

Reviewer 2

We thank the reviewer for the time spent to evaluate our study and for the useful comments. 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 Assessment:

Zhang et al. investigate the impact of the shape parameter of cloud ice on simulated cloud properties and radiation using Community Atmosphere Model Version 6 (CAM6) of Community Earth System Model Version 2. The shape parameter is one of three parameters of the gamma distribution, which is commonly used in the two-moment bulk cloud microphysics scheme. Considering the current microphysics schemes usually set shape parameter to 0, investigate the impact of different values of shape parameter on the cloud properties providing important findings relevant to a GMD readership.

The authors conducted offline analysis and 10-year simulation using different value (0-5) of the shape parameter, in order to show how the shape parameter influences the cloud properties and radiation transfer. The authors suggested that increasing the value of the shape parameter would lead to higher q_i and lower N_i in most regions globally, furthermore, the longwave cloud radiative forcing increases by 5.58 W m^{-2} (25.11%), and the convective precipitation rate decreases by $-0.12 \text{ mm day}^{-1}$ (7.64%).

After serious consideration, I here recommend this manuscript subject to major revisions.

Reply: Thanks for the positive comment.

Major Comments:

- 1) *If I understand correctly, the authors only added the shape parameter to the PSD of cloud ice, the PSD of snow is not considered. This should be indicated in the manuscript, because "ice crystal" represents all the ice particles (cloud ice and snow together).*

Reply: Thanks. In the revised manuscript, we pointed out “ice crystal” only represents cloud ice in this study (Line 42).

2) *Observation data of ice water path (IWP), shortwave cloud forcing (SWCF), and longwave cloud forcing (LWCF) are need in Figure 4, Table 4, and related analysis. This will give important information of which value of shape parameter give more realistic simulation results compared with observation.*

Reply: The following figure and table (Fig. R1 and Table R1) show observations and simulation results. Besides the model simulations used in the manuscript (horizontal resolution is $1.9^\circ \times 2.5^\circ$), we also carried out three more simulations using the same model code but higher resolution ($0.9^\circ \times 1.25^\circ$). Note that, the default namelist configuration (except for μ_i) of model code (namelist_defaults_cam.xml) was used in all simulations. Some tunable parameters of the cloud scheme are different under different horizontal resolutions. For instance, the default size threshold (R_{cs}) used for the autoconversion of ice crystal to snow has significant impacts on ice clouds (e.g., ice crystal size and ice water content; Eidhammer et al., 2014). Under the same model code (CESM2.1.3), the R_{cs} is set to 100 μm and 250 μm for $1.9^\circ \times 2.5^\circ$ and $0.9^\circ \times 1.25^\circ$, respectively. The reference experiment (i.e., the Mu0 experiment) shows that the simulated cloud radiative effects (CRE_{LW} and CRE_{SW}) from both low ($1.9^\circ \times 2.5^\circ$) and high ($0.9^\circ \times 1.25^\circ$) resolutions agree well with the observations. Unlike the cloud radiative effects, the ice water path (IWP) from the reference experiment is obviously less than the observations, especially for the low-resolution simulation. After increasing μ_i (i.e., changing μ_i from 0 to 2, 5), the IWP significantly increases and is closer to observation. Meanwhile, both CRE_{LW} and CRE_{SW} become stronger and corresponding model biases might become a little more obvious.

This study only focuses on the impacts of μ_i , the default tunable parameters (except for μ_i) are used in all the simulations. After improving the representation of μ_i -related processes, further model tuning and analyses are required based on the updated cloud scheme. Therefore, this study does not estimate which value of μ_i could lead to a better simulation. This was clearly mentioned in the revised manuscript (Line 414-416).

The low-resolution and high-resolution sensitivity experiments show similar changes in cloud radiative effects and precipitation rates ($\Delta\text{Mu}2$ and $\Delta\text{Mu}5$, Fig. R1 and Table R1). This indicates that the primary mechanisms for μ_i 's impacts on climate simulation are relatively robust, and not affected by R_{cs} .

