

Impact of Urban Surface Characteristics on Summer Rainfall in the Beijing-Tianjin-Hebei Area

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Abstract: Utilizing daily precipitation data from 24 meteorological stations and results from the Weather Research and Forecasting (WRF) model / Urban Canopy Model (UCM), the impact of urban surface characteristics on summer rainfall in the Beijing-Tianjin-Hebei area was investigated. Results indicated that precipitation at most sites in this region has reduced during the last 30 years, and those sites whose precipitation has reduced the most are mainly centered in the Beijing-Tianjin-Tangshan metropolis. Urbanization is one of the possible factors affecting the precipitation in the Beijing-Tianjin-Hebei area. Comparison of the model results from the control run and sensitivity run indicated that rainfall and rainfall frequency clearly decreased in the Beijing-Tianjin-Tangshan metropolis due to the urban surface. Meanwhile, an increase in rainfall and rainfall intensity was apparent downwind of the urban agglomeration; precipitation above 50 mm changed significantly due to the urban surface, and the contribution to the total could be more than 60%. The percentage of rainfall above 50 mm declined by 6%–20% in the Beijing-Tianjin-Tangshan metropolis, while it increased by 8% downwind. The diurnal structure of rainfall changed due to urbanization: precipitation in Beijing and Tangshan mainly reduced due to urbanization, and the increase downwind occurred mainly in daytime. The findings of this study suggest that the inhibition or enhancement of deep convection, as influenced by changes in latent heat flux and convective available potential energy due to the urban surface, may explain the changes in precipitation.

Keywords: Beijing-Tianjin-Hebei; Weather Research and Forecasting model Urban Canopy Model; Urban surface characteristics; Urbanization; Precipitation

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1 Introduction

In climatology, urbanization refers to the process of physical changes (reflectivity, thermal conductivity, Bowen ratio and thermal capacity, etc.) and dynamic changes (roughness) of land caused by land-use changes during human activities (Oke, 1982). Local climate in and around cities could be influenced by changes of energy budget, temperature and humidity, because of the smaller reflectivity, higher thermal capacity and impenetrability of cities. With the frequent occurrence of floods and droughts in recent years, the impact of urbanization on rainfall has attracted increasingly more attention. Horton (1921) pointed out that rainstorm was more likely to happen around big cities as early as in 1921. Later, Changnon (1968, 1979),

Huff and Changnon (1972) found that precipitation in St. Louis and within a 50–75 km radius of its downwind region increased by 9%–17% in warm seasons due to urbanization through urban meteorological comprehensive observation and measurement experiments (METROMEX) and pointed out that the impact of urbanization on precipitation was more obvious in warm seasons which were dominated by mesoscale forced convection. Thereafter, there were always new results of observation and simulation that supported the conclusions of METROMEX project (Chow and Chang, 1984; Jauregui and Romales, 1996; Burian and Shepherd, 2005). Shepherd and Burian (2003) analyzed the temporal and spatial variation of precipitation in Houston through the data of Tropical Rainfall Measuring Mission (TRMM), and found that average precipitation increased by 28% within the 30–60 km radius of the downwind region. Chen et al.

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(2007) found that the frequency of lightning storm increased by 67% in the afternoon in Taipei due to urbanization. Niyogi et al. (2011) and Yang et al. (2014) pointed out that the severe convection system split up in the upwind zone of the city, then combined in the downwind zone, which may lead to the increase of heavy precipitation in the downwind zone. Recently, some researchers proposed that the decrease of precipitation could be caused by decrease of local evaporation in underlying surface and climatic effects of aerosols in cities (Givati and Rosenfeld, 2004; Kaufmann et al., 2007; Rosenfeld et al., 2007; Wang et al., 2012). Guo et al. (2005) conducted a numerical simulation on a severe convection weather process in Beijing by using Mesoscale Model 5 (MM5), and pointed out that the decrease of accumulated precipitation (especially in urban district) was due to underlying surface of the city. Zhang et al. (2009) indicated that the decrease summer rainfall in the northeast of Beijing may be related with urbanization through analysis of precipitation data from 1981 to 2005 in Beijing and designed several kinds of underlying surface scenes to simulate two severe rainfall processes, and the results showed that urbanization led to decrease of local evaporation, increase of sensible heat flux, more even mixture of water vapor in boundary layer and reduction of convective available potential energy, so as to suppress the development of convective systems.

In recent years, urban agglomerations are formed due to continuous development and expansion of cities. Studies indicated that urban agglomeration would result in more concentrated and stronger heat island (Chen et al., 2006; He et al., 2007). Many researches on the impact of urbanization on precipitation in urban agglomeration in China have been conducted (Li et al., 2009; Qian et al., 2010; Li et al., 2011; Meng et al., 2012; Wan et al., 2013). Most of these work utilized observation data in analyses (Li et al., 2009; Qian et al., 2010; Li et al., 2011), and some studies used numerical simulations to analyze the actual cases of convective precipitation (Meng et al., 2012; Wan et al., 2013). However, the impact of urbanization on precipitation could hardly be separated from internal variability of climate only by observation data, while uncertainty exists in researches on the single case of a weather process. In addition, there are large differences in effects of different cities on precipitation due to complexities, discontinuities and strong localization of precipitation processes. Therefore, numerical simulations on longer duration and more cities as well as urban agglomerations need to be adopted to study the influence of urbanization on precipitation. In this paper, observation data on daily precipitation and numerical simulation results of WRF/UCM would be used to study the impact of surface characteristic changes caused by urbanization on summer rainfall in the Beijing–Tianjin–Hebei area. Daily rainfall above 0.1 mm is regarded as a criterion to count the frequency of summer rainfall.

