Response to Reviewer Comments of the First Reviewer

Dear Reviewer and Editors:

We are sincerely grateful to the editor and reviewer for their valuable time for reviewing our manuscript. The comments are very helpful and valuable, and we have addressed the issues raised by the reviewer in the revised manuscript. Please find our point-by-point response (in blue text) to the comments (in black text) raised by the reviewer. We have revised the paper according to your comments (highlighted in red text of the revised manuscript).

Overview:

This study analyzed the impact of urban areas on thunderstorm organization processes and CG flash activity through ground observations and numerical simulations. City size may be an important factor affecting thunderstorm processes. In addition, the building density may also alter the organization process of thunderstorms. Overall, I believe that the research presented in this article has some innovation and the conclusions are also very interesting. The organization and writing of this article need improvement, and I would like to suggest significant revisions to this paper.

Response: Thank you for your recognition of our work and for your valuable feedback. As per your request, we have undertaken significant revisions throughout the manuscript.

Firstly, we have expanded the Introduction section to provide a more detailed overview of relevant research in the field. We refresh and highlight the scientific question on how to modulate thunderstorm disasters on the urban underlying surface of Beijing.

Secondly, in the Data and Methodology section, we have revised the descriptions of lightning location data, radar products, and LCZ datasets. These updates ensure that readers have a clear understanding of the analytical approach we have taken.

Lastly, we have thoroughly revised the Abstract and Conclusion sections to highlight our main findings. Specifically, we have reorganized the mechanisms by which urban underlying surface play different dominant role in thunderstorm disasters.

We are grateful for your time and effort in reviewing our work and for your guidance in improving the manuscript. We hope that these revisions have addressed your concerns and have enhanced the clarity of our research.

Major comments:

1. The author has failed to provide a definition of a thunderstorm that is grounded in radar reflectivity or other pertinent parameters, leaving the reader without a clear understanding of the term's scientific context.

Response: I apologize for any confusion caused by the lack of clarity in defining thunderstorms based on radar echoes in our previous submission. This was indeed an oversight on our part, and we sincerely appreciate your bringing it to our attention.

In response, we have made substantial revisions in the Data section of the manuscript. Specifically, we have provided additional information on the radar data used and the clearer criteria for identifying thunderstorms from the radar echoes. Line 98-107 in the revised manuscript:

"Doppler Radar Data. This radar observation system consists of a data acquisition subsystem, a product generation subsystem, and a main user terminal subsystem. It enables real-time data transmission and image stitching, significantly boosting the monitoring and early warning capabilities for disastrous weather conditions such as severe convective weather, tropical cyclones, and heavy rainfall. The radar data employed in this paper is the Composite Reflectivity (CR) product generated by the S-band Doppler Radar stationed at the Beijing Nanjiao Observatory. Previous studies have consistently recognized a threshold of 35 dBZ as a pivotal marker signifying the presence of a convective echo (Dixon & Wiener, 1993; Roberts & Rutledge, 2003; Mecikalski & Bedka, 2006). Consequently, this research adopts this well-established reflectivity threshold as the criterion for identifying thunderstorms. In addition, to gain a broader understanding of the synoptic background of thunderstorms, we utilized sounding data from the Beijing Nanjiao Observatory. These sounding data were collected at 02:00, 08:00, 14:00, and 20:00 Beijing time every day."

Reference:

Dixon M, Wiener G.: TITAN: thunderstorm identification, tracking, analysis, and nowcasting–A radar-based methodology. Journal of Atmospheric and Oceanic Technology, 10, 785–797, https://doi.org/10.1175/1520-0426(1993)0102.0.CO;2, 1993.

Mecikalski, J. R., Bedka, K. M.: Forecasting convective initiation by monitoring the evolution of moving cumulus in daytime GOES imagery. Monthly Weather Review, 134, 49–78, https://doi.org/10.1175/MWR3062.1, 2006.

