Response to Reviewer 1

We thank the anonymous reviewer for his/her careful reading and constructive comments on our paper. Our detailed responses to the comments follow. Reviewer's comments are in blue color, our responses are in black color, and our corresponding revisions in the manuscript are in red color.

This manuscript implements new parameterizations of secondary ice production (SIP) including frozen raindrop shattering, ice-ice collisional breakup and the classic Hallett-Mossop parameterization by Cotton et al. 1986 in the CAM6 single column model (SCM) to determine the impact of SIP on Arctic mixed-phase cloud properties compared to observations from the M-PACE field campaign. The authors conclude that SIP reduces the high supercooled liquid bias in Arctic single-layer stratiform mixed phase clouds and improves the low bias in ice crystals at relatively warm temperatures below the supercooled liquid clouds. They also find that the fragmentation of freezing droplets contributes most to ice production in single-layer boundary layer clouds, while ice-ice collisions and rime splintering contribute relatively less to ice production in frontal clouds and multilayer stratus clouds, respectively, and primary ice production is more important for cold multilayer and frontal clouds in CAM6 SCM.

The manuscript presents novel results, is important for the improvement of climate models and is very relevant to Atmospheric Chemistry and Physics. I would recommend publication after major revisions.

Reply: We thank the reviewer for the encouraging comments. We have revised the manuscript following your comments regarding the uncertainties of observation data and clarified the text to improve the paper.

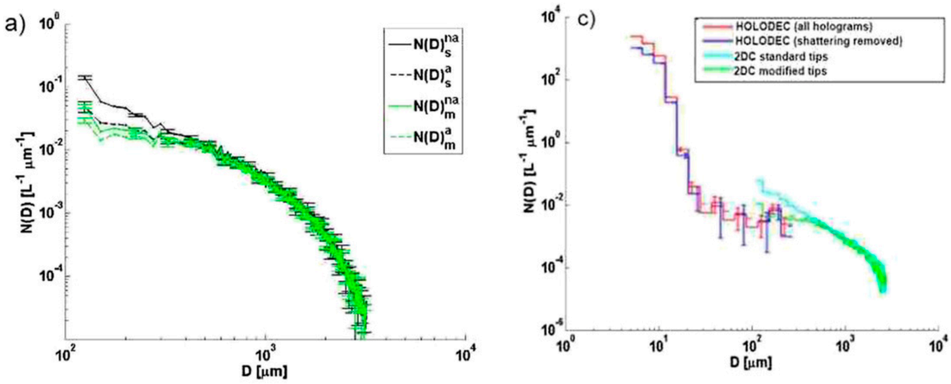
My most major concern is regarding the M-PACE in situ data that was compared against the CAM6 SCM. These data did not correct for the shattering effect which is known to severely overestimate the ice number concentration by up to two orders of magnitude and likely cause misleading conclusions if not accounted for (Korolev et al. 2011, Korolev et al. 2013a, Korolev et al. 2013b, Korolev & Field 2014). I strongly recommend that the authors use data that have corrected for the shattering effect using both correction algorithms using interarrival time and data that have used antishattering tips.

Also, despite apparent better agreement with M-PACE (noting that the M-PACE data for ice number concentration are incorrect), the poor agreement with ice properties were not noted in the conclusions and abstract and underemphasized in the manuscript. Please revise accordingly.

Reply: We thank the reviewer for the constructive comment. We agree with the reviewer that the M-PACE in situ ice number data did not correct for the shattering effect, because the data were collected before the advent of shatter mitigating tips and before algorithms for removing the shattered particles had been developed. Thus, there were no corrections for the shattering in these data. We have discussed this issue with Greg McFarquhar who collected the M-PACE data. He suggested that we can get some estimates of the magnitude of the shattering effect on ice number concentrations from other campaigns, such as ISDAC, IDEAS-2011, and HOLODEC, which also used the 2DC cloud probe, but adopted anti-shattering tips and algorithms for removing the shattered particles.

Previous studies indicated a reduced ice number by 1-4.5 times and up to a factor of 10 depending on particle size for IDEAS-2011 and ISDAC after using the antishattering tips (Jackson and McFarquhar, 2014; Jackson et al., 2014). Figure 10 in Jackson et al.

(2014) below indicates that the shattering effect increases the ice number by 1-4.5 times, and the effect is stronger for smaller ice than larger ice.



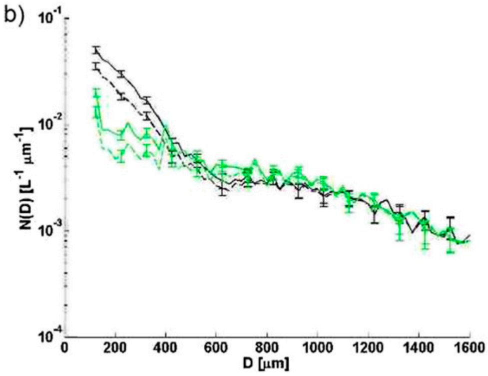


FIG. 10. (a) Mean $N(D)$ from the 2DC with standard and modified tips for 25 Oct 2011 and 1 Nov 2011. (b) Mean $N(D)$ from the 2DC with standard and modified tips for 30 Apr 2008. Error bars indicate standard deviations produced by the bootstrap technique. (c) SDs for IDEAS-2011 flight RF03, 1921:30–1926:41 UTC, comparing the HOLODEC and standard and modified 2DC instruments.

Based on the reviewer's comments, we added a discussion about the M-PACE observed ice number data in Section 3.2 as "However, the M-PACE data were collected before the advent of shatter mitigating tips and before algorithms for removing the shattered particles had been developed. Thus, there are no corrections for the shattering effect in these data. Previous studies indicated an averaged reduction of ice number concentrations by 1-4.5 times and up to a factor of 10 (for some data samples) in other field campaigns, such as Instrumentation Development and Education in Airborne Science 2011 (IDEAS-2011), Holographic Detector for Clouds (HOLODEC), and Indirect and Semidirect Aerosol Campaign (ISDAC), which also used the 2DC cloud probe, but adopted anti-shattering tips and algorithms for removing the shattered particles (Jackson and McFarquhar, 2014; Jackson et al., 2014).

In order to account for the anti-shattering effect, the observed ice number was scaled by a factor of 1/4 and 1/2, respectively to consider the possible range of the shattering effect. Furthermore, to be consistent with Figure 10 in Jackson et al. (2014), only ice particles with diameters larger than 100 μm are included and shown in our model-observation comparison."

