Responses to the comments by Referee #1

Takashi Unuma

Thank you very much for taking the time to review and provide constructive comments on my manuscript. Your comments are very useful in improving the original manuscript. I will respond to your comments in the following. Your comments are written in *grey Italic*, while my responses are written in Roman. I have also included the document with track changes for your reference.

This manuscript presents idealized simulations of a heavy-rain convective cloud. The author uses a bin microphysics scheme along with a variety of experiments on environmental controls of the rain amount and intensity. The author shows that a more unstable temperature lapse rate leads to larger raindrops and thus larger rain intensity, while a moister sub-cloud layer leads to more raindrops of moderate sizes and thus larger rain amounts. The interplay of environmental parameters with well-resolved microphysics from a bin scheme is very interesting, along with the comprehensive experiments performed. The paper reads mostly well, apart from some minor formatting issues detailed below. I believe the paper will be fit for publication in ACP once they are addressed.

> **Reply:** Thank you very much for taking the time to provide your thoughtful comments. I am really encouraged by your evaluation of the submitted manuscript. However, I apologise that some descriptions were not sufficiently organised in the original manuscript. In light of your comments, I have significantly refined and polished the main text as much as possible, as described below.

RC1-01. Some more details on the model setup and the details of the microphysics scheme would be of interest to the readers. Are the experiments limited to warm-rain microphysics? What are the parameterizations chosen for the collision kernel, the breakup scheme, and the evaporation of rain?

> **Reply:** Thank you for pointing this out. With regard to cloud microphysical processes, the calculations include all processes handled by WRF-SBM. However, as mentioned in Introduction, the focus of this study is on the warm rain process within this framework.

In addition, in terms of the collision kernel, the breakup scheme, and the evaporation of rain, the following sentences have added in Lines 109-123 in the revised manuscript.

‘The changes in DSDs caused by collisions among raindrops, as well as between raindrops and ice particles, and among ice particles themselves, are calculated by solving stochastic collection equations Khain et al. (1995; 1996) using the low dissipation method proposed by Bott (1998). The collision efficiencies and collision kernels for raindrop-raindrop, graupel-raindrop, and hail-raindrop interactions were calculated offline using an advanced superposition method (Khain et al. 2001, 2004; Pinsky et al. 2001). The breakup of drops occurs through two mechanisms: spontaneous breakup and collisional breakup. The probabilities associated with spontaneous breakup and the resulting fragment distribution are derived from laboratory measurements (Kamra et al. 1991). Additionally, the changes in the size distribution function due to collisional breakup are according to the method of Seifert et al. (2005). Diffusion rates for growth and evaporation, as well as deposition and sublimation, are calculated by solving supersaturation equations for liquid water and ice using an analytic solution. Changes in drop mass are determined through time integrals of supersaturation with microphysical time steps that are much shorter than the dynamical time step. After these processes, drop sizes often do not match points on the regular logarithmic mass grid. To resolve this, the sizes were remapped using a method that conserves three moments of the size distributions, which helps reduce artificial broadening of the droplet spectrum (Khain et al. 2008}. Regarding cloud microphysical processes, whilst calculations that include all processes handled by WRF-SBM were performed, this study focuses on the warm rain process within this framework, as highlighted in Sect. 1.’

RC1-02. l. 103: ”For the boundary-layer turbulence process, (Deardorff, 1980) scheme,”: For the boundary-layer turbulence scheme (Deardorff, 1980),

