

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 (Eric Bruning):

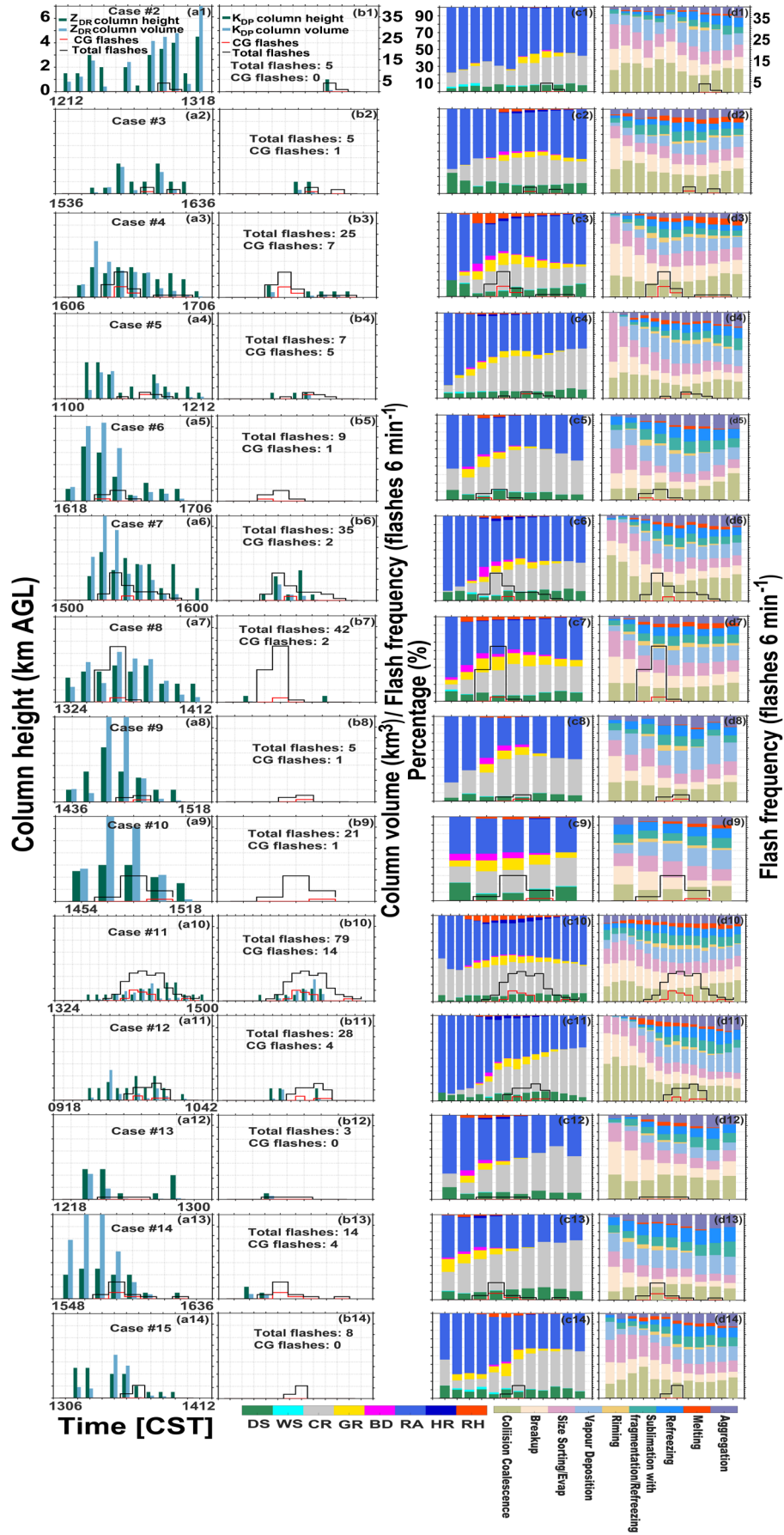
I thank the authors for their thorough revisions to this study, which have greatly improved the manuscript. The expansion from one to fourteen cases is accompanied by a thoroughly updated discussion of physical reasoning. The new manuscript makes quite clear the primary sequence of processes during development of thunderstorms to the lightning-producing stage. The authors show consistency across the cases, and the results are now much more significant, and an excellent contribution to the literature.

Below I provide a few minor technical corrections for final revisions.

Figs. 10-11 are quite pixelated, even after zooming in, and the fonts are too small for publication. The data in the plots are readable when zoomed out, so it might be as simple as labeling more efficiently, with just a few axis values and greater sharing of common axis labels and legends, though other reorganization might also be possible. The volume fraction time series are a very nice way of showing the evolution of each storm, and comparing many of these on the same page allows for identification of shared patterns and variation from storm to storm.

