), and the Noah land surface model (Chen and Dudhia 2001) with SLUCM. Initial and boundary conditions of the large-scale atmospheric conditions are provided by the six-hourly 0.75° × 0.75° European Center for Medium range Weather Forecasts (ECMWF) reanalysis data, including surface and upper air. We perform the simulations from 00:00 UTC on 21 May to 00:00 UTC on 1 September for the years 1994 and 1997. Mode results in summer (June to August) over the innermost domain (D3) are used for further analysis. The results are output 1 h a time.

The land cover data used in this study is the Model Land Cover Data sets version 1.0, obtained from Earth Observation of Climate Change (EOCC) research group (see http://green.tea.ac.cn/) (Hu and Jia 2010). It includes data of 2009 with three horizontal resolutions (30, 10, and 3.3 km), providing the nested land surface information input for regional climate model simulation. We design two different urban land use scenarios for numerical experiments (Fig. 2): (1) U09 (control simulation; Fig. 2a), the urban land cover fractions are updated based on the 2009 land use data; (2) NoUB (sensitivity simulation; Fig. 2b), with all urban land cover fractions removed and other land cover fractions increased proportionately. If the urban land cover fraction in a grid cell is 100%, we replace the urban land cover fraction by interpolating from the fractions of surrounding land cover types. The boxes in Fig. 2a represent the urban regions including Beijing, Tianjin, Tangshan, and Shijiazhuang, as well as downwind area of these urban agglomerations. The downwind area is consistent with our previous study (Zhang et al. 2015), which we can see from the 10 m and 850 hPa wind (figure ellipsis). The 10-m wind field showed that southerly winds dominate over Beijing and Tangshan, followed by southeasterly and southwesterly winds. Southeasterly winds are the most frequent over Tianjin. According to the 850-hPa wind field, there is a uniform southwesterly trend at Beijing–Tianjin–Hebei region. We define the downwind intersection region as "DOWN" region (Fig. 2a). The ranges of light rain, moderate rain, heavy rain, and rainstorm are 0–10, 10–25, 25–50, and ≥50 mm, respectively.

3 Validation of control case

We used the gridded precipitation dataset with resolution of 0.5° latitude by 0.5° longitude to validate the performance of the model. The gridded data is based on the interpolation from over 2400 observing stations in China Meteorological Data Sharing Service System. The thin plate spline (TPS) method is applied in this interpolation.

Table 1 The difference in rainfall amount between U09 and NoUB of different regions

Unit: mm	Beijing	Tianjin	Tangshan	Shijiazhuang	DOWN	Beijing–Tianjin–Hebei
1994	−141.35	−29.23	−133.95	−46.43	−87.96	−80.13
1997	−2.93	45.07	103.8	−128.73	124.84	14.70

Figure 3 displays the spatial pattern of simulated and observed 1994 and 1997 summer rainfall in Beijing–Tianjin–Hebei region. The simulated results were from U09 (control run; Fig. 3a, c), which was more consistent with the observations compared with NoUB run (sensitivity simulation; figures not shown). In general, the impact of urban land use on precipitation is well captured by the WRF/UCM model. For the year 1994 (Fig. 3a, b), the simulated spatial distribution of precipitation is consistent with the observation, so was the location and intensity of precipitation center. There were some small differences between the observed and simulated precipitation due to their different resolutions. The simulated intensity of precipitation center is slightly larger than that of the observation. For 1997 (Fig. 3c, d), WRF model reproduces well both the strong and weak precipitation centers in northeastern and southwestern part of Beijing–Tianjin–Hebei region. However, the model tends to underestimate the precipitation in Beijing and south region of Beijing. On the whole, the simulated results are reasonable and credible to do further analysis.

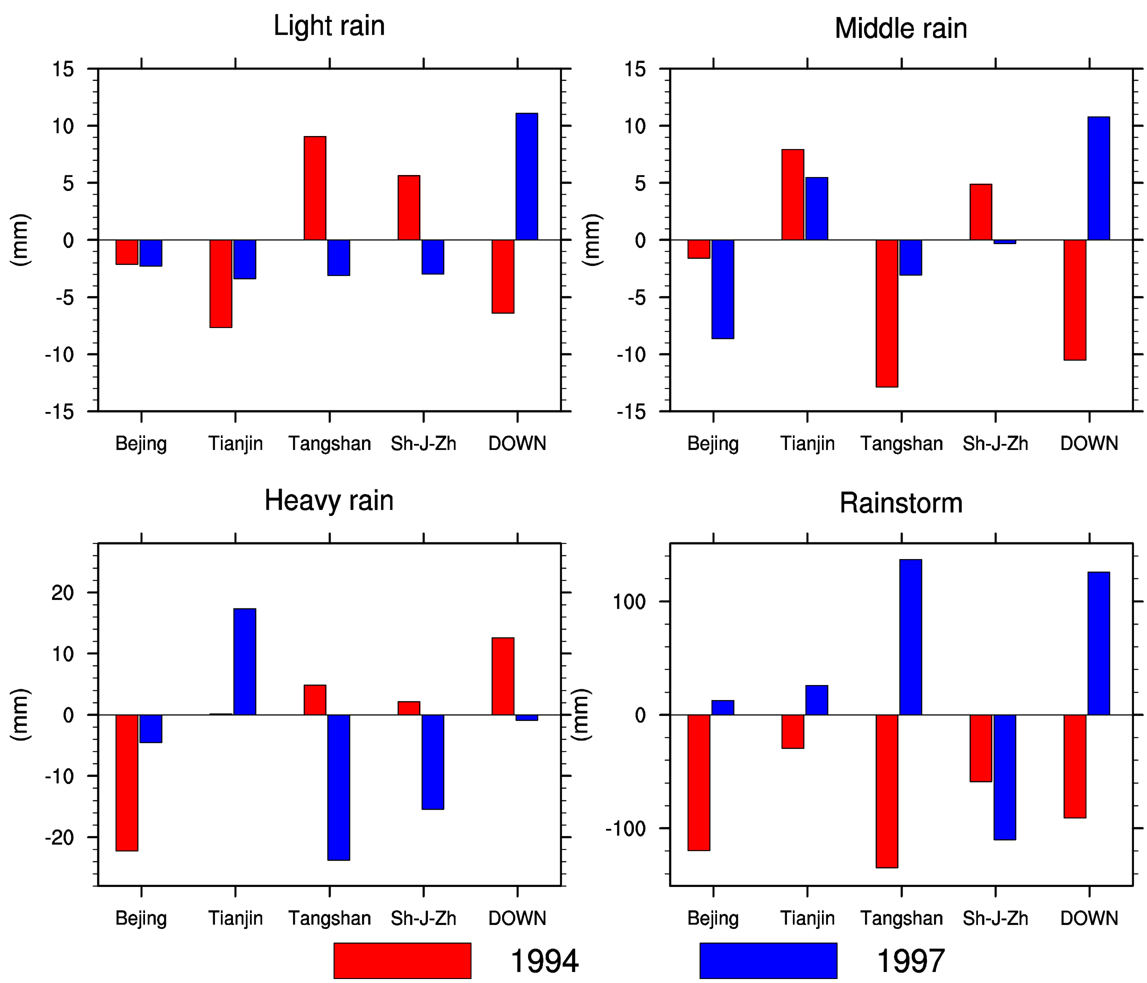

Fig. 5 The difference in rainfall amount (light rain, moderate rain, heavy rain, and rainstorm) of 1994 and 1997 between U09 and NoUB tests (unit: mm)

