Responses to Reviewers' Comments

We sincerely appreciate the time and effort devoted by the reviewers and editor. Again, we thank the reviewers for these constructive and professional comments. Our point-to-point responses can be found below. The reviewer comments/suggestions are in *italic* font, and our responses are underlined and in blue. The file name "Manuscript with marked changes" is abbreviated as "mms".

Referee #1 Evaluations:

Comment to "Physical Interpretation and Implications of Convective Impulses in Thunderstorms Based on Lightning and Polarimetric Radar Observations"

Using polarimetric radar and lightning observations, along with the model simulations, this study investigates the potential physical mechanisms that result in the convective impulses in thunderstorms – the breakup of large raindrops and the released energy from frozen small size raindrops. In principle, the results are interesting and worthy for publication, with following revision comments.

Even though I like the proposed mechanism that has been simply evaluated with model simulations, I still wonder the reliability or observational support for this hypothesis, solution of which could highly improve the value of this study. Of course, even without further study, this work is still worthy for publication.

Reply: We sincerely appreciate your evaluation and valuable revision comments. We have revised this manuscript according to your suggestions. To support this hypothesis in this study, we provide a severe thunderstorm case in different region and detected by other S-band dual-polarization radar. This severe thunderstorm occurred in Henan Province, China. The results from this case are only shown in the response letter; we are preparing for this paper.

The convective impulses (CIs) indicated by the Z_{DR}/K_{DP} columns and 50 dBZ echo top are shown in Figure R1. In this severe thunderstorm case, the 50 dBZ echo top exceeded the lapse-rate tropopause (~16 km) indicating the intense convection, allowing clear identification of Z_{DR}/K_{DP} columns and associated CI events. We also retrieved the microphysical fingerprints within this case. The temporal evolution of the grid volumes of these fingerprints and Z_{DR}/K_{DP} columns is shown in Figure R2. From an observational perspective, the results indicate that the raindrop breakup process is closely related to CI events and further support the presence of supercooled raindrops (indicating by Z_{DR}/K_{DP} columns) that revealed in this study, which is associated with the graupel formation and latent heat releasing; thus, enhancing convection.

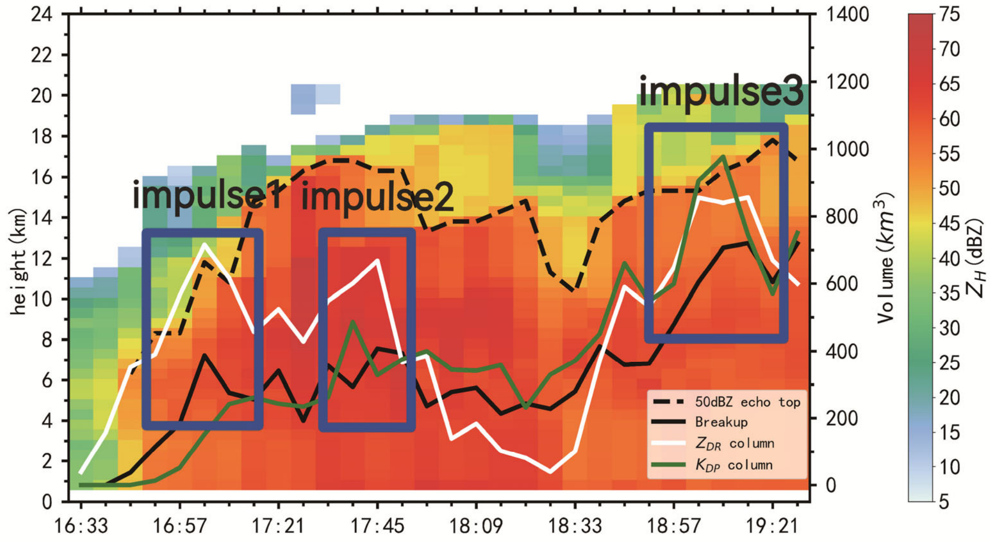

Figure R1. Evolution over time of the volumes occupied in Cartesian coordinates by the Z_{DR}/K_{DP} columns and by microphysical fingerprints in space. The white solid line indicates the volume of the Z_{DR} column, the green solid line represents the volume of the K_{DP} column, and the black solid line represents the volume of the breakup fingerprints. The shaded background shows the maximum Z_H at each altitude, and the black dashed line indicates the 50 dBZ echo-top height. Three impulses are marked.