[Reply: Corrected as suggested. Figures 10-11 have been combined into one figure, Figure 10.](#)

Point-to-point responses



[Figure 10. The variation in \$Z_{DR}\$ column height and volume with the life cycle of thunderstorms \(cases #2 to #15\) \(a1-a14\). The variation in the \$K_{DP}\$ column height and volume with the life cycle of thunderstorms \(cases #2 to #15\) \(b1-b14\). The dark green bars indicate the column heights, and the light blue bars indicate the column volumes. The texts display the number of total flashes and CG flashes in a thunderstorm. The variation in percentages of hydrometeor types with the life cycle of thunderstorms \(cases #2 to #15\) \(c1-c14\). The variation in percentages of microphysical fingerprints with the life cycle of thunderstorms \(cases #2 to #15\) \(d1-d14\). The black stair lines indicate the total flashes, and the red stair lines indicate the CG flashes. Hydrometeor types are abbreviated: 'DS' is dry aggregate snow, 'WS' is wet snow, 'CR' indicates crystals of various orientations, 'GR' is graupel, 'BD' is big drops, 'RA' indicates light and moderate rain, 'HR' is heavy rain, and 'RH' indicates a mixture of rain and hail.](#)

Caption to Fig. 12: "The lagged time is for flash frequency lags these eight radar-retrieved variables." From the caption and text, I think this could mean "positive lagged time means that an increase in the variable comes before the increase in lightning," and might be clearer.

[Reply: Corrected.](#)

Line 807: "obey theoretical cognition" might be better replaced with "consistent with [expectations from] theory". interpretation.

[Reply: Corrected.](#)

Referee #2 Evaluations:

The General Comments:

While previous studies have established the relationship between polarimetric variables and lightning, in this paper authors have suggested the potential application of ZDR and KDP columns identified using 3d mapping columns method to predict lightning activity. This study initially presents a detailed analysis of a single storm with multiple cross sections of polarimetric and microphysical variables. Additionally, it includes timeseries and cross-correlation analysis of lightning frequency, ZDR and KDP columns, radar-derived hydrometeor variables and microphysical processes of 14 additional storms in a variety of CAPE environments ranging from 400 to up to 2500 J Kg⁻¹. This revised manuscript has addressed all previous comments, but there is still substantial room for improvement in the revised content. The recommendation is to reconsider this manuscript after the authors address the following concerns.

Specific comments:

1 Section 2.1 needs a brief comment on how storm cases were selected. Were there only 15 isolated lightning producing storms in two months period (between 29 May 2016 to 27 July 2016) in the GZ radar and LFEDA domain? This explanation is important to justify the authors' claim, 'lightning is not observed in the absence of a ZDR column and a KDP column is not observed without ZDR column' (line 594-595). Since this statement may not be universally true given the analysis of limited number of storms, the claim, needs to be rephrased to include additional factual words such as limited number, isolated and over South China and can also potentially be combined with lines 597-599.

Reply: [Thank you for your suggestions and constructive comments. Yes, we agree that a brief comment on how storm cases were selected should be stated in Section 2.1.](#)

[These fifteen isolated thunderstorms were selected in accordance with the rules of Zhao et al. \(2021, 2022\), and the initiation of such thunderstorms was defined as the first radar volume scan in cases where the composite reflectivity was \$\geq 5\$ dBZ and the locations of the thunderstorms were within the effective range of the radar and lightning array. When the maximum reflectivity of this cell starts to fade with a value of less than 30 dBZ later, the evolutionary process of a cell is marked as the end. Moreover, we required the subsequent lightning activity to be present after the first lightning occurrence in this study. Under this selection method, there were only 15 isolated thunderstorms in an approximately two-month period \(between 29 May 2016 and 27 July 2016\) in the GZ radar and LFEDA domains. Please see in mms \(Lines 179–185\).](#)

[The sentence "lightning is not observed in the absence of a \$Z_{DR}\$ column, and a \$K_{DP}\$ column is not observed without a \$Z_{DR}\$ column" has been rephrased to include additional factual words. Please see in mms \(Lines 559–562\).](#)

Lines 179–185 in mms:

["These isolated thunderstorms were selected in accordance with the rules in Zhao et al. \(2021, 2022\). The initiation of such thunderstorms was defined as the first radar volume scan in cases where the composite reflectivity was \$\geq 5\$ dBZ and the locations of thunderstorms were within the effective range of the radar and lightning array. When the maximum reflectivity of this cell starts to fade with a value of less than 30 dBZ later, the evolutionary process of a cell is marked as the end. Moreover, we required the subsequent lightning activity to be present after the first lightning occurrence in this study."](#)

Lines 559–562 in mms:

“The results of our study, from 15 isolated thunderstorms over South China, indicate that lightning is not observed in the absence of a Z_{DR} column, and that a K_{DP} column is not observed without a Z_{DR} column, which are consistent with the observations of Bruning et al. (2024).”