2 Change characteristics of summer rainfall in Beijing–Tianjin–Hebei urban agglomeration

The urban agglomeration in the Beijing–Tianjin–Hebei area is one of the three biggest urban agglomerations in China, and the city area in the Beijing–Tianjin–Hebei area increased rapidly in the last 30 years. The Beijing–Tianjin–Hebei area is located in temperate monsoon region, where precipitation mainly occurs in summer (from June to August), and the summer precipitation can account for 75%–85% of total precipitation in the whole year (Huang et al., 2011). The precipitation mainly happens in the second half of July and the first half of August. Due to the influence of East Asian summer monsoon, inter-annual variation of precipitation in the Beijing–Tianjin–Hebei area is great (Fig. 1). The terrain of the Beijing–Tianjin–Hebei area is high in the northwest and low in the southeast (Fig. 4b), and there is a certain relationship between precipitation distribution and terrain. High precipitation zones are located in windward slope in front of Yanshan Mountains and Taihang Mountains and southeastern coastal areas (Zhang et al., 2010). The northwest areas are dominated by light rain with more rainy days and less total precipitation, while heavy rain and rainstorm occur more frequently in southeastern coastal areas.

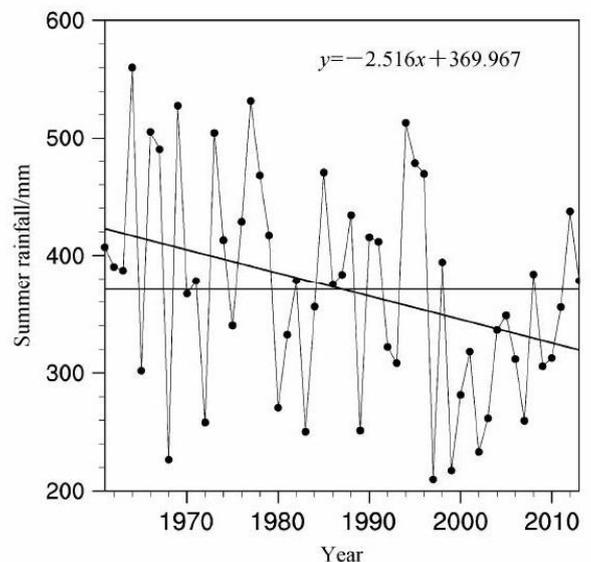


Fig. 1 The interannual variation of summer rainfall (unit: mm) in the Beijing-Tianjin-Hebei area during 1961–2010. The regression equation is indicated in the top-right corner, and the corresponding regression line (downward-sloping, left to right) is shown

There was less precipitation in the Beijing–Tianjin–Hebei area from the late 1990s to the early 21st century (Fig. 1). The inter-annual variation of precipitation decreased obviously, compared with that before the 1990s. It may be affected by human activities to a certain extent besides natural variability of climate system.

Fig. 2 shows the spatial distribution of linear trends of the summer rainfall obtained from 24 meteorological stations in the Beijing–Tianjin–Hebei area during 1981–2010. It can be seen that rainfall increases slightly only at three stations (Langfang, Botou and Huanghua), and the maximum value of change trend is only 6 mm/10a during the recent 30 years of rapid urbanization. The change trends are negative in other stations, of which 11 stations are over the 80% significance level. Stations with apparent decreased precipitation are mainly concentrated in the urban areas of Beijing–Tianjin–Tangshan. The decreasing trend is over -60 mm/10a in Beijing, Miyun and Tangshan, and -45.7 mm/10a and -34.1 mm/10a in Baodi and Tanggu of Tianjin, respectively. Moreover, rainfall frequency shows a negative trend in most stations (figure not shown), with a maximum of -3.4 d/10a. In the Beijing–Tianjin–Tangshan, rainfall intensity shows a negative trend as well (figure not shown), with a decreasing value between -1.3 mm/10a and -0.25 mm/10a. In order to investigate the relative contribution of precipitation at different levels to the total precipitation, the precipitation is divided into 10 classes in this paper: 0 – 5 mm, 5 – 10 mm, 10 – 15 mm, 15 – 20 mm, 20 – 25 mm, 25 – 30 mm, 30 – 40 mm, 40 – 50 mm, 50 – 100 mm, and ≥ 100 mm. Fig. 3 shows the contribution rates (the percentage between absolute values of variation trend of precipitation at every level and total precipitation) of precipitation variation trends at different levels at stations of Miyun, Beijing, Tangshan and Tanggu. It can be seen that contribution rates of precipitation variation trends at almost all levels are negative. Positive variation trends only exist in precipitation with 10–15 mm and 40–50 mm at Tangshan station and precipitation with moderate intensity (10–25 mm) and 40–50 mm in Tanggu station, while there are negative trends for other precipitation levels in Tanggu. Among them, contribution rates of precipitation variation trends above 50 mm are more than -70% at Beijing, Tangshan and Tanggu stations and that was about -50% at Miyun station, and precipitation above 50 mm accounts for 30% of total precipitation. These results are consistent with those of Zhang et al. (2009) and Li and Ma (2011). It indicates that the decrease of precipitation in the Beijing–Tianjin–Tangshan is caused by reduction of extreme precipitation to a large extent.

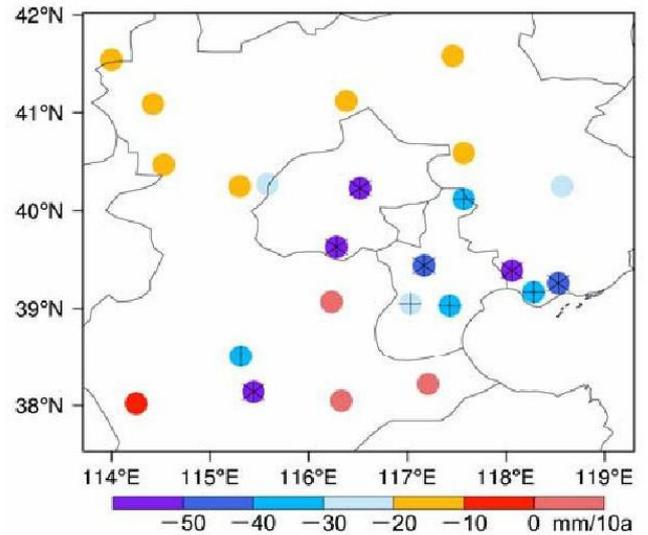


Fig. 2 The spatial distribution of the linear trends in 1981–2010 summer rainfall in the Beijing-Tianjin-Hebei area (units: mm/10a). The “+” and “*” symbols signify the confidence levels of 80% and 95%, respectively

