Reviewer 2

We appreciate the thorough review and constructive comments, which have helped us to substantially improve the quality of the manuscript. We hope that the modified manuscript and our responses to the comments are satisfactory. The reviewer's comments are in italics, and our responses are in standard font below.

1.) This manuscript documents experiments with variable ice nucleation number, by adjusting the ice concentration in a GCM to prevent homogenous freezing and thin cirrus clouds as a form of geo engineering. The manuscript is well written and thought out. It should be publishable in ACP with minor revisions.

My major concern is a lot of the effects are from liquid and mixed phase clouds that the method is not directly perturbing. Or should not be directly perturbing. But the mechanism is not explained well in the text. It is not clear if the compensating effects for mixed and liquid clouds from adding ice crystals to pure ice clouds is an artifact of the model, or has a solid physical basis. This should be detailed further in the discussion of the cases and the conclusions. It may require a bit more in depth analysis.

Reply: Thank you very much for your kind statement. We totally understand the reviewer's concern about the compensating effect (i.e., warming effect of liquid and mixed-phase clouds) caused by cirrus seeding. Gasparini et al. (2017) pointed out the compensating effects induced by cirrus thinning. There seems to be a relatively solid physical reason that cirrus thinning reduces atmospheric stability via the radiative budget and convective activity becomes more intense (Kristjánsson et al., 2015; Storelvmo and Herger, 2014), which would consume more cloud water and lead to the warming effect of liquid clouds (Gasparini et al., 2017; Rapp et al., 2011). The warming effect of liquid clouds in our study (0.94 ± 0.11 W m^{-2} from the OPT experiment) is similar to that reported by Gasparini et al. (2017; Table 5, 0.96 ± 0.25 W m^{-2} from the ECHAM-HAM model simulation with seeding 1 ice nuclei particle L^{-1} of 50 μm). However, the warming effect of mixed-phase clouds in our study (1.09 ± 0.11 W m^{-2}) is several times stronger than that from their results (Table 5, 0.15 ± 0.10 W m^{-2}). In our study (using the CAM model), the warming effect of mixed-phase clouds mainly comes from the increasing longwave component (not shown), which is consistent with the increased ice water content (IWC) in mixed-phase clouds. The main reason for the increased IWC might be that the convective detrainment is obviously increased due to cirrus thinning. The ratio of ice to total cloud condensate detrained from the convective parameterizations is a linear function of temperature between −40 °C and −10 °C (Morrison and Gettelman, 2008). Furthermore, ice crystals can grow through the Bergeron process in mixed-phase clouds (Morrison and Gettelman, 2008). The warming effect of mixed-phase clouds induced by cirrus thinning seems more sensitive to the cloud-related scheme used in the climate model. In the reversed manuscript, we added more analyses about the compensating effect (i.e., the warming effect of mixed-phase and liquid clouds) in Section 3. In the discussion section, we clearly pointed out that the climatic response to cirrus seeding is complex and might differ among different climate models and seeding methods. The compensating effects introduced in this study are derived from the atmosphere-only simulations with prescribed ocean surface conditions, the coupled model simulations might show different results (e.g., Gasparini et al., 2017).

Specific comments:

2.) Page 1, L11: is cooling positive or negative? Do the values in lines 10 and 11 with different signs represent the same direction? Please clarify: if the same direction then should be the same sign.

Reply: We thank the reviewer for pointing this out. Cooling should be negative even if it has been declared a cooling effect. A negative sign was added in the revised manuscript. Furthermore, we have checked the signs throughout the manuscript and emphasized this issue in the revised manuscript.

3.) Page 1, L14: cirrus clouds typically do not contain liquid, so why would cirrus seeding impact mixed phase clouds?

Reply: Thank you for this comment. Cirrus seeding can directly reduce the cirrus clouds and then indirectly impact mixed-phase and liquid clouds via different mechanisms. For instance, convective activity becomes more intense because cirrus thinning reduces atmospheric stability via the radiative budget, and the increased convective activity could impact liquid and mixed-phase clouds.

4.) Page 1, L16: could yield. Also, what sign is intended here?

Reply: Thanks. Done. The cooling effect is always quantified by a negative value in the revised manuscript.

5.) Page 3, L80: this seems like a pretty significant change to shut off homogeneous freezing below 205K. What is the impact of that?

