A summary of relevant changes made in the revised manuscript

Thank you very much for your efforts to review my paper. According to the referee's comments, I have revised the main text in the revised manuscript. A summary of relevant changes made in the revised manuscript is as follows. The full responses to the referee's comments can be found at separated post of 'Author Comment' and 'Author Response'.

1. Title: Changed to ' Observed relationship between drop size distribution and environmental properties near Kumagaya in eastern Japan' in the revised manuscript, which is related to Referee 1's Specific comment 1.
2. Introduction: It has altered in the revised manuscript, which is related to Referee 1's Specific comment 2, Technical comments 1--3.
3. Data and Methods: I have added detailed procedure for the ground-based disdrometer and the polarimetric weather radar to get DSD parameters, which is related to Referee 1's Specific comments 2, 3-1--3-10, 3-13--3-14, 4, 5, Technical comments 4--5, and Referee 2's Major comment 1--2.
4. Results: It has modified in the revised manuscript, which is related to Referee #1's Specific comments 3-12, 4-1--4-6 and 5, Technical comments 6, Referee #2's Major comments 3-i.
5. Discussion: It has significantly altered in the revised manuscript, which is related to Referee 1's Specific comments 6-2--6-6, Technical comments 7--8, and Referee 2's Major comment 3-ii.
6. Conclusions: It has slightly altered in the revised manuscript, which is related to Referee 2's Major comment 3-ii.
7. Deleted Table 1.
8. Added new Fig. 1, which is mainly related to Referee 1's Specific comments 3-4, and Technical comment 6.
9. Added new Fig. 2, which is mainly related to Referee 1's Specific comments 3-3, 3-5, and 3-6.
10. Added new Fig. 3, which is related to Referee 2's Major comments 2-i and 2-ii.
11. Modified Fig. 1 of the original manuscript as Fig. 4 in the revised manuscript, which is related to Referee 1's Specific comments 3-2, 3-5, 3-9, and 3-11.
12. Added new Fig. 5, which is mainly related to Referee 1's Specific comment 3-1.
13. Added new Fig. 6, which is mainly related to Referee 1's Specific comments 3-1 and 5.
14. Changed figure number of original Fig. 2 to Fig. 7 in the revised manuscript.
15. Changed figure number of original Fig. 3 to Fig. 8 in the revised manuscript.

16. Changed figure number of original Fig. 4 to Fig. 9 in the revised manuscript.
17. Changed figure number of original Fig. 5 to Fig. 10 in the revised manuscript.
18. Changed figure number of original Fig. 6 to Fig. 11 in the revised manuscript.
19. Modified Fig. 7 of the original manuscript as Fig. 12 in the revised manuscript, which is related to Referee 1's Specific comments 4--5, and Referee 2's Major comment 3-i.
20. Modified Fig. 8 of the original manuscript as Fig. 13 in the revised manuscript, which is related to Referee 1's Specific comments 4--5, and Referee 2's Major comment 3-i.
21. Modified Fig. 9 of the original manuscript as Fig. 14 in the revised manuscript, which is related to Referee 1's Specific comments 4--5, and Referee 2's Major comment 3-i.
22. Changed figure number of original Fig. 10 to Fig. 15 in the revised manuscript.
23. Changed figure number of original Fig. 11 to Fig. 16 in the revised manuscript.

Responses to the comments by Referee #1

Takashi Unuma

Thank you very much for your thorough reviews and constructive comments on my manuscript. Your comments are very useful in improving the original manuscript. I will respond to your comments in the followings. Your comments are written in *gray Italic*, while my responses are written in Roman. I have also included the document with track changes for your reference.

General Comment

This study investigated raindrop size distribution (DSD) characteristics of precipitation cells observed by a polarimetric radar and ground-based disdrometer data using three-year datasets and environmental factor that can impact the DSD characteristics. The analysis method is adequate, and the figures are clean and easy to see. However, I am concerned with the sample size used in this study. I think that the data period (3 years) is good and enough to collect samples. However, the sampled cases shown in Figs. 7-9 were very small, and the correlation coefficients were very small. Therefore, I cannot be convinced with the impacts of the environmental factors discussed using Figs. 7-9. Moreover, the title says "… eastern Japan," however, the radar data used in this study are from one radar at one location, and the disdrometer data are also from one location. I am not sure if this dataset is enough to represent the characteristics in "eastern Japan." It is also unclear in the manuscript what types of precipitation cases were focused and why this study focused on equilibrium shape of DSD. Definitions of cells are not clear. Details are listed below. The author should address those or perhaps needs additional analyses before publication.

Reply: Thank you very much for taking the time to provide your thoughtful comments. The sample size depends mainly on the observation interval of upper-air sounding data, which are used as the environmental field for convective clouds in this study. I apologise that these points were not sufficiently explained in the original manuscript. Regarding the correlation, I have revised the discussion to focus on statistically significant relationships only. Regarding the title, I have changed it to '... **near Kumagaya** in eastern Japan' and have clarified that it refers to the characteristics of the area around Kumagaya, located in eastern Japan. Regarding precipitation cases, I have targeted convective clouds where collisional breakup signals were observed at the ground level.

To be clarify, I have explicitly shown the characteristics of drop size distributions for each precipitation type and intensity at the ground level. Additionally, the original manuscript's description of convective clouds was poorly organised, so I have significantly revised the analytical methods. The detailed revisions are outlined below.

Specific comments

R1-SC1. Title: As I mentioned above, the title says "… eastern Japan," so I expected this study used large datasets from multiple locations in the eastern Japan. However, the radar data used in this study are from one radar at one location, and the disdrometer data are also from one location. I am not sure which area in Japan is represented by "eastern Japan" and if this dataset is enough to represent the characteristics in "eastern Japan."

Reply: Thank you for pointing this out. I have changed the title to 'Observed relationship between drop size distribution and environmental properties **near Kumagaya** in eastern Japan' in the revised manuscript.

R1-SC2. Introduction: It is unclear in the manuscript what types of precipitation cases were focused in this study. I supposed that the author was interested in heavy rainfall, but I am not sure why this study focused on equilibrium shape of DSD. The instruction mentioned multimodality in DSD shapes, but the mainstream of this study did not account for the multimodality (I think).

Reply: I apologise for the inadequately structured Introduction in the original manuscript. While it has been noted that the equilibrium drop size distribution (EDSD) rarely occurs in natural rain, it has also been pointed out that it can occur frequently under heavy rainfall. Although the observed DSD has not been closely approached by the equilibrium shape or a stationary distribution, recent studies over multiple regions have reported observational examples exhibiting the breakup signal, which is one of the characteristics of EDSD, suggesting that such features may play a key role during heavy rain. In some cases, a decrease in the value of Λ can diagnose multimodality, which may be related to heavy rain. However, few studies have statistically investigated the vertical structures these phenomena form or the atmospheric conditions under which they occur. I have revised the Introduction to address these points as shown below.

'Therefore, the value of Λ is expected to capture one of the characteristics of DSDs that

have approached a stationary distribution which may frequently observed in heavy rain events (Garcia-Garcia and Gonzalez, 2000; Unuma, 2024). In addition, recent studies show that such characteristics seem important for heavy rain producing convective systems (Ding et al., 2023; Jung and Jou, 2023; Unuma et al., 2023). However, fewer studies statistically investigate the microphysical characteristics within convective clouds or their environments for development.'
(In Lines 66-71 in the revised manuscript)

'Therefore, by investigating the characteristics of DSD within convective clouds and their relationship with the surrounding atmosphere, it is possible to bridge the gap between the cloud microphysical properties within convective clouds that cause heavy rain and the mesoscale environments.'
(In Lines 105-107 in the revised manuscript)

R1-SC3. Definitions: Definitions of cells and target cases are unclear. Methods of tracking cells are also unclear. I have the following specific questions.

