

Journal: Weather and Climate Dynamics

Manuscript Number: egusphere-2025-4746

Type: Research Article

Title: Impacts of orography and urbanization on extreme precipitation event in Beijing during 2023

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We highly appreciate two anonymous reviewers for their very helpful and insightful comments, which lead to the significant improvement of the manuscript quality. We also thank the editor for the evaluation of our manuscript. We have checked our work carefully according to these comments and made request changes.

Below we indicate the comments and use blue font for our responses. The corresponding revised texts are also used blue font in the revised version of our manuscript.

Reviewer #1: Review of “Impacts of orography and urbanization on extreme precipitation event in Beijing during 2023” by Haobo Cui et al.

General Comments

This manuscript investigates the impacts of orography and urbanization on the extreme precipitation event in Beijing during July 29 - August 2, 2023, using WRF model sensitivity experiments. The topic is timely and relevant given the increasing frequency of extreme weather events in urban areas with complex topography. The authors employ a reasonable experimental design with three scenarios to isolate effects of terrain and land use. However, several significant concerns need to be addressed before the manuscript can be considered for publication. The issues are substantial but addressable. Therefore, major revisions are recommended.

Response: We highly appreciate you for your thorough review and constructive comments, which significantly improve the quality of our manuscript. We have carefully considered all comments and have made the following changes.

(1) The evaluations of model simulation with meteorological observation were complemented and the quantitative statistics were listed to make the results more convincing.

(2) The water vapor budget was quantitatively assessed to improve the physical mechanism.

(3) The methodological choices were better justified to enhance the scientific contribution.

(4) More discussion including the ensemble simulation, the uncertainty quantification and the important limitations of our study were added.

We have also checked the English texts carefully and corrected the grammatical errors through the manuscript. Below we indicate the comments and use blue font for our responses. We hope the following point-to-point response could address your concern.

Major Comments

1. One of the concerns is the substantial precipitation overestimation in the southwestern mountainous region, which is precisely the area of primary scientific interest. The model simulates over 800 mm while CMORPH shows less than 700 mm (lines 276-278). This raises fundamental questions about whether the diagnosed physical mechanisms are correctly represented in the model. When the model gets the magnitude wrong in the key region, how confident can we be that it correctly represents the processes causing those differences between sensitivity experiments?

Response: Thanks for your comments. Previous studies have recognized that there are large uncertainties in precipitation observations and satellite-derived products across regions with complex terrain (Zhou et al. 2008, Yu et al. 2009, Yu et al. 2025), a concern our research also acknowledged. However, this study focused on evaluating the model's ability to reproduce the spatial distribution characteristics of precipitation and the comparison among different experiment schemes. Although the control experiment exhibits a certain wet bias over the southwestern mountainous area, all sensitivity experiments employ exactly the same dynamical and physical configurations.

“The simulated precipitation was compared with meteorological station observations and satellite products to evaluate the accuracy of the model outputs. It was found that, the maximum observed precipitation is 772.2 mm, which was comparable with the simulation result of approximate 800.0 mm. The average precipitation amount was 237.0 mm for all the station observations during this precipitation event, and the average simulated value on the grid where the station located in is 228.4 mm. Therefore, the magnitudes were comparable between model simulation and observation on the stations.”

The corresponding parts were added in [lines 272-279](#).

The authors should provide comprehensive quantitative validation metrics including RMSE, bias, and correlation coefficients for different sub-regions, not just qualitative, descriptive comparisons.

Response: To evaluate the simulation accuracy of the WRF model across different study areas (D04 in the manuscript), it is divided into mountain area (where terrain height greater than 100 m) and plain area (where terrain height smaller than 100 m). The Figure 4 in the initial version was reproduced with the scatter plots shown separately for the mountain and plain areas. The quantitative statistics were listed in Table 2 in the revised version. The more explanations are added as follows. (Lines 288-295)

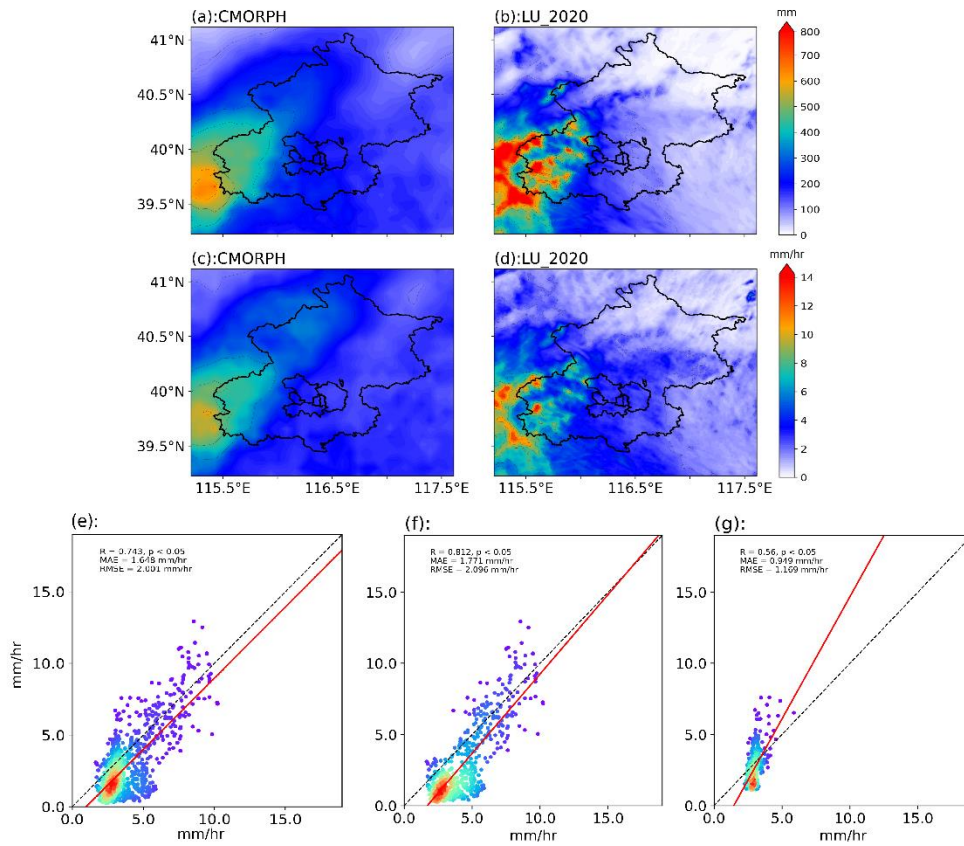


Figure 4: Comparison of simulated and observed precipitation: (a)–(b) accumulated precipitation for CMORPH and LU_2020, respectively; (c)–(d) average precipitation intensity for CMORPH and LU_2020; and (e) scatter plots for the precipitation intensity for CMORPH in x axis and LU_2020 in y axis, while the red line represents the linear regression; (f) and (g) representing area where terrain height greater than 100 m and smaller than 100 m.

Table 2: Statistics of the precipitation intensity between simulations and CMORPH data.

	R	RMSE	MAE
All	0.743	2.001	1.648
Mountain	0.812	2.096	1.771
Plain	0.560	1.169	0.949

“Thus, the WRF simulation results provided a reasonable representation of the overall precipitation event, and the LU_2020 simulation results were used to analyze the differences due to orography and land use. The correlation coefficient of the plain areas shows a smaller value ($R=0.56$) compared with mountain areas ($R=0.81$). For the result of MAE and RMSE, the statistics in the plain areas are smaller than those in the mountainous areas and the entire study region (Table 2). This may be due to that there are more stations in the plain areas, and the precipitation is smaller than mountain areas.”

More importantly, they need to explicitly discuss how this bias might affect their interpretation of the sensitivity experiments. Does the overestimation suggest the model is too sensitive to orographic forcing? If so, might the diagnosed “impacts” of terrain removal be exaggerated? Additionally, while the authors note limitations in mountain station data, surely some station data from the plains areas were available and could strengthen the validation.

Response: We admitted that there are limitations of regional models for simulations with removed orography may influence the meteorological boundary conditions. However, the terrain-removal experiment adopted in this study follows the idealized sensitivity framework widely used is used to investigate the impact of orographic effects (Boos and Kuang 2010, Arushi et al. 2017, Babaei et al. 2021). In addition, we only removed the topographic elevation without altering any other variables in LU_nohgt experiments. Thus, the impacts of orographic may introduce errors but the impacts are limited. We also explored the scheme with setting the terrain above 0 m to exactly 0 m, to detect the simulation uncertainty in terrain removal schemes. Please our response to your major concern 3.

2. Throughout the manuscript, results are presented with spurious precision and no uncertainty estimates. For example, stating that “accumulated precipitation was 229.42 mm higher” (line 301) implies 0.01 mm accuracy that simply does not exist in

numerical weather prediction. These are not measurements but model outputs from a single realization with one choice of parameterizations.

Response: Thanks for your comments. In this study, the cumulative precipitation was actually the mean obtained by averaging the grid-point precipitation over the study area. However, we indeed ignored the fact that the precipitation values simulated by the model are accurate to 0.1 mm. In the revised version, we have corrected the descriptions related to average precipitation to enhance the precision of expressions.

The entire attribution analysis rests on differences between model experiments, yet there is no assessment of whether these differences exceed natural variability or model noise. What if you ran the simulation starting 6 hours earlier? What if you used different physics schemes? The differences might vary substantially. Without any ensemble members or uncertainty quantification, readers cannot assess the robustness of the conclusions.

