Reviewer 1

We thank the reviewer for the constructive suggestions and valuable comments for improving this manuscript. We hope that the modified manuscript and our response to the comments are satisfactory. The reviewer's comments are in italics and our responses in standard font below. Line number in our responses are referring to the revised manuscript.

General Comments:

Global Climate Models (GCMs) simulate ice clouds using "two-moment schemes" having prognostic solutions for ice particle number concentration (Ni) and cloud ice water content (IWC). The ice particle size distribution (PSD) is generally parameterized as a gamma PSD as described in Eq. 1 in this manuscript, consisting of three variables: N0, λ and μ. Knowing Ni and IWC, N0 and λ are solved for, but in order to obtain mathematical closure for the PSD, μ is given an arbitrary constant value. To my knowledge, there are very few papers investigating the impact of μ on ice cloud microphysical processes in climate models, and this paper appears to be the most thorough and appropriate for GCMs to date. The paper is well organized and well written, providing important new findings relevant to a GMD readership.

Reply: We do appreciate the positive comments.

In the study by Mitchell et al. (2006, Atmos. Res.), a snow growth model was developed and tested against aircraft PSD probe measurements where the aircraft descends from cloud top to cloud base under quasi-steady state widespread snowfall conditions, where PSDs were modeled as gamma PSDs. Optimal agreement between the height-evolution of measured and predicted PSDs was obtained for a μ value of -0.6. Assuming the snow growth model was developed properly, this suggests that the PSDs sampled on this flight were characterized by slightly negative μ. Other studies (e.g., Herzegh and Hobbs, 1985, QJRMS; Gordon and Marwitz, 1986, JAS; Mitchell, 1988, JAS) suggest μ typically ranges between 1 and -1 in ice clouds, while Heymsfield (2003, JAS, Part 2) finds μ lies mostly between -2 and 2 when natural ice PSDs are parameterized as gamma PSDs. Thus, the μ values of 2 and 5 assumed for ice clouds in this study appear atypical, but the impacts of changing μ from 0 to 2 (shown in this study) are relevant to real cloud microphysical and radiative processes. This paper would be much more realistic and useful if it also *evaluated the impact of changing μ from 0 to -1. Negative values of μ are common when ice crystal nucleation rates are relatively high (Herzegh and Hobbs, 1985, QJRMS).*

Reply: Thanks for these comments. We are in complete agreement that it would be more realistic and useful to evaluate the impact of changing μ from 0 to −1.

The three-parameter gamma distributions of the form $N'(D)=N_0D^{\mu}e^{-\lambda D}$ are usually used to represent the measured particle size distribution (PSD, bin-averaged data). The three parameters (i.e., N_0, λ, μ) are derived using fitting techniques. The PSDs are relatively wide with negative μ (Fig. R1). Under negative μ, the particle number densities (N') are increased with decreasing D, and become very huge at $D < 1$ µm (Fig. R1 left). In the real world, the ice crystals are usually not less than 1 µm. Furthermore, in the study of Heymsfield (2003, JAS, Part 2), the author pointed out that the gamma-fitted PSD partially compensates for the absence of aircraft PSD measurements below 50 µm, although the functional form used for ice particles below 50 µm represents an extrapolation that is not known explicitly from the data. When only considering the ice crystals over sizes (D) from as small as 10 µm to as large as 2000 µm (measured ice crystal size), the uncertainty from the extrapolation below 50 µm is negligible in the linear space of particle size (Fig. R1 right). Generally speaking, the contribution from very small particles is usually neglected for getting the gamma-fitted PSD from observations.

