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 #2 Evaluations:

The authors investigate the physical mechanism driving convective impulses (CI) in thunderstorms using polarimetric radar and lightning observations. They found that higher supercooled liquid water and graupel content occur prior to the CI, and raindrop breakup is associated with an increase in supercooled raindrops. These smaller droplets freeze into graupel-like particles, releasing latent heat, which may enhance the CI. However, before the publication of this manuscript, the concerns below need to be addressed.

Reply: We sincerely appreciate your evaluation and insightful comments, which have helped us improve this manuscript. We have revised the manuscript according to your suggestions, and the details are provided below.

Line 61-63: Although information about the occurrence of CI is given but it is not clearly defined what is CI.

Reply: Thank you for this comment. We have added more information about the CI definition in Section 1. Please see in mms (Lines 67−76). And the CI definition in this study is shown in Section 3.2. Please see in mms (Lines 343−347).

Lines 67−76 in mms:

"CI is a complex definition in meteorology because of the ambiguous definition of convective intensity. As Zipser et al. (2006) discussed, updraft magnitude, lightning flash rate, and hailstone size, with or without a tornado, were utilized to implicitly equate the convective intensity, whose parameters were selected on the basis of the intent of the researcher. The local maxima of vertical wind velocity or the upwards extension of a high-reflectivity zone were previously used to define updraft impulses or CI via radar observations (Foote and Frank, 1983; Schmid et al., 1999). Such updraft impulse behaviour is also closely linked to cloud microphysical processes. For example, enhanced condensation, freezing, and graupel formation can release latent heat and further accelerate vertical motion, reinforcing short-term updraft intensification (Carey et al., 2019) and associated with lightning activity (Bruning et al., 2024; Zhao et al., 2025)."

Lines 343−347 in mms:

"The convective intensity indicated by the lightning frequency, echo-top height of 50 dBZ, and maximum Z_H value clearly displays short-term impulses (Fig. 4a, b, c, and d). We utilized the variation in the lightning frequency to define the duration times of the convective impulse (CI) and pre-CI. There are two CI events and two corresponding pre-CI events in each thunderstorm (Fig. 4e, f). The overlapping time between the pre-CI and CI indicates CI initiation, and vice versa."

Line 159: Is there any reason using the ERA Interim data instead of newer ERA-5, also is this data spatially interpolated to 0.175º×0.175º? Because as per Dee et al., 2011, the ERA Interim has T159 horizontal resolution which corresponds to a Gaussian lon/lat 0.75° × 0.75°. Also is there any validation conducted for this data? And why 6 hourly and not 1 /2 hourly data used

Reply: Thank you for this important comment. We revised this section, and the newer ERA5 data were introduced to replace the older ERA-Interim data. The environmental temperature, relative humidity, CAPE, and CIN provided by sounding data, which were obtained from the Qingyuan meteorological observatory (as marked by dark blue diamonds in Fig. 1), were regarded as the true observations for comparison with the ERA5 reanalysis data. Comparisons of the CAPE, relative humidity, and wind shear for the preconvective hour (the nearest hour prior to the first echo) in both cases A and B were performed. In addition, hourly ERA5 reanalysis data, with a 0.25°×0.25° horizontal resolution (Bell et al., 2020), were regridded to 0.1°×0.1° via linear interpolation to better match the scale of thunderstorms in this study. Please see in mms (Lines 185−218).

Lines 185−218 in mms:

