Response to reviewers

We thank reviewers for their comments and suggestions. Please find the point-by-point reply (normal font) to the reviewer's comments (in bold) below. Blue text refers denote the changed text.

REVIEWER 1

This is a well written paper. I have a few suggestions to help to clarify it, however.

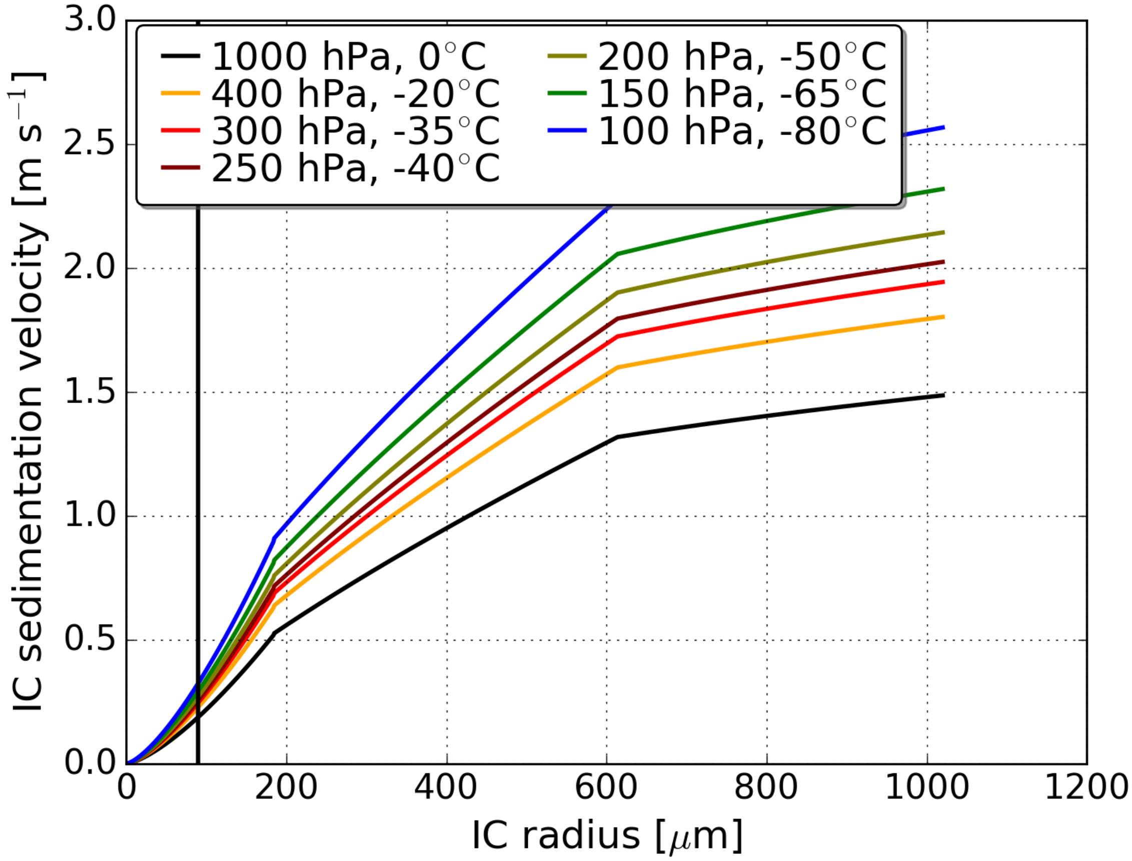
Page 2, Sentence lines 19, 20: The idea that cirrus seeding does not influence the IC that nucleated at temperatures between 0 and -35 degrees seem wrong, since you state in abstract that ice seeding modifies liquid clouds.

Thanks for pointing that out, changed in text, page 2 line 30.

Page 3, Line 27: what is the radius associated with a 2 m/s sedimentation velocity. This must be outside of the normal realistic range as shown in Fig 1.

According to the sedimentation velocity parametrization used in our model (Spichtinger et al., 2009), we need an ice crystal of about 1 μm size to reach such velocities. Please see the attached plot with the extended IC size range.

Added in the manuscript, page 4, line 18.
Only an IC of about 1 mm size would fall with a velocity of 2 m s^{-1}.