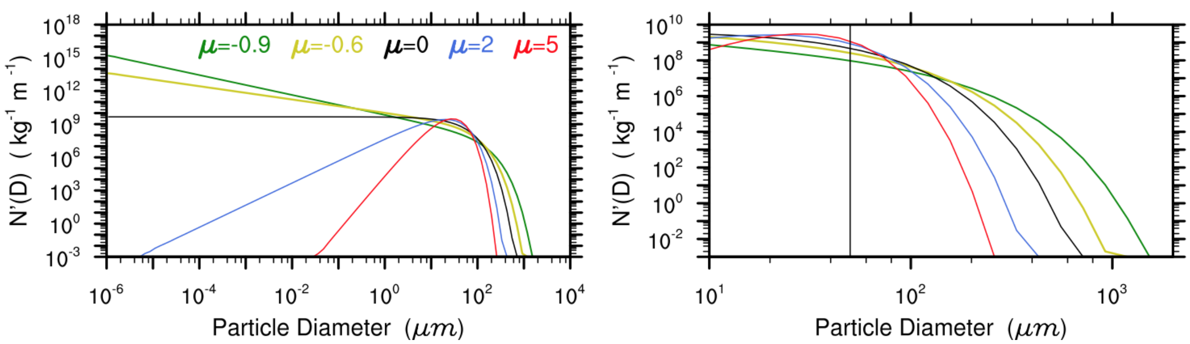

Figure R1. The particle number densities (N', which is a function of D) calculated from the gamma distributions with various μ values. Here, the total particle number and mass-weighted diameter (D_q) are set to 10^5 kg^{-1} (~50 L^{-1}) and 40 µm, respectively. Note different markers in the Y-Axis and X-Axis between the left column and right column. The vertical black line indicates D= 50 µm.

While observations showed negative μ, the bulk cloud microphysics schemes usually constrain μ to be nonnegative. Eidhammer et al. (2017, JC) explained this by the singularity of gamma distribution ($N'(D)=N_0D^{\mu}e^{-\lambda D}$). Under negative μ, the particle number density (i.e., N', which is a function of D) would be non-finite at D=0. Here, we discuss the reason in more detail. In the bulk cloud scheme, the other two gamma distribution parameters (N_0 and λ) are calculated by the particle's mass (q) and number

(N), and some μ's gamma functions ($\lambda = [\frac{\pi\rho}{6}\frac{N}{q}\frac{\Gamma(4+\mu)}{\Gamma(1+\mu)}]^{1/3}$, $N_0 = \frac{N\lambda^{(1+\mu)}}{\Gamma(1+\mu)}$). Because the negative integer and zero are the singularity of the gamma function, the μ must be greater than −1 in these calculation formulas (i.e., N_0=… and λ=…). Furthermore, because the gamma function, $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}\,dt$, is used for derivating these calculation formulas, the q and N in these calculation formulas indicate the mass and number of particles with radius from 0 to ∞ (hereafter, mathematical size range). Under negative μ (the N' is very huge at $D < 1$ µm, Fig. R1 left), more attention should be paid to using the gamma function because it integrates from 0 to ∞. Fig. R2 shows the relative number (upper panel) and mass (lower panel) contributions from each radius bin of ice crystals. At $\mu_i \geq 0$ (i.e., μ_i= 0, 2, and 5), both the number and mass contributions are mostly in the radius range from 1 µm to 1000 µm (hereafter, realistic size range). However, at $\mu_i = -0.9$, the number of particles with a radius from 1 µm to 1000 µm (i.e., realistic size range) only contributes ~1/3 to the total number (i.e., the N from the mathematical size range). In other words, the calculation formulas for gamma distribution parameters (N_0 and λ) used in the bulk cloud schemes are not suited for representing realistic cloud particles. Therefore, our study only evaluates the impacts of changing μ_i from 0 to 2, 5.

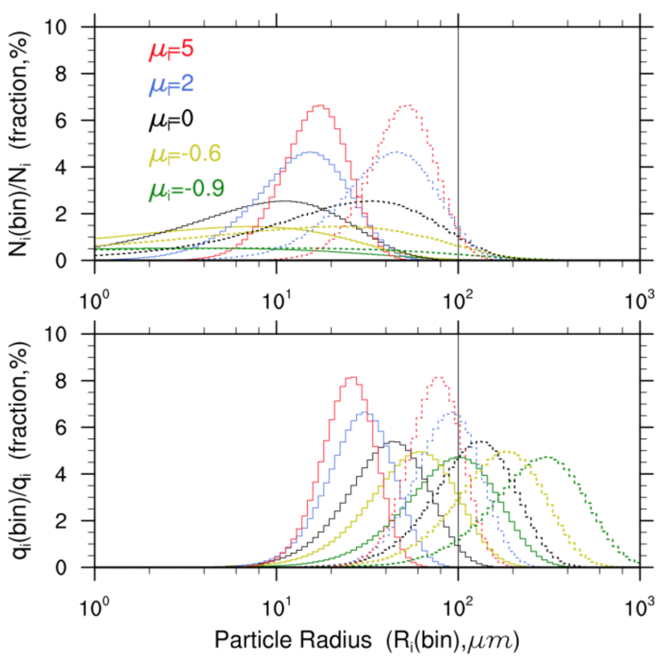

Figure R2. The relative number (upper panel) and mass (lower panel) contributions from each radius bin of ice crystals (ICs). Each bin width is the same based on the logarithm of the particle radius. N_i and q_i are the total number and mass of ICs, respectively. A total of 100 bins were used here. The solid lines indicate the normal IC scenario (i.e., R_{qi} = 20 µm), and the dotted lines indicate the large IC scenario (i.e., R_{qi} = 60 µm).