"**2.3. ERA5 data and environmental observations**

Hourly ERA5 reanalysis data, with a 0.25°×0.25° horizontal resolution (Bell et al., 2020), were regridded to 0.1°×0.1° via linear interpolation to better match the scale of thunderstorms in this study. The environmental temperature and relative humidity provided by the sounding data, which were obtained from the Qingyuan meteorological observatory (as marked by the dark blue diamonds in Fig. 1), were regarded as the true observations for comparison with the ERA5 reanalysis data. Because case A occurred at 17:18 on 20 June 2016 (Beijing time hereafter) and case B occurred at 11:48 on 13 June 2016, we selected the adjacent sounding moment as the reference time for comparison, namely, 20:00 and 08:00, respectively. Comparisons of the temperature and relative humidity between the sounding and ERA5 data from 1000 hPa to 400 hPa at the same spatial–temporal position revealed that the average difference in temperature was approximately 0.6°C and that the mean difference in relative humidity was approximately 7% (Fig. 2). In addition, the difference in CAPE between the sounding and ERA5 data is approximately −246 J kg^{-1}, and the difference in convective inhibition is −171 J kg^{-1}. The hourly observed particulate matter ($PM_{2.5}$) mass concentration data were provided by the Ministry of Ecology and Environment of the People's Republic of China (Wang and Zhang, 2020), and three ground sites for aerosol concentrations within the analysed area were used, as marked by the dark blue dots in Fig. 1.

