Response to Reviewer #1' Comments

This manuscript presents a comprehensive analysis of an extreme wind gust event associated with a quasi-linear convective system (QLCS) in Beijing on 30 May 2024. The study leverages a high-resolution observational mesonet, including radar wind profilers, a meteorological tower, and multi-source remote sensing data, to elucidate the multi-scale dynamical processes involved. The findings provide valuable insights into the mechanisms of convective gust generation and have potential implications for nowcasting and model improvement. Thus, I recommend the publication of this paper in Atmospheric Chemistry and Physics after the following points have been addressed:

Response: We appreciated tremendously your positive and invaluable comments, which indeed help improving the quality of our manuscript. We have addressed the reviewers' concern one by one to the best of our abilities. For clarity purpose, here we have listed the reviewers' comments in blue plain font, followed by our response in black bold italics, and the modifications to the manuscript are in black italics.

Major comments:

The manuscript would benefit from a detailed description about the conceptual model in Figure 10. A discussion about key findings of this observed mechanism compared with those in previous QLCS studies, especially from other terrain regions, would also enhance this study.

Response: Per your kind suggestions, we have supplemented section 5 in this revised manuscript, mainly including the following two points:

(1) A detailed description of the conceptual model (Fig. 10) in the main text has been added to elucidate the observed dynamical structures and multi-scale processes responsible for this Beijing extreme gust event:

"Before the merger of the QLCS (Fig. 10a), the northern convection portion maintained and developed rapidly due to the convergence of southerly winds along the southern slopes of Mt. Yan. Meanwhile, a convergence line formed at the boundary of convectively generated cold outflows, mostly associated with the southern portion. During the downhill process, the environmental southerly winds in the near-surface layer facilitated efficient storm-relative inflow of highly unstable air, supporting the continued regeneration of strong convection along the advancing cold

pool, where a very large area of nearly contiguous radar reflectivity echoes greater than 45 dBZ was concentrated over the foot of western mountains. The presence of pronounced convergence from the PBL in updrafts led to the rapid intensification of surface-based cyclonic vorticity through vertical stretching during the early stages. Evaporative cooling enhanced the generation of the extreme winds via downward momentum transport and pressure gradient forcing.

As shown in Fig. 10b, the two convective segments merged into a well-organized squall system, moving perpendicular to the mean deep-layer wind/shear and developing a larger-scale bow-echo structure after reaching the plain. In the merger stage, a midlevel layer of intense cyclonic vorticity favored the development of RIJ behind the precipitation area, driven by the superposition of ambient flow and the rotational flow on the west side of the mesovortex. The calculation of the zonal momentum budget further confirmed the importance of horizontal momentum downward transport in accelerating lower-level flows within the descending RIJ.

Large-scale analyses show that the deep, well-mixed PBL with very steep lower-tropospheric lapse rates and conditional instability provided a favorable background for consolidating the dispersed multicell thunderstorm. The emergence of pronounced low-level frontogenesis, coupled with significant shearing deformation, created a highly favorable synoptic-scale environment for sustained convection. These processes supplied persistent forcing for ascent and low-level convergence, continuously transporting moisture and instability to promote the organization and maintenance of the circulation. By further examining the property of turbulent kinetic energy transfer derived from three-dimensional ultrasonic anemometers on the meteorological tower, we found that the frequency and intensity of inverse energy cascades increased significantly during this near-surface high wind event. These findings bridge the gap between meso- and small-scale physical processes in the lower troposphere and large-scale weather system, which potentially consolidate our understanding of the dynamics and their roles in the evolution of convection."

(2) The discussion has been expanded to include a comparison between our observed mechanisms and previous QLCS studies:

"Based on the above results, this case shares commonality with other QLCS cases in previous studies while exhibiting terrain-modulated uniqueness. Similar to QLCS events documented over plains (e.g., the U.S. Central Plains), the storm exhibited a well-defined cold pool, a descending RIJ, and strong low-level convergence leading to bow-echo development (Bentley and Mote, 1998; Bentley and Sparks, 2003; Wakimoto et al., 2006; Evans et al., 2014).