Page 4, Line 6, 7: please explain why you consider this a "problem". Were there inaccuracies within the calculation?

We call the "problem" the limiting factor to effective cirrus seeding (i.e. seeding which brings a cooling effect). Indeed, that is our internal jargon and has been removed from the text.

Page 4, line 28: replace: "decreases for about" to "decreases by about"

replaced

Page 5,line 6: "15-20% smaller radiation effect decrease: smaller than VELmax, but not smaller than VEL8. Please be specific.

changed in text

Page 5, line 5: this seems to say that the total CRE is 1 W/m2 during the day. Really?

Yes, the total cirrus CRE is about a 1 W/m^2 warming during daytime, where daytime is defined based on the solar zenith angle. We added a new figure (Figure 3) to the manuscript showing annual average (a), annual day average (b), and night (c) cirrus CRE estimates as diagnosed from our model.

Page 5, line 6-8: I'm not sure what you are saying here. cCRE in Table 3 is 4.35 W/m2. Is this 50% smaller than that in REF? Please add values for REF in Table 3.

We are comparing the cirrus CRE for the VELmax simulation with the REF. VELmax has a cirrus CRE of about 1.1 W/m^2 (or, as seen from Figure 2a, the cirrus CRE is about 3.3 W/m^2 smaller compared to REF). REF has about 4.4 W/m^2, as stated in Table 3. Therefore, we reduced the cirrus CRE by about 75%, and not by the stated 50%, which was our typo that has been removed.
Rephrased in the manuscript on page 5, lines 28-30.
The VELmax simulation, which sets the cirrus IC sedimentation velocity to the unrealistically unrealistically high value (Fig. 1), shows that globally uniform cirrus cloud thinning can reduce the cirrus CRE by about 3.3 W m^{-2} which is equivalent to ~75% of its full value (Table 3).

Page 6 line 22: a lifetime of a couple of hours seems small. Are there observations to examine whether this number is reasonable?

We estimated the cirrus lifetime by dividing the total ice water content by its source and got a result of about 2-6 hours, with the longest lifetimes at the tropical tropopause.
Yet, we note that the model-derived cirrus lifetime is highly dependent on its formulation, and may therefore well be larger.

Luo and Rossow (2004) give a lifetime of about 30 h for tropical detrainment cirrus or 12 h for tropical in-situ formed cirrus. Their lagrangian trajectory analysis is based on the ISCCP satellite dataset. Gehlot and Quaas (2012) used a similar lagrangian trajectory analysis for cirrus lifetime in ECHAM5 model and which resulted in similar tropical cirrus lifetimes. Jensen et al. (2011) on the contrary estimate the lifetime of cirrus in the tropical tropopause layer of about 12-24 hours, based on in-situ measurement data.

In summary, it is not straightforward to calculate cirrus lifetimes and the estimates have to be treated with caution.

Added in text on page 7, lines 17-20.
The effective cirrus cloud lifetime is in the range of several hours as diagnosed from our model, with values around 6 hours in the tropical tropopause region. This is shorter compared with available studies, which estimated it to 12-30 hours (Luo and Rossow, 2004, Jensen et al., 2011, Gehlot and Quaas, 2012).

Page 7 line 1, 2: In the model description section you need to specify how cloud cover is calculated. Is it just related to relative humidity?

Yes, it is a diagnostic cloud cover scheme by Sundqvist et al., 1989, only related to relative humidity.

We added a sentence on it in the model description, page 4, lines 6-8.
The model gridboxes are considered partially cloudy above a certain relative humidity threshold, and fully cloud covered when relative humidity reaches 100%, following Sundqvist et al., 1989.

Page 7: lines 4 – 6: "where the IC sedimentation velocity is restored to the reference values." Doesn't this assumption essentially change the removal treatment for cirrus?

Yes, increasing the sedimentation velocity of cirrus ice crystals changes the sinks of cirrus clouds.

Is this a common assumption in models that alter the sedimentation velocity to simulate geoengineering?

Yes, the sedimentation velocity increase to our knowledge is valid only for clouds at temperatures colder than -35°C, as described for example in Kravitz et al., 2015 (and is mentioned in the introduction, page 3, lines 11-16).