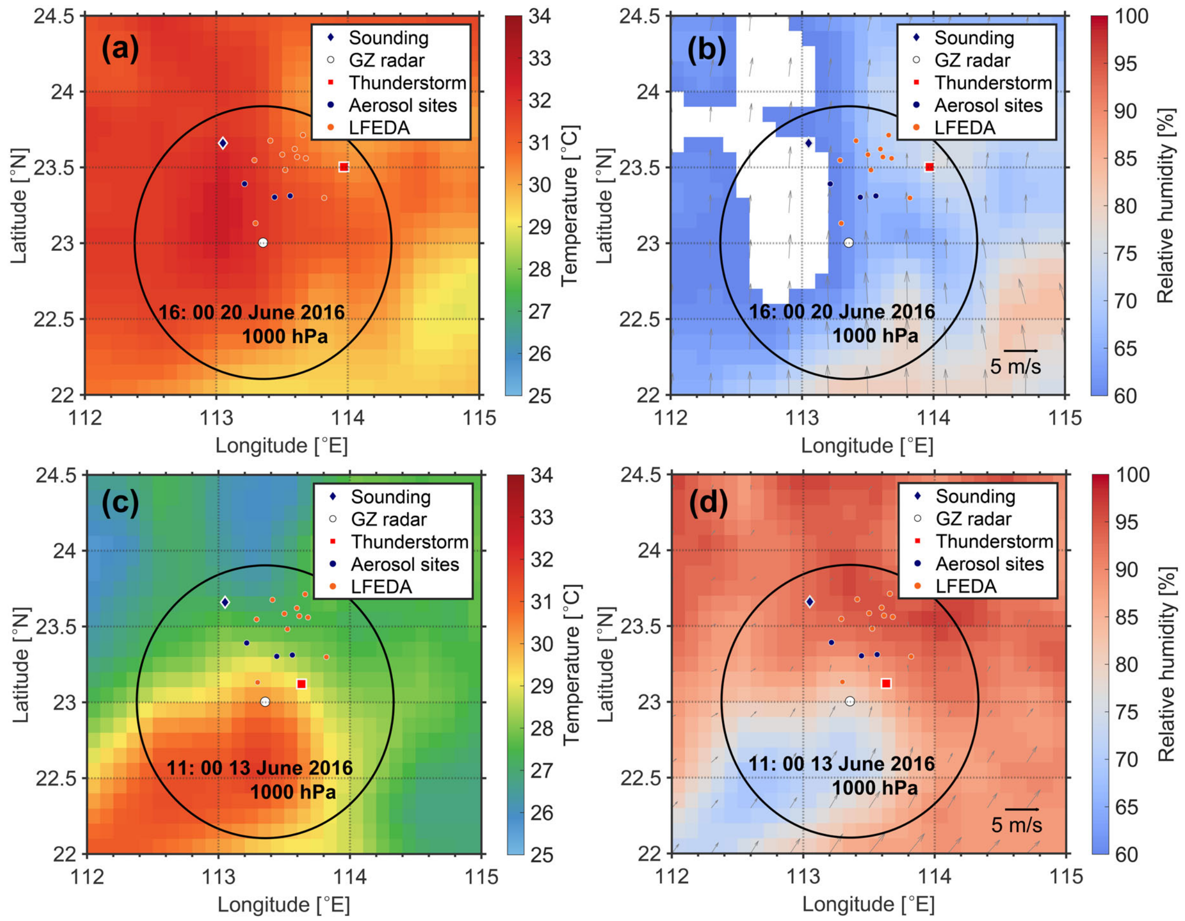

Figure 1. Distribution of observational systems and weather backgrounds derived from ERA5. The conditions of the temperature (**a**, **b**) and relative humidity overlaid horizontal wind field

(**c**, **d**) were derived from hourly ERA5 reanalysis data at 1000 hPa, prior to the occurrence of these two thunderstorms (case A occurred at 17:18 on 20 June 2016; case B occurred at 11:48 on 13 June 2016, Beijing time). The upper row indicates case A, and the bottom row indicates case B. The dark blue diamond indicates the Qingyuan meteorological observatory, and the three dark blue dots represent aerosol sites. The white circle indicates the GZ radar, and the 10 orange dots represent the LFEDA network. In addition, the red square indicates the location of the maximum reflectivity of thunderstorm, which occurred at the first identified moment by the GZ radar.

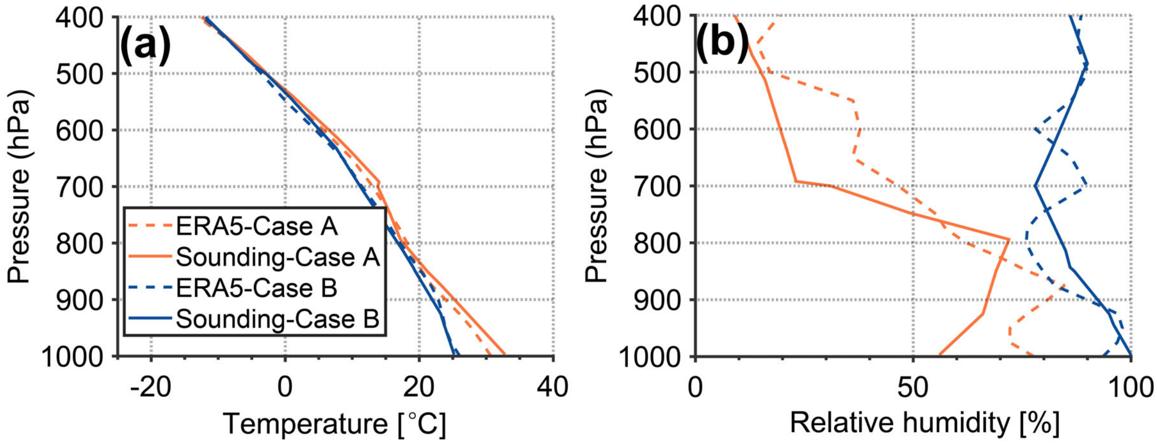

Figure 2. Comparison between sounding and ERA5 data. (**a**) Temperature versus pressure. (**b**) Relative humidity versus pressure. The orange line indicates case A at 20:00 on 20 June 2016 and the blue line indicates case B at 08:00 on 13 June 2016. The solid line represents the observations from the sounding, and the dashed line represents the ERA5 data."

1. *Line 199-200 Does 6 hourly average wind shear and humidity conditions represent the actual pre-convective environment? As the wind shear may have been different near the initiation hour. It would be beneficial to compare the wind-shear for pre-convective hour (nearest 1 or 2 hour prior to first echo) in both A and B cases.*

Reply: Yes, we agree with your opinion that the data from the last hour before the occurrence of these two thunderstorms (case A and case B) may be beneficial for comparisons of the environmental conditions. We have revised the related content as you suggested. The relative humidity and wind shear conditions from the hour before the occurrence of these two thunderstorms (case A and case B), derived from the hourly ERA5 reanalysis data are shown in Figure 3. Please see in mms (Lines 282−301).