R1-SC3-1) What type of precipitation cells targeted is not clear. The sampled period included all seasons in 3 years. Did the study target any types of precipitation, including monsoon, MCSs, isolated, embedded, Baiu, snow, and etc.? If so, what type did have most cells? It would be great if the author provided the numbers sampled for each precipitation type.

Reply: Thank you for your comments. As mentioned in the response to R1-SC2, the analysis is limited to heavy rain cases with breakup characteristics on the ground and does not distinguish between seasons or convective systems. The percentages of precipitation types, manually categorised with isolated convection, convective system, and embedded system, were 18.5, 44.7, and 36.8, respectively. Typical cases are shown in below. However, this categorisation may differ depending on researcher's thought, which needs to be more quantitative ways. Thus, I did not include these in the revised manuscript.

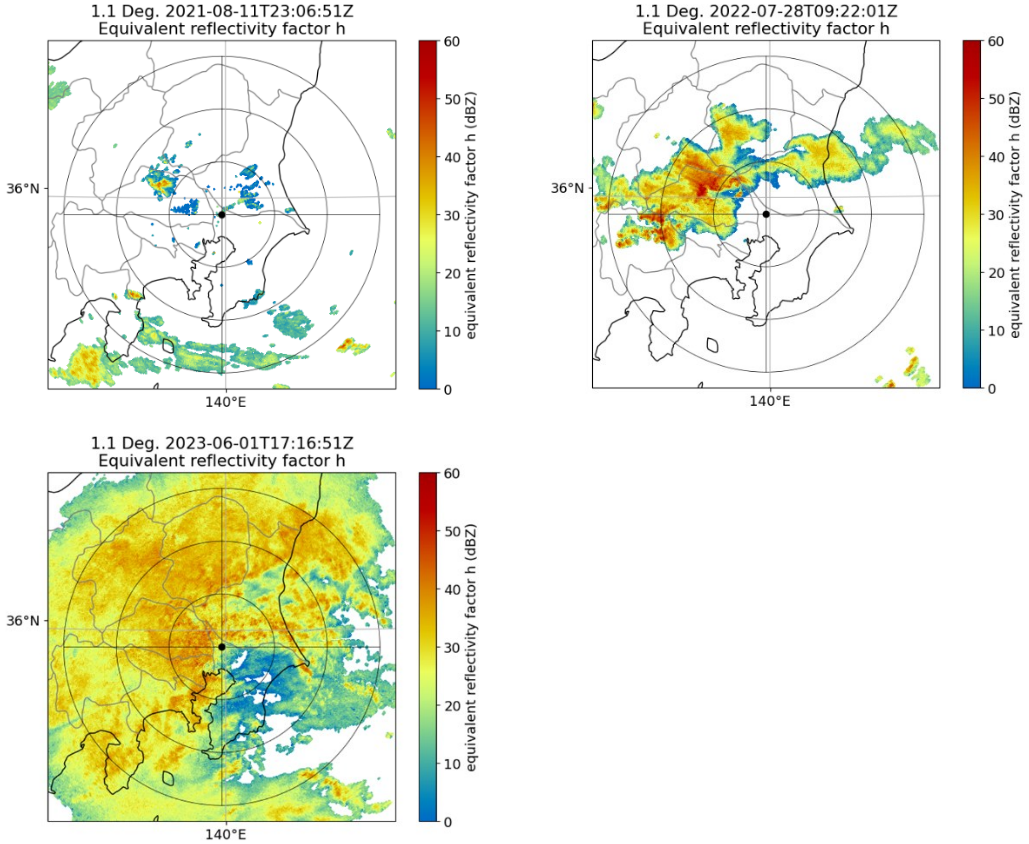

Fig. S1: Horizontal distribution of horizontal reflectivity factor (dBZ) obtained from Tokyo Radar. Typical case of isolated convection (upper left panel), convective system (upper right panel), and embedded system (lower left panel) are displayed.

Alternatively, by reading the weather code from the Parsivel disdrometer, I determined the precipitation type on the ground, and over 97% were classified as RA+. It means that almost all of the target event were to be convective rain. Also, the present work focuses on convective clouds that produce heavy rain having a characteristics of breakup signatures on the ground, and thus I have added the following sentences in the revised manuscript.

‘To see what kinds of precipitation type on the target events is observed in this study, the precipitation type is diagnosed using the weather code obtained from the Parsivel observation. Ninety seven percent of the precipitation type was classified as RA+ (i.e., Strong rain), with the remaining three percent was classified as RASN+ (i.e., Strong Rain, drizzle with snow). The characteristics of the DSD observed at the ground-based disdrometer depending on *R* are also shown in Fig. 5. As *R* increases, the overall number concentration increases, and the distribution approaches an exponential distribution (e.g., Eq. 8). On the other hand, when R is weaker than 30 mm h^{-1}, there is a tendency for the frequency of the diameter in the 1–3 mm range to increase, which is one of the unique characteristics observed in the present study.' (In Lines 232-238 in the revised manuscript)

Furthermore, I have added a discussion on the characteristics of drop size distributions at each rainfall intensity and how these are related to environmental field analysis as follows.

'When the instability indices such as CAPE and TLR are high, D_0 tends to be large, and Λ tends to be small (Figs. 12 and 13); that is, a broader shape of the DSD is likely to be formed concerning the gamma DSD with shape parameter μ is larger than zero value. Here, the three-parameter gamma distribution $N(D)_{\text{gam}}$ is defined as following;

$$N(D)_{\text{gam}} = N_0\, D^{\mu} \exp(-\Lambda D)$$

This form is quite similar to $N(D)_{\text{exp}}$ in Eq. (8) but with the shape parameter μ. If μ is negative, the smaller value of μ results in smaller value of Λ due to its shape is to be concave. As shown in Fig. 5, almost all of the observed DSD shape is convex, envisaging μ is larger than zero in the present study. On the other hand, the weaker vertical shear affects the liquid water content within the convective clouds (Fig. 14d).' (In Lines 402-409 in the revised manuscript)

R1-SC3-2) Lines 142-143: I am not sure what cell life stages were targeted by using the lambda values. Could the lambda values capture from the cell initiation through the cell decay? What radar reflectivity or rainfall rate values corresponded to those lambda values? Were the lambda cells in Fig. 1 consistent with reflectivity cells?

Reply: Thank you very much for pointing this out. When comparing cases tracked with horizontal reflectivity factor Z_H and the slope parameter Λ, I believe that tracking with Λ directly captures the portion corresponding to heavy rain within convective clouds from the perspective of drop size distribution parameters. For example, Λ tracking for the cell number 292 is started simultaneously as well as Z_H tracking (corresponding cell is #307) and the tracking time is longer in Λ than Z_H (Fig. S2 or Fig. 4 in the revised manuscript). Also, a smaller value of Λ indicates an increase in the frequency of larger raindrops, i.e. a broadening of the tail slope, which may be important for increasing in R as an integral value of DSD (e.g., Unuma et al. 2025).

Considering that, the Λ tracking is potential to detect stronger *R* area within convective cloud compared to the Z_H tracking.