Roberts, R. D., Rutledge, S.: Nowcasting storm initiation and growth using GOES-8 and WSR-88D data. Weather and Forecasting, 18, 562–584, https://doi.org/10.1175/1520-0434(2003)0182.0.CO;2, 2003.

2. This article highlights a specific thunderstorm process that exhibited barrier effect through both observations and simulations. However, to strengthen the argument that this phenomenon is widespread or common, the author should provide additional cases or statistical results to support their findings.

Response: Thank you for bringing to my attention the lack of clarity regarding the definition of thunderstorms. I apologize for any confusion caused by the previous omission. I have now supplemented the manuscript with the necessary information. Specifically, I have included statistical results from recent years, focusing on thunderstorms that have traversed the Beijing area and exhibited the barrier effect. Line 254-262 in the revised manuscript:

"Based on the above analysis, when the thunderstorm passed over the built-up area, it exhibited a bifurcated process due to the barrier effect. Utilizing this pattern as a screening criterion, we categorized thunderstorms passing over the built-up area of Beijing from 2010 to 2017 into bifurcated thunderstorms (BT) and non-bifurcated thunderstorms (NBT). According to Figure S3, the year with the highest number of BT was 2013, with eight events, accounting for 23.5% of the total thunderstorms; the lowest number of BT was observed in 2010, with two events, representing 15.4% of the total thunderstorms. These results indicated that the barrier effect of the urban underlying surface was a prevalent phenomenon in long-term thunderstorm observations."

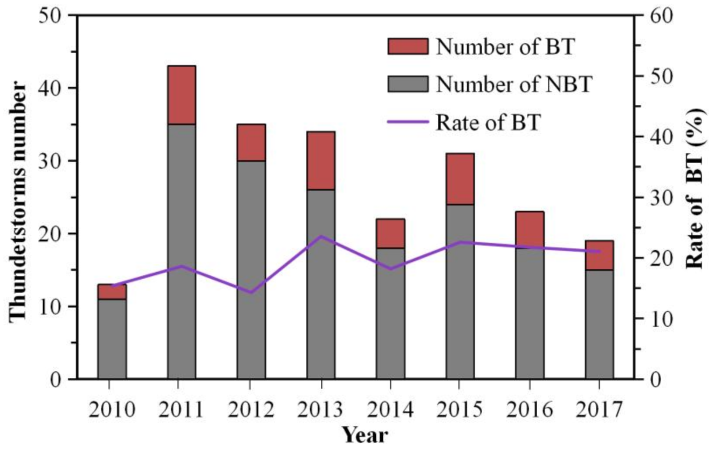

Figure S3: Interannual variation of bifurcated thunderstorms (BT) and non-bifurcated thunderstorms (NBT) in the built-up area of Beijing.

3. Has Figure 3 exclusively analyzed CG events that occurred during the summer? If so, please include a relevant description in the caption of Figure 3. Furthermore, the author should provide a clear description of the data in the data section.

Response: Thank you for bringing this to our attention. We apologize for the oversight and have made the necessary revisions to clarify the information.

We have updated the caption of Figure 3 to explicitly state that it exclusively analyzes CG events that occurred during the summer months. Additionally, in the Data section of our manuscript, we have included a clear description of the data used, specifying that the summer period refers to June through August.

We appreciate your careful review and hope these revisions address your concerns. Please let us know if you have any further questions or suggestions.

