<u>Anonymous Referee #1, 1st review</u> **(**Review comments in regular**; response in bold**.)

General Comments:

This paper was well prepared and written, and organized quite well. The content of new science is also considerable and represents an important advancement in our understanding of cirrus clouds. There is little that I could find to improve upon. Therefore I recommend that this paper be accepted in ACP with minor revisions.

This ACPD paper demonstrates the sensitivity of the relative roles of homo- and heterogeneous ice nucleation (henceforth hom and het) in a GCM to the treatment of cirrus updrafts, the presence of pre-existing ice, ice nuclei (IN; including SOA) and/or the accommodation coefficient. The article implies that by representing the cirrus updraft parameterization as a function of temperature or height, the contributions of het and hom to the cirrus microphysics (in the presence of pre-existing ice) can be modified substantially. Similar changes can be affected through the accommodation coefficient α. By using different updraft parameterizations with lower updrafts at colder T, a key finding in this paper is that predicted ice crystal number concentrations (Ni) are more in conformity with in situ Ni measurements.

The lead author is a co-author on the 2015 GRL paper titled "Can cirrus cloud seeding be used for geoengineering?". In that paper as well as this one, pre-existing ice can dramatically affect the relative roles of hom and het since pre-existing ice will limit the in-cloud RHi whenever ice saturation is exceeded (RHi > 100%), and it often prevents the RHi from reaching the RHi hom threshold. Since the ice surface area from preexisting ice is often much greater than that produced by freshly nucleated crystals via het, these factors make pre-existing ice a more powerful limiter for RHi. The main question I would like to pose here is this: assuming pre-existing ice and competition between het and hom (with reasonable IN concentrations), is it possible that some combination of physically plausible updraft schemes and a plausible value for could change the results in Penner et al. (2015) such that a net radiative cooling is produced by seeding the cirrus clouds?

Answer:

To produce a net radiative cooling effect by seeding the cirrus clouds, we need to see decreased ice number after seeding. From the bottom graphs of Fig. 3 in the manuscript, we can see that the in-cloud ice numbers from the WGRID_COMP+PRE cases are already lower enough and further analysis showed that heterogeneous nucleation is already dominant. Adding 0.1% of SOA IN will not decrease the ice number significantly. This means if WGRID is used in the model, we should not expect to see some significant cooling effect. So the potential choice left is WGARY or WTKE. Penner et al. (2015) used WTKE and an accommodation coefficient α of 0.1. Here we repeated Penner et al. (2015) using WGARY with α of 0.1 and 1, plus WTKE with α of 1. The results from these three cases are shown in Fig 1. No significant net cooling was found for a seeding from 10 to 200 #/L.

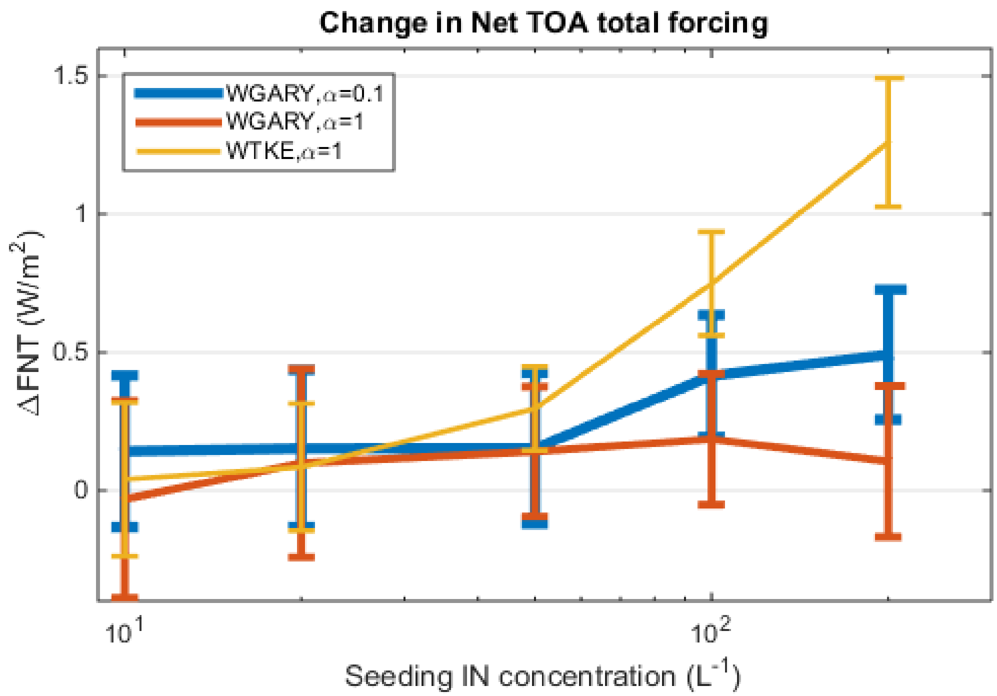

Fig 1. Change in net TOA total cloud forcing with different updraft velocities and α.