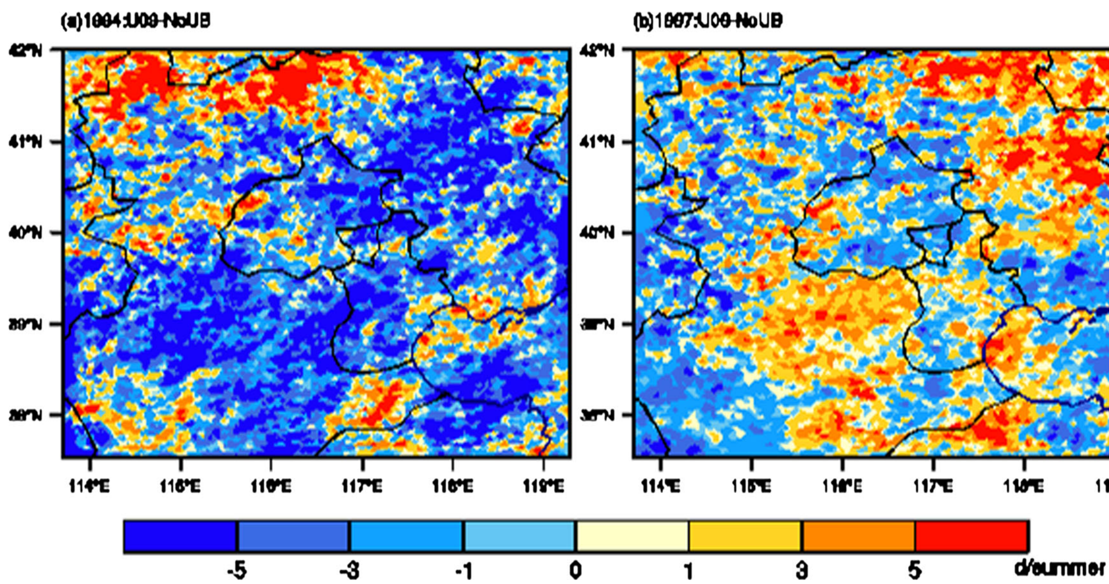

Fig. 6 The same as Fig. 4, but the difference of rainfall frequency (unit: day)

4 Urbanization effect on summer rainfall under dry and wet backgrounds

4.1 Urbanization effect on summer rainfall amount

Figure 4 shows the pattern of difference in rainfall amount between the U09 and NoUB tests, for 1994 (Fig. 4a) and 1997 (Fig. 4b), respectively. It can be seen that the patterns differ in the two extreme years, and this indicates that urbanization effect on precipitation cannot be generalized even in the same city area. The impacts may vary under different climate backgrounds. In 1994, rainfall amount decreases over the urban areas and most of the surrounding areas of the metropolis because of urbanization effect, even in the downwind area. Table 1 shows the region mean values of rainfall amount difference between the U09 and NoUB in different regions. It can be seen that the precipitation differences in Beijing, Tianjin, Tangshan, Shijiazhuang, and DOWN are negative in 1994, and the decreases are most in Beijing and Tangshan (−141.35 and −133.95 mm). In the dry year 1997, there is also a decrease in southwestern area of Beijing–Tianjin–Hebei, and the average rainfall in Shijiazhuang city is reduced by more than 100 mm (Table 1) due to urbanization. In contrast, the rainfall amount increases over the downwind area of the northeast metropolis and Tangshan region, with the average increment reaching 100 mm. Thus, it is inferred that the existence of the urban agglomeration intensifies the drought in the southwestern part of metropolis in 1997.

For the wet year 1994, the light rain, moderate rain, heavy rain, and rainstorm are reduced in different degrees (Fig. 5) over the urban area of Beijing due to the urban land use modification. The rainstorm (above 50 mm) is decreased in all five regions, including Beijing, Tianjin, Tangshan, Shijiazhuang city, and the downwind area. However, the responses of other levels are not consistent. For the dry year 1997, the rainstorm amount increased over Beijing and Tangshan city due to urbanization, while the light rain, moderate rain, and heavy rain are decreased. In details, the light rain is decreased in all regions in addition to the downwind of the urban area; the rainstorm amount is increased in all regions except for Shijiazhuang city. The rainfall produced by rainstorm accounts for 30–40% of the total precipitation in Beijing–Tianjin–Hebei, which is an important factor to the change in total precipitation.

4.2 Urbanization effect on summer rainfall frequency

Figure 6 shows the pattern of differences in rainfall frequency between the U09 and NoUB for 1994 (Fig. 6a) and 1997 (Fig. 6b). It can be seen that the urbanization has significantly different impact on the precipitation frequency in the two extreme years. In 1994, due to urbanization, the precipitation

Table 2 The difference in rainfall frequency between U09 and NoUB of different regions

Unit: day	Beijing	Tianjin	Tangshan	Shijiazhuang	DOWN	Beijing–Tianjin–Hebei
1994	−2.16	−3.99	−2.01	−1.17	−4.0	−2.06
1997	−0.69	0.40	−1.29	−2.35	2.83	0.16

