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Numerical Simulation of the Impact of Urban Non-uniformity on Precipitation

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ABSTRACT

To evaluate the influence of urban non-uniformity on precipitation, the area of a city was divided into three categories (commercial, high-density residential, and low-density residential) according to the building density data from Landsat satellites. Numerical simulations of three corresponding scenarios (urban non-uniformity, urban uniformity, and non-urban) were performed in Nanjing using the WRF model. The results demonstrate that the existence of the city results in more precipitation, and that urban heterogeneity enhances this phenomenon. For the urban non-uniformity, uniformity, and non-urban experiments, the mean cumulative summer precipitation was 423.09 mm, 407.40 mm, and 389.67 mm, respectively. Urban non-uniformity has a significant effect on the amount of heavy rainfall in summer. The cumulative precipitation from heavy rain in the summer for the three numerical experiments was 278.2 mm, 250.6 mm, and 236.5 mm, respectively. In the non-uniformity experiments, the amount of precipitation between 1500 and 2200 (LST) increased significantly. Furthermore, the adoption of urban non-uniformity into the WRF model could improve the numerical simulation of summer rain and its daily variation.

Key words: urban non-uniformity, urban precipitation, WRF model

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1. Introduction

Urbanization takes place at an exceptionally rapid rate in China. The areas of cities in China, particularly in the Beijing–Tianjin–Hebei, Yangtze River Delta, and Pearl River Delta urban agglomeration regions, have continued to grow. The process of urbanization has altered the natural surface and resulted in increases in anthropogenic heat and pollutant emissions, which inevitably have impacts on urban meteorological environments. Problems such as “urban heat islands” (UHIs), “dry islands”, “rain islands” and “turbid islands”, have arisen in association with urbanization.

Many studies have been conducted on these phenomena, and important progress has already been accomplished. However, the urban effect on precipitation is relatively complicated. Potential mechanisms of the effects of cities on precipitation include the dynamic actions of urban buildings and thermodynamic actions of UHIs altering the flow field characteristics, the impervious surfaces of urban areas affecting the evaporation process and influencing land–surface water vapor transfer, and urban air pollution (e.g., the direct and indirect effects of aerosols) affecting radiation and cloud microphysical processes. Studying the urban effect on precipitation has become a frontier of focus for the atmospheric sciences, with a large number of studies devoted to the subject (Jauregui and Romales, 1996; Lowry, 1998; Li et al., 2008). Liao et al. (2011) analyzed the pattern of variation in precipitation in Guangzhou using daily observed precipitation data from 1959 to 2009 and found that the number of heavy rain days is increasing. The study conducted by Zhang et al. (2007) determined that urban expansion reduces the coverage of natural vegetation, which further reduces surface evaporation and local water vapor supply. Meanwhile, it increases the boundary layer height and enhances the mixing of atmospheric water vapor, ultimately decreasing the amount of precipitation. Sun et al. (2006) analyzed the formation mechanism and the role of the urban boundary layer in a relatively independent meso-β-scale convective rainstorm system in Beijing. The observational study conducted by Chen et al. (2000) determined that precipitation in the Yangtze River Delta region increased in response to urbanization, while the temperature in surrounding regions decreased. Based on mesoscale weather dynamics theory and a scale analysis method, Sun and Yang (2008) found that a meso-β-scale rainstorm was affected by the interaction of the terrain and UHIs. Shepherd et al. (2002) analyzed the distribution of summer precipitation in several cities in the U.S. from 1998 to 2000 using TRMM satellite data. They reported a 28% increase in the mean monthly precipitation at locations 30–60 km from cities in the downwind

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direction, and an approximate 5.6% increase in urban areas. Rosenfeld (2000) suggested that urbanization and industrial pollution would result in increased precipitation and snowfall in downstream locations. And finally, the results of the study conducted by Wu et al. (2000) demonstrated that the most significant urban effect attributed to the thermal and dynamic effects of cities was the increase in short-term precipitation.

A high-resolution numerical simulation is a common and effective tool for studying the effects of cities on precipitation. As a result of its exceptional performance, the WRF model has been widely applied in the field of urban meteorology. Details on the WRF model can be found in Skamarock et al. (2008). The WRF model classifies cities into three categories: commercial, high-density residential (hi-dens res), and low-density residential (low-dens res). The buildings in commercial cities are the tallest, whereas the buildings in low-dens res cities are the shortest. In most cases, when using WRF (the version in this study is 3.3.1) to simulate urban meteorology, a city is determined to belong to one of the aforementioned categories based on its building density (Song et al., 2009). However, due to the non-uniformity of urban density, all three types of urban area exist within a city. Therefore, it is difficult to conclude that a city belongs solely to one of these categories. Hu et al. (2013) considered urban non-uniformity in a study on low-level jets. For the city of Nanjing, there are numerous skyscrapers in the downtown area, i.e., in Gulou and Xinjiekou, which is commercial. However, the south of the city is close to the Qinhuai River, which belongs to the hi-dens res category. And the eastern part, i.e., Xianlin, belongs to the low-dens res category. Categorizing a city into only one classification may cause relatively large deviation in the model. Some studies (Song et al., 2014a, b) show that the surface energy balance, temperature and wind are significantly influenced by urban non-uniformity, but there have been few studies on the link between urban non-uniformity and precipitation. Building dynamics, UHIs and aerosols have influences on precipitation. In addition, the former two affect each other. When urban non-uniformity is considered, urban dynamic parameters change, which also leads to a change in the UHI effect. Therefore, urban non-uniformity is an important factor and should be considered in precipitation simulation. In the present study, Nanjing was recategorized based on the characteristics of different areas of the city, and the potential effect of the urban non-uniformity on precipitation was investigated.

2. Methods

2.1. *Model description*

The WRF model system is composed of a new-generation mesoscale forecasting model and assimilation system, jointly established in 1997 by the Mesoscale & Microscale Meteorology Division of the NCAR, the Environmental Modeling Center at the NCEP, the Forecast Research Division of the Forecast Systems Laboratory, and the Center for Analysis and Prediction of Storms at the University of Oklahoma. The WRF model system has been applied extensively.

The urban canopy model (UCM) in the WRF model was used in the present study. The UCM includes the following features: (1) streets with 2D structures are parameterized to calculate their thermal characteristics; (2) the shadows and reflections of buildings are considered; (3) the courses of streets and the daily variation of the solar elevation angle are considered; (4) the thermal effects of road surfaces, wall surfaces and roofs are differentiated.

2.2. *Non-uniform distribution of Nanjing*

Three experiments (A, B and C) were designed for the present study. In experiment A, the non-uniformity of the city was considered; different areas of the city were classified into three categories: commercial, hi-dens res, and low-dens res. In experiment B, the city was considered to be uniform (hi-dens res). And in experiment C, the effect of a non-urban environment was considered; the original land surface types of the city were replaced by irrigated cropland and pasture.