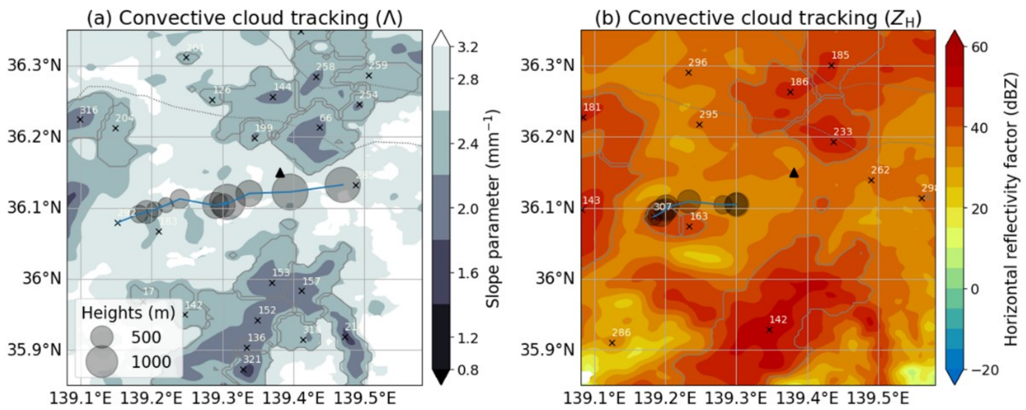

Fig. S2: An example of detecting and tracking convective clouds using tobac algorithm. (a) Colour shades indicate that the slope parameter (Λ; mm^{-1}) of the DSD parameters retrieved from the polarimetric radar variables, the crosses show the location when the feature detected in the algorithm, and the blue line displays that a trajectory of an identified cell #292. The heights of feature detection are represented with black circles. The triangle shows the location of the disdrometer site used in this study. The target area of approximately 10 km square centred on the disdrometer site is displayed with dotted square. (b) the same as (a), but identified with horizontal reflectivity factor (Z_H; dBZ) and a corresponding cell #307.

To be clarify above mentioned interpretations, I have added the following sentences in the revised manuscript as follows.

‘Regarding feature detection, only #142 is detected by Z_H (Fig. 4b), but in the case of Λ, multiple convective clouds were identified, such as #17, #21, #31, #136, #142, #152, #153, and #321 (Fig. 4a). Additionally, regarding the tracking cells, even in the same convective cloud, splits are likely to occur on Z_H tracking (Fig. 4b’s blue line), but in the case of Λ, it seems to be tracked as the same convective cloud in time series (Fig. 4a’s blue line). Also, the initially detected time corresponds to early stage of a convective cloud in both cases. As mentioned in Sect. 1, a smaller value of Λ indicates an increase in the frequency of larger raindrops, i.e. a broadening of the tail slope, which may be important for increasing in *R* as an integral value of DSD (e.g., Unuma et al. 2025). Considering that, the Λ tracking is potential to detect stronger *R* area within convective cloud compared to the Z_H tracking.’

(In Lines 204-211 in the revised manuscript)

R1-SC3-3) How did the radar data cover the 3D volume? What is the maximum height? The radar PPI volume scans cannot see higher altitudes near by the radar. What is the height limitation? Were vertical structures retrieved from all cells without the impact of this limitation?

Reply: Thank you for pointing this out. First, I have added a figure of the scan strategy of Tokyo radar directed toward the ground-based observation site. The observation area analysed is the surroundings of the ground-based observation site, and the maximum height available to use in CAPPI data is approximately 14 km (Fig. S3 or Fig, 2 in the revised manuscript). The target area is approximately 60 km from the radar site, and I believe that the 3D volume of CAPPI data obtained from the PPI scans covers the convective clouds passing through that area.

Additionally, when tracking with Λ, the target events are focused on raindrop size distribution below the melting layer, and it is considered that only the precipitating core within a convective cloud is to be obtained. The feature detection's height is approximately 1 km or below 1 km (Fig. S2a or Fig. 4 in the revised manuscript), and the influence of the maximum height obtained from the PPI scans over the target area is considered relatively small, at least in this study.

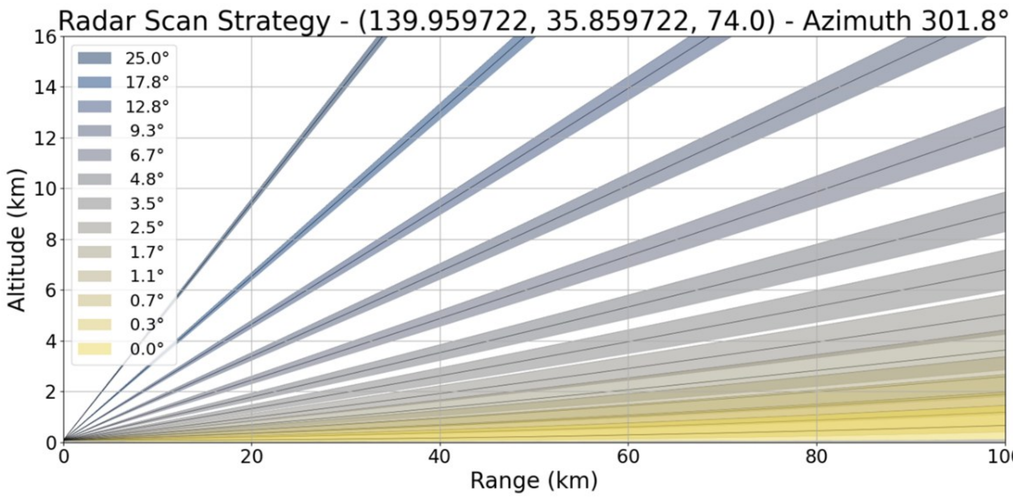

Fig. S3: Radar scan strategy at Tokyo Radar with the azimuthal angle of 301.8◦ which directs to the disdrometer site at Kumagaya.

I have added following sentences to be clarified above-mentioned explanations.

‘Figure 2 shows a scan strategy of Tokyo Radar for the direction to the disdrometer site, which obtained by using Heistermann et al. (2013). The highest angle over the disdrometer site (~ 60 km range from the Tokyo radar) is about 14 km, so that the maximum height of convective clouds to be identified in the following subsection is less than 14 km, which is a limitation to detect convective clouds in this study.’
(In Lines 160-163 in the revised manuscript)

R1-SC3-4) Section 2.2: Please provide the domain.

Reply: Thank you for your suggestion. I have added a figure that includes the sites of operational polarimetric radar, upper-air sounding, and ground-based disdrometer as Fig. 1 in the revised manuscript. The same one is shown below.