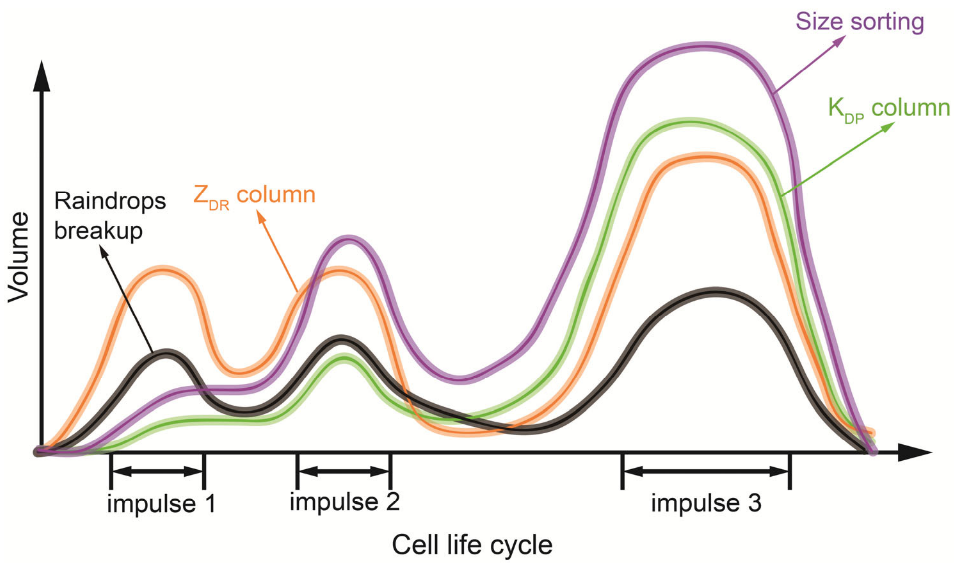

Figure R2. Conceptual model of the grid-volume evolution of microphysical fingerprints and Z_{DR}/K_{DP} columns.

Line 59-61, no need to use ";".
Reply: Corrected. Please see in mms (Lines 59−61).

Lines 59−61 in mms:

"Thunderstorms are intense convective clouds that play important roles in weather and climate, produce copious amounts of precipitation, lightning, and tornadoes, and affect cloud radiative forcing (MacGorman and Rust, 1998; Williams et al., 2005; Zhang et al., 2009)."

Line 74-78, Regarding the aerosol impacts, a study by Wang et al. (2018, doi: 10.5194/acp-18-12797-2018) could be referred.
Reply: We agree with your comment. This literature investigated the aerosol microphysical effect on convective activity, which is related to our paper. Now, we have referred to this paper. Please see in mms (Line 92).

Line 92-94, Why unlikely?
Reply: The original sentence was expressed improperly. We have rewritten it. Please see in mms (Lines 109−115).

Lines 109−115 in mms:

"The knowledge above essentially clarifies convection development in the real world, as the observational resolutions of CAPE, wind shear, and/or aerosol concentrations are not enough to reveal these relatively short-lived CI events in thunderstorms; thus, convective cloud development or behaviour characteristics during subsequent evolution are unclear, which explains why the CAPE and wind shear cannot be perfect proxies for thunderstorms (Liu N. et al., 2020)."

Line 125, "Figs."
Reply: Corrected.
Line 152, Why do the authors use linear interpolation?

Reply: The original description was improper expression. The radar data were bilinearly interpolated onto a Cartesian grid at a horizontal resolution of 250 m and a vertical resolution of 500 m from 0.5 to 20 km above the mean sea level.

We have revised this sentence. Please see in mms (Lines 181−184).

Lines 181−184 in mms:

"The quality-controlled radar data were bilinearly interpolated onto a Cartesian grid at a horizontal resolution of 250 m and a vertical resolution of 500 m from 0.5 to 20 km above the mean sea level (Zhang et al., 2017; Zhao et al., 2024a, b)."

Line 168-190, Uncertainties associated with these assumptions should be briefly introduced. Also, Is 0.31-0.36 mm bias small enough for this study?

Reply: Thank you for this important comment. We acknowledge that uncertainties are associated with the assumptions used in the raindrop size estimation, and that the reported bias (0.31–0.36 mm) reflects these limitations. Such uncertainties are common in radar-based microphysical retrievals.