The city classification was mainly based on its building density (Song et al., 2014a, Fig. 1). The building densities were obtained by statistically analyzing the 25-m resolution land surface type data developed by Landsat satellites. When the building density was less than 0.3, the area was defined as low-dens res; when it was greater than or equal to 0.45, the area was defined as commercial. The distributions of the land surface types in the third level of the model for experiments A and B can be found in Song et al. (2014a, Fig. 2). The commercial area accounted for 23.7% in the non-uniform category, while the hi-dens res and low-dens categories accounted for 41.2% and 35.1%, respectively. However, in the uniform category, the city area was completely hi-dens res. The land types of the central and peripheral areas of Nanjing change when the spatial variation is considered. Even though the height of the city decreases, the non-uniform distribution of the city increases.

Compared to a uniform city, the mean values of sensible heat, UHI and friction velocity are less in a non-uniform

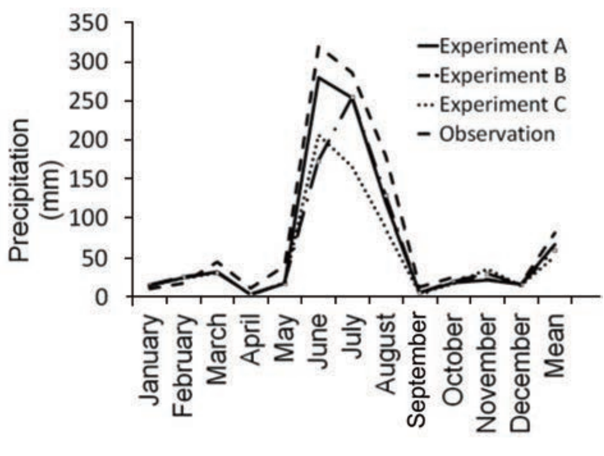

Fig. 1. Observed and simulated monthly mean precipitation at Nanjing station.

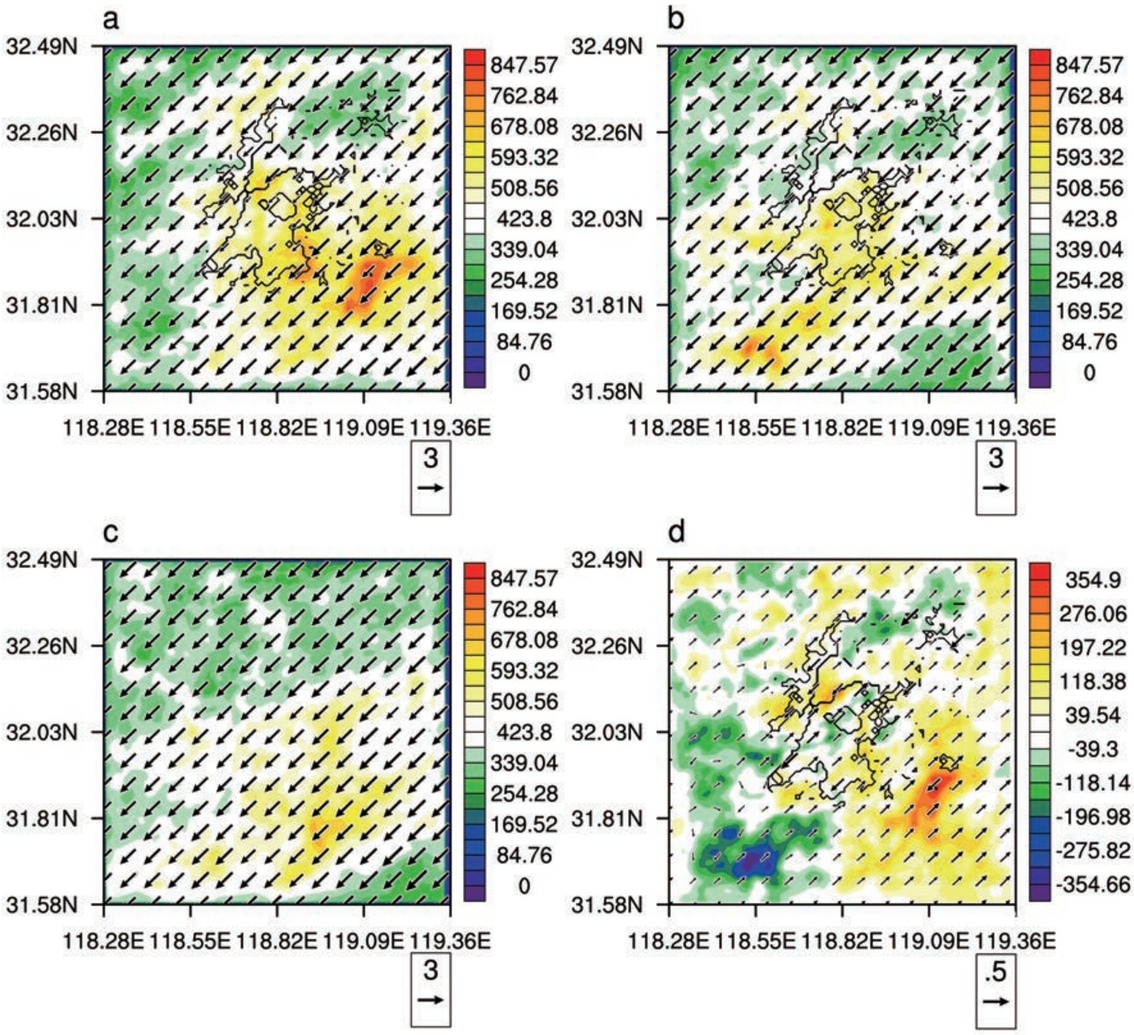

Fig. 2. Spatial distribution of summer accumulated precipitation (mm) in the Nanjing region: (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison. The wind fields in the figure are the mean wind fields at 10 m for rainy summer days (m s^{-1}).

city. However, the extreme values are larger (Song et al., 2014a). This demonstrates that a non-uniform city provides weaker land-surface forcing, but enhances the land-surface forcing turbulence corresponding to a uniform city. Obviously, the enhancement of precipitation is due to the urban non-uniformity rather than the mean land-surface forcing.

2.3. *Experimental design*

A three-level nested grid with a two-way nesting experiment was used for the simulation. The central longitude and latitude of the domain were 32.1004°N and 118.8986°E, respectively. The outer domain was 900 km × 900 km, with 9-km horizontal grid spacing; the middle domain was 303 km × 303 km, with 3-km spacing; and the innermost domain was 101 km × 101 km, with 1-km spacing. The model top was set at 100 hPa and there were 27 vertical layers. The simulation period was from 0000 UTC 1 January 2011 to 1800 UTC 31 December 2011, and the model ran month by month. The 1° × 1° resolution NCEP data were used as the boundary conditions, which were forced every 6 h. The result was output every hour. The model parameterization can be found in Song et al. (2014a, Table 1). The Multi-layer Building Environment Model, Noah land–surface, Monin–Obukhov, and unified Noah land–surface schemes were chosen in this study.