2 Line 451-508: The discussion of the case study using Figure 7 needs more clarity. Following comments are presented in the context of Figure 7.

Line 458-460: Was the overlapping of ZDR column with reflectivity core persistent between 17:48 CST and 17:54 CST? If yes, it would be beneficial to include 17:54 CST in Figure 7 to explain ZDR column structure prior to initiation of lightning.

Reply: Figure R1 shows the Z_{DR} column structures from 17:24 CST to 18:06 CST, including the Z_{DR} column structures at 17:48 CST and 17:54 CST. During the early stage, the Z_{DR} column and reflectivity core (≥ 20 dBZ) overlap well (Figure R1 a-b). Then, the Z_{DR} column and reflectivity core begin to separate at 17:48 CST and 17:54 CST (Figure R1 c-d). At 18:00 CST and 18:06 CST, the Z_{DR} column and reflectivity core (≥ 40 dBZ) are almost separated (Figure R1 e-f).

Yes, we agree with your suggestion; the polarimetric structure at 17:54 CST has been added to Figure 7. Please see in mms (Lines 435–441).

Lines 435–441 in mms:

“Figure 7 a1-e1 shows the polarimetric structure prior to the initiation of lightning. The Z_{DR} column and reflectivity core (≥ 25 dBZ) begin to separate, having previously been overlapping during the initial development stage of the thunderstorm (Figure 4a, b). Riming and graupel are present; specifically, the locations of graupel particles are associated with low Z_{DR} values. At 18:00 CST (Figure 7 a2-e2), the lightning activity begins, and the locations of the flash sources are high and correspond mainly to graupel particles. Riming occurrence surrounds the flash sources. The Z_{DR} column and reflectivity core (≥ 40 dBZ) are almost separated.”