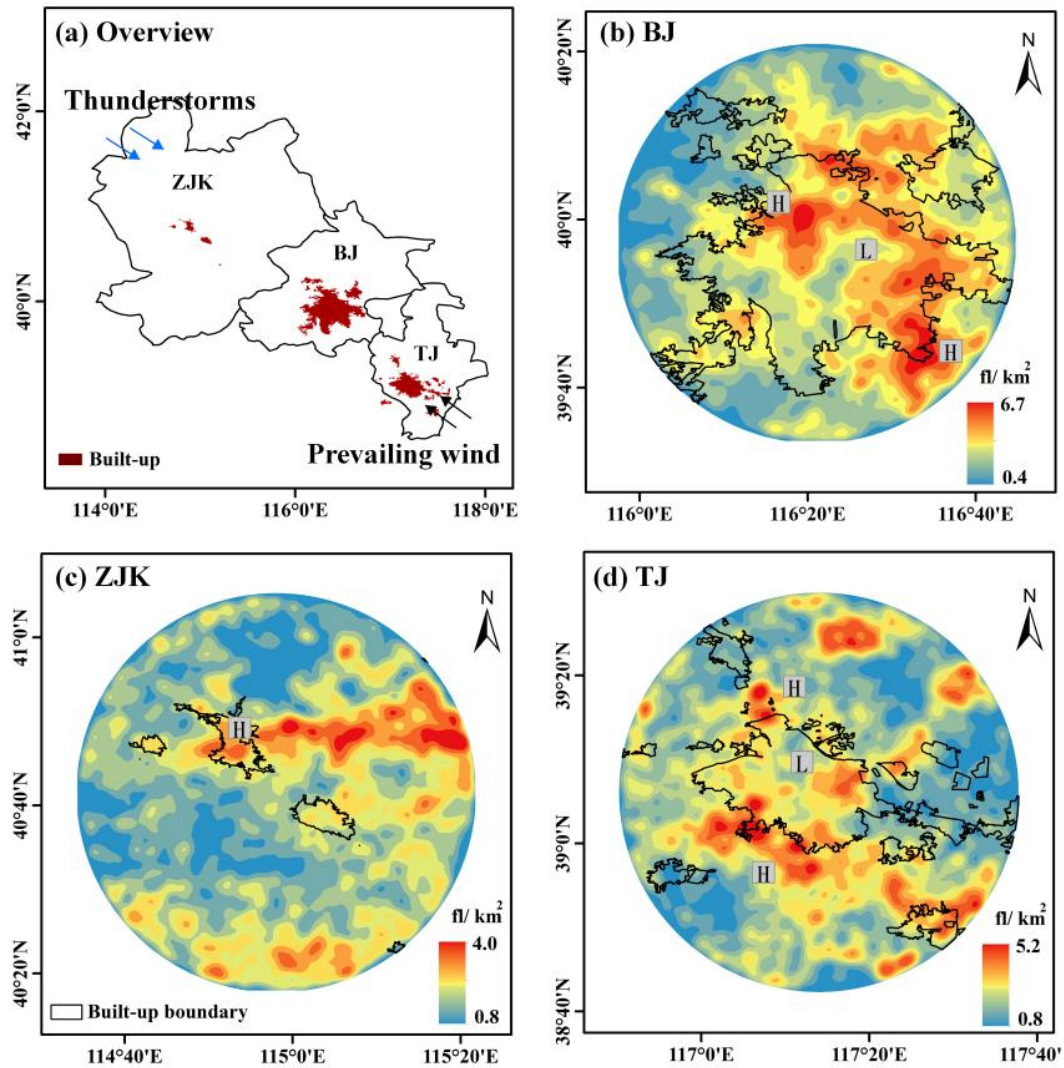

Figure: 3 Overview of the built-up areas in Beijing (BJ), Zhagnjiakou (ZJK), and Tianjin (TJ) (a). Spatial patterns of CG density in the built-up areas of Beijing (b), Zhangjiakou (c), and Tianjin (d) during the summertime of 2010-2017.

4. Please add the symbolization of red line in Figure 8.

Response: Thank you for bringing this to our attention. We sincerely apologize for any confusion caused by the absence of clear symbolization for the red line in Figure 7 (original Figure 8). In response to your feedback, we have promptly revised the figure to include a clear explanation of the meaning of the red line.

Furthermore, we have conducted a thorough review of all figures in the manuscript to prevent any similar oversights in the future.

We appreciate your careful scrutiny and the opportunity to improve our work.

