RESEARCH ARTICLE

Influence of the urban canopy on the numerical simulation of the “720” rainstorm process in Beijing

Ming Zhang1,2 | Shanyou Zhu1 | Fan Ping3

1School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, China
2Meteorological Disaster Prevention Center, Hebei Xiongan New Area Meteorological Service, Baoding, China
3Key Laboratory of Cloud-Precipitation Physics and Severe Storms (LACS), Institute of Atmospheric Physics Chinese Academy of Sciences, Beijing, China

Correspondence
Shanyou Zhu, School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China.
Email: zsyzgx@163.com
Fan Ping, Key Laboratory of Cloud-Precipitation Physics and Severe Storms (LACS), Institute of Atmospheric Physics Chinese Academy of Sciences, Beijing 100029, China.
Email: pingf@mail.iap.ac.cn

Funding information
the National Key Research and Development Program of China, Grant/Award Numbers: 2018YFC1506801, 2018YFF0300102; the National Natural Science Foundation of China, Grant/Award Numbers: 41405059, 41675059, 41875077; Technological Innovation and Guidance Program of Hebei Province in China, Grant/Award Number: 19975414D

Abstract
Based on high-resolution underlying surface data and revised urban parameters, a heavy rainfall process that occurred on July 20, 2016 in Beijing was simulated using the Weather Research and Forecasting Model, version 4.0 (WRF4.0). Sensitivity experiments by changing the land-use type and terrain height, and coupling a slab urban canopy model (UCM) with modified parameters, were carried out to investigate the effects of the urban canopy on this rainstorm process in Beijing. The simulation results confirmed that the urban canopy of Beijing had significant impacts on the heavy rainfall, and its impacts on the rainfall could mainly be attributed to the internal structure and related processes of the urban canopy. The urban canopy increased the convergence of water vapor flux in the urban area, leading to strengthened rainfall in the urban area. In addition, employing the UCM also had an influence. The experiment uncoupled with the UCM suggested that the urban heat island effect of Beijing was relatively weak; its barrier effect of the urban canopy played a leading role that blocked and delayed the movement of rain bands, which divided the airflow and increased the amount of rainfall outside the urban area. The experiment coupled with the UCM took into account the parameters of building height, albedo, and anthropogenic heat, which helped improve the accuracy of rainfall simulation. Its urban heat island phenomenon was obvious, which benefited the convergence and upward movement of urban airflow and promoted the movement of the front and the total rainfall in the urban center.

KEYWORDS
“720” rainstorm in Beijing, mesoscale regional numerical model, numerical simulation, urban canopy

1 | INTRODUCTION

From the 20th century onward, the influence of human activities has led to the rapid development of cities. Studies have shown that the replacement of natural land cover by impervious surfaces has caused obvious changes in surface parameters, including albedo, thermal conductivity, heat capacity, and roughness of the underlying surface (Oke, 1982), which locally affect the large-scale atmospheric composition and surface energy balance, as well as water-
and carbon-cycle processes (Paul et al., 2018). High-impact extreme rainfall events are not only affected and restricted by weather systems at various scale, but are also related to the local conditions of the local underlying surface, such as the terrain height, roughness, surface albedo, land cover, and other parameters whose characteristics are obviously affected by human activities (Wang et al., 2016; Xiao et al., 2017; Yang et al., 2019). Therefore, correctly assessing the impact of cities on weather and climate is particularly important in climate analysis and weather forecasting.