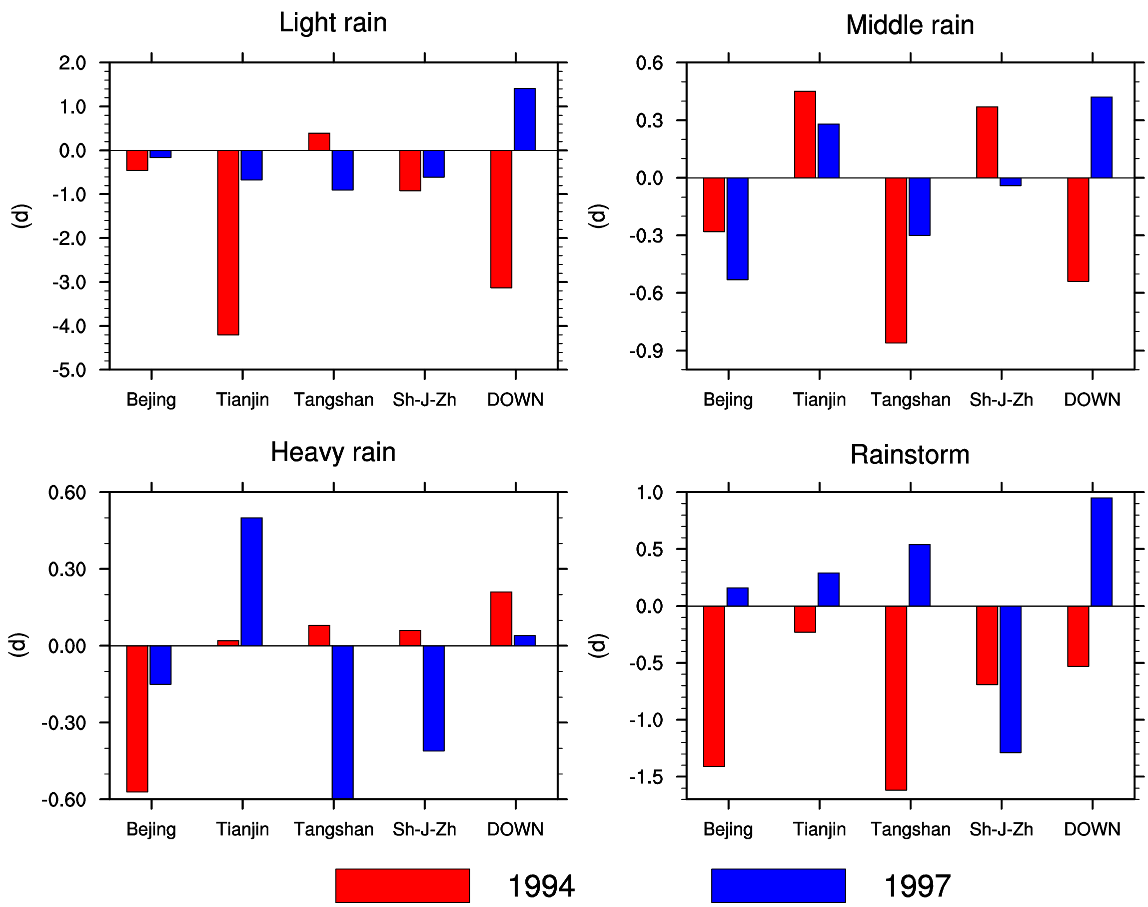

Fig. 7 The same as Fig. 5, but the difference of rainfall frequency (unit: day)

frequencies are decreased in most urban areas and the surrounding areas. The decrease value of each region is shown in Table 2. Tianjin city experienced the most reduction (up to −3.99d). In 1997, the rainfall frequencies are increased in both the upwind and downwind of the urban agglomerations, reaching 5 days at most. However, the rainfall frequencies are decreased to different degrees over the urban areas of Beijing, Shijiazhuang, and Tangshan City (Table 2). Figure 7 shows the histogram of rainfall frequency differences, including light rain, moderate rain, heavy rain, and

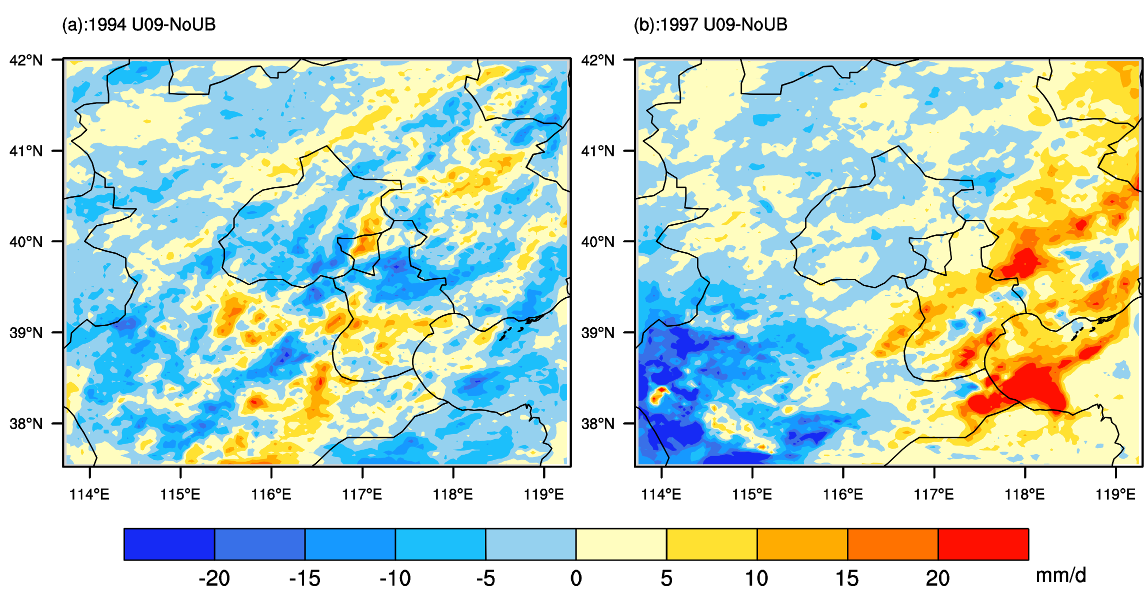

Fig. 8 The same as Fig. 4, but the precipitation intensity (unit: mm/day)

Table 3 The difference in rainfall intensity between U09 and NoUB of different regions

Unit: mm/day	Beijing	Tianjin	Tangshan	Shijiazhuang	DOWN	Beijing–Tianjin–Hebei
1994	−3.76	3.27	−3.56	−1.64	0.51	−1.38
1997	−0.03	6.4	9.28	−19.78	4.3	0.67

rainstorm. The change of rainfall frequency is similar to that of rainfall amount, and it is not repeated here.