Page 7, line 23: "in Vel2 all cirrus IC sediment regardless of their origin". So you are not applying the 2 m/s sedimentation only to the added INP for geoengineering?

No, all ice crystals at T<-35°C, regardless of their origin, sediment with 2 m/s instead of their calculated sedimentation velocity.
In the seeding case, the large, geoengineered ice cystals sediment by their model-calculated sedimentation velocity. So we model either seeding by geoengineered INP particles or increase of sedimentation velocity for all ice crystals at cirrus conditions.

We added a sentence pointing that out explicitly on page 4, line 13.
The sedimentation velocity increase applies for all the cirrus ICs, regardless of their microphysical origin.

We additionally added a sentence on page 4, lines 22-25.
In our simulations we either increase the cirrus IC sedimentation velocity or seed with geoengineered INP, which sediment with the size dependent sedimentation velocities (Spichtinger et al., 2009).

Page 8 lines 3,4: Are you surmising that these changes are responsible for increases in ICNC due to detrainment? i.e. you do not show this, so how do you know?

Thanks for pointing that out.
The prevalent driver of the ICNC increase at mixed-phase is the way the sedimentation velocity increase simulations are set up, with the sedimentation suddenly being restored to the (smaller) standard value at temperatures warmer than -35°C. Interestingly, we observe also an increase in the global ICNC burden, as shown by Figure 4, which might be not as intuitive after showing the IWC decreases in the global average.

After re-evaluating the plots we suggest that the net ICNC increase is due to the mixed-phase cloud glaciation effect, in which the initial redistribution of IC to lower lying mixed-phase clouds leads to a positive feedback and more secondary ice crystal production in clouds at temperatures between -35°C and 0°C. Unfortunately we cannot provide a quantitative proof of this hypothesis but will explore this further in future studies.

Nevertheless, we can still attribute part of the ICNC increase to the observed increase in mid-level convection (see lower plot). In our model the ice crystal sizes of convectively detrained IC follow the parametrization by Boudala et al., 2002. Convective detrainment therefore produces large concentrations of relatively small IC.
We note that the interpretation has to be taken with care, as we show the convective type frequency only for fixed SST model setup and not the MLO setup.
In addition we also note that the convective part of the precipitation increases in the simulation VEL2 by 1.5% and in SEED1r50 by 1.2%, additionally pointing at the enhanced convective activity.

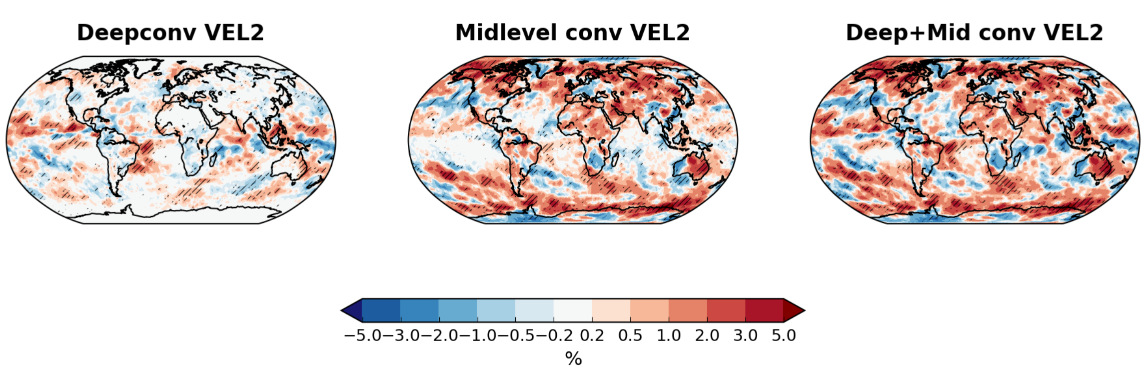


Figure 1: Annually averaged occurrence frequency of deep, mid-level or deep and mid-level convection from a 5-year long fixed SST simulation. Hatching is applied for areas at 90% significance level.

Page 8, line 8, 9: Why does an increase in convective activity lead to a decrease in CDNC?