As early as the beginning of the last century, Horton (1921) found that thunderstorms are more likely to occur in urban than rural areas. Much later, Paul et al. (2018) also pointed out that short-term heavy rainfall occurs most frequently in urban centers, and urban effects can change the spatial distribution of rainfall intensity. Metropolitan Meteorological Experiment showed comparing with the spatial distribution of rainfall intensity. Metropolitan rainfall frequently in urban centers, and urban effects can change also pointed out that short-term heavy rainfall occurs most upwind areas. Study of Zhang, Miao, Dai, et al. (2017) found that urbanization had an important impact on short-term rainfall and its distribution (Yang et al., 2019; Yu & Liu, 2015). The risk of extreme rainfall has gradually increased with the development of urbanization (Kong et al., 2018; Zhang et al., 2015) and the relevant researches have been more and more targeted. Koh et al. (2016) studied the influence of urban morphology in Singapore on local rainfall and found that differences in the urban pattern can cause the downwind areas experience more rainfall than the upwind areas. Study of Zhang, Miao, Dai, et al. (2017), Zhang, Miao, Li, et al. (2017), and Zhang, Wang, Zhang, et al. (2017) on urban rainstorm reported urban canopy increased rainfall in the periphery of the main urban area but reduced rainfall in the urban center. The above analysis of relevant research shows that the urban canopy and its related processes of land–air interaction can change the intensity, movement speed, and distribution pattern of the rainfall system (Bornstein & Lin, 2000). However, the influence of the urban canopy, such as the scale of the urban canopy, the spatial distribution, geometry, and nonuniformity of the urban canopy, on heavy rainfall and the potential mechanisms involved, are still to debate. Therefore, further research on heavy rainfall cases in different regions is necessary.

Beijing continues to develop rapidly, and so its urban canopy has become increasingly important in assessing the influence on high-impact weather. In this context, the aim of the present article is to establish the extent of the influence of Beijing’s urban canopy on the extreme rainfall event that took place there on July 20, 2016, by analyzing the results of numerical experiments. Different from previous work, which was mainly based on experiments with and without urban land use, or on urban expansion, we conducted experiments that considered the height and distribution of the urban canopy in Beijing.

2 | Rainfall Case, Model Description, and Experimental Design

2.1 | Rainfall Case

July 19–21, 2016 (Beijing time, the same below), an extreme rainstorm hit Beijing–Tianjin–Hebei. The duration of this rainfall event was about 54 h. Its average rainfall in Beijing was 210.7 mm and the urban area was 274 mm, exceeding historical extremum. Researchs show that the rainfall can be divided into two stages, and the part in the urban area of Beijing was mainly concentrated in the second stage, which was caused by a spiral rain belt on the north side of the low vortex, that lasted from the night of July 19, 2016 to the early morning of July 21, 2016 (Fu et al., 2017; Zhao et al., 2018). The low vortex played a decisive role in the storm. Thus, whether or not the urban canopy influenced the second rainfall stage is key to determining its influence on the rainstorm as a whole.

2.2 | Model Description

In this study, the WRF4.0 was employed to simulate the “720” rainstorm in Beijing. In order to reproduce the heavy rainstorm well, high-resolution data of the underlying surface were introduced, including the global 30-m land-cover dataset FROM-GLC (2015), which was produced by Gong Peng’s team at Tsinghua University. This is a high-resolution land cover data with high classification accuracy in China (Figure 1b1). Also employed was the third edition data of ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) with 30 m spatial resolution, which was jointly developed by Ministry of Economy, Trade and Industry of Japan and
National Aeronautics and Space Administration. The elevation dataset includes the height of buildings ([https://lpdaac.usgs.gov/documents/220/Summary_GDEM2_validation_report_final.pdf](https://lpdaac.usgs.gov/documents/220/Summary_GDEM2_validation_report_final.pdf)) and can cover the global land surface (Figure 1c2).

The simulation domain was designed with triple-nested grids at resolutions of 3, 1, and 0.333 km for the three domains (D1, D2, and D3, respectively), with 37 layers in the vertical direction and 50 hPa at the highest layer. The grid numbers were 355 × 361 for D1, 619 × 652 for D2, and 703 × 733 for D3 in the east–west and south–north directions, covering the urban areas of Beijing and most of the surrounding areas (Figure 1a). The initial and boundary conditions were from the 0.25° × 0.25° reanalysis data provided by the National Centers for Environmental Prediction Global Forecast System, which were obtained every 6 h. The model integrated for 30 h from 2000 LST 19 July to 0200 LST 21 July, 2016.