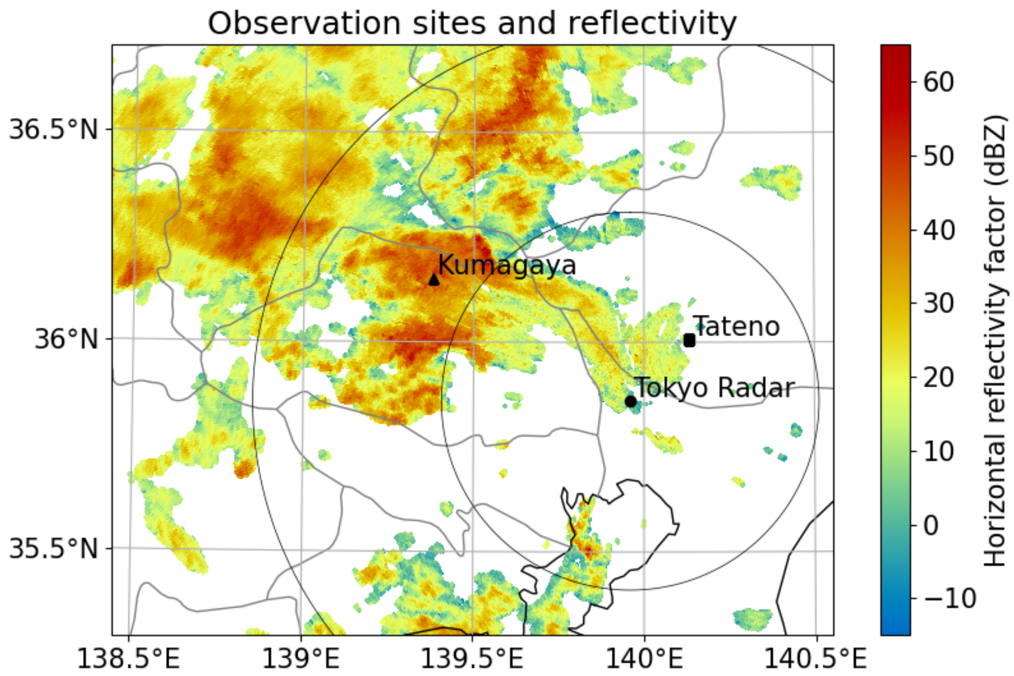

Fig. S4: Horizontal reflectivity factor (dBZ) from the 0.3 degree plan position indicator (PPI) scan at 09:22 UTC 12 July 2022 conducted by the C-band polarimetric weather radar at Tokyo site (black-filled circle). Range rings (grey circles) are displayed with 50 km intervals. The locations of the disdrometer site at Kumagaya (black-filled triangle) and the upper-air sounding site at Tateno (black-filled square) are plotted.

R1-SC3-5) It was unclear for me that it was tracked in 2D or 3D. If 3D, I have the similar question to. 3). Was the tracking impacted by the radar data limitation at higher angles?

Reply: Thank you for pointing this out. The convective clouds were sorely tracking in 3D. As described in my response to your comment of R1-SC3-3), I believe that the impact of the maximum height due to the radar PPI scan is small in this study. I have altered the corresponding sentences as follows.

"The area covered over the feature is determined as a 'segmentation' using a water shedding algorithm (Carpenter et al., 2006; van der Walt et al., 2014), whose boundaries were determined horizontally and vertically."
(In Lines 189-190 in the revised manuscript)

'Area and volume of a cell were calculated within the boundaries determined by the segmentation process (i.e., $\Lambda < 3.0$ mm^{-1}) as described the following sentences.'
(In Lines 195-196 in the revised manuscript)

R1-SC3-6) Line 153: "the maximum of each slope is defined as highest": I cannot follow this. Does each slope have multiple slope values? I cannot understand.

Reply: I apologise for the poorly structured sentence. I have modified the main text of the revised manuscript as follows.

'In this algorithm, over 5 bins from smaller (i.e., 1.0 mm) to larger diameters, the linear best fit of the considered 2-min averaged DSD is calculated. Starting points are considered from 1.0 mm to 1.6 mm with 0.2-mm-diameter spreads, and then four linear relationships are calculated. The maximum slope among the four relationships is defined as the highest slope (HS; mm^{-2} m^{-3}).'
(In Lines 214-217 in the revised manuscript)

R1-SC3-7) Lines 156-157: This sentence does not make sense to me. CAPPI data is available every 5 min. What does "before and after 1 hour of CAPPI" mean?

Reply: I apologise for the poorly structured sentence. I have modified the main text of the revised manuscript as follows.

'The CAPPI data is used to track convective clouds within ± 12 time steps centred on the time when HS > 0 was detected at the ground-based disdrometer.'
(In Lines 221-222 in the revised manuscript)

R1-SC3-8) Table 1: What is the difference between feature and cell? What is the difference between event and cell?

Reply: Thank you for pointing this out. I have altered the sentences in the revised manuscript as follows.

"Here, 'feature' refers to a detected object within the analysis domain at each time step, and 'cell' refers to the set of features in the time direction. 'Target event' refers to those 'cells' that are the subject of this study."
(In Lines 219-221 in the revised manuscript)

R1-SC3-9) Lifetime: Similar question to #3-2). What life stages were captured? Can it capture cell initiation, beginning of precipitation, beginning of cloud formation, just life stages of heavy rainfall, or time with raindrops >1 mm?

Reply: Thank you for your comments. As far as I obtained in this study, the life stages of convective cloud defined by the slope parameter can capture from a cell initiation to cell peak at least, in some time, to cell decay, whose capabilities are similar to the reflectivity tracking (e.g., Fig. S2 or Fig. 4 in the revised manuscript). For example, even in the same convective cloud, splits are likely to occur on the reflectivity tracking (Fig. S2a or Fig. 4a's blue line), but in the case of the slope parameter, tracking is possible as the same convective cloud (Fig. S2b or Fig. 4b's blue line).

R1-SC3-10) How did you calculate the volume and area? How did you define the volume/area? Did you use the lambda values?

Reply: Thank you for your comments. The area covered over the feature is determined as a 'segmentation' using a water shedding algorithm, whose boundaries were determined horizontally and vertically using the slope parameter value is less than 3.0 mm^{-1}. I have altered the corresponding sentences as follows.

“The area covered over the feature is determined as a ‘segmentation’ using a water shedding algorithm (Carpenter et al., 2006; van der Walt et al., 2014), whose boundaries were determined horizontally and vertically.”
(In Lines 189-190 in the revised manuscript)

‘Area and volume of a cell were calculated within the boundaries determined by the segmentation process (i.e., $\Lambda < 3.0\ mm^{-1}$) as described the following sentences.’
(In Lines 195-196 in the revised manuscript)

R1-SC3-11) Line 212: Similar question to #3-2). What life stage corresponds to the first detection?

Reply: Thank you for your comment. As shown in Fig. 4 of the revised manuscript (also shown in Fig. S2), the initial detection time in the reflectivity tracking and that in the slope parameter were almost the same. Considering that, this corresponds to the initial stage of convective cloud formation.

R1-SC3-12) Line 217: Why 2 km?

Reply: Thank you for pointing this out. The reason why the 2-km height are selected is that the vertical trends of the DSD parameters were changed at the height as shown in Fig. 10 of the revised manuscript. To be clarify, I have added the sentence as follows.

‘The reason why the 2-km height is selected is that the vertical trends of the DSD parameters were gradually changed at the height (Fig. 10).’
(In Lines 302-303 in the revised manuscript)

R1-SC3-13) How did you decide the inside and outside features of the convective clouds. How did you define the convective cell boundary?

Reply: Thank you for pointing this out. The area covered over the feature is determined as a ‘segmentation’ using a water shedding algorithm, whose boundaries were determined horizontally and vertically using the slope parameter value is less than 3.0 mm^{-1}. The feature should exist within the boundary, so that the inside and outside characteristics were easily determined in this study.

R1-SC3-14) Line 228: How did you define the volume?

Reply: Thank you for your comment. The convective cloud's volume is determined as the segmentation process of the *tobac* algorism, whose boundaries were defined horizontally and vertically using the slope parameter < 3.0 mm^{-1}.