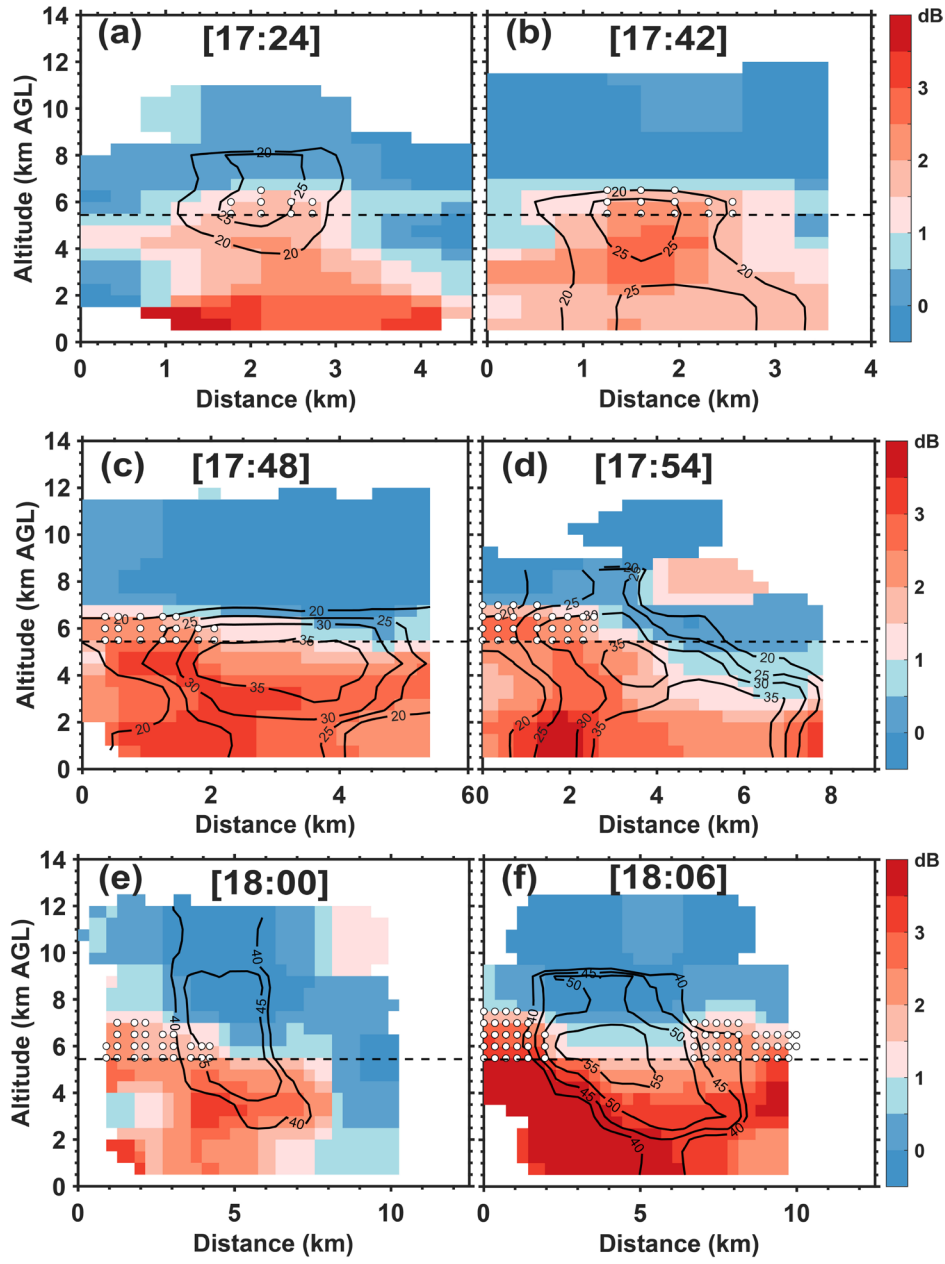


Figure R1. Cross sections from the Cartesian grid of the studied isolated thunderstorm (case #1) at (a) 17:24 CST, Z_{DR} ; (b) 17:42 CST, Z_{DR} ; (c) 17:48 CST, Z_{DR} ; (d) 17:54 CST, Z_{DR} ; (e) 18:00 CST, Z_{DR} ; and (f) 18:06 CST, Z_{DR} . The black dashed line indicates the 0°C isotherm height. The white dots indicate the areas of the identified Z_{DR} columns. The black contours with values indicate the reflectivity structure. AGL (above ground level).

