Response to Reviewer Comments

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).

Sincerely yours,
Dr. Yuanjian Yang, representing all co-authors

Reviewer #1:

This study focuses on the canopy urban heat island (CUHI) for the city of Beijing, based on surface weather station observations. It seeks to understand the effects of intensification of the UHI phenomenon during heat waves, and the role of local breeze circulations (mountain and valley) and of urban parameters on the temporal and spatial variability of the intensification. It is an interesting scientific subject that looks at the urban climate of cities in complex environments, and that fits in well with the target scientific journal. It is addressed through an experimental approach, made possible by a fairly dense surface observation network in the city and surrounding area.

Nevertheless, the central scientific questions of the study are not, in my opinion, presented and structured clearly enough. The article would be clearer and more interesting if these questions were clearly stated and accompanied by a well-structured step-by-step analysis. As it is, the article investigates many different issues (CUHII, the effect of heatwaves, the effect of breeze circulation,

the effects of urban parameters, cross-effects, the comparison of statistical approcahes, etc.),and it is sometimes difficult to see the coherence of the whole. And in the end, the main findings don't stand out clearly enough. Also, the data used and the methodologies chosen (as well as the Figures) could be explained more precisely.

Response: Thanks very much for taking time out of your busy days to provide us with such valuable comments that significantly improve the quality of our manuscript. In line with your comments and suggestions, we have revised our manuscript carefully and prepared a list of point-by-point responses below.

Firstly, the Introduction section is updated carefully to better highlight the central scientific questions of this study. In our revised manuscript, we focus on the scientific question of how mountain-valley breeze and urban morphology drive the amplified CUHII during HW periods (ΔCUHII) in the Beijing megacity.

Secondly, we have revised the descriptions of the key concepts and calculation methods for CUHII, HW, mountain-valley breeze, and urban morphology in the Data and Methodology section. These updates ensure that readers have a clear understanding of the approach in this manuscript.

Additionally, a summary of the key findings and the corresponding subsequent analysis are appended at the end of each subsection of the section of Results to improve the coherence of this study.

Finally, we have thoroughly revised the Abstract and Conclusion sections to highlight our main findings. Specifically, we have emphasized the influence of wind speed and direction on the temporal and spatial distribution of the positive feedback effect between HW and CUHII, as well as the driving role of both 2D and 3D indicators of urban morphology in the effect.

You can find the details in our revised manuscript.

Major comments:

1.There is no clear understanding of the available network,i.e. the location of stations according to urban typologies, the different land use characteristics in and around the city. This should be presented in the section on methods and data.

Response: Thanks very much for your valuable comment. In our revised manuscript, the details of the method for identifying urban stations and reference stations are added in the section of Data and Methodology.

In general, the CUHII is defined as the temperature difference between the urban station and the rural reference station (Ren et al., 2007; Shi et al., 2015). Thus, identifying the urban stations and rural reference stations is very important for investigating urban climate. In the region of our study, Beijing has undergone massive and rapid urbanization, with its urban space continually expanding into the suburbs over the past few decades. Currently, Beijing boasts a population of 20 million and a built-up area spanning 1400 km^2. Due to this expansion, a swift transportation system has become imperative for urban development, prompting Beijing to commence the construction of a Multiple-ring-road system since the 1990s (Wang et al., 2010). These rings effectively represent the radial expansion of urban zones, with varying population and building densities. Notably, the Fifth Ring Road, with a length of 98.6 km and a built-up area of approximately 300 km^2 (depicted as the blue ring in Fig. R1), encompasses the primary regions of the built-up area (Yang et al., 2013). The distribution characteristics of average air temperature around the built-up area of Beijing are illustrated in Fig. R1, showing that the high-temperature zone in the city center aligns closely with the extent of the Fifth Ring Road. Additionally, the proportion of densely built-up areas within the Fifth Ring Road exceeds 85%, significantly higher than that outside this ring. Therefore, we have designated stations within the Fifth Ring Road as urban stations in this study.

The identification of reference stations is shown below. Firstly, the reference stations should have significantly lower temperatures than those of urban stations, based on the spatial distribution characteristics of average temperatures. Secondly, the reference stations must be located more than 50 km away from the city center, in a rural environment, predominantly situated within areas of sparse trees and shrubs (Yang et al., 2023). Thirdly, the reference stations should also be evenly distributed across different directions of the entire city. According to these criteria, eight reference stations were selected (green plot in Fig. R2), with an average altitude of 39.6 m, which is only 8.8 m lower than the average altitude of 45 urban stations (red plot in Fig. R2).

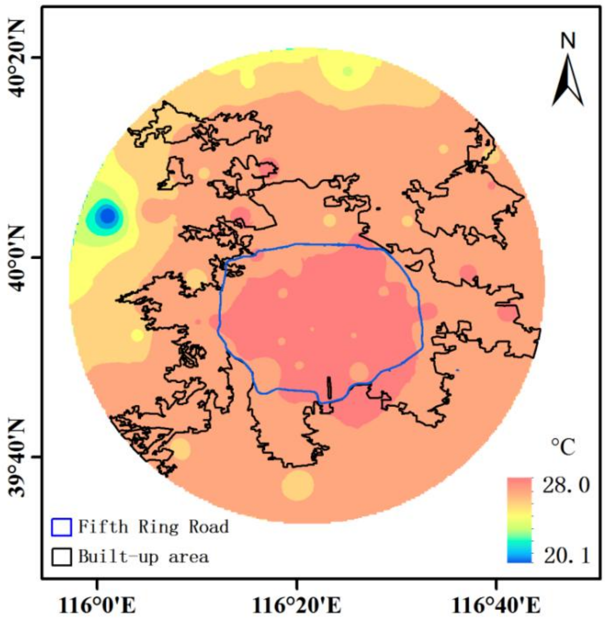

Fig. R1 The distribution characteristics of average air temperature around the built-up area of Beijing.

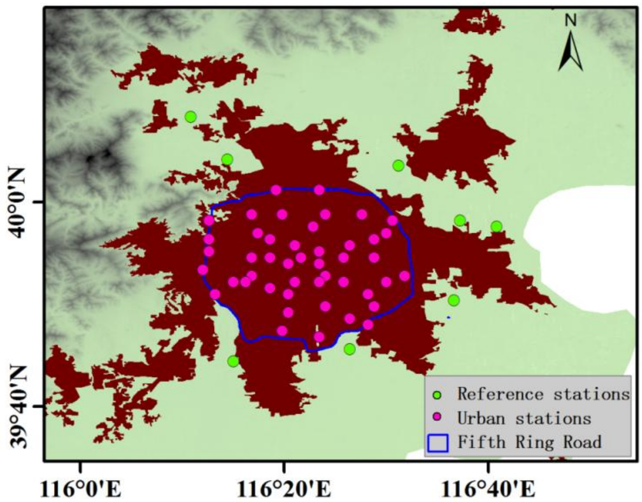

Fig. R2 Spatial distribution of urban stations and reference stations in Beijing.

Reference:

Yang, P., Ren, G., Liu, W.: Spatial and temporal characteristics of Beijing urban heat island intensity. Journal of Applied Meteorology and Climatology, 52, 8, 1803-1816, http://doi.org/10.1175/JAMC-D-12-0125.1, 2013.

Ren, G., Chu, Z., Chen, Z., Ren, Y.: Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations, Geophysical Research Letters, 34, 5, https://doi.org/10.1029/2006GL027927, 2007.

Shi, T., Huang, Y., Shi, C., & Yang, Y.: Influence of Urbanization on the Thermal Environment of Meteorological Stations: Satellite-observational Evidence, Advances in Climate Change Research, 1, 7–15, https://doi.org/10.1016/j.accre.2015.07.001, 2015.

Yang, Y., Guo, M., Wang, L., Zong, L., Liu, D., Zhang, W., Wang, M., Wan, B., Guo, Y.: Unevenly spatiotemporal distribution of urban excess warming in coastal Shanghai megacity, China: Roles of geophysical environment, ventilation and sea breeze, Building and Environment, 235, https://doi.org/10.1016/j.buildenv.2023.110180, 2023.

Wang, X., Li, X., Feng, Z.: Research on Beijing urban expansion based on the principle of information entropy. China Population,Resources and Environment, S1, 88–92, https://doi.org/CNKI:SUN:ZGRZ.0.2010-S1-024, 2010.

2.The geographical context is presented, but there is a lack of a more complete description of mountain and valley breeze situations (based in particular on the existing literature, which is apparently fairly extensive): the mechanisms involved, the factors of variability in terms of intensity and daily cycle, the influence of HW conditions, etc.

Response: Thanks very much for your valuable comment. In response to your feedback, we have provided a more comprehensive explanation of the mechanisms, varying factors, and potential impacts of mountain-valley breeze in our revised manuscript as below.

Line 41-55 in the introduction:

"Mountain-valley breeze represents a local circulation within mountainous terrains induced by the mesoscale-to-small-scale thermal effects between mountain and valley. In detail, the air in valleys and slopes warms up more significantly than the free atmosphere at the same altitude in mountainous regions during the daytime, leading to a temperature gradient that drives the air to ascend along the slopes, forming the valley breeze. In contrast, the adjacent air rapidly cools and becomes denser in mountainous regions during nighttime as the radiative cooling over the underlying surface, thereby flowing downslope, giving rise to mountain breeze (Jiang et al., 1994; Fu, 1997; Dong et al., 2017). The characteristics of the mountain-valley breeze are contingent upon various factors, including local topography and large-scale synoptic conditions (Whiteman et al., 1993; Zängl, 2009), atmospheric stability (Rao & Snodgrass, 1981; Whiteman & Zhong, 2008), underlying surface types (Wang et al., 2015; Letcher & Minder, 2018), and insolation conditions (An et al., 2002). Notably, under the effects of the urban underlying surface surrounding mountains, the CUHI circulation and mountain-valley breeze at mountain slopes interact and reinforce each other (Li et al., 2017). However, a limited number of studies have delved into the influence of mountain-valley breeze on the synergies between HW and CUHI (Xue et al., 2023; Yang et al., 2024). During HW periods, the mountain-valley breeze enhanced the vertical turbulent heat transfer, and improved ventilation conditions reduced aerosol concentration (the urban canopy received more short-wave radiation), both of which are beneficial to the enhancement of CUHII in Lanzhou (Xue et al., 2023). The current understanding of how local circulations modulate the ΔCUHII is still in the exploratory stage."

Line 84-93 in the data and methodology:

"Under the control of a weak weather system with no clouds or few clouds (You et al., 2006; Liu et al., 2009; Dong et al., 2017), the mountain-valley breeze formed by the complex terrain plays a dominant role in the atmospheric circulation of the Beijing area (Liu et al., 2009; Miao et al., 2013; Dou et al., 2014). The near-surface boundary layer features including wind and temperature fields during summer in Beijing, China are investigated by numerical simulation (Hu et al., 2005). The results revealed a notable CUHII effect in the city center, with the boundary layer wind field being significantly influenced by the mountainous terrain in the northwest. Furthermore, the impact of mountainous terrain on the lower atmospheric boundary layer in the Beijing area during summer was also investigated (Cai et al., 2002; You et al., 2006). They discovered that the influence of mountain-valley breeze could extend to cover the plain regions around Beijing to a significant degree."