Another question concerns the accommodation coefficient α. As noted in the paper, one laboratory study estimated that α for ice was around 0.006 (Magee et al., 2006). As shown in Lamb and Verlinde (2011, Physics & Chemistry of Clouds, Cambridge Univ. Press, p.339) and Fukuta and Walter (1970, JAS) for liquid water droplets, changing α from 1.0 to 0.1 has a very modest impact on diffusional mass growth rates, but changing α from 0.1 to 0.01 will have a relatively huge impact. The same physics applies to ice crystal growth. Please comment on how assuming an α of 0.01 would impact the results shown here. A new figure would be helpful in this regard.

Answer:

We ran all experiment set-ups with an α of 0.01. The following Fig. 2 combine Fig3-5 in the manuscript together for an easier comparison with the added left column showing the results from α being 0.01, the middle column showing the results from α being 0.1, and the right column showing the results from α being 1. Changing α from 0.01 to 0.1 does have a relatively larger impact than changing α from 0.1 to 1 in reducing the formed ice numbers especially for cases in which the effect from the water vapor deposition onto pre-existing ice particles is not considered. However, the conclusions/findings from this study do not change without these new cases. Furthermore, the more recent study by Skrotzki et al. (2013) constrained value of α is in the range of 0.2-1 with AIDA experiments and Kay and Wood (2008) showed that α is ⩾ 0.1 for small ice crystals forming at high ice supersaturations and the

small value of α (=0.006) from (Magee et al., 2006) may only be appropriate for large ice crystals or at low ice supersaturations thus may be less relevant for cold cirrus clouds. So we decided not to include these new results in the manuscript.