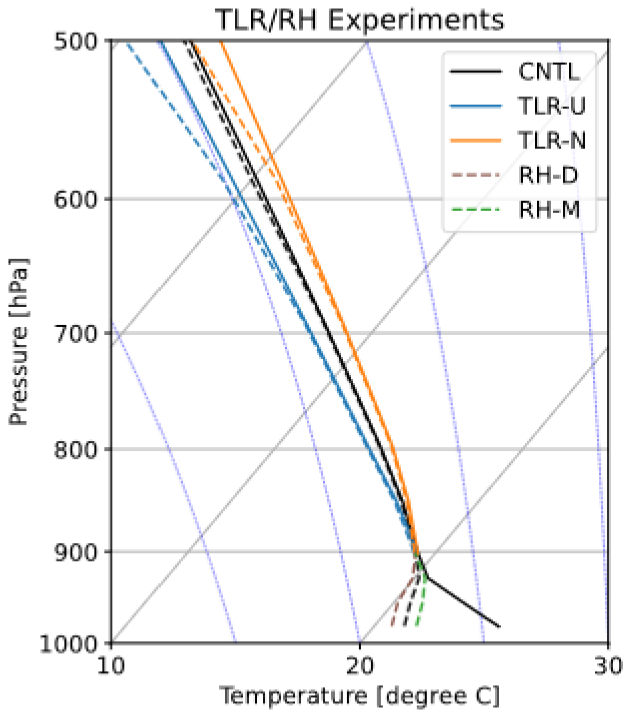
Reply: I have altered the sentence accordingly in Lines 123-124 in the revised manuscript.

RC1-03. l. 104: ”based on a heavy-rain-produced convective”: heavy rain-producing

Reply: I have corrected the word as you suggested in Line 102 in the revised manuscript.

RC1-04. Figure 2 is difficult to read. The symbols shown in the legend are not the same as *the ones on the plot. I would recommend using one color per experiment and one line style per temperature plotted, or some other clearly unambiguous scheme.*

Reply: Thank you for pointing this out. According to your comments, I have modified the way to show the experiments clearly in Fig. 2 in the revised manuscript as shown in below.



Also, I have slightly altered the corresponding sentences to clearly describe how the profiles were modified in the experiments in Lines 127-131 in the revised manuscript.

‘Based on observational relationships obtained in Unuma (2025), the experiments of increasing or decreasing the relative humidity in the layer below the lifting condensation level by up to 2 % but keeping the other profile as in CNTL (RH experiment: RH-D and RH-M in Fig. 2); of changing the temperature lapse rate in the layer above the lifting condensation level by up to 2 K km^{-1} but keeping the other profile as in CNTL (TLR experiment: TLR-N and TLR-U in Fig. 2); and of varying the wind speed throughout the troposphere to 0.5 or 1.5 times its original value (SH experiment: SH-W and SH-S in Fig. 3) were conducted.’

RC1-05. l. 108: ”Based on observational relationships obtained in Unuma (2025).”: this sentence is missing a verb.

Reply: I am very sorry for the sentence is not organised well. I have modified the sentence and connected to the following sentences in Lines 127-131 in the revised manuscript.

RC1-06. l. 112: What is ”the height of the temperature lapse rate”? Do you mean ”magnitude”?

Reply: Thank you for pointing this out. Yes, I do and have corrected the word in Line 132 in the revised manuscript.

RC1-07. section 2.3: please consider remplacing the bin numbers, which are not very useful to the readers not already intimate with the scheme used, with the actual sizes.

Reply: Thank you for suggesting. I have modified the sentence to describe the actual size of cloud (ranging from 4 to 160 μm in diameter) and rain (ranging from 0.2 to 6.6 mm in diameter) in Lines 146-148 in the revised manuscript.

RC1-08. l. 131: What is a ”momentum technique”? Do you mean moment?

Reply: I am sorry for the confusion. I have revised the sentence to make it clear that this study uses a moment-based calculation. This method utilises a drop-size distribution as normalised moments and is widely used to analyse the size distribution of raindrops. To be clarified, I have added the following sentence in Line 154-157 in the revised manuscript:

‘For the retrieval of DSD parameters on raindrops, i.e., the mass-weighted volume diameter (D_m; mm), the generalised intercept parameter (N_w; mm^{-1} m^{-3}), the liquid water content (LWC; g m^{-3}), were calculated assuming the normalised gamma distribution using a moment-based calculation (Hardin and Guy, 2017) as following procedures. This method handles a DSD as normalised moments and is widely used to analyse the size distribution of raindrops’

RC1-09. l. 152: ”When the R calculation, the data within ±50% of the raindrop-fall velocity formula of Atlas et al. (1973) are used.”: Can you clarify what this means?