We also added the following sentences in the section 4.3.2: "We note that the agreement between observed and modeled ice number concentrations is improved, as shown in Figures 10 and 11 with a correction factor of ¼ and in supplementary Figures S2 and S4 with a correction factor of 1/2, compared to that without the correction factor (Supplementary Figures S1 and S3). This is because all model simulations including SIP_PHIL underestimate the observed ice number concentrations without the correction of the shattering effect."

The original Figures 10 and 11 without the correction of observed ice number are moved to the supplement (now Supplementary Figures S1 and S3).

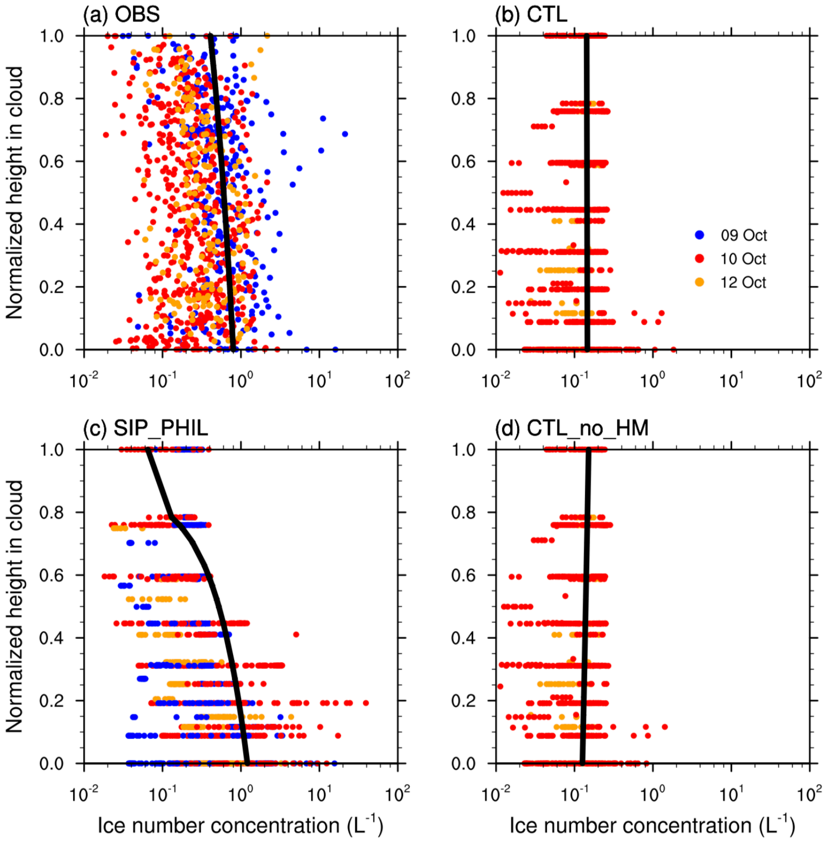


Figure 10. Ice number concentrations as a function of normalized cloud height from cloud base from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM. Black solid lines show the linear regression between ice number concentration and height. Only ice particles with diameters larger than 100 μm from observations and model simulations are included in the comparison. A correction factor of ¼ is applied to the observed ice number concentrations in (a).

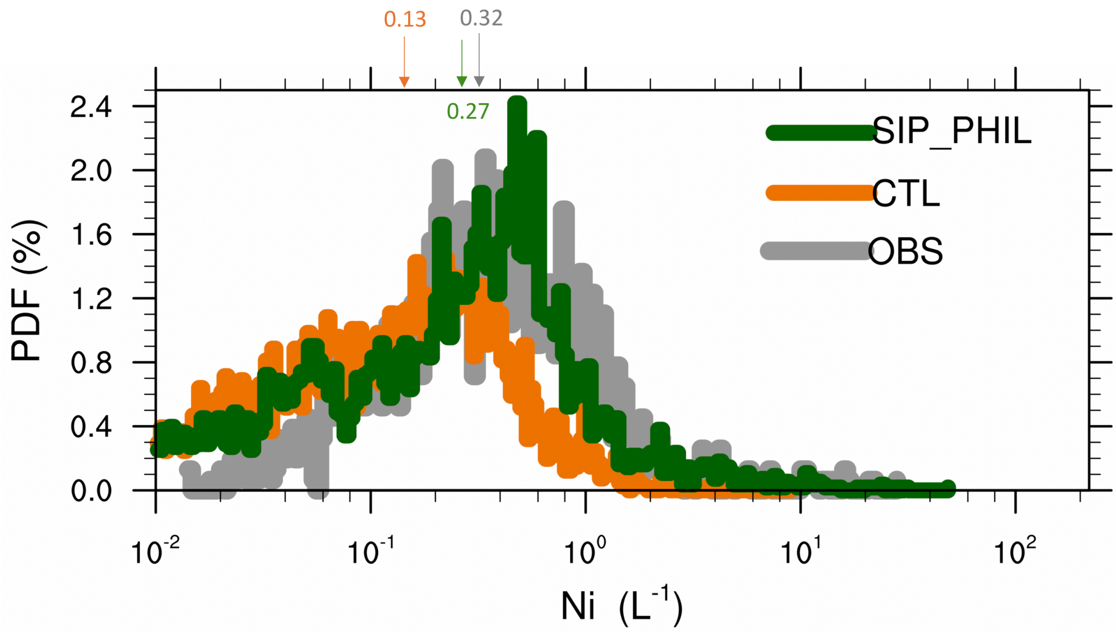


Figure 11. The probability density function (PDF) of ice crystal number concentrations from observation (gray line), CTL (orange line), and SIP_PHIL simulations (green line). The arrow indicates the median of each distribution which means that the set of values less (or greater) than the median has a probability of 50%. Only ice particles with diameters larger than 100 μm from observations and model simulations are included in the comparison. A correction factor of ¼ is applied to the observed ice number concentrations.

Minor revisions:

- Section 4.1.1: A discussion of why the ice properties are so poorly represented in the model is much needed. Please include.