The authors acknowledge this limitation briefly in the discussion but do not adequately address its implications. Even a small ensemble of 3-5 members with perturbed initial conditions would greatly strengthen confidence in the results. Additionally, the language throughout should be more cautious, using phrases like “the model suggests” rather than definitive statements about impacts.

Response: We admitted that, physical parameterization options have significant influences on precipitation simulations, not only for the magnitude and duration, but also for spatial and temporal distribution. The parameterization method adopted in this study had also been used in other studies about urban extreme precipitation events (Ryu et al. 2016, Wang et al. 2018, Luo et al. 2023, Wang et al. 2023, Xian et al. 2023), which can partly can prove the rationality of this study. Following your suggestion, the model uncertainty was further accessed using an ensemble simulation of LU_2020 scheme, where are originated from 10 ensemble members of ERA5. They provide estimates of the short-range forecast uncertainty, and can be considered to represent the evolution of the errors in the high-resolution component of ERA5 (Hersbach et al. 2020). The results were shown in Supplementary Figure S4 and the

following tests were added in the revised version. (Lines 296-306)

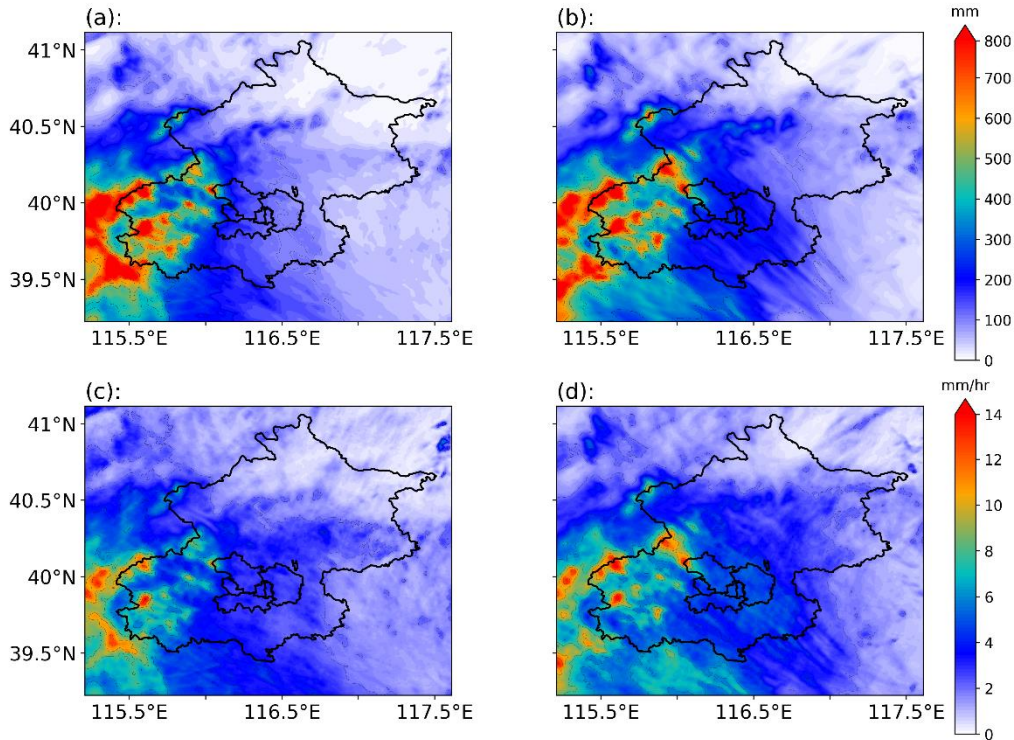


Figure S4: Comparison between simulated results of the events. (a), (b) represents the accumulated precipitation amount of LU_2020 experiment and 10 members ensemble mean, while (c), (d) represents the corresponding intensity simulation, respectively.

“In addition, the model uncertainty was further accessed using an ensemble simulation of LU_2020 scheme, where are originated from 10 ensemble members of ERA5. They provide estimates of the short-range forecast uncertainty, and can be considered to represent the evolution of the errors in the high-resolution component of ERA5 (Hersbach et al., 2020a). The results show that there is slightly difference between the ensemble mean simulation and our experimental results (Figure S4). Statistically, the average precipitation intensity is 3.6 mm/hr for LU_2020 scheme and 4.1 mm/hr for the ensemble mean. The RMSE and MAE of precipitation intensity is 1.17 mm/hr and 0.86 mm/hr for the two simulation results and the correlation coefficient is 0.90. Therefore, the experimental scheme and simulation results in this study are convincing.”

Additionally, we have revised the language throughout the manuscript, to be more cautious as you suggested.

3. The choice to set all terrain above 100 m to exactly 100 m (lines 201-204) creates an artificial plateau. This decision appears arbitrary and is inadequately justified. Why 100 m specifically? A supplementary experiment with completely flat terrain would help clarify whether results depend on this somewhat arbitrary choice.

Response: Thanks for your comments. In our manuscript, the choice of removing the terrain with an elevation above 100 meters to ensure that the terrain in other regions would not be affected while eliminating the terrain of the Taihang Mountains and the Yanshan Mountains and exploring the impact during the precipitation event. Similar experimental design had been used in several other researches (Boos and Kuang 2010, Insel et al. 2010, Saurral et al. 2015, Song and Shao 2023). To detect the influence of the terrain removal operation, the experiment was repeated after removing all the terrain in the entire research area to explore the simulation of completely flat terrain. The experimental results were shown in Supplementary Figure S5 as follows. (Lines 763-781)

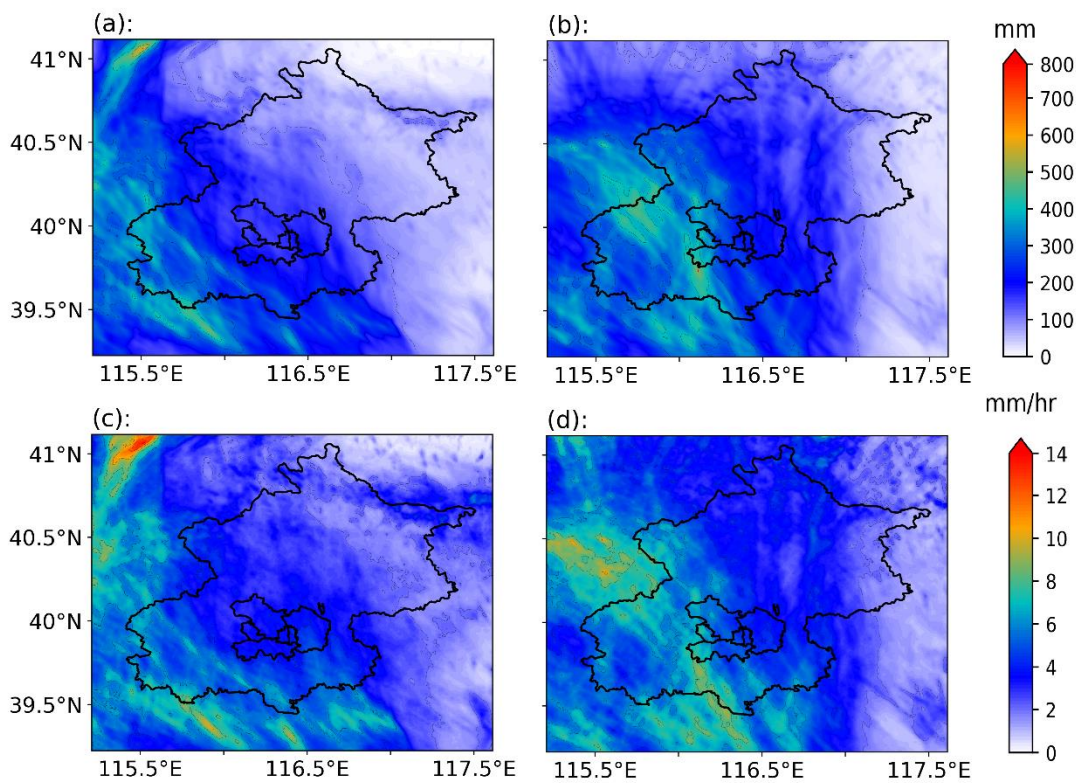


Figure S5: Accumulated precipitation and intensity distribution of the event. (a, b) represents the accumulated precipitation amount of 100 m removal experiment and 0 m removal experiment, respectively.

while (c, d) represents the corresponding precipitation intensity, respectively.

“The choice of removing the terrain with an elevation above 100 meters was adopted in this study to ensure that the terrain in other regions would not be affected while eliminates the terrain of the Taihang and Yanshan Mountains. Similar experimental design had been used in other researches (Boos and Kuang, 2010; Insel et al., 2010; Saurral et al., 2015; Song and Shao, 2023). To detect the influence of the terrain removal operation, the experiment was repeated after removing all the terrain in the entire research area and the simulation of completely flat terrain was explored. It can be seen from Figure S5 that the spatial patterns of precipitation are similar for the schemes of 100 m and 0 m removal experiment. The center of maximum precipitation in 0 m removal experiment shifts eastward. This is mainly because the flat terrain enhanced the northward transport of water vapor and further slowed the dissipation of the remnant low of Doksuri. It therefore increases the precipitable water over the region and leads to a more intense precipitation event. Statistically, the mean precipitation intensity is 4.2 mm/hr and 4.7 mm/hr for the 100 m and 0 m removal experiment, respectively. The RMSE and MAE of precipitation intensity is 1.54 mm/hr and 1.17 mm/hr between these two schemes and the correlation coefficient is 0.74. The results proved the strong relationships between the precipitations from 100 m and 0 m removal experiment schemes, which may apply to other precipitation related variables.”