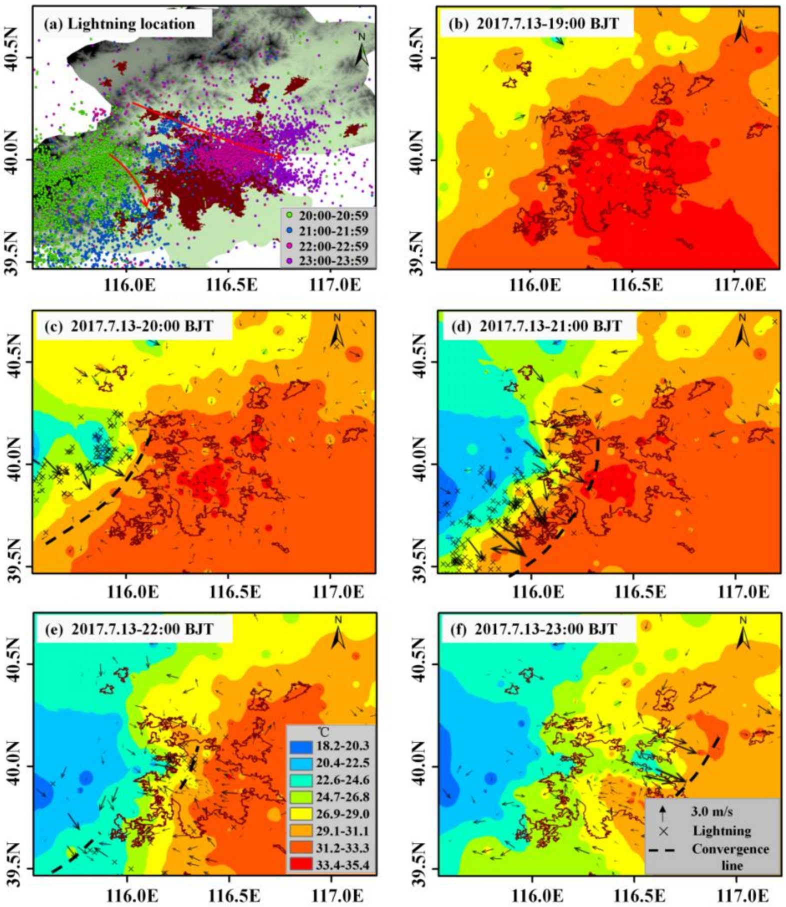

Figure 7: (a) The spatial pattern of CG activities. The dots represent cloud-to-ground lightning, and the red line represents the movement trajectory of the thunderstorm. (b-f) The near-surface thermal-dynamic fields of the "0713" case passing over the built-up area.

Response to Reviewer Comments of the Second Reviewer

Dear Reviewer and Editors:

We are sincerely grateful to the editor and reviewer for their valuable time for reviewing our manuscript. The comments are very helpful and valuable, and we have addressed the issues raised by the reviewer in the revised manuscript. Please find our point-by-point response (in blue text) to the comments (in black text) raised by the reviewer. We have revised the paper according to your comments (highlighted in red text of the revised manuscript).

This manuscript examines lightning location data, along with a numerical model, which indicates that urban morphology in Beijing's metropolitan area influence where lightning strikes—a phenomenon known as the urban barrier effect. By integrating lightning data with a model that considers building size and height, the manuscript presents interesting case studies demonstrating how large cities can influence weather conditions, thus affecting lightning patterns. However, the manuscript lacks sufficient clarity in its data presentation, methodological approach and structural hierarchy, causing confusion for readers. After addressing my primary comments, I recommend publishing this manuscript in ACP.

Response: Thank you for your recognition of our work and for your valuable feedback. As per your request, we have undertaken significant revisions throughout the manuscript.

Major comments:

1. Figure 1 provides an overview of the study area, encompassing the boundaries and spatial locations of China, Beijing-Tianjin-Hebei region, and Beijing.

However, as the focus of this study is the urban area of Beijing, Figure 1 lacks a sufficiently detailed depiction. While Figure 2 offers some insight, I believe it is crucial to supplement Figure 1 with more specific information about the urban area of Beijing.