The model parameterization schemes included the Dudhia shortwave radiation scheme, RRTM longwave radiation scheme, Noah land surface scheme, and Yonsei University boundary layer scheme, which is suitable for the complex terrain of Beijing. In addition, sensitivity experiments of cloud microphysics schemes were also conducted due to the great influence of microphysical process such as phase transformation of particles on the simulation of a rainstorm. The simulation results show that, the general patterns of the rainstorm can be produced by different microphysics schemes, but there were some differences in the intensity and range of the rainstorm (Figure A1). Among them, Lin scheme produced the strongest precipitation intensity and the widest area
of precipitation than the other schemes. Meanwhile it improved the northward simulation of rain belt in WSM6 scheme and was more consistent with the observation. Therefore, Lin scheme is used to simulate the rainstorm in this article.

2.3 Experimental design

To evaluate the impact of the urban canopy on the rainfall system over Beijing, three sets of experiments were designed. The control (CTL) experiment introduced fine-scale land-cover and topographic data (Figure 1b1,c2). Compared with the CTL experiment, two other sets of sensitivity experiments were set up. The NOURBAN experiment replaced the Beijing urban land-use type in the CTL experiment with farmland (Figure 1c1), and subtracted the height of Beijing’s buildings from its topographic data (Figure 1b2) to analyze the impact of Beijing’s urban canopy upon this rainfall case. Meanwhile, in the urban canopy model (UCM) experiment, the underlying surface of the urban area in the CTL experiment was subdivided into high- and low-density residential areas and industrial/traffic areas (Figure 1c3) according to the spatial distribution data set of construction land in China from the geographical situation monitoring cloud platform (http://www.dsac.cn/DataProduct/Index). In addition, a single-layer UCM, which considered the direction and distribution of the urban canopy and the diurnal changes of the solar zenith angle, was coupled with the WRF model to analyze the influence of the additional UCM on the simulation of rainfall. The building parameters in the single-layer UCM were calculated from the building data of Beijing that provided by Beijing Land Bureau (Figure A2). Parameters such as anthropogenic heat and reflectance were set by reference to Miao et al. (2012), Zhang, Miao, Dai, et al. (2017), Zhang, Miao, Li, et al. (2017), and Zhang, Wang, Zhang, et al. (2017).

3 RESULTS

3.1 Influence of the urban canopy on rainfall

3.1.1 Spatial distribution of rainfall

The observed rainfall data used in this study were the 0.1° × 0.1° merged rainfall products of automatic weather station data in China and the CMORPH satellite data (Shen et al., 2013). The observed data (Figure 2a) show that the accumulated rainfall in most parts of Beijing exceeded 100 mm, and the extreme rainfall area was located in the southwest and south of Beijing. From the perspective of the large-scale rainfall distribution, the rainfall simulated by the three sets of experiments (Figures 2b–d) were basically consistent with the observed, indicating that the physical parameterizations of the model were successful in reproducing this heavy rainstorm. To further verify the urban canopy’s performance with respect to this heavy rainstorm process, we compare the spatial distribution of the cumulative rainfall simulated by the CTL, NOURBAN, and UCM experiments (Figure 2). The main impact of the urban canopy was on the extreme rainfall areas, where the total rainfall exceeded 200 mm. In the CTL (Figure 2b) and UCM experiments (Figure 2d), the simulated rainfall in the urban area of Beijing was significantly higher than that in the NOURBAN experiment (Figure 2h). The NOURBAN experiment (Figure 2c) failed to simulate the extreme rainfall in the south of Beijing. The CTL experiment (Figure 2c) improved the simulation results compared to the NOURBAN experiment. The distribution of extreme rainfall in the UCM experiment (Figure 2d) was closest to the observation.