3. Results

3.1. *Total summer precipitation*

The precipitation for Jiangsu province in the summer of 2011 ranged from 247.1 mm (Guanyun) to 1243.6 mm (Jiangyin), mainly concentrated in the southern part of Jiangsu and over the Yangtze River. The mean was 731.2 mm, which was approximately 50% of the annual value. Figure 1 compares the simulated and observed total monthly precipitation (mm) in the three experiments. The surface data from a representative station in Nanjing (58238; coordinates: 31.93°N, 118.90°E) were selected as the observation. The observed annual precipitation amount in 2011 was 989.2 mm. The simulated precipitation amount for the station in Nanjing, based on the three experiments, was 810.4 mm, 723.2 mm and 625.7 mm, respectively. In winter, spring and fall, the precipitation simulated in the non-uniform, uniform and non-urban experiments was relatively close to the observation. However, in summer, the accumulated precipitation simulated in the uniform and non-urban experiments was significantly lower than observed, whereas that simulated in the non-uniform experiment was closest to the observation. The error of the monthly mean accumulated precipitation for 2011 was 14.9 mm in the non-uniform experiment, which was lower than that of the uniform experiment. Thus, the simulation accuracy regarding urban precipitation can be effectively increased when urban non-uniformity is considered in the WRF model.

Compared with uniform experiments, the accumulated precipitation for the 12 months of the non-uniform experiments increased by 0.68%, −0.33%, 0.50%, −2.40%, −1.13%, 14.51%, −6.81%, 2.42%, −0.31%, −0.45%, −2.41% and −0.52%, respectively. For summertime (June, July, August), the values were 14.51%, −6.81% and 2.42%, respectively. The differences among the three experiments were greatest in summer because the amount of precipitation is largest in this season. Therefore, the effect of urban non-uniformity on summer precipitation (June, July and August) is mainly discussed hereafter. Figure 2 presents the spatial distribution of the simulated accumulated precipitation in summer in the Nanjing region. It shows a mean northeasterly wind field on rainy days. The wind speed significantly decreased in the urban area, especially centrally in the non-uniform experiment. Compared with the uniform experiment, the airflows also converged at the center in the non-uniform experiment (Fig. 2d). The simulated summer mean accumulated precipitation amount for the entire region was 423.09 mm, 407.40 mm and 389.67 mm in experiments A, B and C, respectively. There was a significant difference among the simulations, and the non-uniform experiment result was the highest. Compared with the non-urban experiment, the existence of the city resulted in a significant increase in precipitation in the urban area and downstream locations. The distribution patterns of the summer precipitation were significantly different in the non-uniform and uniform experiments. Precipitation increased more significantly in the urban areas and the southeast in the non-uniform experiment, whereas it decreased in downstream areas. Besides, the maximum precipitation amount was greater in the non-uniform experiment.

Figure 3 presents the spatial distributions of the simulated

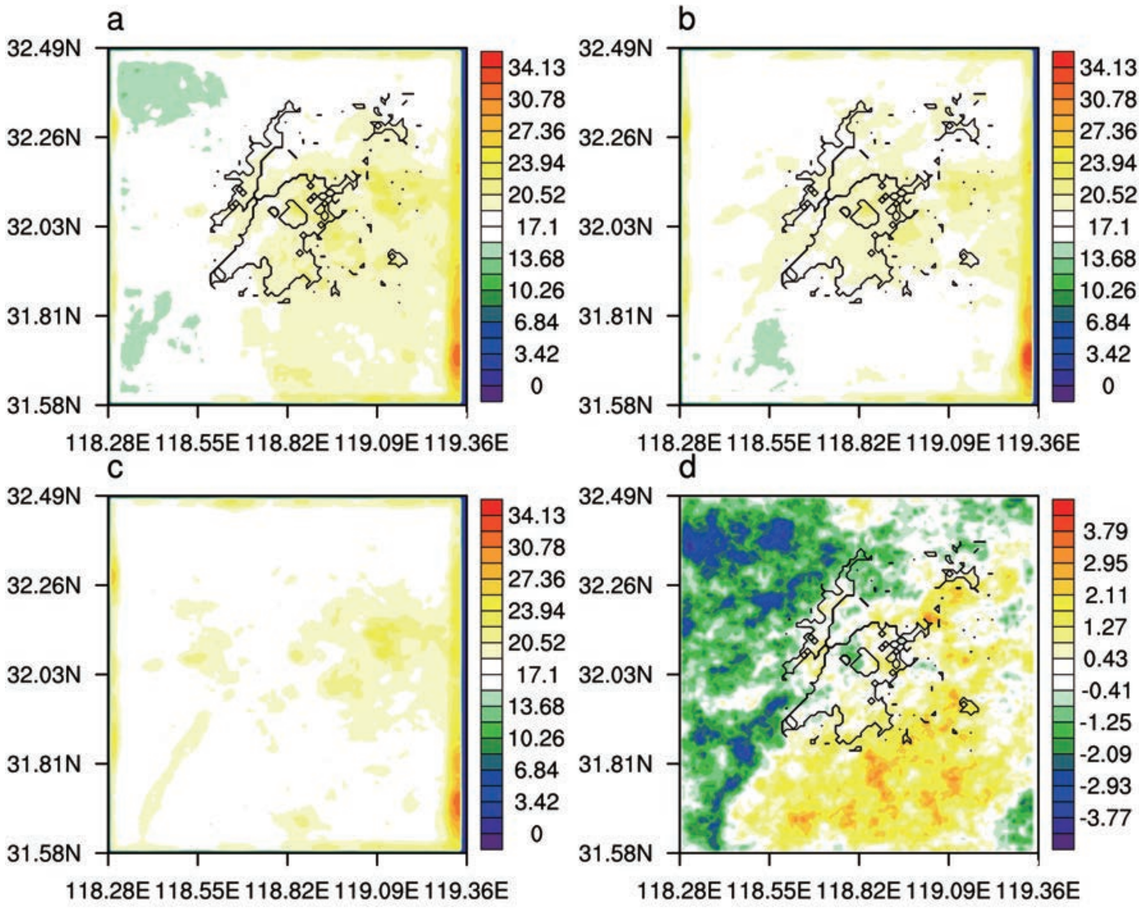

Fig. 3. Frequency of summer (June, July and August) precipitation in the Nanjing region (%): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison.

summer precipitation frequency (the ratio of total precipitation to summertime precipitation) in the Nanjing region. Compared to the non-urban experiment (experiment C), the precipitation frequency was higher in the urban areas of experiments A and B. In general, the presence of the city resulted in an increasing trend for the precipitation frequency in the urban area. Also, it increased in the southeastern direction of the city, but decreased, to a certain extent, in the northwestern direction.