R1-SC4. The sample size (tracked cells) seems to be enough to me in Table 1 and Figures 2 and 3. However, the samples shown in Figures 7-9 are very small (30-40 points only). Why? Moreover, the correlations are small. All discussions about the environmental factors were based on those plots with very small correlations. Therefore, I cannot be convinced with the impacts of the environmental factors discussed using Figs. 7-9. I have the following specific comments:

Reply: Thank you very much for pointing this out. As in Unuma and Takemi (2016), upper-air sounding data corresponding to the detected cells were used to represent environmental conditions. As a result, the number of environmental conditions is reduced depending on the number of upper-air sounding data, which is one of the limitations of using observational data. To be clarify, I have added the following sentences in the revised manuscript.

'As a result, the number of samples representing environmental conditions of the extracted convective clouds is reduced depending on the number of upper-air sounding data, which is one of the limitations of using observational data. It is crucial to investigate the environmental conditions in nature using observational data as much as possible, and thus, this study conducted analyses and discussions to the best of our ability, considering the constraints imposed by the available observations.'
(In Lines 250-254 in the revised manuscript)

R1-SC4-1) Lines 243-244: I cannot see this in the figure. It looks to me that D0 and lambda are scattered widely, too. Perhaps, did you mention the correlation coefficient values?

Reply: I apologise for the poorly structured sentence. Yes. I have modified the corresponding sentence of the revised manuscript as follows.

‘The variability of the scatter points in N_w and *LWC* is relatively higher than in D_0 and Λ, which are reflected to no apparent relations on N_w and *LWC* with CAPE value (*p*-value > 0.05).’

(In Lines 330-331 in the revised manuscript)

R1-SC4-2) Lines 250-251: It is difficult to see this… Figure 7a and 7b both showed positive correlation coefficient values. Could you revise the sentence?

Reply: I apologise for the poorly structured sentence. I have altered the sentences of the revised manuscript as follows.

‘The larger D_0 seems to be related to the larger KI (Fig. 13a), but the correlation coefficient is much smaller. D_0 is proportional to TLR (Fig. 13b) and shows positive correlations between D_0 and TLR with *p*-value < 0.05.’

(In Lines 339-341 in the revised manuscript)

R1-SC4-3) Line 251 “D_0 is negatively…”: This does not make sense to me. Fig. 6 shows that LWC increases when D0 increase. I suppose that LWC can increase when PW increase, so D0 increases when PW increases. Why D0 has negative correlation with PW?

Reply: Thank you for pointing this out. The cases selected in this study was the observed breakup signature on the ground-based disdrometer. In this case, the frequency of relatively smaller drop sizes (< 2 mm diameter) increases as shown in Fig. 5 of the revised manuscript, so the D_0 value is expected to be small in this study. On the other hand, *LWC* correlates most strongly with water vapour content at an altitude of 1-2 km rather than PW (Fig. 13d of the revised manuscript), which is an expected result as well as your thought. To be clarify, I have added the following sentences in the revised manuscript.

‘D_0 is sensitive to environmental instability (e.g., TLR) but is not sensitive to PW, which probably due to selecting breakup signature on the ground in the present study (Sect. 2.4). Actually, the number concentration of the diameter < 3 mm is dominant for the case of R < 30 mm h^{-1} as shown in Fig. 5b and c).’

(In Lines 343-346 in the revised manuscript)

R1-SC4-4) Lines 254-255: This cannot make sense to me, too. Why does the large amount of water vapor contribute to the high concentration of raindrops? What is the mechanism? Is there an aerosol effect?

Reply: Thank you for pointing this out. I have deleted the sentence from the revised manuscript due to the poorly structured sentence.

R1-SC4-5) Line 263 "These results…": I cannot see this in Fig. 9.

Reply: Thank you for pointing this out. I have deleted the sentence from the revised manuscript because the sentence is not organised well in the original manuscript and the relationships between them were not statistically significant (i.e., p-value > 0.05).

R1-SC4-6) Figs. 7-9: Correlation coefficients are very low for all relations in those figures. Absolute values for all correlation coefficients are less than 0.4 (weak correlation), except Fig.8b. The discussions about the relationships between DSD parameters and environmental factors are based on such low correlations. Moreover, the number of samples for each plot is small (<50). I do not think that the small numbers of samples can represent general characteristics of convective cells in eastern Japan.

Reply: Thank you for pointing that out. First, I have changed the title to 'Observed relationship between drop size distribution and environmental properties **near Kumagaya** in eastern Japan'.

Next, I re-analysed and found that the median volume diameter mainly had a positive correlation with the temperature lapse rate and the vertical shear at 0-3 km (correlation coefficients are 0.57 and 0.42, both p-values are less than 0.05), while the number concentration had a negative correlation with the vertical shear at 0-3 km (correlation coefficient: -0.44 with p-values < 0.05). Although the correlation coefficient values are somewhat smaller than the above-mentioned parameters, there was a positive correlation between *LWC* and water vapour content at 1–2 km height (correlation coefficient: 0.34 with p-values < 0.05). Also, to show statistical significance of the obtained correlation coefficients, p-values of the correlation coefficient is displayed if p-values are less than 0.05. These results were shown in Figs. 12-14 and the related main text of the revised manuscript.

Regarding the number of samples, as you pointed out, although there are more corresponding convective clouds, there are only two times representative upper-sounding data per day. Using reanalysis data to represent the environmental field may be effective, as in Saha et al. (2022). However, considering the reproducibility within the analysis domain of reanalysis data and errors from numerical models, I believe it is important to investigate the actual conditions as much as possible using observational data. this study conducted analyses and discussions to the best of our ability, considering the constraints imposed by observational data. To be clarify, I have added the following sentences in the revised manuscript.

'As a result, the number of samples representing environmental conditions of the extracted convective clouds is reduced depending on the number of upper-air sounding data, which is one of the limitations of using observational data. It is crucial to investigate the environmental conditions in nature using observational data as much as possible, and thus, this study conducted analyses and discussions to the best of our ability, considering the constraints imposed by the available observations.' (In Lines 250-254 in the revised manuscript)

R1-SC5. Environmental factors

The environmental factors discussed are limited. CAPR, KI, PW, wind shear, and TLR could be major factors, but other factors should also be discussed, such as humidity (low level/mid levels), aerosols, seasons, etc. As I mentioned above, the correlations shown in Figs. 7-9 are very low. I would suspect that there could be other factors that can better correlate with the DSD parameters.

Reply: Thank you very much for pointing this out. I have further examined the relationship between moisture content (lower, middle, and upper layers) and DSD parameters. Additionally, I have calculated the *p*-values for the correlation coefficients to show those statistically significance.

First, only the relationships between D_0 and CAPE, and between Λ and CAPE showed significant correlations (p-value < 0.05). At the same time, there were no significant correlations between N_w and CAPE, and between *LWC* and CAPE (Fig. 12 in the revised manuscript).

I also investigated the environmental parameters by changing the height at which they correlate. The results showed that D_0 and TLR remained positively correlated with *p*-

value < 0.05, whilst no significant correlations existed between D_0 and KI or D_0 and PW (Fig. 13 in the revised manuscript).

Additionally, a positive correlation was found between water vapour content at 1–2 km height and *LWC* (Fig. 13d in the revised manuscript). By changing the height at which correlations were calculated to near the ground revealed significant correlations between D_0 and MS03, and between N_w and MS03 (Fig. 14 in the revised manuscript). On the other hand, no significant correlation was found for EH03, and this result remained unchanged even when the heights for correlation analysis were changed (not shown).