We focus on the relative variations and temporal evolution of the mean drop size, which are more robust to systematic biases. Therefore, the reported bias is considered within an acceptable range for the purpose of this study and does not affect the interpretation of the results.

Furthermore, the inferred microphysical processes are not solely based on the drop size estimates. The results are consistently supported by independent polarimetric radar variables (e.g., Z_{DR} and Z_H), which provide well-established microphysical fingerprints. The agreement between the drop size variations and the polarimetric signatures offers mutual constraints and strengthens the robustness of our interpretation.

Therefore, although uncertainties exist, their impact is mitigated by the focus on relative changes and by the consistency across multiple independent observational indicators.

We have added a brief discussion of this topic. Please see in mms (Lines 274−279).

Lines 274−279 in mms:

"Notably, uncertainties are inherent in the radar-based estimation (e.g., D_m, N_t, and ice and rain water contents). However, our analysis focuses on the relative variations and comparisons rather than their absolute values, which are less sensitive to such systematic errors. Moreover, the interpretation of microphysical processes is jointly supported by multiple polarimetric radar variables and retrieved parameters, providing independent constraints. Therefore, the impact of these uncertainties on the main conclusions is limited."

Line 247, Is this local time or Beijing time?

Reply: Beijing time. Corrected.

Line 315-316, Why cannot the small secondary ice crystals grow into graupel size particles within a few minutes? (can grow into more than 10 um within 1 minute and then collision-coalescence processes or Bergeron process)

Reply: Thank you for this insightful comment. Here, we provide an order-of-magnitude estimate of the time required for a 10 μm ice crystal to grow into a 1 mm graupel particle under realistic mixed-phase convective cloud conditions. We assume a temperature of −10°C, supercooled liquid water content (*LWC*) of 1 g m^{-3}, collection efficiency $E = 0.8$, and bulk graupel density (ρ_g) of 400 kg m^{-3}.

For a graupel particle with diameter 1 mm (radius 5×10^{-4} m), the particle mass is:

$$m = \frac{4}{3}\pi r^3 \rho_g \approx 2.1 \times 10^{-7}\ kg$$

The riming growth rate is estimated as:

$$\frac{dm}{dt} = E\pi r^2 V_t LWC$$

Using a typical terminal velocity (V_t) of 1 m s^{-1} for a 1 mm graupel particle gives:

$$\frac{dm}{dt} \approx 0.8\pi(5 \times 10^{-4})^2(1)(10^{-3}) \approx 6.3 \times 10^{-10}\ kg\ s^{-1}$$

Thus, the characteristic timescale for the final riming growth stage to reach 1 mm is:

$$t = \frac{m}{dm/dt} = \frac{2.1 \times 10^{-7}}{6.3 \times 10^{-10}} \approx 333\ s \approx 5.5\ min$$

Importantly, this estimate applies only once the particle has already grown large enough for efficient droplet collection. The earlier stage, from 10 μm ice crystal to ~0.1–

0.3 mm ice particle, is slower and mainly controlled by vapor deposition and aggregation, typically requiring 5–20 min in strong updrafts.

Therefore, the total time for a 10 μm ice crystal to develop into a 1 mm graupel particle is approximately 10–30 min in vigorous convective clouds, with the early growth dominated by diffusional processes and the later rapid growth dominated by riming. This timescale is consistent with classical cloud microphysics (Pruppacher and Klett, 1997; Rogers and Yau, 1989) and recent convective simulations (Vongpaseut and Barthe, 2025).

We have revised this sentence for clarify. Please see in mms (Lines 423−433).

Lines 423−433 in mms:

“While the mechanism through which secondary ice production occurs increases the number concentration of ice crystals, the total time for a 10 μm ice crystal to develop into a 1 mm graupel particle is approximately 10–30 min in vigorous convective clouds, with the early growth dominated by diffusional processes and the later rapid growth dominated by riming (Pruppacher and Klett, 1997; Rogers and Yau, 1989; Vongpaseut and Barthe, 2025). Thus, we consider it challenging for these secondary ice crystals (typically on the order of micrometres) to grow to graupel-sized particles (typically on the order of millimetres) within a few minutes (~ 6 min). In light of the previous hypothesis and observations, we suggest that the raindrops freeze into graupel particles may dominate the graupel formation during the initial phase of warm-based thunderstorms.”