Comment response
Referee 1

Masaya Iwashima, Ryo Onishi

Major Comments

1

comment

> The manuscript makes no reference to "eddy hopping" , a key mechanism for turbulence-induced broadening of cloud droplet size distributions (DSDs). Foundational studies such as Grabowski and Abade (2017), Abade et al. (2018), and Saito et al. (2021) are highly relevant to the present vertically extended quasi-1D configuration, yet they are neither cited nor discussed. This represents a major gap in both the Introduction and Discussion sections.

response

According to your comment, we added a description of the overview of the turbulence effects including turbulence-enhanced collision, eddy hopping and entrainment, together with relevant references (Grabowski and Abade, 2017; Abade et al., 2018; Saito et al., 2021) in the Introduction section (L41-53). We added a description of our focus, which is turbulence-enhanced collision (L54). We also added a description that the effect of turbulence on water-vapor field (supersaturation fluctuation) is not considered in this framework (L200-201).

The representation of eddy hopping is outside the scope of the present study. Eddy hopping is associated with droplet transport by large-scale eddies of convection, whereas the limited horizontal domain size used in this study does not resolve such large-scale motions. Therefore, the present framework can represent micro-scale turbulence-induced collisions but cannot explicitly represent eddy hopping.

2

comment

> The “Results and Discussion” section is dominated by detailed interpretation of the authors’ own simulations (e.g., enhanced autoconversion in the middle layer, earlier precipitation onset by 270 s, and larger initial raindrops in the turbulent case). However, it provides very limited comparison with existing literature and observations. Specifically, the manuscript lacks:
>
> - Comparison with aircraft observations from warm-cloud field campaigns (e.g., RICO; Rauber et al. 2007) regarding DSD broadening, precipitation onset timing, and altitude-dependent microphysical properties.
> - Benchmarking against high-resolution LES studies using Lagrangian or bin microphysics, as well as other 3D DNS and stochastic parcel/updraft models.

response

According to your comment, we added descriptions to clarify the connections between our study and previous studies. In addition, related to this topic, we clarified the objective of the present study.

KiD warm-1 benchmark was developed based on the Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) Rain In Cumulus over the Ocean (RICO) composite intercomparison (Rauber and coauthors, 2007), which is an in-situ observation-based intercomparison campaign (L204-206). Kunishima and Onishi (2018) used the KiD warm-1 benchmark and demonstrated good agreement between the present Lagrangian framework and a spectral-bin model (L107-109). We confirmed that the results obtained in the present LAM-case are consistent with those reported in Kunishima and Onishi (2018), which is expected because the model configuration is essentially identical (L307-308).

Although direct comparisons with aircraft observations or LES studies for the TURB-case was not conducted, this is justified because the primary objective of the present study was not to reproduce the detailed evolution of a realistic marine cumulus cloud, but to conduct a controlled kinematic sensitivity experiment that isolates the effects of prescribed dissipation-scale turbulence on collision-coalescence under cloud-depth thermodynamic conditions (L116-118).

3

comment

> The inherent limitations of the kinematic driver approach (KiD warm-1) — including the absence of entrainment and mixing, simplification of large-scale updraft structure, lack of time evolution in the HIT snapshots, and artificial vertical repetition — are not adequately discussed in terms of their implications for the robustness and generalizability of the results to real clouds.

response

According to your comment, we substantially expanded the discussion of the model limitations at the end of the Conclusion section (L486-497).

The present framework does not consider the large scale of convection. Consequently, large-scale processes such as eddy hopping are not represented. The present framework adopted a kinematic framework, in which the interaction between cloud dynamics and cloud microphysics is neglected. Thus, entrainment and mixing processes cannot be represented. In addition, the assumption of frozen turbulence may lead to an overestimation of collision rates (Zhou et al., 1998; Franklin et al., 2005). Furthermore, artificial vertical repetition of turbulence field required a treatment to suppress curtain-like particle structures. This may introduce errors into the turbulence-enhanced collision statistics. In the present study, we only conducted a single simulation for each case. When the initial conditions (e.g., the initial droplet positions), HIT snapshots, or the treatment of the curtain-like structures are changed, the results may vary. These limitations should be addressed in future work.