Reply: Thank you for pointing this out. In raindrop size distributions obtained from real-world observations, unnatural fall velocities may sometimes be obtained due to various factors. This method is employed because a theoretical relationship between the fall velocity (i.e., terminal velocity) of raindrops and their size has been established, allowing their variation. To be clarified, I have added the following sentences in Lines 180-183 in the revised manuscript.

‘When the R calculation, the data within ± 50 % of the raindrop-fall velocity formula of Atlas et al. (1973) are used. In actual observations of raindrop size distributions, unnatural fall speeds may sometimes be obtained due to various factors. Since a theoretical relationship between the fall speed (i.e., terminal velocity) of raindrops and their size has been obtained as mentioned above, this method is also applied even if the simulation results are used in this study’

RC1-10. l. 165 states ”when the temperature lapse rate is high (TLR-U)”, while l. 182 states instead ”when the temperature lapse rate was low (TLR-U)”: which one is it?

Reply: Thank you for pointing this out. The higher temperature lapse rate should be represented as TLR-U. I have corrected the related sentences in Lines 213-216 in the revised manuscript.

RC1-11. l. 206: ”In the horizontal distribution, the spread of total rainfall increases with stronger vertical shear, suggesting that the statistical value tends to be higher.” I don’t understand what ”the statistical value” refers to.

Reply: I am very sorry for the description is not organised well. To be clarified, I have significantly altered the sentences as follows in Lines 238-240 in the revised manuscript.

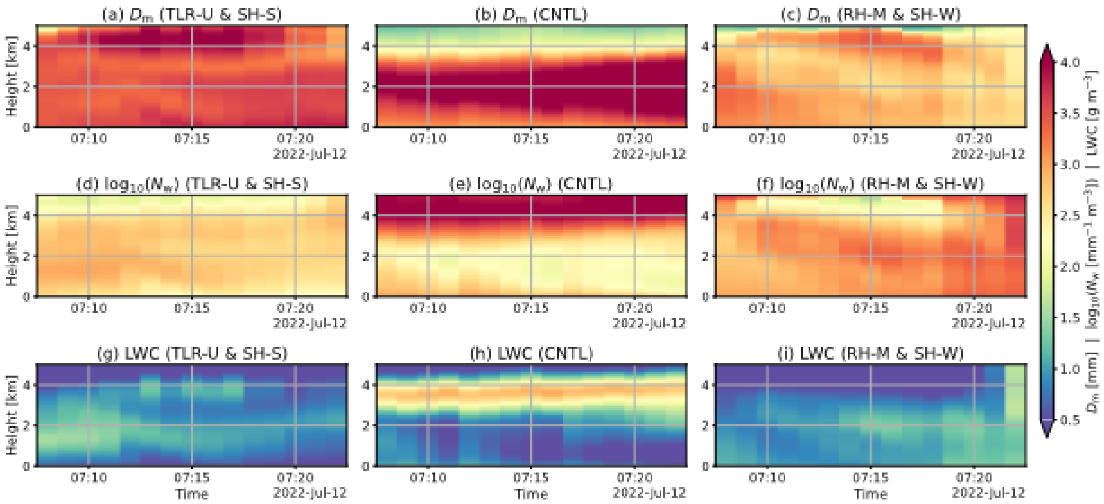
‘In the horizontal distributions, the horizontal spread of accumulated rainfall increases with stronger vertical wind shear (Figs. 4d, 4g, 5d, and 5g); however, the statistical value (e.g., 25th and 75th percentile values) tends to be smaller (Fig. 8b), which probably due to broader rainfall distribution.’