Lines 282−301 in mms:

"The data from the last hour before the occurrence of these two thunderstorms (case A and case B), derived from hourly ERA5 reanalysis data and hourly averaged concentration observations of particulate matter ($PM_{2.5}$) from three ground sites show lower CAPE and $PM_{2.5}$ concentrations in case A (2669 J kg^{-1} and 23 μg m^{-3}) and higher CAPE and $PM_{2.5}$ concentrations in case B (4076 J kg^{-1} and 47 μg m^{-3}, respectively). The $PM_{2.5}$ concentrations suggest that the environments prior to the presence of these two thunderstorms were clean, especially for case A. The conditions of relative humidity and wind shear derived from the hourly ERA5 reanalysis data indicate more vapour and stronger low-level wind shear (i.e., the variation in the wind speed between 1000 and 850 hPa) in case B than in case A (Fig. 3a, b). These environments suggest that the conditions are more favourable for thunderstorm development in case B than in case A.

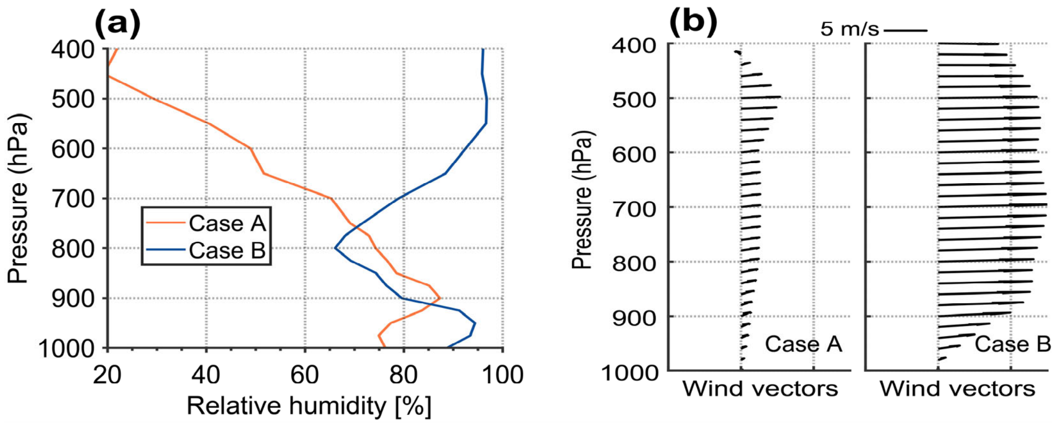

Figure 3. The environmental characteristics of the two thunderstorms. The conditions of relative humidity and wind shear from the last hour before the occurrence of these two thunderstorms (case A occurred at 16:00 on 20 June 2016; case B occurred at 11:00 on 13 June 2016) were derived from hourly ERA5 reanalysis data. (**a**) Relative humidity; the orange line indicates case A, and the blue line indicates case B. (**b**) Vertical wind vectors; the left column represents case A, and the right column represents case B."

2. *Line 199: When it is called wind shear, what type of wind shear exactly is or between what levels(or heights) such as low/high level shear ,*

Reply: Thank you for your helpful comment. In this study, "wind shear" refers to vertical wind shear in the lower troposphere, defined specifically as the variation in the wind speed between 1000 hPa and 850 hPa. We agree that the original description was not sufficiently clear. Therefore, we have revised the manuscript to explicitly specify "low-level vertical wind shear (1000–850 hPa)" to avoid ambiguity. Please see in mms (Lines 292−293).

Lines 292−293 in mms:

"…indicate more vapour and stronger low-level wind shear (i.e., the variation in the wind speed between 1000 and 850 hPa) in case B than in case A (Fig. 3a, b)."

Line 165-166: Although many studies are cited about the "fingerprint" of microphysical process, more details need to be added specifically about how it is done in the context of this study.

Reply: We have revised the manuscript to clarify how "fingerprint" is performed in this study, as you suggested. Please see in mms (Lines 237−247).

