Reviewer #3

This manuscript is focused on the development of a new prognostic parameter that controls graupel density and fall terminal speed in the WDM6 microphysics scheme. The 2-D idealized simulation of a squall line scenario was compared with observations from the ICE-POP 2018 field campaign during the Winter Olympics in Pyeongchang, Korea. Overall, the manuscript is well written and easy to follow. The reviewer has 3 main comments related to the impacts on cloud microphysical processes, the relationship with thermodynamic conditions specifically relative humidity, and the evaluation against more measurements. Reviewer recommends the manuscript being revised by addressing the following comments. Below are the main comments.

: Thank you for your constructive feedback. We have thoroughly addressed all comments raised by the reviewer in the revised manuscript. The detailed responses are noted as below.

1. Figure 6 shows the evolution of graupel density and mixing ratio as well as the key source and sink terms. This figure is very helpful for understanding the formation of graupel. Can the authors also provide this figure for the WDM6_FD simulation? In addition, the reviewer suggests more discussion about the impacts and differences related to cloud microphysical processes. The authors can consider adding supplemental figures showing this type of cross sections in an evolutionary view for other variables, including cloud liquid, cloud ice, snow, and relative humidity with respect to ice.

: In response to the reviewer’s comments, we have added Figure 7, presented graupel mass mixing ratio and key source and sink terms for the WDM6_FD, with the following additional sentences in the revised manuscript:

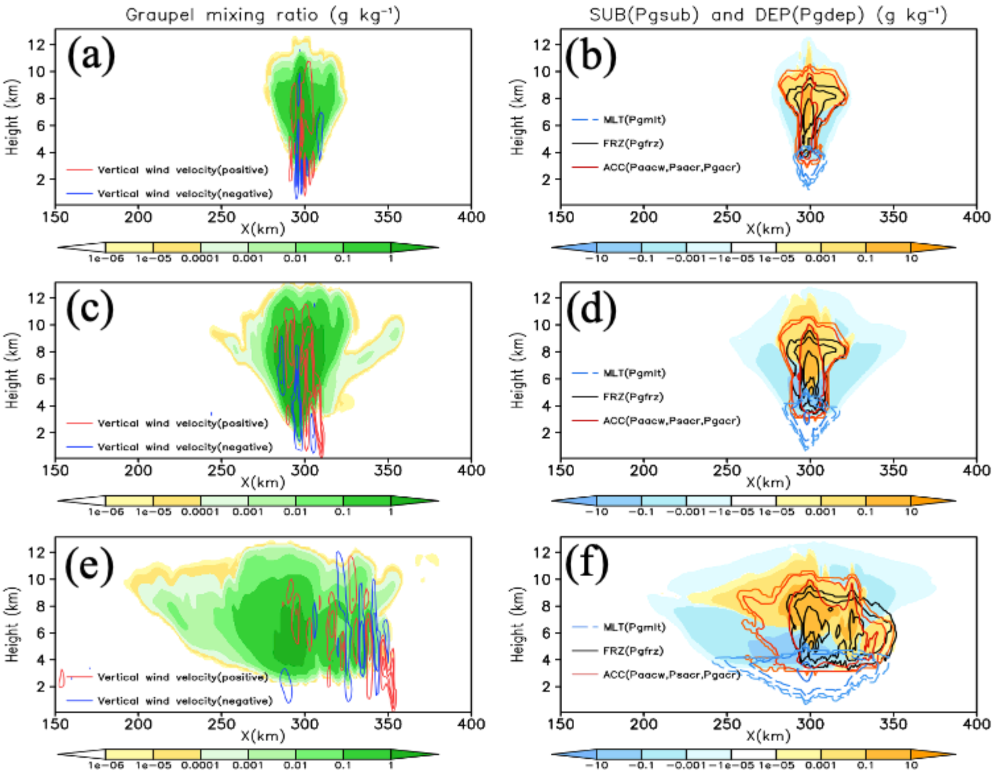

Figure 7. Same as Figure 6, but for WDM6_FD.

Line 317: “Same microphysical properties as in Figure 6, but for WDM6_FD, are shown in Fig. 7 except ρ_G. Note that ρ_G in WDM6_FD is pre-defined as 500 kg m^{-3}. Throughout the simulation period, WDM6_FD produces a more abundant mass mixing ratio of graupel, reaching higher vertical levels and simulating a wider region for SUB (compare Figs. 7 and 6). At 2 h, graupel continues to be generated through DEP, ACC and FRZ, and the region with active SUB expands compared to the initial stage (Figs. 7c and d). At 4 h, more graupel is transported into the anvil cloud region at relatively lower levels compared to WDM6_FD due to active DEP and ACC in the corresponding region (Figs. 7e and f)."