Regarding aerosol effects, the analysis could not be performed due to the lack of available data around the target area unfortunately.

Regarding seasonality, approximately 80% of the data fell within the summer season, with peak occurrence times around 09 UTC and 21 UTC (Fig. 6 in the revised manuscript).

Considering the above-mentioned explanations, overall characteristics of the convective clouds that produce heavy rain having a characteristics of breakup signatures on the ground in relation to its surrounding environmental conditions near Kumagaya in eastern Japan were investigated in the present study.

R1-SC6. Others:

R1-SC6-1) Lines 238-239: Was this also associated with cell's shape and where is the "center" of the cell?

Reply: Thank you for your comment. Probably yes. It also relates to the cell direction to move, and thus I have modified the sentence in the revised manuscript as follows.

'The value of Λ is generally larger than at maximum time, and the standard deviation becomes more scattered around the centre of the convective cloud or to the westward and southwestward. These features are probably related to the convective cell's shape and direction of movement.'
(In Lines 322-325 in the revised manuscript)

Also, the centre of the cell represented in Fig. 11 of the revised manuscript is the point (0,0) (donated as crosses).

R1-SC6-2) Lines 293-295: Was there a size sorting effect for the horizontal distributions?

Reply: Thank you for your comment. I think there is a possibility that size sorting may have had an effect. The slightly biased distribution of larger Z_{DR} values in the south to southwest of the convective clouds and the significant standard deviation may be related to the characteristics of the upstream side of the convective clouds. I have clarified this point in the main text of the revised manuscript as follows.

'It may also relate to be size sorting signal (e.g., McFarquhar and List, 1991; Kollias et al., 2001; Kumjian et al., 2014).'
(In Lines 389-390 in the revised manuscript)

R1-SC6-3) Lines 309-310: This also does not make sense to me. Please explain the mechanisms why weaker vertical wind shear contributed to a high number concentration.

Reply: Thank you for pointing this out. During strong vertical shear, collisions and coalescence between raindrops are more likely to occur, resulting in relatively large raindrops (> 2 mm diameter) as the median volume diameter (Fig. 13a of the revised manuscript). At the same time, smaller raindrops are likely to evaporate more easily. On the other hand, when vertical shear is weak, the opposite occurs: the proportion of collisions and coalescence between raindrops decreases, and the probability of raindrops evaporating decreases. In such cases, the larger raindrops are less likely to form, and smaller raindrops (< 2 mm diameter) are more likely to form, contributing to the higher number concentrations. The number concentration of raindrops with diameters of approximately 1–2 mm diameter was high on the ground, regardless of rainfall intensity (Fig. 5 in the revised manuscript). Considering the above, I have significantly altered the main text in the revised manuscript as follows.

'In terms of microphysical perspectives, collisional coalescence between raindrops tends to occur under the stronger vertical shear environment, which promotes to producing larger (> 2 mm diameter) raindrops. At the same time, smaller raindrops are likely to evaporate more easily under the stronger vertical shear. On the contrary, the probability of collisional coalescence between raindrops and that of evaporation are decreases under the weaker vertical shear environment. In such cases, smaller (< 2 mm diameter) raindrops are more likely to form, contributing to higher number concentrations. In fact, the number concentration of raindrops with the diameters of ~ 1–2 mm was high regardless of *R*, as observed in the ground-based DSD observation (Fig. 5).'

(In Lines 416-422 in the revised manuscript)

R1-SC6-4) Lines 313-314: Why was the change in Nw larger with increasing rainfall amount under the humid environment? "change" is an unclear word. Do you mean increase or decrease in Nw? please clarify.

Reply: Thank you for pointing this out. I have deleted the sentence from the revised manuscript because the sentence is not organised well in the original manuscript.

R1-SC6-5) Line 315-316: This sentence is also unclear. Do you mean "a broader shape .... non-zero mu gamma DSD? If so, need a few more sentences to explain why large D0 and small lambda can represent non-zero mu.

Reply: Thank you for your helpful suggestion. According to your comments, I have significantly altered the main text in the revised manuscript as follows.

'Here, the three-parameter gamma distribution $N(D)_{\mathrm{gam}}$ is defined as following;
$N(D)_{\mathrm{gam}} = N_0 D^{\mu} \exp(-\Lambda D)$. (13)
This form is quite similar to $N(D)_{\mathrm{exp}}$ in Eq. (8) but with the shape parameter μ. If μ is negative, the smaller value of μ results in smaller value of Λ due to its shape is to be concave. As shown in Fig. 5, almost all of the observed DSD shape is convex, envisaging μ is larger than zero in the present study.'
(In Lines 404-408 in the revised manuscript)

R1-SC6-6) Line 344 "even though breakup signal is obtained.": I do not know why you need this phrase here. Break up or coalescence does not affect LWC. Breakup (increase of small raindrops and decrease of large raindrops) can increase LWC at a given Rain fall rate (because fall speed decreases).

Reply: Thank you for pointing this out. I have deleted the sentence from the revised manuscript because the sentence is not organised well in the original manuscript.

Technical comments

R1-TC1. Lines 21-22: Unclear sentence. Do you want to say "frequently observed in heavy rain events?"

Reply: Thank you for your comment. I have modified the sentence in the revised manuscript.

'… which is rarely observed on the ground (McFarquhar et al., 1996; D'Adderio et al., 2018; Unuma et al., 2025) but may be frequently observed during heavy rain events (Garcia-Garcia and Gonzalez, 2000; Unuma, 2024).'
(In Lines 21-23 in the revised manuscript)

R1-TC2. Line 55 "recent studies": The following study is not a recent study (in 2013, more than 10 years ago)

Reply: Thank you for your comment. I have altered the sentence in the revised manuscript as follows.

'However, this problem has been eliminated as the instrumental performance of the disdrometer has improved, and similar trends have been demonstrated in a few recent decades.'
(In Lines 57-58 in the revised manuscript)

R1-TC3. L first appeared here. Please define.

Reply: Thank you for pointing this out. I have added the values of transmitting frequencies in the revised manuscript.

R1-TC4. What type of disdrometer was used? Please provide the model or specifications.

Reply: Thank you for pointing this out. I have used the first-generation OTT-Parsivel in this study and have added its details in Sect. 2.1 as follows.

'A first-generation laser-optical (650 nm wavelength) OTT-Parsivel measures the drop size and fall velocity of precipitation particles. The original data $n(D)$ are measured within a laser beam sheet with 32 drop-size classes (D_i) and 32 fall-velocity classes ($V_j(D_i)$). The drop diameters range from 0.2 to 25 mm in i direction and velocities range from 0.2 to 20 m s^{-1} in j direction, respectively. The laser beam sheet of OTT-Parsivel is 180 mm long, 30 mm wide, and 1 mm tick. The effective sampling area S (m^{-2}) is expressed as

0.180 × (0.030 − *L*/2), where L is a size parameter depending on the drop size. The two smallest drop size classes were not used in this study due to their low signal-to-noise ratios (Tokay et al., 2013). Observed drop size classes were converted into the equivalent volume diameter (D_e; mm) according to Adachi et al. (2013) (hereafter, D_e is represented simply as D). The time interval of the disdrometer data (Δt) was 1 min.'
(In Lines 124-131 in the revised manuscript)

R1-TC5. Where is the radar location in Fig. 1?