Line 154-163 in the data and methodology:

"Referencing relevant methods (Cao et al., 2015; Zheng et al., 2018), the mountain-valley breeze is extracted and the details are shown as below. Firstly, the hourly wind data from each observation station were decomposed into the components of u (east-west direction) and v (north-south direction). From June to August between 2016 and 2020, the average values of the hourly wind components were calculated, yielding hourly average values $\overline{u}$ and $\overline{v}$. Subsequently, the diurnal average values U and V were obtained by averaging all the hourly average values $\overline{u}$ and $\overline{v}$, respectively. The hourly anomalies u' and v' were then derived by subtracting the diurnal average values U and V from the hourly average values $\overline{u}$ and $\overline{v}$, respectively. The diurnal average values U and V can be interpreted as the systematic wind or background wind, while the hourly average values $\overline{u}$ and $\overline{v}$ can be considered as the actual wind. The local wind u' and v' obtained by subtracting the systematic wind from the actual wind, can be utilized in studies focused on regional local circulations, in particular for the mountain-valley breeze."

Reference:

An, X., Chen, Y., Lv, S.: Mesoscale Simulations of Winter Low-Level Wind and Temperature Fields in Lanzhou City. Plateau Meteorology, 21, 2, 186–192, https://doi.org/10.3321/j.issn:1000-0534.2002.02.011, 2002.

Cai, X., Guo, Y., Liu, H., Chen, J.: Flow Patterns of Lower Atmosphere over Beijing Area, Acta Scientiarum Naturalium Universitatis Pekinensis, 38, 5, 698–704, https://doi.org/10.3321/j.issn:0479-8023.2002.03.015, 2002.

Cao, J., Liu, X., Li, G., Zou, H.: Analysis of the phenomenon of Lake-land breeze in Poyang Lake area, Plateau Meteorol. Chin., 426–435, https://doi.org/10.7522/J.ISSN.1000-0534.2013.00197, 2015.

Dong, Q., Zhao, P., Wang, Y., Miao, S., Gao, J.: Impact of Mountain-Valley Wind Circulation on Typical Cases of Air Pollution in Beijing. Environmental Science, 38, 6, 2218–2230, https://doi.org/10.13227/j.hjkx.201609231, 2017.

Dou, J., Wang, Y., Miao, S.: Fine Spatial and Temporal Characteristics of Humidity and Wind in Beijing Urban Area. Journal of Applied Meteorological Science, 25, 5, 559–569, https://doi.org/10.11898/1001-7313.20140505, 2014.

Fu, B.: A method for calculating local circulation velocity from wind data. Journal of the Meteorological Sciences, 17, 3, 258–267, 1997.

Hu, X., Liu, S., Liang, F.,Wang, J., Liu, H., Li, J., Wang, Y.: Numerical Simulation of Features of Surface Boundary-Layer over Beijing Area, Acta Scientiarum Naturalium Universitatis Pekinensis, 41, 4, 514–522, https://doi.org/10.3321/j.issn:0479-8023.2005.04.003, 2005.

Jiang, W., Xu, Y., Yu, H.: Fundamentals of boundary layer meteorology. Nanjing: Nanjing University Press, 1994.

Letcher, T., Minder, J.: The simulated impact of the snow albedo feedback on the large-scale mountain-plain circulation east of the Colorado Rocky mountains. Journal of the Atmospheric Sciences, 75, 3, 755–774, https://doi.org/10.1175/JAS-D-17-0166.1, 2018.

Li, M., Wang, T., Xie, M., Zhuang, B., Li, S., Han, Y., Cheng, N.: Modeling of urban heat island and its impacts on thermal circulations in the Beijing–Tianjin–Hebei region, China. Theoretical and Applied Climatology, 128, 3–4, 999–1013, https://doi.org/10.1007/s00704-016-1903-x, 2017.

Liu, S., Liu, Z., Li, J., Wang, Y., Ma, Y., Liu, H., Sheng, L., Liang, F., Xin, G., Wang, J.: Numerical simulation of the coupling effect of local atmospheric circulation in the Beijing Tianjin Hebei region. Scientia Sinica (Terrae), 39, 1, 88–98, 2009.

Miao, Y., Liu, S., Chen, B., Zhang, B., Wang, S., Li, S.: Simulating urban flow and dispersion in Beijing by coupling a CFD model with the WRF model, Advances in Atmospheric Sciences, 30, 6, 1663-1678, https://doi.org/10.1007/s00376-013-2234-9, 2013.

Rao, K., Snodgrass, H.: A nonstationary nocturnal drainage flow model. Boundary-Layer Meteorology, 20, 3, 309–320, https://doi.org/10.1007/BF00121375, 1981.

Tian, Y., Miao, J.: Overview of Mountain-Valley Breeze Studies in China. Meteorological Science and Technology, 47, 1, 11. https://doi.org/10.19517/j.1671-6345.20170777, 2019.

Wang, X., Wang, C., Li, Q.: Wind regimes above and below a temperate deciduous forest canopy in complex terrain: Interactions between slope and valley winds. Atmosphere, 6, 1, 60–87, https://doi.org/10.3390/atmos6010060, 2015.

Whiteman, C., Doran, J.: The relationship between overlying synoptic-scale flows and winds within a valley. Journal of Applied Meteorology, 32, 11, 1669–1682, https://doi.org/10.1175/1520-0450(1993)0322.0.CO;2,1993.

Whiteman, C., Zhong, S.: Downslope Flows on a Low-Angle Slope and Their Interactions with Valley Inversions. Part I: Observations. Journal of Applied Meteorology and Climatology, 47, 7, 2023–2038, https://doi.org/10.1175/2007JAMC1669.1, 2008.

Xue, J., Zong, L., Yang ,Y., Bi, X., Zhang, Y., Zhao, M.: Diurnal and interannual variations of canopy urban heat island (CUHI) effects over a mountain-valley city with a semi-arid climate, Urban Climate, 48, https://doi.org/10.1016/j.uclim.2023.101425, 2023.

Yang, Y., Luo, F., Xue, J., Zong, L., Tian, W., Shi, T.: Research Progress and Perspective on Synergy Between Urban Heat Waves and Canopy Urban Heat Island, 39, 4, 1–16, https://doi.org/10.11867/j.issn.1001-8166.2024.032, 2024.

You, C., Cai, X., Song, Y., Guo, H.: Local Atmospheric Circulations over Beijing-Tianjin Area in Summer. Acta Scientiarum Naturalium Universitatis Pekinensis, 42, 6, 779–783, https://doi.org/10.3321/j.issn:0479-8023.2006.06.015, 2006.

Zängl G. The impact of weak synoptic forcing on the valley-wind circulation in the Alpine Inn valley. Meteorology and Atmospheric Physics,105, 37–53, https://doi.org/10.1007/s00703-009-0030-y, 2009.

Zheng, Z., Ren, G., Gao, H. Analysis of the local circulation in Beijing area, Meteorological Monthly, 44, 3, 425–433, https://doi.org/10.7519/j.issn.1000-0526.2018.03.009, 2018b.

3.The method used to calculate CUHI is unclear to me. Is it based on all days of the year vs heatwave days, or on summer days vs heatwave days?

Response: Thank you for bringing this clarification to our attention. The method used to calculate CUHII was specifically based on comparing the air temperature differences between urban stations and reference stations during the summertime.

$$CUHII = T_{urban} - T_{reference} \qquad (1)$$

CUHII is the canopy urban heat island intensity during the summertime, T_{urban} is the air temperature of the urban stations, and $T_{reference}$ is the summer air temperature of the reference stations. Based on the above method, the diurnal variation of CUHII is also calculated in this study and is shown in Fig. R3. In Fig. R3, the blue line represents the diurnal variation of summer temperature at the urban station, while the green line depicts the diurnal variation of temperature at the reference station. By calculating the difference between these two stations, we obtained the diurnal variation of CUHII during the summertime.

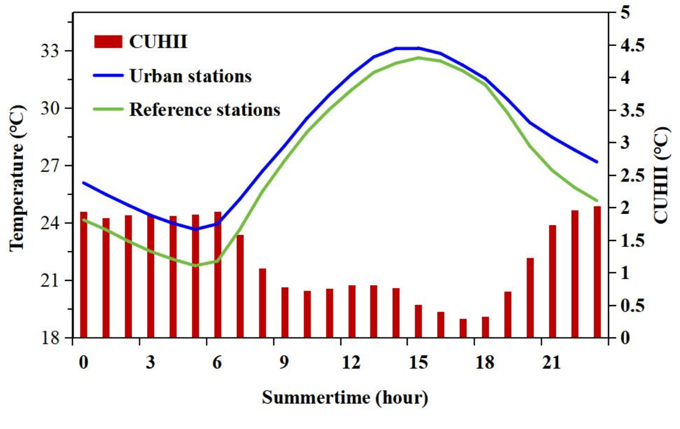

Fig. R3 The diurnal variation of CUHII in the built-up areas of Beijing during the summertime.

4.The time period 2016-2020 is far too short to be considered as a climatology; a time series of around thirty years is needed to extract HW detection thresholds. Some of the stations are located in urban environments, so the maximum daily temperature can potentially be influenced. If the objective here is to identify HWs on a regional/local scale, I suggest applying detection only to non-urban stations (to avoid any urban influence), and selecting stations for which very long time series are available.

Response: Thank you for your thoughtful comments and suggestions. You are absolutely right that short-term observational data may not fully capture the regional climate characteristics. However, due to the constraints of data access permissions and the use of high-density automatic weather stations, we were unable to obtain 30 years of observational data for our study. Thus, we have adopted the HW criteria published by the China Meteorological Administration in line 133-148 of the revised manuscript:

"Due to variations in climatic backgrounds, geographical conditions, socioeconomic factors, and other variables, different standards have been adopted for studying HW events across the world. The World Meteorological Organization suggests that an HW event occurs when the daily maximum temperature exceeds 32°C and persists for more than three consecutive days. The National Oceanic and Atmospheric Administration of the United States defines an HW index that combines temperature and relative humidity, issuing a heat alert when the HW index exceeds 40.5°C for at least 3 hours in two consecutive days during the daytime, or when it is anticipated to exceed 46.5°C at any time. The Royal Netherlands Meteorological Institute stipulates that an HW event occurs when the daily maximum temperature is above 25°C for more than five consecutive days, with at least three of those days having a maximum temperature exceeding 30°C. In contrast, the China Meteorological Administration (CMA) defines an HW event as a period when the daily maximum temperature exceeds 35°C for three consecutive days. In this study, the HW criteria published by the CMA were finally adopted. Considering that the daily maximum temperature at urban stations can be influenced by urbanization, this study utilizes the daily maximum temperature from reference stations to identify HW events. During the summer, if more than two reference stations experience an HW event on a given day, the day during the HW event is defined as an HW day; otherwise, it is considered an NHW day."