Additionally, as shown in the newly added flowchart of mass mixing ratio and number concentration (Fig. A1) in the appendix, the modified microphysics processes due to the predicted graupel density affect the evolution of other hydrometeors including graupel. We have included the following supplemental figures (Figs. S2-S5) depicting the cross-sections of cloud liquid, cloud ice, snow mass mixing ratio, and relative humidity with respect to ice (RHice) with the following sentences in the revised manuscript:

Line 324: "As we mentioned in section 2, varying parameters with the predicted graupel density can affect the mass mixing ratio and number concentration of other hydrometeors. The spatial distribution of the mass mixing ratio of other variables (cloud water, cloud ice, and snow) and the relative humidity with respect to ice (RHice) during the development stage of convection are available in Figures S2 to S5 of the supplement."

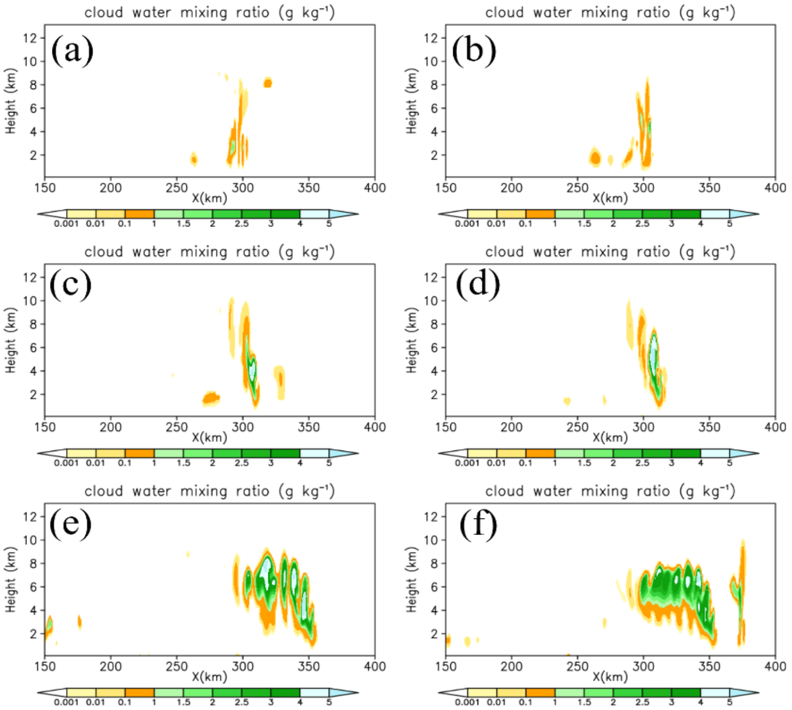

Figure S2. Spatial distribution of cloud water mass mixing ratio (g kg^{-1}) in WDM6_FD (a, c, and e) and WDM6_PD (b, d, and f) at 1 hour (a and b), 2 hour (c and d), and 4 hour (e and f).

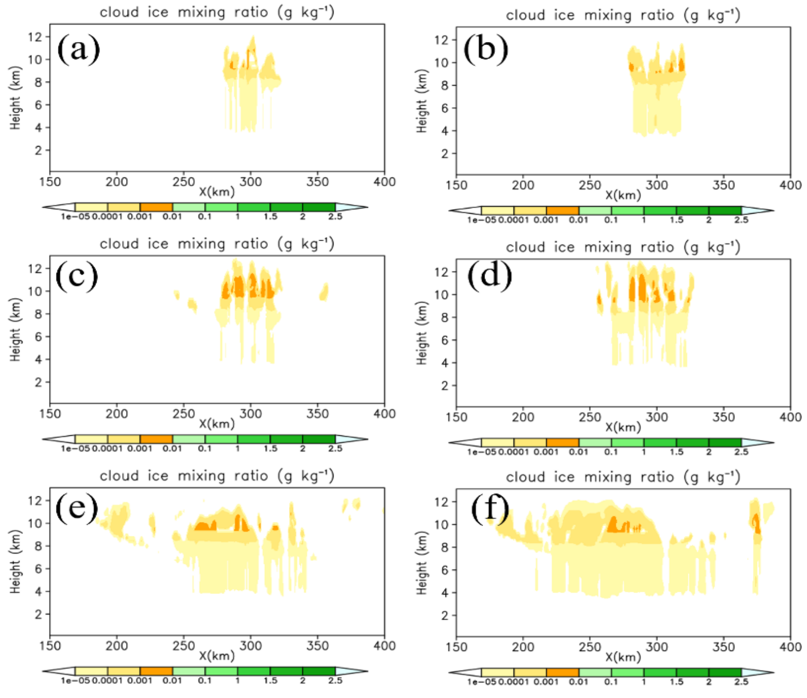

Figure S3. Same as Figure 1, but for cloud ice.