4. While the manuscript presents extensive diagnostics, the analysis often remains qualitative when quantitative assessment is needed. The moisture budget analysis (Figures 8-9) shows flux magnitudes, but nowhere do the authors calculate the net moisture convergence. How much moisture actually enters through the southern boundary? How much exits through the northern boundary? What is the net convergence, and how does it relate to the precipitation amount?

Response: Thanks for your comments. We realized that the results can be more convincing, with the quantitative calculation of moisture budget analysis. Following

your suggestion, the quantitative water vapor fluxes were listed in Table 4.

Table 4: The water vapor flux (kg/(m s)) during each period for different schemes.

Time	Scheme	North	South	Zonal	East	West	Meridional	Net
T1	LU_2020	58.63	-19.52	39.11	130.50	-100.61	29.89	69.00
	LU_nohgt	78.89	-83.09	-4.20	141.79	-110.93	30.86	26.66
	LU_nourb	55.42	-22.42	33.00	133.97	-94.19	39.78	72.78
T2	LU_2020	146.94	-109.39	37.55	146.05	-160.02	-13.97	23.58
	LU_nohgt	222.99	-146.99	76.00	176.09	-199.31	-23.22	52.78
	LU_nourb	152.31	-113.83	38.48	139.02	-150.29	-11.27	27.21
T3	LU_2020	199.32	-169.36	29.96	71.65	-95.36	-23.71	6.25
	LU_nohgt	228.22	-237.85	-9.63	32.12	-0.69	31.43	21.80
	LU_nourb	206.16	-160.40	45.76	74.65	-64.38	10.27	56.03

In addition, in order to enable readers and reviewers to more clearly discern the variations in moisture transport from different boundaries, the corresponding figures (Figures 8 and 9 in the initial version) was reproduced as Figures 8, 9 and 10. In these new figures, positive moisture flux denotes the transport of water vapor into the region, whereas negative values indicate the export of water vapor from the region. The corresponding texts were revised to make the results quantitatively explicit. (Lines 427-501)

“Figure 8 shows the magnitudes of the water vapor flux at the four boundaries of RegP for LU_2020. An increase in net moisture convergence during each period leads to higher precipitable water over the region, which in turn provides more favorable conditions for precipitation. Specifically, the moisture inflow across the southern boundary (Figure 8(a), (e), (i)) and the eastern boundary (Figure 8(d), (h), (l)) represents meridional and zonal sources of water vapor entering the region. The outflow across the northern boundary (Figure 8(b), (f), (j)) and the western boundary (Figure 8(c), (g), (k)) reflects the moisture exported from the region. The difference between the inflow and outflow moisture flux indicates net moisture income in each time period (shown in Table 4).

During period T1, about 49.58 kg/(m s) water vapor was transported southward at lower latitudinal levels along the southern boundary, while it was transported totally 58.63 kg/(m s) northward at high latitudes. As the Taihang Mountains extend

in a southwest-northeast direction in the study area, the eastern zonal airflow was totally 130.50 kg/(m s), blocked by the Mountainous area and shifted southward which explained why water vapor was transported southward in northern boundary. Overall, the moisture input into the RegP was dominated by zonal water vapor transport. Although the meridional transport contributed a relatively large amount of moisture inflow, its substantial outflow resulted in a comparatively small net contribution to the regional moisture budget.

The water vapor flux distributions were similar during periods T2 and T3, while the magnitude of water vapor decreased from 23.58 kg/(m s) to 6.25 kg/(m s). Although the zonal water vapor transport increased to some extent, the total moisture inflow during the two periods remained comparable. Meridionally, the eastward water vapor flux decreased from -13.97 kg/(m s) to -23.71 kg/(m s). In addition, the water vapor transport during T3 became more concentrated in the lower layers which indicated the contribution of low-level water vapor transport to the precipitation process. Compared with that in T1, the northward water vapor flux at the southern boundary was significantly increased in T2 and T3. The northwestward transport increased and led to strong uplift motion in the mountainous area. Consequently, the mountainous areas may have been more prone to intense convective weather events due to the sufficient water vapor and air uplift during T2 and T3.”

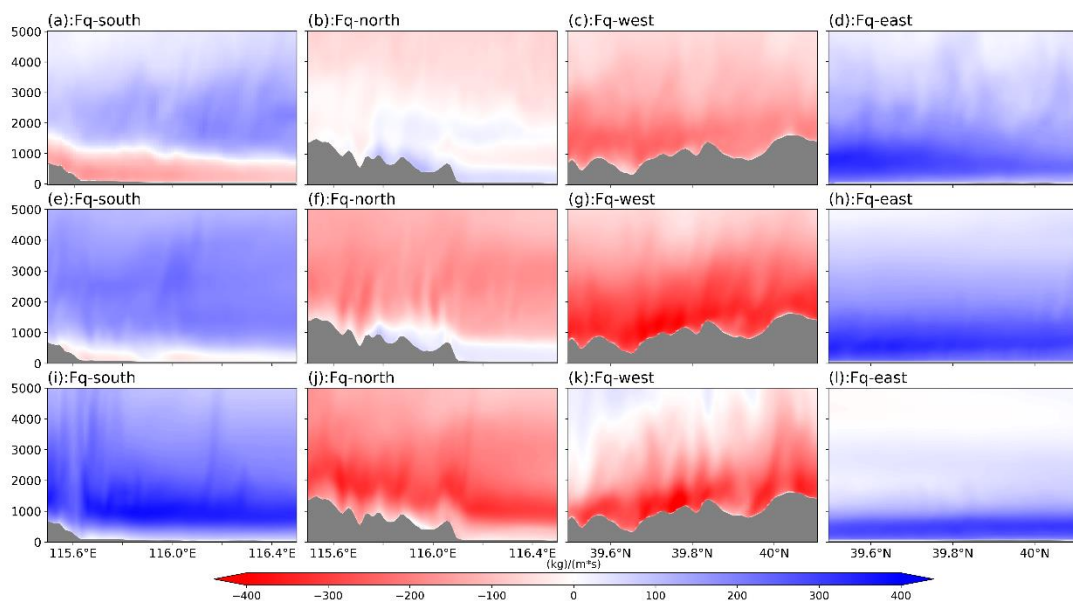


Figure 8: Distribution of water vapor flux magnitude in the LU_2020 scheme across latitude-

height/longitude-height coordinates of RegP. Figures show the water vapor flux magnitude for time periods T1 (a - d), T2 (e - h), and T3 (i - l), with fluxes from the south (a, e, i), north (b, f, j), west (c, g, k), and east (d, h, l). Positive and negative water vapor flux values correspond to input and output water vapor flux relative to RegP.

“Orographic height significantly impacted water vapor flux transport, as shown by the differences in the water vapor distribution between LU_2020 (Figure 8) and LU_nohgt (Figure 9) and the corresponding water vapor flux transport in table 4. From a zonal perspective, orography considerably influenced the water vapor distribution within RegP. Due to orographic effects, water vapor was lifted and its northward transport was prevented, statistically reduced about 63.57 kg/(m·s) in the LU_2020 (Figure 9 (a), (e), (i)), which also increased the total amount of zonal water vapor flux in LU_2020. From meridional perspective, the meridional water vapor flux output from western boundary substantially decreased by 49.41 kg/(m·s) and 79.38 kg/(m·s) during the whole period, resulting in a noticeable rise in the water vapor content in the entire region. Furthermore, the easterly winds were blocked and diverted by the orographic effect of the mountains to the west of Beijing, which also leads to a modest increase in the magnitude of the southward water vapor flux at the southern boundary in the lower atmospheric layers.”

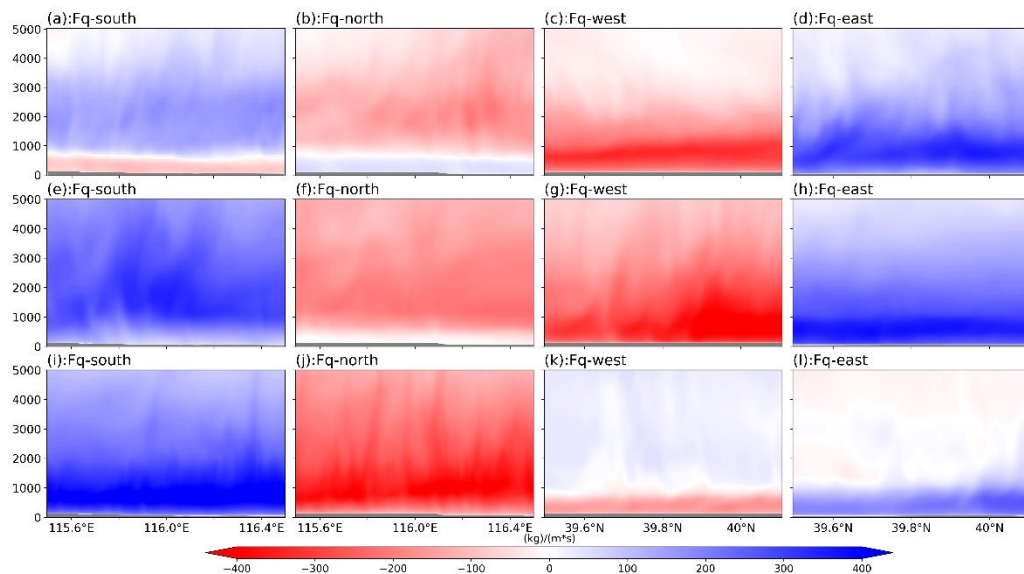


Figure 9: Water vapor fluxes as shown in Figure 8, where a - l depict the magnitude of the water vapor flux from four directions in the LU_nohgt scheme.