Reply: We thank the reviewer for the suggestion. We have added a detailed discussion of why the ice properties are so poorly represented in the model in Section 5 conclusions as: "The representation of ice properties is highly simplified in the current model. First of all, ice particles in nature are featured with continuous size distributions with complex shapes and a wide range of densities. In contrast, the current model artificially classifies them into two categories (i.e., cloud ice and snow) with fixed densities, e.g., densities of 500 kg m^{-3} for cloud ice and of 250 kg m^{-3} for snow. Moreover, the shape of all ice particles is assumed to be spherical. The parameters, *a* and *b* in the relationship of terminal velocity and diameter (V-D, $V=aD^b$) are fixed values for cloud ice and snow. These assumptions cannot represent the complexities of ice properties (e.g., size distribution, density, shape, and fall speed) in the measurement. Furthermore, the riming intensity of ice particles changes as ice collides with supercooled liquid, leading to significant changes in density and fall speed of ice. This evolution of ice properties is currently not represented in the model. A promising method is to represent the ice-phase microphysics with varying ice properties (Morrison and Milbrandt, 2015; Zhao et al., 2017)."

- What are the initialization and forcing conditions of the model?

Reply: We thank the reviewer for the suggestion. We have added a brief explanation about the initialization and forcing data in Section 3.3 as: "The model is initialized and driven by the large-scale forcing data at every 3 hours. The forcing data which were developed by Xie et al. (2006) include divergences and advections of moisture and temperature as well as the surface flux."

- The title would be more accurate if "CAM6 single column model" is used in place of CESM2. Please modify.

Reply: We thank the reviewer for the suggestion. We have modified the title as: "Impacts of Secondary Ice Production on Arctic Mixed-Phase Clouds based on ARM Observations and CAM6 Single-Column Model Simulations"

- Please include more information about the formulation of the Hallett-Mossop parameterization.

Reply: We thank the reviewer for the suggestion. We have added more detailed description of the Hallett-Mossop parameterization in the revised manuscript as:

"The ice number production rate is based on the parameterization of Cotton et al. (1986), which is given as:

$$N_{HM} = C_{sip\_HM} \times p_{sacws} \quad (11)$$

where p_{sacws} is the riming rate of cloud droplets by snow and is expressed as:

$$p_{sacws} = \frac{\pi \times a_{vs} \times \rho \times N_{0s} \times E_{ci} \times \Gamma(b_{vs}+3)}{4 \times \lambda^{b_{vs}+3}} \quad (12)$$

in which E_{ci} is the collection efficiency for the riming of cloud droplets by snow based on Thompson et al. (2004), a_{vs} and b_{vs} are the fall speed parameters for snow particles, $b_{vs} = 0.41$, and $a_{vs} = 11.72 \times \frac{\rho_{850}}{\rho}$, ρ and ρ_{850} are the air density and the typical air density at 850 hPa, respectively, and N_{0s} and λ are the parameters for the snow particle size distribution.

The conversion coefficient C_{sip_HM} in Equation (11) depends on temperature T_c in ºC:

$$C_{sip\_HM} = \frac{3.5\times10^8 \times (-3-T_c)}{2}, \text{ when } -5 < T_c < -3, \text{ and} \quad (13)$$

$$C_{sip\_HM} = \frac{3.5\times10^8 \times (T_c-(-8))}{3}, \text{ when } -8 < T_c < -5 \quad (14)$$

The production rate for cloud ice mixing ratio is given as:

$$P_{HM} = N_{HM} \delta m_{ice} \quad (15)$$

in which δm_{ice} is mass for a single ice particle in the HM process, prescribed as 2.09×10^{-15} kg."

- Lines 35-39: not only is the cloud radiative effect important but also the impact of Arctic cloud properties in climate change scenarios: Vavrus 2004, Zhang et al. (2018),Tan & Storelvmo 2019.

  Reply: We agree with the reviewer's comment, and have added a sentence as: "Cloud properties further play a key role in the Arctic climate change through cloud feedbacks (Vavrus, 2004; Zhang et al., 2018; Tan and Storelvmo, 2019)."

- Line 422: there are more references related to this than the single ones mentioned for the CAM3/CAM5 model: e.g. Klein et al. 2009, Cesana et al. 2015, Tan & Storelvmo 2016, Zhang et al. 2019, Tan & Storelvmo 2019.

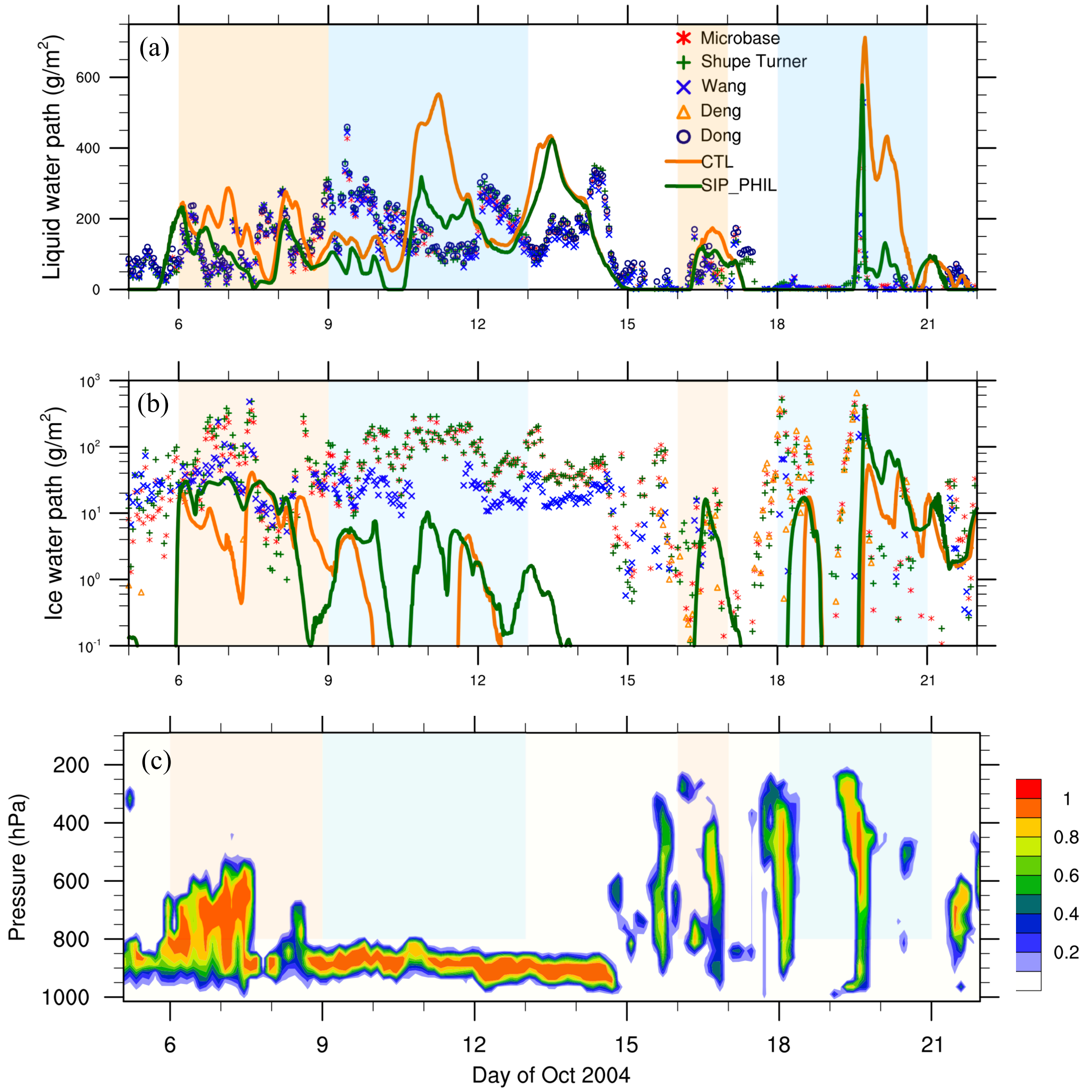
  Reply: We thank the reviewer for the suggestion. We have added more references based on your comments as: "CAM5 showed an underestimation of the liquid fraction (Liu et al., 2011; Cesana et al., 2015; Tan and Storelvmo, 2016; Zhang et al., 2019; Tan and Storelvmo, 2019),"