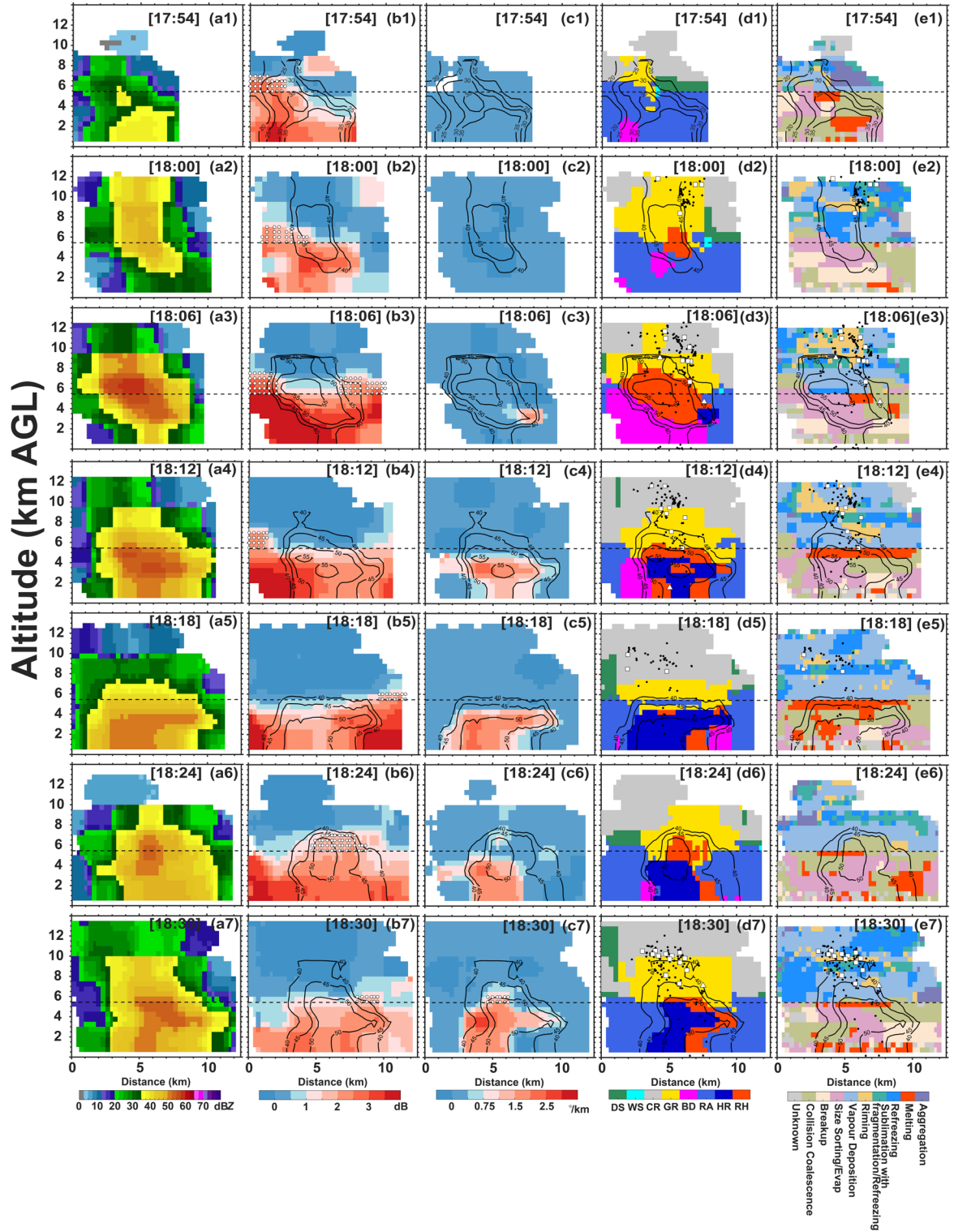


Figure 7. Cross sections of polarimetric radar variables (Z_H , Z_{DR} , and K_{DP}) and microphysics (hydrometeor types and microphysical fingerprints) from the Cartesian grid of the isolated thunderstorm (case #1). At 17:54 CST (a1-e1), 18:00 CST (a2-e2), 18:06 CST (a3-e3), 18:12 CST (a4-e4), 18:18 CST (a5-e5), 18:24 CST (a6-e6), and 18:30 CST (a7-e7). The black dashed

line indicates the 0°C isotherm height. The white dots indicate the areas of the identified Z_{DR}/K_{DP} columns. The black contours with values indicate the reflectivity structure. The black dots indicate the flash sources, the white square represents the first source of the intracloud flash, and the triangle represents the CG flash. Hydrometeor types are abbreviated, 'DS' is dry aggregate snow, 'WS' is wet snow, 'CR' indicates crystals of various orientations, 'GR' is graupel, 'BD' is big drops, 'RA' indicates light and moderate rain, 'HR' is heavy rain, and 'RH' indicates a mixture of rain and hail.

Line 460: The beginning of the riming process is not 'obvious' if we ignore Figure 7 e2 since both the ZDR [b2] and KDP [c2] values above melting level are quite low indicating rarity or absence of large supercooled raindrops. Based on the presence of riming process in both e1 and e2, it is possible that it was initiated before 18:00 CST.

Reply: Yes, we fully understand your concern; the word "obvious" may be inappropriate in here.

In a radar volume scan, the characteristics of the variables are dominated by large particles; for example, if graupel and supercooled raindrops coexist, the characteristics of the radar variable are dominated by graupel. In addition, as these supercooled raindrops begin to freeze and mix with water-coated graupel and hail, the corresponding Z_{DR} values decrease. That is, once graupel or hailstone particles form, the Z_{DR} column starts to collapse (as discussed in Kumjian et al., (2014)). Notably, the K_{DP} values are strongly related to the number concentration of supercooled raindrops or the significant water fraction covered by large ice particles (Snyder et al., 2017).

Thus, the locations of low Z_{DR} and K_{DP} values are likely riming (we can infer that from riming production, graupel particles).

The "obviously" has been replaced with "increased". Please see in mms (Line 443).

Line 443 in mms:

"Then, at 18:06 CST (Figure 7 a3-e3), riming has increased..."

Line 461-462: The increased reflectivity and its altitude are not sufficient to explain intensification of the updraft, especially with collapsed ZDR column. Although cold cloud processes may have increased, low ZDR [b2] and low KDP [c2] and hailstones [d2] in high reflectivity region above melting level together indicate that observed high reflectivity could be due to dry hailstones present in the examined volume. On the contrary, weakening of updraft and strengthening of downdraft may have occurred considering collapsed ZDR columns and heavy rain below freezing level after 18:06

CST until 18:24 CST. This further makes referring lightning peaks to the impulse in the conclusion (line 764-765) ambiguous as strengthening of updraft is questionable as discussed in this case.

Reply: We have carefully considered your comment and respect your professional suggestion. We have corrected this statement. Please see in mms (Lines 443–447).

Lines 443–447 in mms:

“Then, at 18:06 CST (Figure 7 a3-e3), riming has increased, the echoes strengthen (≥ 55 dBZ), and the heights of the strong echoes are lifted. The lightning activity reached the first peak, where the locations of the flash sources mainly corresponded to graupel and ice particles. This finding indicates that the convective strength is obviously increased and that the cold cloud processes are heavily.”

Line 490-491: Referring to panel b1, the ZDR column ‘partly’ overlaps with the reflectivity core.

Reply: Corrected. Please see in mms (Lines 476–478).