“The impacts of the urbanization on water vapor transport are shown in Figure 10. There was no significant difference between LU_2020 and LU_nourb in water vapor flux during periods T1 and T2 as the difference between net convergence is smaller than $10 \text{ kg}/(\text{m}\cdot\text{s})$. However, the differences mainly appeared at the western boundaries of RegP during period T3. At the western boundary, the westward water vapor flux was $30.98 \text{ kg}/(\text{m}\cdot\text{s})$ higher compared with that in LU_nourb (Figure 10(k)). These differences of moisture flux between different schemes were mainly due to wind speed in lower troposphere. As urban land use can influence local atmospheric circulation, such strong ascent induces horizontal convergence and a subsequent conversion of horizontal momentum into vertical motion. Such momentum redistribution can reduce the horizontal wind speed, particularly within the convectively active region, leading to a reduction in moisture flux across the western and northern boundaries.”

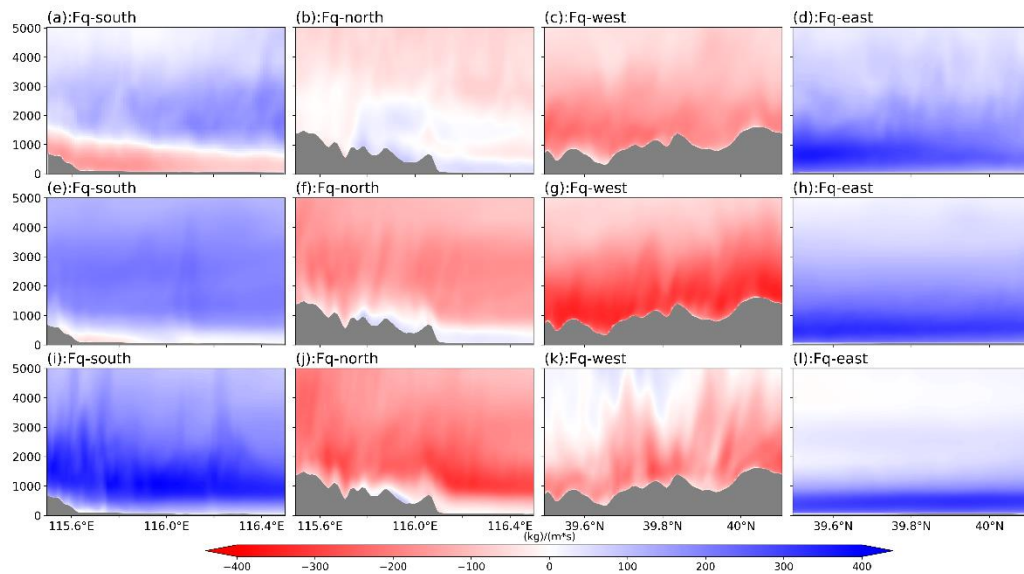


Figure 10: Water vapor fluxes as shown in Figure 8, where a - 1 depict the magnitude of the water vapor flux from four directions in the LU_nourb scheme.

Additionally, the authors should track the low-pressure center explicitly, show geopotential height evolution, and calculate steering flow to demonstrate the blocking mechanism quantitatively. Similarly, the subtropical high is mentioned repeatedly as an important factor but is never analyzed with actual diagnostics of its position and

strength.

Response: Thanks for the comments. We acknowledge that analyses based solely on three key time points are insufficient to fully represent the evolution of the synoptic circulation. Therefore, the temporal resolution has been refined and the circulation maps are newly provided in Figure 3 to illustrate the evolution of the weather system. The corresponding parts were added in [line 218-268](#).

“As shown in Figure 3, the remnant low of Typhoon Doksuri maintained considerable intensity at the 500-hPa level on July 29, with its center located near 112° – 114° E, 32° – 34° N. At this time, the main body of the Western Pacific Subtropical High (WPSH) was situated along the eastern coastal region of China and the adjacent seas, with the westernmost position of the 5880-gpm geopotential height contour around 118° E, indicating its limited westward extension. The Beijing area was primarily located within the weakly influenced northwestern periphery of the WPSH, where low-level moisture transport was relatively weak and heavy precipitation had not developed.

By July 30, the WPSH had extended westward, with the 5880-gpm contour reaching approximately 105° – 110° E and stretching northward to Mongolia. It thereby established a relatively stable high-pressure ridge to the north of the Doksuri remnant low and formed a typical blocking circulation pattern. Consequently, the center of the remnant low oscillated slightly within 112° – 115° E and 33° – 35° N, illustrating a pronounced quasi-stationary state that persisted until around 12:00 UTC July 31. During this period, Beijing was located between the southern of the blocking high and the northern of the remnant low. This configuration was favorable for sustained southeast flow and continuous moisture toward Beijing area.

After 12:00 UTC July 31, the remnant low of Doksuri gradually weakened and shifted slightly westward, while the blocking high also began to decay. Meanwhile, Typhoon Khanun over the offshore waters of China (Figures 3(f)–(i)) established a strong cyclonic circulation on its northwestern side, further enhancing moisture transport into North China. It greatly increased precipitable water, thereby triggered the heavy precipitation event between 12:00 UTC July 31 and 00:00 UTC August 1.

Then, the WPSH further intensified and continued to westward extension, with the 5880-gpm contour maintained at the west of 108°E. The western ridge of the strengthened WPSH subsequently blocked the moisture transport pathway from Typhoon Khanun toward North China, leading to a pronounced reduction in the moisture transportation. The precipitation process then gradually weakened and terminated.

The differences among the experimental groups are mainly reflected in the local circulation. A comparison of Figures S1 and S2 shows that the removal of terrain elevation exerts a noticeable influence on the circulation associated with the remnant low-pressure system. In the absence of the orographic blocking effect of the Taihang Mountains, the remnant low of Typhoon Doksuri continued to move northward and prolonged the duration of the low-pressure circulation. Consequently, the changed dynamical and thermal conditions over the Beijing region were prone to alter the spatiotemporal distribution of precipitation. In comparison, the differences between Figures S1 and S3 indicate that urban underlying surface has a relatively weak effect on the large-scale circulation. It resulted in the reduction of the regional surface roughness and an increase in wind speed over Beijing area. In addition, the dissipation time of the remnant low circulation in the LU_nourb scheme is slightly prolonged due to the reduction of anthropogenic heat. Therefore, the large-scale circulation pattern in the LU_nohgt and LU_nourb schemes are generally similar to LU_2020. This suggests that the differences in simulated precipitation are primarily induced by the changes in local circulation.”