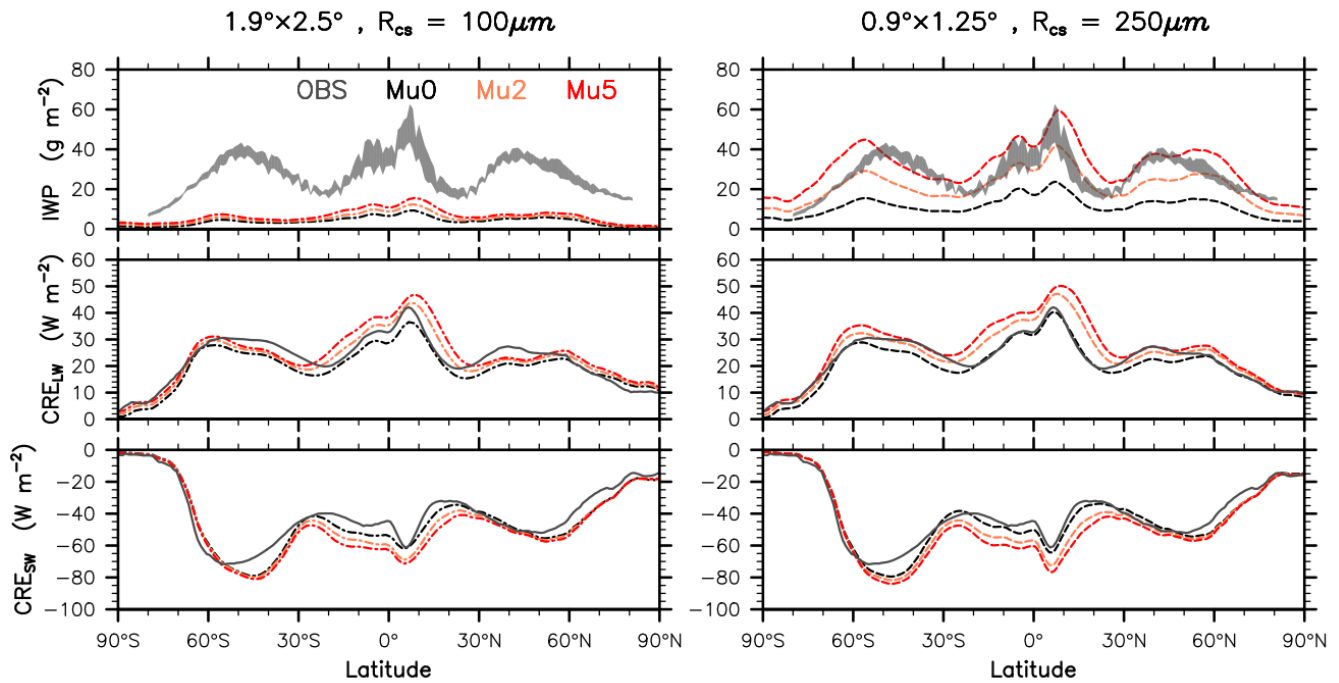


Figure R1. Annual zonal mean distributions of the ice water path (IWP), longwave and shortwave cloud radiative effects (CRE_{LW} and CRE_{SW}) from observations (Loeb et al., 2018; Li et al., 2020) and our model experiments (Mu0, Mu2, and Mu5). The left panel represents the model simulations used in the manuscript, and the left panel represents the model simulations with relatively high resolution. The horizontal resolution and corresponding R_{cs} values are shown on the top.

Table R1. The global annual mean ice water path (IWP), longwave and shortwave cloud radiative effects (CRE_{LW} and CRE_{SW}), and convective and large-scale precipitation rates (RainC and RainL) from model simulations with two different resolutions ($1.9^\circ \times 2.5^\circ$ and $0.9^\circ \times 1.25^\circ$) and observations. “ Δ ” is used to denote the difference from the Mu0 experiment. The corresponding standard deviations calculated from the difference of each year for 10 years are shown in brackets.