Response: Thank you for your valuable feedback. I appreciate your observation that while Figure 1 provides a broad overview of the study area, including China, the Beijing-Tianjin-Hebei region, and Beijing, it may lack sufficient detail for the specific focus of this study, which is the urban area of Beijing.

To address this, I agree that it is essential to enhance Figure 1 or introduce an additional figure that presents a more detailed depiction of Beijing's urban area. I have revised the figure to include a closer look at the topography and built-up area in Beijing megacity.

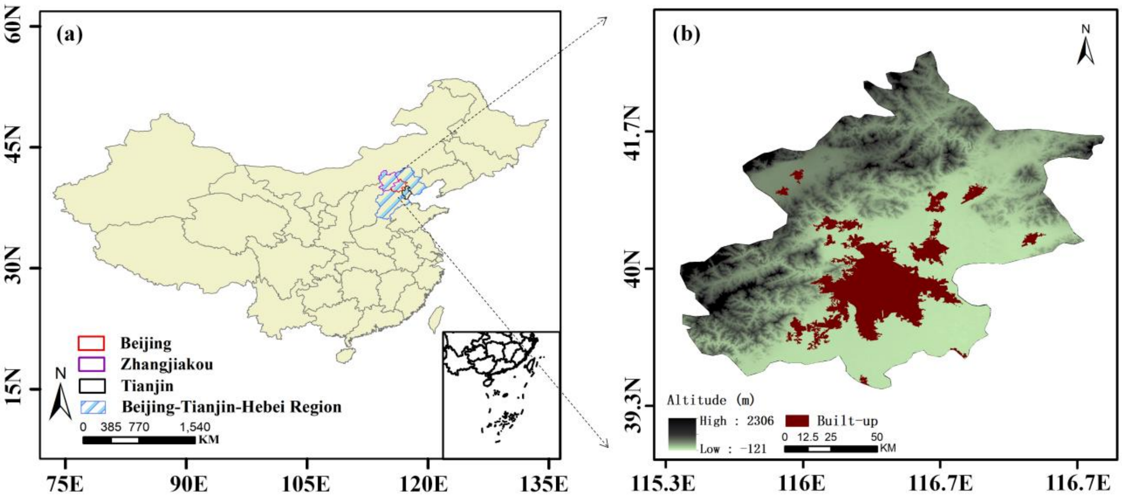

Figure 1: Overview of the study area (a). Topography and built-up area in Beijing megacity (b).

2. The observation section of this article has obtained many interesting statistical results based on compact high rise, compact mid rise, compact low rise, open high rise, open mid rise, and open low rise. However, sensitivity tests were conducted in the simulation section based on compact rise and open rise, and the test results to some extent explained the mechanism of the influence of urban morphology on the process of thunderstorm organization. What are the standards used for the classification of urban morphology in the observation and

simulation sections? Is it consistent? Please provide a detailed explanation.

Response: I apologize for any confusion my previous explanation may have caused regarding the classification of urban morphology in the observation and simulation sections of our article. Allow me to clarify and provide a more detailed explanation.

In the observation section, we classified urban morphology into six distinct categories: compact high-rise, compact mid-rise, compact low-rise, open high-rise, open mid-rise, and open low-rise. Please refer to Fig. S1 and Tab. S1 for a spatial morphology diagram and classification criteria. This comprehensive classification scheme was designed to capture the nuances in urban structures that might impact the thunderstorm process and CG activity.

For the simulation part (Fig. 2), the classification criteria for urban morphology are consistent with those for the observation part. However, considering the computational efficiency of the model, the simulation scheme of WRF focuses on two broad categories: compact rise and open rise. The compact rise includes compact high-rise, compact mid-rise, compact low-rise. The open rise includes open high-rise, open mid-rise, and open low-rise. This simplification helps us effectively explore the potential physical effects of urban morphology on thunderstorm organization processes while ensuring computational efficiency.