Figure 4 presents the spatial distributions of the simulated summer precipitation intensity (the ratio of accumulated summer precipitation to total precipitation) in the Nanjing region. The distributions were relatively similar to the accumulated summer precipitation. The mean intensity of the precipitation simulated in the non-uniform, uniform and non-urban experiments was 1.37 mm h^{-1}, 1.33 mm h^{-1} and 1.26 mm h^{-1}, respectively.

Figure 5a presents the observed accumulated precipitation every 6 h at Nanjing station. The data indicate that the occurrence of precipitation was greatest between 0200 and 0800 (LST), slightly lower between 0800 and 1400 (LST) and between 1400 and 2000 (LST), and lowest between 2000 and 0200 (LST). Figure 5b presents the daily variation of the summer mean accumulated precipitation for the entire Nanjing region. Compared to the observation, the lowest precipitation simulated by the three experiments occurred at night, while the highest occurred in the morning. In the morning, the precipitation was lowest in the non-uniform experiment. However, in the afternoon, the precipitation in the uniform and non-urban experiments was much lower than in the morning, while the non-uniform experiment results were much higher and equivalent to the simulations in the morning. Clearly, the results of the non-uniform experiment were better. Therefore, urban non-uniformity can significantly increase convective

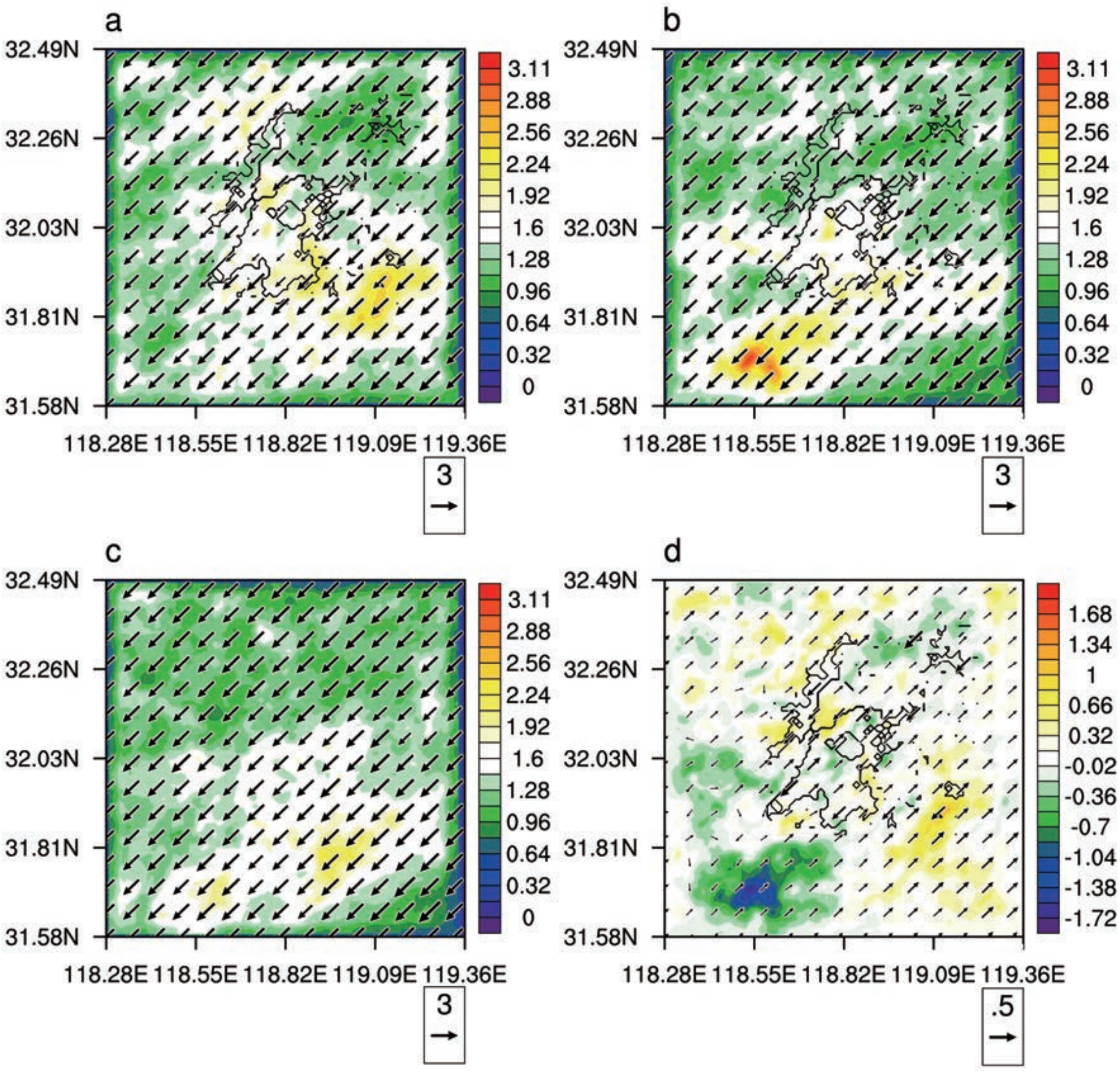

Fig. 4. Intensity of summer precipitation in the Nanjing region (mm h^{-1}): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison. The wind fields in the figure are the mean wind fields at 10 m for rainy summer days (m s^{-1}).

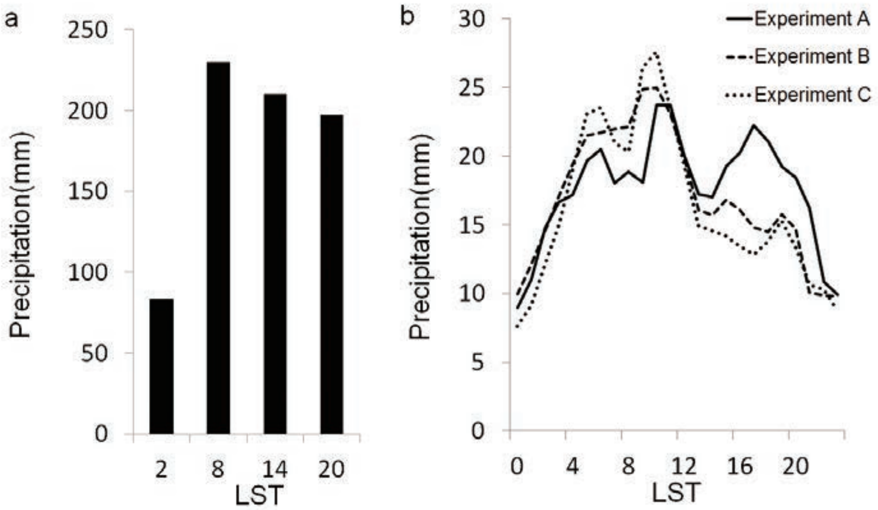

Fig. 5. Daily variation of summer precipitation in the Nanjing region: (a) observation data from Nanjing station; (b) simulation results.