Lines 237−247 in mms:

"The classified fingerprint of cloud microphysical processes was based on dual-polarization radar observations. Vertical changes in polarimetric variables towards the surface (e.g., Z_H or Z_{DR}) can clearly discriminate different microphysical processes (Kumjian et al., 2022). Kumjian and Prat (2014) utilized a one-dimensional bin-microphysical rain shaft model and S-band polarimetric radar observations to display the distinctive signatures related to coalescence, breakup, size sorting/evaporation, and balanced breakup and coalescence processes within specific areas of the Z_H–Z_{DR} space. In this study, we used the changes in Z_{DR} and Z_H from heights of 0.5-km to 3.5-km to determine the warm-rain microphysical processes. Moreover, the mass-weighted mean drop diameter (D_m, mm) was retrieved from the Z_H and Z_{DR} to support these fingerprints. The D_m retrieval method followed Tokay et al. (2020) and the absolute bias of D_m ranged from 0.31–0.36 mm in their study."

Line 178-179: Isn't the standard error of 1dB between ZDP AND ZH relationship related to the specific study region (Tiwi island) and not the current study?

Reply: Yes. The standard error of approximately 1 dB reported by Carey and Rutledge (2000) is derived from observations over the Tiwi Islands and may be region-dependent. In this study, we cited this value primarily as a reference magnitude rather than implying its universal applicability. To avoid potential misunderstanding, we have revised this sentence. Please see in mms (Lines 258−260).

Lines 258−260 in mms:

"The standard error for the relationship between the horizontal reflectivity and Z_{DP} has been reported to be approximately 1 dB in previous studies (e.g., Carey and Rutledge, 2000)."

Line 185-187: Although it is noted that the radar retrieval techniques were valid in stratiform region and Z<30 dBZ, How the ice and graupel above melting level estimated

Reply: We would like to clarify that the limitation of applying the radar retrieval technique in stratiform regions with a $Z_H \leq 30$ dBZ is specifically associated with the estimation of the ice crystal number concentration (N_t), following Hu and Ryzhkov (2022). In our study, this constraint is applied only when ice N_t is retrieved. For the ice mass (e.g., ice and graupel content above the melting layer), we do not estimate their number concentrations. Instead, we follow the method of Carey and Rutledge (2000) to estimate their ice water content. Therefore, the aforementioned reflectivity threshold does not apply to the estimation of ice and graupel above the melting layer in our analysis. We have revised the manuscript to clarify this distinction. Please see in mms (Lines 268−270).

Lines 268−270 in mms:

"Notably, the reflectivity constraint ($Z_H \leq 30$ dBZ) is applied only to the retrieval of ice N_t and does not affect the estimation of the ice or graupel content above the melting layer."

Line 201: Actually both environments are favorable for thunderstorms. Maybe using wording as "more favorable than A" will be more appropriate.

Reply: We agree that both environments are favourable for thunderstorm development. The sentence has been revised to "These environments suggest that the conditions are more favourable for thunderstorm development in case B than in case A." to improve clarity and accuracy. Please see in mms (Lines 294−295).

Line: 239 It is mentioned that the thunderstorm is rapidly collapsed in A and slowly dissipated in B. But looking at figure S1. Case A is purely isolated and well separated(no merging with other cells) whereas in S2, It is clear that the track of cell is not properly taken into account for example at 1242 the composite Z is reduced and at the next step of 1248 the Z again started to increase, again similar pattern at 1318 which suggest that this cell is regenerating (it is a newer updraft), and also signatures of two cells merging together can be observed. So how can we say this cell as an *isolated? This answers why Cell B is long lived, Best option would be to create a similar time series of RHI scans to separate the target cell.*

Reply: Thank you for the detailed comments. We agree that the evolution of Cell B is more complex than initially described.

We have revised the manuscript to clarify that Cell B is not strictly isolated and may involve cell merging and splitting processes, as suggested by the reviewer. The description has been updated throughout the text to more accurately reflect its structural evolution. Please see in mms (Lines 134−144).