According to Figure 2, compared with the CTL and UCM experiments, the simulated rainfall in the NOURBAN experiment, which removed the urban land use and the height of buildings in Beijing, was reduced in the upwind of Beijing’s urban area and increased in the downwind. Conversely, comparing the CTL experiment (Figure 2c) and the UCM experiment (Figure 2d), the increase in rainfall in the CTL experiment was mainly concentrated in the periphery and the upwind of the Beijing city, while the increase simulated by the UCM experiment is mainly concentrated in the urban center. Based on the above analysis, it can be concluded that the urban canopy of Beijing had an important influence on the location of the extreme rainfall. Combined with the evolution of urban precipitation (Figure 2e,f), it can be known that the urban canopy has an important impact on the location, intensity, and timely of extreme precipitation. The urban canopy will increase precipitation, and the time of heavy precipitation will be further prolonged after coupling the UCM.

3.1.2 Comparison of simulated results and meteorological stations observations

In order to analyze the influence of the urban canopy on the rainfall in the urban area of Beijing, we compare the relative error distribution of the cumulative rainfall simulated by the three sets of experiments (Figure 3). The results show that the three sets of experiments underestimated the extreme rainfall. In the NOURBAN experiment, the relative errors near the main urban area
were around $-30\%$ as compared to the NOURBAN experiment, the CTL experiment (Figure 3a2) reduced the relative error of the stations in the periphery of the main urban area. The UCM (Figure 3a3) experiment significantly reduced the relative error of the stations in the main urban area of Beijing to $-20\%$. Overall, the CTL experiment increased the rainfall in the periphery of the main urban area, whereas the UCM experiment increased it in the urban areas, which was closer than the CTL experiment to the observation situation.

To further verify the urban canopy’s performance with respect to this heavy rainfall process, we also analyze the simulated hourly rainfall of the three experiments during 2000 LST 19 July to 0200 LST 21 July, 2016. Since the rainfall at this time was caused by a spiral rain belt on the north side of a low vortex, three stations near the center of Beijing along the rain belt from west to east, including Haidian, Nanchangjie, and Guanxiangtai, were selected to analyze the effects of rainfall simulation in different locations. The fitting results of the simulation rainfall of the three groups of experiments and the observation data show that the correlation coefficients ($r$) between the simulated rainfall in the UCM experiment and the measured data of Haidian, Nanchangjie, and Guanxiangtai Stations were 0.63, 0.66, and 0.65, respectively, and the coefficients of determination ($R^2$) is 0.40, 0.43, and 0.43, which are better than the CTL simulation results ($r = 0.62, 0.60, and 0.56; R^2 = 0.39, 0.37, and 0.31$), indicating that the accurate urban canopy parameters and coupling with the UCM could better simulate the evolutionary process of this rainfall and have positive significance for the demand of urban fine quantitative rainfall.
In addition, comparing the differences in the fitting trend lines between the three groups of experiments, it can be seen that the greater the hourly rainfall, the more obvious the difference in the trend line (Figure 3b1–b3). This indicates that the urban canopy had a greater impact on the simulation of heavy rainfall, and would have caused more severe rainfall.

3.2 Potential mechanism of the urban canopy’s impact on rainfall simulation

The underlying surface of city is different from that of natural vegetation. Most of the natural vegetation in the urban area has been replaced by buildings, and the ground surface is covered by concrete, which reduces surface evaporation and enhances the absorption of short-wave radiation in the urban area. As a result, surface energy is transported to the atmosphere, mainly in the form of sensible heat.

The simulated surface sensible heat flux and the 2 m temperature in the CTL and UCM experiments are significantly greater than those in the NOURBAN experiment (Figure 4a1,a2). In particular, in the UCM experiment, the model considers parameters such as anthropogenic heat and the reflectivity of buildings, which makes the simulated surface sensible heat flux and 2 m temperature far higher than those in other experiments. The release of surface sensible heat flux causes the near-surface temperature to rise, and they have the same trend over time.