4.3 Urbanization effect on summer rainfall intensity

Figure 8 shows the pattern of differences in precipitation intensity. The precipitation intensity is defined as total summer rainfall frequency divided by total summer rainfall amount. In 1994, the precipitation intensity is decreased in most urban areas of Beijing, Tangshan, and Shijiazhuang, but increased in Tianjin due to urban expansion (Fig. 8a, Table 3). However, the difference is small in downwind area. In 1997, there is an obvious precipitation intensity increase over the urban areas of Tianjin, Tangshan, and the downwind areas (Fig. 8b), and the increase amounts are 6.4, 9.28, and 4.3 mm/day, respectively (Table 3). In addition, the precipitation intensity is decreased remarkably due to urbanization in the southwestern area of Beijing–Tianjin–Hebei metropolis. The average decrease in Shijiazhuang urban area was 19.78 mm/day, while the change in Beijing area was not obvious in the dry year 1997.

4.4 Urbanization effect on diurnal variation of summer precipitation

In 1994, due to urbanization, the precipitation is decreased in most urban areas. In 1997, the precipitation over the urban areas of Tianjin, Tangshan, and downwind is increased, while that in the southwestern area is decreased. To investigate these changes, we also provide the diurnal variation of summer precipitation from simulated results for both the wet year and the dry year. Figures 9 and 10 show the simulated diurnal variation of rainfall amount in different regions for 1994 and

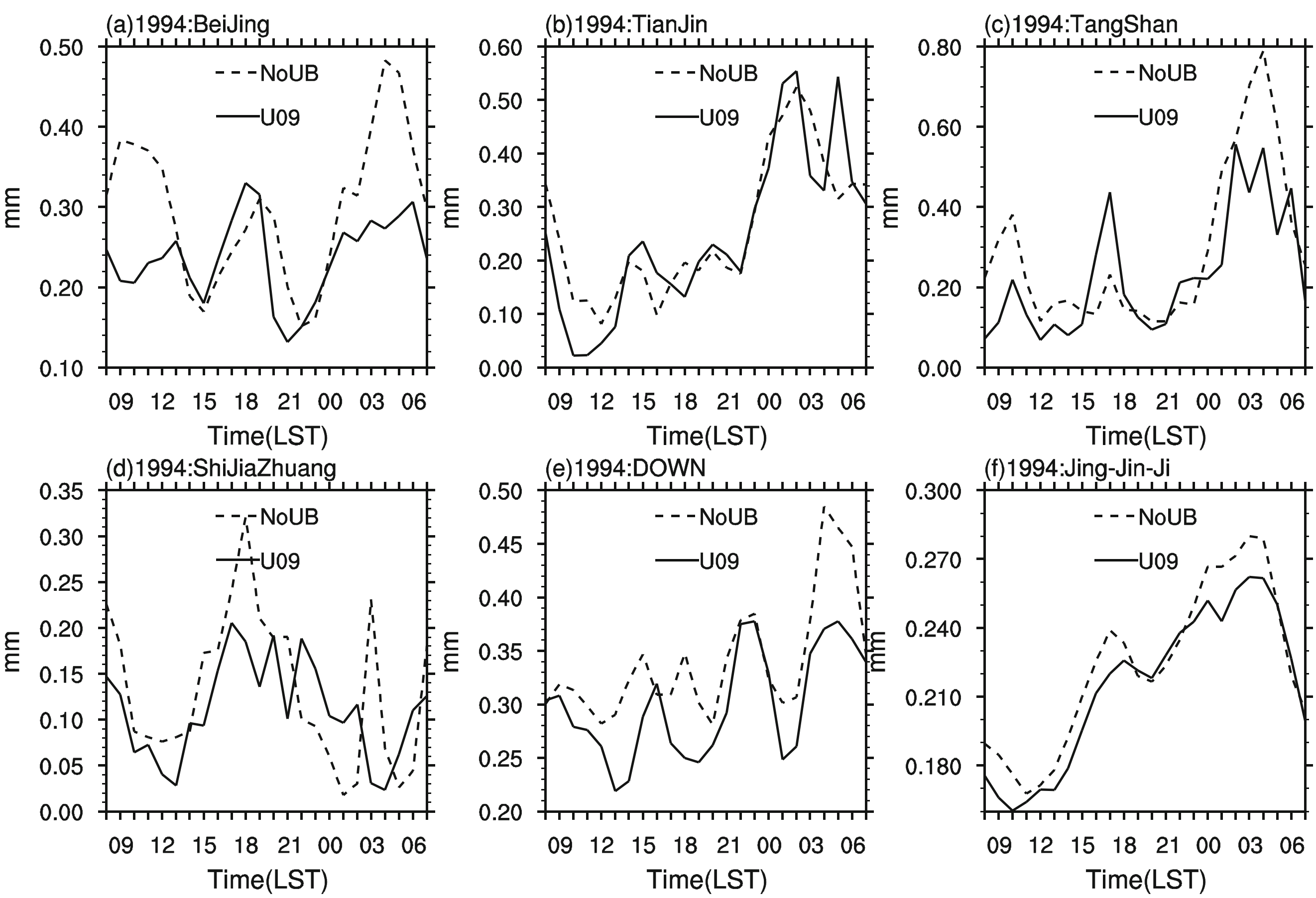

Fig. 9 1994 diurnal variation of summer precipitation depends on U09 and NoUB (unit: mm). **a** Beijing, **b** Tianjin, **c** Tangshan, **d** Shijiazhuang, **e** DOWN, **f** Beijing–Tianjin-Hebei (the x-coordinate signifies Beijing time, the value at 8:00 represents 07:00–08:00 cumulative rainfall, and so on)