- Figure 4a: Why does LWP decrease in the SIP_PHIL experiment? Is this related to the Bergeron-Findeisen process?

  Reply: We thank the reviewer for the suggestion. Yes, as you suggested, the decrease of LWP is related to the Bergeron-Findeisen process. Even though SIP is not the direct reason for the LWP decrease, it triggers a chain of microphysical process interactions. We have examined the SIP-induced LWP and IWP changes based on the budget analyses of cloud hydrometeors in Zhao and Liu (2021, submitted).

- Figure 4b: consider using a nonlinear scale to improve visibility of small values.

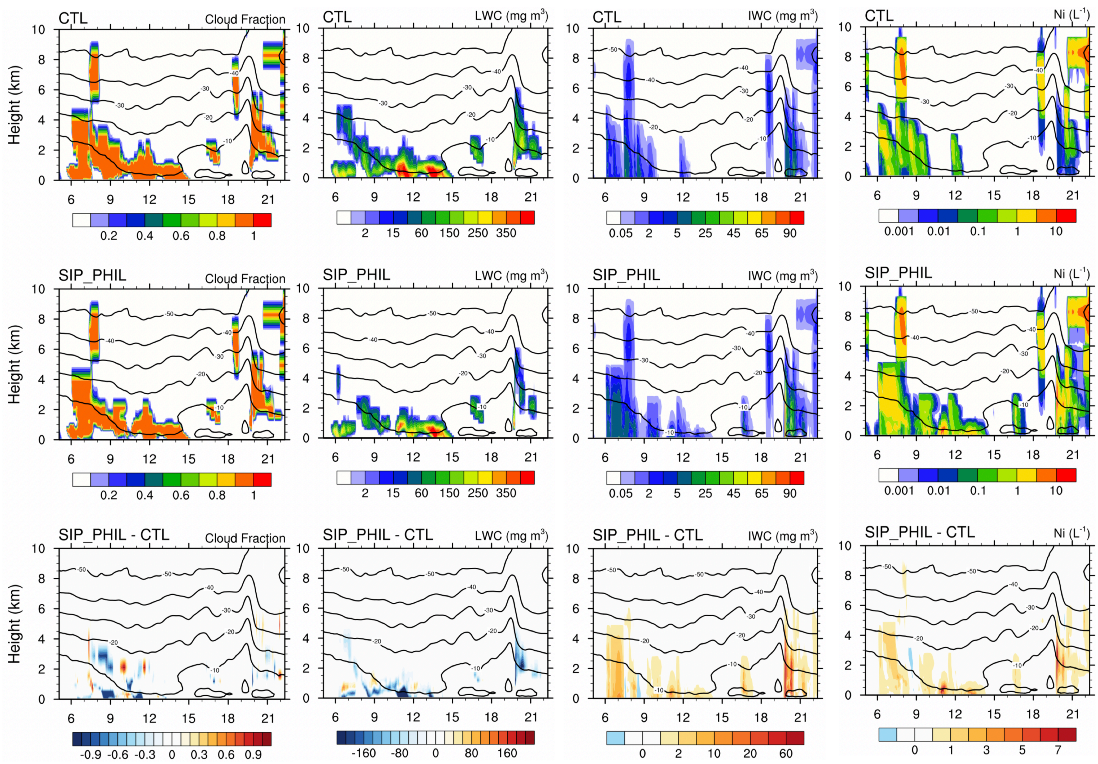
Reply: We thank the reviewer for the suggestion. We have revised Figure 4b according to your suggestion as:



- Figure 5 and lines 352-353: To my eye, it is not clear that the "decoupling" is much improved in the SIP simulation; also has a typo in bottom row, should be "LWC", CF is not labelled in first column.

Reply: We thank the reviewer for the suggestion. We have revised the sentence by removing "decoupling" in the sentence: "This bias is alleviated in SIP_PHIL during 8-12 October (Fig. 5)."

We have also corrected the typo and added the "Cloud Fraction" label in the first column of Figure 5:



- I suggest Figure 12 go to the Supplementary Info.

Reply: Following the reviewer's suggestion, we have moved Figure 12 to the Supplementary Information as Figure S5.

- In terms of the writing style, in general, there are too many short subsections that might be better combined into a broader section. Also, the grammar could improve.

Reply: We thank the reviewer for the suggestion. Following your comment, we have combined section 4.1.1, section 4.1.2, section 4.1.3, section 4.1.4, and section 4.1.5 into a single section 4.1 in the revised manuscript.

References:

Cesana, G., Waliser, D. E., Jiang, X. and Li, J. -L. F.: Multimodel evaluation of cloud phase transition using satellite and reanalysis data, Journal of Geophysical Research: Atmospheres, 120(15), 7871–7892, https://doi.org/10.1002/2014JD022932, 2015.