The difference field of surface sensible heat flux in the three experiments (Figure 4b1,b2) shows that the UCM experiment simulated a stronger urban heat island than the CTL experiment, and the surface heat in the urban center was higher than in the surrounding area. This was conducive to the convergence of low-level wind fields (Figure 4c2) and leading to the concentration of rainfall in the urban center. This result explains why the rainfall in the urban center simulated by the UCM experiment is stronger than that by CTL and NOURBAN experiment, and is consistent with the results of Xie et al. (2011) and Su et al. (2019). In addition, combined with the time-height evolution of horizontal wind field and vertical velocity (Figure 5a1–a3) and the changes of precipitation (Figure 2e,f) in urban area, it can be seen that the variation of precipitation simulated by the three groups of experiments is consistent with that of vertical velocity. The urban canopy leads to the increase of urban vertical velocity, and the strengthening of upward movement leads to the increase of precipitation intensity, it is shown that the enhancement effect of urban canopy on vertical velocity is an important factor affecting the extreme precipitation.

The intensity of the urban heat island and the convergence of the wind field in the CTL experiment were weaker than in the UCM experiment. The areas with relatively high heat island intensity were distributed in the periphery of the main urban area. The heat difference between the urban periphery and the suburbs, combined
with the barrier effect of the urban canopy, made the low-level airflow converge at the edge of the urban area and produced an upward movement (Figure 4b1,c1), which caused an increase in rainfall outside the urban area. This result is consistent with the conclusion of Zhang, Miao, Dai, et al. (2017), Zhang, Miao, Li, et al. (2017), and Zhang, Wang, Zhang, et al. (2017).

Many studies have pointed out that cold pools play a key role in the propagation of rainfall systems (Zhang et al., 2018; Zhou et al., 2016). Accordingly, we calculated the temperature anomalies of the three experiments to compare the cold pool strength of each group during the second stage. The results show that Beijing was under the control of cold air from 0200 LST 20 July. Up until 1500 LST 20 July, there was a positive temperature anomaly in the east of Beijing and a negative temperature anomaly in the west. The temperature distribution shows a clear frontal structure (Figure 4b1,b2). Combined with the surface wind field (Figure 4b1,b2), it can be seen that is the front on the north side of the vortex. At 1600 LST 20 July, the front on the north side of the vortex simulated by UCM experiment had reached the main urban area of Beijing. At 1800 LST, the UCM experiment (Figure 5b3) simulated a strong negative temperature anomaly, and the temperature gradient on both sides of the front was large. Due to the urban heat island effect, the moving speed of rain belt was faster and the intensity of rainfall was stronger than that in the CTL (Figure 5b2) and NOURBAN (Figure 5b1) experiments. At 1900 LST 20 July, however, when the front moved through the urban area, the moving speed of the front in the NOURBAN experiment (Figure 5c1) was significantly faster than that in the CTL (Figure 5c2) and
UCM (Figure 5c3) experiments, indicating that the urban canopy hindered the movement of the rain belts to a certain extent (Bornstein et al., 2015). The barrier effect of the urban canopy made the rain belts stagnate in the urban periphery and windward areas. This was also the reason why the CTL experiment simulated increased rainfall in these areas.

Moisture is one of the necessary conditions for the formation of heavy rain, which requires a steady transportation of water vapor. Water vapor flux and water vapor flux divergence can quantitatively describe the direction and volume of water vapor transportation and where the water vapor converges (Wen, 1980). According to the water vapor flux divergence of the rain belt passing through Beijing’s urban areas, it can be seen that the urban canopy was conducive to the water vapor accumulation in the surrounding areas of the urban area (Figure 5). The intensity of water vapor convergence in the urban windward area (the lower right corner of black square) of the CTL (Figure 5d2) and UCM (Figure 5d3) experiments was about 20% higher than that of the NOURBAN experiment (Figure 5d1). At the
same time, the UCM experiment produced a higher intensity of water vapor convergence than the CTL experiment in the main urban area (blue square). Compared with Figure 2, it can be seen that the area of water vapor convergence in the two experiments corresponded to that of rainfall, which indicates that the urban canopy was instrumental in water vapor accumulation in urban area, and played a positive role in the increase of urban rainfall.