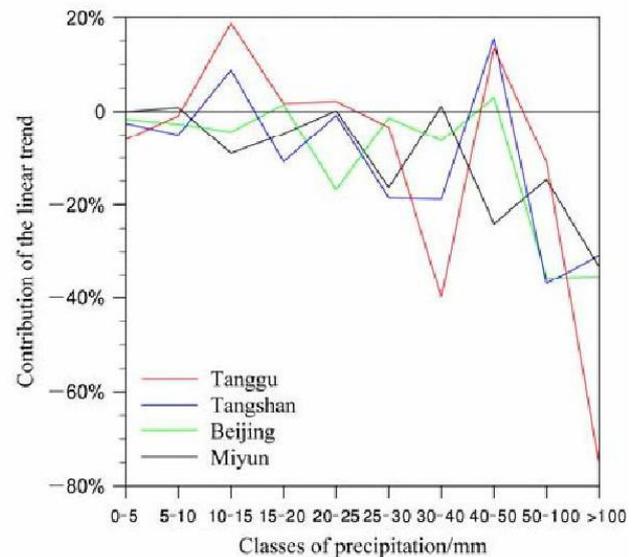


Fig. 3 The contributions of the linear trends of the different classes of precipitation at the sites of Miyun (black), Beijing (green), Tangshan (blue), and Tanggu (red)

Urbanization, as an important form of human activities, has a great influence on local climate. During the last 30 years, urbanization development in the Beijing–Tianjin–Hebei area is so fast that it is difficult to figure out the impact of urbanization on summer rainfall in this region observation data. Therefore, WRF/SLUCM model will be utilized to explore the impact of surface characteristic changes caused by urbanization on summer rainfall in the Beijing–Tianjin–Hebei area through numerical experiments.

3 Experimental design

The model used in this paper is the mesoscale Weather Research and Forecasting (WRF) model (V3.5.1) coupling Single Layer Urban Canopy Model (SLUCM). SLUCM was first proposed and established by Kusaka et al. (2001) and Kusaka and Kimura (2004), then Chen et al. (2004) and Miao et al. (2009) improved it and coupled with mesoscale models MM5 and WRF. SLUCM considers not only the direction and geometric features of streets as well as the shadow and reflection of buildings, but also the changes of solar elevation angle; and the thermal effects on roof, wall and streets are calculated, respectively (Chen et al., 2011). This model better improves the simulation on the effects of urban thermodynamics and kinetics. Characteristics could be reproduced by simulation results from WRF/SLUCM, such as diurnal variation and spatial pattern of urban heat island effect, diurnal variations of wind velocity and direction, local circulation in valleys and heat island, turbulent flow in boundary layer and low-level jet at night (Miao and Chen, 2008; Lin et al., 2008; Miao et al., 2009; Kusaka et al., 2009; Meng et al., 2010). Changes of meteorological element fields and distribution of precipitation in severe convection weather could be described better as well (Zhang et al., 2007; Wu and Tang, 2011; Zheng et al., 2013), and its simulation results are better than those of models without coupling UCM in most situations (Miao et al., 2010; Zhang et al., 2013). So it can be used for predicting and evaluating the effects of urbanization on climate changes. The simulated domain is allocated with triple nests in this paper, and their horizontal resolutions are 30 km, 10 km and 3.3 km, respectively, and the projection method is Lambert. The center of the outermost simulation domain is located at (38°N, 118°E). The model is divided into 35 layers in the vertical direction with atmospheric pressure of 50 hPa in the top layer. The simulated domain is shown in Fig. 4, and the innermost D3 region is the Beijing–Tianjin–Hebei area where would be analyzed seriously in this paper. Physical parameterization schemes adopted during the simulation process include: Rapid Radiative Transfer Model (RRTM) (Iacono et al., 2008), Single-Moment 5-class scheme (WSM5) (Hong et al., 2004), K-F (Kain-Fritsch) cumulus convection parameterization scheme (Kain, 2004), YSU (Yonsei University) boundary layer scheme (Noh et al., 2003) and NOAH land-surface process model (Chen and Dudhia, 2001) (coupling UCM). Initial fields and boundary fields used in the model are Final Operational Global Analysis (FNL) data of $1^{\circ} \times 1^{\circ}$ with 6-h interval provided by National Centers for Environment Prediction (NCEP). The simulation period is from 0800 May 21 (Beijing Time, BT the same below) to 0800 September 1 in every year during 2008–2010. Simulation results are output every one hour and analyses are only made for results from June to August

in D3 region.

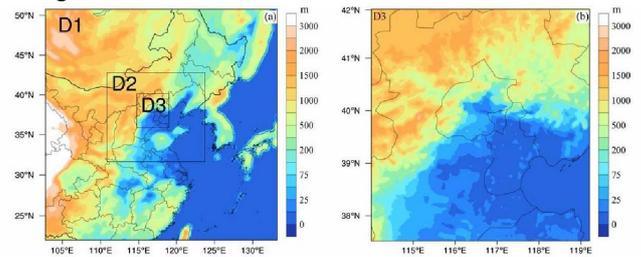


Fig. 4 The simulation domain and terrain (units: m) distribution: (a) Nested configuration of D1, D2, and D3; (b) the D3 (Beijing-Tianjin-Hebei) region

The land-use data used in the simulation are remote sensing data products (Model Land Cover Data sets version 1.0) (Hu and Jia, 2010) developed by Earth Observation of Climate Change (EOCC) research group (see [http://green.tea.ac.cn/\[2014-04-23\]](http://green.tea.ac.cn/[2014-04-23])), including three kinds of data with spatial resolutions of 30 km, 10 km and 3.3 km in 1990, 2000 and 2009. Contrast tests under three sets of underlying surface situations are designed (Fig. 5): (1) U09 (the control run, Fig. 5a), using land-use information of underlying surface in WRF which is updated by the above remote sensing data product of 2009 (based on MODIS land cover classification); (2) U90 (the sensitivity run, Fig. 5b), using the remote sensing data product of 1990 to replace land-use information of underlying surface which is default in WRF; (3) NoUB (the sensitivity run, Fig. 5c), using the interpolation of other surrounding land-use types to replace the urban part on the basis of land-use information which was default in WRF, namely, the experiment without urban surface. Regions labeled by black lines in Fig. 5a represent the urban areas of Beijing, Tianjin, Tangshan and Shijiazhuang as well as the DOWN zone which will be introduced in section 4.2.