In addition, the threshold analysis you emphasized, based on long-term climate data during HW periods, indeed represents a significant scientific issue. This area of research has also sparked further explorations, such as the use of multivariate approaches to identify HW events (Kuglitsch et al., 2010; Chen & Li, 2017; Freychet et al., 2017) and the definition of diurnal/nocturnal compound HW (Nairn & Fawcett, 2013; Wang et al., 2020). We plan to employ different HW definitions in our future work to analyze various types of HW events, which hold significant practical implications and application values for studying the interactions between HW and CUHI, as well as developing effective mitigation strategies.

Finally, regarding the identification of heatwaves, you have made a valid point that we overlooked the potential influence of urbanization on daily maximum temperatures recorded at urban stations. We sincerely apologize for this oversight. Following your advice, we have re-examined the HW events using temperature series from reference stations that were less affected by urbanization. The updated findings revealed that the number and duration of HW events in 2019 were overestimated to some extent. We have accordingly revised the relevant figures and statistics in our revised manuscript.

Reference:

Kuglitsch, F. G., Toreti, A., Xoplaki, E., Della-Marta, P. M., Zerefos, C. S., Türkeş, M., Luterbacher, J.: Heat wave changes in the eastern Mediterranean since 1960. Geophysical Research Letters, 2010, 37, 4, https://doi.org/10.1029/2009GL041841, 2010.

Chen, Y., Li, Y.: An inter-comparison of three heat wave types in China during 1961-2010: observed basic features and linear trends. Scientific Report, 7, https://doi.org/10.1038/srep45619, 2017.

Freychet, N., Tett, S., Wang, J., Hegerl, G.: Summer heat waves over Eastern China: dynamical processes and trend attribution. Environmental Research Letters, 12, 2, https://doi.org/10.1088/1748-9326/aa5ba3, 2017.

Nairn, J., Fawcett, R.: Defining heatwaves: heatwave defined as a heat- impact event servicing all community and business sectors in Australia. South Australia: CAWCR Technical Report No. 060, 2013.

Wang, J., Chen, Y., Tett, S. F. B., Yan, Z., Xia, J.: Anthropogenicallydriven increases in the risks of summertime compound hot extremes. Nature Communications, 11, https://doi.org/10.1038/s41467-019-14233-8, 2020.

5. Again, if some of the stations are located in urban environments, they should not be considered when calculating the synoptic wind (the urban environment disturbs the surface wind measurement). The synoptic wind should be calculated on the basis of rural stations only.

Response: Thank you for your insightful comment regarding the need to consider the impact of urban environments on near-surface wind measurements. According to your comment, we have refined our approach by utilizing only the observational data from reference stations to recalculate the hourly wind direction and speed of mountain-valley breeze, and we have updated the relevant figures and content in line 256-261 of the revised manuscript:

"Based on previous research, it is well-established that there exists a pronounced wind direction reversal between the mountain breeze phase and the valley breeze phase, characterized by significant differences in wind speeds (Jiang et al., 1994; Fu, 1997; Dong et al., 2017). To mitigate the influence of the urban environment disturbing the surface wind measurement, this paper first analyzed the diurnal variation of mountain-valley breeze solely using observation data from reference stations."

It is worth noting that when analyzing the improvement of ventilation conditions in the thermal environment, we still use the observation data of urban stations, so as to analyze the correlation between the ΔCUHII and the wind speed. Unfortunately, due to the constraints imposed by data access permissions, we were unable to secure 30 years of continuous observational data for our current study. We plan to make efforts to obtain a longer time series of automatic station data, which will enable us to delve deeper into the climate characteristics of mountain-valley breeze in the Beijing megacity.

6. Generally all the captions need to be improved, especially the legends which are not detailed enough, so that it can be difficult to understand what is presented.

Response: Thank you for your insightful comments. According to your suggestions, I have thoroughly revised the captions and legends of all figures.

Taking Fig. 11 as an example, I have made the following improvements:

Fig. 11 Caption: I have clarified the meaning of the vertical short lines on the X-axis, ensuring that readers understand their significance and purpose.

Fig. 11c Legend: I have added a clear explanation of interpolated colors. This should help readers interpret the data presented in this figure more accurately.

In addition, I have added a color legend directly within Fig. 11c.

I believe that these revisions will significantly improve the readability and comprehensiveness of our manuscript. Once again, thank you for your constructive feedback.

7. It seems to me that it is difficult to conclude from these figures about the influence of mountain or valley breezes on the CUHII knowing that the phenomenon of CUHI has a marked diurnal cycle. On the other hand, the effect of the wind on the UHI may be delayed over time: if there was wind during the day, there is less heat accumulation and then possibly less UHI at night. Same for urban parameters: it's very interesting to see how the different urban parameters rank in terms of their influence on CUHII. However, I wonder about the relevance of comparing this for the"mountain breeze" and "valley breeze" cases. The CUHI phenomenon is different during the day and at night, and is not related to the same physical processes, so it seems difficult to draw relevant

conclusions from these comparisons.

Response: I apologize for any lack of clarity in my previous response. I would like to clarify further the relationship between the mountain-valley breeze and the ΔCUHII using the examples of four representative stations and you can find the details below. As shown in Fig. 12 and 13, during the mountain breeze phase (from 05:00 to 10:00), we observed high ΔCUHII values when wind speeds were relatively low. Conversely, during the valley breeze phase (from 11:00 to 10:00 the next day), the ΔCUHII values decreased when wind speeds increased significantly. This observation strongly suggested that wind speed was a factor that influenced the ΔCUHII. To further validate this, we examined the comparison between S1 and S2, two stations located in similar urban north. During the mountain breeze phase, S1 experienced higher wind speeds than S2, and correspondingly, S1 exhibited lower ΔCUHII values than S2. This finding aligned with our hypothesis that wind speed played a pivotal role in modulating the ΔCUHII (Yang et al., 2023; Xue et al., 2023). Moreover, we conducted a detailed analysis by plotting scatter diagrams of the wind speed versus the ΔCUHII from 2016 to 2020, as presented in Fig. R4. This analysis revealed a clear negative correlation between the two variables, confirming that as wind speed increased, the ΔCUHII tended to decrease. This observation reinforced the idea that wind speed was a key factor influencing the ΔCUHII. Additionally, the wind direction might also play a role in the thermal environment (Xie et al., 2022). For instance, during the mountain breeze phase, when the wind blew from urban north to urban south, S3, located in the urban south, experienced a stronger ΔCUHII compared to S1 in the urban north. In summary, the ΔCUHII might be influenced by both the speed and direction of the mountain-valley breeze.

We fully acknowledge that the diurnal cycle of CUHII, as you mentioned, is a confounding factor. Indeed, disentangling the effects of the diurnal cycle from those of the mountain-valley breeze represents a substantial challenge. In the future, we plan to utilize the Weather Research and Forecasting (WRF) model to conduct sensitivity tests with varying wind speeds, with the aim of isolating and investigating the independent influence of wind speed on the ΔCUHII.

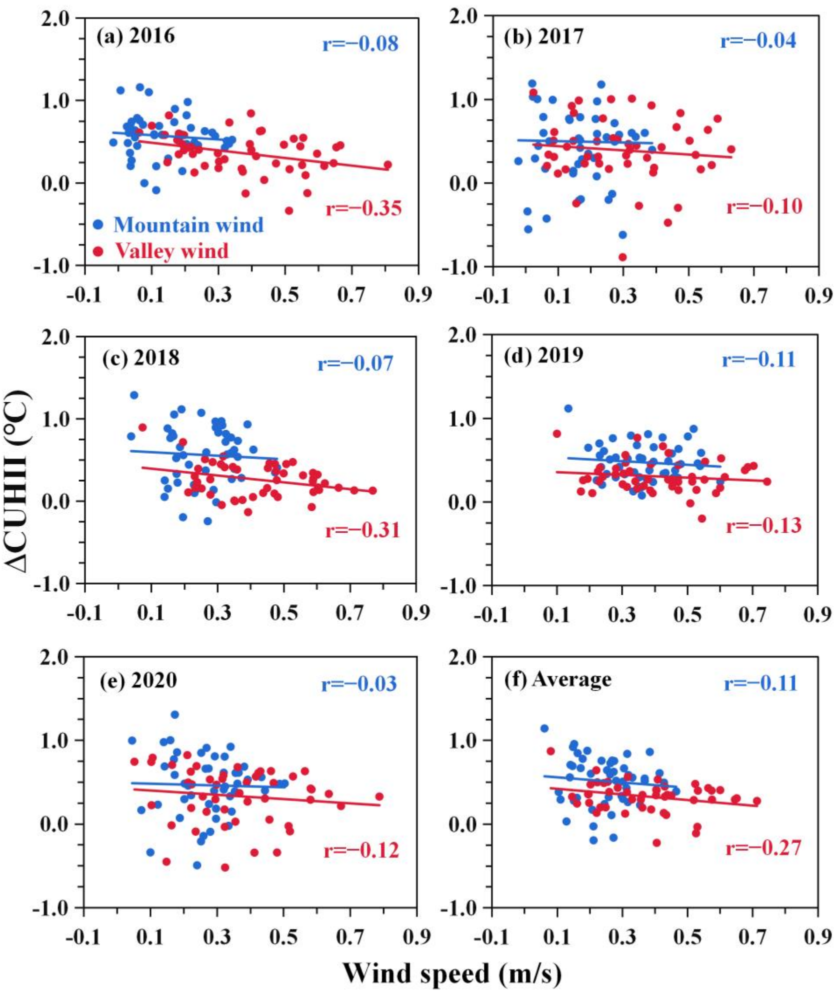

Figure: R4 Scatter plots of the wind speed and the ΔCUHII at urban stations from 2016 to 2020 during the mountain breeze phase and the valley breeze phase.

In addition, thank you very much for acknowledging my work on ranking the impact of various urban parameters on the ΔCUHII. I sincerely apologize for any lack of clarity in my previous presentation.

As you pointed out, the ΔCUHII curves during the mountain breeze phase and valley breeze phase are indeed markedly distinct. Our intention in comparing the contribution rankings of urban morphology during these two phases was to delve deeper into the driving mechanisms of urban morphology on the synergistic effects. To address your concern and enhance clarity, we have specifically created a schematic diagram that illustrates how the mountain-valley breeze and urban morphology modulate the ΔCUHII in Beijing (as shown in Fig. R5).

During the mountain breeze phase, the wind direction is from north to south. The

ΔCUHII in the urban south was higher than that in the urban north. This study considered that this pattern might be related to the influence of large-scale horizontal heat transport. In the next, we examined the influence of urban morphology on the ΔCUHII. Using urban north stations (S1 and S2) as examples, S2 (surrounded by high rise) exhibited stronger ΔCUHII than S1 (surrounded by low rise). High rise residential buildings are associated with higher population densities with greater capacities to mitigate heat, translating to more air conditioners which when operating release additional heat (Ryu & Baik, 2012). High rise neighborhoods have smaller SVF and thus have less outgoing long-wave radiation (Unger, 2004). High rise with smaller SVF neighborhoods tend to experience lower wind speeds (Hang et al., 2011). The lower wind speed limited the loss of sensible heat through atmospheric convection and advection, making it difficult for heat to dissipate from the streets (Wang et al., 2009). During the mountain breeze phase, the SVF of buildings primarily exhibited an enhancing effect on the ΔCUHII.