Jackson, R. C. and McFarquhar, G. M.: An assessment of the impact of antishattering tips and artifact removal techniques on bulk cloud ice microphysical and optical properties measured by the 2D cloud probe, Journal of Atmospheric and Oceanic Technology, 31(10), 2131–2144, https://doi.org/10.1175/JTECH-D-14-00018.1, 2014.

Jackson, R. C., Mcfarquhar, G. M., Stith, J., Beals, M., Shaw, R. A., Jensen, J., Fugal, J. and Korolev, A.: An assessment of the impact of antishattering tips and artifact removal techniques on cloud ice size distributions measured by the 2D cloud probe, Journal of Atmospheric and Oceanic Technology, 31(12), 2567–2590, https://doi.org/10.1175/JTECH-D-13-00239.1, 2014.

Morrison, H. and Milbrandt, J. A.: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part I: Scheme description and idealized tests, Journal of the Atmospheric Sciences, 72(1), 287–311, https://doi.org/10.1175/JAS-D-14-0065.1, 2015.

Tan, I. and Storelvmo, T.: Sensitivity study on the influence of cloud microphysical parameters on mixed-phase cloud thermodynamic phase partitioning in CAM5, Journal of the Atmospheric Sciences, 73(2), 709–728, https://doi.org/10.1175/JAS-D-15-0152.1, 2016.

Tan, I. and Storelvmo, T.: Evidence of Strong Contributions From Mixed-Phase Clouds to Arctic Climate Change, Geophysical Research Letters, 46(5), 2894–2902, https://doi.org/10.1029/2018GL081871, 2019.

Vavrus, S.: The impact of cloud feedbacks on Arctic climate under Greenhouse forcing, Journal of Climate, 17(3), 603–615, https://doi.org/10.1175/1520-0442(2004)017<0603:TIOCFO>2.0.CO;2, 2004.

Xie, S., Klein, S. A., Yio, J. J., Beljaars, A. C. M., Long, C. N. and Zhang, M.: An assessment of ECMWF analyses and model forecasts over the North Slope of Alaska using observations from the ARM Mixed-Phase Arctic Cloud Experiment, Journal of Geophysical Research, 111(D5), D05107, https://doi.org/10.1029/2005JD006509, 2006.

Zhang, R., Wang, H., Fu, Q., Pendergrass, A. G., Wang, M., Yang, Y., Ma, P. and Rasch, P. J.: Local Radiative Feedbacks Over the Arctic Based on Observed Short-Term Climate Variations, Geophysical Research Letters, 45(11), 5761–5770, https://doi.org/10.1029/2018GL077852, 2018.

Zhao, X., Lin, Y., Peng, Y., Wang, B., Morrison, H. and Gettelman, A.: A single ice approach using varying ice particle properties in global climate model microphysics, Journal of Advances in Modeling Earth Systems, 9(5), 2138–2157, https://doi.org/10.1002/2017MS000952, 2017.

Response to Reviewer 2

We thank the anonymous reviewer for his/her careful reading and constructive review of our paper. Our detailed responses to the reviewer's comments follow. Reviewer's comments are in blue color, our responses are in black color, and our corresponding revisions in the manuscript are in red color.

General Comments:

This study explores the impact of three secondary ice production (SIP) mechanisms on Arctic clouds observed during M-PACE in CAM6. CAM6 already includes a description of the Hallet-Mossop process, while the authors have implemented two additional mechanisms: drop-shattering and collisional break-up. Their results indicate that the additional parameterizations improve the representation of Arctic clouds, by reducing biases in liquid and ice content. Moreover, both the vertical distribution and magnitude of ice crystal number concentrations is improved with the activation of SIP. Drop-shattering is found to be most important SIP mechanism in boundary layer clouds, while primary ice nucleation dominates ice formation in deep cold clouds. The study suggests that including additional SIP mechanism in global climate models can substantially improve the representation of mixed-phase Arctic clouds. Given the fact that the poor microphysical representation of these clouds in GCMs is a main source of uncertainty in future projections of the Arctic climate, the scientific impact of the study is significant and thus I recommend it for publication. My only main comment concerns the technical implementation of the processes and to which extent this is consistent with the rest of the Morrison-Gettelman (MG) microphysics scheme.

Reply: We thank the reviewer for the encouraging comments on our study. We have revised the manuscript following the reviewer's comments. We have provided more details of implementing the SIP processes and their integration with the MG microphysics scheme in our revised manuscript (see our response to your main comment below).

Main comment:

In the standard MG scheme snow-snow collisions, snow-ice collisions and snow-rain also lead to aggregation/accretion. Are these processes still active in the modified scheme? For example pracs and npracs is the accreted mass and number concentration predicted by the scheme for snow-rain collisions. Are these parameters generally consistent with mass and number predicted by the bin framework? Please provide details about how existing collisions in the standard scheme are combined with additional parameterizations to ensure consistency in mass transfers.

Reply: We thank the reviewer for the suggestion. As the reviewer points out, the standard MG scheme considers the accretion of cloud ice by snow and the accretion of rain by snow. Only the self-aggregation of snow is considered during the collisions between snow-snow. These processes consider the collision/coalescence between particles, i.e., the decrease of the number during the collisions. These processes are still active in the modified scheme, and we did not modify the parameterizations of these processes.

However, the added SIP processes consider the break-up of the colliding particles, which is opposite to the particle collision/coalescence processes. These SIP processes are added as a supplement to, not a replacement of the pre-existing collision processes in the standard MG scheme.

The bin-approach is only adopted for the SIP processes, while other processes, including the existing collisions in the standard MG scheme, still use the bulk microphysical approach. Thus, the modified MG scheme becomes a hybrid scheme that combines the bulk and bin parameterizations. The advantage of this hybrid scheme is that the scheme can provide an accurate representation of the SIP processes while still maintains a relatively high computational efficiency, which is very important for global climate models. We note that the hybrid schemes have been widely used. For example, previous studies used the bin approach for the warm rain processes, while adopted the bulk approach for the ice-related processes (Onishi and Takahashi, 2012; Grabowski et al., 2010; Kuba and Murakami, 2010). Other previous studies used the bin approach for the sedimentation (Morrison, 2012) or lookup tables for the collision processes in the bulk schemes (Feingold et al., 1998).

