Response to Reviewer #2

We are grateful to the reviewer for comments. Please find our responses below. Comments are in italics and our responses in normal style. Manuscript file with highlighted changes is available.

1 Major Comments

Validity of the conclusion *This paper provides valuable information to cloud modelers and is thus suitable for publication. On the other hand, the authors need to be more careful in drawing conclusions through deeper analysis, as the general validity of the conclusion is important for cloud modelers. The paper also lacks a proper explanation for the cause of the results. Most importantly, there is no clear explanation for why $\langle P \rangle$ and σ do not converge with N_{SD}^{bin} in 2D cumulus congestus (CC) simulations, contrary to the case of box simulations. Furthermore, the paper fails to elucidate why the decrease of $\langle P \rangle$ is caused by the increase of σ in CC simulations. The hypothesis that 'A smoother spatial distribution of the DSD, together with mixing may lead to more precipitation' (L347) does not provide proper evidence (The convergence with Δt_{coal} does not prove this hypothesis). It lacks an in-depth analysis of how DSD or σ develops with time within a cloud in both dynamics and kinematic simulations. They also argued that the increased variance negatively affects precipitation without proper evidence (L350).*

It is clear why σ does not converge in CC simulations (nor in box simulations). That is because N_{SD}^{bin} is smaller than the number of real droplets, hence the number of random trials for collision is smaller than it should be (Shima et al., 2009).

We do not claim to know why $\langle P \rangle$ converges slower in CC than in box. We do hypothesize that it is linked to the spatial distribution of the DSD. We made changes in the text to emphasize that this is a hypothesis and not a conclusion. To give the hypothesis more substance, we added a figure with a frequency histogram of the rain water content in the cloud at different moments in time. It shows that for small N_{SD}^{bin} the spatial distribution of rain is less uniform than for large N_{SD}^{bin} and that accumulated precipitation converges when its spatial distribution converges. We do not agree that convergence with Δt_{coal} is not compatible with this hypothesis. Box simulations show that σ is not sensitive to Δt_{coal}. The highly speculative paragraph at L350 has been removed.

Difference between CC and box simulations *To clarify the difference between CC and box simulations, I suggest carrying out another set of simulations; that is, the multi-box simulations with mixing between boxes, possibly using isotropic turbulence simulation. It can bridge the gap between box and CC simulations and helps to clarify the effect of mixing between grids, as suggested by the authors. For example, one can examine how DSD and σ are modified by directly comparing them with box simulation results. The direct comparisons of P and σ are not possible between box and CC simulations. One of the most serious drawbacks of this paper is that there are no one-to-one simulation results for CC simulations, so one cannot assess how close the simulation with $N_{SD}^{bin} = 10^5$ is to reality. The multi-box simulations allow one-to-one simulations that can be used as the reference simulation. It also supports the generality of the present result from CC simulations.*

We performed multi-box simulations as suggested. Their results are discussed in a new section after the box simulations section. Simulated domain is the same as in box simulations, but it is divided into smaller cells. SDs move due to isotropic turbulence and sedimentation. We found that in one-to-one simulations the DSD in multi-box is the same as in box even for very small multi-box cells that on average contain only one real droplet. When SDs represent more than one real droplet, we observe discrepancies from the reference result as cell size is decreased. Nevertheless, fewer SDs per cell are needed in multi-box than in box simulations. This suggests that mixing helps reach convergence, as already observed by Schwenkel et al. (2018). To understand how mixing affects convergence in CC, we also ran CC simulations with a model for sub-grid scale motion of super-droplets. We found that using this model helps reach convergence in precipitation, hence mixing plays a positive role in CC just like it does in multi-box simulations.

2 Minor comments

- *L40: a more detailed reference model ?*

  We now explicitly mention the name of the more detailed model, which is the one-to-one simulation, and provide a reference to Dziekan and Pawlowska (2017).

- *L125: There is no explanation of how the initial DSD is assigned for the LCM and*

SCE simulations, and how they are consistent with one-to-one simulations.

The method for initializing SD radii and multiplicities from a prescribed DSD is detailed in subsection 2.1 titled 'Initialization of SD Radii and Multiplicities'. SCE simulations are solved with the well-known flux method Bott (1997). To make sure that the initial DSD is the same for all methods used, we show it in Fig. 2 (a).