However, its evolution was markedly influenced by complex topography (Houze, 2012). The initial convection was anchored and intensified by orographic lifting along the southern slopes of Mt. Yan, and the downhill propagation of the system resulted in an unusually concentrated zone of high reflectivity near the foot of Mt. Taihang. These findings underscore that while the overall dynamical framework of QLCS remains consistent, local topography can fundamentally alter the initiation, sustenance, and peak intensity of severe winds by modifying convergence patterns, cold-pool propagation, and vortex dynamics. Future nowcasting and high-resolution modeling for complex terrain regions should therefore explicitly incorporate such terrain–convection interactions."

Minor comments:

1. The acronym "RWP" is defined early on, but "QLCS" is used in the abstract before being spelled out in the introduction. Please ensure all acronyms are defined upon first use.

Response: All acronyms are defined upon first use.

2. The study relies heavily on RWP-derived parameters (e.g., divergence, vorticity, frontogenesis). The uncertainty associated with these calculations should be quantified and discussed.

Response: Thanks for your kind reminder. In our previous study (i.e., Guo et al., 2023), the uncertainties associated with the errors of horizontal wind retrievals, the spatial scales and the shape of triangles in the calculation of RWP-derived parameters have been discussed. To ensure the stability of the results, obtuse angles of more than 140° and areas of less than 500 km^2 should be avoided for constructing a reasonable triangle. Here, four triangles from west to east are constructed based on the positions of six RWPs to meet the consistency in shape and area. It is noteworthy that the value of four dynamic parameters is still inversely proportional to the area of triangle as the denominator. This coincides with the fact that the gradient of velocity between two points will increase when the distance is shortened. The discussion has been supplemented in section 2.4.

3. For the frontogenesis calculation, surface observations are implied for gradients of θe. Please comment on the potential implications of using surface data to represent low-level processes, and any associated limitations.

Response: We fully agree with your concern. In the revised manuscript, we elaborate on the underlying assumptions, key limitations, and their potential impact on the interpretation of results in section 2.5.

"Limited by the lack of vertical profiles of thermal parameters in real-time, the gradients of θ_e are obtained from surface observations from AWSs in Beijing. Indeed, the core drivers of frontogenesis are dynamic processes, while the gradient of θ_e mainly acts as a scaling coefficient that modulates the efficiency of these dynamic contributions. This simplification of assuming this "efficiency coefficient" remains relatively homogeneous in the lower layer is available to capture regions of dynamically dominated frontogenesis. However, it must be acknowledged that surface observations may not adequately represent baroclinic structures aloft, especially in the presence of temperature inversion or strong vertical shear. Consequently, the diagnostic results are most applicable to near-surface environments and shallow frontogenesis. Future improvements would benefit from incorporating vertically resolved thermal variables obtained from operational high-frequency detection (e.g., microwave radiometers) for a more comprehensive assessment."

4. Line 286: Hiamwari -> Himawari.

Response: Corrected as suggested.

5. Why you choose the 95th percentile of 10-m wind speed in the triangle rather than the maximum value or another percentile?

Response: Good question! We chose the 95th percentile instead of the maximum value primarily due to considerations of statistical robustness and representativeness. The maximum value can be easily influenced by extreme outliers or observational noise, and may not consistently reflect the overall distribution of wind speeds within the region. In contrast, the 95th percentile effectively captures strong wind signals while remaining less sensitive to extreme outliers, providing a more reliable representation of high wind speeds in the triangular area.

6. Section 4.4: The link between IEC and gust intensity is intriguing. but needs more physical explanation.

Response: Per your suggestion, we deeply explored the link between IEC and the organization of convection associated with high winds. More physical explanation has been added in Section 4.4, which is shown as follows:

"As the well-sustained mesoscale convection created a favorable dynamic environment for the evolution of small-scale turbulent processes, the interaction between the organized squall system (and its embedded mesovortex and rear-inflow jet) and the ambient flow laid the foundation for the subsequent intensification of turbulent energy transfer, which is essential for the evolution of severe convective gust and related convective activities (Adler and Kalthoff, 2014; Dai et al., 2014; Dodson and Griswold, 2021; Su et al., 2023). Understanding mechanisms of the turbulent kinetic energy (TKE) transferring in the PBL between the surface and atmosphere is crucial for turbulence parameterization in numerical models, especially for extreme wind events (Powell et al., 2003; Monahan et al., 2015; Lyu et al., 2023).