Reply: Thank you for this comment. At temperatures below 205 K, the observed ice number concentration (N_i) is usually in the range of 10-80 L^{-1} (Krämer et al., 2009), whereas the modeled N_i without switching off homogeneous freezing is usually in the range of 50-2000 L^{-1} (Shi et al., 2015). In this study, the main purpose of this artificial setting is to make the modeled N_i to be close to observations at temperatures below 205 K (Shi et al., 2013). We mentioned this purpose in the revised manuscript.

6.) Page 4, L97: I think the formulas are an important part of the study, and should be in the main text.

Reply: Thanks for this suggestion. The flexible seeding method used for estimating the potential cooling effect of cirrus thinning includes the optimal seeding number concentration and the flexible seeding strategy. In the main text, we focus on introducing the advantages of the flexible seeding method, which are important for estimating the potential cooling effect of cirrus thinning. The formulas for calculating the optimal seeding number concentration provided by this study depend on the ice nucleation parameterization used in the climate model. However, the design idea of the optimal seeding number concentration is not model-dependent. For instance, some ice nucleation parameterizations provide the critical number concentration (N_{lim}) of ice nuclei particles (INPs) for the only heterogeneous freezing scenario (e.g., Barahona and Nenes, 2009). N_{lim} could also be used as the optimal seeding number concentration with INPs. Therefore, we prefer to focus on the design idea of the flexible seeding method in the main text.

7.) Page 5, L134: if you add ice number do you have to worry about conservation or inconsistencies? Not for number, but do such affects bleed into humans.

Reply: In the cirrus seeding experiments in this study, the seeding ice crystals are made from ambient atmospheric water vapor rather than artificially adding water into the atmosphere. Therefore, it is unnecessary to consider conservation or inconsistencies. We emphasized this in the experimental setups of the revised manuscript.

8.) Page 5, L140: does the ice added feedback through the microphysics?

Reply: Yes, it does. The seeding ice crystals not only impact the ice nucleation process but also impact other cloud microphysics processes because the ice crystals are directly added to the microphysics scheme. As shown in Section 3 of the manuscript, the impacts of cirrus seeding are very complicated. There is not only the direct instantaneous impact but also the feedback through microphysics.

9.) Page 10, L226: for clarity maybe you could pull out the global mean values into a table or a set of histograms.

Reply: Thank you for the comment. A new table was added in the revised manuscript as follows:

Table 2. Global annual mean cloud radiative effects from all experiments [a]. The corresponding standard deviations calculated from the difference of each year for 10 years are shown in brackets.

Experiments	REF	HET−REF	OPT−REF	INP20−REF	INP200−REF	R10−REF	GT−REF
$iCRE_{SW}$ (W m^{-2})	−5.30	3.39(0.03)	3.25(0.05)	0.38(0.07)	0.30(0.05)	2.81(0.05)	1.99(0.04)
$iCRE_{LW}$ (W m^{-2})	11.79	−6.84(0.04)	−6.29(0.07)	−0.83(0.10)	−0.31(0.08)	−5.40(0.07)	−4.33(0.06)
iCRE (W m^{-2})	6.49	−3.45(0.02)	−3.04(0.03)	−0.44(0.04)	−0.01(0.04)	−2.58(0.03)	−2.34(0.03)
Effectiveness (%)		56.19(0.70)	49.40(0.62)	6.69(1.45)	−2.22(1.32)	43.02(0.85)	39.01(0.95)
mCRE (W m^{-2})	−6.20	1.06(0.13)	1.09(0.11)	0.20(0.11)	0.15(0.13)	0.90(0.10)	0.81(0.12)
lCRE (W m^{-2})	−24.69	1.06(0.14)	0.94(0.11)	0.07(0.17)	−0.07(0.13)	0.62(0.13)	0.03(0.17)
CRE (W m^{-2})	−28.43	−1.98(0.26)	−1.36(0.18)	−0.27(0.26)	0.35(0.28)	−1.25(0.22)	−2.00(0.25)

[a] Shown are the ice cloud shortwave radiative effect ($iCRE_{SW}$), ice cloud longwave radiative effect ($iCRE_{LW}$), ice cloud radiative effect (iCRE), cirrus seeding effectiveness (Effectiveness), mixed-phase cloud radiative effect (mCRE), liquid cloud radiative effect (lCRE), and all cloud radiative effect (CRE).

10.) Page 10, L240: please name and make a formal equation for the seeding effectiveness.