Lines 476–478 in mms:

“When the first impulse event initially develops, the Z_{DR} column is obvious and overlaps or partly overlaps with the reflectivity core (Figure 4a, b, and Figure 7 b1):”

Lines 496-498: Authors tried to justify the second impulse event with invigoration of updraft due to freezing of raindrops in mixed phase region. This hypothesis (also identified as mixed-phase invigoration or cold-phase invigoration) is widely criticized in the literature (Varble et al., 2023: <https://doi.org/10.5194/acp-23-13791-2023>) due to the relatively low magnitude of latent heat of fusion. The increased loading of updraft due to large hydrometeors compensate the marginal increase in updraft strength due to release of latent heat. So, observed changes in updraft strength in this case cannot be justified if it were due to natural intensification of storm due to meteorological factors or due to cold-phase invigoration.

Reply: Yes, we noticed the critical evaluation of the evidence for warm-phase invigoration or cold-phase invigoration (e.g., Grabowski and Morrison, 2020, 2021; Varble et al., 2023). We fully agree with your comment. This opinion has been corrected. Please see in mms (Lines 482–486).

Lines 482–486 in mms:

[“These raindrops could recirculate into the updrafts and be lifted to the mixed-phase region, forming the \$Z_{DR}\$ column first, and raindrops could transfer to abundant graupel and even hailstones, promoting convection, i.e., increasing lightning activity \(indicating the second impulse event\).”](#)

[Grabowski, W. W., H. Morrison, Do Ultrafine Cloud Condensation Nuclei Invigorate Deep Convection? *Journal of the Atmospheric Sciences* **77**, 2567–2583 \(2020\).](#)

[Grabowski, W. W., H. Morrison, Supersaturation, buoyancy, and deep convection dynamics. *Atmospheric Chemistry and Physics* **21**, 13997–14018 \(2021\).](#)

[Varble, A. C., A. L. Igel, H. Morrison, W. W. Grabowski, Z. J. Lebo, Opinion: A critical evaluation of the evidence for aerosol invigoration of deep convection. *Atmospheric Chemistry and Physics* **23**, 13791–13808 \(2023\).](#)

Line 504-506: Following argument for Lines 496-498, the presence of ZDR column within reflectivity core cannot be justified as indicator of imminent invigoration. For example, ZDR column was within reflectivity core at 17:24 CST [Figure 4a] but it disappeared at next scan at 17:30 CST [Figure 5a] which would not be expected from a strengthening updraft. A strengthening updraft should be able to support and perhaps deepen the ZDR column. Further, since ZDR column is where supercooled liquid drops and wet graupel are lifted above melting level and reflectivity core is where collision and fallout typically occur, ZDR column within reflectivity core can thus be an ideal indicator of active storm electrification and not invigoration.

[Reply: Yes. This opinion has been corrected according to your suggestion. Please see in mms \(Lines 491–493\).](#)

[Lines 491–493 in mms:](#)

[“Thus, the \$Z_{DR}\$ column within the reflectivity core is likely an indicator of imminent ice microphysics, and then, the formation of abundant graupel particles promotes lightning activity via noninductive charging.”](#)

3 How did authors determine the beginning and end of storm cloud lifecycle? Please classify if there is any reflectivity threshold considered to identify a particular radar scan time as the beginning and end of storm lifecycle. Objective identification of these points is important to justify the cross-correlation analysis results. As a suggestion, time series alignment can be well compared if matched with peak updraft strength or first lightning occurrence. Line 770: Figure 18 captions can be discussed in more detail.

Use the observed data to make cloud lifecycle more definitive by including discussion of formation, mature and dissipation phases.

Reply: [Thank you for your suggestions and constructive comments. We have added a brief comment on how storm cases are selected in Section 2.1.](#)

[These fifteen isolated thunderstorms were selected in accordance with the rules of Zhao et al. \(2021, 2022\). The initiation of such thunderstorms was defined as the first radar volume scan in cases where the composite reflectivity was \$\geq 5\$ dBZ and the locations of thunderstorms were within the effective range of the radar and lightning array. When the maximum reflectivity of this cell starts to fade with a value of less than 30 dBZ later, the evolutionary process of a cell is marked as the end. Moreover, we required the subsequent lightning activity to be present after the first lightning occurrence in this study. Please see in mms \(Lines 179–185\).](#)

[We have revised the caption for Figure 12 according to your suggestion. The formation and dissipation phases are determined. However, the mature phases of these isolated thunderstorms are not discussed in this study.](#)

[Please see in mms \(Lines 688–693\).](#)

Lines 179–185 in mms:

[“These isolated thunderstorms were selected in accordance with the rules in Zhao et al. \(2021, 2022\). The initiation of such thunderstorms was defined as the first radar volume scan in cases where the composite reflectivity was \$\geq 5\$ dBZ and the locations of thunderstorms were within the effective range of the radar and lightning array. When the maximum reflectivity of this cell starts to fade with a value of less than 30 dBZ later, the evolutionary process of a cell is marked as the end. Moreover, we required the subsequent lightning activity to be present after the first lightning occurrence in this study.”](#)