During the valley breeze phase, the wind direction is from south to north. The ΔCUHII in the urban north was higher than that in the urban south. Between 11:00 BJT and 18:00 BJT, the ΔCUHII at S3 (surrounded by high rise) was 0.01°C lower than that at S4 (surrounded by low rise), indicating that the inhibitory effect of high rise on the ΔCUHII was dominant. Although high rise can enhance the ΔCUHII by reducing outgoing longwave radiation and wind speed, on the other hand, they block more shortwave solar radiation from reaching the ground, and their shading effect contributes to a decrease in near-surface air temperature (Zhang et al., 2016; Krayenhoff & Voogt, 2016; Taleghani et al., 2016; Cai, 2017). After sunset (19:00 BJT), the ΔCUHII observed at S3 was 0.07°C higher than that at S4, signifying that the enhancement of the ΔCUHII by high rise reasserted its dominance. During the valley breeze phase, the high rise with smaller SVF exerted a dual influence on the ΔCUHII.

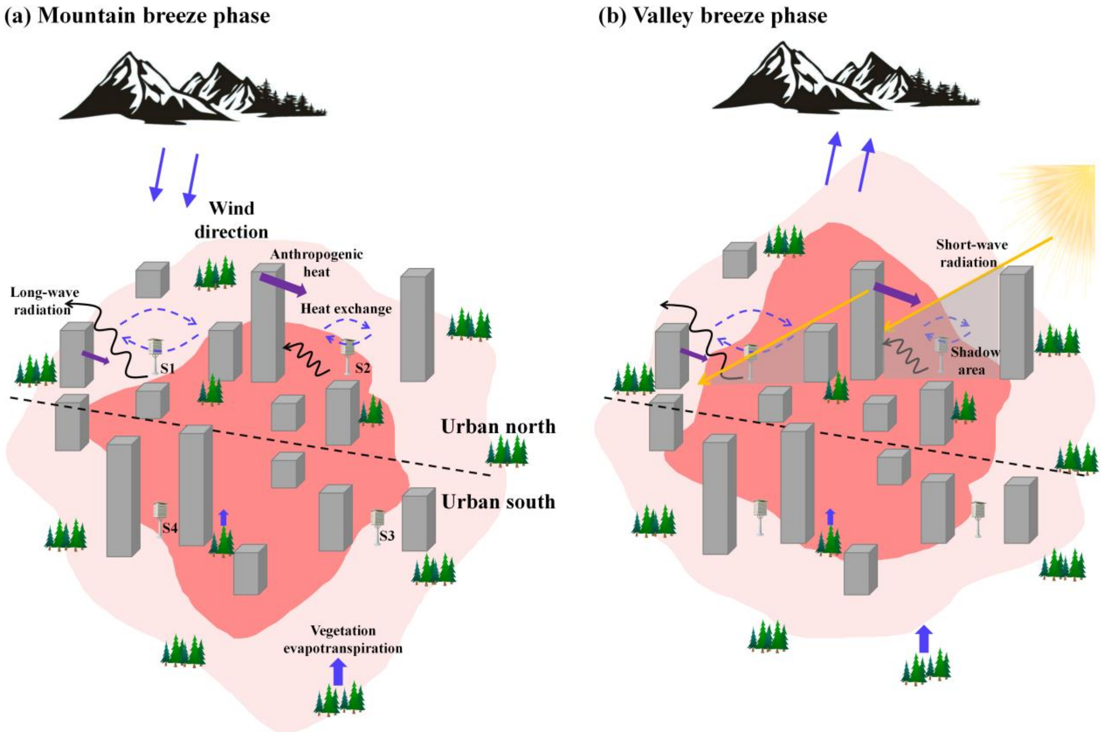

Figure: R5 Schematic diagram illustrating the modulation of ΔCUHII by mountain-valley breeze and urban morphology.

Reference:

Xie, J., Sun, T., Liu, C., Li, L., Xu, X., Miao, S., Lin, L., Chen, Y., Fan, S.: Quantitative evaluation of impacts of the steadiness and duration of urban surface wind patterns on air quality, Sci. Total Environ., 850, https://doi.org/10.1016/j.scitotenv.2022.157957, 2022.

Xue, J., Zong, L., Yang ,Y., Bi, X., Zhang, Y., Zhao, M.: Diurnal and interannual variations of canopy urban heat island (CUHI) effects over a mountain-valley city with a semi-arid climate, Urban Climate, 48, https://doi.org/10.1016/j.uclim.2023.101425, 2023.

Yang, Y., Guo, M., Wang, L., Zong, L., Liu, D., Zhang, W., Wang, M., Wan, B., Guo, Y.: Unevenly spatiotemporal distribution of urban excess warming in coastal Shanghai megacity, China: Roles of geophysical environment, ventilation and sea breeze, Building and Environment, 235, https://doi.org/10.1016/j.buildenv.2023.110180, 2023.

Ryu, Y. H., Baik, J. J.: Quantitative analysis of factors contributing to urban heat island intensity. J. Appl. Meteorol. Climatol., 51, 5, 842–854, https://doi.org/10.1175/JAMC-D-11-098.1, 2012.

Unger J.: Intra-urban relationship between surface geometry and urban heat island: review and new approach. Clim. Res., 27, 253–264, https://doi.org/10.3354/cr0272532004, 2004.

Hang, J., Li, Y., Sandberg, M.: Experimental and numerical studies of flows through and within high-rise building arrays and their link to ventilation strategy. J Wind Eng Ind Aerodyn, 99, 1036–1055, https://doi.org/10.1016/j.envsoft.2016.06.021, 2011.

Wang, Y., Zheng, D., Li, Q.: Urban meteorological disasters. Beijing: China Meteorological Press, 2009.

Cai, H.: Impacts of built-up area expansion in 2D and 3D on regional surface temperature, Sustainability, https://doi.org/10.3390/su9101862, 2017.

Taleghani, M., Sailor, D., Ban-Weiss, G. A.: Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. Environ. Res. Lett., 11, 2, https://doi.org/10.1088/1748-9326/11/2/024003, 2016.

Zhang, H., Zhu, S., Gao, Y., Zhang, G.: The Relationship Between Urban Spatial Morphology Parameters and Urban Heat Island Intensity Under Fine Weather Condition. Journal of Applied Meteorological Science, 27, 2, 249–256. https://doi.org/10.11898/1001-7313.20160213, 2016.

Krayenhoff, E. S., Voogt, J. A.: Daytime thermal anisotropy of urban neighbourhoods: morphological causation, Remote Sens., 8, 2, https://doi.org/10.3390/rs8020108, 2016.

Taleghani, M., Sailor, D., Ban-Weiss, G. A.: Micrometeorological simulations to predict the impacts of heat mitigation strategies on pedestrian thermal comfort in a Los Angeles neighborhood. Environ. Res. Lett., 11, 2, https://doi.org/10.1088/1748-9326/11/2/024003, 2016.

Minor comments:

P3, L69

"... more than 1,400 km2 ... "

Response: According to your comments, "... more than 1,400 km2 ... " was revised as "... more than 1,400 km^2 ... ".

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

P3, L71

"The altitudes of those mountains exceede 2,000 meters. "

Response: "... exceede ... " was revised as "... exceed ... ".

P3, L71

"The northeastern part comprises ... "

Response: "... part ... " was revised as "... region ... ".

P3, L73

Please clarify what you mean by "weak weather system"

Response: Clear information about "weak weather system" has been added in the revised manuscript.

The weak weather system here mainly refers to a weather system with no or few clouds (You et al., 2006; Liu et al., 2009; Dong et al., 2017) and is characterized by clear weather and strong solar radiation.

Reference:

Dong, Q., Zhao, P., Wang, Y., Miao, S., Gao, J.: Impact of Mountain-Valley Wind Circulation on Typical Cases of Air Pollution in Beijing. Environmental Science, 38, 6, 2218–2230, https://doi.org/10.13227/j.hjkx.201609231, 2017.

Liu, S., Liu, Z., Li, J., Wang, Y., Ma, Y., Liu, H., Sheng, L., Liang, F., Xin, G., Wang, J.: Numerical simulation of the coupling effect of local atmospheric circulation in the Beijing Tianjin Hebei region. Scientia Sinica (Terrae), 39, 1, 88–98, 2009.

You, C., Cai, X., Song, Y., Guo, H.: Local Atmospheric Circulations over Beijing-Tianjin Area in Summer. Acta Scientiarum Naturalium Universitatis Pekinensis, 42, 6, 779–783, https://doi.org/10.3321/j.issn:0479-8023.2006.06.015, 2006.

P3, L73-75

It would be interesting to summarise here the main findings of these various studies on breezes and local atmospheric circulations.

Response: Thank you very much for the valuable suggestion. We have added the role of valley winds in the middle and lower atmosphere in the revised manuscript as below.

Line 85-93 in the data and methodology:

"Under the control of a weak weather system with no clouds or few clouds (You et al., 2006; Liu et al., 2009; Dong et al., 2017), the mountain-valley circulation formed by the complex terrain plays a dominant role in the atmospheric circulation of the Beijing area (Liu et al., 2009; Miao et al., 2013; Dou et al., 2014). The near-surface boundary layer features including wind and temperature fields during summer in Beijing, China are investigated by numerical simulation (Hu et al., 2005). The results revealed a notable urban heat island effect in the city center, with the boundary layer wind field being significantly influenced by the mountainous terrain in the northwest. Furthermore, the impact of mountainous terrain on the lower atmospheric boundary layer in the Beijing area during summer was investigated (Cai et al., 2002; You et al., 2006). They discovered that the influence of mountain-valley winds could extend to cover the plain regions around Beijing to a significant degree."

Reference:

Cai, X., Guo, Y., Liu, H., Chen, J.: Flow Patterns of Lower Atmosphere over Beijing Area, Acta Scientiarum Naturalium Universitatis Pekinensis, 38, 5, 698–704, https://10.3321/j.issn:0479-8023.2002.03.015, 2002.

Dong, Q., Zhao, P., Wang, Y., Miao, S., Gao, J.: Impact of Mountain-Valley Wind Circulation on Typical Cases of Air Pollution in Beijing. Environmental Science, 38, 6, 2218–2230, https://doi.org/10.13227/j.hjkx.201609231, 2017.

Dou, J., Wang, Y., Miao, S.: Fine Spatial and Temporal Characteristics of Humidity and Wind in Beijing Urban Area. Journal of Applied Meteorological Science, 25, 5, 559–569, https://doi.org/10.11898/1001-7313.20140505, 2014.

Hu, X., Liu, S., Liang, F.,Wang, J., Liu, H., Li, J., Wang, Y.: Numerical Simulation of Features of Surface Boundary-Layer over Beijing Area, Acta Scientiarum Naturalium Universitatis Pekinensis, 41, 4, 514–522, https://10.3321/j.issn:0479-8023.2005.04.003, 2005.

Liu, S., Liu, Z., Li, J., Wang, Y., Ma, Y., Liu, H., Sheng, L., Liang, F., Xin, G., Wang, J.: Numerical simulation of the coupling effect of local atmospheric circulation in the Beijing Tianjin Hebei region. Scientia Sinica (Terrae), 39, 1, 88–98, 2009.

