Response to the reviewer's comments on the manuscript

Title: Constraining a Radiative Transfer Model with Satellite Retrievals: Implications for Cirrus Cloud Thinning
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We wish to thank the reviewers for their detailed and helpful comments on our paper. As you will see below, we have responded to all the comments with revisions designed to address the concerns of the reviewers. In the following response, the original reviewer comments appear in blue, and our responses appear in black. New text added to the manuscript appears in black italics.

REVIEWER COMMENTS:

Reviewer #1:

This is the second time I have reviewed this manuscript since its first submission. As it is an improved version, a summary of the manuscript is not provided here. I would like to thank the authors for their careful and detailed responses to the comments from the first two reviews. The manuscript has improved, and I do agree with the changes that have been made. Therefore, I recommend the manuscript for publication.

We thank the reviewer for their helpful and constructive comments.

Reviewer #2:

Review of "Constraining a Radiative Transfer Model with Satellite Retrievals: Implications for Cirrus Cloud Thinning"

The authors have addressed many of the comments from the reviewer's first round of comments. The reviewer applauds the efforts of the authors for adding impacts of new cirrus formed from clear-sky ice supersaturation, as well as adding clarifications on the regions of interests (instead of the entire global analysis). In addition, the revised section 5 also provides a better structure with implications for global climate models, compared with the original section before.

The reviewer still has a major concern regarding the first bullet point, which is that the currently existing heterogeneous cirrus clouds likely will not share the same microphysical properties as the type of heterogeneous cirrus to be formed from cirrus seeding. The reviewer realized that the authors probably didn't get the meaning of my original comments and therefore explains this point in more detail below. Because cirrus thinning is an important focus of this paper and if not treated carefully can be misunderstood by the readers, the reviewer urges the authors to take more action upon the following comment.

Let's say in the current world we have two sets of environmental conditions, Type A that supports the formation of homogeneous cirrus, and Type B that supports the formation of heterogeneous cirrus. Type A usually leads to higher RHice such as 150% - 180% of RHice and has fewer INPs; while Type B usually leads to about 110% - 130% of RHice and has more INPs.

Type A (a combination of synoptic scale to microscale conditions, a combination of T, RHice, dynamics, aerosols, etc.) -> homogeneous cirrus (cirrus Hom-A)

Type B (a combination of synoptic scale to microscale conditions, a combination of T, RHice, dynamics, aerosols, etc.) -> heterogeneous cirrus (cirrus Het-B)

Just as the authors also mentioned, homogeneous cirrus tends to form at different regions, synoptic conditions, or seasons, compared with heterogeneous cirrus. This means that it is not only the amount of INPs that are different between Type A and Type B, but many other physical factors are different too.

Now we are going to add more INPs to Type A -> seeded heterogeneous cirrus with more INPs (cirrus Het-A), which forms in conditions that previously supported homogeneous cirrus formation. It is very unlikely that these modified cirrus Het-A have the same microphysical properties as the cirrus Het-B, because they experience very different environmental conditions. In fact, Figures 3 and 6 in the revised manuscript also show that the mean IWC of Hom-A is always higher at every vertical level compared with the mean IWC of Het-B in both Arctic and Antarctic, over land and ocean. This again supports the reviewer's argument that Type A and Type B are two sets of conditions. Higher IWC is very likely caused by the higher amount of ice supersaturation produced by the Type A condition (it can be many reasons, orographic, uplifting, etc.) that supports RHice to rise to higher values and therefore providing higher amount of excess water vapor over ice saturation to form ice crystals.

If this manuscript only focuses on the comparisons of cirrus radiative forcing between homogeneous and heterogeneous cirrus (as seen in the real world by the satellite data), then there will be no problem just comparing Hom-A and Het-B, because that is what the real cirrus clouds are like. But right now, the layout of the manuscript focuses quite a lot on cirrus thinning. The way that the introduction is written revolves around this key topic. So when the readers saw the comparison between Hom-A and Het-B cirrus, they would think that is what we will get if we seed the Hom-A cirrus with more INPs. But that is not the case, because the cirrus Het-A formed from the Type A condition will likely be something in between Hom-A and Het-B, because it is subject to similar environmental conditions as Hom-A but has added more INPs.