Lines 688–693 in mms:

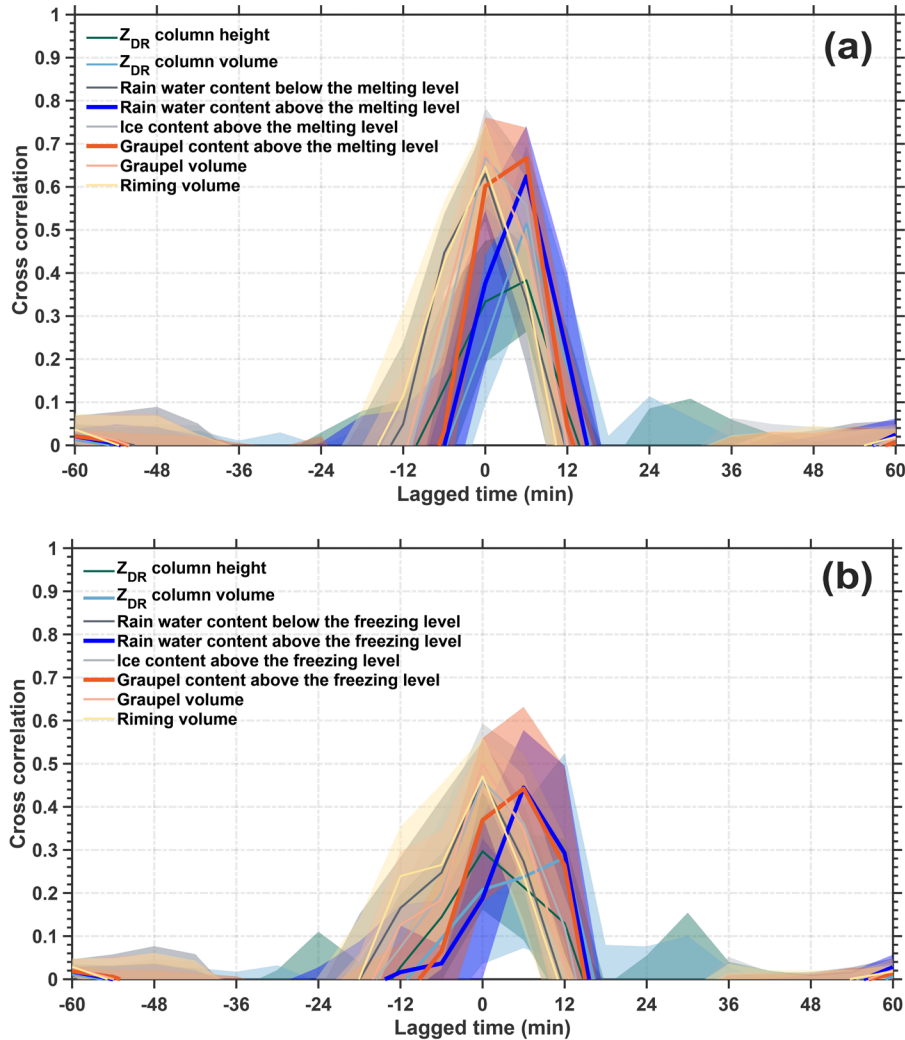
[“Figure 12. A conceptual model bridging the polarimetric structure and lightning activity. Cloud formation is defined as the first radar volume scan in cases where the composite reflectivity is \$\geq 5\$ dBZ. The end of the thunderstorm cloud lifecycle is defined as the radar volume scan in cases where the maximum reflectivity starts to fade with a value of less than 30 dBZ. The impulse events in terms of the convective strength correspond to be lightning activity peaks. The magnitude of the amplitudes among these curves has no practical meaning; it is merely for visualization purposes.”](#)

4 Is autocorrelation removed from each time series before cross-correlation as ZDR column height, graupel mass, and lightning flash rate etc. can show strong temporal autocorrelation during storm lifecycle. The cross-correlation without this type of correction may overestimate the strength of relationship.

[Reply:](#) In response to your comment, a related discussion on this issue has been added. Please see in mms (Lines 613–615).

[Lines 613–615 in mms:](#)

[“In addition, the autocorrelation of each variable in the time series would overestimate the strength of the relationship by approximately 0.15.”](#)



[Figure R2. Cross-correlations between flash frequency \(total flashes \(a\), CG flashes \(b\)\) and eight radar-retrieved variables \(\$Z_{DR}\$ column height/volume, rain water content below/above the melting level, ice content above the melting level, graupel content above the melting level, graupel volume, and riming volume\); the lines indicate the mean values and the shaded area](#)

indicates the 95% confidence interval. Positive lagged time means that an increase in the variable comes before the increase in lightning. The autocorrelation is removed from each time series before cross-correlation of each variable.