Miao, Y., Liu, S., Chen, B., Zhang, B., Wang, S., Li, S.: Simulating urban flow and dispersion in Beijing by coupling a CFD model with the WRF model, Advances in Atmospheric Sciences, 30, 6, 1663-1678, https://doi.org/10.1007/s00376-013-2234-9, 2013.

You, C., Cai, X., Song, Y., Guo, H.: Local Atmospheric Circulations over Beijing-Tianjin Area in Summer. Acta Scientiarum Naturalium Universitatis Pekinensis, 42, 6, 779–783, https://doi.org/10.3321/j.issn:0479-8023.2006.06.015, 2006.

P4, L82-83

"...and accurate land cover data is the basic parameter of climate research..." I should remove the second part of the sentence.

Response: Amended and thanks.

P5, L85

"...released by Professor Yang and Professor Huang of Wuhan University. Yang & Huang (2021) made the land cover datasets..." should be revised as "...released

by Yang & Huang (2021). They made the land cover datasets..."

Response: Amended and thanks.

P5, L88

Define the acronym LCZ (local climate zone) which is use here in the text for the first time, and include the ref to Stewart and (2012).

Response: Thanks very much for your valuable comment. I have now corrected this oversight by including a clear definition of LCZ in line 105-110 of our revised manuscript as below.

"The LCZ datasets in this article were provided by the Institute of Urban Meteorology, China Meteorological Administration. Stewart & Oke (2012) introduced the concept of LCZs, defining them as geographical regions spanning from hundreds to thousands of meters in size. These zones are characterized by uniformity in land use patterns, comparable spatial arrangements and building materials, and congruent patterns of human activity."

Reference:

Stewart, I. D., & Oke, T. R.: Local Climate Zones for Urban Temperature Studies. Bulletin of the American Meteorological Society, 93, 12, 1879-1897, http://doi.org/10.1175/BAMS-D-11-00019.1, 2012.

P5, L90

"... within the research buffer areas of the target stations" This information should be introduced later in the text once the stations have been presented.

Response: I apologize for the misplacement of the phrase "the target stations" in the text. Your suggestion is spot on, and I have revised the text accordingly.

P5, L94-95

Replace "encompasses" (not really appropriate) and clarify what you mean by "related elements"

Response: We replaced "encompasses" with "includes", and the "related elements" referred to specific meteorological factors such as humidity and precipitation.

P5, L110

"... otherwise, it was considered as a non heat wave (NHW) day. " Are NHW days defined for the whole year or just for the summer period?

Response: To clarify, the NHW days in this context are indeed defined specifically for the summer period in the revised manuscript.

P5, L111-112

"... by selecting reference stations for ground temperature observations and urban stations" Please clarify this sentence, do you mean "... by selecting urban reference stations for retrieving near-surface air temperature observations"?

Response: According to your comment, I have revised the relevant section in the revised manuscript as below.

"In general, scholars define CUHII as the temperature difference between the urban station and the reference station."

P5, L113

"... located outside of a 50km radius" Please add a space between "50" and "km" (and do the same everywhere in the rest of the text)

Response: Amended and thanks.

P5, L112-114

Based on which temperature distribution (day, night, average)? Why not base it on the land use map?

Response: We apologize for any confusion caused by our previous expression. Average air temperature and land use were both used as the selection criteria for reference stations, which have been re-described in the revised paper.

P5, L116

"... than the average altitude of the 45 urban stations" How is the station's rural environment defined? From the land use map, I presume ? As I understand it, this means that the other 45 stations (which are not classed as "rural") are all urban, and that they all meet the min distance to the city centre and land use conditions?

Response: Thank you for your valuable suggestion. As you mentioned, the designation of a rural environment is indeed based on land use classification. Additionally, I apologize for any confusion in my previous expression. Regarding the selection of urban stations, we have made supplementary details in the revised manuscript. Line 122-129 in the revised manuscript:

"In general, scholars define CUHII as the temperature difference between the urban station and the reference station (Ren et al., 2007; Shi et al., 2015). The Fifth Ring Road in Beijing, with a length of 98.6 km and an area of approximately 300 km^2 (depicted by the blue loop in Fig. 1), essentially covers the primary regions of the built-up area (Yang et al., 2013). Therefore, in this study, we have designated stations within the Fifth Ring Road as urban stations. The selection of reference stations is crucial for calculating the CUHII. In this study, we first identified reference stations with significantly lower temperatures than those of urban stations. Additionally, the reference stations must be located more than 50 km away from the city center, in a rural environment, predominantly situated within areas of sparse trees and shrubs (Yang et al., 2023). They should also be evenly distributed across different directions of the entire city. "

Reference:

Yang, P., Ren, G., Liu, W.: Spatial and temporal characteristics of Beijing urban heat island intensity. Journal of Applied Meteorology and Climatology, 52, 8, 1803-1816, http://doi.org/10.1175/JAMC-D-12-0125.1, 2013.

Ren, G., Chu, Z., Chen, Z., Ren, Y.: Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations, Geophysical Research Letters, 34, 5, https://doi.org/10.1029/2006GL027927, 2007.

Shi, T., Huang, Y., Shi, C., & Yang, Y.: Influence of Urbanization on the Thermal Environment of Meteorological Stations: Satellite-observational Evidence, Advances in Climate Change Research, 1, 7–15, https://doi.org/10.1016/j.accre.2015.07.001, 2015.

P6, L119-121

You should explain more clearly what is a valley/mountain breeze.

Response: Thank you for your detailed feedback on our paper. We have provided a more comprehensive explanation of the mechanisms, varying factors, and potential impacts of mountain-valley breeze in line 41-55 of Introduction section.

P6, L125

"... the daily average wind U and V were obtained ... " ->

"... the daily average components of the wind U and V were obtained ... "

Response: Amended and thanks.

Section 2.3.3 and Tab1

Not all morphological indicators are well described or easy to understand. The methodology lacks precision. For example: (1) what does "patch" mean? (2) on which zone are the indicators calculated, is this the case for all? (3) what is the size of the buffer? What are the final results?

Response: Thank you for your patience in reviewing our manuscript. In our manuscript, "patch" refers specifically to "buildings patch," which we have now explicitly defined in the text. The urban morphological indicators mentioned in our manuscript were calculated within a 500 m buffer zone surrounding the AWS (Oke, 2004).

Furthermore, we fully concur with your observation that a clearer description of the evaluation metrics is needed. To address this, we have described the parameters in Table 1 in detail. In addition, we also provide a schematic diagram of key indicators (Fig. R6) to further improve clarity.

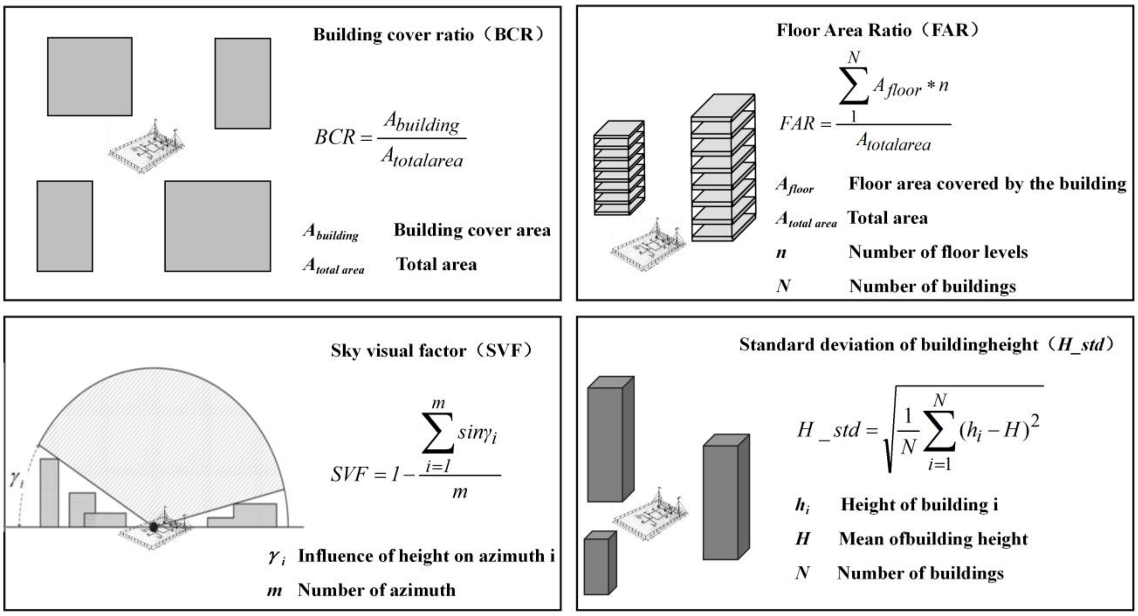

Fig. R6 The schematic diagrams and mathematical formulas of spatial morphological indicators.

Reference:

Oke, T. R.: Initial guidance to obtain representative meteorological observations at urban sites. University of British Columbia, Vancouver, 2004.

P7, L151-152

What means "The impact of urban spatial morphology on urbanization bias was evaluated" ?

Response: The "urbanization bias" was corrected to "the ΔCUHII".

P8, 164-175

The presentation and analysis of Fig 2 are extremely confusing. Personally, I don't understand what is presented here. Is it a difference between urban and rural areas, given that the aim is to study "urban warming excess" ?

Response: Thank you for your detailed feedback on our paper. I have revised the figure caption and legends to provide a more straightforward and accurate description. Fig. 2a now clearly states that it represents the temperature difference between urban stations and reference stations, which we refer to as the CUHII. This metric is a crucial indicator of urban warming excess, as it measures the excess warming in urban areas compared to their surrounding rural or natural environments.

Fig. 2b and Fig. 2c show the number and duration of HW events, respectively, based on the temperatures recorded at the reference stations. These metrics represent the climate background of the study region.

P9, L180-189 and Fig. 3

• CUHII values are relatively low for a city like Beijing. We would expect higher intensities, particularly during heatwaves. How do you explain this? And could it have something to do with the methodology?

Response: Thank you for your insightful comments and feedback on our manuscript.

In our analysis, we observed that the maximum CUHII during HW periods was 2.06°C, compared to 1.32°C during NHW periods. There is a significant increase of 59.33% in the average daily CUHII during HW periods compared to NHW periods. The maximum ΔCUHII reached 0.76°C. These findings are generally consistent with previous studies conducted by Jiang et al. (2019) and Zong et al. (2020).

In response to your question about the ΔCUHII values during HW periods being relatively low for a city like Beijing, we have specifically reviewed relevant research on the ΔCUHII during HW periods in other major cities worldwide in Tab. R1. During HW periods from 2013 to 2018, Shanghai experienced an increase of approximately 0.9°C in CUHII. Beijing and Guangzhou recorded increases of 0.9°C and 0.8°C, respectively (Jiang et al., 2019). In Guangzhou, China, the average CUHII increased by 103% (around 0.9°C) during HW periods compared to NHW periods (Luo et al., 2023). Lanzhou experienced a 103.6% increase in average CUHII (about 1.22°C) (Xue et al., 2023). Athens, Greece, had an average increase of 3.5°C, with peaks reaching 8.0°C under certain conditions (Founda et al., 2017). Seoul, South Korea, witnessed a maximum CUHII increase of 4.5°C (Ngarambe et al., 2020). Across 50 cities in the United States, the average CUHII during HW periods was 0.4~0.6°C higher than during NHW periods (Zhao et al., 2018). During the 2016 HW in the northeastern US, cities like New York, Washington D. C., and Baltimore experienced CUHII amplification of 1.0~2.0°C (Ramamurthy & Bou-Zeid, 2017).