Due to the above-mentioned limitations, the quantitative magnitude of the turbulence effects obtained in this study, such as the 270 s *difference in precipitation onset, cannot be directly generalized to real clouds. Nevertheless, the present results demonstrate the capability of the present framework to conduct direct analysis of turbulence-induced collision-coalescence through explicit tracking of the individual droplets while accounting for the cloud-depth thermodynamic structures.*

Minor Comments

1

comment

The Introduction should include a more comprehensive literature review covering eddy hopping / stochastic condensation studies and recent 1D versus 3D turbulence-microphysics modelling efforts.

response

According to your comment, we added a more comprehensive literature review in Introduction section (L45-53).

The mechanism of turbulent dispersions of cloud droplets was suggested by Cooper (1989). The key idea is that droplets arriving at the same location experience different supersaturation histories due to turbulent transport. The resulting variability in condensational growth broadens the size distributions of cloud droplets. Subsequent studies investigated this mechanism using both 1D stochastic frameworks and 3D direct numerical simulations (DNS). Stochastic parcel models investigated droplet spectral broadening caused by unresolved turbulent supersaturation fluctuations and the resulting differences in droplet growth histories (Grabowski and Abade, 2017; Abade et al., 2018; Saito et al., 2021). DNS studies directly resolved local supersaturation fluctuations and investigated their influence on condensational spectral broadening (Vaillancourt et al., 2002; Sardina et al., 2015). Grabowski and Wang (2013) proposed the name "eddy hopping" for this mechanism.

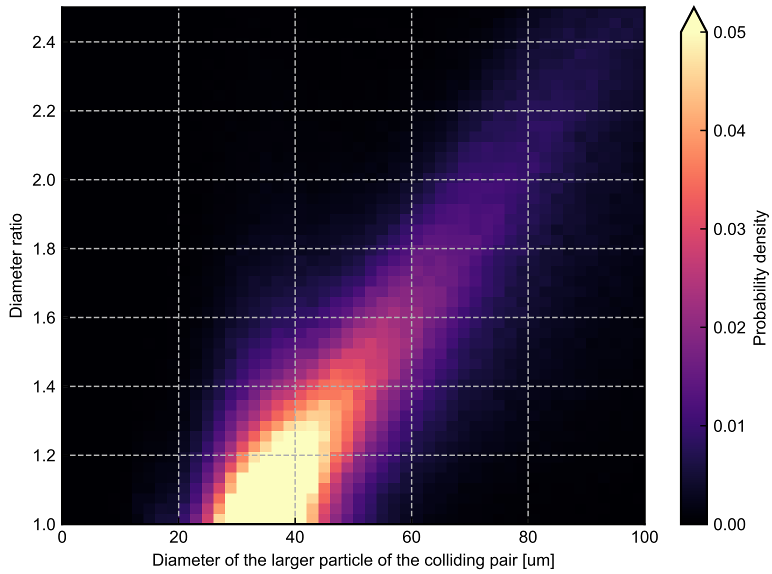

Figure S1: 2D histogram of collision probability as a function of the larger particle diameter in a colliding pair and the particle-diameter ratio of the pair in TURB-case.