I hope this clarifies our classification schemes and addresses your concerns about consistency. Thank you for your patience and valuable feedback.

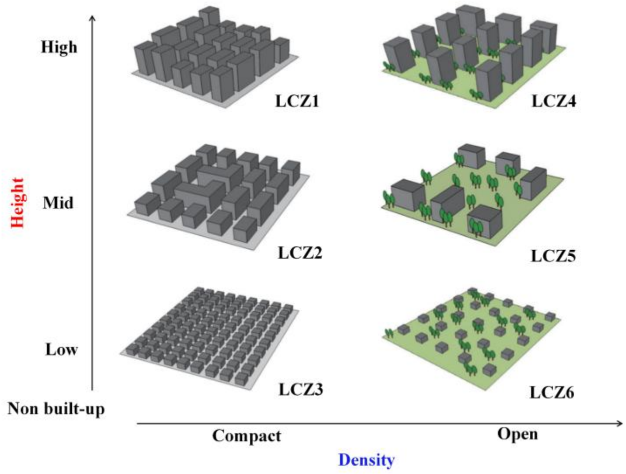

Figure S1: Schematic diagram of urban morphology based on different categories of LCZ datasets.

Table S1: Descriptions and attribute parameters of different categories of LCZ datasets.

LCZ datasets	Descriptions	Attribute parameters
LCZ 1: Compact high-rise	The building are taller than 10 stories. High density of buildings and ground cover mostly hard pavement with little vegetation.	Aspect ratio >2 Sky view factor: 0.2-0.4 Building surface fraction: 40-60 Impervious surface fraction: 40-60 Pervious surface fraction < 10 Height of roughness elements >25
LCZ 2: Compact mid-rise	Building heights span from 3 to 9 stories. High density of buildings of buildings and ground cover mostly hard pavement with little vegetation.	Aspect ratio: 0.75-2 Sky View Factor: 0.3-0.6 Building surface fraction: 40-70 Impervious surface fraction: 30-50 Pervious surface fraction <20 Height of roughness elements: 10-25
LCZ 3: Compact low-rise	Building heights ranging from 1 to 3 stories. High density of buildings and ground cover mostly hard pavement with little vegetation.	Aspect ratio: 0.75-1.5 Sky view factor: 0.2-0.6 Building surface fraction: 40-70 Impervious surface fraction: 20-50 Pervious surface fraction <30 Height of roughness elements: 3-10
LCZ 4: Open High-rise	Building heights of 10 stories or more. Low density of buildings and low ground cover mostly permeable ground or vegetation.	Aspect ratio: 0.75-1.25 Sky View Factor: 0.5-0.7 Building surface fraction: 20-40 Impervious surface fraction: 30-40 Pervious surface fraction: 30-40 Height of roughness elements >25
LCZ 5: Open mid-rise	Building heights in the range of 3-10. Low density of buildings and low ground cover mostly permeable ground or vegetation.	Aspect ratio: 0.3-0.75 Sky view factor: 0.5-0.8 Building surface fraction: 20-40 Impervious surface fraction: 30-50 Pervious surface fraction: 20-40 Height of roughness elements: 10-25
LCZ 6: Open low-rise	Building heights ranging from 1 to 3 stories. The low density of buildings and the ground cover is mostly permeable ground or vegetation.	Aspect ratio: 0.3-0.75 Sky View Factor: 0.6-0.9 Building surface fraction: 20-40 Impervious surface fraction: 20-50 Pervious surface fraction: 30-60 Height of roughness elements: 3-10

