Review of

Does prognostic seeding along flight tracks produce the desired effects of cirrus cloud thinning?

by
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General:

In this study, the climate impact of cirrus cloud thinning due to artificially induced ice nucleating particles (INPs) is assessed by using a new approach to simulate the injection of the INPs into the atmosphere. In view of the ongoing anthropogenic climate warming, the topic is of great current relevance. However, in all earlier cirrus geoengineering studies, INPs have been globally equally distributed in the atmosphere. Here, they are seeded only along aircraft flight tracks, which is a much more realistic approach, as in reality that would be the way to bring the particles into the atmosphere. The results are then compared to the globally uniform approach: seeding along the flight tracks significantly reduces the number of INPs compared to global seeding. Therefore, to achieve a significant signal in the radiative feedback of the cirrus, the properties of the INPs had to be set to unrealistic values in terms of size and concentration (very small particles with very high concentrations). However, this always led to overseeding associated with warming, because instead of fewer and larger, more and smaller ice particles formed in comparison to natural conditions. That means, this cirrus geoengineering approach also does not lead to the desired result.

Overall, this is an important study that will help to close the debate on the likelihood of being able to reduce the global warming by geoengineering of cirrus clouds that has been lively discussed over the last decade. For that reason, the manuscript is well within the scope and will be a valuable contribution to ACP. I recommend the study for pulication after considering some comments / questions which are listed below - they are mostly (but not all) minor, intended to improve the Figures and make the study more fluently readable.

Specific comments:

1) Section 3.1: To my feeling, section 3.1 needs more structure so that the important results are easier to locate. Below I suggest some sub-sections where I think it is helpful.

2) Line 284ff: As expected, we find the largest positive net TOA anomaly when seeding with the largest average seeding particle number concentration (> 105 L−1 , Fig. 2) that is associated with the case with a mean emissions radius of 0.01 μm (r0.01) and a mass scaling factor of 1000 (high-seeding).

Comment: Why it is expected that a large number of seeding INPs result in a large positive net TOA?

And why does the size matter ? For example, the INP concentration from r0.1 and x1000 is almost identical with r0.01 and x10 /Fig. 4.2), but without a response (Fig. 4.3). Why is that ?
In nature, we know that mostly larger INPS (> 0.5 μm) will be activated, how does that correspond with your finding ?

If it is explained later in the paper what causes the radiation feedbacks, please note that here (cross reference).

3) Line 286 f: The large TOA anomalies are driven by a large increase in the LW cloud radiative effect (CRE) by 10.1 Wm−2 (Tab. 3), indicating a significant change in cirrus cloud properties.

Comment: Please specify 'properties' (see also comment to Table 3).

4) Line 321 – the following paragraph:

Comment: This paragraph could be a sub-section with the title ‚Ice crystal sizes‘

Question on the paragraph: Why you discuss here in detail the size anomaly? Is this because the size is one parameter influencing the radiative feedback ?
Because less sedimenation of smaller ice particles keeps the cirrus at higher altitudes (--> more warming) ? Please explain.

5) Line 336 – the following paragraph:

Comment: This paragraph could be a sub-section with the title ‚Tropics‘.

6) Line 340 …. by up to -10 mg m−3 (Figure 4.4h). (*Comment*: line break here)
Nevertheless, the main effect we find in the tropics is the formation of a large number ...

7) Line 350 – 374: *Comment:* This could be a sub-section with the title ‚Northern Hemisphere‘.

8) Line 352: ...we find positive ICNC HET anomalies up to 1000 L−1 at lower levels and a reduction of IWC up to 1.0 mg.m−3 (see Figure 4, f,h).

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9) Line 359f: This directly influences the large positive LW CRE we find for the r0.01 high-seeding case (Fig. 3 and Tab. 3) *Question*: maybe better Figure 4 b and Figure 6?

10) Line 375 – end of Section: *Comment:* This could be a sub-section with the title ‚Conclusions: global aircraft seeding‘.

11) Line 394ff: However, we restricted seeding particle emissions further by only seeding during NH wintertime (November-February) as this was suggested to optimize cirrus seeding efficacy (Storelvmo and Herger, 2014; Storelvmo et al., 2014). *Comment:* Please briefly mention why.

12) Line 435: However, as the seeding particles themselves are so small (0.01 µm), combined with their high number concentration, it is likely that they form numerous ice crystals that remain small due to rapid water vapor consumption such that the average ice crystal size remains roughly the same.