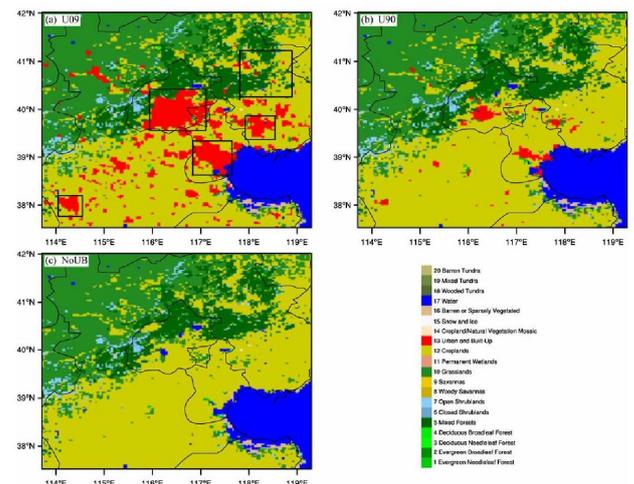


Fig. 5 The land-use classifications used in the Weather Research and Forecasting / Urban Canopy Model simulations, with the urban land-use fraction updated based on (a) 2009 and (b) 1990 remote sensing data products. (c) No urban surface

4 Analysis of results and discussion

4.1 Evaluation of model

Comparison is made between simulation results of the control run (U09) and observation data of daily precipitation from TRMM3B42 satellite (horizontal resolution is $0.25^\circ \times 0.25^\circ$) as well as surface temperature data provided by China Meteorological Data Sharing Service System (horizontal resolution is $0.5^\circ \times 0.5^\circ$) in this section. Temperature data are based on high-density surface data of stations in China (about 2400 national meteorological stations), and a gridded data set is created through spatial interpolation by using Thin Plate Spline (TPS) method of ANUSPLIN software. Fig. 6 shows spatial pattern of average summer rainfall (Figs. 6a and 6b) and surface temperature (Figs. 6c and 6d) obtained by observation and simulation from 2008 to 2010 in the Beijing–Tianjin–Hebei area. It can be seen that distribution of precipitation and temperature could be roughly simulated by the model, and simulated precipitation is stronger in some areas. Compared with TRMM, simulated precipitation has a virtual heavy-rain center in the north–northeast of Beijing. The estimation of daily rainfall may be smaller by TRMM, except for deviation of model simulation (Luo et al., 2011). Simulated temperature at 2-m in the model is basically consistent with observations in every region except for urban region, where simulated temperature is higher than observations by 1–2 °C. Meanwhile, we also calculate spatial correlation coefficients between simulated precipitation as well as simulated temperature and corresponding observations. Results are 0.404, 0.524, 0.958 for average summer rainfall, rainfall frequency and 2-m temperature, respectively, in the Beijing–Tianjin–Hebei area. All of them are over the 99% significance level. The model has a better simulation ability on the spatial distribution of light and heavy rain frequency, and correlation coefficients between simulation results and observations are 0.716 and 0.582, respectively.

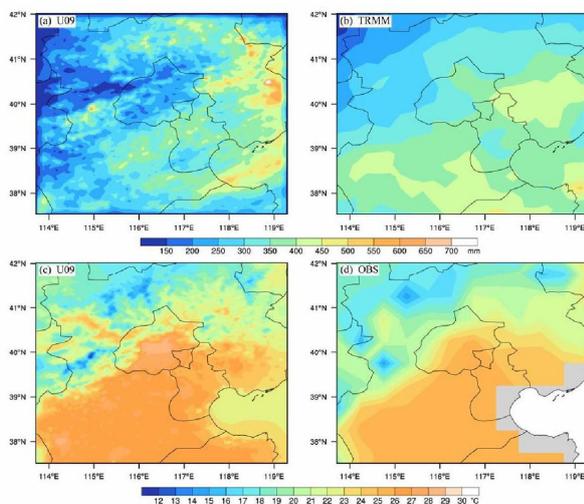


Fig. 6 Spatial pattern of 3-year (2008–2010) averaged (a, b) summer rainfall (units: mm) and (c, d) temperature (units: °C) at 2-m height in the Beijing–Tianjin–Hebei area: (a, c) Simulation (Expt U09); (b, d) observations

4.2 Impact of urban surface characteristics on summer rainfall, rainfall frequency and intensity in the Beijing–Tianjin–Hebei area

Fig. 7 shows spatial patterns of difference between average summer rainfall of the control run (U09) and sensitivity run (U90 and NoUB) as well as that between rainfall frequency of U9 and U90 & NoUB. It can be seen that spatial pattern of precipitation is influenced by changes of surface characteristics in the Beijing–Tianjin–Hebei area. As shown in Figs. 7a and 7b, most regions were negative value areas, except the northeast corner of the Beijing–Tianjin–Hebei area with positive value. Compared with U90 and NoUB, precipitation simulated by U09 decreases clearly in the urban areas of Beijing, Tianjin and Tangshan, while the increase or decrease of precipitation is not apparent in regions with scattered cities, such as Shijiazhuang and Baoding. The exact values of regional precipitation changes are listed in Table 1, in which average differences of precipitation between U09 and NoUB are –98 mm, –71.3 mm and –105.3 mm in Beijing, Tianjin and Tangshan, respectively. However, in Shijiazhuang, difference between U09 and U90 was negative while it was positive between U09 and NoUB, which indicates that there was a certain relationship between the impact of urban surface characteristics on precipitation and the location and size of city. The internal mechanism on the impact of urban surface characteristics on precipitation will be discussed in section 4.5. Figs. 8a, 8b, and 8c show rose diagrams of wind direction in Beijing, Tianjin and Tangshan at 10-m height, respectively (results of the control run U09). It can be seen that these three regions are dominated by southerly air flow in summer, and the frequency of south wind is the highest in Beijing and Tangshan, followed by southeast wind and southwest wind. The frequency of southeast wind is the highest in Tianjin, and warm moist air carried by southerly air flow is an important reason for the formation of summer rainfall in the Beijing–Tianjin–Hebei area. Combined with 850 hPa wind field (not shown), it can be figured out that southwest air flow exists at the lower atmospheric layer in the Beijing–Tianjin–Hebei area. Therefore, precipitation region with positive value at the northeast corner of Figs. 7a and 7b is located exactly in the intersection for downwind regions of three big cities, which is consistent with research results on that increase of downwind precipitation caused by urbanization obtained by predecessors (Chow and Chang, 1984; Shepherd et al., 2010). Regions with obvious increase of precipitation caused by changes of urban surface characteristics are defined as DOWN (Fig. 5), and urbanization leads precipitation to increase by 23–50 mm in this region (Table 1). Contributions of precipitation in