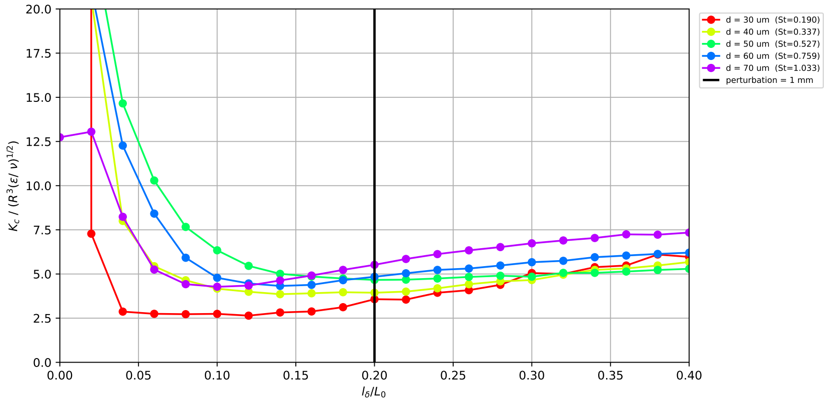

Figure S2: (Figure 3 in the revised manuscript.) The dependency of the collision kernel, K_c, to the maximum perturbation length normalized by the domain size l_δ/L_0.

2

comment

Greater transparency and sensitivity testing regarding the vertical stacking of HIT snapshots and the random particle position perturbations (±1 mm) would strengthen the Methods section.

response

According to your comment, we have expanded the discussion of the vertical stacking of HIT snapshots and the random particle position perturbations. The paragraph describing the perturbations was moved from Overview section to Homogeneous isotropic turbulence section (L247-273). In addition, the limitation of this treatment was included in the Conclusion section (response to Major Comment 3).

The discussion of the vertical stacking of HIT snapshots is as follows. *When particles settle under gravity in a periodic turbulent field, curtain-like particle structures form because of the interaction between large-scale turbulent eddies and the particle settling velocity (Woittiez et al., 2009). The formation of the curtain-like structures is related to the ratio of the time required for particles to cross one HIT block by gravitational settling,* T_L*, and the large eddy turnover time,* T_e*. The structures form when* $T_L/T_e < 1$*. In order to avoid those artificial structures affecting the particle collisions, we added random perturbations to the horizontal particle positions when settling particles cross the horizontal boundary of the vertically aligned cubic snapshot of HIT. The perturbations were set to follow a uniform distribution between* $l_\delta/L_0 = 0.2$ *and* $l_\delta/L_0 = -0.2$*, where* l_δ *is the maximum perturbation length and* L_0 *is the size of the HIT snapshot.*

To examine the influence of this treatment, we performed test simulations in a periodic box domain. The flow field was given by the same HIT snapshot used for the simulation in the vertically-elongated domain. The number of particles was set to be 10000 *to obtain sufficient collision statistics. The particle positions were homogeneously distributed at the initial time. In the present HIT setting, the condition* $T_L/T_e < 1$ *corresponds to* $\mathrm{d_p} > 31.4\ \mu\mathrm{m}$*. Therefore, monodisperse particles with diameters of* $30,\ 40,\ 50,\ 60,\ 70\ \mu\mathrm{m}$ *were considered. The upper diameter limit of* $70\ \mu\mathrm{m}$ *was selected because collisions between particles of comparable size larger than* $70\ \mu\mathrm{m}$ *was negligibly rare compared to the different-sized droplet collisions due to the settling velocity differences in the vertically-elongated simulations (figures not shown).* This is supported by Figure S1, which shows the 2D histogram of collision probability as a function of the larger particle diameter in a colliding pair and the particle-diameter ratio of the pair in TURB-case. *The time interval was set to be* 5.0×10^{-5} s*, which was identical to that used in TURB-case (see Table 4 in Section 3.4). Duration time was* 50 s*. The statistics were averaged from* $t = 20$ s *to* $t = 50$ s*, which was enough to reach the statistically steady state since* $20\ \mathrm{s} > 100T_e$*.*

Figure 3 shows the dependency of the collision kernel, K_c*, on the maximum perturbation length normalized by the domain size* l_δ/L_0*.* K_c *was larger for small perturbation length, indicating an artificial enhancement associated with the curtain-like structures. It decreased as the perturbation length increased. Around a perturbation length of* $l_\delta/L_0 = 0.2$*,* K_c *became much less sensitive to further increases in the perturbation length.*