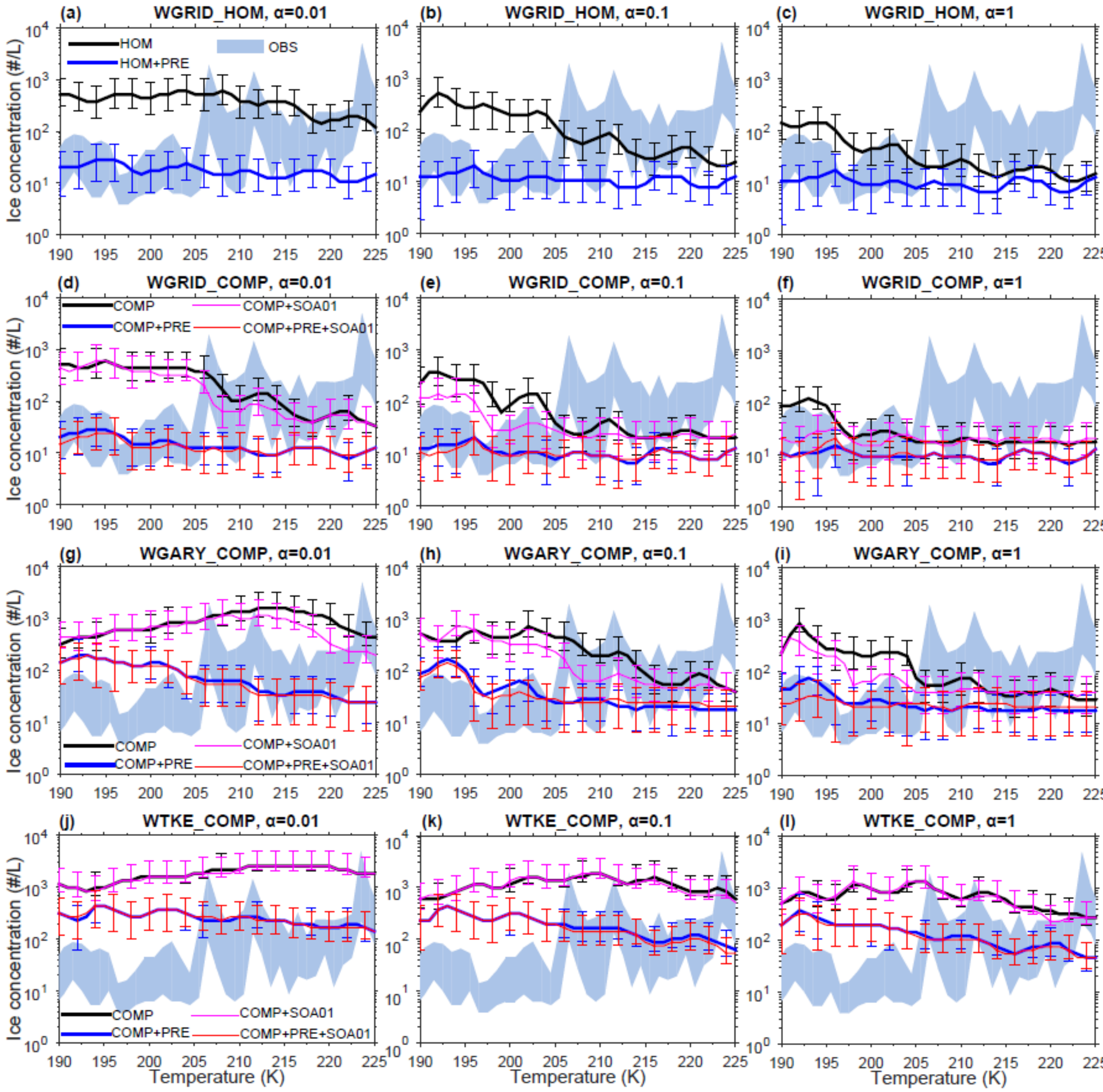

Fig. 2 Similar to Fig3-5 but with three different α (left: 0.001; middle: 0.1; right: 1).

Last but not least, the recent work of Minghui Diao and colleagues uses in situ observations of RHi and Ni to understand the Lagrangian evolution of cirrus clouds (e.g. Diao et al. 2013, GRL; Diao et al. 2014, GRL; Diao et al. 2015, JGR). The horizontal extent of ice supersaturated regions (ISSRs) and ice crystal regions (ICRs) were measured by aircraft. During the ice nucleation phase of cirrus cloud growth (when cirrus are not produced through deep convection), the ICR/ISSR ratio is relatively small (< ~0.5) and the probability of this phase being sampled (a measure of temporal duration) is relatively small (3 to 4%). The ice nucleation zone is generally near cloud top (Diao et al., 2015). These findings suggest that ice nucleation is a short-lived transient event that occurs in an ISSR in the absence of pre-existing ice. Thus pre-existing ice is not likely to accompany ice nucleation events as assumed in many of the simulations in this paper. This point needs to be made in the paper along with the above references to the work of Diao et al.

Answer:
We thank the reviewer for pointing us to Diao et al. (2013; 2014; 2015) papers, which discuss the phases of ice crystal evolution based on the in situ aircraft measurements. The ice nucleation phase as defined by the small ICR/ISSR ratio between 0 and 1 occurs generally near the cloud top (Diao et al., 2015). We agree that this ice nucleation is a short-lived transient event. But to argue that it "occurs in an ISSR in the absence of pre-existing ice**", one needs to agree that the ice crystals in an ISSR are all newly nucleated. However, the aircraft-detected ice crystal in an ISSR may be produced in the nearby clouds and then advect and sediment into the ISSR. Thus the phase definition method by Diao et al. (2013) for ice nucleation particularly cannot ambiguously assert either ice crystals in an ISSR are produced from the ice nucleation within the ISSR, or are from pre-existing ice, or both. Therefore, it is likely that the preexisting ice produced elsewhere is present and affects the ice nucleation in ISSRs.**

We now cite Diao et al. papers in the manuscript.

Minor comments:

1. Page 35909, line 6: Suggest modifying sentence to read: Cirrus clouds (T < 235 K) cover about 30% : : :.
Answer: Done.

2. Page 35910, line 11: RHi is used for the first time here; please define it.
Answer: RHi is now given as an abbreviation of ice supersaturation in the first line of the second paragraph in Section 1.

3. Page 35915, line 14: Please indicate what SOA01 refers to, or indicate the section where it is explained.
Answer: We moved "Table 1 gives the definition …" right after this sentence.

4. Page 35917, line 23: sizes => values?
Answer: modified as suggested.

5. Page 35919, line 21: concentrations is misspelled
Answer: corrected.