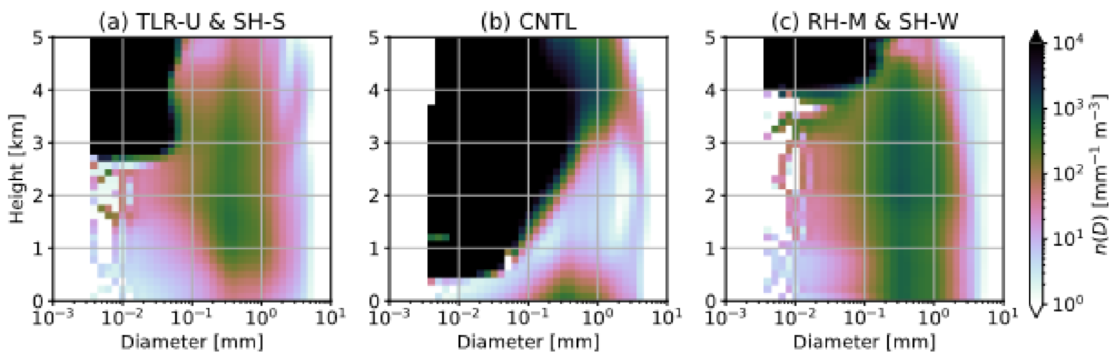
RC1-12. l. 207: What does "vertical flow" refer to?

Reply: Thank you for pointing this out. It should be vertical wind shear. To be clarified, I have changed the words to vertical wind shear in Line 241 in the revised manuscript.

RC1-13. The center column presenting the CTRL experiment is missing on Figure 9. Likewise, it would be interesting to show the CTRL experiment on Figure 10.

Reply: Thank you for suggestion. I have added CNTL experiment on both Fig. 9 and 10 in the revised manuscript as shown below.





In addition, I have altered the corresponding sentences to describe the characteristics of CNTL experiment in Sect. 3.4 in the revised manuscript.

RC1-14. l. 247: "vertical shear is sensitive to the time required for rainfall intensity to reach its peak and to its maximum intensity.": Isn't it the other way around, that the time of peak rainfall is sensitive to vertical shear?

Reply: Thank you for pointing this out. That's correct. As you suggested, I have altered the main text accordingly in Line 291 in the revised manuscript as follows.

'At the same time, the time of peak rainfall intensity is sensitive to vertical wind shear (Fig. 6).'

RC1-15. l. 249: what does "sensitivity to the speed of convective clouds" refer to?

Reply: I am very sorry for the description is not organised well. I was referring to the movement speed of the simulated convective clouds. Although this is not explicitly shown in Figs. 4 and 5, the horizontal distribution of accumulated rainfall indicates the peak location with crosses, and I was referring to the results of an analysis examining how far that location deviates from the start of the simulations. I have altered the main text to clarify this point in Lines 290-298 in the revised manuscript as follows.

'The results of this study indicate that the temperature lapse rate fundamentally controls the peak rainfall intensity (Fig. 4). At the same time, the time of peak rainfall intensity is sensitive to vertical wind shear (Fig. 6). Conversely, when the lower troposphere is highly moist, the propagating speed of convective clouds seems to be slowed down according to its peak location of the accumulated rainfall (Fig. 5). Furthermore, the strength of vertical wind shear can control both the speed of convective cloud motion and its maximum intensity (Fig. 5). Specifically, as shown in the rainfall intensity time series for temperature lapse rate (Fig. 6) and maximum intensity (Fig. 8a), the maximum rainfall intensity tends to be larger when the temperature lapse rate is high (i.e., more unstable) and when vertical wind shear is strong. This result is also reflected in the DSD parameters, where it fundamentally increases the Dm value (Fig. 9), thereby contributing to the rainfall intensity, as reflected in its integral value (i.e., Eq. (7)).'

RC1-16. l. 259: "the height of Nw": the magnitude of Nw.

Reply: Thank you for pointing this out. I have corrected the word accordingly in Line 302 in the revised manuscript.