Tab. R1 The research results on the ΔCUHII in recent years

Research city	Country	ΔCUHII	Reference
Guangzhou	China	0.8–0.9°C	Jiang et al., 2019; Luo et al., 2023
Beijing	China	0.9°C	Jiang et al., 2019
Shanghai	China	0.9–1.26°C	Ao et al., 2019; Jiang et al., 2019; Yang et al., 2023
Lanzhou	China	1.2°C	Xue et al., 2023
Athens	Greece	3.5°C–8.0°C	Founda et al., 2015
50 cities	United States	0.4°C–0.6°C	Zhao et al., 2018
Seoul	South Korea	4.5°C	Ngarambe et al., 2020
New York City, Washington D.C., and Baltimore	United States	1.0–2.0°C	Ramamurthy & Bou-Zeid, 2017

As you've noticed, the ΔCUHII during HW periods in Beijing, as a major city, may not be as pronounced as in some other cities. This can be attributed to various factors beyond urbanization levels, such as climatic background, geographical characteristics, and differing standards for defining HW events, which may contribute to the disparities in research on the synergistic effects of HW and CUHI (An & Zuo, 2021). Indeed, various standards have been employed globally to study HW events. The World Meteorological Organization (WMO) defines an HW event as when the daily maximum temperature exceeds 32°C for more than three consecutive days. The National Oceanic and Atmospheric Administration (NOAA) of the United States, on the other hand, has developed an HW index that incorporates both temperature and relative humidity, issuing heat alerts when this index surpasses 40.5°C for at least 3 hours on two consecutive days during daylight hours, or when it is forecasted to exceed 46.5°C at any time. The Royal Netherlands Meteorological Institute sets a threshold for HW occurrence when the daily maximum temperature remains above 25°C for more than five consecutive days, with at least three of those days exceeding 30°C. Conversely, the China Meteorological Administration (CMA) defines an HW event as a period when the daily maximum temperature exceeds 35°C for three straight days. Moreover, some scholars have explored bivariate approaches to identify HW events, such as methods that consider both daily maximum and minimum temperatures exceeding specified thresholds over multiple consecutive days (Kuglitsch et al., 2010; Chen & Li, 2017). In light of these diverse definitions, we plan to adopt various HW criteria in our future research to delve deeper into the characteristics of HW activity in the Beijing region.

Thank you again for your valuable comments. We hope these clarifications address your concerns and strengthen our manuscript.

Reference:

An, N., Zuo, Z.: Structural changes of heat waves in China from 1961 to 2017. Science China: Earth Sciences, 51, 8, 1214–1226, https://doi.org/10.1360/N072020-0380, 2021.

Ao, X., Wang, L., Zhi, X., Gu, W., Yang, H., Li, D.: Observed synergies between urban heat islands and heat waves and their controlling factors in Shanghai, China, J. Appl. Meteorol. Climatol., https://doi.org/10.1175/jamc-d-19-0073.1, 2019.

Chen, Y., Li, Y.: An inter-comparison of three heat wave types in China during 1961-2010： observed basic features and linear trends. Scientific Reports, 7. https://doi.org/10.1038/srep45619, 2017.

Founda, D., Pierros, F., Petrakis, M., et al.: Interdecadal variations and trends of the urban heat island in Athens (Greece) and its response to heat waves. Atmospheric Research,161–162, 1–13, https://doi.org/10.1016/j.atmosres.2015.03.016, 2015.

Jiang, S., Lee, X., Wang, J., Wang, K.: Amplified urban heat islands during heat wave periods, J. Geophys. Res. Atmos., 124, 14, 7797–7812, https://doi.org/10.1029/2018jd030230, 2019.

Kuglitsch, F. G., Toreti, A., Xoplaki, E., et al.: Heat wave changes in the eastern Mediterranean since 1960. Geophysical Research Letters, 37, 4, https://doi.org/10.1029/2009GL041841, 2010.

Luo, M., & Lau, N. C.: Urban expansion and drying climate in an urban agglomeration of east China. Geophysical Research Letters, 46,2, 6868–6877, https://doi.org/10.1029/2019GL082736, 2019.

Ngarambe, J., Nganyiyimana, J., Kim, I., Santamouris, M., Yun, G. Y.: Synergies between urban heat island and heat waves in Seoul: The role of wind speed and land use characteristics. PLoS ONE, 15, 12, https://doi.org/10.1371/journal.pone.0243571, 2020.

Ramamurthy, P., & Bou-Zeid, E.: Heatwaves and urban heat islands: a comparative analysis of multiple cities. Journal of Geophysical Research: Atmospheres, 122, 168–178, https://doi.org/10.1002/2016JD025357, 2017.

Xue, J., Zong, L., Yang ,Y., Bi, X., Zhang, Y., Zhao, M.: Diurnal and interannual variations of canopy urban heat island (CUHI) effects over a mountain-valley city with a semi-arid climate, Urban Climate, 48, https://doi.org/10.1016/j.uclim.2023.101425, 2023.

Yang, Y., Guo, M., Wang, L., Zong, L., Liu, D., Zhang, W., Wang, M., Wan, B., Guo, Y.: Unevenly spatiotemporal distribution of urban excess warming in coastal Shanghai megacity, China: Roles of geophysical environment, ventilation and sea breeze, Building and Environment, 235, https://doi.org/10.1016/j.buildenv.2023.110180, 2023.

Zhao, L., Oppenheimer, M., Zhu, Q., et al.: Interactions between urban heat islands and heat waves. Environmental Research Letters, 13, 3, 034003, https://doi.org/10.1088/1748-9326/aa9f73, 2018.

• I don't think that the variability is any greater during the day than at night. It also follows a plateau during the day (except in the transition phases).

Response: Thank you for your valuable time and constructive comments on our manuscript. We have revised the relevant content of the in line 219-222 of the manuscript to ensure clarity and accuracy:

"CUHII started to slowly decrease from 06:00 Beijing Time (BJT) and hit its lowest point at 16:00 BJT. Then, CUHII gradually increased and remained at a high plateau consistently from 22:00 until 05:00 the next day. The diurnal variation of the ΔCUHII was also examined in this study."

• "The diurnal variation of CUHII may be modulated by anthropogenic heat

emissions, aerosols, atmospheric circulation, etc. (Zheng et al., 2018; Zheng et al., 2020; Yang et al., 2020)." This sentence is off-topic, there is no link with the discussions of the dirunes cycles.

Response: I sincerely apologize for including the off-topic sentence in my previous submission. I have now removed this sentence from the manuscript to ensure that all content aligns directly with the core focus of our discussions. I apologize for any confusion or inconvenience this may have caused.

- **Fig.3: I suggest plotting the daily CUHII cycles centred on the night-time hours (when intensities are at their highest).**

Response: Thank you very much for your insightful and valuable suggestions. We have taken your advice seriously and have revised Fig. 3 accordingly.

Furthermore, to ensure consistency across our presentation, we have also re-drawn Fig. 5 and Fig. 13 in a similar manner.

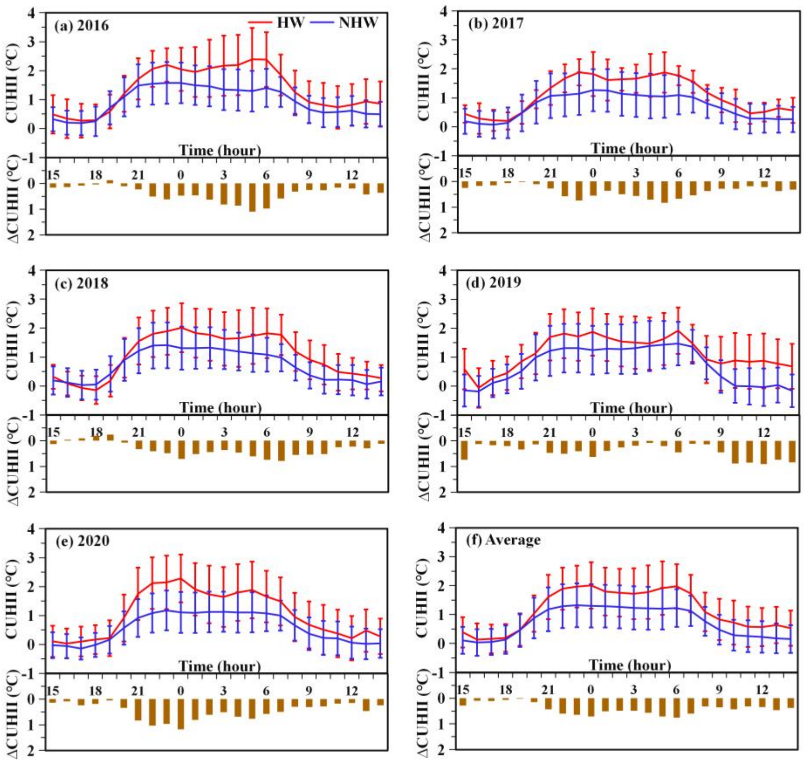

Figure: 3 Summer diurnal variation (Beijing time, BJT) and standard deviation of CUHII during HW periods and NHW periods based on the urban stations and reference stations in Beijing. (a) 2016, (b) 2017, (c) 2018, (d) 2019, (e) 2020, (f) average value from 2016 to 2020. The red line represents the CUHII during HW periods, while the blue line depicts the CUHII during NHW periods. The bars indicate the ΔCUHII during HW periods.

• Explain in the text what means BJT

Response: To clarify for the readers, I have now explicitly explained in the text that BJT stands for Beijing Time.

• The fact that urban heat islands are stronger during heatwaves is well known. It is based on the physical processes involved and has been observed in a large number of situations/cities.

Response: Thank you for your thorough review. As you mentioned, the fact that CUHII becomes more pronounced during HW periods is well-established. You are absolutely correct, and I would like to provide some additional insights and supplementary explanations regarding this matter.

Some studies have shown that the interactions between HW and CUHI are not always apparent, and in some cases, the CUHII may even decrease during HW periods (Ramamurthy & Bou-Zeid, 2017; Scott et al., 2018; Rogers et al., 2019; Richard, 2021). The above study suggested that there are significant differences in the coupling effect between CUHI and HW across different regions, necessitating in-depth research that takes into account specific research methods, the geographical location of the research subjects, and other influencing factors.

Our study focuses on analyzing the diurnal variations of the ΔCUHII and their potential causes in Beijing from an observational angle. Nevertheless, we recognize the limitations of this approach and plan to further explore this topic through numerical simulations in the future.

Reference:

Jiang, S., Lee, X., Wang, J., Wang, K.: Amplified urban heat islands during heat wave periods, J. Geophys. Res. Atmos., 124, 14, 7797–7812, https://doi.org/10.1029/2018jd030230, 2019.