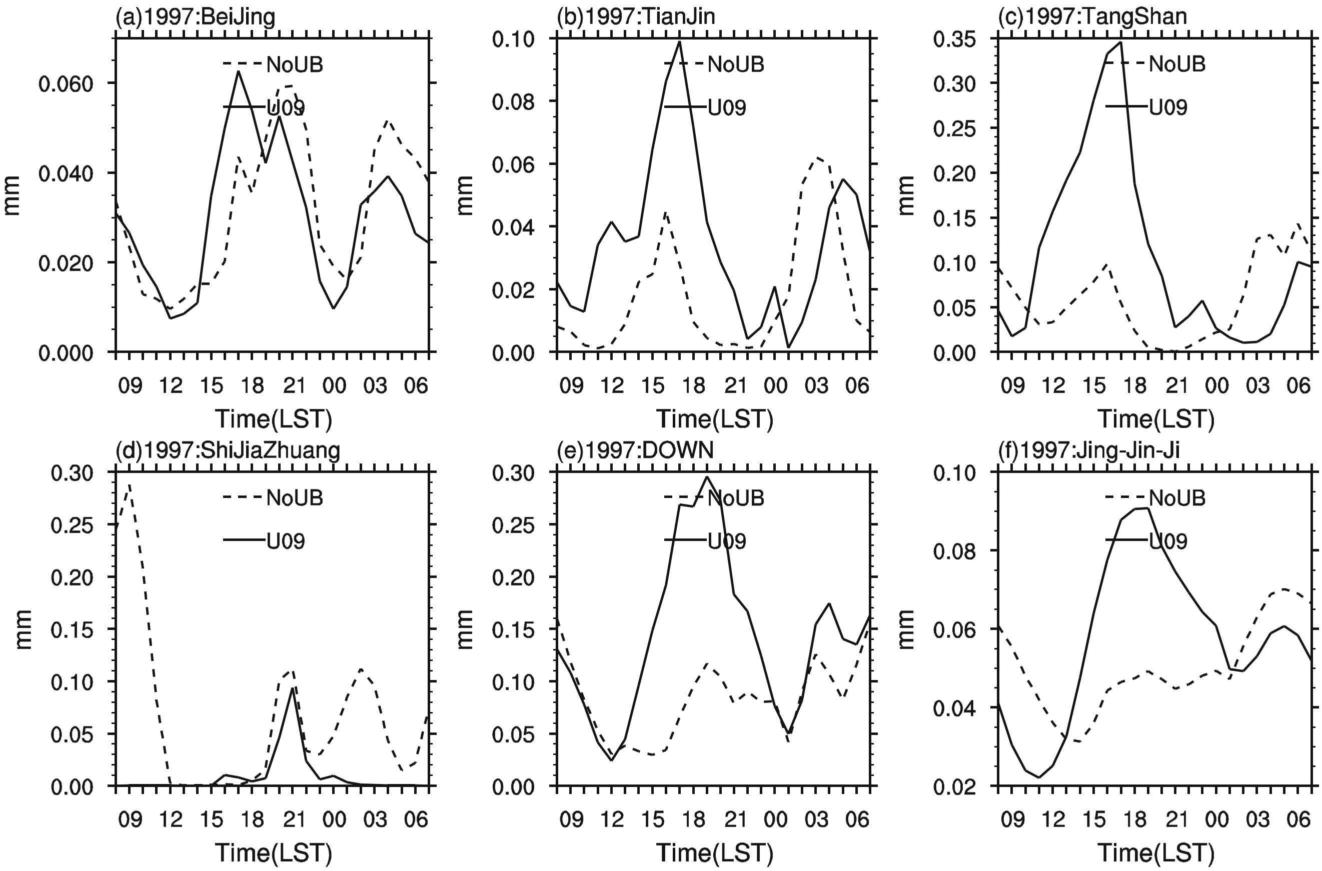

Fig. 10 The same as Fig. 9, but of 1997

1997. It can be seen that the urbanization had significantly different impact on the diurnal variation of summer rainfall in the two extreme years. For the whole region, the precipitation is decreased in most of the day due to urban expansion in1994 (Fig. 9f), while it is increased in the period of 12:00 local standard time (LST) to 0:00 LST in the dry year 1997 (Fig. 10f). For Beijing city, the precipitation is decreased in the period of 12:00 LST to 0:00 LST. However, urban land use condition does not cause obvious change for other periods in 1994 (Fig. 9a). The urbanization does not cause obvious

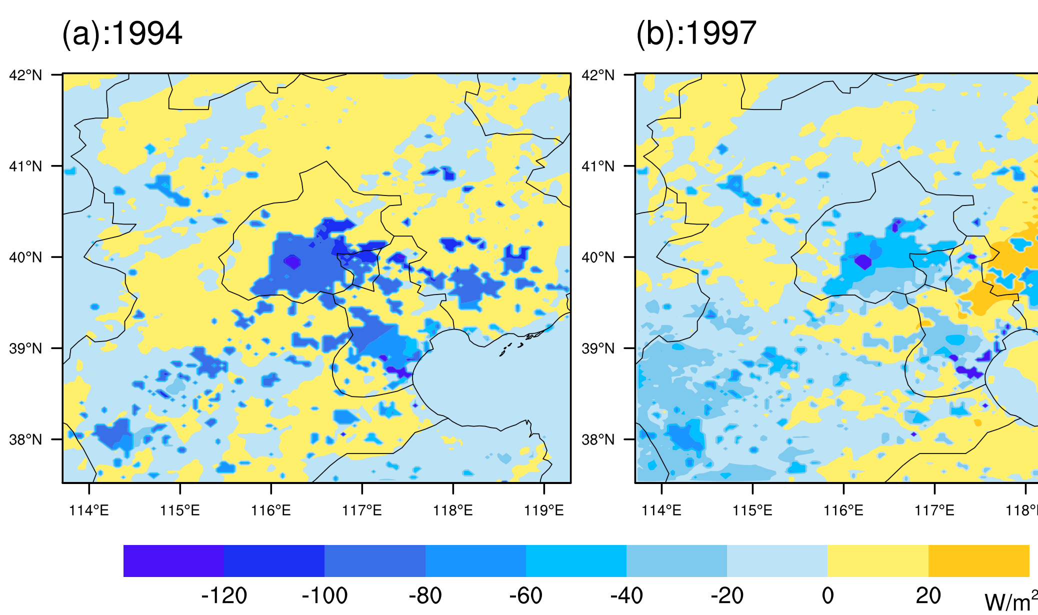

Fig. 11 Spatial pattern of the difference in summer latent heat flux (unit: W/m^2) between U09 and NoUB