Mitchell (1991, JAS) found that for negative μ values (i.e., superexponential PSD), aggregation was the only growth process that substantially increased ice particle sizes, whereas for positive μ, both aggregation and vapor diffusion contributed to ice particle size increases. This is an example of how ice particle growth processes act differently depending on the sign of μ and illustrates the need to consider both positive and negative μ values.

Reply: Thanks for this comment. It is clear that the PSD of ice crystals (ICs) becomes wider with decreasing μ, and the PSD is very wide at $\mu_i \leq -0.6$ (Fig. R2). Therefore, as compared to positive μ_i (i.e., relatively narrow PSD), the interaction between small ICs and large ICs (e.g., the accretion of small ICs by large ICs) should become more important under negative μ_i (i.e., wide PSD). Although the sensitivity experiments with negative μ_i were not carried out, more discussion about the impact of μ_i (i.e., PSD is wide or narrow) on ICs growth was added in the revised manuscript (Line 418-420).

Major Comments:

Line 68: Sentence states that μi is not considered in the default MG scheme because μi = 0. While it is true that μi = 0, stating that it was not considered is misleading. On a number of occasions, Hugh Morrison indicated to me that he was seeking more information about μi and was exploring new ways of treating it (prior to the release of CAM5). After consulting with his peers, he decided a value of zero was most reasonable if a fixed value was to be used.

Reply: Thanks. The "(i.e., not considered)" is removed from the original sentence "…μ_i is zero (i.e., not considered) in the default MG scheme" (Line 72).

Table 1: In the MG scheme, the air density prefactor for the mass-weighted ice fall speed is raised to the power of 0.54 (following Heymsfield and Bansemer 2007), not 0.35 as shown in Table 1. The simulations may need to be rerun if this incorrect value of 0.35 was used.

Reply: Thanks. All default parameters of the CAM6 model (except for the modification of μ_i) were used in this study. In the code, 0.35 is used for ice crystals and 0.54 is used for snows. In the study of Morrison and Gettelman (2008, JC), 0.54 is used for all cloud and precipitation species.

Line 317: There are references to support this statement; please add some.

Reply: Thanks. We have added references (Mitchell, 1991, JAS; DeMott et al., 2010, PNAS; Storelvmo et al., 2013, GRL) to support this statement (…the ICs grow faster and their lifetimes become shorter) in the revised manuscript (Line 322).

Lines 381-383: This finding appears similar to that reported in Mitchell (1991, JAS) titled "Evolution of snow size spectra in cyclonic storms. Part II: Deviations from the exponential form", where it was found that the IC vapor deposition process was accelerated by increasing μi.

Reply: Thanks. In the revised manuscript, we pointed out "this is consistent with the previous finding (ICs vapor deposition process is obviously accelerated by increasing μ_i) reported by Mitchell (1991)" (Line 168).

Technical Comments:

Line 47: Common Atmosphere Model => Community Atmosphere Model?

Reply: Thanks. Done.

Line 89: PDF => PSD?

Reply: Thanks. Done.

Caption for Fig. 2 near bottom: "The two black lines" => "The two black dashed curves"?

Reply: Thanks. Done.

*Lines 279-280: Are the superscripts for *Mu and Mu correct?*

Reply: Thanks. The R_{qi}^{*} denotes the updated R_{qi}. Here, $R_{qi}^{*\mathrm{Mu0}}$ and R_{qi}^{Mu0} indicate the R_{qi}^{*} and R_{qi} from the Mu0 experiment. In the revised manuscript, to avoid misunderstanding, a comma was added between "*" and the experiment name (e.g., $R_{qi}^{*,\mathrm{Mu0}}$). Furthermore, more introduction about R_{qi}^{*} was added, such as "The R_{qi}^{*} denotes the updated R_{qi}, which includes the changes caused by the deposition/sublimation and autoconversion processes at this model time step (Line 284).