Reply: Thank you for pointing this out. I have added the observation domain in Fig. 1 in the revised manuscript by specifying the locations of radar, disdrometer, and upper-air sounding (see also Fig. S5).

R1-TC6. Line 229: Does not need "is"

Reply: Thank you very much for pointing this out. I have deleted one in the revised manuscript.

R1-TC7. Lines 296: Did you remove large ZDR? Unclear.

Reply: Thank you for pointing this out. The answer is 'No'. According to your comment, the sentence in the original manuscript is not organized well, so I have altered the sentence in the revised manuscript as follows.

'These characteristics are likely to have a similar structure to the results obtained by Chudler et al. (2022). It may also relate to be size sorting signal (e.g., McFarquhar and List, 1991, Kollias et al., 2001; Kumjian et al. 2014). The larger raindrops (e.g., > 4 mm in diameter) may not exist in this study, probably due to an active breakup process near the ground level (Fig. 10a and b).'
(In Lines 388-391 in the revised manuscript)

R1-TC8. Lines 311-312: This sentence is unclear. Please revise it.

Reply: Thank you for pointing this out. I have altered the sentence in the revised manuscript as follows.

‘This is probably related to the higher precipitation intensity under the weaker vertical shear condition (Unuma and Takemi, 2016; Unuma, 2024). Unuma and Takemi (2016) extracted quasi-stationary convective systems and divided them into those with the faster- and slower-moving ones, and compared their characteristics. As a result, the slower-moving convective systems tended to occur under the weaker vertical shear environment compared to the faster-moving ones. In addition, precipitation intensity tended to be stronger and its area tended to be smaller in the cases of slower-moving systems, which may be one of the reasons for the resulting larger rainfall amount because the systems remain to be located nearly same location.’
(In Lines 409-415 in the revised manuscript)

Responses to the comments by Referee #2

Takashi Unuma

Thank you very much for your thorough reviews and constructive comments on my manuscript. Your comments are very useful in improving the original manuscript. I will respond to your comments in the followings. Your comments are written in *gray Italic*, while my responses are written in Roman. I have also included the document with track changes for your reference.

General comments

This study focuses on the relationship between the drop size distribution (DSD) of convective clouds and environmental properties in eastern Japan. It conducts research using multiple observational data and analysis methods. The topic holds significant scientific importance and contributes positively to understanding precipitation processes and mechanisms. The research content is comprehensive, the methods are reasonable, and the data are abundant. However, there is still room for improvement. With revisions and refinements, it has the potential for publication.

> **Reply:** Thank you very much for taking the time to read my paper and for your comments. I am very encouraged by your evaluation of the submitted manuscript. I have responded to your comments as appropriately as possible. Details are as follows.

Major Comments

R2-MC1. Lines 116–118: The four parameters discussed here are central to the manuscript's analysis. While the authors cite relevant literature, further clarification is warranted. Specifically, the manuscript should explicitly outline the calculation methods for these variables and elaborate on their physical significance within the context of this study. This addition would enhance reproducibility and help readers interpret the results more effectively.

> **Reply:** Thank you for pointing this out. According to your comments, I have added the procedures of calculating the DSD parameters retrieved from C-band polarimetric radar data in Sect. 2.2 of the revised manuscript as follows.

‘On this method, β (mm^{-1}) need to be calculated as follows;

$\beta = a\,(K_{DP}/Z_H)^b\,(10^{0.1ZDR} - \kappa)^c$, (9)

where coefficients of a, b, c, and κ are 2.55, 0.355, 0.439, and 0.8 based on Gorgucci and Baldini (2009)’s Table 1. The units of K_{DP}, Z_H, Z_{DR} are degree km^{-1}, dBZ, dB, respectively. Then, D_0, N_w, and LWC were calculated as following equations;

$D_0 = 0.59\,Z_H^{0.083}\,(10^{0.1ZDR})^{0.021\beta-1.16}$, (10)

$\log_{10} N_w = 3.01\,Z_H^{0.054}\,(10^{0.1ZDR})^{-0.02\beta-1.25}$, (11)

and

$LWC = 1.73 \times 10^{-5}\,N_w\,D_0^4$, (12)

where coefficients are based on Gorgucci et al. (2000,2002). Λ (mm−1) is calculated with $\Lambda = 3.67/D_0$. These DSD parameters were calculated only if the conditions of Z_H > 35 dBZ, Z_{DR} > 0.2 dB, and K_{DP} > 0.3 degree km^{-1} are satisfied simultaneously.’

(In Lines 165-177 in the revised manuscript)

R2-MC2. DSD Data Sources and Uncertainties: The drop size distribution (DSD) is derived from both radar retrievals and ground-based disdrometer measurements. To strengthen the validity of the findings, the authors should:

R2-MC2-i. Address whether comparative analyses were conducted between the radar and disdrometer datasets to assess consistency or discrepancies.

Reply: Thank you very much for your suggestion. I have added a figure to compare the DSD parameters retrieved from C-band polarimetric radar data and obtained from ground-based disdrometer data as shown in below (Fig. 3 in the revised manuscript).