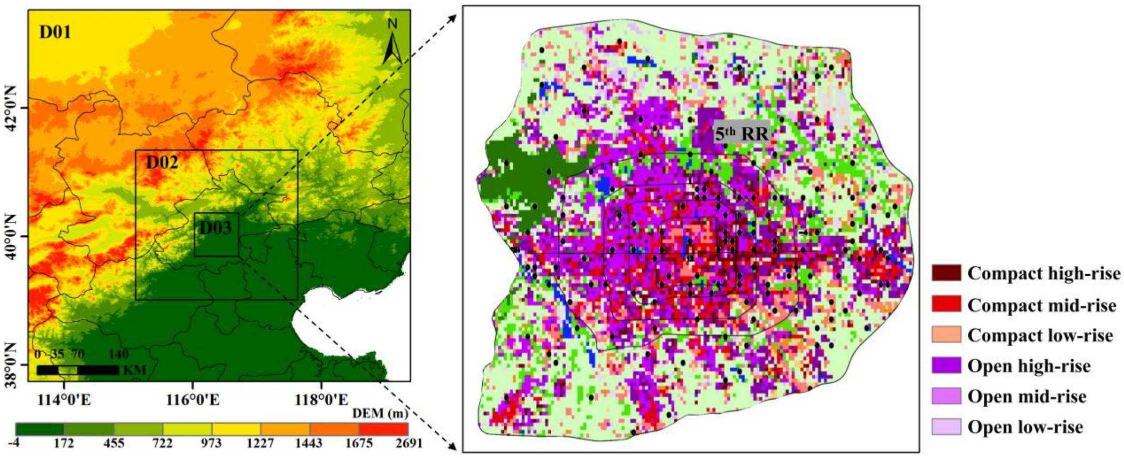

Figure 2: Terrain height distribution and the building types of the WRF mesoscale numerical model.

3. Weather Research and Forecasting (WRF) serves as a vital tool in this paper for analyzing the mechanisms of how urban morphology impacts the thunderstorm process. However, the author's introduction to WRF lacks sufficient detail, especially regarding the WRF model coupled with the urban canopy, which poses challenges for researchers unfamiliar with this system. The author should provide a more comprehensive explanation of WRF and the simulation scheme to enhance the readability of the paper and ensure the reproducibility of the experimental results.

Response: Thank you for your insightful comments on our manuscript. We apologize for any lack of clarity in our discussion of the WRF model and its integration with the urban canopy model. We understand that this may have been confusing for readers who are less familiar with these modeling techniques.

In response to your comments, we have added an additional detailed explanation regarding the WRF model and its integration with the urban canopy model in line 10-15. This enhanced description aims to provide a more comprehensive understanding of the model's capabilities.

We hope that these revisions will improve the readability of our paper. We are grateful for your feedback and the opportunity to strengthen our work through these revisions.

Line 114-135.

"Currently, the Weather Research and Forecasting (WRF) model holds a prominent position as the primary tool for simulating urban environments. The WRF model, collaboratively developed by institutions such as the National Center for Atmospheric Research (NCAR) and the National Centers for Environmental Prediction (NCEP) in the United States, is primarily designed for operational forecasting and atmospheric research. This model enables researchers to simulate real-world or hypothetical scenarios computationally, offering a highly flexible and efficient predictive framework that can be applied to studies examining the impacts related to urban meteorology (Chen et al., 2012b). The WRF model, when coupled with the Urban Canopy Model (UCM), is employed to describe the dynamic, thermal, and radiative interactions between urban land surface processes and the upper atmosphere (Kusaka et al., 2001; Chen et al., 2012b). The UCM not only accounts for the geometric measurements of urban buildings and roads but also optimizes the physical parameters of urban canopies. Furthermore, it calculates heat transfer across building roofs, walls, and road surfaces. The UCM is widely utilized in studies examining atmospheric boundary layer processes and environmental issues related to urbanization (He et al., 2019).

In this study, the WRF 4.0 version, integrated with UCM, was configured to use a triple-nested grid system with horizontal resolutions of 5 km, 1 km, and 200 m, respectively (Fig. 3). The model center is located at (40.0°N, 116.6°E), with grid dimensions of 515×151, 256×251, 506×501, and 38 vertical layers. The underlying surface data encompassed land use and urban canopy datasets with a resolution of 10 m. This model employed the WRF Single Moment 6-class microphysical process scheme (WSM6), the rapid radiative transfer longwave radiation scheme (RRTM), the Dudhia shortwave radiation scheme, the step-mountain similarity theory near-surface layer scheme, and the BouLac boundary layer scheme (Lim & Hong, 2010; Lacono et al., 2008; Janjic, 1994; Melin, 2017; Tewari et al., 2004)."