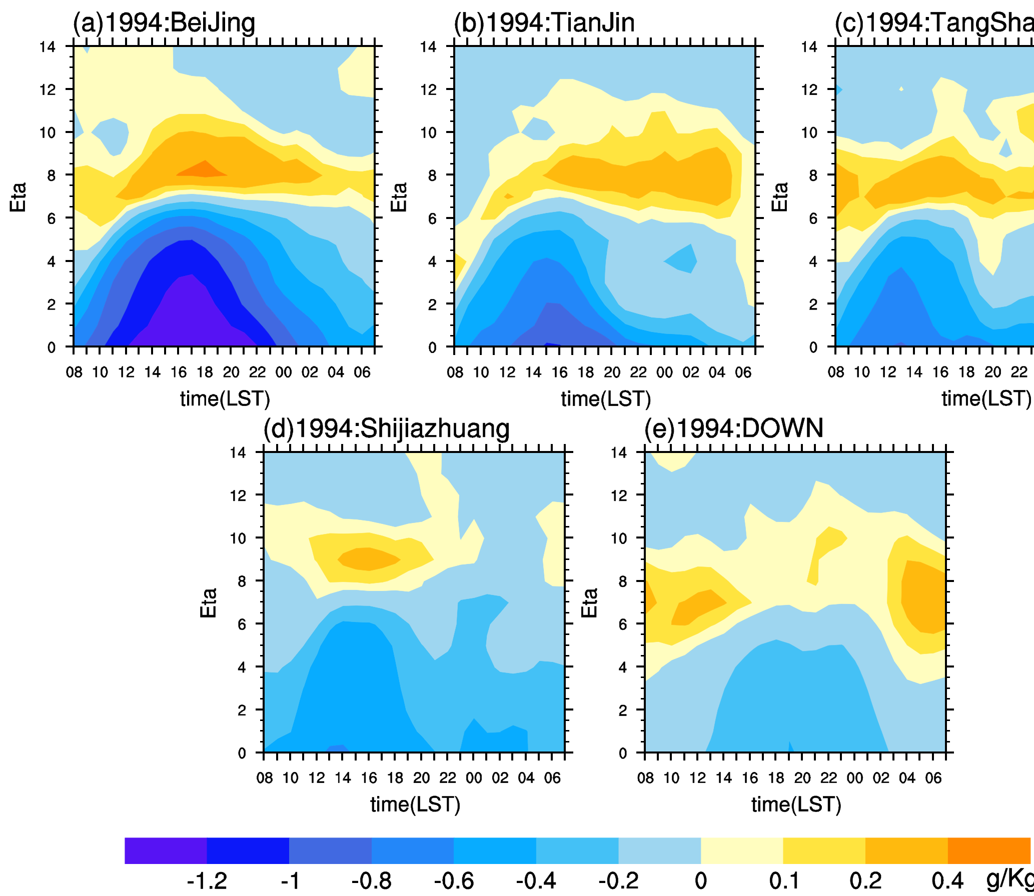

Fig. 12 Diurnal variation of difference in summer water vapor mixing ratio between U09 and NoUB tests in troposphere for 1994 (unit: cm/s): **a** Beijing, **b** Tianjin, **c** Tangshan, **d** DOWN (the corresponding Eta values for 0–14 in y-coordinate are 0.997, 0.988, 0.977, 0.962, 0.944, 0.921, 0.895, 0.860, 0.821, 0.782, 0.742, 0.688, 0.620, 0.558, and 0.500)

difference in the dry year 1997 except for the increase in the period of 3:00 LST to 6:00 LST (Fig. 10a). There was no apparent difference between U09 and NoUB for all periods of the wet year 1994 in Tianjin city (Fig. 9b). The urbanization intensifies the precipitation mainly in daytime in the dry year 1997 (Fig. 10b). Similar change occurred in Tangshan and the downwind areas (Fig. 10c, e). In the wet year 1994, the precipitation of Tangshan decreased in the period of 1:00 LST to 11:00 LST (Fig. 9c), Shijiazhuang (15:00 LST to 20:00 LST and 3:00 LST to 4:00 LST, Fig. 9d), and the downwind area (all day, Fig. 9e), respectively. In the dry year 1997, the urbanization weakens the precipitation for most of the day in Shijiazhuang city (Fig. 10e).

5 The mechanisms related to urban-induced precipitation

There are two possible mechanisms that are related to urban-induced precipitation. One is the urban thermal effect and increased surface roughness which can bring about the enhancement of convergence in lower atmosphere. The other is the reduced water vapor evaporation of urban areas, which results in the decrease of vapor in the boundary layer. The convergence in lower atmosphere is in favor of the development of convection, while the decrease of water vapor in the boundary layer can reduce the convective available potential energy (CAPE) and then the convection is suppressed (Zhang et al. 2009). In this chapter, we will discuss which mechanism is dominant for the wet year 1994 and dry year 1997.

5.1 The change of surface latent heat flux

The dense population in city, the decrease of vegetation cover, and the increase of cement surface lead to the reduction of evaporation and transpiration, and then the surface energy budget and vapor content in lower atmosphere change. Figure 11 shows the spatial distribution of differences in surface latent heat flux between U09 and NoUB. We can see that the surface latent heat flux is decreased in the four urban areas. Compared to the wet year 1994, the augment in the downwind area was more obvious in 1997. The change of surface latent heat flux can affect the vapor content in atmosphere and then modifies precipitation.

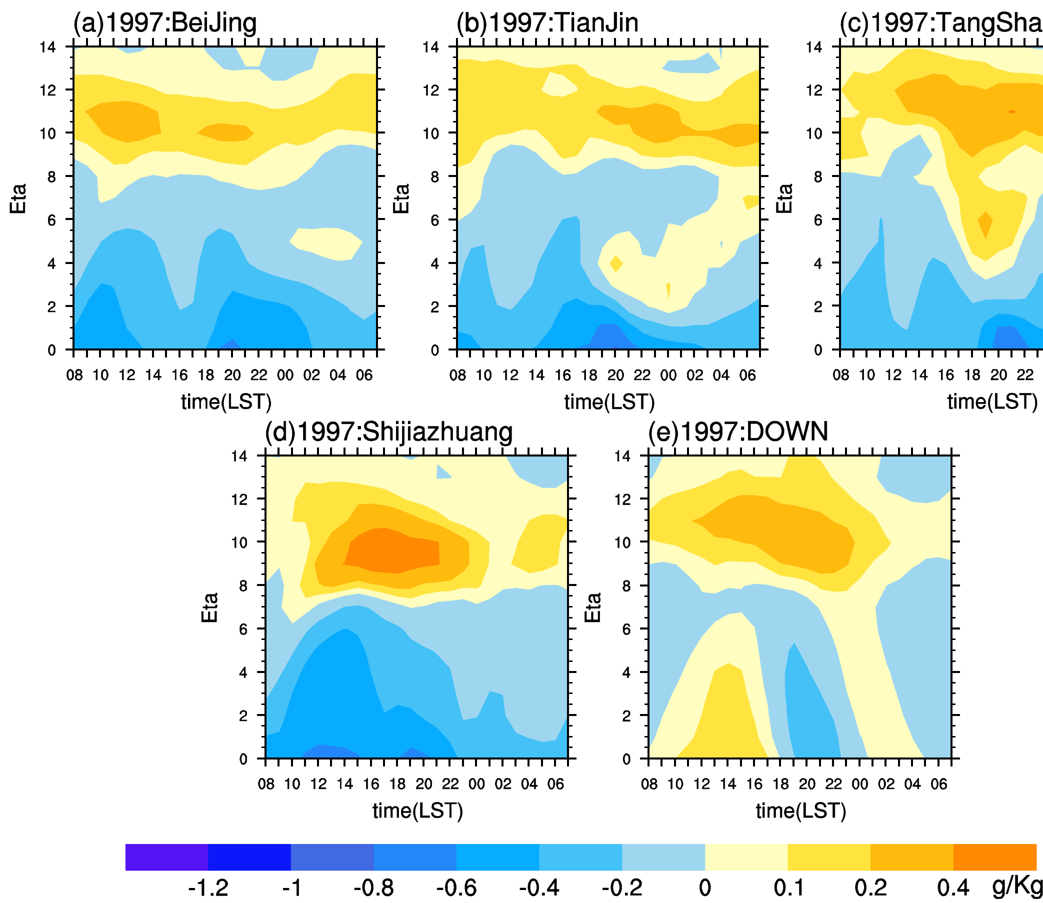

Fig. 13 The same as Fig. 12, but the difference of water vapor mixing ratio for 1997