We would like to emphasize that, although Cell B exhibits signs of regeneration and possible cell interactions, these processes do not affect the main results and conclusions of this study, which are based on overall environmental and microphysical characteristics.

Following the reviewer's suggestion, we have added a time series of RHI scans at the relevant times in the Supplementary Information (Figure S3) to better illustrate the vertical structure and to help distinguish the target cell from neighbouring convection.

These additions and revisions have improved the clarity and robustness of the analysis.

Lines 134−144 in mms:

"We selected two special thunderstorms that occurred during the warm season over South China, as detected by a three-dimensional lightning location system and an S-band dual-polarization radar. One thunderstorm cell was a near-stationary thunderstorm with high CAPE, weak wind shear, and a clean environment; this thunderstorm remained isolated throughout its life cycle, was referred to as case A, and occurred on 20 June 2016 (the initiation location of case A was marked as red squares in Fig. 1a, b). The other thunderstorm was a moving thunderstorm with significant CAPE, strong wind shear, and a clean environment; this thunderstorm remained isolated during the early stage of its life cycle, but later experienced partial merging and splitting; this case was referred to as case B and occurred on 13 June 2016 (the initiation location of case B was marked as red squares in Fig. 1c, d)."

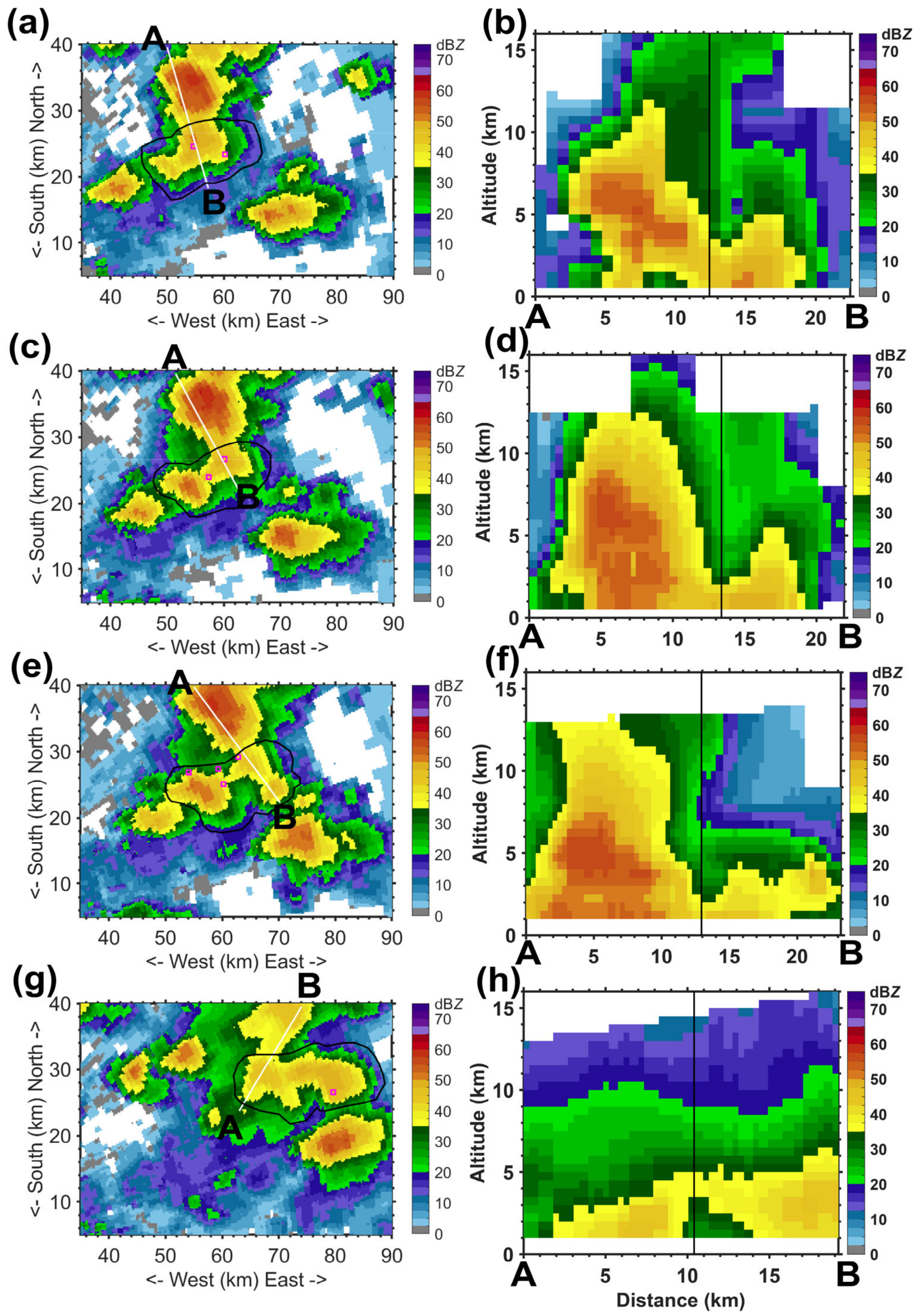

Figure S3. Composite reflectivity and cross sections of case B at 12:42 (a) and (b), 12:48 (c) and (d), 12:54 (e) and (f), and 13:12 (g) and (h). The left column represents the composite reflectivity and the right column is for cross sections. The white lines in the left column represent the cross-section lines. Text A and B mark the ends of the cross-section line. The black line in the right column indicates the boundary site. The pink square indicates the first source location of one lightning flash in the left column.

Line 315-316, What is the proof for the statement "we do not agree that these secondary ice crystals grow into graupel sized particles within a few minutes". Even a very small time (a minute) is very significant in growth of hydrometeors in convection.

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."

The details about model configuration such as initiation mechanism, grid spacing, domain size, input sounding, aerosol conditions, etc. need to be included.