In the size range of $30-70\ \mu\mathrm{m}$*,* $\tau_\eta/T_L = 0.067-0.37$*, where* τ_η *is the Kolmogorov time scale. The ratio* τ_η/T_L *represents the extent to which particles can experience dissipation-scale turbulent motions while settling across one HIT block, which is related to the RDF. Furthermore, in this size range,* $\tau_\mathrm{p}/T_L = 0.015-0.46$*, where* τ_p *is the particle relaxation time. The ratio* τ_p/T_L *represents the degree to which particle velocities can adjust to the local flow during the settling motion, which is related to the RRV. These time-scale ratios suggest that the perturbation treatment is not expected to substantially alter the contact RDF, RRV, or collision kernel in the present parameter range. However, the values of* τ_η/T_L *and* τ_p/T_L *are not much smaller than unity, indicating that some influence on the detailed collision statistics may still remain.*

Others

1

comment

L234: “corrposonding” -> “corresponding”

response

According to your comment, we corrected the spell (L411).

References

G C Abade, W W Grabowski, and H Pawlowska. Broadening of cloud droplet spectra through eddy hopping: Turbulent entraining parcel simulations. *J. Atmos. Sci.*, 75:3365–3379, 2018. doi: https://doi.org/10.1175/JAS-D-18-0078.1.

W A Cooper. Effects of variable droplet growth histories on droplet size distributions. part i: Theory. *J. Atmos. Sci.*, 46:1301–1311, 1989. doi: https://doi.org/10.1175/1520-0469(1989)046<1301:EOVDGH>2.0.CO;2.

C N Franklin, P A Vaillancourt, M K Yau, and P Bartello. Collision rates of cloud droplets in turbulent flow. *J. Atmos. Sci.*, 62:2451–2466, 2005. doi: https://doi.org/10.1175/JAS3493.1.

W W Grabowski and G C Abade. Broadening of cloud droplet spectra through eddy hopping: Turbulent adiabatic parcel simulations. *J. Atmos. Sci.*, 74:1485–1493, 2017. doi: https://doi.org/10.1175/JAS-D-17-0043.1.

W W Grabowski and L P Wang. Growth of cloud droplets in a turbulent environment. *Annu. Rev. Fluid Mech.*, 45:293–324, 2013. doi: https://doi.org/10.1146/annurev-fluid-011212-140750.

Y Kunishima and R Onishi. Direct lagrangian tracking simulation of droplet growth in vertically developing cloud. *Atmos. Chem. Phys.*, 18:16619–16630, 2018. doi: https://doi.org/10.5194/acp-18-16619-2018.

R M Rauber and coauthors. Rain in shallow cumulus over the ocean: The rico campaign. *Bull. Am. Meteorol. Soc.*, 88:1912â 1928, 2007. doi: https://doi.org/10.1175/BAMS-88-12-1912.

I Saito, T Watanabe, and T Gotoh. Statistical properties of a stochastic model of eddy hopping. *Atmos. Chem. Phys.*, 21:13119â 13130, 2021. doi: https://doi.org/10.5194/acp-21-13119-2021.

G Sardina, F Picano, L Brandt, and R Caballero. Continuous growth of droplet size variance due to condensation in turbulent clouds. *Phys. Rev. Lett.*, 115:184501, 2015. doi: https://doi.org/10.1103/PhysRevLett.115.184501.

P A Vaillancourt, M K Yau, P Bartello, and W W Grabowski. Microscopic approach to cloud droplet growth by condensation. part ii: turbulence, clustering, and condensational growth. *J. Atmos. Sci.*, 59:3421–3435, 2002. doi: https://doi.org/10.1175/1520-0469(2002)059<3421:MATCDG>2.0.CO;2.

E J P Woittiez, H J J Jonker, and L M Portela. On the combined effects of turbulence and gravity on droplet collisions in clouds: a numerical study. *J. Atmos. Sci.*, 66:1926–1943, 2009. doi: https://doi.org/10.1175/2005JAS2669.1.

Y Zhou, S Anthony, and L P Wang. On the collision rate of small particles in isotropic turbulence. ii.

finite inertia case. *Phys. Fluids*, 10:1206–1216, 1998. doi: https://doi.org/10.1063/1.869644.