Resolutions	$1.9^\circ \times 2.5^\circ$			$0.9^\circ \times 1.25^\circ$			
Experiments	Mu0	Δ Mu2	Δ Mu5	Mu0	Δ Mu2	Δ Mu5	OBS
IWP ($g\ m^{-2}$)	4.74	1.37(0.10)	2.97(0.06)	12.97	10.69(0.21)	21.77(0.31)	24.74
CRE_{LW} ($W\ m^{-2}$)	22.22	3.40(0.12)	5.58(0.13)	23.82	4.51(0.15)	7.27(0.17)	25.78
CRE_{SW} ($W\ m^{-2}$)	-49.25	-3.00(0.43)	-5.34(0.31)	-47.79	-4.38(0.31)	-7.37(0.39)	-45.33
RainC ($mm\ day^{-1}$)	1.57	-0.08(0.01)	-0.12(0.01)	1.40	-0.09(0.01)	-0.13(0.01)	
RainL ($mm\ day^{-1}$)	1.39	0.01(0.01)	0.01(0.01)	1.53	0(0.01)	-0.02(0.01)	

References

- Eidhammer, T., Morrison, H., Bansemmer, A., Gettelman, A., and Heymsfield, A. J.: Comparison of ice cloud properties simulated by the Community Atmosphere Model (CAM5) with in-situ observations, *Atmospheric Chemistry and Physics*, 14, 10103-10118, <https://doi.org/10.5194/acp-14-10103-2014>, 2014.
- Loeb, N. G., Doelling, D. R., Wang, H. L., Su, W. Y., Nguyen, C., Corbett, J. G., Liang, L. S., Mitrescu, C., Rose, F. G., and Kato, S.: Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.0 Data Product, *J. Climate*, 31, 895–918, <https://doi.org/10.1175/JCLI-D-17->

0208.1, 2018.

Li, J. F., Xu, K., Jiang, J. H., Lee, W., Wang, L., Yu, J., Stephens, G., Fetzer, E., and Wang, Y.: An Overview of CMIP5 and CMIP6 Simulated Cloud Ice, Radiation Fields, Surface Wind Stress, Sea Surface Temperatures, and Precipitation Over Tropical and Subtropical Oceans, *J. Geophys. Res.-Atmos.*, 125, e2020JD032848, <https://doi.org/10.1029/2020jd032848>, 2020.

3) *From Figure 4, the IWP, LWCF, and SWCF have dramatic changes over the tropics, with much smaller changes in the mid-and high latitude. As we know most of the cloud and precipitation process over the tropics is governed by the convection scheme. Since the shape parameter is only introduced in the large-scale microphysics, while the convection scheme is not changed. Why do the IWP, precipitation, and cloud forcing have the largest change over the tropics? The reader may expect that the largest change is noticed in the mid-and high latitude, where larger-scale microphysics treated most of the cloud process, therefore, your modifications should have a larger impact over there. Considering the convection precipitation changed also largely, this may indicate the change of IWP, precipitation, and cloud forcing is directly caused by the convection process (as a result of changed climate state), not by the shape parameter in the microphysics scheme.*

Reply: The treatment of clouds in climate models is usually divided into two categories: convective cloud scheme with simplified cloud microphysics and large-scale stratiform cloud scheme with relatively detailed cloud microphysics (e.g., considering the cloud particle size distribution). The intense convective activity over the tropics is usually very short (a few model time steps). The detrained water and ice from convective activity (e.g., cirrus anvils) could left in the atmosphere for a relatively longer time. The convective detainment is usually considered as a source of stratiform clouds and would be treated by the stratiform cloud scheme. Note that, the main cloud formation mechanism is the condensation/deposition of cloud water and ice calculated from the stratiform cloud scheme. More information about the representation of clouds can be found in the model description. The single column model version is a good tool for illustrating the simulated cloud evolution.