RC1-17. l. 307: ”In this regard, this study succeeded in deciphering signals derived from limited observational data”: I do not believe this is true. The author does not present observational data in this manuscript.

Reply: I am very sorry for the description is not organised well. This study is intended as an extension of Unuma (2025)’s work, which demonstrated observed relationships between dominant in-cloud properties and environmental conditions using polarimetric weather radar, ground-based disdrometer, and upper-air sounding data. The term ‘limited observational data’ used here refers to the results presented in Unuma (2025). As you point out, this study does not utilise observational data. To clarify these intentions, I have altered the corresponding sentences in Lines 433-441 in the revised manuscript as follows.

‘However, whilst convective clouds that produce heavy rain are expected to interact with the surrounding atmosphere, few studies have investigated the dominant cloud microphysical processes by extending these interactions to the DSD within the convective clouds. This is simply because observational data, even when available, are merely snapshots, making it difficult to establish causal relationships (e.g., Feingold et al., 2025). In this regard, this study succeeded in deciphering signals derived from the available observational data by analysing these relationships (Unuma, 2025), and obtained results in this study that shed light on the underlying physical processes—albeit under idealised conditions in the numerical modelling framework. It has the potential to serve as a pioneering study that bridges mesoscale and microscale processes in meteorology. In this context, it could improve QPE and refines the physical processes handled in microphysics schemes within a numerical weather prediction model.’

Responses to the comments by Referee #2

Takashi Unuma

Thank you very much for taking the time to review and provide constructive comments on my manuscript. Your comments are very useful in improving the original manuscript. I will respond to your comments below. Your comments are written in *grey Italic*, while my responses are written in Roman. I have also included the document with track changes for your reference.

This article attempts to explore the impact of environmental stability, moisture, and vertical shear on raindrop size distributions in warm convective systems. The study uses WRF as a cloud resolving model coupled to a single moment bin-microphysics scheme to explicitly capture the formation of rain drops. The study uses an idealized setup (initial conditions) based on Unuma et al 2023. The study also has interesting results - the environmental lapse rate perturbations and moisture perturbations result in different microphysical responses. However, a deeper analysis is missing. Furthermore, the paper is not well-written and requires a lot of grammatical fixes. Most important issue is with the way results are presented. They read like mere presentations of numerical outputs. The authors have not put in any effort to carry out a more detailed or deeper analysis. Without that I cannot recommend the acceptance of this paper. The paper started off with an interesting premise: to assess the relationship between the environmental conditions and cloud microphysical processes. That is not achieved here.
In addition, the discussion section is mainly a summary of the results section. It would be good to put it in the context of the original premise.
My recommendation is a major revision.

> **Reply:** Thank you very much for taking the time to provide your thoughtful comments. I apologise that some descriptions were not organised well and that the interpretations of the results obtained in this study were not sufficiently clear in the original manuscript. In light of your comments, I have carried out additional simulations and added a new subsection; I have also made substantial revisions to the main text to clarify the interpretations and implications of the results obtained in this study, as described below.

RC2-01. Line 100 - Can you explain what radiative boundary conditions are? Provide mathematical expressions?

Reply: Thank you for your comments. Yes, it is one of the boundary conditions in a regional numerical model based on the approaches of Klemp and Wilhelmson (1978) and Klemp and Lilly (1978), which is also referred to as gravity-wave radiating boundary conditions.

Changes are applied to the horizontal velocity, scalar quantity, and non-normal momentum along the specified boundary. In terms of the normal horizontal velocities along a boundary on which the condition is specified, the momentum equation for the horizontal velocity is replaced by

$$\frac{\partial u}{\partial t} = -(u + c_*)\frac{\partial u}{\partial x},$$

where u is east-west component velocity and c_* is an approximated intrinsic phase velocity, respectively. In WRF-ARW, the term $(u + c_*)$ is replaced with $\min(u + c_*, 0)$ at the western boundary and is replaced with $\max(u + c_*, 0)$ at the eastern boundary. Likewise, the velocity is replaced for the south and north boundaries for the south-north component.