- *L162: I cannot understand why the authors suddenly discussed the LES model here.*

  Based on your suggestion, we have removed the discussion about the LES model. It indeed seemed out of place and could be distracting.

- *L227: proportional to N_{SD}^{bin-1}? (L227)*

  Yes, we've fixed it.

- *L260: I do not agree that dimensionality does not affect numerical convergence. If mixing between grid boxes is important for numerical convergence, as argued by the authors, the number of neighboring grids is different between 2D and 3D.*

  We agree, the paragraph has been revised.

- *L309: The difference in CWP is clear between LR, MR, and HR, contrary to the statement*

  The statement has been revised.

- *L348: Reference is required for 'lucky droplets'.*

  The paragraph about 'lucky droplets' has been removed as it was too speculative.

- *L365: only at large N_{SD}^{bin}*

  We don't agree. Even at small N_{SD}^{bin}, differences in the flow field (D simulations) give 4 times greater relative standard deviation of precipitation than differences in realization of collision-coalescence (MR simulations).

- *Fig. 2: σ does not converge with increasing N_{SD}^{bin}. What it shows is that σ approaches the result from one-to-one simulation. Without one-to-one simulation, the results are not that different from those from CC simulations (Fig. 9)*

  Yes, we agree. That's what we were trying to convey in the paper.

- *Fig. 2: I cannot see that $\langle m \rangle$ is smaller for N_{SD}^{bin} 10^2 for r > 50μm.*

  This can't be seen in Fig. 2 because of the logarithmic axis. It is visible in Fig. 3 (d). Figure 3 (d) is now referenced in the line where we write that $\langle m \rangle$ is smaller for N_{SD}^{bin} 10^2 for r > 50μm.

- *Fig. 5: The authors selected LR, MR, and HR based on $\langle P \rangle$, but Fig. 5 shows the frequency histogram of P.*

  Correct. To show a frequency histogram of $\langle P \rangle$ (average from an ensemble of kinematic simulations) we would need to run an ensemble of simulations for velocity field from each of around 1000 dynamical simulations shown in Fig. 5. That would be massive work for no clear reason, since our goal was to find 3 velocity fields that give different $\langle P \rangle$. Once such 3 fields were found, we stopped running kinematic ensembles.

- *Fig. 5: Horizontal axis is bin center? (P/10^2 ?)*

  Correct. The values are small because that is accumulated precipitation over the entire simulation time and the entire simulation domain, while the cloud precipitates only for a short time and over a small part of the domain. Maximum of the domain-averaged precipitation rate divided by cloud cover is around 10 mm/h (HR case).

- *Fig. 6: Isn't it natural to produce smoother variations, if the ensemble size of dynamical simulations is larger than that of kinematic simulations (= 20)? I also think that the authors should provide information on the ensemble size of box simulations and dynamic CC simulations (D) in the manuscript.*

  The final simulation ensemble of kinematic simulations for $N_{SD}^{bin} = 10^2$ (that is shown in the figure in question) was much larger than 20. We modified the text to emphasize that these 20 simulations were just a preliminary ensemble. The final ensemble size is now given in Tab.1 (for CC simulations) and in the text (for box and multi-box simulations).

References

Bott, A.: An efficient numerical flux method for the solution of the stochastic collection equation, Journal of Aerosol Science, 28, 2284–2293, https://doi.org/10.1016/S0021-8502(97)85371-2, 1997.

Dziekan, P. and Pawlowska, H.: Stochastic coalescence in Lagrangian cloud microphysics, Atmospheric Chemistry and Physics, 17, 13 509–13 520, https://doi.org/10.5194/acp-17-13509-2017, 2017.

Schwenkel, J., Hoffmann, F., and Raasch, S.: Improving collisional growth in Lagrangian cloud models: development and verification of a new splitting algorithm, Geoscientific Model Development, 11, 3929–3944, https://doi.org/10.5194/gmd-11-3929-2018, 2018.

Shima, S., Kusano, K., Kawano, A., Sugiyama, T., and Kawahara, S.: The super-droplet method for the numerical simulation of clouds and precipitation: A particle-based and probabilistic microphysics model coupled with a non-hydrostatic model, Quarterly Journal of the Royal Meteorological Society, 135, 1307–1320, https://doi.org/10.1002/qj.441, 2009.