different levels to total precipitation in this region and diurnal variation characteristics of precipitation will be discussed in sections 4.3 and 4.4.

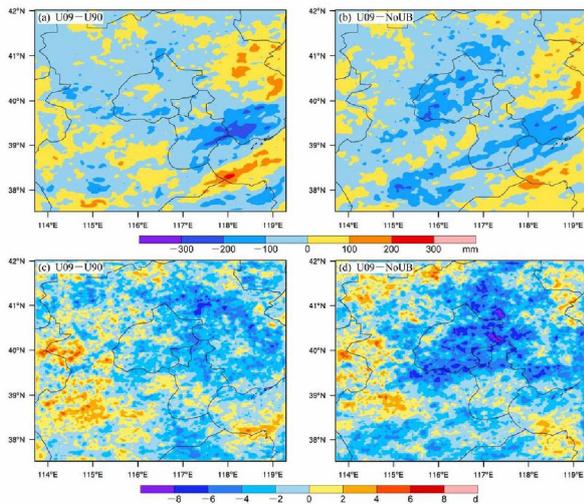


Fig. 7 Spatial patterns of the differences in (a, b) summer precipitation (units: mm) and (c, d) rainfall frequency (units: d) between the control run and sensitivity run: (a, c) Expt U09 minus Expt U90; (b, d) Expt U09 minus Expt NoUB

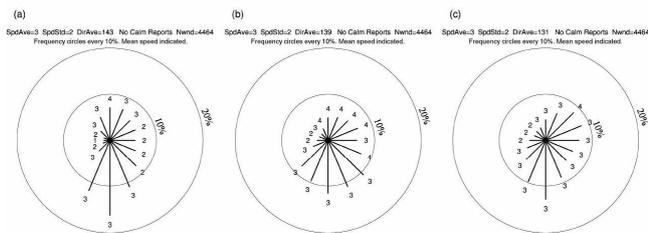


Fig. 8 Summer-averaged wind rose of three years from Expt U09, the numbers represent the wind speed: (a) Beijing; (b) Tianjin; (c) Tangshan

Table 1 The difference in precipitation between the control run and sensitivity run

	Difference value of precipitation/mm					Beijing-Tianjin-Hebei area
	Beijing	Tianjin	Tangshan	Shijiazhuang	DOWN	
ExptU09-ExptU90	-46.90	-89.39	-143.63	-29.67	50.55	-23.79
ExptU09-ExptNoUB	-98.70	-71.33	-105.34	1.847	23.97	-34.46

As shown in Figs. 7c and 7d, changes of urban surface characteristics lead rainfall frequency to decrease in most regions of the Beijing-Tianjin-Hebei area, especially in regions with concentrated cities, and the largest decrease of rainy day is more than 7 days. The positive value areas of rainfall frequency change are small areas in the west and southwest of the Beijing-Tianjin-Hebei area. Fig. 9 shows the spatial pattern of the difference of rainfall intensity (ratio between total precipitation and total rainfall frequency) between the control run (U09) and the sensitivity run (U90 and NoUB). It can be seen that changes of surface characteristics result in the weakening of rainfall intensity in major cities and most regions around the Beijing-Tianjin-Tangshan metropolis, and the maximum value of decrease is 10 mm/d, while it leads to the enhancement of rainfall intensity in scattered regions, such

as the downwind regions of the urban agglomeration (DOWN), northwest of Tianjin and northwest of Beijing, in which the enhancement could be more than 8 mm/d in DOWN region.

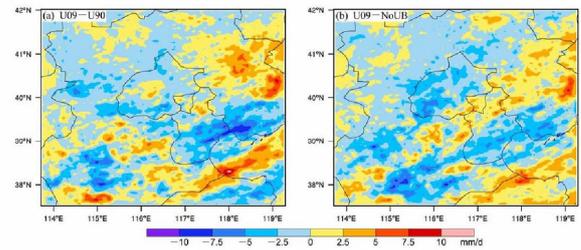


Fig. 9 As in Fig. 7, but for the difference in precipitation intensity (units: mm/d)

4.3 Impact of urban surface characteristics on summer rainfall of different levels in Beijing-Tianjin-Hebei area

In order to illustrate which precipitation level is influenced by changes of surface characteristics caused by urbanization significantly, daily precipitation is divided into 10 levels in this section as well: 0-5 mm, 5-10 mm, 10-15 mm, 15-20 mm, 20-25 mm, 25-30 mm, 30-40 mm, 40-50 mm, 50-100 mm and > 100 mm. Fig. 10 shows the contribution rates of the differences between different precipitation levels (Fig. 10a) as well as rainfall frequency (Fig. 10b) in 5 regions simulated by U09 and NoUB:

$$C = (P_{U09} - P_{NoUB}) / \left| \sum (P_{U09} - P_{NoUB}) \right| \times 100\% \quad (1)$$