5 Line 595-597: Presence of both ZDR and KDP columns at same instance may not necessarily result in highest flash frequency. Although this statement is true for case #11, other cases (#1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14) also have both these columns co-present at multiple times but with only limited flash count. In case #8, the highest lightning frequency was observed in the absence of both ZDR and KDP columns. No lightning was observed when these two columns were co-present in this case. Therefore, authors can try to accommodate such exceptions in their language while stating any such observations.

Reply: Thank you for your comment and suggestion. We have corrected this statement. Please see in mms (Lines 563–566).

Lines 563–566 in mms:

“Moreover, although the highest lightning flash frequency (in case #11) is observed when the Z_{DR} and K_{DP} columns are copresent, the total flashes in cases (e.g., #6, #10, and #15) with only the Z_{DR} column are not lower than those in cases (e.g., #2, #3, and #5) where both Z_{DR} and K_{DP} columns are present.”

6 Line 771-773: Again, following earlier argument for lines 451-508, ZDR column within reflectivity core may not always indicate convective invigoration. At 17:24 CST [Fig 4a] and at 17:42 CST [Figure 4b] the ZDR column is within the reflectivity core, but it was not followed by imminent invigoration and onset/increase in lightning activity.

Reply: Corrected as suggestion. Please see in mms (Lines 694–697).

Lines 694–697 in mms:

“In our opinion (Figure 12), the Z_{DR} column within the reflectivity core is likely an indicator of increasing convective strength, after which the formation of abundant graupel particles promotes lightning activity via noninductive charging.”

7 Line 783-785: The statement “high temporal resolution observations of phased-array radar may decrease the uncertainty.” is too general. Please rephrase it to be more specific. Will shorter volume scan time increase the lead time of more than 6 minutes or decrease it? Also add at least one more sentence on why and how you think it will increase or decrease it. Radar volume sampling depends on scanning strategy

adopted, while it is good to comment on phased-array radar, there are still a lot of conventional dish radar out there which can benefit from this study. Therefore, a short explanation will be helpful.

[Reply: Corrected as suggestion. Please see in mms \(Lines 706–711\).](#)

[Lines 706–711 in mms:](#)

[“In addition, the 6-min or 12-min warning time in our results is likely due to the temporal resolution \(6 minutes\) of the radar data used in this study; the update time of a full volume scan of phased-array radar is approximately 1 min; thus, the high temporal resolution observations provided by phased-array radar may decrease the uncertainty resulting from the radar scanning strategy.”](#)

8 The conclusion and discussion section will need to be updated based on the comments above. Extrapolating conclusions to all storms in general terms introduces ambiguity and does not account for exceptions (refer to specific comments #5, #6, #7, #8). Therefore, only specific conclusions based on the analysis of 15 observed storms are encouraged. Similarly, discussion can be made more direct and clearer by mentioning specific microphysical or dynamical variables and processes considered in the study instead of referring to them with these general terms.

[Reply: Corrected as suggestion. Please see in mms \(Lines 623–734\).](#)

Technical Corrections:

1 Line 506, 779: Word Kdr should be KDP.

[Reply: Corrected.](#)

2 Line 767-768: This line should be a part of Figure 13 caption.

[Reply: Corrected.](#)

3 Figure 5: Mention case #1 either on figure or in caption and indicate total flashes and CG flashes similar to Figures 10, 11.

[Reply: Revised as suggestion.](#)

4 Figure 7 (d1-d7), Figures 10, 11 (c1-c7): The full names for acronyms of hydrometeor types are not found in the text. Please mention it in the figure captions or at line 455.

[Reply: Revised as suggestion. Please see in mms \(Lines 460–462; 584–587\).](#)

[Lines 460–462 \(584–587\) in mms:](#)

Point-to-point responses

“Hydrometeor types are abbreviated: ‘DS’ is dry aggregate snow, ‘WS’ is wet snow, ‘CR’ indicates crystals of various orientations, ‘GR’ is graupel, ‘BD’ is big drops, ‘RA’ indicates light and moderate rain, ‘HR’ is heavy rain, and ‘RH’ indicates a mixture of rain and hail.”

5 Figures 10, 11: All subpanels in the figure need to be replotted as the text including labels is not visible when zoomed in.

Reply: Corrected.

6 Figure 12: Please explain the meaning of positive/negative lags in the captions. revisions.

Reply: Revised as suggestion. Please see in mms (Lines 620–621).

Lines 620–621 in mms:

“Positive lagged time means that an increase in the variable comes before the increase in lightning.”