The flux divergence terms in the equations of motion for horizontal velocity, as well as for the scalar (ψ) and non-normal momentum variables, perpendicular to the boundary are replaced by

$$u\frac{\partial \psi}{\partial x} + \psi\frac{\partial u}{\partial x} = u^*\frac{\partial \psi}{\partial x} + \psi\frac{\partial u}{\partial x},$$

where u^* is replaced with $\min(u, 0)$ in WRF-ARW at the western scalar boundary, and is replaced with $\min(u, 0)$ at the eastern scalar boundary. Likewise, the flux divergence terms for the south and north boundaries are replaced using south-north component velocity.

In both cases, these terms are evaluated one-sidedly based on the difference between the boundary value and the value one grid-point inward from the boundary.

The above-mentioned explanations are very redundant and imbalanced for the main text, so I have simplified the descriptions as ‘Lateral boundary conditions were treated as open, following the approach of Klemp and Wilhelmson (1978) and Klemp and Lilly (1978).’ in Lines 101-102 in the revised manuscript.

RC2-02. Can you state what physical processes were ignored - lines 101-102?

Reply: Thank you for your comment. Yes, I can. Cumulus parameterisation, radiation process including longwave and shortwave, land surface process, and surface layer process were ignored in our simulations. To be clarified, I have altered the corresponding sentences in Lines 106-107 in the revised manuscript as follows.

‘To focus on the dynamics of individual convective clouds, the physical processes were simplified to include only cloud microphysics and boundary-layer turbulence schemes, i.e., excluding cumulus, radiation, land surface, and surface layer schemes.’

RC2-03. It would be good to report the CAPE for each experiment.

Reply: Thank you for your suggestion. I have added Table 1 in the revised manuscript to describe surface-based CAPE and PW using initial sounding data of each experiment as follows.

Environmental parameters	CNTL	TLR-N	TLR-U	RH-D	RH-M
sbCAPE (J kg^{-1})	828	438	1315	609	1071
PW (mm)	59.5	60.7	56.1	59.2	59.7

RC2-04. Line 108 - incomplete sentence.

Reply: I am very sorry for the description is not organised well. I have altered the sentence in Lines 127-131 in the revised manuscript as follows.

‘Based on observational relationships obtained in Unuma (2025), the experiments of increasing or decreasing the relative humidity in the layer below the lifting condensation level by up to 2 % but keeping the other profile as in CNTL (RH experiment: RH-D and RH-M in Fig. 2); of changing the temperature lapse rate in the layer above the lifting condensation level by up to 2 K km^{-1} but keeping the other profile as in CNTL (TLR experiment: TLR-N and TLR-U in Fig. 2); and of varying the wind speed throughout the troposphere to 0.5 or 1.5 times its original value (SH experiment: SH-W and SH-S in Fig. 3) were conducted.’

RC2-5. Line 112 - what do you mean by "height of the temperature lapse rate"?

Reply: Thank you for pointing this out. I was referring to the magnitude of temperature lapse rate and have changed the word to ‘magnitude of’ in Line 132 in the revised manuscript to make this clear.

RC2-6. Lines 116-118 - please provide a reference for this statement.

Reply: Thank you for pointing this out. I have altered the corresponding sentences in Lines 132-140 in the revised manuscript as follows.

‘The TLR experiment was conducted primarily because there is a positive correlation between the magnitude of the temperature lapse rate and the drop size within convective clouds (Unuma, 2025); such numerical experiments (e.g., Houston and Niyogi, 2007; Takemi, 2007; Sueki, 2024) have been conducted with similar assumptions. The RH experiment was conducted primarily because there is a positive correlation between water vapour content near the surface and rainfall (Unuma, 2025); the numerical experiments (e.g., Kato et al., 2003; Schumacher, 2015) have been performed under similar assumptions. Environmental parameters of surface-based convective available potential energy and precipitable water obtained from these initial profiles are summarised in Table 1. The SH experiment was conducted primarily because there is a positive (negative) correlation between the magnitude of the vertical wind shear of the horizontal wind within the troposphere and the drop size (number concentration) (Unuma, 2025).’