Although the tropical precipitation is mainly from the convective scheme, the cloud over the tropics is mostly represented by the larger-scale stratiform cloud scheme. Furthermore, the cloud ice mass mixing ratio (q_i) is obviously larger in the upper tropical troposphere (Fig. 2 in the manuscript). Therefore, the modifications in the stratiform cloud scheme have a larger impact over the tropics.

Minor Comments:

1) Line 22: "cloud-related process", to be consistent with the beginning and ending of the sentence, better to use "cloud microphysical processes"

Reply: Thanks. "cloud-related processes" not only includes "cloud microphysical processes" but also "diagnosing cloud optical properties".

2) Line 24: "atmospheric models", may be better to use the "global climate model" instead since some ideal model could describe the evolution of each cloud particle.

Reply: Thanks. "atmospheric models" not only includes "global climate model" but also some other kinds of atmospheric models (e.g., regional climate model and cloud-resolving model). In the revised manuscript, we added "commonly-used" before "atmospheric models" (Line 23 and 26).

3) Line 26: "From the outset, the development of cloud microphysics schemes has resulted in two distinct categories: bulk microphysics parameterization and spectral (bin) microphysics"
The recently developed Lagrangian particle-based scheme is another type.

Reply: Thanks. We pointed out that the atmospheric models exclude the ideal model with the recently developed Lagrangian particle-based scheme (Line 26).

4) Line 28: "The spectral (bin) approach represents" added explicitly before represents

Reply: Thanks. Done (Line 30).

5) Line 33: "In climate models with bulk cloud microphysics scheme," may change to "In bulk cloud microphysics schemes of climate models"

Reply: Thanks. "In climate models with bulk cloud microphysics scheme" was changed to "In the bulk cloud microphysics schemes used for climate models" (Line 36).

6) Line 65: "number density" actually, it is number mixing ratio

Reply: Here, "number density" indicates $\delta N/\delta D$. The N and D are ice crystal number and size, respectively.

7) *Line 67: "number concentration" actually, number mixing ratio*

Reply: Thanks. The original sentence was rewritten to "...in-cloud IC mass and number mixing ratio (q_i and N_i , prognostic variables in units of kg kg^{-1} and kg^{-1} , respectively)" (Line 70).

8) *Line 127: "30 vertical layers", the default model setting is 32 layers, did you reset it to 30 layers?*

Reply: Thanks. The default configuration and tunable parameters (except for μ_i) were used for all the simulations of this study. The vertical layer is 32.

9) *Line 135: "the PSD of ICs and μ_i -related cloud microphysical processes are first illustrated by off-line tests." PSD is illustrated by off-line tests looks wired, may try: "the impacts of μ_i on are investigate using off-line test"*

Reply: Thanks. Done (Line 138).

10) *Line 139: "Fig. 1 shows the impact of μ_i on the PSDs." --> Fig. 1 shows the impact of μ on the normalized PSD of cloud ice.*

Reply: Thanks. Done (Line 142).

11) *Line 141-144: using normalized PSD instead of PSD for accuracy.*

Reply: The shape of PSD (i.e., the relative number or mass contributions of each bin) is the normalized PSD.

12) *Line 143: "in terms of number" is it number fraction or number?*

Reply: Because the normalized PSD is diagnosed by the relative number or mass contributions of each size bin, the "number" indicates "number fraction".

13) *Line 145: "large IC scenario" large size or mass?*

Reply: The large ice crystal (IC) scenario indicates the mass-weighted radius of ICs is $60 \mu\text{m}$ (i.e., $R_{qi} = 60 \mu\text{m}$).

14) Line 191: "climate equilibrium states." We usually use "equilibrium climate states".

Reply: Thanks. Done (Line 195).

15) Line 194: "cloud microphysical process during one model time step." Looks weird, is it process rate?

Reply: "δ" is used to denote the changes in cloud properties that are caused by the cloud microphysical process during one model time step (tendency × one time step).