*Comment***:** How realistic is the assumption of r = 0.01 µm given that the consequences for CCT are strong but in nature only INP > ~0.5 um form ice crystals ?
→ I think this point should be discussed in the paper in some detail.

13) Line 441: At the same time we find higher rates of heterogeneous nucleation on background dust particles in the stratosphere.

*Comment / question***:** Here and at other places of the manuscript:

Wouldn't it be better to call the region above the mean tropopause 'upper tropopause' instead of stratosphere ?
If cirrus clouds form there, then obviously there is enough moisture present - but the 'real' stratosphere is dry so that no cirrus clouds can form.

Another possibility is that the tropopause height increases in comparison to the WMO tropopause height due to the induced warming (Fig. 6) ? Then, what you called stratosphere could be still upper troposphere ? It could be interesting for the reader to discuss that.

14) Line 473f: Therefore, relative to the unseeded reference case, the new ice crystals forming in the stratosphere in this case are smaller. This behavior also explains the vertical mean ice crystal radius anomalies we found in the global seeding cases in Fig. 5.

Comment: It would be good to have a Figure here same as Fig. 4.5, I think seeing the vertical structure if the ice radius anomaly would help understanding the complex processes.

15) Line 474 – end of Subsection: *Comment:* This could be a sub-section with the title
‚Conclusions: Northern hemisphere-only wintertime seeding‘

16) Line 476f: Fig. 9 presents the vertical IWC and liquid water content (LWC) anomalies averaged over the NH during Novemver to February for all r0.01 cases with mass emission scaling.

Comment / Question: It can be seen from Fig. 9 that the positive IWC anomaly is mostly below the mean NH tropopause (~250 hPa), though also above numerous ice particles are injected.

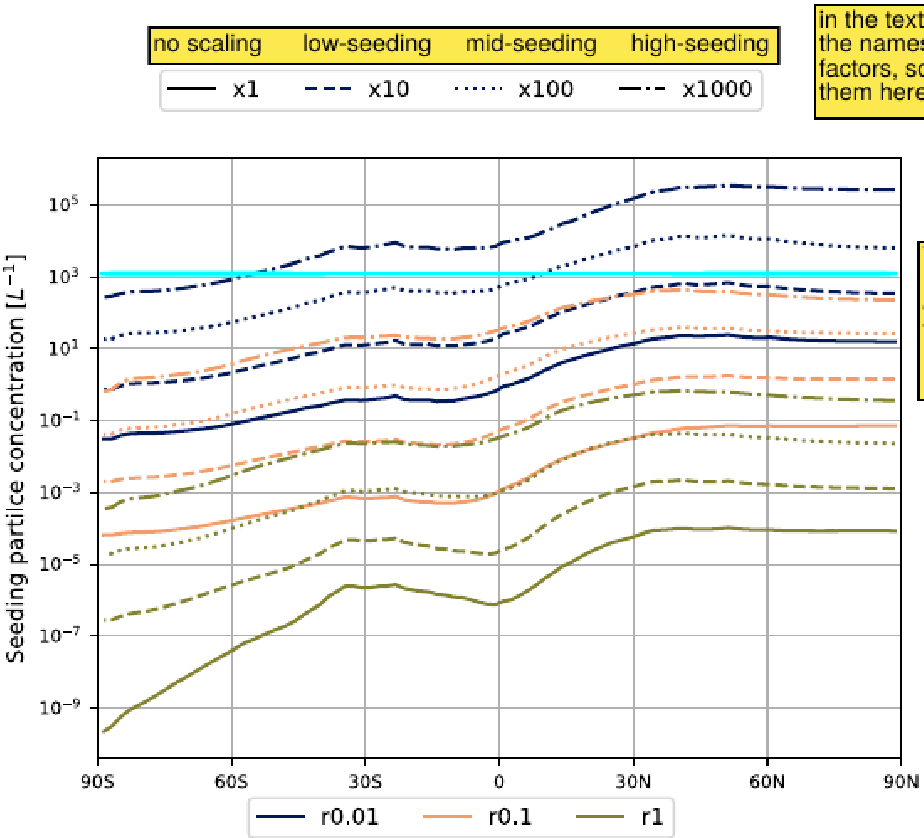
From this one can derive that the ice particles above the WMO tropopause are much smaller so that they do not cause an IWC anomaly, right?

17) Line 480f: As shown above, this is the result of more numerous and smaller ice crystals that formed on the injected seeding particles. This appears to have an impact on ice crystal sedimentation, …

Comment: reduced sedimentation because the ice particles are small - I would mention this instead of stating imprecisely 'impact'.