Reference:

Chen, M., & Wang, Y.: Numerical simulation study of interactional effects of the low-level vertical wind shear with the cold pool on a squall line evolution in

North China, Acta Meteorologica Sinica, 70, 3, 371–386, https://doi.org/10.11676/qxxb2012.033, 2012b.

Kusaka, H., H. Kondo, Y. Kikegawa, & F. Kimura.: A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. Bound. Layer Meteorol., 101, 329–358, https://doi.org/10.1023/A:10192079230782001, 2001.

He, X., Li, Y., Wang, X., Chen, L., Yu, B., Zhang, Y.: High-resolution dataset of urban canopy parameters for Beijing and its application to the integrated WRF/Urban modelling system. Journal of cleaner production, 208, 373–383, https://doi.org/10.1016/j.jclepro.2018.10.086, 2019.

Lim, K., and Hong, S.: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models, Monthly Weather Review, 138, 1587–1612, https://doi.org/10.1175/2009MWR2968.1, 2010.

Lacono, M., Delamere, J., Mlawer, E., Shephard, M. W., And, S. A. C., and Collinset, W. D.: Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models, Journal of Geophysical Research-Atmospheres, 113, D13103, https://doi.org/10.1029/2008JD009944, 2008.

Janjic, Z.: The step-mountain eta coordinate model: further developments of the convection, viscous sublayer, and turbulence closure schemes, Monthly Weather Review, 122, 927–945, https://doi.org/10.1175/1520-0493(1994)1222.0.CO;2, 1994.

Melin, H., Bormin, H., and Hung-Lung, A. H.: Acceleration of the WRF Monin-Obukhov-Janjic surface layer parameterization scheme on an MIC-based platform for weather forecast, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 10, 4399–4408, https://doi.org/10.1109/JSTARS.2017.2725743, 2017.

Tewari, M., Chen, F., Wang, W., Dudhia, J., and Cuenca, H.: Implementation and verification of the unified NOAH land surface model in the WRF model, 20th conference on weather analysis and forecasting/16th conference on numerical weather prediction, pp.11–15, 2004.

Minor comments:

P1Line15: "mega cities", should be "megacities"

Response: We greatly appreciate the time and patience you have taken to provide your insights on my work. I deeply apologize for the small errors and oversights that you have pointed out.

I have carefully addressed each of your minor comments and double-checked the entire manuscript for any other potential issues.

Once again, I apologize for any inconvenience caused by these minor errors and appreciate your patience and understanding.

P1Line18: "weakening" should be preceded by "the"

Response: Amended and thanks.

P1Line30: "population" should be revised as "populations"

Response: Amended and thanks.

P2Line45: "that" in "....despite that....." should be deleted

Response: Amended and thanks.

P2Line49: "millions" -> "million"

Response: Amended and thanks.

P2Line61: "built up" -> "built-up"

Response: Amended and thanks.

P2Line67: What does "BJ" mean? Is Beijing an abbreviation?

Response: Amended and thanks.

P2Line67: "sof" may be "of"

Response: Amended and thanks.

P4Line96: "refers" -> "refer"

Response: Amended and thanks.

P6Line118: deleted "the" in "....the Table 2....."

Response: Amended and thanks.

P6Line125: deleted "the" in "....the Table 3....."

Response: Amended and thanks.

P8Line141: "an average and maximum densities"

-> "an average and maximum density"

Response: Amended and thanks.

P8Line145: "exists a potential" has one more space

Response: Amended and thanks.

P9Line146: "by high" should be added "a"

Response: Amended and thanks.

P12Line203: "during "0713" case" should be added "the"

Response: Amended and thanks.

P18Line305: "all types of building" should be "all types of buildings"

Response: Amended and thanks.