5.2 The change of water vapor mixing ratio

Figures 12 and 13 display the diurnal variation of difference in summer water vapor mixing ratio between U09 and NoUB in lower troposphere. For the four urban areas in both 1994 and 1997, due to urbanization, the water vapor mixing ratio decreased in lower atmosphere (surface to about 850 hPa), with the largest decrease in Beijing city in 1994 with the maximum value reaching −1.2 g/kg. Overall, the reductions were more visible in the wet year 1994, especially in Beijing, Tianjin, and Tangshan. This indicates that the "dry island effect" may be stronger in wet year. In Beijing, Tianjin, and Tangshan, for the year 1994, the reductions were obvious from 9:00 LST to 22:00 LST, while for 1997, the reducing peak was from 19:00 LST to 22:00 LST. For the downwind area, the water vapor mixing ratio had a slight increase from 10:00 LST to 16:00 LST in 1997. Based on the two mechanisms we have mentioned before, we infer that the suppression effect was stronger than the enhancement effect for the wet year 1994, while it was opposite for Tianjin and Tangshan of 1997. At the height from about 850 to 600 hPa, due to urbanization, the water vapor mixing ratio increased instead, and this change may be caused by the enhancement of convection in the lower atmosphere, which may strengthen the vertical transport of water vapor. Additionally, the positive center in the dry year 1997 was higher than that in 1994.

5.3 The change of the vertical velocity

Zhang et al. (2015) compared the diurnal variation of precipitation and differences of tropospheric vertical velocity between U09 and NoUB for the summer of 2008–2010. They found that the urban land use may suppress (strengthen) the vertical motion in the upper troposphere, resulting in the decrease (increase) of precipitation. By analyzing the vertical velocity of 1994 (Fig. 14) and 1997 (Fig. 15) in the five regions, and comparing with the corresponding diurnal variation of precipitation (Figs. 9 and 10), we also came to the same conclusion.

For the wet year 1994, the precipitation is decreased in five regions (Beijing, Tianjin, Tangshan, Shijiazhuang, and the downwind area) due to the urbanization (Fig. 9). The decrease time periods mainly correspond to the reduction of vertical velocity in upper troposphere (Fig. 14). In 1997, the urbanization induces the increase of precipitation in Tianjin, Tangshan, and the downwind areas (Fig. 10), which coincides with the positive center of the vertical velocity in upper troposphere (Fig. 15). The precipitation is decreased over

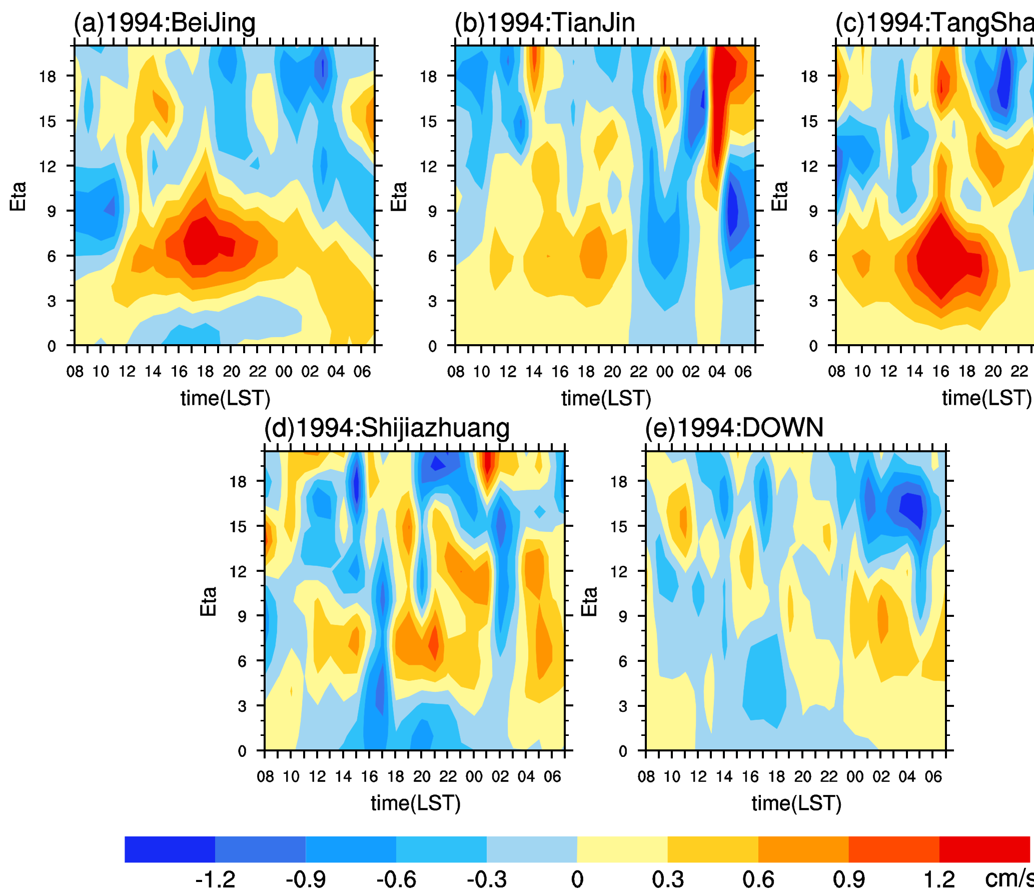

Fig. 14 1994 diurnal variation of difference in summer vertical velocity between U09 and NoUB in troposphere (unit: cm/s): **a** Beijing, **b** Tianjin, **c** Tangshan, **d** DOWN (the corresponding Eta values for 0–19 in y-coordinate are: 0.997, 0.988, 0.977, 0.962, 0.944, 0.921, 0.895, 0.860, 0.821, 0.782, 0.742, 0.688, 0.620, 0.558, 0.500, 0.447, 0.398, 0.353, 0.312, and 0.274)

Shijiazhuang in most of the day due to urbanization (Fig. 10d), corresponding to the negative value in upper troposphere (Fig. 15d). As for the city of Beijing, the vertical velocity in upper troposphere is not weakened significantly (Fig. 15a), and so, the variation of precipitation is not obvious (Fig. 10a). Therefore, the inhibition (enhancement) of the deep convection may be an important reason for the decrease (increase) of precipitation. The urbanization has significant different impact on vertical motions for the years 1994 and 1997. It could be mainly due to the differences between the two climate backgrounds, partly because of the different urbanized modification on water vapor condition.