Comments on Figures/Tables:

Figure 2: *Comment:* ‚three emissions radii: 0.01 µm, 0.1 µm, and 1 µm‘ - 0.01 µm is very small for INP, are they really activated ??



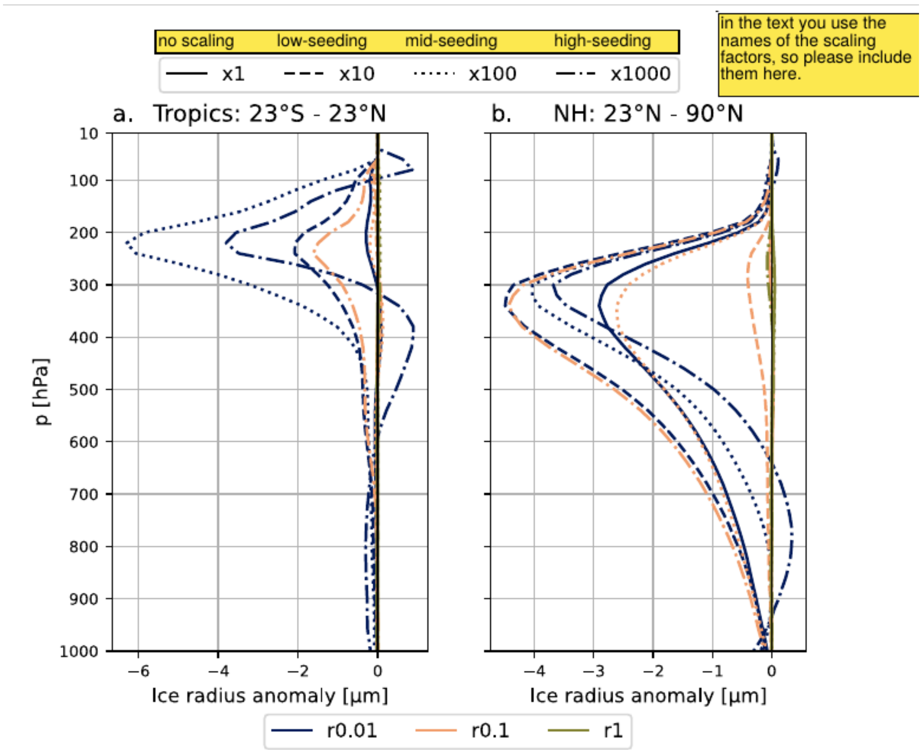
in the text you often use the names of the scaling factors, so please include them here.

You mention later that 1000 is a threshold to cause a radiative feedback. I suggest to mark that in the Figure.

Figure 3: **Caption:** Five-year annual global mean net TOA radiative anomalies (in Wm−2) for ~~the~~ each seeding particle emissions mass scaling factor ….

Figure 4: *Comment:* Please note in the title of the right column that this is the case of high seeding; also, please define the solid and the dashed lines

Figure 5:



in the text you use the names of the scaling factors, so please include them here.

Figure 6: *Comment:* Please note in the title of the figure that this is the case of high seeding;

Figure 7, Caption: *Comment:* (b) does not show temperature, but Delta_Rice.
Figure: *Comment:* please note above or below the figure that the panels are for r = 0.01μm

Figure 8:

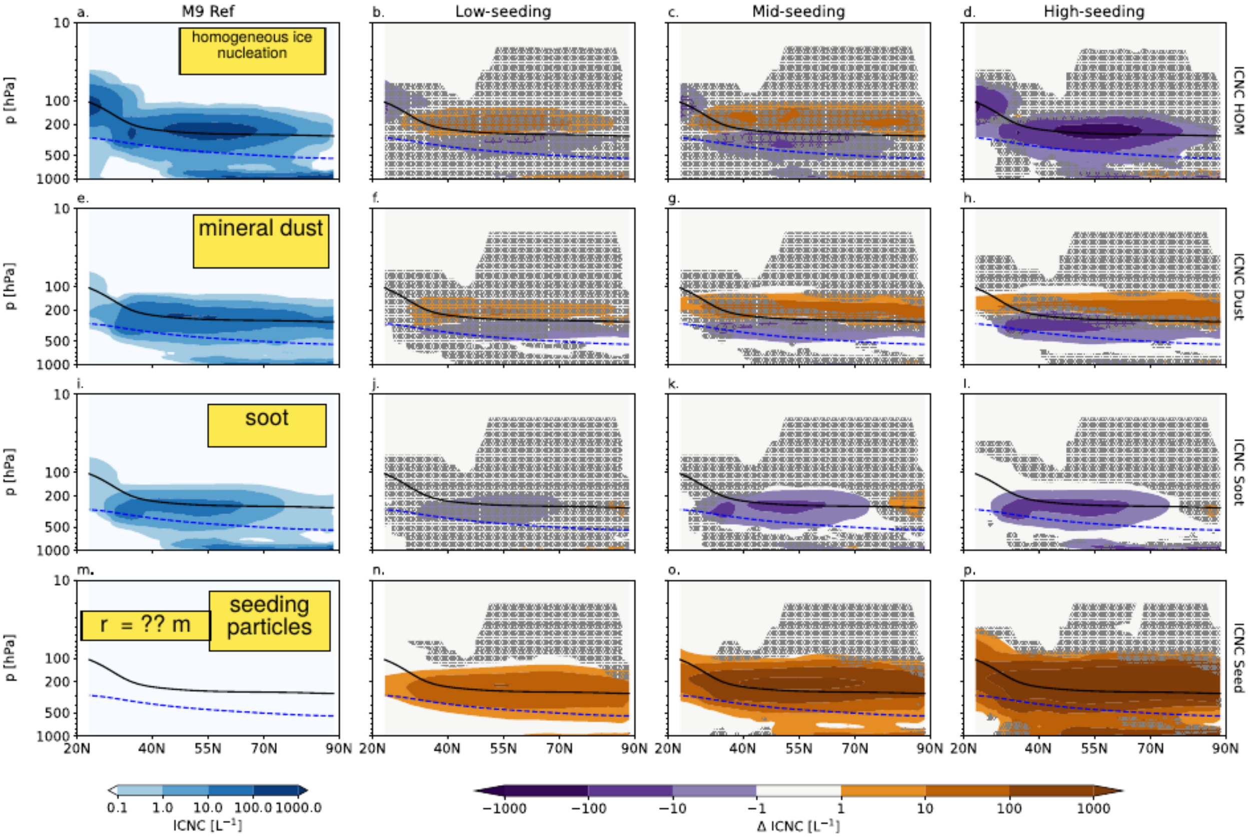
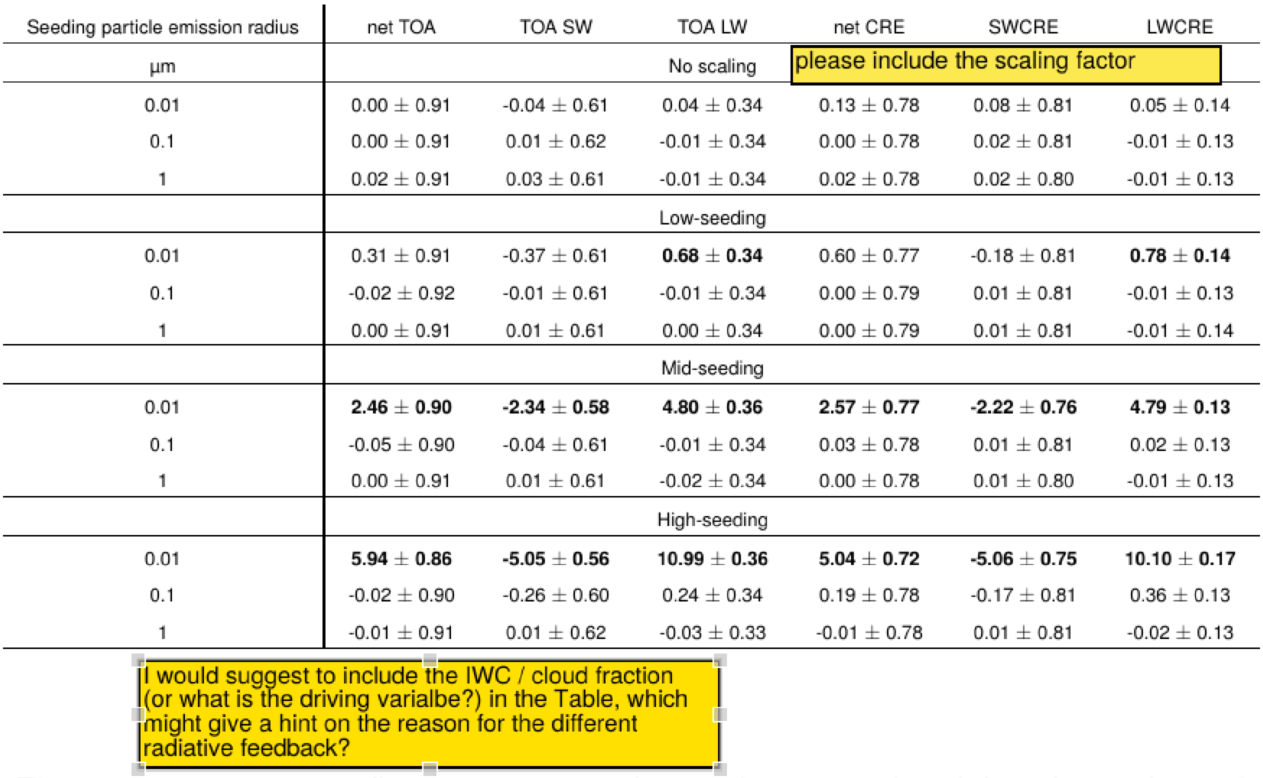