To improve the clarity, we provided more details about how the parameterizations of existing collisions in the standard MG scheme are combined with the SIP parameterizations in section 2.2 of the revised manuscript as:

"The bin approach is only adopted in the SIP processes, while other processes, including the existing collisions in the standard MG scheme, still use the bulk microphysical approach. Thus, the modified MG scheme becomes a hybrid scheme that combines the bulk and bin parameterizations. The advantage of this hybrid scheme is that the scheme can provide an accurate representation of the SIP processes while still maintains a relatively high computational efficiency, which is very important for global climate models. The hybrid schemes have been widely used. For example, previous studies used the bin approach for the warm rain processes, while adopted the bulk approach for the ice-related processes (Onishi and Takahashi, 2012; Grabowski et al., 2010; Kuba and Murakami, 2010). Other previous studies used the bin approach for the sedimentation

(Morrison, 2012) or look-up tables for the collision processes in the bulk schemes (Feingold et al., 1998)."

We also added a detailed discussion regarding the mass conservation in the supplementary materials: "The conservations of mass and number mixing ratios are ensured in the modified scheme. The tendencies of cloud hydrometeors are updated after we consider the SIP processes in the model. In the following equations, SIP related terms are in italic font and other processes are in the standard font:

For cloud ice:

nitend = nnuccd + nnucct + nnuccc + nnudep + nsacwi + nsubi -nprci – nprai + nnuccri + *nf_1mode* + *nf_2mode* + *nf_isc* + *nf_ssc* + *nf_gisc* + *nf_ggc*

qitend = mnuccc + mnucct + mnudep + msacwi – prci – prai + vap_dep + berg + ice_sublim + mnuccd + mnuccri + *mf_1mode* + *mf_2mode* + *mf_isc* + *mf_ssc* + *mf_gisc* + *mf_ggc*

For rain:

nrtend = nprc + (nsubr – npracs – nnuccr – nnuccri + nragg – *nsipr*)

qrtend = pra + prc + pre – pracs – mnuccr – mnuccri – (*mf_1mode* + *mf_2mode* + *mf_big*)

For snow:

nstend = nsubs + nsagg + nnuccr + nprci + *nf_big* – *nsips*

qstend = prai + prci + psacws + bergs + prds + pracs + mnuccr + *mf_big* – *mf_isc* – *mf_ssc* – *mf_gisc* – *mf_ggc* in which the process names are listed as follows:

nnuccd/mnuccd	homogeneous and heterogeneous nucleation from water vapor
nnucct/mnucct	contact freezing of cloud water
nnuccc/mnuccc	immersion freezing of cloud water
nnudep/mnudep	deposition nucleation in mixed-phase clouds
nsacwi/msacwi	H-M splintering
nprci/prci	autoconversion of cloud ice to snow
nprai/prai	accretion of cloud ice by snow
nnuccri/mnuccri	freezing of rain to form ice
vap_dep	deposition of cloud ice
ice_sublim/nsubi	sublimation of cloud ice
berg	WBF between cloud water and cloud ice
nprc/prc	autoconversion of cloud droplet to rain
nsubr/pre	evaporation of rain
npracs/pracs	collection of rain by snow
nnuccr/mnuccr	freezing of rain to form snow
nragg	self-collection of rain
pra	accretion of cloud water by rain
nsubs	sublimation of snow
nsagg	self-aggregation of snow
psacws	collection of droplets by snow
bergs	WBF between cloud water and snow
prds	sublimation of snow
nf_1mode/mf_1mode	SIP from the first mode of freezing rain break-up
nf_big/mf_big	SIP from the first mode of freezing rain break-up (big fragments)
nf_2mode/mf_2mode	SIP from the second mode of freezing rain break-up
nf_isc/mf_isc	SIP from cloud ice and snow collision
nf_ssc/mf_ssc	SIP from snow and snow collision
nf_gisc/mf_gisc	SIP from graupel and cloud ice/snow collision
nf_ggc/mf_ggc	SIP from graupel and graupel collision
nsipr	decrease of rain number due to SIP
nsips	decrease of snow number due to SIP

”

Minor comments:

Section 2.2b:

- How parameter ‘rim’ is treated? Not explained.

Reply: We thank the reviewer for the question. we have revised the sentence to read as "γ is a parameter related to ice particle riming intensity (rim), $\gamma = 0.5 - (0.25 \times rim)$, and rim is assumed to be 0.1."

- *Figure 1:* a planar or a dendritic ice habit was eventually assumed in the presented simulations, since MG does not predict shape?

Reply: We thank the reviewer for the suggestion. Following Phillips et al. (2017), the ice habit is assumed to be dendrites when air temperature (T) is between –12°C and –17°C and to be spatial planar when –40°C <T<–17°C and –12°C<T<–9°C.

To improve the clarity, we revised the caption of Figure 1 as:

"Figure 1. The number of fragments per collision as a function of initial collision kinetic energy (CKE). The ice habit is assumed to be dendrites when air temperature (T) is between –12°C and –17°C and to be spatial planar when –40°C<T<–17°C and –12°C<T<–9°C, following Phillips et al. (2017)."

- *Equation 4:* why sticking efficiency is included in the calculation? (I assume the default 0.5 value of MG is applied). I think mechanical break-up occurs when ice particles grow rimed branches that break after collisions with other frozen hydrometeors. Is accretion/aggregation a prerequisite for this mechanism?

Reply: We thank the reviewer for the suggestion. The E_c in Equation 4 is the accretion efficiency, and we assumed E_c to be 0.5 to be consistent with the MG scheme.

To improve the clarity, we revised the related sentence as: "in which E_c is the accretion efficiency, and assumed to be 0.5 to be consistent with the MG microphysical scheme".

Yes, as the reviewer said, the collision is the prerequisite for the ice-ice collision break-up mechanism.

Section 2.2c:

- Why rhoi is set to 920 kg/m^3 for this process and not be consistent with the rest of MG code? I think rhoi is set to 500 kg/m^3 in the default model version. Unless here it set to 920 kg/m^3 for the whole scheme and not only for this particular process.

Reply: We thank the reviewer for the question. We agree with the reviewer that the density for the ice should be set to 500 kg/m^3 to be consistent with the MG scheme. Previously, we set the density for the newly formed ice from the droplet shattering as 920 kg/m^3 following Phillips et al. (2018). Now, we changed the density of ice in the modified scheme to be 500 kg/m^3 as the reviewer suggested, and updated the related model results. There are no significant impacts on the model results from this ice density change.

