Response to Reviewer #1

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

1 Major Comments

Condensation-coalescence bottleneck. *Similar to the study by Hill et al. (2023), I believe that the high susceptibility to the number of computational particles is the very narrow droplet size distribution(DSD) caused by condensation, from which it is very hard to initiate collision-coalescence. For such distribution, producing sufficiently large precipitation embryos to start the collision-coalescence process is very important, and depends heavily on the number of computational particles to sample the tails of the DSD correctly. I suspect condensation narrowing is much more prominent in the kinematic simulations, in which condensation does not interact with the dynamics. Accordingly, the convergence in the kinematic simulations is much slower than in the dynamic simulation (Figs. 8 and 9). If this is true, the slow convergence cannot be seen as an inherent defect of Lagrangian cloud microphysical schemes, but must be considered a result of the artificially narrow DSD. To address this issue, additional analyses on the development of the SD width before the onset of collision-coalescence are highly recommended. Are there differences in the DSD width between the dynamic and kinematic simulations before collision-coalescence onset? How does the DSD width before collision-coalescence onset change with the computational particle number? If there are substantial differences between the dynamic and kinematic simulations, I highly recommend adding stochastic supersaturation fluctuations to the condensational growth [e.g., the approach by Grabowski and Abade (2017)] to obtain a realistic DSD width.*

We expanded the analysis of simulations without collision-coalescence by adding a figure with profiles of droplet number concentration, mean radius and relative dispersion. This is done to check how the DSD width before onset of collision-coalescence (which up to that point is solely dependent on the condensational growth) changes with the number of SDs. We find that all profiles converge for 1000 SDs. That is faster than the convergence of precipitation, hence differences in precipitation are unlikely to be caused by differences in modeling of condensational growth.

The DSD width is similar in kinematic and dynamic simulations. Relative dispersion is around 0.2, indicating a narrow DSD, but within the range of observed values in stratiform (Miles et al., 2000; Pawlowska et al., 2006) and cumuliform (Lu et al., 2013) clouds. Therefore, the collision-coalescence algorithm should be expected to perform well for the DSD we get in the model. Nevertheless, we attempted to increase the DSD width by using the stochastic supersaturation model of Grabowski and Abade (2017) (henceforth GA17). Resulting profiles are shown in fig. 1. We observed a significant number of cloud droplets above the level at which there is cloud top in simulations without the GA17 model. This is most probably a consequence of randomness in GA17 – some 'lucky' SDs have a large positive supersaturation fluctuation, large enough for them to grow despite the fact that on average the grid cell is subsaturated. The number of such lucky SDs increases with the number of SDs, so we do not find convergence of results with the number of SDs. Due to these issues, we decided to not include simulations with GA17 in the paper.

More quantities. *The number of analyzed quantities to determine convergence is relatively low. While I understand the choice for the surface precipitation rate as the main subject, I recommend also checking the cloud base precipitation rate. Differences in the convergence of surface and cloud-base precipitation rates could indicate differences in the evaporation below cloud base. Furthermore, I miss deeper analyses of the convergence of the liquid water path (LPW) and rain water path (RWP), as well as the cloud droplet concentration. As all these parameters determine the surface precipitation rate, a comprehensive convergence on precipitation study should not negate them.*

Convergence of time series of cloud water path, RWP, cloud top height, cloud cover and surface precipitation is already shown in the supplement. In the main text, we have added plots of convergence of vertical profiles of precipitation flux. These help understand how differences in rain are distributed with height, including the cloud base level.

As described in the response to comment 1, we also added convergence plots for profiles of the liquid water content and cloud droplet concentration for simulations without collision-coalescence. These figures for simulations with collision-coalescence look very similar, hence we do not show them.

Cloud-type dependence. *This study makes a strong statement on how many computational particles must be used in Lagrangian cloud microphysics schemes. However, these results are only obtained for one specific cloud type, a single cumulus congestus cloud. First, cumulus congestus are not a singularity. If a first cloud does not rain sufficiently, preconditioning might allow a second cloud to rain more, and vice versa. Thus, the convergence rate of an individual cloud has limited meaning. Thus, I recommend adding simulations of a cloud field. As I see that simulating several cumulus congestus can be cumbersome, I suggest simulating a standard shallow cumulus case (BOMEX, RICO). Furthermore, the convergence of drizzling stratocumulus can be a worthwhile extension (DYCOMS-II, RF02), primarily since they can easily be represented in a two-dimensional framework.*

The collision-coalsecence algorithm, which is the subject of this study, works in the same way in different cloud types. For generality, we study cases with different amounts of rain, but we do not agree that it is necessary to study different cloud types. It is true that for some cloud types, e.g. ones with a wider DSD, it may be easier to reach convergence in precipitation. However, we believe that it is better to study convergence for the more demanding, yet realistic cases (as in our study: the DSD is narrow, but within observational range). Convergence in the difficult case implies convergence in the simple case.