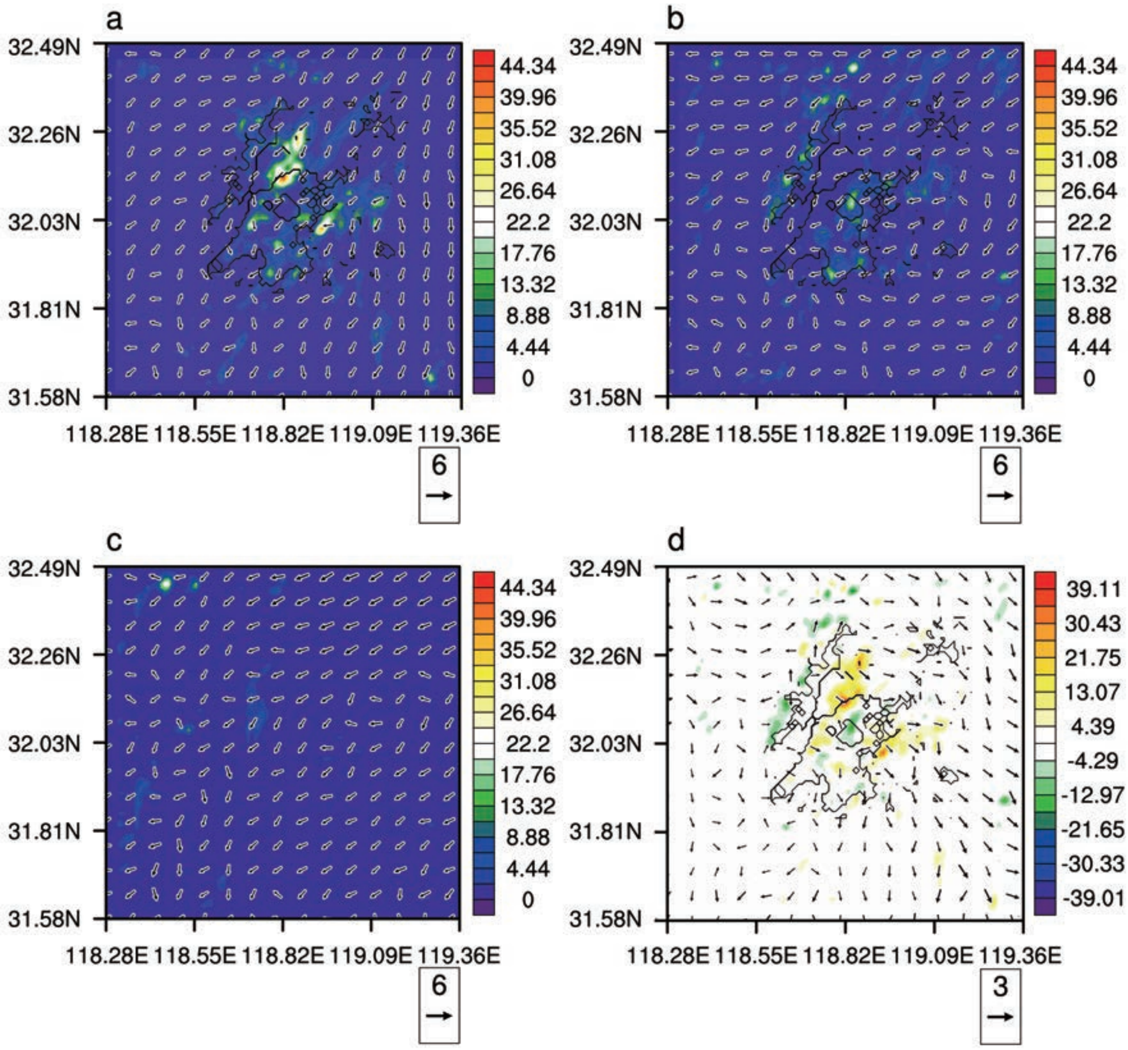

Fig. 6. Spatial distribution of accumulated precipitation on 20 July 2011, in Nanjing (mm): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison. The wind fields in the figure are the mean wind fields at 10 m on 20 July 2011 (m s^{-1}).

precipitation in summer afternoons, and improve the model's performance in terms of the pattern of daily precipitation.

In the present study, light, moderate and heavy rain were defined as daily precipitation from 0.02 to 10 mm, from 10 to 20 mm, and greater than 20 mm, respectively. The effects of the three experiments on these three grades of rain were also compared. There was no significant difference between the spatial distribution of accumulated precipitation simulated in the three experiments for light and moderate rain (data not shown). The mean accumulated precipitation for light rain simulated in experiments A, B and C was 73.5 mm, 79.9 mm and 75.3 mm, respectively. And for moderate rain, the values were 71.5 mm, 76.9 mm and 77.9 mm, respectively. However, there were significant differences among the accumulated precipitation amounts for heavy rain in the three experiments: 278.2 mm (experiment A); 250.6 mm (experiment B), and 236.5 mm (experiment C). Hence, the effect of urban non-uniformity on precipitation was primarily manifested during heavy precipitation events in summer.

3.2. *Analysis of a precipitation event*

Figure 6 shows the distribution of simulated precipitation for an event that occurred on 20 July 2011 in the Nanjing region. The precipitation and its intensity were smallest in the non-urban experiment and largest in the non-uniform experiment. In addition, the majority of precipitation was distributed in and around the urban area. For both the precipitation range and its intensity, the results of the uniform experiment (experiment B) were between those of the non-urban and non-uniform experiments. The mean accumulated precipitation simulated in the three experiments was 1.24 mm, 0.93 mm and 0.23 mm, respectively.

Figure 7 presents the spatial distributions of mean daily friction velocity on 20 July 2011. The friction velocity in the urban area was significantly greater than that in the suburban area. When urban non-uniformity was considered, the friction velocity exhibited a more complicated spatial distribution. The friction velocity increased obviously in the central urban area and also increased over downstream locations, even where the friction velocity was relatively low. Though the overall urban building height decreased, the non-uniformity of the urban distribution increased in the non-uniform city. Overall, the roughness increased, resulting in significant disturbances in the flow field across the urban area.