We have revised the related sentence as "The mass of a large fragment is $m_B = \chi_B m_{rain}$, in which $\chi_B = 0.4$, and the mass of a small fragment is $m_S = \frac{\pi\rho_i}{6}D^3$, in which $\rho_i = 500\ kg\ m^{-3}$."

- Big fragments are added to snow or cloud ice? Please clarify.

Reply: We thank the reviewer for the question. Big fragments are added to snow. We have shown the snow mass and number conservation equations in the supplementary materials to clarify:

"nstend = nsubs + nsagg +nnuccr + nprci + *nf_big – nsips*

qstend = prai + prci + psacws + bergs + prds + pracs + mnuccr + *mf_big – mf_isc – mf_ssc – mf_gisc – mf_ggc*"

- Is a minimum raindrop size threshold used in mode 2 for the process to be activated? I think in Phillips et al. (2018) a minimum size of 150 μm is assumed to initiate the mechanism. Anyway, if no threshold is used, please clarify.

Reply: We thank the reviewer for the question. Yes, the minimum size is set as 150 μm. We revised the related sentence as:

"where *DE* is the dimensionless energy and is expresses as:

$$DE = \frac{k_0}{S_e}, \tag{9}$$

where k_0 is the initial kinetic energy which is given in Eq. (3), S_e is the surface energy, expressed as $S_e = \gamma_{liq}\pi D^2$ (for D>150 μm)"

Section 3.2:

Please state the instruments' uncertainty. Also different retrievals seem to have been applied for the measured variables in Figure 4. Please provide the corresponding references in this section. It would also be nice if a short description on the differences between these algorithms is provided here, along with the estimated uncertainty for each retrieval.

Reply: We thank the reviewer for the suggestion. We have added some discussions of the observed data and instruments' uncertainty in Section 4.1 as

"The LWP and IWP data are obtained from Zhao et al. (2012). Specifically, the Shupe and Turner's data are based on the retrievals of cloud properties measured by a 35-GH millimeter cloud radar (Shupe et al., 2005), with the uncertainties for LWC within 50% and for IWC within a factor of 2. For the Wang's data, IWP is retrieved from the combined Millimeter Wave Cloud Radar and micropulse lidar measurements (Wang and Sassen, 2002) with an uncertainty of 35% (Khanal and Wang, 2015). LWP is retrieved from the ARM Microwave Radiometer (MWR) measurements with an uncertainty of 50% (Wang, 2007). Deng's data is based on millimeter-wavelength Doppler radar measurement, with the retrieval algorithm error within 85% for IWC (Deng and Mace, 2006). For Dong's data, LWC is derived from microwave radiometer measurement with the uncertainty within 113% (Dong and Mace, 2003)."

Section 3.3:

What happened to the CTL_no_HM experiment? I cannot find relevant results in any of the Figures or Tables. It would be very interesting to include this simulation in the paper too.

We thank the reviewer for the great suggestion. We have added results from the CTL_no_HM experiment in the tables and figures, and also added some discussions about the CTL_no_HM experiments in the revised manuscript.

In Section 4.3.1: "The CTL and CTL_no_HM experiments have similar results, and both underestimate the ICNCs in all the cloud layers, with a mean ICNC of ~0.25 L^{-1} and the maximum concentration of 3 L^{-1}."

In Section 4.1: "CTL_no_HM has similar results as the CTL experiment."

We updated Tables 2 and 3 and Figures 9 and 10 to include the results from the CTL_no_HM experiment.

Table 2. The temporally-averaged IWP, LWP (unit: g m^{-2}), and vertically-integrated ice crystal number concentration ICNC (unit: m^{-2}) during the four periods from observation, and CTL, CTL_no_HM and SIP_PHIL experiments.

		Multilayer stratus	Single-layer stratus	Transition	Frontal cloud
IWP	OBS	55.6	74.7	5.6	97.0
	CTL	11.2	0.9	0.0001	10.4
	CTL_no_HM	11.1	0.9	0.0001	8.2
	SIP_PHIL	17.1	2.5	3.6	26.1
LWP	OBS	134.4	190.2	58.3	50.2
	CTL	165.1	217.6	88.4	127.6
	CTL_no_HM	166.0	218.0	88.4	129.8
	SIP_PHIL	102.8	131.0	62.1	41.2
ICNC	CTL	5.77×10^6	3.22×10^5	7.66	2.26×10^6
	CTL_no_HM	5.70×10^6	3.17×10^5	0.77	1.57×10^6
	SIP_PHIL	7.09×10^6	1.30×10^6	4.57×10^5	4.67×10^6

Table 3. Percentage of occurrence of liquid, mixed-phase, and ice clouds during single layer mixed-phase clouds from observation, and CTL, CTL_no_HM and SIP_PHIL experiments.

	Liquid	Mixed-phase	Ice
OBS (%)	16.0	62.7	22.3
CTL (%)	73.0	26.9	0.1
CTL_no_HM (%)	73.0	26.9	0.1
SIP_PHIL (%)	40.8	58.0	1.2