4 | CONCLUSIONS AND DISCUSSION

In this study, a torrential rainstorm that occurred in Beijing on July 20, 2016 was simulated with the WRF model and using fine-scale underlying-surface data. The aim was to assess the effect of the urban area and its geometric and physical characteristics on the simulation of heavy rain. The major findings of the study can be summarized as follows:

1. Comparing the results of the three sets of experiments, it was found that the urban canopy increased the rainfall in the urban area, and the magnitude of the increase was related to the internal structure of the urban area. Compared with the results of the NOURBAN experiment, the increase in rainfall in the CTL experiment was 10 and 20 mm in the urban center and the east side of the urban periphery, respectively. The increased rainfall in the UCM experiment was mainly concentrated in the center of urban area, with a magnitude of 30 mm.

2. The urban canopy had a marked impact during the periods of strong rainfall, and enhanced the intensity of rainfall, indicating that the urban canopy was more likely to cause extreme rainfall. In addition, the urban canopy intensified water vapor accumulation in the urban areas, which played a positive role in the increase in rainfall in the corresponding location.

3. In the CTL experiment, the nonuniform distribution of the urban area and the parameters of artificial heat were not considered, which weakened the thermal effect of the urban area to a certain extent. The barrier of urban buildings played a leading role, and the rain belt was blocked by the underlying surface of the city at its periphery and in its upwind areas, leading to the rain belt stagnating and dividing the airflow, which strengthened the rainfall outside the main urban area.

4. The UCM experiment, which considered the geometric and physical characteristics of the urban canopy, better described the thermal conditions of the urban area. The intensity of the urban heat island was higher than that in the CTL experiment, which was conducive to the concentration of rainfall in the urban center. In addition, the correlation coefficient between the simulated hourly rainfall in the UCM experiment and the observed was above 0.6, indicating that considering the geometric characteristics of the uneven distribution of the urban canopy and its related processes improved the accuracy of the rainfall simulation.

In this article, the results from a case study in which a heavy rainfall event in summer in Beijing was simulated have been analyzed, and some preliminary conclusions drawn. According to these preliminary conclusions, the influence mechanism of urban canopy on this precipitation process is given. The urban underlying surface changes the surface thermal environment, resulting in the increase of surface energy and the change of low-level convergence and ascending movement. At the same time, the distribution of urban canopy has an obvious blocking and segmentation effect on the rain belt, resulting in the change of precipitation intensity and precipitation area in the urban area (Figure A3). But, for rainfall processes caused by systems of different scale and with different influences, the effect of the urban canopy may also be various. Thus, it is necessary to study other rainfall cases in the future.

AUTHOR CONTRIBUTIONS
Ming Zhang: Data curation; formal analysis; validation; writing – original draft; writing – review and editing. Shanyou Zhu: Data curation; investigation; supervision. Fan Ping: Conceptualization; formal analysis; funding acquisition; project administration; visualization.

ORCID
Ming Zhang https://orcid.org/0000-0001-9935-4594

REFERENCES
Bornstein, R., Dou, J.J., Wang, Y.C & Miao, S.G. (2015) Observed spatial characteristics of Beijing urban climate impacts on summer thunderstorms. Journal of Applied Meteorology and Climatology, 54(1), 94–105. https://doi.org/10.1175/JAMC-D-15-0355.1
Bornstein, R. & Lin, Q. (2000) Urban heat islands and summertime convective thunderstorms in Atlanta: three case studies. Atmospheric Environment, 34(3), 507–516. https://doi.org/10.1016/S1352-2310(99)00374-X
Changnon, S.A. (1992) Inadvertent weather modification in urban areas: lessons for global climate change. Bulletin of the American Meteorological Society, 73(5), 619–752.
Fu, J.L., Ma, X.Q., Chen, T., Zhang, F., Zhang, X.D. & Sun, J. (2017) Characteristics and synoptic mechanism of the july 2016 extreme precipitation event in north China. Meteorological Monthly, 43(5), 528–539. https://doi.org/10.7519/j.issn.1000-0526.2017.05.002
Horton, R.E. (1921) Thunderstorm-breeding spots. *Monthly Weather Review*, 49, 193–194. https://doi.org/10.1175/1520-0493(1921)49<193a:TS>2.0.CO;2

Huff, F.A. & Champaign, S.A. (2010) Potential urban effects on precipitation in the winter and transition seasons at St. Louis, Missouri. *Journal of Applied Meteorology*, 25(12), 1887–1907.