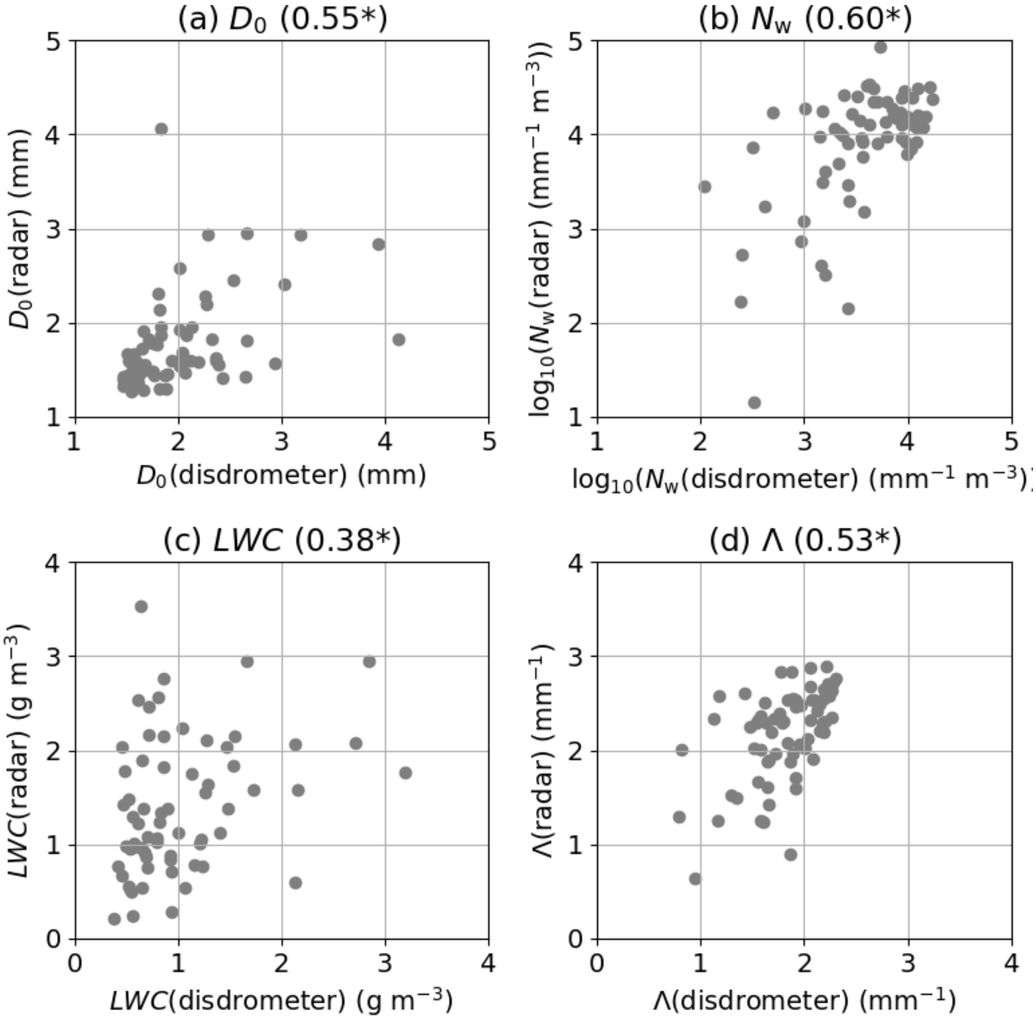

Fig. S1: The scatter diagram of the drop size distribution parameters of median volume diameter (D_0; mm), generalised intercept parameter (N_w; mm^{-1} m^{-3}), liquid water content (LWC; g m^{-3}), and slope parameter (Λ; mm^{-1}) retrieved from Tokyo radar data against the disdrometer data at Kumagaya. Correlation coefficient values are displayed each panel and an asterisk $*$ is added if the p-value for the correlation coefficient is less than 0.05.

R2-MC2-ii. Discuss potential uncertainties inherent in radar-based retrievals (e.g., calibration errors, resolution limitations) and their implications for the DSD estimates.

Reply: Thank you for pointing this out. I have added a sentence describing potential uncertainties during the radar-based retrievals as follows.

‘Observational errors caused by such as radar calibration, range/azimuth resolution limitations, wet antenna radome, low signal-to-noise ratio, and nonuniform beam filling may affect the DSD parameter retrievals, which are potential uncertainties of the radar-based retrievals used in this study.'

(In Lines 179-181 in the revised manuscript)

R2-MC3. Figures 7 and 8 (Relationships and Causality):

R2-MC3-i. While these figures illustrate associations between environmental parameters and shape parameters, the strength of the correlations remains unclear. Incorporating statistical analyses (e.g., correlation coefficients, p-values, or confidence intervals) would quantitatively substantiate these relationships.

Reply: Thank you for your suggestion. The correlation coefficient and *p*-value were calculated, and an asterisk was added to the figure when the correlation coefficient and *p*-value were less than 0.05 (Figs. 12-14 in the revised manuscript). Also, I have significantly altered the main text in the revised manuscript as follows.

'Here, the relationships between the DSD parameters at 2 km height and CAPE were investigated (Fig. 12). D_0 is positively correlated with CAPE (Fig. 12a), whilst Λ is negatively correlated with CAPE (Fig. 12d), whose *p*-value is less than 0.05, respectively. The variability of the scatter points in N_w and *LWC* is relatively higher than in D_0 and Λ, which are reflected to no apparent relations on N_w and *LWC* with CAPE value (*p*-value > 0.05).**'**

(In Lines 328-331 in the revised manuscript)

'Figure 13 shows relationships between D_0 and KI, D_0 and TLR, D_0 and PW, and LWC and PW integrating 1–2 km height (PW12), respectively. Note that the height of the DSD parameters selected in Fig. 13 is near the ground because the higher correlation coefficient values is obtained among the other analysis height. The larger D_0 seems to be related to the larger KI (Fig. 13a), but the correlation coefficient is much smaller. D_0 is proportional to TLR (Fig. 13b) and shows positive correlations between D_0 and TLR with *p*-value < 0.05. D_0 is negatively correlated with PW (Fig. 13c), whilst the relationship between them were weaker than TLR due to the higher variance of the distribution. The larger value of *LWC* seems to be related to the larger value of PW12 (Fig. 13d), whose relationship is statistically significant (*p*-value < 0.05).**'**

(In Lines 337-343 in the revised manuscript)

‘The relationships between the environmental vertical shear of the horizontal winds and the DSD parameters were further investigated (Fig. 14), as the DSDs tend to be affected by the environmental vertical shear as described in Sect. 1. The value of D_0 is likely to be large when the value of MS03 is large (Fig. 14a), whilst the value of N_w is likely to be small (Fig. 14b). The relationships between the environmental directional shear of horizontal winds and the DSD parameters were also investigated. The D_0 value tends to be smaller when the EH03 value is larger (Fig. 14c), whilst the N_w value tends to be larger when the EH03 value is larger (Fig. 14d). These trends are different from those in MS03 but are not statistically significant (p-value > 0.05).’
(In Lines 348-355 in the revised manuscript)

R2-MC3-ii. The discussion should explicitly acknowledge that correlation does not imply causation. For instance, the observed trends could be influenced by unaccounted variables or confounding factors. Revising the text to temper causal language and highlight the exploratory nature of these relationships would improve scientific rigor.

Reply: Thank you for your suggestion. I have revised the main text to avoid expressions that suggest a causal relationship based on correlation in the revised manuscript as follows.

‘When the instability indices such as CAPE and TLR are high, D_0 tends to be large, and Λ tends to be small (Figs. 12 and 13); that is, a broader shape of the DSD is likely to be formed concerning the gamma DSD with shape parameter μ is larger than zero value. Here, the three-parameter gamma distribution $N(D)_{gam}$ is defined as following;
$N(D)_{gam} = N_0 D^{\mu} \exp(-\Lambda D)$.
This form is quite similar to $N(D)_{exp}$ in Eq. (8) but with the shape parameter μ. If μ is negative, the smaller value of μ results in smaller value of Λ due to its shape is to be concave. As shown in Fig. 5, almost all of the observed DSD shape is convex, envisaging μ is larger than zero in the present study. On the other hand, the weaker vertical shear affects the liquid water content within the convective clouds (Fig. 14d). This is probably related to the higher precipitation intensity under the weaker vertical shear condition (Unuma and Takemi, 2016; Unuma, 2024). Unuma and Takemi (2016) extracted the quasi-stationary convective systems and divided them into those with the faster- and slower-moving systems, and compared their characteristics. As a result, the slower-moving convective systems tended to occur under the weaker vertical

shear environment compared to the faster-moving systems. In addition, precipitation intensity tended to be stronger and its area tended to be smaller in the cases of slower-moving systems, which may be one of the reasons for the resulting larger rainfall amount because the systems remain to be located nearly same location.

In terms of microphysical perspectives, collisional coalescence between raindrops tends to occur under the stronger vertical shear environment, which promotes to producing larger (> 2 mm diameter) raindrops. At the same time, smaller raindrops are likely to evaporate more easily under the stronger vertical shear. On the contrary, the probability of collisional coalescence between raindrops and that of evaporation are decreases under the weaker vertical shear environment. In such cases, smaller (< 2 mm diameter) raindrops are more likely to form, contributing to higher number concentrations. In fact, the number concentration of raindrops with the diameters of ~ 1–2 mm was high regardless of *R*, as observed in the ground-based DSD observation (Fig. 5).

The amount of water vapour in the surrounding atmosphere may increases *LWC* for the DSD parameters, as shown in Fig. 13d, and the intensity of precipitation in the DSD that has approached an equilibrium shape can be more sensitive to the amount of water vapour.'

(In Lines 402-425 in the revised manuscript)