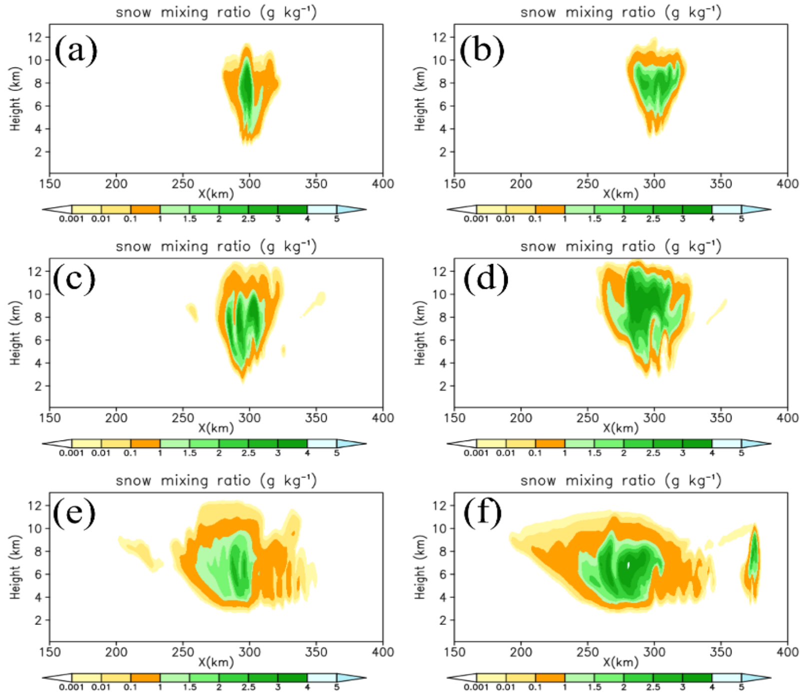

Figure S4. Same as Figure 1, but for snow.

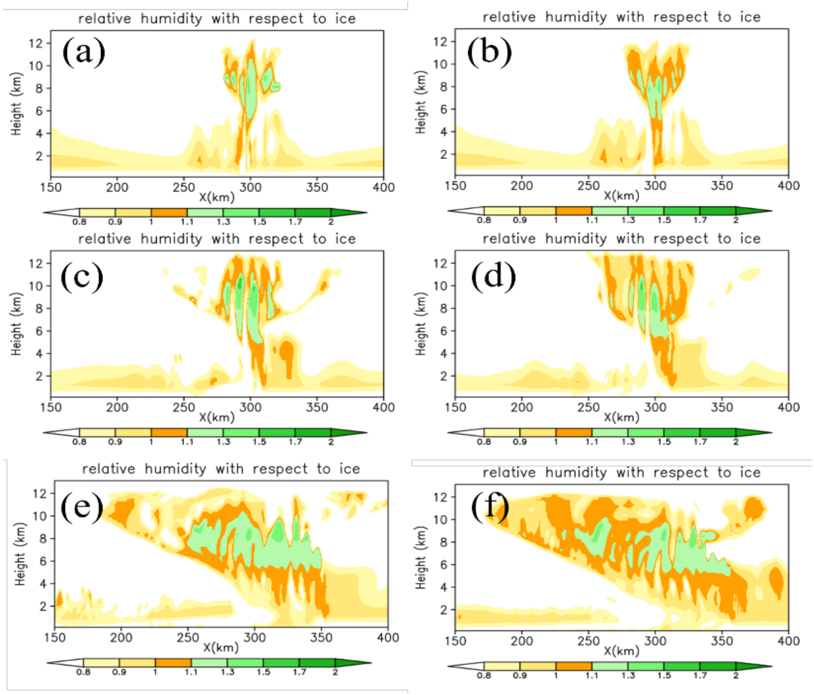

Figure S5. Same as Figure 1, but for relative humidity with respect to ice.

2. Table 4 provides a critical assessment of the performance of the new scheme. However, there is not much description of this table. The review only found this sentence on line 310, stating that the RMSE for all CL cases is much improved. Is this a comparison of the graupel mass collected at surface?