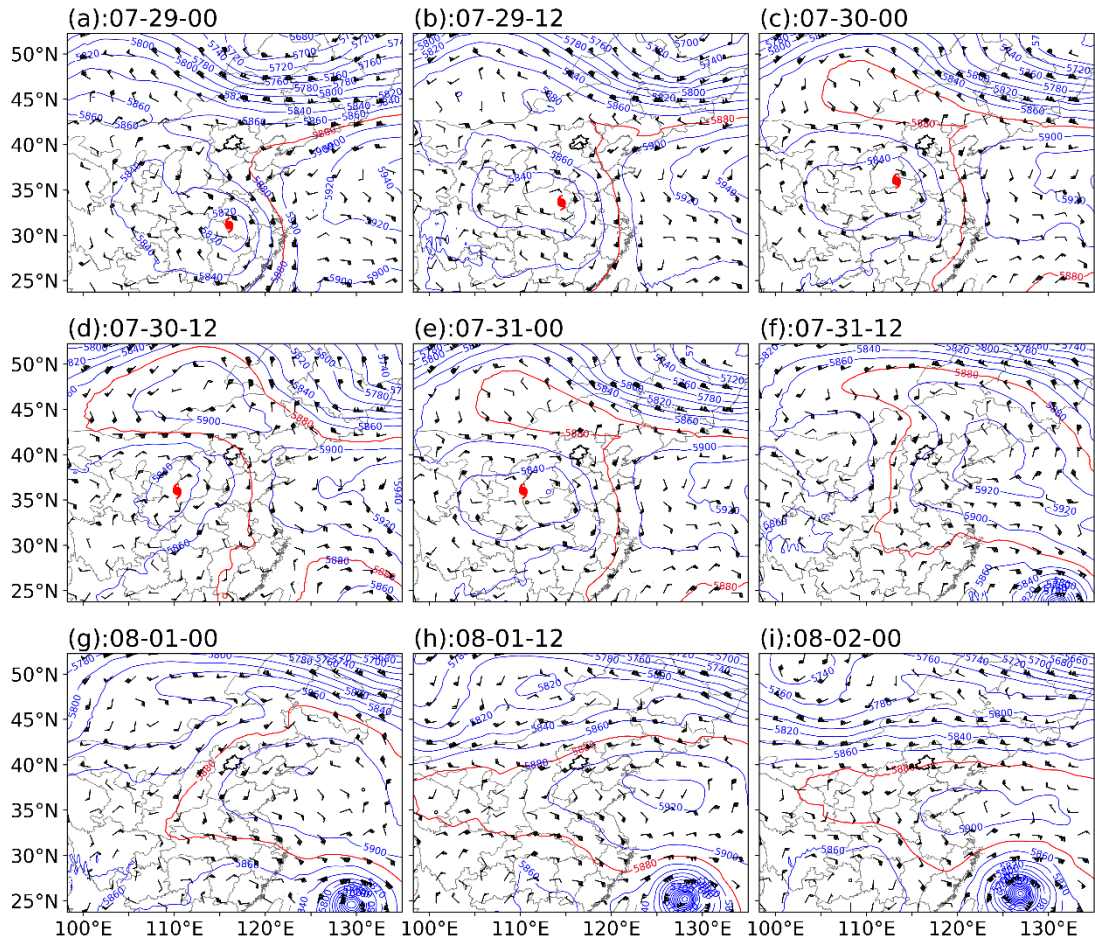


Figure 3: 500hpa circulation pattern for the precipitation event (source: ERA5). The blue solid lines represent geopotential height contours; the red solid contours represent position of subtropical high; the typhoon symbols in (a) - (e) represent residual circulation center of typhoon Doksuri.

5. The discussion section does not adequately address important limitations or place the results in broader context. The authors note that their precipitation distribution differs from multi-year averages found in previous studies (lines 680-695) but do not adequately explain what makes this event anomalous or how that affects generalizability. Are the topographic and urban effects similar in other Beijing extreme rainfall events, or is this case unusual? Such context would help readers understand what aspects of these findings might apply more broadly.

Response: Thanks for your comments. We admitted that the interpretation of this section was not sufficiently clear and caused confusions. In the revised version, the discussion section is divided into three parts: “4.1 The intention of experiment design”, “4.2 Comparisons with related studies” and “4.3 Uncertainty in the

experiment simulation”. We addressed the important limitations of this study and added more discussions to place the results in broader context. (lines 724-760)

“According to previous research, the maximum reduction in precipitation due to urbanization during warm-season rainfall occurs in the northeastern region of Beijing (Song et al., 2014; Wang et al., 2018). However, in the present study, the largest reduction in precipitation induced by urbanization was observed in the southwestern mountainous region. This difference is mainly caused by the different response patterns of mean and extreme precipitation events. The climatological statistics represent response of mean state, while extreme precipitation is often governed by nonlinear, specific dynamical forcing, and that may cause different distribution pattern (Liu and Niyogi, 2019). As shown in the results, the water vapor transport of this precipitation event was mainly dominated by the southeasterly water vapor flux governed by the large-scale circulation, which thus triggered precipitation in the southwestern piedmont area of the Taihang Mountains. Although precipitation also occurred in the northwestern region, its intensity was weaker than that in the southwestern region, which is also the reason why this precipitation event is distinct from others. Therefore, compared with the changes in the average distribution of seasonal precipitation in Beijing found in previous studies, individual case experiments may simulate precipitation distribution patterns that differ from the multi-year observed accumulated precipitation.

Previous studies also found that, the modifications of local urban land surface can influence local-scale atmospheric circulation (Kim et al., 2021; Sui et al., 2024; Zajic et al., 2011). The widespread presence of impervious surfaces in urban areas restrained surface evaporation, by reducing the upward transport of moisture into the atmosphere. This process can lead to low relative humidity and reduce atmospheric instability, which in turn modifies the local precipitation distribution (Wang et al., 2018). For the extreme precipitation event occurred on July 21 2012, the precipitation event was mostly generated by convective cells that were triggered by local orography and then propagated along a quasi-stationary linear convective system (Zhang et al., 2013a). According to analyses of multiple extreme precipitation events in Beijing in

recent years, urbanization can reduce rainfall in the urban area and increases rainfall downwind of the city. In some cases, the larger percentage of sealed area could give rise to the heavier precipitation or extreme rain events (Liu et al., 2021). As different types of precipitation or different weather conditions can lead to complex relationships between precipitation and elevation, even along the same slope (Gnann et al., 2025; Houze Jr., 2012). Therefore, urban effects of each event should be analyzed independently (Liu et al., 2021). This precipitation event is somewhat representative; however, for precipitation events under different initial conditions, further investigation is needed.”

Aerosols are acknowledged as potentially important but the complete absence of aerosol effects in the experiments is not adequately justified. Either the authors should explain why aerosols can be neglected for this particular event, or they should acknowledge this as a significant limitation that could be affecting their results, particularly for the urban impact attribution.

Response: Thanks for your comments. Aerosols have a significant impact on the weather in urban areas, especially on extreme weather events. We have acknowledged the absence of aerosol effects as a limitation and would be investigated in future research. (lines 801-810)

“Besides, the concentrations of aerosols emitted in urban areas could also have influenced the extreme precipitation because it is largely driven by the coalescence of cloud droplets. Studies have shown that aerosols can lead to the formation of smaller-sized cloud droplets, increasing the effective radius of precipitation, and thus impact convective rainfall (Sun et al., 2022; Zhong et al., 2015). In addition, topographic variations can also affect the generation of cloud particles (Lee et al., 2018; Mazzetti et al., 2021). However, this study focuses on the impact of natural factors, particularly the underlying surface, on precipitation events. Aerosols are largely attributed to anthropogenic factors, therefore are not involved in this study and would be considered in future research.”

Minor Comments - - - - -

The introduction provides good context but has some redundancy

Response: We have polished the language and make the text more concise.

Unclear phrasing: “The setting of altitude in the numeric model” (line 73)

Response: It has been revised to “The altitude used in the numeric model”

Several methodological choices need better justification, e.g. the upper boundary at 50 hPa and the assimilation coefficient. Are these values standard, or were they optimized for this case?

Response: Thanks for your comments. The reason why we configure the upper boundary at 50hPa is to resolve the vertical structure of the subtropical high and upper-level jet streams while minimizing spurious wave reflection near the upper boundary. The value is standard and can be seen in other researches on extreme precipitation events. We have added these expressions in the method section of the revised version in **lines 164-177**.

“In addition, 49 vertical layers were employed in the simulation and the upper boundary was set at 50 hPa to resolve the vertical structure of the subtropical high and upper-level jet streams while minimizing spurious wave reflection near the upper boundary (Wang et al. 2018, Yu et al. 2024, Pei et al. 2025). ... The assimilation coefficient was set to $3 \times 10^{-4} \text{ s}^{-1}$ suggested in other previous researches (Holst et al., 2016; Liu et al., 2012; Ma et al., 2016; Pei et al., 2025), and the cut-off wave number was set to 3 in both the zonal and meridional directions as the length-scale is more accurate at 1000 km (Gómez and Miguez-Macho, 2017; Kukulies et al., 2023). The hourly output for region D04 was used in the following analysis.”

The use of MODIS 2020 land cover for a 2023 event raises questions about whether significant land cover changes occurred in the interim, particularly given Beijing’s continued development. This should at least be acknowledged as a potential limitation.

Response: Thanks for your comment. The reason why we used 2020 rather than 2023 land cover type is that the latest version provided by MODIS corresponds to the year 2020. We referred to the data provided by Sentinel-2 and the land cover type between 2020 and 2023 and added the related discussion. (lines 792-800)

“Furthermore, due to constraints in data accessibility, only the 2020 MODIS land use dataset was obtained and used in our simulations, despite potential temporal mismatches with other input data periods. The Sentinel-2 satellite observations were further detected to assess the potential biases in land use between 2020 and 2023. The urban extent exhibited minimal variation between these years (Figure S6), validating the temporal stability of the MODIS baseline. However, the inherent differences in classification schemes between MODIS and Sentinel-2 precluded direct data integration or substitution. Therefore, the 2020 MODIS dataset was retained as the most recent consistent one, though it may introduce some uncertainties into the results.”

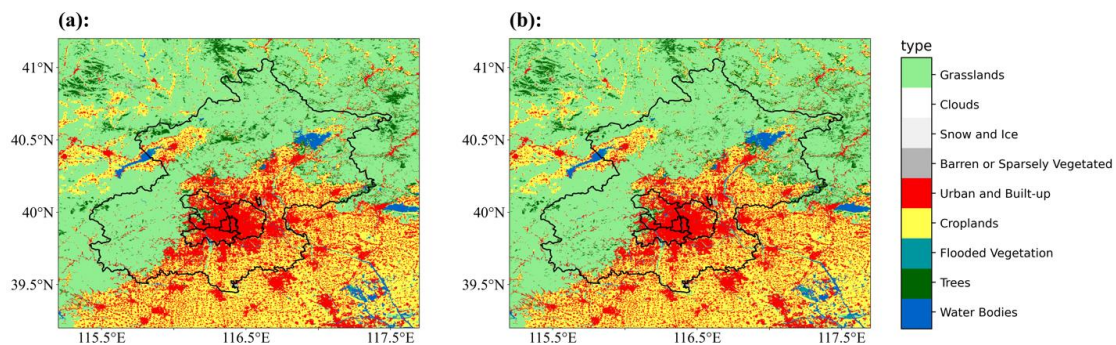


Figure S6: Comparison between land cover type in 2020 (a) and 2023 (b) in Beijing region from Sentinel-2.