Reply: We sincerely appreciate your helpful comment. In response to your suggestion, we have added the details of the model configuration in Section 2.4. We hope these additions improve the clarity and completeness of the manuscript. Please see in mms (Lines 219−228).

Lines 219−228 in mms:

"**2.4. Numerical model configuration**

The Weather Research and Forecasting (WRF) model was utilized in this study. The simulation scheme was an ideal simulation for the squall line (squall2d_x), while the Morrison two-moment scheme (Morrison et al., 2009) was used instead of the original Kessler microphysics scheme. To investigate the effects of raindrop breakup on the number concentration of graupel and on the convective intensity (updraft velocity) within clouds, the parameterization of raindrop breakup follows that of Verlinde and Cotton (1993). The domain size is 50 km × 50 km in the horizontal direction with the model lid at 20 km. The horizontal and vertical grid spacings are approximately 250 m. Convective is initiated by inserting a warm bubble, assuming thermal perturbation to kick off convection. The sounding data for the simulation are shown in the *supporting information*."

Line 340-341: Is there any study supporting this statement "the weaker environmental wind shear and CAPE promote raindrop breakup"?

Reply: We agree that there is no direct evidence linking weaker environmental wind shear and CAPE to enhanced raindrop breakup. Raindrop breakup is primarily controlled by microphysical processes such as collision-induced breakup and aerodynamic instability, and its relationship with environmental conditions is complex. Previous studies have shown that the interaction between breakup processes and environmental wind shear is highly nonlinear and depends on storm dynamics (e.g., Morrison et al., 2012).

Therefore, in the revised manuscript, we have modified the statement to avoid implying a direct causal relationship. Instead, we now describe that wind shear and CAPE may influence storm dynamics and microphysical processes, which could indirectly affect raindrop breakup. Please see in mms (Lines 466−468).

Lines 466−468 in mms:

"Therefore, compared with case B, the relatively weaker environmental low-level wind shear and CAPE in case A may influence the storm dynamics and microphysical processes, which could indirectly favour raindrop breakup (e.g., Morrison et al., 2012)"