In another way of putting it, this is like we have two types of fruit trees, one has more fruit, and the one has less fruit, but they grow in different environments. There is no guarantee that if one plants the tree with more fruit into a different environment, that tree will still produce more fruit (probably not the best analogy since the plant's DNA plays an important role in this case).

The reviewer also understands that the authors mentioned that the next step would be to run a model, either cloud model or climate model, to assess the impacts of seeding cirrus, and therefore one can control all the environmental conditions to be the same and only test the difference of adding more INPs. The reviewer understands that the modeling work is not the method used in this work. But the way that currently this work lays out as if the comparison of Hom-A and Het-B is the way to estimate cirrus thinning can be very misleading and may lead to more observational work to follow this line of logic. Since the geoengineering topic already involves a level of high uncertainty, the reviewer wants to be extra careful of how the method is being used to assess the impact of these techniques.

The reviewer tried to think about what a better way would be to present this result. The reviewer can see the value of showing the difference between Hom-A and Het-B, since the Het-A will likely be something in between Hom-A and Het-B. Right now, the danger is that this Het-B is presented as the one and only scenario as if it is going to be exactly what we will get for Het-A, which is not true. So, the reviewer thought of a remediation plan, which is to present another scenario, as another bound of this estimate. That new scenario would be to assume that Het-A has the same IWC as Hom-A (which would likely be the maximum IWC bound of this Het-A) but also assume Het-A has the same De as Het-B for each vertical level at specific regions (allowing them to be large ice crystals like heterogeneous cirrus). This new estimate combined with the Het-B will likely provide the two ends of estimates for Het-A, because this new scenario's estimate uses the maximum IWC possible for Het-A (large ice crystals should fall faster and the IWC should be reduced from the original IWC of Hom-A), but also the Het-B as presented currently in the manuscript has the lower end of IWC estimate because Type B supports less ice supersaturation.

Basically, if the manuscript presents two possible scenarios, it will not be misunderstood as if the Het-B is the only likely scenario that Het-A will look like. And this way the manuscript provides a range of estimates, instead of just providing a single value estimate that is skewed towards underestimation of IWC because it is based on IWC from Type-B.

The reviewer also thought of a more accurate estimate, which would be to compare pairs of homogeneous and heterogeneous cirrus that share very similar physical conditions (such as thermodynamic, dynamic conditions, seasons, regions, etc.) but only have different INPs. As the authors pointed out, the example of the volcanic eruption is a very unique experiment, because it happens around similar time and location, and with significantly different INPs. Thus, one can almost control all other factors to be the same and only evaluate the impacts of adding INPs. In this study, satellite observations include a large suite of conditions that contribute to Type A and Type B. The reviewer would also be open to methods proposed by the authors if they can isolate the control group from the experiment group with everything kept the same except for INPs, to quantify impacts of INPs. But that may be a more different path to take.

We appreciate the reviewer's thoughtful clarification regarding the distinction between naturally formed heterogeneous cirrus (Het-B) and the seeded heterogeneous cirrus that could form under conditions that otherwise support homogeneous cirrus (Het-A). We agree that these two cases likely differ microphysically because of their distinct environmental conditions. As seen in the vertical profiles of IWC and De from satellite observations in our manuscript, the De profiles under homogeneous and heterogeneous conditions are very similar. Therefore, conducting new RTM simulations by keeping those De profiles but using the homogeneous IWCs in both cases would result in little to no difference in CRE between the pre- and post-seeding states. Such an RTM experiment would correspond to conditions where cloud updrafts were sufficiently strong to render seeding effects within homogeneous cirrus clouds as impotent, and where INP seeding produces new cirrus clouds.