Throughout the results, equivalent potential temperature fields are shown but rarely analyzed quantitatively. The authors should calculate and discuss gradients, baroclinic zones, and frontal features rather than just presenting the visualization.

Response: Thanks for your comments. We have recognized that presenting only the surface equivalent potential temperature is insufficient to fully illustrate the mechanism of the event occurrence and the impact of underlying surfaces. Considering that the 2-m equivalent potential temperature varies with altitude, we

selected the equivalent potential temperature at 850 hPa for quantitative analysis. The results are shown in Figure 12 in the revised version and the following explanations were added. (lines 584-612)

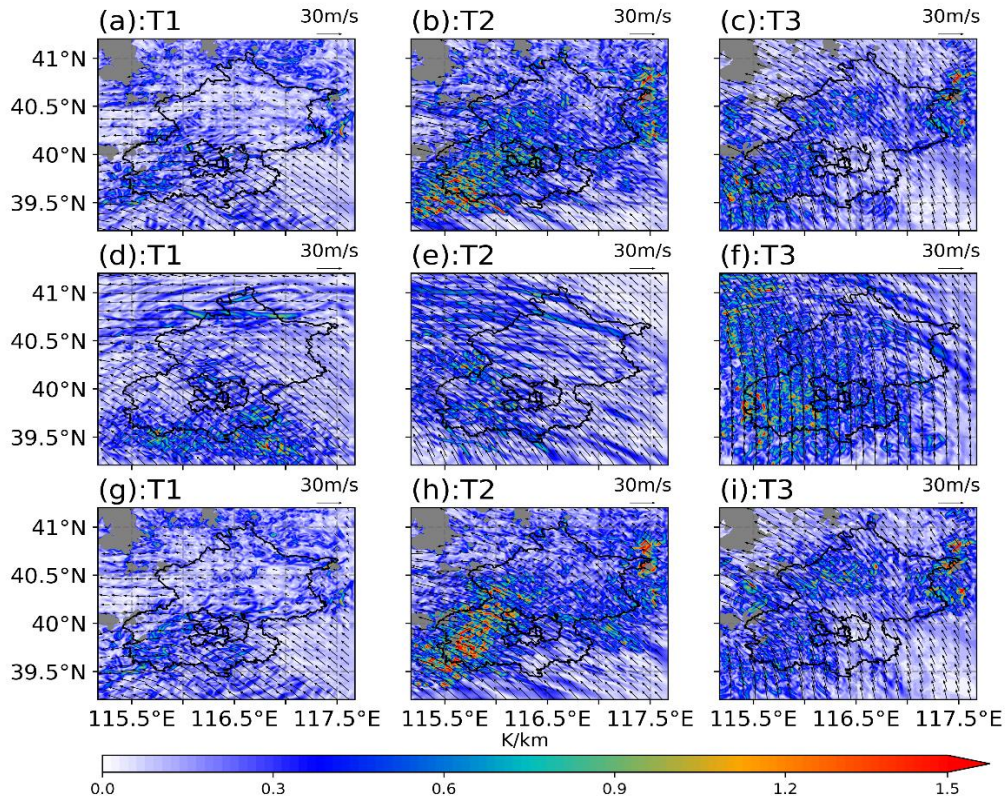


Figure 12: Gradient of equivalent potential temperature field for LU_2020 scheme (a–c), LU_nohgt scheme (d–f), and LU_nourb scheme (g–i) from 850 hPa. Three consecutive time periods were selected: T1 (a, d, g), T2 (b, e, h), and T3 (c, f, i)

“Since presenting only the surface equivalent potential temperature could be insufficient to fully explain the influence mechanisms of the underlying surface, the gradient of equivalent potential temperature at representative times is further analyzed to characterize the atmospheric stability (Figure 12). The orographic lifting exerts a significant modulation on the spatial distribution of the horizontal equivalent potential temperature gradient. During the T1 period, the LU_nohgt scheme exhibits an eastward displacement of the maximum gradient compared with the LU_2020, accompanied by a noticeable shift in the 850-hPa wind shear location. This indicates that, orographic lifting alters the low-level flow and thermodynamic structure, thereby modulates the distribution of moist baroclinicity and the position of the potential

frontal zone. Therefore, it can provide a more favorable thermodynamic environment for convective development over the mountainous areas. During the T2 period, orographic lifting further enhances low-level moist baroclinicity and makes the high-gradient zone more continuous. Combined with the low-level wind shear, these conditions are conducive to frontogenetic processes and convective systems.

In contrast, although relatively large gradients still exist in the LU_nohgt during the T3 period, the low-level convergence and vertical ascent are substantially weakened. It prevents the effective release of thermodynamic instability, and therefore the precipitation process consequently comes to an end. Meanwhile, the changes in urban land use also influence the precipitation intensity, especially during the T2 period. The LU_2020 scheme exhibits larger horizontal gradients over the southwestern mountainous region than LU_nourb. This indicates that urbanization can enhance low-level moist baroclinicity in this area, which is favorable for strengthening frontal structures and increasing the likelihood of intense convection precipitation.”

Figure 12 with 18 panels becomes difficult to read. Consider restructuring, perhaps by moving some panels to supplementary material or combining related diagnostics.

Response: Thanks for your comments. Considering the completeness of presenting the overall experimental results, the vertical cross-sections in different directions need to be included in the manuscript. To improve the readability, we have divided the results of the terrain removal experiment and the land use modification experiment into two separate figures (Figures 14 and 15 in the revised version), while each figure can be clearly displayed.

The manuscript is generally well-written but could be more concise.

Some grammatical issues appear, e.g. “prevented the low-pressure system propagate northward” (line 23) which most likely should read “prevented...from propagating”

Response: Thanks for your recommendation. We have checked the English texts carefully and corrected the grammatical errors through the manuscript to make it more

concise.

Again, thanks for your thorough review and valuable comments.

Reviewer #2: This study analyzed the impact factors in an extreme precipitation event that occurred during July 2023 in Beijing, based on the Weather Research and Forecasting (WRF) model. Several experiments were selected to assess the impacts of topography and land use, with examining the causes of the event and the related mechanisms. It concludes that topographical features caused the uplift of air masses in the mountainous regions leading to significant enhancement of the convective intensity over Beijing and precipitation for a prolonged duration. The presence of urban surfaces contributed to reductions in the latent heat flux and wind speed, resulting in decreased energy transfer to the southwestern mountainous regions via easterly winds.

This study is interesting and the manuscript is well written. There are some issues that could be addressed to improve the manuscript quality.

Response: We highly appreciate you for your thorough review and constructive comments, which significantly improve the quality of our manuscript. We have carefully considered all comments and have made the following changes.

(1) The methodological choices were better justified to enhance the scientific contribution.

(2) The water vapor budget was quantitatively assessed to improve the physical mechanism.

(3) More discussion including the ensemble simulation, the uncertainty quantification and the important limitations of our study were added.

We have also checked the English texts carefully and corrected the grammatical errors through the manuscript. Below we indicate the comments and use blue font for our responses. We hope the following point-to-point response could address your concern.

Introduction: This part is generally coherent and logical, but there are some expression issues that need improvement.

Lines 57-59: The last sentence is related to the effect of surface roughness induced by cities. Therefore, it better remove this to the paragraph of introducing urbanization.

Response: Thanks for your comments. Revisions have been made as suggested.

Line 79: ... another key factors ..., since the authors have pointed out topography as one of the most important factors.

Response: We have revised the manuscript to make the expression explicitly.

Lines 82-83: Delete "which significantly increases the surface roughness". Urban heat island can cause convergence and upward lifting in the lower atmosphere, but is not the cause of surface roughness.

Response: Thanks for your comments. The description in the original text is indeed ambiguous, which has been deleted.

Lines 87: Delete "modifying".

Response: Revised.

Lines 102-103: This sentence introduces the research area, but the expression is not coherent and needs to be revised.

Response: The sentence has been revised to "Beijing is located in the northwest of the North China Plain, where is the transitional zone between the Taihang Mountains, Yanshan Mountains, and North China Plain." (lines 86-88)

Experimental Design:

The WRF simulation is carried out on 49 vertical layers and the upper boundary was set as 50 hPa. Is there any evidence or literature supported this setting?

Response: Thanks for your comments. Previous sensitivity studies have demonstrated

that the number of vertical levels in WRF significantly influences the representation of vertical atmospheric structures (Jenney et al. 2023, Jiang and Hu 2023). It is apparent that the finer vertical resolution can enhance the accuracy in representing the extreme precipitation process. However, an excessively large number of vertical levels would substantially increase computational costs. Therefore, a configuration with 49 vertical levels was adopted, which improves the simulation accuracy while ensuring computational efficiency and timely output of the simulation results.

The reason why we configure the upper boundary at 50hPa is to resolve the vertical structure of the subtropical high and upper-level jet streams while minimizing spurious wave reflection near the upper boundary. The value is standard and can be seen in other researches on extreme precipitation events (Wang et al. 2018, Yu et al. 2024, Pei et al. 2025).