Reply: Thanks. The cirrus seeding effectiveness (−100 * |ΔiCRE / iCRE|) was first proposed in Gasparini et al. (2020), which was used to show what proportion of iCRE is eliminated by cirrus seeding. In the revised manuscript, the equation has been clarified.

11.) Page 12, L274: can you comment more on the mechanism: why does adding ICs impact mixed phase and liquid clouds? Is this a real effect or a feature of the model formulation?

Reply: As discussed above, the impact on liquid clouds seems to be a real effect, and the impact on mixed phase clouds might be an artifact of the bulk model physics. In the revised manuscript, further comments on the mechanism were given in Section 3 (experimental results), and the robustness of the mechanism was analyzed in the discussion section.

12.) Page 12, L283: can you explain in a sentence or so why N increases with decreasing R?

Reply: The large ice crystal (R is relatively larger) has a larger surface area, consuming water vapor via deposition growth more efficiently. For the same amount of ice crystals, it is easier for larger ice crystals to prevent homogeneous nucleation from happening.

13.) Page 12, L284: which experiments are "these"?

Reply: Thank you for this comment. "In these seeding experiments" refers to the OPT, R10 and GT experiments. In the revised manuscript, we have clarified this.

14.) Page 12, L285-7: Im lost here. I thought the point of seeding was not to reach Sihom? Please clarify.

Reply: Yes, the point of seeding was not to reach S_{ihom}. Notably, seeding occurs only where homogeneous nucleation would occur without seeding. This seeding strategy was clearly described in Section 2.3 (flexible seeding method).

15.) Page 14, L314: can you explain why? Does it have to do with liquid and mixed phase clouds?

Reply: As shown in Fig. S1, the cooling effect of cirrus seeding is more significant in the winter hemisphere. In low solar noon zenith angle regions, the warming effects from liquid clouds are pronounced because the water vapor is sufficient and convective activity is intense. Thus, avoiding seeding in low solar noon zenith angle regions (GT experiment in the manuscript) can obtain a stronger cooling effect.

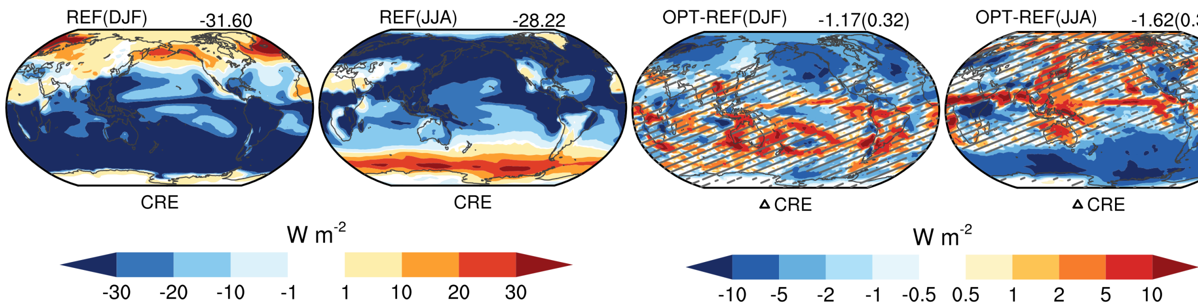

Figure S1: The annual mean spatial distribution of all cloud radiative effects (CREs) from the REF experiment for DJF and JJA (left panel) and the differences between the OPT and REF experiments (right panel). Global mean values are shown in the upper right corner, and the corresponding standard deviations calculated from the difference of each year for 10 years are shown in brackets.

16.) Page 14, L324: but don't you need INP to make IC?

Reply: It can be assumed that there is a machine that can make ice cubes from atmospheric water vapor and break the ice cubes into ice crystals.

17.) Page 15, L311: This is attributed to...

Reply: Thanks. Done.

18.) Page 15, L342: what is the mechanism for the effects on liquid and mixed phase clouds? You need to figure out of this is real or an artifact of the bulk model physics.

Reply: There might be many mechanisms for the effects on liquid and mixed-phase clouds. In the revised manuscript, the main possible mechanism was given. However, based on simulation results from one climate model, it is difficult to determine whether this is a real or an artifact of the bulk model physics. As discussed above, the comparison between our study and the study of Gasparini et al. (2017) suggests that the mechanism for the effect on liquid clouds might be a real physical mechanism, and the mechanism for the effects on mixed-phase clouds might be an artifact of the bulk model physics.

19.) Page 15, L353: is sedimentation the mechanism then? Can you test that?