Figure 9: **Figure:** the x-axes, aren‘t they Delta_LWC and Delta_IWC (not LWC, IWC) ?
Also, please note above or below the figure that the panels are for r = 0.01µm.

Caption: Five-year vertical mean anomalies as a function of pressure for ~~(a) IWC and (b) LWC~~ for the NH during the period November to February for seeding with an emissions radius of 0.01 µm for a mass scaling factor of one (solid line), 10 (dashed line), 100 (dotted line), and 1000 (dot-dashed line). (a) IWC and (b) LWC: ~~T~~the orange dotted line represents the 5-year NH November-February mean temperature vertical profile centred around the homogeneous freezing temperature limit (238 K).

Table 1: *Comment:* You might add to the column 'Freezing method' if all or only a part of the INPs are activated (AF = 1 or AF = f(x);
AF: activated fraction; x: Si, T, ...)

Table 3: *Comment:* please define the solid and the dashed lines



Seeding particle emission radius	net TOA	TOA SW	TOA LW	net CRE	SWCRE	LWCRE
µm			No scaling			
0.01	0.00 ± 0.91	-0.04 ± 0.61	0.04 ± 0.34	0.13 ± 0.78	0.08 ± 0.81	0.05 ± 0.14
0.1	0.00 ± 0.91	0.01 ± 0.62	-0.01 ± 0.34	0.00 ± 0.78	0.02 ± 0.81	-0.01 ± 0.13
1	0.02 ± 0.91	0.03 ± 0.61	-0.01 ± 0.34	0.02 ± 0.78	0.02 ± 0.80	-0.01 ± 0.13
			Low-seeding			
0.01	0.31 ± 0.91	-0.37 ± 0.61	**0.68 ± 0.34**	0.60 ± 0.77	-0.18 ± 0.81	**0.78 ± 0.14**
0.1	-0.02 ± 0.92	-0.01 ± 0.61	-0.01 ± 0.34	0.00 ± 0.79	0.01 ± 0.81	-0.01 ± 0.13
1	0.00 ± 0.91	0.01 ± 0.61	0.00 ± 0.34	0.00 ± 0.79	0.01 ± 0.81	-0.01 ± 0.14
			Mid-seeding			
0.01	**2.46 ± 0.90**	**-2.34 ± 0.58**	**4.80 ± 0.36**	**2.57 ± 0.77**	**-2.22 ± 0.76**	**4.79 ± 0.13**
0.1	-0.05 ± 0.90	-0.04 ± 0.61	-0.01 ± 0.34	0.03 ± 0.78	0.01 ± 0.81	0.02 ± 0.13
1	0.00 ± 0.91	0.01 ± 0.61	-0.02 ± 0.34	0.00 ± 0.78	0.01 ± 0.80	-0.01 ± 0.13
			High-seeding			
0.01	**5.94 ± 0.86**	**-5.05 ± 0.56**	**10.99 ± 0.36**	**5.04 ± 0.72**	**-5.06 ± 0.75**	**10.10 ± 0.17**
0.1	-0.02 ± 0.90	-0.26 ± 0.60	0.24 ± 0.34	0.19 ± 0.78	-0.17 ± 0.81	0.36 ± 0.13
1	-0.01 ± 0.91	0.01 ± 0.62	-0.03 ± 0.33	-0.01 ± 0.78	0.01 ± 0.81	-0.02 ± 0.13

please include the scaling factor

I would suggest to include the IWC / cloud fraction (or what is the driving varialbe?) in the Table, which might give a hint on the reason for the different radiative feedback?

Table 4: *Comment*: See comments on Table 3.