We have added this explanation to the method section in the revised version.
(lines 164-167)

“In addition, 49 vertical layers were employed in the simulation and the upper boundary was set at 50 hPa to resolve the vertical structure of the subtropical high and upper-level jet streams while minimizing spurious wave reflection near the upper boundary (Wang et al. 2018, Yu et al. 2024, Pei et al. 2025).”

Results:

Line 225: Is “EP” shorted for “extreme precipitation”? This abbreviation is only used once and need be changed.

Response: Sorry for the misleading, which has been revised to the full name.

The authors state that using CMORPH data to validate the simulation results was highly reasonable, although it is an indirect observation data. The average precipitation intensity obtained from the simulations was compared with the precipitation intensity of CMORPH. Therefore, it suggests presenting the results of the statistics of MAE, RMSE and R, or at least listing them in a table.

Response: Thanks for your comments. To quantitatively evaluate the simulation accuracy of the WRF model across different study areas (D04 in the manuscript), it is divided into mountain area (where terrain height greater than 100 m) and plain area (where terrain height smaller than 100 m). The quantitative statistics were listed in Table 2 in the revised version. The more explanations are added as follows. (lines 291-295)

Table 2: Statistics of the precipitation intensity between simulations and CMORPH data.

	R	RMSE	MAE
All	0.743	2.001	1.648
Mountain	0.812	2.096	1.771
Plain	0.560	1.169	0.949

“The correlation coefficient of the plain areas shows a smaller value ($R=0.56$) compared with mountain areas ($R=0.81$). For the result of MAE and RMSE, the statistics in the plain areas are smaller than those in the mountainous areas and the entire study region (Table 2). This may be due to that there are more stations in the plain areas, and the precipitation is smaller than mountain areas.”

For the physical mechanism of this precipitation event, the authors can focus on the water vapor transport, especially the differences in water vapor budget at each of the boundary.

Response: Thanks for your comments. We realized that the results can be more convincing, with the quantitative calculation of moisture budget analysis. Following suggestion from you and the first reviewer, the water vapor fluxes were shown in Figures 8, 9, and 10 for the three schemes, and quantitatively listed in Table 4. (lines 427-501)

“Figure 8 shows the magnitudes of the water vapor flux at the four boundaries of RegP for LU_2020. An increase in net moisture convergence during each period leads to higher precipitable water over the region, which in turn provides more favorable conditions for precipitation. Specifically, the moisture inflow across the southern boundary (Figure 8(a), (e), (i)) and the eastern boundary (Figure 8(d), (h), (l))

represents meridional and zonal sources of water vapor entering the region. The outflow across the northern boundary (Figure 8(b), (f), (j)) and the western boundary (Figure 8(c), (g), (k)) reflects the moisture exported from the region. The difference between the inflow and outflow moisture flux indicates net moisture income in each time period (shown in Table 4).

During period T1, about 49.58 kg/(m s) water vapor was transported southward at lower latitudinal levels along the southern boundary, while it was transported totally 58.63 kg/(m s) northward at high latitudes. As the Taihang Mountains extend in a southwest-northeast direction in the study area, the eastern zonal airflow was totally 130.50 kg/(m s), blocked by the Mountainous area and shifted southward which explained why water vapor was transported southward in northern boundary. Overall, the moisture input into the RegP was dominated by zonal water vapor transport. Although the meridional transport contributed a relatively large amount of moisture inflow, its substantial outflow resulted in a comparatively small net contribution to the regional moisture budget.

The water vapor flux distributions were similar during periods T2 and T3, while the magnitude of water vapor decreased from 23.58 kg/(m s) to 6.25 kg/(m s). Although the zonal water vapor transport increased to some extent, the total moisture inflow during the two periods remained comparable. Meridionally, the eastward water vapor flux decreased from -13.97 kg/(m s) to -23.71 kg/(m s). In addition, the water vapor transport during T3 became more concentrated in the lower layers which indicated the contribution of low-level water vapor transport to the precipitation process. Compared with that in T1, the northward water vapor flux at the southern boundary was significantly increased in T2 and T3. The northwestward transport increased and led to strong uplift motion in the mountainous area. Consequently, the mountainous areas may have been more prone to intense convective weather events due to the sufficient water vapor and air uplift during T2 and T3.”

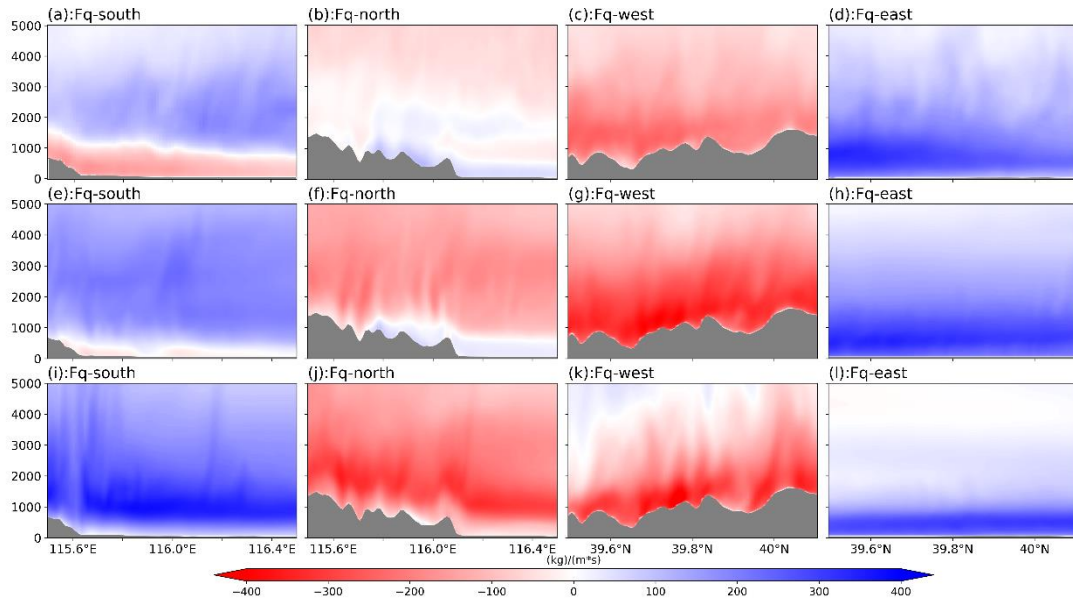


Figure 8: Distribution of water vapor flux magnitude in the LU_2020 scheme across latitude-height/longitude-height coordinates of RegP. Figures show the water vapor flux magnitude for time periods T1 (a - d), T2 (e - h), and T3 (i - l), with fluxes from the south (a, e, i), north (b, f, j), west (c, g, k), and east (d, h, l). Positive and negative water vapor flux values correspond to input and output water vapor flux relative to RegP.

“Orographic height significantly impacted water vapor flux transport, as shown by the differences in the water vapor distribution between LU_2020 (Figure 8) and LU_nohgt (Figure 9) and the corresponding water vapor flux transport in table 4. From a zonal perspective, orography considerably influenced the water vapor distribution within RegP. Due to orographic effects, water vapor was lifted and its northward transport was prevented, statistically reduced about 63.57 kg/(m s) in the LU_2020 (Figure 9 (a), (e), (i)), which also increased the total amount of zonal water vapor flux in LU_2020. From meridional perspective, the meridional water vapor flux output from western boundary substantially decreased by 49.41 kg/(m s) and 79.38 kg/(m s) during the whole period, resulting in a noticeable rise in the water vapor content in the entire region. Furthermore, the easterly winds were blocked and diverted by the orographic effect of the mountains to the west of Beijing, which also leads to a modest increase in the magnitude of the southward water vapor flux at the southern boundary in the lower atmospheric layers.”

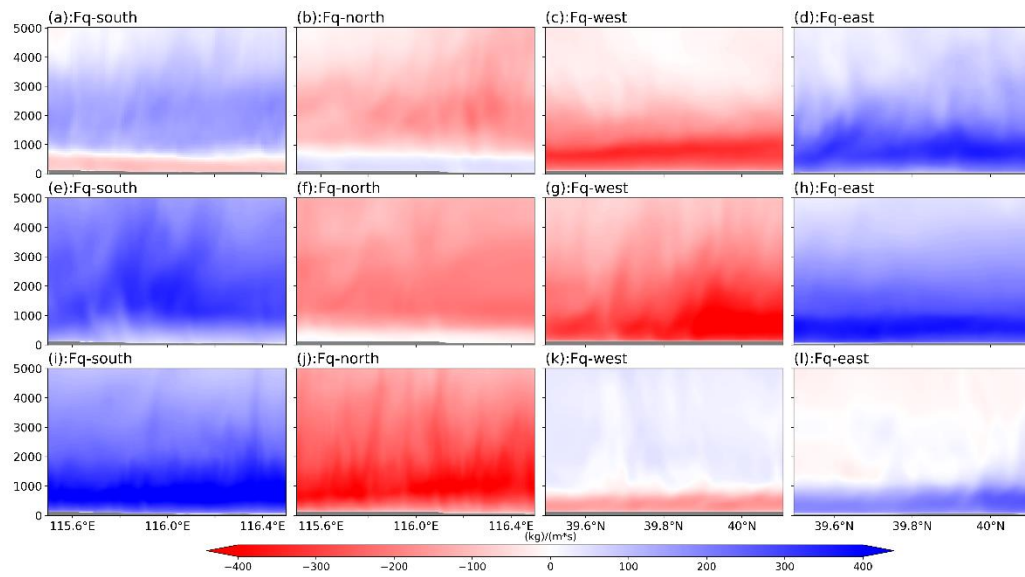


Figure 9: Water vapor fluxes as shown in Figure 8, where a - l depict the magnitude of the water vapor flux from four directions in the LU_nohgt scheme.