To address this important point, we now interpret our results in terms of two bounding cases that together define the plausible range of instantaneous CCT efficacy. The lower bound assumes a complete microphysical transition from existing homogeneous to heterogeneous cirrus and production of new cirrus, representing the idealized maximum cooling scenario. The upper bound assumes that the atmospheric dynamics enable homogeneous cirrus to form regardless of the INP concentration, which conceptually corresponds to warming (due to the INPs producing new cirrus clouds). This reframing captures the reviewer's suggested approach while remaining consistent with our RTM framework, which represents instantaneous radiative changes rather than time-evolving feedbacks.

This bounding formulation provides a physically sound way to a range of potential outcomes without over-interpreting the exact microphysical state of seeded cirrus. It emphasizes that the true post-seeding state (Het-A) falls somewhere between these limits, depending on the state of the atmospheric dynamics. The revised manuscript highlights this framework in the Methods, Results, Conclusion, and Abstract sections. Below, we explicitly explain these changes.

First, we changed methodology to account for upper and lower bounds of CRE change depending on whether microphysical conditions change during the transition (beginning at L333 in the revised manuscript):

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2.3.1 CCT under ideal microphysical change

In this study, we define the lower bound of CCT efficacy (cooling effect) under the assumption of a complete microphysical transition from the observed mixture of homogeneous and heterogeneous cirrus clouds to heterogeneous cirrus. This bound represents an idealized condition where an increase in available INPs due to seeding enables heterogeneous freezing to completely suppress homogeneous nucleation. We assume that the cirrus clouds then form under the microphysical conditions typically associated with natural heterogeneous cirrus, e.g., conditions that generally result in lower IWC than in homogeneous cirrus. The derived IWC and D_e *profiles for heterogeneous and homogeneous regimes are based on CALIPSO retrievals (Fig. 3). This idealized bound enables us to quantify the maximum cooling impact of CCT, using the net CRE difference between these two regimes. We calculate this as:*

$$\Delta CRE = \langle CRE_{net_z,het} - CRE_{net_z,hom} \rangle, \qquad (4)$$ ”

Beginning at L374 in the revised manuscript:

“$$\Delta CRE_{tot,lb} = \Delta CRE_{max} + CRE_{new\ cirrus}\ , \qquad (7)$$

where lb refers to lower bound. This calculation provides a lower-bound estimate for CCT-induced radiative impact by assuming full microphysical change under ideal meteorological conditions for heterogeneous cirrus formation.

2.3.2 CCT under minimal microphysical change

To complement the lower-bound condition, we also define a conceptual upper bound for CCT efficacy by assuming that the change in microphysical conditions is minimal after seeding, such that the seeded cirrus cloud IWC and D_e *remain identical to those of homogeneous cirrus. This would correspond to conditions where cloud updrafts were sufficiently strong to render seeding effects within homogeneous cirrus clouds as impotent, and where INP seeding produces new cirrus clouds. An example might be cirrus formed over steep mountains by orographic gravity waves (OGWs). Since these IWC and* D_e *are the same RTM inputs as for homogeneous cirrus, this bounding condition means that* ΔCRE *from Eq. (4) and* ΔCRE_{max} *from Eq. (5) are zero. This framing provides a physically plausible upper limit for the efficacy of CCT and acknowledges that not all seeding events will produce sufficient microphysical changes to yield meaningful cooling. The total* ΔCRE *can be calculated as:*

$$\Delta CRE_{tot,ub} = CRE_{new\ cirrus}\ , \quad (8)$$

where ub refers to upper bound.

Together, the upper- and lower-bounds define a range of possible radiative outcomes from CCT interventions, constrained by satellite observations and calculated within an RTM that assumes fixed cloud profiles and instantaneous radiative changes, without time-dependent feedbacks."