: We also explained the results of statistical scores for WL case as "The reduction in surface precipitation amount in WDM6_PD results in an improvement in the RMSE scores for all WL cases, as well as biases for all WL cases except for Case5 (Table 4)." in the original manuscript.

Additionally, to clarify what these statistical scores pertain to, we have revised the following sentence:

Line 371: "Statistical skill scores of the root mean square error (RMSE) (mm), bias (mm) and equitable threat score (ETS) for different cases with WDM6_FD and WDM6_PD." → "Statistical skill scores for surface precipitation, including the root mean square error (RMSE) (mm), bias (mm), and equitable threat score (ETS), for different cases with WDM6_FD and WDM6_PD."

3. There are other measured properties that the authors mentioned in section 3.2, and line 220, which are the 2DVD measured diameter, fall velocity, and geometry of each hydrometeor falling. However, the reviewer didn't find comparisons on these three properties, or maybe they were mentioned only in the text but not in any figures and tables.

: Thank you for your insightful comments. As mentioned in section 3.2 of the original manuscript, we used the 2DVD measured data of diameter, fall velocity, and geometry of hydrometeor to validate whether the model effectively reproduces the observation-derived density–fall velocity relationship of graupel. The 2DVD observed diameter and geometry of particles are used to identify graupel particles and estimate their density. Therefore, the 2DVD measured falling velocity (V_G) and derived graupel density (ρ_G) from diameter and geometry are used to verify the model simulated $\rho_G - V_G$ relationships, as shown in the Figure 12 of the revised manuscript.

4. Can the authors provide additional comparison on these properties? In addition to surface measurements, are there other types of observations available? What about radiosonde measurements of temperature, humidity and wind speed, and satellite observations of cloud properties?

: We appreciate your suggestion to provide additional comparisons of properties of the modified graupel species. We agree that more thoughtful verification with other observational data such as thermodynamic or hydrometeors profiles would be benefit the improvement of the model performance. However, our study put an effort on the development of new microphysics scheme containing predicting graupel density and its evaluation. Therefore, the verification of our study focusses on the ρ_G– V_G relationships. As we added the discussion in the revised manuscript below, we will leave further verification with other observation for future works.

Line 505: "The derived V_G–D relationship in our research could be refined by incorporating a broader range of graupel observational data, including hexagonal, conical, lump graupel, or graupel-like snow. Improvements in the representation of V_G–D relationship can lead to better simulation of precipitation and microphysical processes in environments where various types of graupel are generated. Additionally, the potential benefits of the predicted graupel density could be further evaluated in future works through comparison with additional observational data such as sonde and satellite."

5. **Another main comment is about the relationship with thermodynamic conditions, especially with RHice. In previous studies evaluating other double moment microphysics schemes against in situ aircraft observations, the results showed large sensitivities of the cloud microphysical properties (I.e., ice crystal mass and number concentrations) to the ice nucleation thresholds in terms of RHice threshold. For example, the Morrison 2 moment scheme uses a default 108% RHice, and the Thompson 2 moment scheme uses a default 125% RHice for initiating ice nucleation at lower temperatures, which may lead to transition from clear sky ice supersaturation to ice crystals too early (D'Alessandro et al., 2017). And this RHice threshold was found to be more realistic if it is set at 125-130% in an idealized squall line scenario when compared with the NSF DC3 field campaign (Diao et al., 2017). The reviewer wonders what is the current ice nucleation threshold used in the WDM scheme, and if that parameter has a very large impact on the simulated graupel density and fall speed. If a similar RHice threshold is adopted in WDM scheme around 108% similar to the Morrison 2 moment scheme, then the reviewer recommends testing increasing that threshold to 125% or 130%.**

: Thank you for your insightful comments regarding the relationship with thermodynamic conditions, especially with RHice. In both WDM6_FD and WDM6PD, the RHice threshold is set at 108%. Based on the reviewer's suggestion, we have conducted additional 2D idealized squall line experiments with the RHice threshold increased to 130%, maintaining the same experimental setup as in the original manuscript. The results of this analysis are presented in Figure R7. The experiments are labeled as WDM6_PD with the original RHice value (PD108) and WDM6_PD with the increased RHice value (PD130).