where, C is the contribution rate, P represents the precipitation or rainfall frequency in every level (subscript represents the name of experiment), \sum is the symbol of summation. Beijing, Tianjin, Tangshan and DOWN in Fig. 10 represent corresponding regions in the black boxes of Fig. 5a, respectively (the same in following sections), Beijing-Tianjin-Hebei represents the whole the Beijing-Tianjin-Hebei area (D3). Precipitation and rainfall frequency at all levels decrease in Beijing (black solid line) and the Beijing-Tianjin-Hebei area (purple solid line), which are caused by urban underlying surface. Precipitation and rainfall frequency in every level decrease in urban district of Tangshan (red solid line), except precipitation in the level of 5-20 mm, while only light precipitation events of 0-5 mm and extreme precipitation events above 50 mm show negative contribution rates in the urban district of Tianjin (green solid line), in which the negative contribution rate of precipitation above 50 mm is 140%. There is an obvious difference in the impact of urban surface characteristics on precipitation between Tianjin and Beijing, which could be results of interaction between urban heat island and sea-breeze circulation due to the fact that Tianjin is close to Bohai (Shepherd et al., 2010). In the view of the influence of underlying surface on precipitation in DOWN

region (blue solid line), increases of precipitation and rainfall frequency over 40mm in this region are mainly caused by urbanization, while precipitation in other levels shows negative contribution rate. As shown in Fig. 10a, negative contribution rates of precipitation above 50 mm are more than 60% in these three cities, while the percentage between precipitation above 50 mm and total precipitation was from 30% to 40%, which indicates that urban surface characteristics may result in decrease of the ratio between extreme precipitation and total precipitation. Percentage between precipitation above 50 mm and total precipitation, percentage between rainfall frequency and total precipitation in different experiments in 5 regions as described above are listed in Table 2 and Table 3, respectively. It can be seen that changes of surface characteristics indeed lead the percentages of extreme precipitation and extreme rainfall frequency to decrease in the Beijing–Tianjin–Tangshan area in different extents, and precipitation and rainfall frequency decrease from 6% to 20% and from 0.8% to 3.6%, respectively. However, percentages of precipitation above 50 mm and rainfall frequency increase by 8% and 1.5% in DOWN region, respectively.

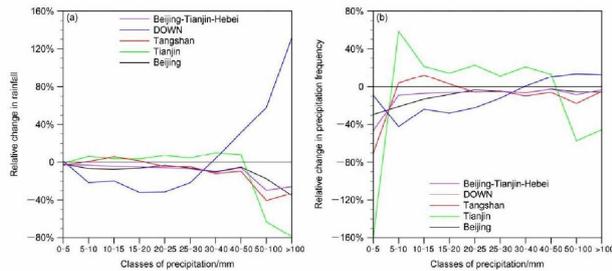


Fig. 10 The relative change in (a) rainfall and (b) precipitation frequency for the different classes of precipitation in the regions of Beijing (black), Tianjin (green), Tangshan (red), Beijing–Tianjin–Hebei (purple), and DOWN (blue) due to urbanization (U09 minus NoUB). “DOWN” means the downwind area of urban

Table 2 The percentage of extreme precipitation (≥ 50 mm) in the control run and sensitivity run

Region	Percentage of extreme rainfall				
	U09	U90	NoUB	U09–U90	U09–NoUB
Beijing	27.6%	28.3%	35.4%	–0.7%	–7.8%
Tianjin	34.0%	55.6%	53.7%	–21.6%	–19.7%
Tangshan	42.6%	51.5%	49.1%	–8.9%	–6.5%
Beijing–Tianjin–Hebei area	30.4%	32.0%	37.6%	–1.6%	–7.2%
DOWN	44.8%	34.5%	36.8%	+10.3%	+8.0%

Table 3 The percentage of extreme rainfall (≥ 50 mm) frequency in the control run and sensitivity run

Region	Percentage of extreme rainfall frequency				
	U09	U90	NoUB	U09–U90	U09–NoUB
Beijing	3.7%	4.4%	4.7%	–0.7%	–1.0%
Tianjin	6.4%	9.4%	10.0%	–3.0%	–3.6%
Tangshan	6.6%	9.1%	8.6%	–2.5%	–2.2%
Beijing–Tianjin–Hebei area	4.3%	5.2%	5.1%	–0.9%	–0.8%
DOWN	7.0%	5.2%	5.5%	+1.8%	+1.5%

4.4 Impact of urban surface characteristics on diurnal variation of summer rainfall in Beijing–Tianjin–Hebei area

Changes of surface characteristics caused by urbanization lead precipitation to decrease in major cities and increase in downwind regions of urban agglomeration, It needs to be researched which period of one day this change is obvious. Fig. 11 shows diurnal variation of summer rainfall simulated by U09 and NoUB in six regions. As for the general circumstance of the whole the Beijing–Tianjin–Hebei area (Fig. 11f), changes of underlying surface result in decrease of precipitation in all periods of one day, but it does not have an obvious influence on diurnal variation of precipitation: there are peaks at 08 a.m. and 15 p.m., and minimum at 22 p.m. for precipitation in both two experiments. As for the Beijing–Tianjin–Tangshan area, urban surface characteristics have an obvious effect on diurnal variation of precipitation: in Beijing area (Fig. 11a), precipitation of U09 in all periods is lower than that of NoUB. Especially from evening to early morning of the next day, precipitation simulated by NoUB has a peak in the evening (1800–2000 BT), while precipitation simulated by U09 shows a lower value in the corresponding period; decrease of precipitation caused by changes of surface characteristics mainly occurs during 1500–1700 BT and 2100–0200 BT and 0600–0800 BT (Fig. 11c), and precipitation changes a little in other periods; urban surface characteristics have a different effect on precipitation in Tianjin compared with those in Beijing and Tangshan. As shown in Fig. 11b, due to urban agglomeration in the Beijing–Tianjin–Hebei area, precipitation in Tianjin increases clearly during 0200–0900 BT. As mentioned in section 4.3, changes of surface characteristics lead precipitation and rainfall frequency at of 5–50 mm level to increase in the urban district of Tianjin (Figs. 10a and 10b), which may be caused by the interaction between heat island circulation and sea-breeze circulation at night. Compared with former three big cities, urban surface characteristics influence precipitation less in Shijiazhuang (Fig. 11d), and precipitation of U09 is more than that of NoUB during 1000–1300 BT, while results are opposite during 0400–0800 BT. Thus, changes of surface characteristics have different effects on precipitation in different cities. Overall, urban underlying surface may be one factor for decrease of precipitation in the Beijing–Tianjin–Hebei area. As shown in Fig. 11e, increase

of precipitation caused by urban underlying surface in the DOWN region mainly occurs in daytime, while due to changes of surface characteristics, precipitation in this region decreases in the period from midnight to early morning of the next day.