RC2-7. Line 120 - how is the magnitude of shear defined?

Reply: Thank you for pointing this out. The magnitude of the vertical wind shear was calculated using mean shear whose value averaged between 0 and 3 km as in Rasmussen and Blanchard (1998). To be clarified, I have added a sentence in Line 143-144 in the revised manuscript as follows.

‘The vertical wind shear of the horizontal wind speed averaged between 0 and 3 km was used and evaluated among SH experiments as in Rasmussen and Blanchard (1998); Unuma and Takemi (2016a).’

RC2-8. Line 123 - state the size range between cloud DSD and rain DSD.

Reply: Thank you for your suggestion. I have added the sentences describe actual size range of cloud (ranging from 4 to 160 μm in diameter) and rain (ranging from 0.2 to 6.6 mm in diameter) in Lines 146-148 in the revised manuscript.

RC2-9. Line 131 - why assume Gamma? You have the actual DSD from the SBM method.

Reply: Thank you for your question and comment. Yes, the DSDs for both cloud droplets and raindrops are calculated using WRF-SBM in our simulations. However, DSD parameters have traditionally been calculated primarily based on observational data; as such data is influenced by sensor sensitivity, very few observations actually extend to cloud droplets. Consequently, many previous studies have employed methods that calculate DSD parameters based on DSDs assumed to represent raindrops. Here, in line with this approach, I have carried out the calculations under conditions that are as similar as possible to those in previous studies, so that a comparison can be made. I have added some sentences in Lines 156-157 and Lines 174-176 in the revised manuscript to clarify this intention as follows.

'This method handles a DSD as normalised moments and is widely used to analyse the size distribution of raindrops.'

'The bin ranges from 17 to 33, whose sizes are ranging from 0.20 to 6.6 mm in diameter, were selected for retrieving the parameters because the parameters were envisaged to raindrops following previous studies (e.g., Seliga and Bringi, 1976; Gorgucci et al., 2000; Testud et al., 2001; Zhang et al., 2001; Thurai et al., 2008; Unuma et al., 2025).'

RC2-10. Fig 4 - what is the unit for accumulated rainfall?

Reply: Thank you for pointing this out. I have added the unit of mm in Figs. 4 and 5 in the revised manuscript.

RC2-11. Can you state the duration of each simulation?

Reply: The simulation period for all experiments conducted in this study is 2 hours. To clarify, I have added the following sentence in Line 124-125 in the revised manuscript.

'All simulations conducted in this study are integrated for 2 h with the large time step of 2 sec and their output interval is every 1 min.'

RC2-12. Can you provide some explanation for the observations presented in the results section?

Reply: Thank you for pointing this out. According to your comment, I have significantly altered Sect. 3 and Sect. 4 to describe the implications of the results obtained in this study. In particular, I have added a new subsection describing how raindrop breakup and evaporation affect in-cloud properties in our simulations. I have further developed the discussion regarding the relationship between dominant in-cloud properties and environmental conditions obtained in this study. Furthermore, I have thoroughly revised the interpretation of the results presented throughout Sect. 3 and polished the main text as a whole to ensure it flows smoothly into the discussion in Sect. 4.1 to 4.3.
The key finding is that, under humid and weaker shear conditions, the drop-size distribution tends to become vertically uniform regardless of whether raindrop evaporation occurs. These results explicitly demonstrate that, under humid and low-shear conditions, evaporation of raindrops is less likely in our simulations. Furthermore, these results suggest that under such conditions, an equilibrium distribution—which is rarely observed in nature—is formed; consequently, this may increase accumulated rainfall on the ground.

I hope you find Sect. 3 and 4 in the revised manuscript satisfactory, as it provides useful explanations based on the simulations obtained in this study as much as possible during the limited time.