16) Line 211: "in the tropopause region, where homogeneous freezing produces a large number of ICs (not shown) due to sufficient soluble aerosol particles," in the tropics, is a large number of ICs from convection detrainment and homogeneous freezing of cloud droplet or from "sufficient soluble aerosol particles"?

Reply: Homogeneous freezing of ambient liquid aerosols produces a large number of ICs.

17) Line 355: "increases atmospheric stability via the radiative budget and then leads to weaker convective precipitation" How? could the author give a more detailed explanation?

Reply: As compared to warm cloud (CRE_{LW} is weaker than CRE_{SW}), ice cloud absorbs the earth's surface outgoing longwave radiation more efficiently (CRE_{LW} is stronger than CRE_{SW}), and then exerts a net warming radiative effect (Boucher et al., 2013). As shown in Andrews et al. (2010), the fast response in precipitation is strongly correlated with the atmospheric component of changes in radiative fluxes, which is defined as changes in the atmospheric absorption and is calculated as the difference between changes in net TOA radiative fluxes and changes in net surface radiative fluxes. Ice clouds increasing can heat the tropopause, enhance atmospheric stability, and then inhibit convective activity to some extent (Wang et al., 2014).

References

- Andrews, T., Forster, P. M., Boucher, O., Bellouin, N., and Jones, A.: Precipitation, radiative forcing and global temperature change, *Geophysical Research Letters*, 37, L14701, <https://doi.org/10.1029/2010GL043991>, 2010.
- Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M.,

Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2013.

Wang, M., Liu, X., Zhang, K., and Comstock, J. M.: Aerosol effects on cirrus through ice nucleation in the Community Atmosphere Model CAM5 with a statistical cirrus scheme, *Journal of Advances in Modeling Earth Systems*, 6, 756-776, <https://doi.org/10.1002/2014MS000339>, 2014.

Technical comments:

1) *Line 9-12: “The calculating formulas of statistical 10 mean radii indicate that, under the same mass (q_i) and number (N_i) of ice crystals, the ratios of the mass-weighted radius (R_{qi} , not related to μ_i) to other statistical mean radii (e.g., effective radiative radius) are completely determined by μ_i .”*

This sentence is too long, separating it into two or three sentences.

Reply: Thanks. The long sentence was rewritten as “The μ_i ’s impact on the statistical mean radii of ice crystals can be analysed based on their calculating formulas. Under the same mass (q_i) and number (N_i), the ratios of the mass-weighted radius (R_{qi} , not related to μ_i) to other statistical mean radii (e.g., effective radiative radius) are completely determined by μ_i ” (Line 10-13).

2) *Line 22: “cloud-related process”, to be consistent with the beginning and ending of the sentence, better to use “cloud microphysical processes”*

Reply: “cloud-related processes” not only includes “cloud microphysical processes” but also “diagnosing cloud optical properties”.

3) *Eq. (1), (2), (3)... according to GMD publication format, a comma should be added after equations.*

Reply: Thanks. We checked this kind of format. “Eq. (a) and (b)” was changed to “Eqs. (a), (b)” and “Eq. (a-c)” was changed to “Eqs. (a), (b), (c)”.

4) *Separate Fig. 1 and Fig. 3 into two Figures, currently they are too small.*

Reply: During the evolution of stratiform clouds, the properties of ice clouds (e.g., q_i , N_i , and R_{ni} , including mixed-phase clouds) largely determine the ice-phase cloud microphysical processes. Meanwhile, these cloud microphysical processes in turn change the cloud properties. They interact as both cause and effect and finally reach climate equilibrium states. To facilitate the subsequent analyses, the cloud properties

and μ_i -related cloud microphysical processes are shown together in one figure. This study only focuses on illustrating the main mechanisms for μ_i 's impacts based on annual zonal mean in-cloud variables. These figures with many variables (Fig. 2 and 3) are acceptable.