Figure 8 presents the mean daily vertical velocity profiles in the *y* direction that passed through the center of the domain on 20 July 2011. Compared to experiments B and C, there was a significant updraft in the north of the city in ex-

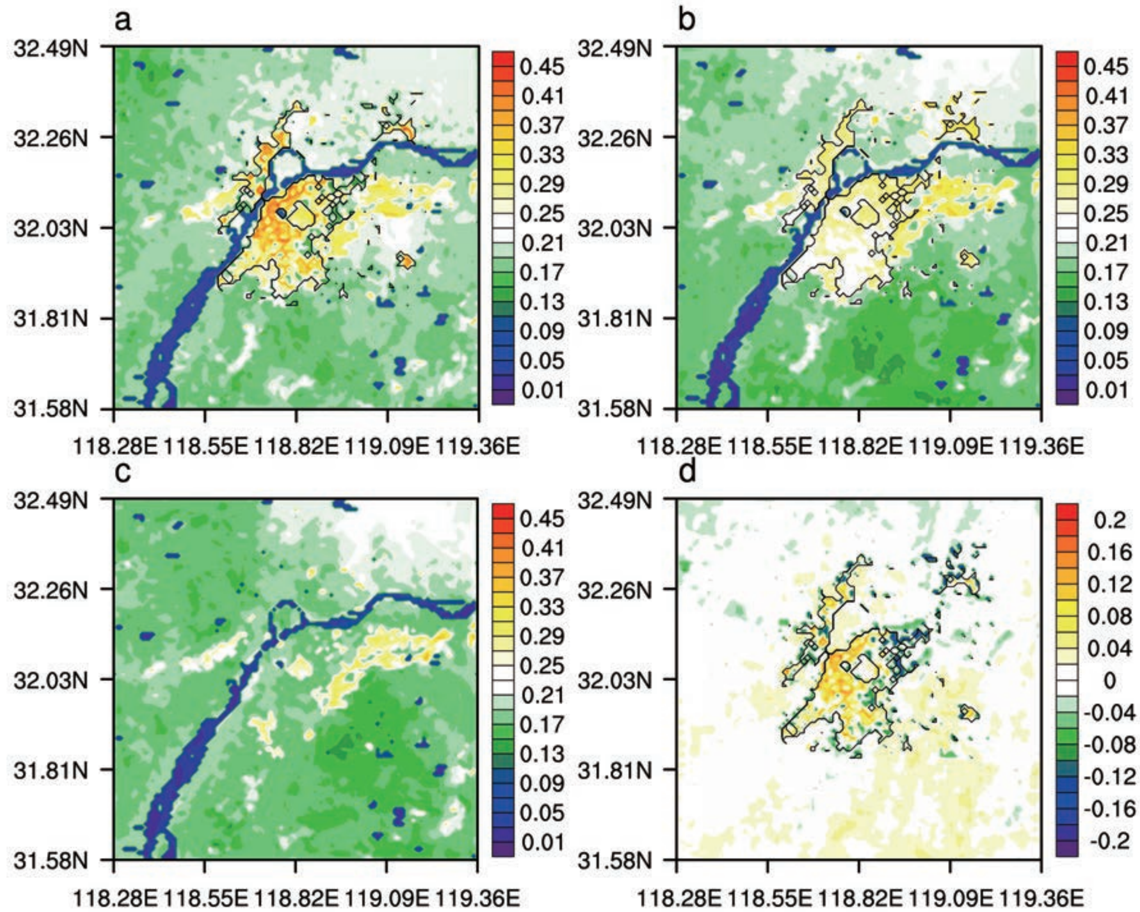

Fig. 7. Daily mean friction velocity on 20 July 2011 across the Nanjing region (m s^{-1}): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison.

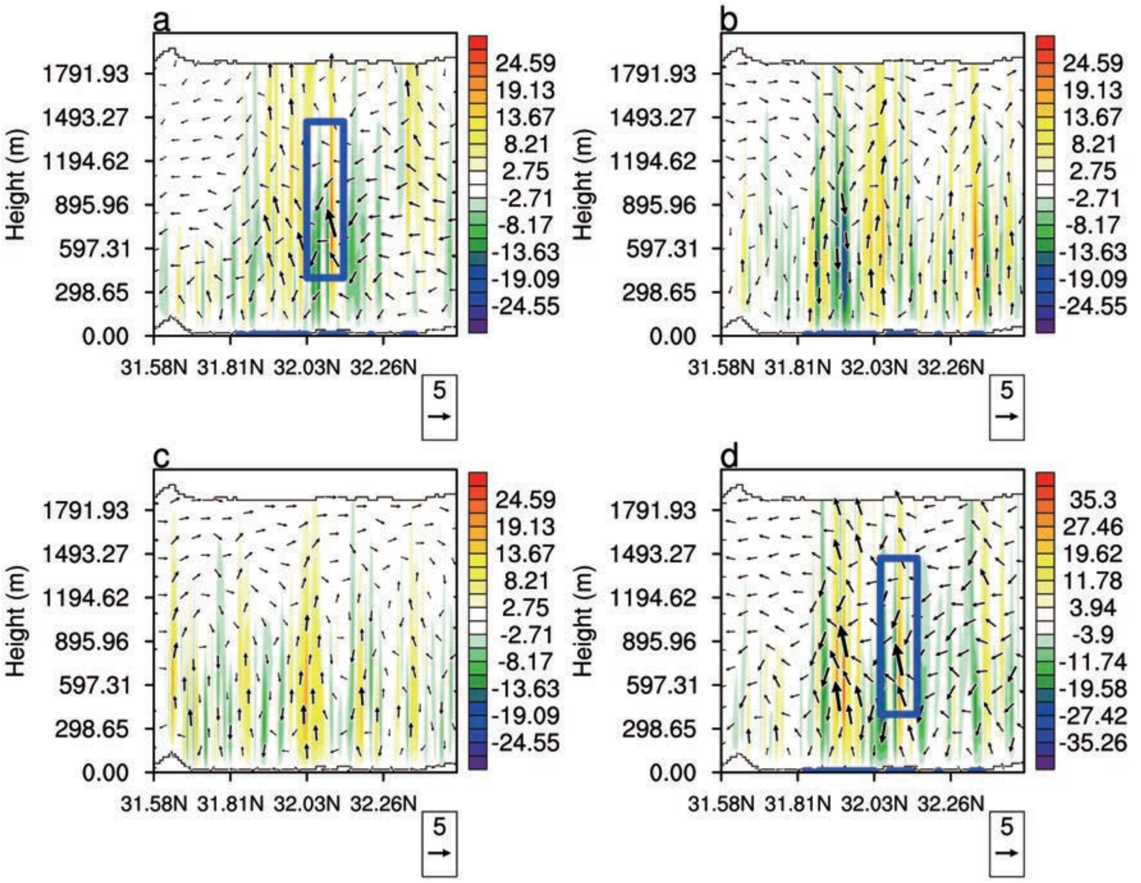

Fig. 8. Daily mean vertical velocity profile on 20 July 2011 across the Nanjing region (cm s^{-1}) [vertical wind vector (***w***) ×25; the blue lines at the bottom of (a, b, d) represent the region of the city]: (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison. The blue boxes reflect the regions that have significant updrafts. The wind fields in the figure are the mean wind fields at the vertical direction on 20 July 2011 (m s^{-1}).

periment A (see the areas within the blue rectangles in Figs. 8a and d), which corresponded very well to the location of the precipitation.