We consider modeling a single cloud as advantageous for studying collision-coalescence. It is true that if in a cloud field one cloud rains less than expected (e.g. due to errors in the collision-coalescence model), then there can be more water vapor left, or the aerosol size spectrum can be different due to in-cloud processing, and in consequence a subsequent cloud may produce more rain than expected. However, the collision-coalescence algorithm should correctly predict the amount of rain already in the first cloud and the effect described above would only make it more difficult to study correctness of the collision-coalescence algorithm.

2 Minor comments

- *L. 96: Is there a reference to support this statement?*

  Yes, we have added a reference to Shima et al. (2009).

- *L. 99: Give an equation for $P_{i,j}$.*

  It has been added.

- *Ll. 124 – 125: From what are the mean and standard deviation calculated? I assume the ensemble of simulations, but this should be stated clearly. Ll. 139 – 140: How* *large is the ensemble?*

It is now clearly stated that these are statistics from an ensemble of simulations. The size of the ensemble is now given in Tab. 1.

- *Ll. 146 – 150: Where do we see this?*

  This can be seen in Fig.1, as now indicated in parentheses.

- *Ll. 160 – 162: How can one estimate the standard deviation from the SCE by taking the square root of the number of droplets? I think this approach can be correct, but the authors must elaborate.*

  This estimation, originating from Gillespie (1975), is introduced in section 3. We have added a reference to Gillespie (1975) in the lines in question.

- *Fig. 3, ll. 165 – 173: This analysis is distracting. I suggest removing it.*

  When comparing droplet size distributions on a log-log plot, as done in Figs. 1 and 2, it is easy to miss smaller errors. In the figure and lines in question, we plot the difference between the result and reference, which is a more detailed comparison. Differences revealed that way are consistent with differences in precipitation found in 2D simulations. For these reasons, we decide to keep this analysis in the manuscript.

- *Ll. 203 – 206: If small differences result in differences in rain formation, they should be visible in the moments that are most susceptible to rain, e.g., the 6th moment of the DSD or the radar reflectivity, which is analyzed in Unterstrasser et al. (2017, 2020).*

  We agree that higher moments are more sensitive to rain (large end of the DSD). Rain formation is in turn sensitive to collision-coalescence, so our intuition is that higher moments should converge more slowly. This is in fact what we find, contrary to Unterstrasser et al. (2017,2020). We have updated the paragraph in this spirit.

- *Eq. 3: What is "n"?*

  It is now clearly written that this is the ensemble size.

- *Fig. 5: Does the ordinate show "the number of simulations with P within a bin"? The resultant number of simulations seems to be very high.*

  Yes, it does. We conducted over 1000 dynamical simulations when generating velocity fields.

- *L. 337: Stating that more than 1000 computational particles per grid box are necessary to simulate condensation correctly, needs to be supported by data.*

  This statement was based on convergence of time series in simulations without collision-coalescence, which is discussed beforehand. Figures with profiles from these simulations, which have been added to the paper, further support this.

  The section about simulations without coalescence is now referenced in the line in question.

- *Sec. 4.7: The initialization method might strongly impact how the aerosol size distribution is represented, and hence droplet activation. Thus, there might be differences in the droplet concentration and, commensurately, the rain rate.*

  Initial size distribution for different initialization methods is shown for box simulations (Fig. 2). When averaged over multiple cells, the agreement is very good. This is now also stated in Sec. 4.7.

- *Ll. 404 – 420: Can the approach by Schwenkel et al. (2018) help to accelerate convergence?*

  Possibly it could help. We have added a comment about it in Conclusions.

3 Technical Comments

The text is understandable, but there is a large number of spelling and grammatical errors that need to be taken care of.

We have tried to fix such errors.

- *L. 79: Write about "bin edges" already here. "Edges" without context is confusing.*

  Changed to "bin edges".

- *Ll. 116 – 117, ff.: When narrative citations (\citet{...}) are used, a semicolon should not separate the individual references, but a comma or an "and".*

  Style of citations is defined by the GMD Latex template.