Reply: The mechanisms for the warming effects from mixed-phase and liquid clouds are complicated. The increased convective activity might be the main mechanism, as discussed in Gasparini et al. (2017). Compared with the 50 μm ice crystal, the sedimentation of the 10 μm ice crystal is slower (i.e., longer lifetime in cirrus). In addition, N_{seedopt} from the R10 experiments (seeding ice crystal is 10 μm) is larger than that from the OPT experiment (seeding ice crystal is 50 μm). As a result, the decrease in the cirrus cloud radiative effect from the R10 experiments is weaker than that from the OPT experiment. Correspondingly, the increase in convective activity from the R10 experiment is weaker than that from the OPT experiment. To avoid misleading that sedimentation is the main mechanism of mixed-phase clouds formation, the sentence has been reworded.

20.) Page 17, L388: you say ICs increase W, but then contradict that in the next phase. This is confusing and unclear.

Reply: Thank you for this comment. Equation (A3) shows that the effect of pre-existing ICs (W_{pre}) and seeding ICs (W_{seed}) on ice nucleation can be taken as reducing the vertical velocity used for driving the ice nucleation parameterization. The effective updraft velocity (W_{eff}) used for ice nucleation is calculated as $W_{\mathrm{eff}} = W - W_{\mathrm{pre}} - W_{\mathrm{seed}}$, where W is the ambient updraft velocity. Increasing seeding ICs would increase the W_{seed}, and W would decrease.

References:

Barahona, D. and Nenes, A.: Parameterizing the competition between homogeneous and heterogeneous freezing in ice cloud formation – polydisperse ice nuclei, Atmos. Chem. Phys., 9(16), 5933–5948, https://doi.org/10.5194/acp-9-5933-2009, 2009.

Gasparini, B., Münch, S., Poncet, L., Feldmann, M. and Lohmann, U.: Is increasing ice crystal sedimentation velocity in geoengineering simulations a good proxy for cirrus cloud seeding?, Atmos. Chem. Phys., 17(7), 4871–4885, https://doi.org/10.5194/acp-17-4871-2017, 2017.

Gasparini, B., McGraw, Z., Storelvmo, T. and Lohmann, U.: To what extent can cirrus cloud seeding counteract global warming?, Environ. Res. Lett., 15(5), 054002, https://doi.org/10.1088/1748-9326/ab71a3, 2020.

Krämer, M., Schiller, C., Afchine, A., Bauer, R., Gensch, I., Mangold, A., Schlicht, S., Spelten, N., Sitnikov, N., Borrmann, S., de Reus, M., and Spichtinger, P.: Ice supersaturations and cirrus cloud crystal numbers, Atmos. Chem. Phys., 9, 3505–3522, doi:10.5194/acp-9-3505-2009, 2009.

Kristjánsson, J. E., Muri, H. and Schmidt, H.: The hydrological cycle response to cirrus cloud thinning, Geophys. Res. Lett., 42(24), 10,807-10,815, https://doi.org/10.1002/2015GL066795, 2015.

Morrison, H. and Gettelman, A.: A New Two-Moment Bulk Stratiform Cloud Microphysics Scheme in the Community Atmosphere Model, Version 3 (CAM3). Part I: Description and Numerical Tests, J. Clim., 21(15), 3642–3659, https://doi.org/10.1175/2008JCLI2105.1, 2008.

Rapp, A., Kummerow, C., and Fowler, L.: Interactions between warm rain clouds and atmospheric preconditioning for deep convection in the tropics. J. Geophys. Res. Atmos., 116, D23210, https://doi.org/10.1029/2011JD016143, 2011.

Shi, X., Wang, B., Liu, X., and Wang, M.: Two-moment bulk stratiform cloud microphysics in the Grid-point Atmospheric Model of IAP LASG (GAMIL). Adv. Atmos. Sci., 30(3),868–883, doi: 10.1007/s00376-012-2072-1, 2013.

Shi, X., Liu, X. and Zhang, K.: Effects of pre-existing ice crystals on cirrus clouds and comparison between different ice nucleation parameterizations with the Community Atmosphere Model (CAM5), Atmos. Chem. Phys., 15(3), 1503–1520, https://doi.org/10.5194/acp-15-1503-2015, 2015.

Storelvmo, T. and Herger, N.: Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere, J. Geophys. Res. Atmos., 119(5), 2375–2389, https://doi.org/10.1002/2013JD020816, 2014.