Second, we changed the Results section (beginning at L462 in the revised manuscript):

"After accounting for the impact of new cirrus formation (Eq. 6), the lower bound of total cloud effect $\Delta CRE_{tot,lb}$ (Eq. 7) at the TOA, Sfc, and Atm is ~ -0.3, -0.2, and -0.1 W m^{-2}, respectively (negative values indicate a cooling effect). The upper bound ($\Delta CRE_{tot,ub}$; Eq. 8), however, results in a warming of 1.1, 0.5, and 0.6 W m^{-2} at TOA, Sfc, and Atm, respectively. Of particular importance for CCT is the cooling at the surface but it should be noted that the RTM provides instantaneous values only. For the atmospheric column, the CRE is similar to the surface CRE. This might have implications for long-term feedback processes and possibly impact of AA, as the lower-bound atmospheric column cooling could lead to lower geopotential thickness over the Arctic, which in turn might affect meridional T gradients, thermal winds, and the extratropical jet stream (Cohen et al., 2020). The upper bound implies the opposite, e.g., warming in both Sfc and Atm CRE, which might lead to enhanced AA. A careful GCM study is required to evaluate the sign and magnitude of CCT and the corresponding feedbacks."

Beginning at L479 in the revised manuscript:

"In addition, the lower and upper bounds of ΔCRE_{tot} at TOA, Sfc, and Atm are approximately [-0.9, 0.6], [-0.5, 0.4], and [-0.4, 0.2] W m^{-2}, respectively."

Beginning at L526 in the revised manuscript:

Table 2. Quantifying the transition from homogeneous to heterogeneous cirrus (for overcast skies) using the change in their cloud radiative effect (ΔCRE) and its maximum value that assumes 35% cloud coverage (ΔCRE_{max}) at various levels based on Eq. (5) for different regions, seasons, and surface types. In addition, total values for lower bound ($\Delta CRE_{tot,lb}$) and upper bound ($\Delta CRE_{tot,ub}$) are provided based on Eqs. (7) and (8) to account for the new cirrus formation.

Region	***Season***	***Surface type***	F_{hom}	ΔCRE (*W m*$^{-2}$)			ΔCRE_{max} (*W m*$^{-2}$)			$\Delta CRE_{tot,lb}$ (*W m*$^{-2}$)			$\Delta CRE_{tot,ub}$ (*W m*$^{-2}$)		
				TOA	***Sfc***	***Atm***	***TOA***	***Sfc***	***Atm***	***TOA***	***Sfc***	***Atm***	***TOA***	***Sfc***	***Atm***
Arctic	*DJF*	*Land*	*0.21*	*-19.3*	*-10.2*	*-9.1*	*-1.4*	*-0.7*	*-0.7*	*-0.3*	*-0.2*	*-0.1*	*1.1*	*0.5*	*0.6*
		Ocean	*0.29*	*-15.1*	*-8.7*	*-6.4*	*-1.5*	*-0.9*	*-0.6*	*-0.9*	*-0.5*	*-0.4*	*0.6*	*0.4*	*0.2*
Antarctic	*JJA*	*Land*	*0.3*	*-15.4*	*-9.2*	*-6.2*	*-1.6*	*-1.0*	*-0.6*	*-0.7*	*-0.4*	*-0.3*	*0.9*	*0.6*	*0.3*
		Ocean	*0.24*	*-13.7*	*-9.3*	*-4.3*	*-1.2*	*-0.8*	*-0.4*	*-0.5*	*-0.3*	*-0.2*	*0.7*	*0.5*	*0.2*
NH midlat	*DJF*	*Land*	*0.15*	*-22.9*	*+0.2*	*-23.1*	*-1.2*	*0.0*	*-1.2*	*+0.3*	*+0.0*	*+0.3*	*1.5*	*0*	*1.5*

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Beginning at L538 in the revised manuscript:

"the lower and upper bounds of ΔCRE_{tot} at the TOA, Sfc, and Atm are approximately [-0.7, 0.9], [-0.4, 0.6], and [-0.3, 0.3] W m^{-2}, respectively (Table 2)."

Beginning at L543 in the revised manuscript:

"With an IWC-weighted average homogeneous fraction of 0.24, ΔCRE_{max} at the TOA, Sfc, and Atm are approximately -1.2, -0.8, and -0.4 W m^{-2}, respectively, and the lower and upper bounds of ΔCRE_{tot} at the TOA, Sfc, and Atm are approximately [-0.5, 0.7], [-0.3, 0.5], and [-0.2, 0.2] W m^{-2}, respectively (Table 2). These values are slightly weaker than those for Antarctic land."