Ramamurthy, P., & Bou-Zeid, E.: Heatwaves and urban heat islands: a comparative analysis of multiple cities. Journal of Geophysical Research: Atmospheres, 122, 168–178, https://doi.org/10.1002/2016JD025357, 2017.

Scott, A. A., Waugh, D. W., Zaitchik, B. F.: Reduced Urban Heat Island intensity under warmer conditions. Environmental Research Letters, 13, 064003, https://doi.org/10.1088/1748-9326/aabd6c, 2018.

Rogers, C. D., Gallant, A. J., Tapper, N. J.: Is the urban heat island exacerbated during heatwaves in southern Australian cities? Theoretical and applied climatology. 137, 441–457, https://doi.org/10.1007/s00704-018-2599-x, 2019.

Richard, Y., Pohl, B., Rega, M., et al.: Is Urban Heat Island intensity higher during hot spells and heat waves (Dijon, France, 2014–2019)?. Urban Climate, 35, 100747, https://doi.org/10.1016/j.uclim.2020.100747, 2021.

P12, L194 and Fig. 4

• The times at which the ΔCUHII is calculated are not specified (day, night, daily average). It would make much more sense to separate the hours of day and night, or even focus of nighttime (the phenomenon being nocturnal).

Response: We sincerely apologize for any lack of clarity in Fig. 4.

We have clarified that the ΔCUHII was derived from daily average data in the caption of Fig. 4. Furthermore, your proposal to analyze the ΔCUHII characteristics separately for daytime and nighttime is extremely insightful. In response, we have conducted additional analyses and have included two response figures, Fig. R7 and Fig. R8. These figures depict the ΔCUHII spatial distributions specifically for daytime and nighttime, respectively. Upon comparing these new results with our previously presented spatial distributions of the ΔCUHII during the mountain breeze phase (Fig. S1 in the original paper) and valley breeze phase (Fig. S2 in the original paper), we observed a remarkable similarity in their patterns. In the future, we will study the characteristics and causes of the synergistic effect between HW and CUHI during the daytime and nighttime.

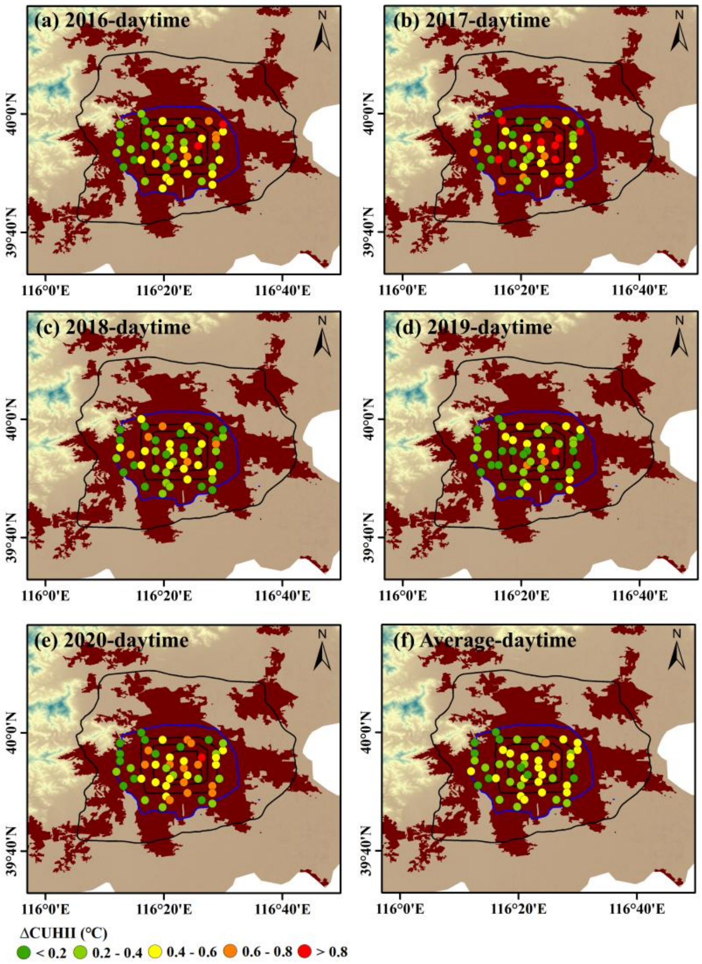

Figure: R7 Spatial patterns of the daytime ΔCUHII based on the urban stations in Beijing during HW periods. (a) 2016; (b) 2017; (c) 2018; (d) 2019; (e) 2020; (f) average value from 2016 to 2020. Different colored dots represent different ranks of the ΔCUHII.

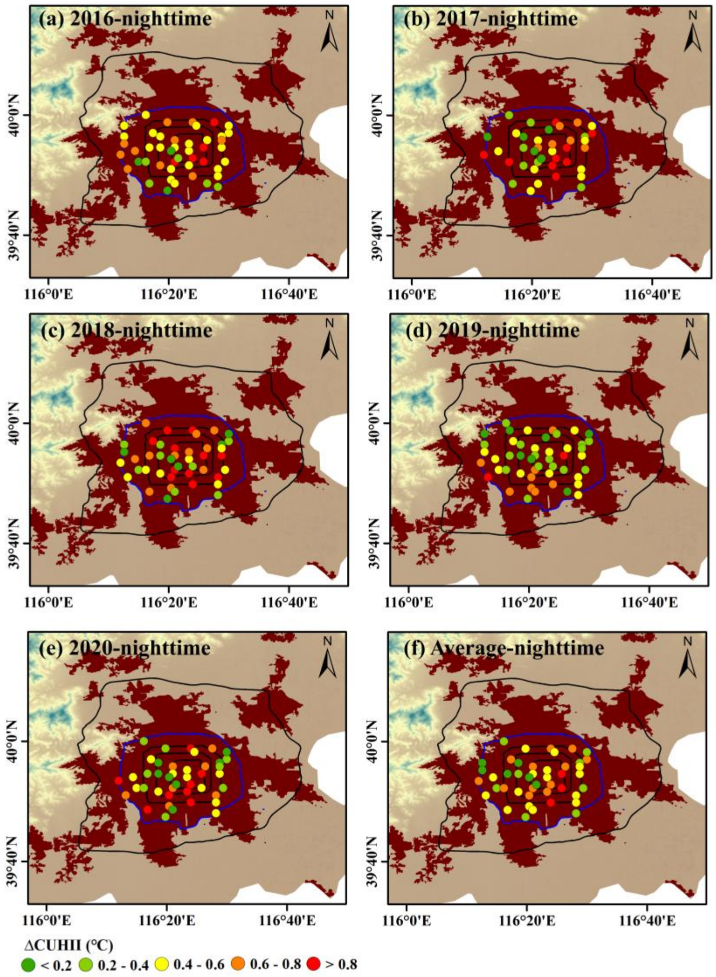

Figure: R8 Spatial patterns of the nighttime ΔCUHII based on the urban stations in Beijing during HW periods. (a) 2016; (b) 2017; (c) 2018; (d) 2019; (e) 2020; (f) average value from 2016 to 2020. Different colored dots represent different ranks of the ΔCUHII.

• Fig. 4: This figure presents both the spatial variability of ΔCUHII and the interannual variability. This could be interesting if the analyzes were a little more in-depth. Here there are no very clear conclusions/messages about the influence of e.g. urban morphology or the variability of synoptic conditions.

Response: Following your suggestions, I have thoroughly revised the depiction in line 231-241 of the revised manuscript, which now provides a more comprehensive and detailed analysis of Fig. 4.

P12, L205

"In this section, this research analyzed the modulation of mountain-valley breeze on the synergies between HW and CUHI... " > "... the modulation of the

synergies between HW and CUHI by the mountain-valley breeze" ?? This is what you mean ?

Response: I apologize for the previous phrasing. The revised text now reads:

"In this section, this research analyzed the modulation of the synergies between HW and CUHII by the mountain-valley breeze using wind field and temperature data from AWS."

P15, L242-244

I don't understand on what basis this comment is made

Response: I apologize if this was not evident from my earlier explanation. You are correct that the previous comment is indeed based on Fig. 6c. To rectify this, I have already added a supplemental explanation in line 289-291 of the revised manuscript.

Section 3.3

The city configuration with variability of building densities and heights is interesting.

P 16, Fig. 7c

According to the figure, D-value (for dense vs open) is stronger for "whole days" case than for both "mountain breeze" and "valley breeze" cases. However, the D-value for "whole days" should be intermediate to the other two cases, if it's calculated as an average over all the hours of the day, right?

Response: We have identified an error where the difference value (dense vs open) for "whole days" inadvertently referenced the difference value for "mountain breeze". We deeply regret any confusion or inconvenience this may have caused.

Rest assured, we have promptly corrected this mistake in Fig 7c. Additionally, during our thorough review of the figures, we also noticed two meaningless blue dots in Fig. 7a and Fig. 7b, which we have removed to ensure the clarity and accuracy of the presentation. We have taken this opportunity to carefully recheck all the figures and tables throughout the manuscript to prevent any further errors.

P17, L287

What do you mean by "during 3D indicators" ? I don't understand this sentence.

Response: I meant to say "among 3D indicators," which I have now corrected in the revised manuscript.

P17, L287

The term "amplified CUHII" could be clearly explained once and then replaced by ΔCUHII (everywhere in the text and figures).

Response: Thank you for your careful review of our manuscript.

As suggested, in the Introduction, we first labeled the acronym ΔCUHII for the first occurrence of amplified CUHII and have consistently used the ΔCUHII throughout the rest of the manuscript to refer to the amplified CUHII. Secondly, we have now provided a comprehensive explanation of the meaning and computation method of the ΔCUHII in section 2.3.1 of the Methods section. Specifically, the ΔCUHII was obtained by subtracting the summer CUHII during the NHW periods from the summer CUHII during the HW periods.

P18, L289-291

You say "Urban morphological indicators had weaker relationships with amplified CUHII during the mountain breeze period but showed stronger correlations with amplified CUHII during the valley breeze period. "

According to Fig. 8, the effect of urban indicators on ΔCUHII according to the breeze circulations is the opposite of what is written here: the effect is stronger during mountain breezes.

Response: Thank you for taking the time to review our manuscript and for bringing this oversight to our attention. You are absolutely correct in pointing out that we inadvertently reversed the description of the relationships between the urban morphological indicators and the ΔCUHII during the mountain breeze phase and the valley breeze phase.

We apologize for this mistake. The revised sentence is shown below:

"During the mountain breeze phase, the relationship between the urban morphological indicators and the ΔCUHII was stronger, whereas during the valley breeze phase, this relationship was weaker."

Fig. 9

We don't understand what is presented here, the names of the axes are not explicit and the legend is not detailed enough. I presume it is ΔCUHII(OBS) vs ΔCUHII(MODEL) ?

Response: Thank you for your thorough review of our manuscript. You are absolutely correct that the label of the axes in Fig. 9 has been inadequate, causing confusion.

The vertical axis represents the observed change in a parameter denoted as the ΔCUHII (OBS), while the horizontal axis depicts the corresponding modeled change, labeled as the ΔCUHII (MODEL). We apologize for the oversight. To rectify this, we have revised the axis labels and legends of Fig. 9.