“The impacts of the urbanization on water vapor transport are shown in Figure 10. There was no significant difference between LU_2020 and LU_nourb in water vapor flux during periods T1 and T2 as the difference between net convergence is smaller than $10 \text{ kg}/(\text{m}\cdot\text{s})$. However, the differences mainly appeared at the western boundaries of RegP during period T3. At the western boundary, the westward water vapor flux was $30.98 \text{ kg}/(\text{m}\cdot\text{s})$ higher compared with that in LU_nourb (Figure 10(k)). These differences of moisture flux between different schemes were mainly due to wind speed in lower troposphere. As urban land use can influence local atmospheric circulation, such strong ascent induces horizontal convergence and a subsequent conversion of horizontal momentum into vertical motion. Such momentum redistribution can reduce the horizontal wind speed, particularly within the convectively active region, leading to a reduction in moisture flux across the western and northern boundaries.”

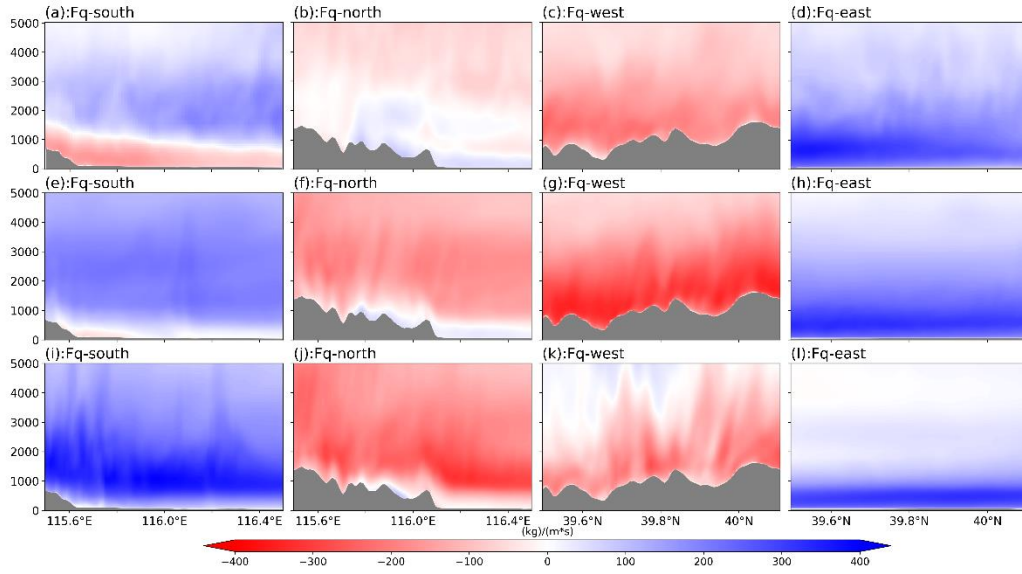


Figure 10: Water vapor fluxes as shown in Figure 8, where a - l depict the magnitude of the water vapor flux from four directions in the LU_nourb scheme.

Table 4: The water vapor flux (kg/(m s)) during each period for different schemes.

	kg/(m s)	North	South	Zonal	West	East	Meridional	All
T1	LU_2020	58.63	-19.52	39.11	130.50	-100.61	29.89	69.00
	LU_nohgt	78.89	-83.09	-4.20	141.79	-110.93	30.86	26.66
	LU_nourb	55.42	-22.42	33.00	133.97	-94.19	39.78	72.78
T2	LU_2020	146.94	-109.39	37.55	146.05	-160.02	-13.97	23.58
	LU_nohgt	222.99	-146.99	76.00	176.09	-199.31	-23.22	52.78
	LU_nourb	152.31	-113.83	38.48	139.02	-150.29	-11.27	27.21
T3	LU_2020	199.32	-169.36	29.96	71.65	-95.36	-23.71	6.25
	LU_nohgt	228.22	-237.85	-9.63	32.12	-0.69	31.43	21.80
	LU_nourb	206.16	-160.40	45.76	74.65	-64.38	10.27	56.03

Discussion:

This study involved the main physics schemes based on the model configurations listed in Table 1. It is recommended to analyze the limitations of this study, or the impacts of different physics schemes.

Response: Thanks for your comments. We admitted that, physical parameterization options have significant influences on precipitation simulations, not only for the magnitude and duration, but also for spatial and temporal distribution. The parameterization method adopted in this study had also been used in other studies about urban extreme precipitation events (Ryu et al. 2016, Wang et al. 2018, Luo et al. 2023, Wang et al. 2023, Xian et al. 2023), which can partly can prove the rationality

of this study.

In the revised version, the discussion section is divided into three parts: “4.1 The intention of experiment design”, “4.2 Comparisons with related studies” and “4.3 Uncertainty in the experiment simulation”. Following your suggestion, the model uncertainty was further accessed using an ensemble simulation of LU_2020 scheme, where are originated from ensemble members of ERA5. The results were shown in Supplementary Figure S4 and the following tests were added in the revised version.

(lines 296-312, 782-791)

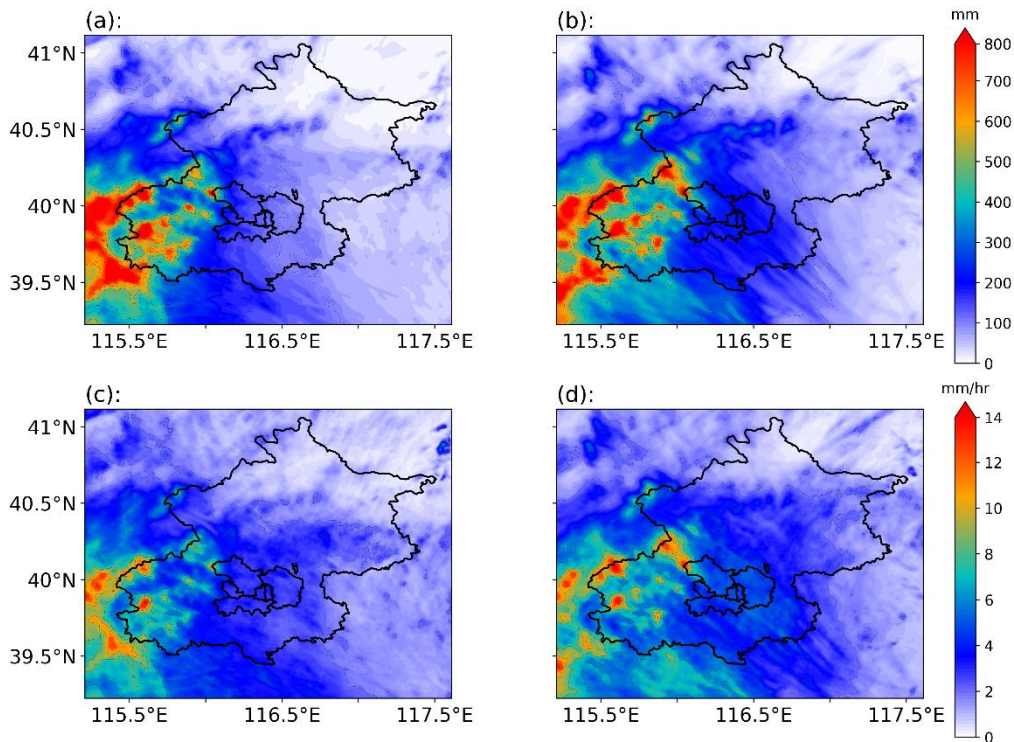


Figure S4: Comparison between simulated results of the events. (a), (b) represents the accumulated precipitation amount of LU_2020 experiment and 10 member ensemble mean, while (c), (d) represents the corresponding intensity simulation, respectively.

“In addition, the model uncertainty was further accessed using an ensemble simulation of LU_2020 scheme, where are originated from 10 ensemble members of ERA5. They provide estimates of the short-range forecast uncertainty, and can be considered to represent the evolution of the errors in the high-resolution component of ERA5 (Hersbach et al., 2020a). The results show that there is slightly difference

between the ensemble mean simulation and our experimental results (Figure S4). Statistically, the average precipitation intensity is 3.6 mm/hr for LU_2020 scheme and 4.1 mm/hr for the ensemble mean. The RMSE and MAE of precipitation intensity is 1.17 mm/hr and 0.86 mm/hr for the two simulation results and the correlation coefficient is 0.90. Therefore, the experimental scheme and simulation results in this study are convincing.”

“The simulations were conducted using selected parameterization schemes and the impacts of the underlying surface were analyzed in this study. Physical parameterization schemes are widely recognized to exert substantial impacts on precipitation simulations, affecting not only intensity and duration, but also spatiotemporal distribution patterns. The parameterization method adopted in this study had also been used in other studies about urban extreme precipitation events (Luo et al., 2023; Ryu et al., 2016; Wang et al., 2018; Wang et al., 2023; Xian et al., 2023), which can partly can prove the rationality of this study. Additional investigations into the parameterization schemes governing this precipitation event are required to elucidate the specific atmospheric conditions and physical mechanisms.”

Again, thanks for your thorough review and valuable comments.

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