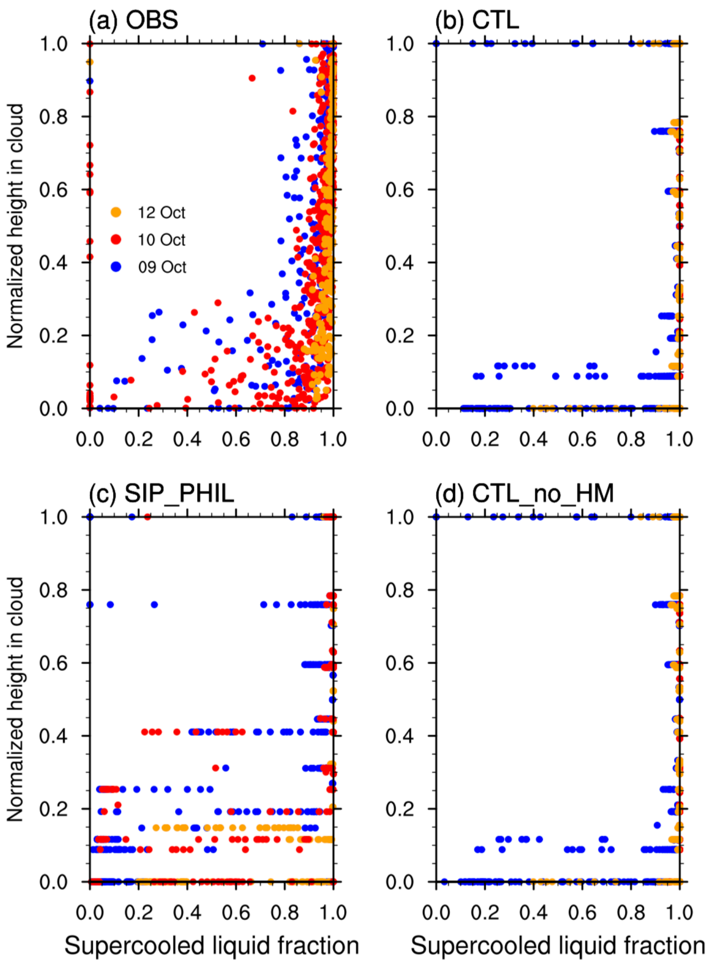


Figure 9. Liquid fraction as a function of normalized cloud height from cloud base. The normalized cloud altitude Z_n is defined as: $Z_n = \frac{z-Z_b}{Z_t-Z_b}$, in which z is the altitude, Z_b is the altitude of cloud base, and Z_t is the altitude of cloud top, from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM.

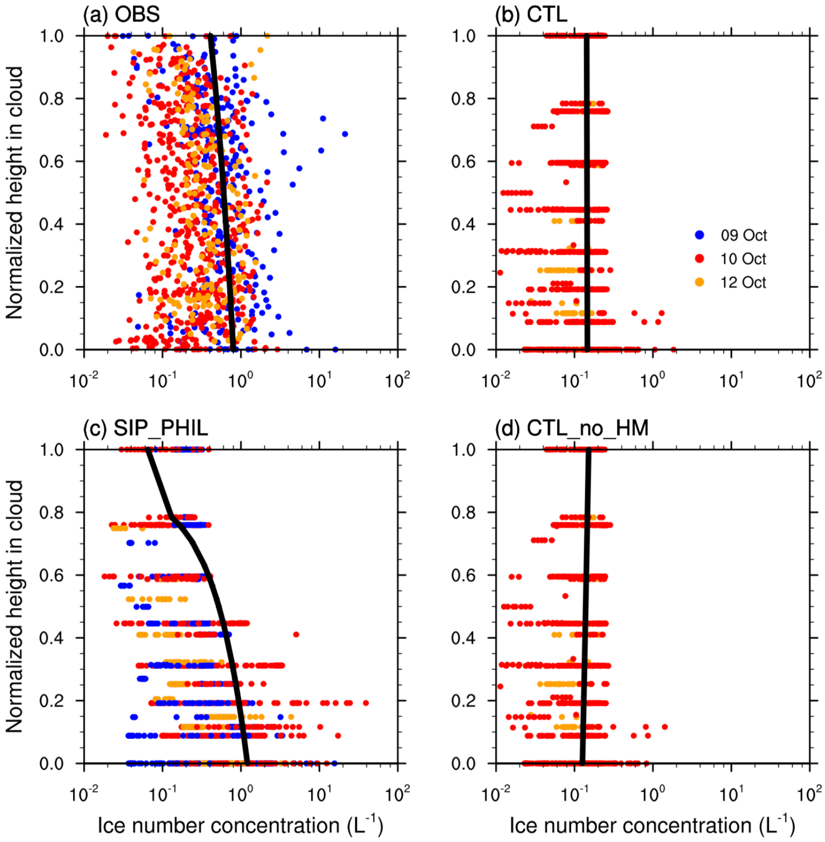


Figure 10. Ice number concentration as a function of normalized cloud height from cloud base from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM. Black solid lines show the linear regression between ice number concentration and height. Only ice particles with diameters larger than 100 μm from observations and model simulations are included in the comparison. A correction factor of ¼ is applied to the observed ice number concentrations (a).

Section 4.1:

Lines 326-327: The simulated LWP is overestimated during the "multilayer stratus" and "frontal cloud"

Actually LWP in Fig 4a seems simulated reasonably well, especially in SIP_PHIL. I would say that it is in the second half of the single-stratocumulus period that LWP is substantially overestimated

Reply: We thank the reviewer for the suggestion. We have revised the sentence according to your comment as: "The simulated LWP is overestimated during the "multilayer stratus", the second half of the "single-stratus", and "frontal cloud" periods in CTL, particularly on 20 October. The SIP_PHIL experiment decreases the LWP from 550 g m^{-2} in CTL to 300 g m^{-2} on 11 October and from 425 g m^{-2} in CTL to 70 g m^{-2} on 20 October (Fig. 4a)."

Section 4.1.3:

Maybe LWC should be also shortly discussed in this section, since it is shown in Figure 7

Reply: We thank the reviewer for the suggestion. We have added a brief discussion about LWC in Section 4.1.3 as: "The simulated LWC is decreased from 80 to 65 mg m^{-3}, which is closer to the observed value of 55 mg m^{-3}."

Section 5:

Lines 558-560: I think MG assumes that rime-splintering only occurs when cloud droplets collide with snow. While for example Morrison scheme also includes raindrop-ice interactions in the Hallet-Mossop process. This means that the overestimation in the H-M efficiency due to lack of size dependency might be balanced by an underestimation of the raindrop splintering production in MG. Also I wonder about what is the impact of the fact that the bulk approach is used to represent H-M, while a bin approach is used for the rest of the processes. Would a 'bin representation' increase the efficiency of H-M? I am not suggesting that the authors should also adapt a bin approach for H-M for consistency, but it would be really interesting to know how this modifies results. Nevertheless this is something that could be discussed along these lines.

Reply: We thank the reviewer for the suggestion. We agree with the reviewer that the overestimation in the HM splintering rate due to lack of the cloud droplet spectrum might be compensated by neglecting the raindrop splintering in the HM process in the MG microphysics. It would also be interesting to examine the impact of a bin approach to represent the HM process on modeled clouds, which will be a topic of our future studies.

We have added the following sentences in the text:

"Lacking the effect of cloud droplet spectrum in the HM process is supposed to result in an overestimated splintering rate in the Arctic clouds, especially for the clouds with cloud-bases close to the freezing level and with small droplets in the clouds. However, the overestimation in the HM splintering rate due to lack of the cloud droplet spectrum might be balanced by neglecting the raindrop splintering in the HM process in the MG microphysics. In this study, we keep using the bulk approach to represent the HM process, to be the same as that in the standard MG microphysics scheme. It would be interesting to examine the impact of a bin approach to represent the HM process on modeled clouds, which will be a topic of our future studies."

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