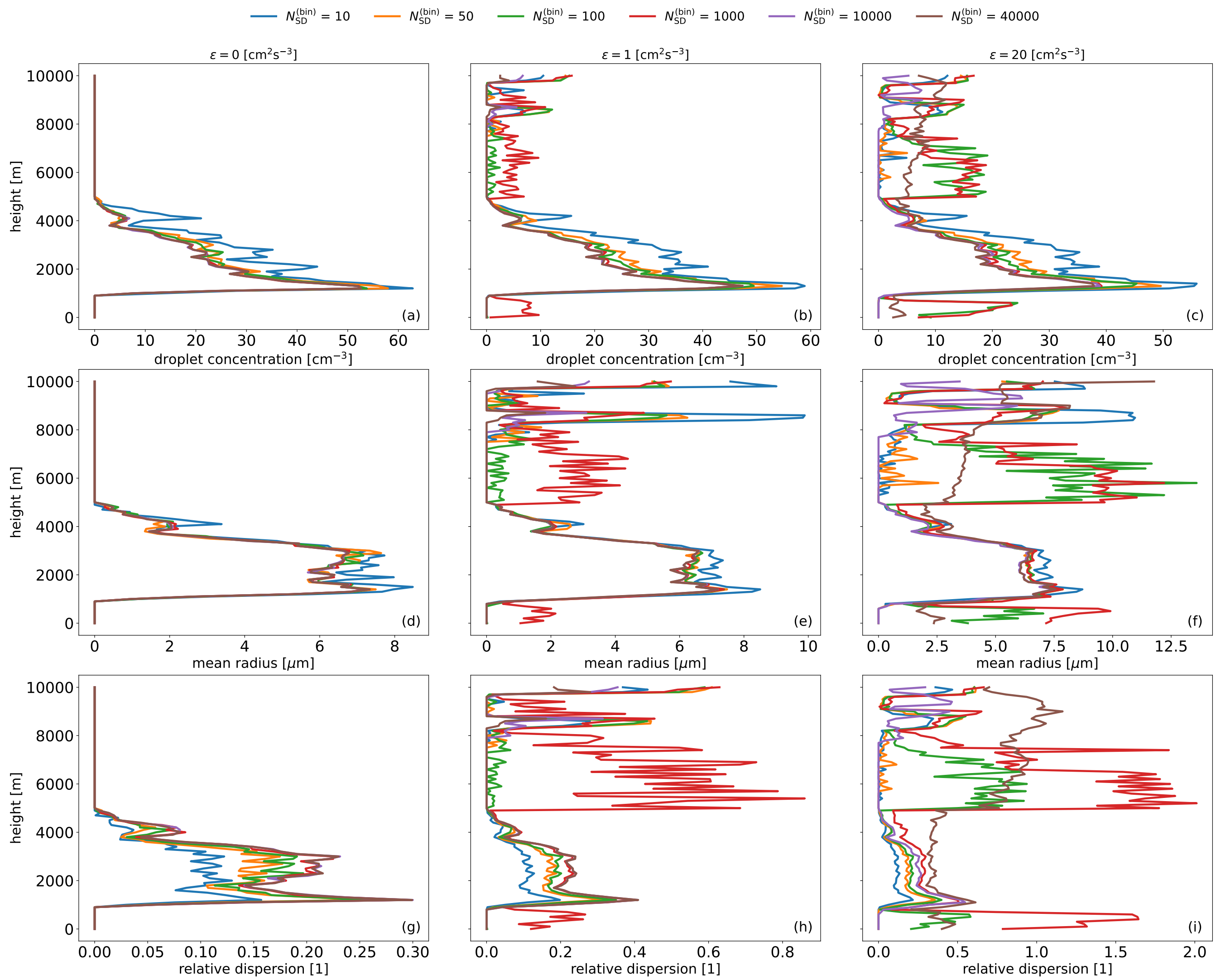

Figure 1. Profiles of cloud droplet concentration (top row), cloud droplet mean radius (center row), and relative dispersion of cloud droplet radius (bottom row) from HR simulations with GA17 and without collision-coalescence. These profiles are averaged across cloudy cells and over a time interval ranging from 1800 s to 9600 s within the ensemble of simulations. Columns show results for different values of the TKE dissipation rate (different SGS turbulence strength): $0\,\mathrm{cm^2 s^{-3}}$ (left), $1\,\mathrm{cm^2 s^{-3}}$ (center) and $20\,\mathrm{cm^2 s^{-3}}$ (right).

References

Gillespie, D. T.: Exact Method for Numerically Simulating the Stochastic Coalescence Process in a Cloud., Journal of the Atmospheric Sciences, 32, 1977–1989, https://doi.org/10.1175/1520-0469(1975)032¡1977:AEMFNS¿2.0.CO;2, 1975.

Lu, C., Niu, S., Liu, Y., and Vogelmann, A. M.: Empirical relationship between entrainment rate and microphysics in cumulus clouds, Geophysical Research Letters, 40, 2333–2338, https://doi.org/https://doi.org/10.1002/grl.50445, 2013.

Miles, N. L., Verlinde, J., and Clothiaux, E. E.: Cloud Droplet Size Distributions in Low-Level Stratiform Clouds, Journal of the Atmospheric Sciences, 57, 295 – 311, https://doi.org/https://doi.org/10.1175/1520-0469(2000)057¡0295:CDSDIL¿2.0.CO;2, 2000.

Pawlowska, H., Grabowski, W. W., and Brenguier, J.-L.: Observations of the width of cloud droplet spectra in stratocumulus, Geophysical Research Letters, 33, https://doi.org/https://doi.org/10.1029/2006GL026841, 2006.

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.