Koh, T., Panda, J., Norford, L.K. & Li, X.X. (2016) Impact of urbanization patterns on the local climate of a tropical city Singapore: an ensemble study. *Journal of Geophysical Research: Atmospheres*, 121(9), 4364–4403. https://doi.org/10.1002/2015JD024452

Kong, F., Wang, Y.F., Fang, J. & Lv, L.L. (2018) Spatial pattern of summer extreme precipitation and its response to urbanization in China (1961-2010). *Resources and Environment in the Yangtze Basin*, 27(5), 996. https://doi.org/10.11870/cjlyzyyhj201805007

Miao, S.G., Dou, J.X., Chen, F., Li, J. & Li, A.G. (2012) Analysis of observations on the urban surface energy balance in Beijing. *Science China: Earth Science*, 55(11), 1881–1890. https://doi.org/10.1007/s11430-012-4411-6

Oke, T. (1982) The energetic basis of the urban heat Island. *Quarterly Journal of the Royal Meteorological Society*, 108, 1–24. https://doi.org/10.1002/qj.49710845502

Paul, S., Ghosh, S., Mathew, M., Devanand, A., Karmakar, S. & Niyoji, D. (2018) Increased spatial variability and intensification of extreme monsoon rainfall due to urbanization. *Scientific Reports*, 8(1), 3918. https://doi.org/10.1038/s41598-018-22322-9

Shem, W. & Shepherd, M. (2009) On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. *Atmospheric Research*, 92(2), 172–189. https://doi.org/10.1016/j.atmosres.2008.09.013

Shen, Y., Pan, Y., Yu, J.J., Zhao, P. & Zhou, Z.J. (2013) Quality assessment of hourly merged precipitation product over China. *Transactions of Atmospheric Sciences* (in Chinese), 36(1), 37–46.

Su, A.F., Shi, D.L. & Ge, X.Y. (2019) Numerical simulation of the influence from urbanization and orography on a severe rainfall event in Zhengzhou. *Journal of Atmospheric Sciences*, 42(3), 434–446. https://doi.org/10.1002/jcli.567

Wang, J., Feng, J. & Yan, Z. (2018) Impact of extensive urbanization on summertime rainfall in the Beijing region and the role of local precipitation recycling. *Journal of Geophysical Research: Atmospheres*, 123(7), 3323–3340. https://doi.org/10.1002/2017JD027725

Wang, J., Feng, J. & Yan, Z. (2015) Potential sensitivity of warm season precipitation to urbanization extents: modeling study in Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Geophysical Research: Atmospheres*, 120(18), 9408–9425. https://doi.org/10.1002/2015JD025372

Wang, Y.W., Ren, X., Zhai, X.F., Liu, S.D. & Wang, C.G. (2016) Numerical study of the three—dimensional thermal environment over a complex underlying surface in Nanjing. *Journal of Atmospheric Sciences*, 39(4), 525–535. https://doi.org/10.13878/j.cnki.dqkxxb.20110608002

Wen, B.A. (1980) Water vapor flux and water vapor flux divergence. *Meteorological Monthly*, 6(6), 34–36. https://doi.org/10.7519/j.issn.1000-0526.1980.06.019

Xiao, X., Sun, J., Chen, M., Qie, X., Wang, Y. & Ying, Z. (2017) The characteristics of weakly forced mountain-to-plain precipitation systems based on radar observations and high-resolution reanalysis. *Journal of Geophysical Research: Atmosphere*, 122(6), 3193–3213. https://doi.org/10.1002/2016JD025830

Xie, N., Wang, Y.Q., Shi, J. & Ni, P. (2011) Numerical simulation of city underlying surface effect on a rainstorm process in Chengdu. *Plateau Meteorology*, 30(6), 1472–1480.