Both simulations (PD108 and PD130) indicate that the simulated features of graupel density and its mass mixing ratio distributions are fairly consistent across the evolution time. The source and sink terms are also similar, though there are only minor differences such as a horizontal feature of sublimation (SUB) at 1 and 2 h between PD108 and PD130 (Figs. 6 and R7). These results implies that the choice of RHice threshold does not significantly affect the simulated graupel properties including its source/sink processes in the WDM6 microphysics scheme. Based on our simulation results and reviewer's comment, we have added the following sentence in the revised manuscript:

Line 328: "Meanwhile, Diao et al. (2017) suggested 125-130% of RHice threshold value is more realistic for an idealized squall line scenario when compared with the National Science Foundation (NSF) Deep Convective Clouds and Chemistry (DC3) field campaign. The increase of RHice from 108% to 130% in our 2D squall line setup does not affect the predicted graupel density features (not shown)."

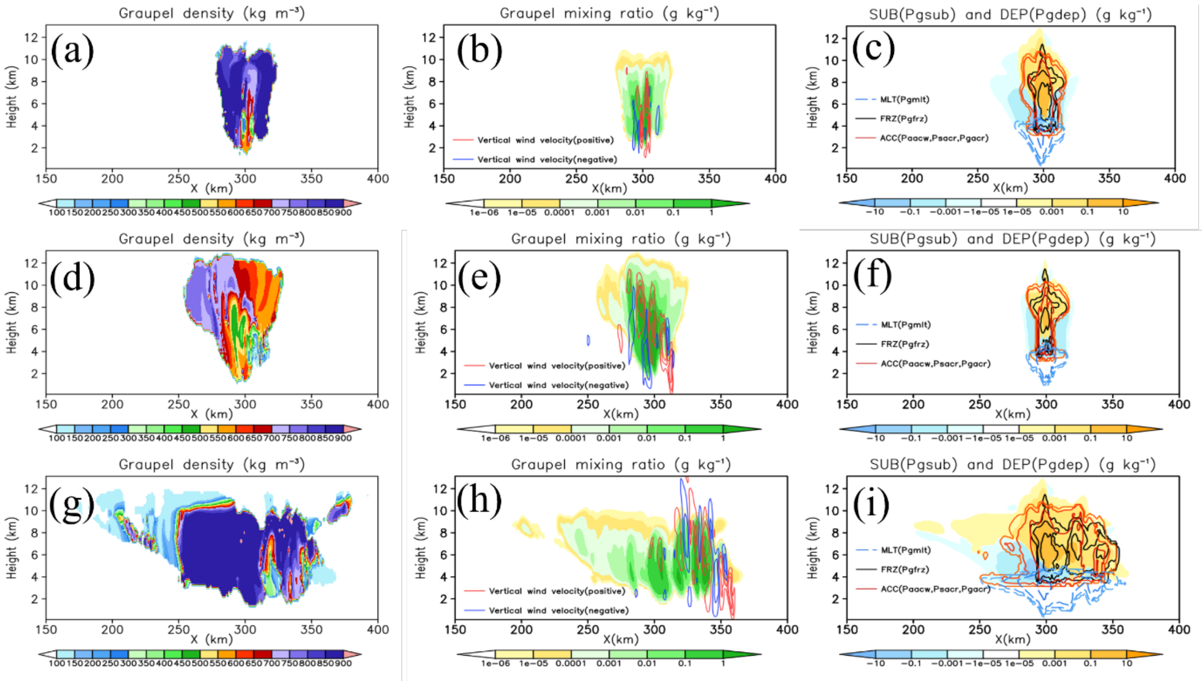

Figure R7. Spatial distribution of $\boldsymbol{\rho_G}$ (kg m^{-3}), $\mathbf{q_G}$ (g kg^{-1}), and the major source/sink microphysics processes (g kg^{-1}) related to $\mathbf{q_G}$ in PD130 at 1 hour (a and b), 2 hour (c and d), and 4 hour (e and f). In (b), (e), and (h), the solid red (blue) line represents positive (negative) vertical wind speed. Contour lines for positive (negative) value are at 2, 5, and 8 (−5 and −2). The unit of wind speed is m s^{-1}. In (c), (f), and (i), the main source processes are analyzed as Pgdep (DEP), the mean of Paacw, Psacr, and Pgacr (ACC), and Pgfrz (FRZ), while the sink ones are represented by sublimation (SUB) and Pgmlt (MLT). Red (blue) color shaded is represented as DEP (SUB). For the detail description of the microphysical processes are shown in Table1.

Minor comment.

6. Some figures seem to have the dimension compressed, such as Figure 4, which seems to be compressed vertically (too narrow in vertical).

: In response to the reviewer’s comment, we have correctly adjusted the dimension of all figures including Figure 4 in the revised manuscript.