P18, 297-303

• Linear model: It's rather debatable to say here that the linear model is good (especially as you go on to say that it doesn't perform well...). The RMSE of 0.14°C is rather high given the average values. You should adapt your comments

Response: Thank you for your careful review of our manuscript. You are absolutely correct that our previous statement was not accurate, and we sincerely apologize for any confusion or misinterpretation it may have caused.

We have now revised the manuscript accordingly, specifically in line 342 to 345 as below:

"As depicted in Fig. 9a, the linear model yielded a coefficient of determination (R^2) of 0.44 and a root mean square error (RMSE) of 0.14°C, indicating a relatively large modeling error. Consequently, while the linear model provided a foundational framework for modeling the ΔCUHII, it might not be the most optimal choice for our study. "

• **SVR and RF: both models overestimate high values and underestimate low values, why?**

Response: Thank you for your insightful questions regarding the modeling biases in our study. We have added two error bars (30%) in the modeling results for SVF and RF to facilitate observation. As you have pointed out, we indeed observe a tendency of overestimation at higher values and underestimation at lower values for both SVF and RF. Notably, the underestimation is more pronounced within the temperature range of 0.0~0.2°C.

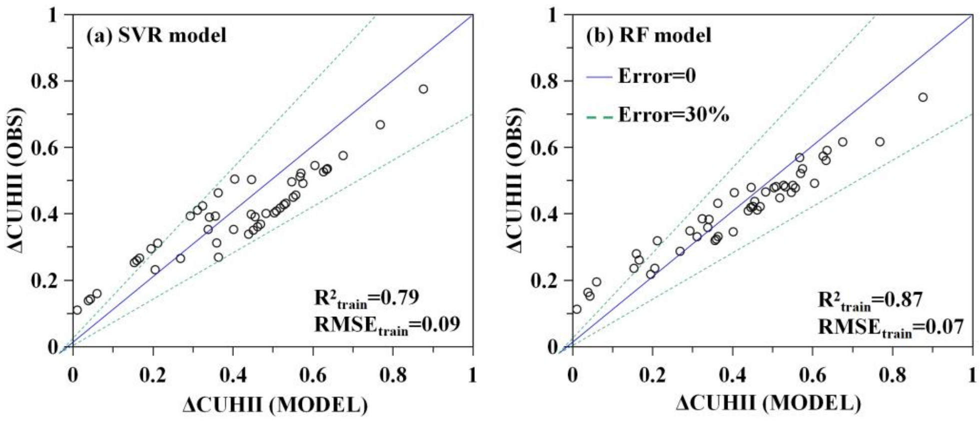

Fig. R5 The performance of the SVR model (a) and RF model (b) in predicting the ΔCUHII.

We believe that two primary factors may contribute to this phenomenon. Firstly, dataset imbalance is a critical factor that could explain the observed biases. According to previous studies (He & Garcia, 2009), when the data set contains more samples from one category (high-value) than other categories (low-value), it often affects the prediction results of the model. Moreover, if the target variable's distribution is nonlinear, with distinct characteristics between high-value and low-value regions, models may fail to adequately capture these complexities, further exacerbating the modeling biases (Breiman, 2001).

Secondly, the specific characteristics of our dataset, particularly the autocorrelation among the urban morphology parameters used as predictors, could also play a role. Autocorrelation among predictor variables can introduce complexities that complicate the modeling process (Dormann et al., 2013). In conclusion, we believe that the observed prediction biases are likely due to a combination of dataset imbalance and the specific characteristics of our dataset.

It is intriguing to note that, the RF model exhibited superior modeling performance for the ΔCUHII compared to the SVF model when applied to the same dataset. We recognize that further investigation is needed to fully understand and mitigate the modeling biases in our study. Your comments have been invaluable in guiding our analysis, and we are committed to incorporating your suggestions into our future research efforts.

References:

He, H., & Garcia, E. A.: Learning from imbalanced data. IEEE Transactions on Knowledge and Data Engineering, 21, 9, 1263-1284, 2009.

Breiman, L.: Random forests. Machine Learning, 45, 1, 5-32, 2001.

Dormann, C. F., Elith, J., Bacher, S., et al.: Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography, 36, 1, https://doi.org/27-46. 10.1111/j.1600-0587.2012.07348.x, 2013.

P20, L331

"... the importance of SVF and BCR in the 2D and 3D indicators ... " should be revised as "... the importance of SVF and BCR in the 3D and 2D indicators ... "

Response: Corrected.

Fig. 11

• Again we don't understand what is presented here, what is the partial dependence? clarify what is presented both in the text and in the caption. Is it ΔCUHII on y-axis?

Response: I apologize for the lack of clarity in our previous submission. I have made the necessary clarifications in both the text and figure captions.

Partial dependence, in the context of machine learning, refers to the assessment of the relationship between a single feature and the model's predicted outcome, while all other features in the dataset are held constant (Friedman, 2001). This function represents the effect of selected explanatory variables and can be used to interpret "black box" models (Cutler et al., 2007; Shiroyama & Yoshimura, 2016). In Fig. 11a-11b, the x-axis represents various feature values, and the y-axis represents the partial dependence value.

• The range of y-axis is different in the different plots, you should use the same.

Response: Corrected.

• What do the small vertical lines on the x-axis represent?

Response: I apologize for the lack of clarity regarding the small vertical lines on the x-axis in Fig. 11a-11b. I have supplemented a detailed explanation in the figure caption. In machine learning, the small vertical lines along the x-axis, known as rug plots, represent the distribution of the feature values. They provide a visual representation of the data's density and can help identify regions of high or low data concentration.

• For (c) panel, do you think it is relevant to interpolate the data? I would use symbols instead. Also you should add a color legend.

Response: Thank you for your insightful comments. Based on your suggestion, I have added color legends in Fig. 11c. All discussions in Fig. 11a-11b have centered around the impact of individual variables on the predicted values, without considering how these variables might simultaneously influence the prediction. Therefore, in Fig11. c, we have introduced the two-way PDP (Partial Dependence Plot), which allowed us to consider the range of values for two feature variables simultaneously and demonstrates their joint influence on the prediction of the dependent variable.

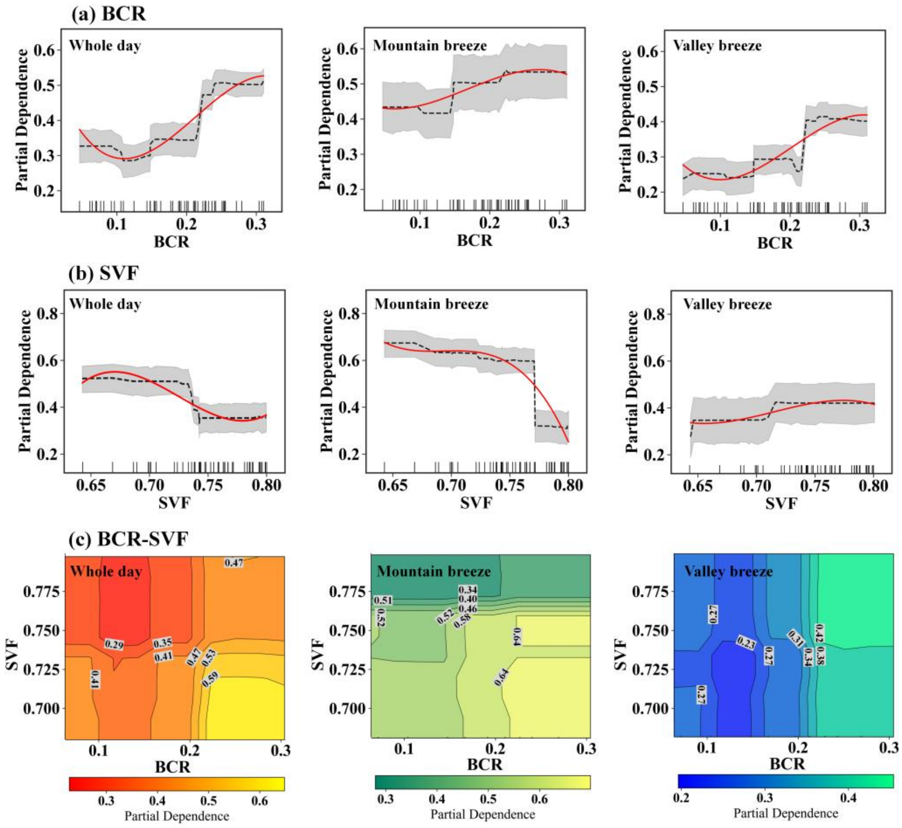

Figure: 11 (a-b) Partial dependence plots of the ΔCUHII on BCR and SVF. The red line represents the fitted curve, while the gray lines indicate the 95% confidence interval. The rug plots (small vertical lines) along the X-axis represent the distribution of the feature values. (c)The two-way plots partial dependence of the ΔCUHII on BCR and SVF. The X-axis represents the BCR feature, while the Y-axis represents the SVF feature. The interpolated colors of the panel, ranging from dark to light, signified the partial dependence decreasing from large to small.

Reference:

Friedman, J.: Greedy function approximation: a gradient boosting machine. Ann.Stat. 29, 1189–1232. http://doi.org/10.1214/aos/1013203451, 2001.

Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Kyle, T., Gibson, J., Lawler, J. J., Beard, H., Hess, T.: Random forests for classification in ecology. Ecology 88, 2783–2792, http://doi.org/10.1890/07-0539.12007.

Shiroyama, R., Yoshimura, C.: Assessing bluegill (Lepomis macrochirus) habitat suitability using partial dependence function combined with classification approaches. Ecological informatics, 35, 9–18, http://doi.org/10.1016/j.ecoinf.2016.06.005, 2016.

P22, L370-372

On what basis do you say here that the synergistic effect observed at S1 and S2 is lower than that observed at S3 and S4 ? The differences are considered as significative for ex. Between S2 and S4 ?

Response: I apologize for any confusion caused by my previous statement. The relevant content was revised in line 426-431 as below:

"As depicted in Fig. 13, the observed ΔCUHII in the urban north (S1 at 0.51°C, S2 at 0.76°C) was lower than that in the urban south (S3 at 0.77°C, S4 at 0.59°C). For the entire city, a more consistent wind field at the ground level results in a stronger heat transport capacity (Xie et al., 2022; Yang et al., 2023). Combining with the statistical results in Fig. 6c-6d, we suggested that the direction of the mountain-valley breeze might alter the pattern of the ΔCUHII across the entire urban area."

Reference:

Xie, J., Sun, T., Liu, C., Li, L., Xu, X., Miao, S., Lin, L., Chen, Y., Fan, S.: Quantitative evaluation of impacts of the steadiness and duration of urban surface wind patterns on air quality, Sci. Total Environ., 850, https://doi.org/10.1016/j.scitotenv.2022.157957, 2022.

Yang, Y., Guo, M., Wang, L., Zong, L., Liu, D., Zhang, W., Wang, M., Wan, B., Guo, Y.: Unevenly spatiotemporal distribution of urban excess warming in coastal Shanghai megacity, China: Roles of geophysical environment, ventilation and sea breeze, Building and Environment, 235, https://doi.org/10.1016/j.buildenv.2023.110180, 2023.