6 Summary

In this study, we conduct a comparative study on the potential sensitivity of summer rainfall to the influence of urban expansion at different climate situations using WRF-SLUCM model. The wet year 1994 and the dry year 1997 are selected for comparison. We find that the influence of urbanization on summer precipitation differs apparently in the two extreme years, indicating that urbanization effect on precipitation cannot be generalized even in the same metropolis. The effect of urbanization should be discussed under a particular climate background. The main results are summarized as follows.

(1) In 1994, the rainfall and rainfall frequency are decreased due to urbanization over the urban areas and most of the surrounding areas of the metropolis. Among them, the rainfall is decreased most in Beijing and Tangshan. The precipitation intensity is decreased in most urban areas of Beijing, Tangshan, and Shijiazhuang, but increased in Tianjin, due to urbanization. In 1997, there is a remarkable decrease in both the rainfall amount and intensity in the southwestern area of Beijing–Tianjin–Hebei metropolis. In contrast, there is an increase over the downwind area of the northeast metropolis, Tianjin, and Tangshan region. In addition, the urbanization has a significant impact on the diurnal variation of summer precipitation and the effects differ in the two extreme years.

(2) Surface latent heat flux is suppressed to different degrees in the urban areas due to urbanization, while it was enhanced in downwind area of the urban agglomerations,

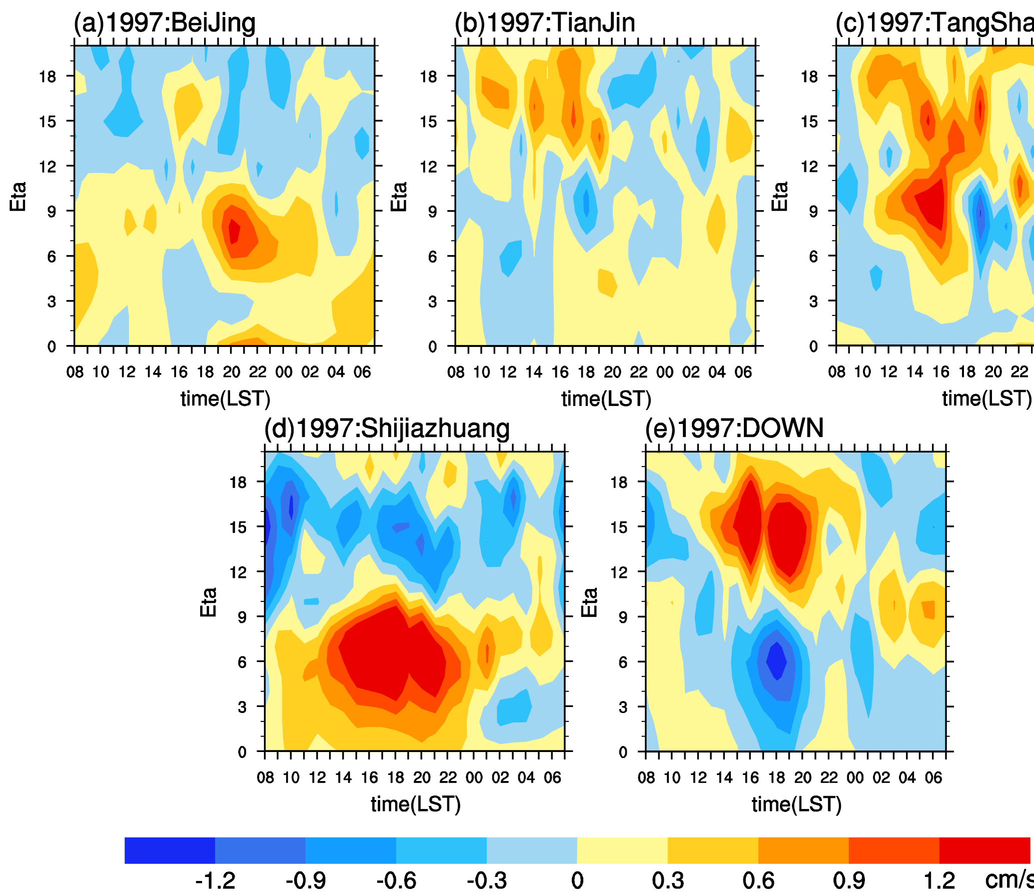

Fig. 15 The same as Fig. 14, but the difference in vertical velocity of 1997

and the enhancement was more obvious in 1997. Urban expansion reduces the water vapor mixing ratio apparently from surface to 850 hPa in urban area of Beijing, Tianjin, Tangshan, and Shijiazhuang, while the water vapor mixing ratio is increased from 850 to 600 hPa. In general, the reduction of water vapor mixing ratio in 1994 is greater than that in 1997. This result indicates that the "dry island effect" in the lower atmosphere caused by urbanization is stronger in the wet year than that in the dry year. For the wet year 1994, the inhibition of convective activity induced by the "dry island effect" is greater than the enhancement of convergence from not only the "urban heat island effect" but also the increased surface roughness. Therefore, the precipitation is decreased in most urban areas of Beijing–Tianjin–Hebei metropolis. The situation may be opposite in Tianjin, Tangshan, and downwind areas of 1997.

(3) Through the analysis of the vertical velocity, we find that the urbanization has significant impact on the vertical motion in the troposphere and the effects largely differ in the wet year and the dry year. Results also indicate that urbanization may suppress (strengthen) the vertical motion in the upper troposphere, resulting in the decrease (increase) of precipitation, which is consistent with the results of Zhang et al. (2015) for 2008–2010.

The results in our study suggest the potential sensitivity of summer rainfall to urbanization at different climate situations to some extent. However, the conclusions require further examinations with more case studies. And the effects cannot be generalized as well.

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