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

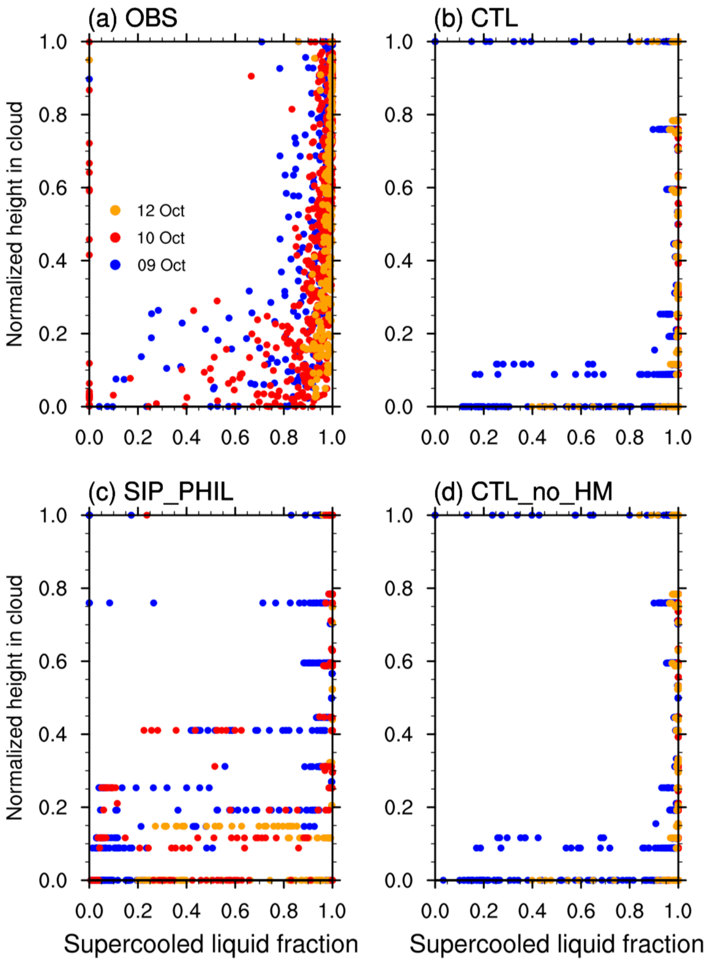

Figure 9. Liquid fraction as a function of normalized cloud height from cloud base. The normalized cloud altitude Z_n is defined as: $Z_n = \frac{z-Z_b}{Z_t-Z_b}$, in which z is the altitude, Z_b is the altitude of cloud base, and Z_t is the altitude of cloud top, from (a) observation, (b) CTL, (c) SIP_PHIL,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

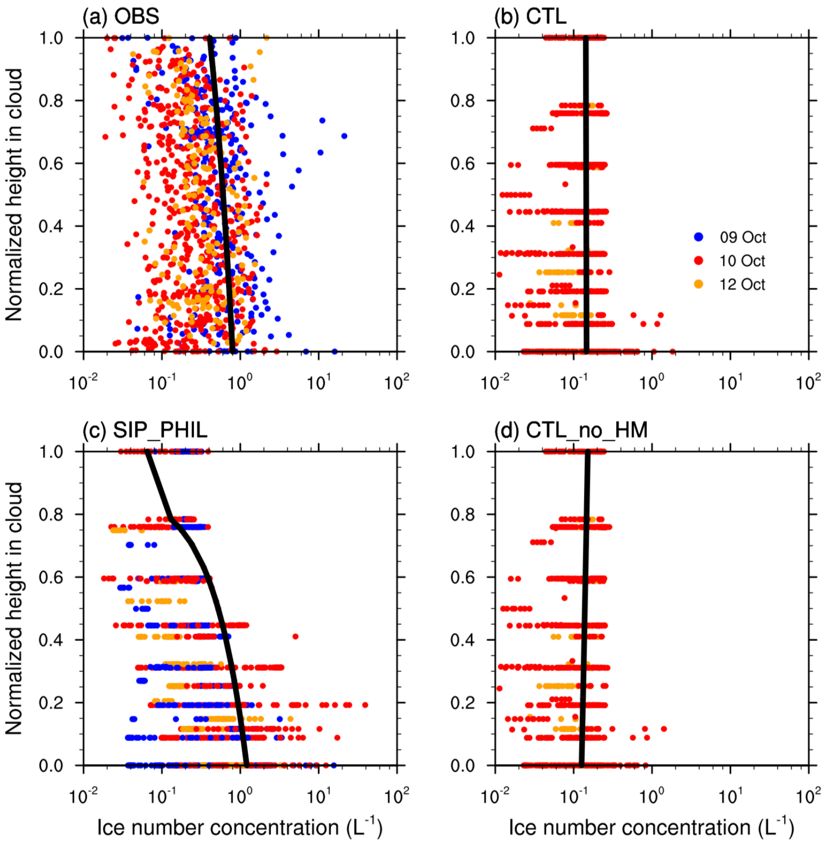

Figure 10. Ice number concentration as a function of normalized cloud height from cloud base from (a) observation, (b) CTL, (c) SIP_PHIL, and (d) CTL_no_HM. Black solid lines show the linear regression between ice number concentration and height. Only ice particles with diameters larger than 100 μm from 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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