Figure 9 presents the spatial distributions of daily mean water vapor flux divergence at 850 hPa on 20 July 2011. For experiment A, there was significant water vapor divergence in the precipitation area (the area within the red rectangle in Fig. 9a). The water vapor flux divergence in the precipitation was -0.268×10^{-6}, -0.055×10^{-6} and -0.045×10^{-6} kg m^{-2} s^{-2} in experiments A, B and C, respectively. The region of water vapor divergence within the precipitation area for the three experiments was 608 km^2, 554 km^2 and 543 km^2, respectively. Hence, water vapor divergence was the most intense and covered the largest area in the non-uniform experiment.

Figure 10 presents the distributions of daily mean vertical velocity at 700 hPa on 20 July 2011. Compared to the other two experiments, there was significant upward movement in the precipitation area in experiment A, and the areas of positive vertical velocity were more concentrated. The mean upward velocity within the precipitation area at 700 hPa was 1.1 cm s^{-1}, 0.1 cm s^{-1} and −0.5 cm s^{-1} for experiments A, B and C, respectively. In addition, the area of upward movement was 553 km^2, 427 km^2 and 268 km^2, respectively. Hence, the upward velocity and area of upward movement was relatively fast and large, respectively, at 700 hPa in experiment A. The upward velocity and area of upward movement in experiment B were the second fastest and largest, respectively. In experiment C, the mean vertical movement was downward, and the area of upward movement was the smallest among the three experiments.

Mechanistically, the urban impact on precipitation involves dynamic, thermodynamic and chemical effects. The dynamic effects involve increases in surface roughness and enhancements to the drag and lift effects on the airflow. Thermodynamic effects encompass changes in the surface energy balance and the impact of the UHI on the structure of the urban boundary layer. And chemical effects mainly relate to artificial increases in the influence of aerosols on the microstructure of clouds—otherwise known as "aerosol indirect effects". In this study, the setup of the WRF model did not include chemical processes. Therefore, the impact of urban non-uniformity on precipitation was restricted to the other

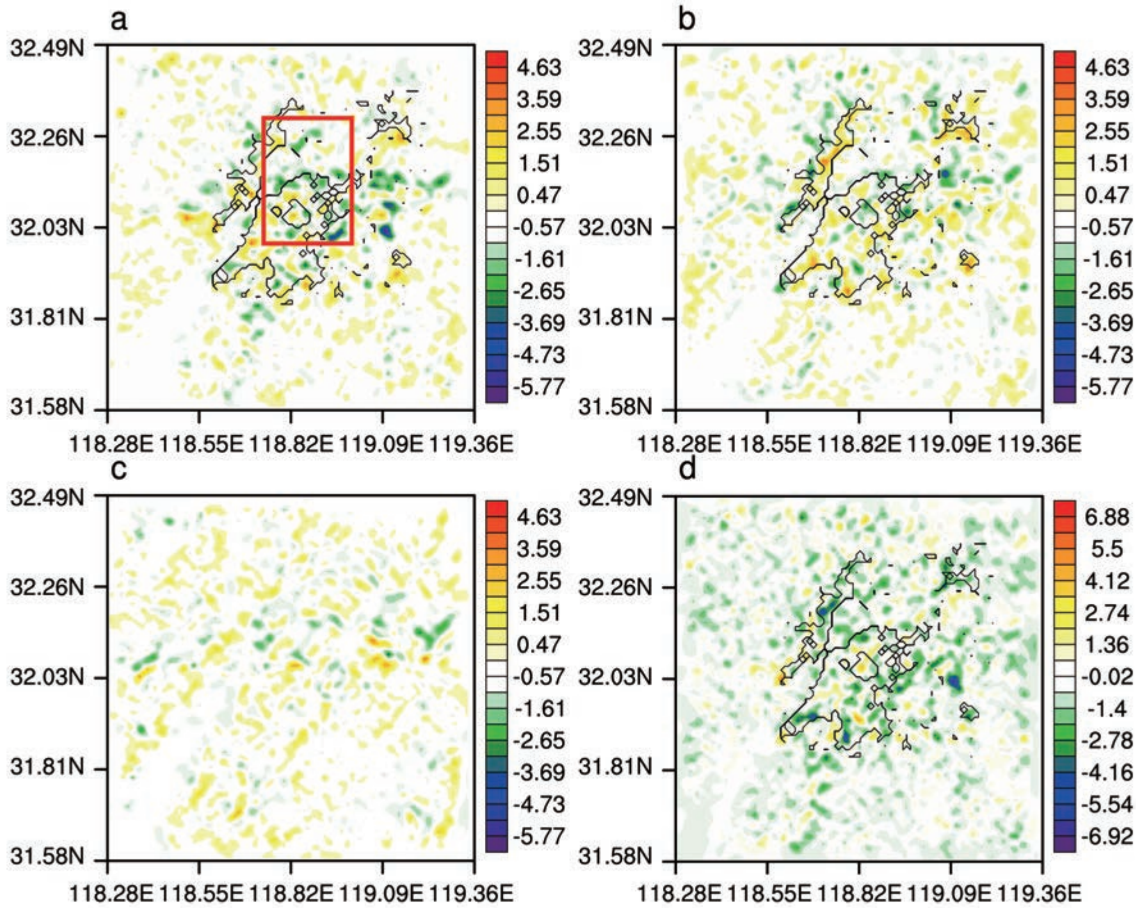

Fig. 9. Daily mean water vapor flux divergence at 850 hPa on 20 July 2011 across the Nanjing region (10^{-6} kg m^{-2} s^{-2}): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison. The red box reflects the region that has significant water vapor divergence.

two aspects: thermodynamic and dynamic effects. Compared to the uniform city, the mean UHI intensity and heat flux of the non-uniform city were lower. Figure 11 shows the diurnal variation of the UHI intensity in the non-uniform and uniform experiments, indicating that the diurnal variation of the UHI could not explain the difference in the diurnal variation of precipitation between these two urban experimental setups (Fig. 5b). We believe that in this simulation, the influence of the UHI was not the main reason for the increased precipitation in the non-uniform city. Certainly, however, the UHI may play an important role in the increase of precipitation compared with the non-urban experiment (Miao et al., 2011).