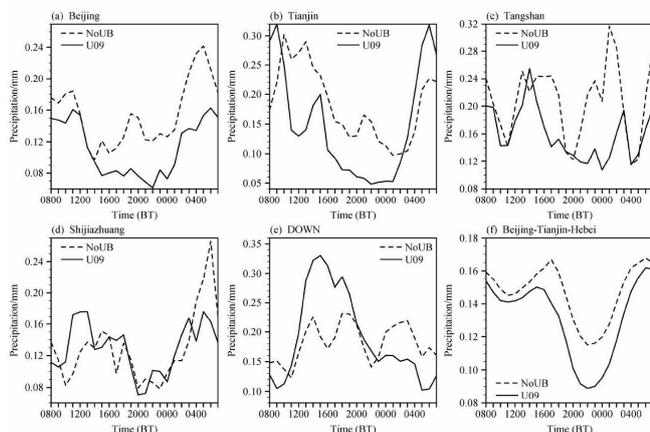


Fig. 11 Diurnal variation of summer precipitation based on Expt U09 and Expt NoUB (units: mm): (a) Beijing; (b) Tianjin; (c) Tangshan; (d) Shijiazhuang; (e) DOWN; (f) Beijing-Tianjin-Hebei. The value at 0800 BT (Beijing time) represents the cumulative rainfall during 0700–0800 BT, the value at 1000 BT represent 0900–1000 BT, and so on. “DOWN” means the downwind area of urban

4.5 Mechanism exploration

Changes of precipitation in and around urban district caused by urbanization could be results of two following factors (simulation in this paper only takes changes of surface characteristics into consideration, without changes of aerosols and anthropogenic heat): (1) convergence of air flow in the lower atmospheric layer was strengthened by the increase of surface roughness and urban heat effects; (2) the decrease of water vapor content in the boundary layer is caused by less moisture evaporation in urban regions. The convergence of air flow in lower layer is so conducive to the enhancement of vertical movement that facilitates the development of convection, while the decrease of water vapor content in the boundary layer will reduce the convective available potential energy (CAPE), so as to inhibit the development of deep convection (Zhang et al., 2009). Which above factor plays a major role in the Beijing-Tianjin-Hebei area? Fig. 12 shows the diurnal variation distribution of differences between vertical velocity in troposphere and convective available potential energy in four regions simulated by U09 and NoUB, and the x-axis is Beijing Time and y-axis is vertical levels. In the view of three urban districts of Beijing-Tianjin-Tangshan (Figs. 12a, 12b and 12c), changes of surface characteristics strengthen vertical movement in lower troposphere during most periods, and weaken vertical movement in the high level, in which enhancement of vertical movement in the lower atmospheric layer mostly occurs in Tianjin and

Tangshan. According to Fig. 12, we found that the reasons for the decrease (increase) of precipitation may be inhibition (enhancement) of vertical movement caused by urban surface characteristics in higher troposphere. For example, enhancement of vertical movement in mid-higher troposphere in the urban district of Tianjin happens during 0200–0900 BT (Fig. 12b), and precipitation in experiments with cities (U09) is obviously more than that without cities in the corresponding period (NoUB) (Fig. 11b); as for Tangshan area (Fig. 12c), there is a negative value center in mid-higher troposphere during midnight, and precipitation of U09 was obviously lower than that of NoUB in the corresponding period (Fig. 11c); as for the DOWN region, increase of precipitation caused by changes of surface characteristics mainly occurs during 1000–2000 BT (Fig. 11e), while it is a positive value center in troposphere at the same time in Fig. 12d. Thus, it may be an important reason for decrease (increase) of precipitation in the Beijing-Tianjin-Hebei area that inhibition (enhancement) of deep convection is caused by urban surface characteristics. Fig. 14 shows the spatial pattern of difference in 3-year average summer latent heat flux in the Beijing-Tianjin-Hebei area between the simulation of U09 and NoUB. It can be seen that obvious decrease of latent heat flux in major cities and their circumambient areas is caused by less water vapor evaporation in cities, with a maximum of 200 W/m², while latent heat flux increases slightly in downwind regions of urban agglomeration. The decrease of water vapor content in the lower atmospheric layer (not shown) is caused by the decrease of latent heat flux in urban regions, so as to reduce convective available potential energy (CAPE) (Figs. 13a, 13b and 13c). Thus, even though vertical movement in lower atmospheric layer is strengthened in urban areas due to convergence of air flow, further development of vertical movement will be suppressed by the decrease of CAPE to some extent, leading the development of deep convection to be inhibited. Therefore, the decrease of precipitation in major cities is caused by urban surface characteristics. These analyses illustrates that, as for urban agglomeration of the Beijing-Tianjin-Hebei area, changes of evaporation is a major factor for changes of precipitation. Miao et al. (2011) pointed out that humidity simulated by SLUCM could be lower, due to not taking anthropogenic emission sources of water vapor into consideration. Therefore, there is a certain limitation for the above conclusions. Many future works should be done to improve the accuracy of description on urban environment in UCM module, so as to promote the credibility of simulation results. The periods for enhancement of vertical movement in middle-high layers and precipitation are during 0200–0900 BT in Tianjin (Fig. 12b) and during 1000–2000 BT in DOWN region (Fig. 12d), respectively, but CAPE decreases in these periods instead of increasing, which indicates that the impact of urban surface characteristics on precipitation is not only

controlled by the above two factors but may also be related to changes of water vapor transport in the lower layer caused by circulation of urban heat island, which still needs to be discussed further.