Yang, L., Smith, J. & Niyoji, D. (2019) Urban impacts on extreme monsoon rainfall and flooding in complex terrain. *Geophysical Research Letters*, 46, 5918–5927. https://doi.org/10.1029/2019GL083363

Yu, M. & Liu, Y. (2015) The possible impact of urbanization on a heavy rainfall event in Beijing. *Journal of Geophysical Research: Atmospheres*, 120(16), 8132–8143. https://doi.org/10.1002/2015JD023336

Zhong, S.H., Xia, R.D. & Wang, Y.Q. (2018) Observational analysis of a local heavy rainfall in Beijing caused by terrain,cold pool outflow and warm moist air interactions. *Journal of Atmospheric Sciences*, 41(2), 207–219. https://doi.org/10.13878/j.cnki.dqkxxb.20160115001

Zhang, C.L., Chen, F., Miao, S.G., Li, Q.C., Xia, X.A. & Xuan, C.Y. (2009) Impacts of urban expansion and future green planting on summer precipitation in the Beijing metropolitan area. *Journal of Geophysical Research*, 114, D02116. https://doi.org/10.1029/2008JD010328

Zhang, S., Huang, G., Wang, J., Liu, Y., Jia, G.S. & Ren, G.S. (2015) Impact of Urban Surface Characteristics on Summer Rainfall in the Beijing-Tianjin-Hebei Area. *Chinese Journal of Atmospheric Sciences*, 39(5), 911–925. https://doi.org/10.3878/j.issn.1006-9895.1411.14199

Zhang, Y.C., Wang, X.F., Zhang, L. & Shu, J. (2017) Numerical simulation of the impacts of the sea-breeze and the urban heat Island on the severe convective event in Shanghai. *Plateau Meteorology*, 36(3), 705–717. https://doi.org/10.7522/j.issn.1000-0534.2016.00056

Zhang, Y.Z., Miao, S.G., Li, Q.C. & Dai, Y.J. (2017) Numerical simulation of the impact of urban underlying surface on fog in Beijing. *Chinese Journal of Geophysics (in Chinese)*, 60(1), 22–36. https://doi.org/10.6038/cjg20170103

Zhang, Y., Miao, S., Dai, Y. & Bornstein, R. (2017) Numerical simulation of urban land surface effects on summer convective rainfall under different UHI intensity in Beijing. *Journal of Geophysical Research: Atmosphere*, 122(15), 7851–7868. https://doi.org/10.1002/2017JD026614

Zhao, S.X., Sun, J.H., Lu, R. & Fu, S.M. (2018) Analysis of the 20 July 2016 unusual heavy rainfall in north China and Beijing. *Meteorological Monthly*, 44(3), 351–360. https://doi.org/10.7519/j.issn.1000-0526.2018.03.002

Zhong, S. & Yang, X.Q. (2015) Mechanism of urbanization impact on a summer cold-frontal rainfall process in the greater Beijing metropolitan area. *Journal of Applied Meteorology and Climatology*, 54(6), 1234–1247. https://doi.org/10.1175/JAMC-D-14-0264.1

Zhou, S., Ma, Y. & Ge, X. (2016) Impacts of the diurnal cycle of solar radiation on spiral rainbands. *Advances in Atmospheric Sciences*, 33(9), 1085–1095. https://doi.org/10.7519/s00376-016-5229-5

How to cite this article: Zhang, M., Zhu, S., & Ping, F. (2022). Influence of the urban canopy on the numerical simulation of the “720” rainstorm process in Beijing. *Atmospheric Science Letters*, 23(8), e1092. https://doi.org/10.1002/asl.1092
APPENDIX

Figures A1–A3.

**FIGURE A1** Cumulative precipitation in Beijing from 2000 LST 19 July 2016 to 0200 LST 21 July 2016 simulated by different cloud microphysical schemes (unit: mm): (a) obs, (b) Lin, (c) WSM6, (d) Thompson, (e) Milbrandt 2-mom, and (f) Morrison 2-mom.

**FIGURE A2** Distribution of buildings in Beijing.
FIGURE A3  Mechanism of urban canopy affecting precipitation