In contrast to the Monin-Obukhov similarity theory that TKE transfers from larger to smaller eddies until it is dissipated at the smallest scales (Kolmogorov, 1941; Monin & Obukhov, 1954), many studies discovered the phenomenon of inverse energy cascades (IEC) in a totally different way (Kraichnan, 1967; Byrne and Zhang, 2013; Tang et al., 2015). Despite these advances in theoretical and numerical studies, observational support for IEC in the atmosphere remains insufficient (Shao et al., 2023a; 2023b). This study further examined the direction of the energy cascade associated with wind gusts using three-dimensional ultrasonic anemometers at seven heights, denoted as z_1 to z_7, on the meteorological tower in Beijing. According to Eq.(11), we can detect the occurrence of IEC at each height in every moment with a time resolution of 0.1 s.

The frequency of IEC during a period was evaluated as the ratio of the number of time-height grids identified as IEC to the total number of samples. In this way, we got height-resolved occurrence frequency of IEC for the study period in Fig. 9a. It is shown that IEC is a more prevalent phenomenon within the near-surface wind field. Notably, the frequency and intensity of IEC at all heights increased significantly when near-surface wind speeds exceeded 10 m s^{-1}. The frequency of IEC reaches up to 45% after 1436 LST, indicating that strong winds are contributed to IEC. The result in Figure 9b and c revealed that the power spectral density (PSD) was higher after 1436 LST in the lower-frequency area, especially for the u and v directions, which confirmed the activity of turbulent kinetic energy from smaller to larger eddies.

The observed surge in the frequency of IEC during the passage of convective outbreak suggests a temporary reorganization of turbulent energy transferring. These features are similar to those proposed by the observational analyses in two-dimensional turbulence (Shao et al., 2022; Zhou et al., 2025), which revealed that the formation of rapid rotation is a crucial driver of IEC. Strong horizontal shear generated by the gust front likely imposes a quasi-two-dimensional constraint on the flow, suppressing the three-dimensional vortex-stretching mechanism that normally drives a forward cascade. In this regime, enstrophy (the square of vorticity) may become partially conserved. Just as vigorously stirring the water in a very shallow pond causes small swirls to merge into a single, large vortex, a massive storm can be seen as the end product of an inverse cascade, where energy from small-scale convection organizes into a giant, coherent vortex. Another possible explanation is that the rapid increase in wind speed abruptly shifts the Reynolds number, possibly triggering transient instabilities that further promoted the generation of quasi-two-dimensional vortex (Browand and Winant, 1973). The amplification of large-scale eddies transfer momentum downstream more efficiently and enhance wind gusts as a form of positive feedback. In addition, the reduction of surface drag coefficient under robust weather systems impedes the dissipation of energy throughout the boundary layer, prolonging the duration of high winds (Raupach, 1994; Mahrt et al., 2003; Powell et al., 2003).

This event illustrates how synoptic-scale disturbances can locally override the classical theory of energy dissipation, leading to a measurable, height-dependent signature of IEC in the PBL. In turn, this shear-driven IEC likely played a catalytic role in consolidating the storm's low-level circulation, demonstrating how microscale turbulent processes can feedback on the mesoscale storm organization. These findings provided favorable evidence for the unique features of 2D turbulence in high wind conditions. These findings have implications for turbulence parameterizations in numerical weather prediction and climate models. Future research should further investigate the mechanisms driving the formation of IEC in more detail and explore the potential link between IEC and different meteorological phenomena."

7. The use of "jet" should be more cautious. According to the definition, wind speed should be greater than a certain threshold to be called a "jet".

Response: We agree that the term "jet" typically implies a wind speed exceeding a certain threshold, which varies across studies and contexts (e.g., midlatitude vs. tropical systems,

boundary layer jets vs. upper-level jets). By comparison, the threshold for the rear-inflow jet has not been clearly defined. It emphasizes more on a concentrated, relatively high-velocity channel of airflow within the wind field, whose speed is significantly stronger than the surrounding environment. As shown in Fig 7a, the rear-inflow region indeed features a localized, sustained core of wind speed maximum exceeding the environmental flow by 20 m s^{-1}. Therefore, we retain using jet here.

8. Ensure all cited references are included and formatted in accordance with ACP guidelines.

Response: Per your suggestions, all cited references are included and have been formatted to make sure their formats totally align with ACP guidelines.