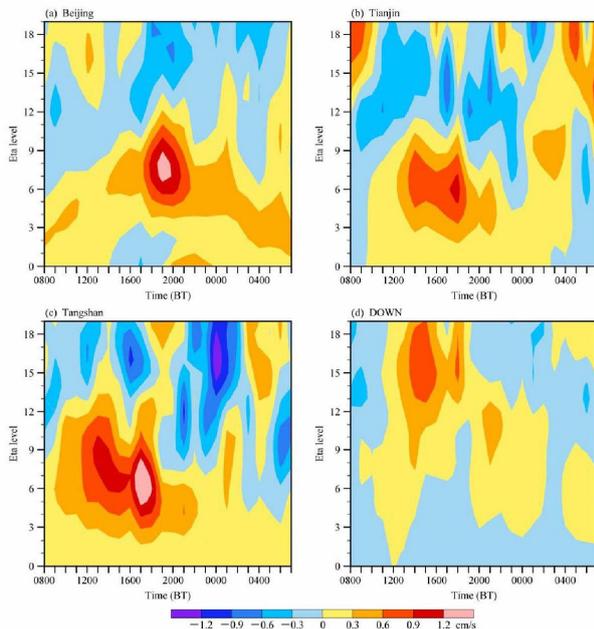


Fig. 12 Diurnal variation of the average difference in summer vertical velocity between Expt U09 and Expt NoUB in the troposphere for three years (units: cm/s): (a) Beijing; (b) Tianjin; (c) Tangshan; (d) DOWN. The corresponding Eta values for 0–19 on the y-axis are: 0.997, 0.988, 0.977, 0.962, 0.944, 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. “DOWN” means the downwind area of urban

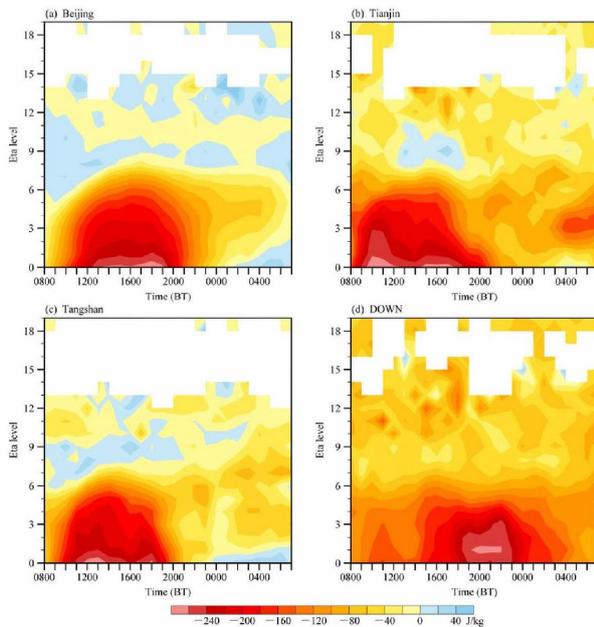


Fig. 13 As in Fig. 12, but for the diurnal variation of the difference in convective available potential energy (units: J/kg)

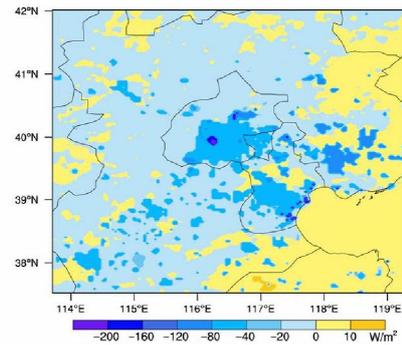


Fig. 14 Spatial pattern of the difference in summer latent heat flux (units: W/m^2) between Expt U09 and Expt NoUB

5 Conclusions

Utilizing daily precipitation data from 24 meteorological stations and simulation results from the Weather Research and Forecasting (WRF) model coupling Simple Layer Urban Canopy Model (SLUCM), the impact of urban surface characteristics on summer rainfall in the Beijing–Tianjin–Hebei area is investigated. The main conclusions are as follows:

(1) Precipitation at most sites in the Beijing–Tianjin–Hebei area with a rapid urban encroachment has reduced during the last 30 years. The sites with the most precipitation decrease are mainly centered in the urban regions of Beijing–Tianjin–Tangshan area. Precipitation reduces at the speed of more than -60 mm/10a at sites of Beijing, Miyun and Tangshan. The decreasing tendencies of precipitation respectively reach -45.7 mm/10a and -34.1 mm/10a at Baoding and Tanggu of Tianjin, in which decreasing tendency of rainfall above 50 mm accounts for over 50% in that of total precipitation. It indicates that the decrease of precipitation in Beijing–Tianjin–Tangshan is mainly caused by the decrease of extreme precipitation.

(2) Comparison between results of the control run and sensitivity run indicates that rainfall and rainfall frequency clearly decrease in the Beijing–Tianjin–Tangshan area due to changes of surface characteristics caused by urbanization, while increases of rainfall and rainfall intensity in downwind area of urban agglomeration are apparent. Precipitation above 50 mm changes significantly, contributing more than 60% of the total precipitation. The percentage of rainfall above 50 mm declines by 6%–20% due to changes of surface characteristics in the Beijing–Tianjin–Tangshan area, while it increases by 8% in downwind area. It should be noted that the decreases of light precipitation at 0–5 mm level and extreme precipitation above 50 mm in urban area of Tianjin are caused by urban surface characteristics, while precipitation in other levels increases obviously. The internal mechanism that leads to this result still needs to be researched further.

(3) The diurnal variation structure of rainfall is influenced by urban surface characteristics in major cities and urban agglomeration: precipitation in Beijing and Tangshan decreases in the whole day; the decrease of rainfall in Tianjin occurs during 1000–0100 BT, while rainfall increases in the rest time; rainfall in downwind area of urban agglomeration mostly increases at daytime and decreases at night.

(4) The study suggests that the inhibition (enhancement) of deep convection caused by urban surface characteristics may be an important reason which causes the decrease (increase) of precipitation in the Beijing–Tianjin–Hebei area, and changes of latent heat flux and convective available potential energy (CAPE) caused by changes of the urban surface evaporation are the important factors for changes of deep convection.

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[致谢]

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[尾注]