In the experiments carried out in this work, the total volume of buildings in the non-uniform and uniform setups was 6.41 km^3 and 6.07 km^3, respectively. The volume in the non-uniform experiment was 5.6% higher, which was close to the percentage increase of precipitation (3.85%) in summer. However, heavy rain in summer increased by 11%—much more than the increase in building volume in the non-uniform experiment. This shows that the increase in summer precipitation was due to two aspects, the increase in buildings and the urban non-uniformity, and the effect of urban non-uniformity on convective precipitation was much greater than that on non-convective precipitation.

4. Conclusions

In the present study, sensitivity simulations using the WRF model were conducted to investigate the effect of urban non-uniformity on precipitation in Nanjing in 2011. The main findings can be summarized as follows:

(1) The effect of urban non-uniformity on precipitation was relatively small in winter, spring and fall, but relatively large in summer. The precipitation simulated in the non-uniform experiment was the most comparable to observations, implying that consideration of urban non-uniformity can significantly improve model performance in terms of urban summer precipitation.

(2) Urbanization will result in increases of total accumulated precipitation, precipitation intensity and precipitation frequency in urban areas, and this effect is further increased when urban non-uniformity is considered. The accumulated summer precipitation was 423.1 mm, 407.4 mm and 389.7 mm in the non-uniform, uniform and non-urban experiments, respectively. Therefore, the amount of precipitation simulated

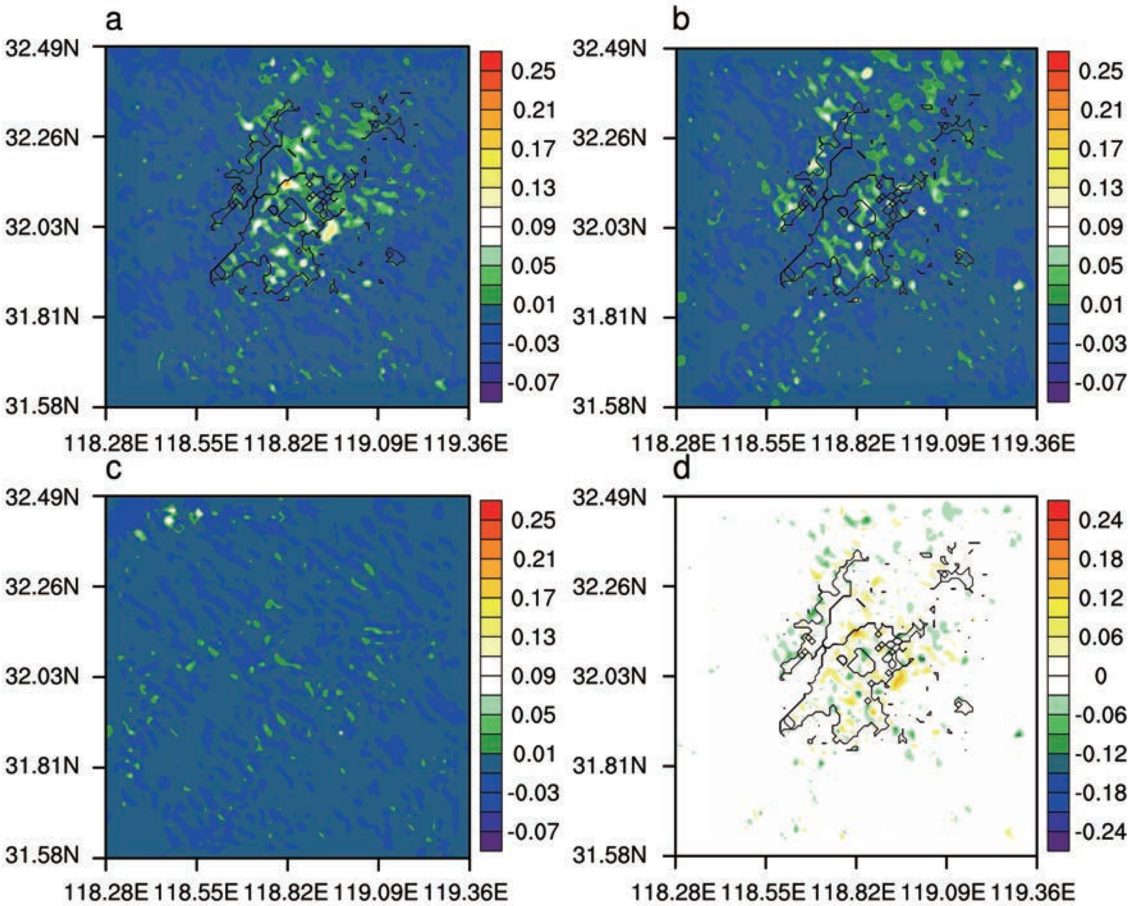

Fig. 10. Daily mean vertical velocity at 700 hPa on 20 July 2011 across the Nanjing region (m s^{-1}): (a) non-uniform experiment; (b) uniform experiment; (c) non-urban experiment; (d) non-uniform–uniform comparison.

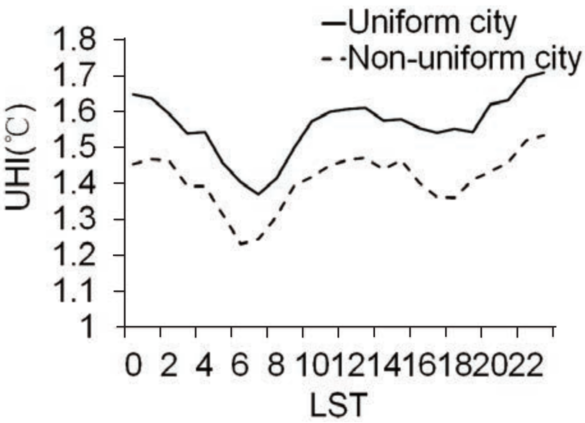

Fig. 11. Daily variation of the summer UHI in the Nanjing region.

in the non-uniform experiment was largest.

(3) The simulated contribution of precipitation to heavy rain (daily accumulated precipitation > 20 mm) in the non-uniform experiment was significantly higher. The summer mean accumulated precipitation for heavy rain was 278.19 mm, 250.61 mm and 236.54 mm in the three experiments, respectively. The effect on light rain and moderate rain was relatively small.

(4) When urban non-uniformity was considered, the precipitation in the morning decreased, but the precipitation between 1500 and 2200 (LST) increased significantly. The pattern of the daily variation was closest to observations in the non-uniform experiment.

(5) The effect of urban non-uniformity on precipitation is mainly realized through increased land surface roughness and surface friction velocity, which in turn increase the low-level water vapor divergence and enhances the mean upward velocity, promoting an increase in heavy precipitation in the afternoon.

It is important to note that in investigating the effect of urban non-uniformity on precipitation in this study, the urban non-uniformity was represented by only three categories. Furthermore, the dynamic and thermodynamic effects relating to urban non-uniformity were not separated. This will be the next step in our continuing research.

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