Beginning at L624 in the revised manuscript:

"However, after accounting for new cirrus formation and the bounds of change in microphysical conditions (from full change to no change), the lower and upper bounds of ΔCRE_{tot} at the TOA, Sfc, and Atm are ~ [+0.3, 1.5], [0.0, 0.0], and [+0.3, 1.5] W m^{-2}, respectively (Table 2), indicating a warming effect in the TOA and Atm, and suggesting that CCT could even result in net warming in this season and latitude band.)"

Third, we changed the Conclusions section (beginning at L838 in the revised manuscript):

"Our results confirm that natural homogeneous cirrus clouds exert a significantly stronger CRE than natural heterogeneous cirrus, highlighting their distinct radiative properties in polar regions during winter. Building on this contrast, we estimate the instantaneous efficacy of CCT by defining two bounding cases: a lower bound assuming complete microphysical change from natural

(observed) cirrus clouds to heterogeneous cirrus and formation of new cirrus, representing the idealized maximum cooling effect. The upper bound assumes that the atmospheric dynamics enable all naturally occurring homogeneous cirrus to form regardless of elevated INP concentrations from CCT, which produces warming (due to the INPs producing new cirrus clouds). ΔCRE_{max} (i.e., CCT radiative effect without producing new cirrus clouds) yields surface cooling of −0.7 to −1.0 W m^{-2} and TOA cooling of −1.2 to −1.6 W m^{-2}, while inclusion of "new cirrus" formation from injected INPs in clear-sky ice-supersaturated regions partially offsets this effect, resulting in total surface cooling of −0.2 to −0.5 W m^{-2} and total TOA cooling of −0.3 to −0.9 W m^{-2} as the lower bound of CCT efficacy. These values fall within the cooling range of -0.25 to -2 W m^{-2} estimated by previous GCM studies (Gasparini et al., 2020; Gasparini and Lohmann, 2016; Storelvmo et al., 2013; Storelvmo and Herger, 2014; Storelvmo et al., 2014). However, the upper bound (due to the exclusive formation of new cirrus clouds) yields a total surface warming of 0.4 to 0.6 W m^{-2} and a total TOA warming of 0.6 to 1.1 W m^{-2}, consistent with studies reporting unexpected warming effects of CCT (Penner et al., 2015; Tully et al., 2022)."

Finally, we changed the Abstract (beginning at L11 in the revised manuscript):

"The efficacy of the climate intervention method known as cirrus cloud thinning (CCT) is difficult to evaluate in climate models, largely due to uncertainties governing the relative contributions of homogeneous and heterogeneous ice nucleation. Here we take a different approach by employing recent satellite retrievals from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) which provide estimates of the fraction of cirrus clouds dominated by homogeneous and heterogeneous ice nucleation and their associated physical properties. We employ a radiative transfer model (RTM) to quantify the cloud radiative effect for homogeneous and heterogeneous cirrus clouds at the top of atmosphere (TOA), Earth's surface, and within the atmosphere. The RTM experiments are initialized using cirrus microphysical profiles derived from CALIPSO retrievals for cirrus clouds dominated by homogeneous and heterogeneous ice nucleation across different regions (Arctic, Antarctic, and midlatitude) and surface types (ocean and land). We define two bounds: the lower bound assumes a full microphysical transition from the observed composition of homogeneous- and heterogeneous-dominated cirrus to only heterogeneous cirrus and production of new cirrus. The upper bound assumes production of new cirrus and that the atmospheric dynamics enables homogeneous freezing nucleation to occur regardless of the concentration of ice nucleating particles. Based on these bounds, we estimate an instantaneous surface effect ranging from −0.5 to +0.6 W m^{-2} and a TOA effect from −0.9 to +1.1 W m^{-2}, respectively, showing the possibility of both cooling and warming. Recommendations are provided to improve the treatment of cirrus clouds in climate models."