The model seems to follow the response mechanism described in Rieck et al., 2012, in which the increase in convective activity decreases RH in the boundary layer. The RH is directly related to cloud cover (Sundqvist et al., 1989). A decrease in RH therefore leads to a decrease in cloud cover, which decreases also the all-sky CDNC.

Added also in text on page 9, lines 12-15.
Furthermore, in SEED1r50 an increase or intensification of convective activity , expressed by an 1.2% increase in globally averaged convective precipitation, leads to a drying of the tropical planetary boundary layer and lower troposphere and a decrease in liquid cloud cover (Fig. 4a). The cloud cover is directly related to RH (Sundqvist et al., 1989); its decrease leads to a cloud cover decrease, which decreases also the all-sky water content and CDNC (Fig. 6 a,c and Fig. 4 e).

Page 8, line 13-15: Why is CDNC higher in mixed phase cloud?

Added in the text, page 9 lines 21-28.
The sedimentation of ICs into mixed-phase clouds leads to the IC growth by riming of supercooled cloud droplets, also known as the seeder-feeder mechanism (Politovich and Bernstein, 1995). The seeder-feeder mechanism, reinforced by the additional growth of ice crystals at the expense of supercooled cloud droplets (Wegener-Bergeron-Findeisen process (Storelvmo and Tan, 2015)) therefore leads to a depletion of CDNC and LWC. A decrease of IC sedimenting flux from cirrus in the simulation SEED1r50 therefore leads to an increase in CDNC and LWC in mixed-phase cloud regime. This is in the tropics contrasted by the large RH decrease (Fig. 5f), leading to a decrease in cloud cover (Fig. 5a), and consequently also a decrease in all-sky CDNC in Fig. 6a.

Page 8, line 31: "T anomalies follow cCRE anomalies" Not in general true, since you do not see warm pool anomalies.

Thanks for pointing that out.
Indeed, that is not the case for the warm pool. We did not dig in the details of such a disagreement, as that goes beyond the scope of this publication.
Changed also in text, page 10, lines 10-11.
Yet, the temperature anomaly in the Pacific warm pool area is an exception to this general trend, which needs to be addressed in future studies.

Page 10: line 10: Why do change in tropical convection lead to a large number of small IC and an increase in ICNC?

This is due to the used parametrization of the formation of detrained IC, which follows Boudala et al., 2002.

Included also in the text, page 11, lines 29-33.

The surprising result can be explained by the parametrization of the size of the detrained ICs, which assumes an IC radius of about 10-20 μm (Boudala et al., 2002), distributing the detrained IWC over a large number of ICs and is part of the reason for the ICNC increase pattern in mixed-phase cloud conditions (Fig. 5w). Moreover, the freezing in mixed-phase clouds in our model occurs only rarely in-situ on dust or black carbon aerosols and is largely affected by the sedimented ICs from cirrus levels, initiating a seeder-feeder type of IC growth.

Page 10, line 14: replace "on some climatic" with "for some climatic"

Done

Page 11, line 24 – 26: Zhou and Penner, JGR, 2014 show different model assumptions that are used to describe the number of homogeneous and heterogeneous particles.

Good point, we added their assumptions on background aerosols in the text on page 13, line 14-15.
We also expect the cirrus seeding effectiveness to be dependent on the amount of background aerosol available for both homogeneous and heterogeneous freezing (Zhou and Penner, 2014).

Page 11, line 28: what is the "inhomogeneity parameter for ice clouds"

The model cannot resolve variability in the cloud field at scales smaller than the grid box size, where the clouds' natural variability is still large. Therefore, the use of a cloud inhomogeneity factor with values smaller than one improves the model agreement with observations of the planetary albedo and radiative fluxes (Cahalan et al., 1994). However, the uncertainty of the inhomogeneity parameter for clouds is large, and is therefore often used as a tuning parameter (Mauritsen et al., 2012).

We do not mention inhomogeneity parameter in the manuscript text any more.

Page 11: last line: what does "to which fraction of the total cirrus CRE this radiative anomaly corresponds" mean? The fraction due to liquid or mixed phase clouds?

Rephrased in text.

Figure 2: Please explain why CRE is not the same as the net (all sky) results. Also, why does it switch from higher than net to lower than net?

We explain the reasons for the disagreement between the net and cirrus CRE (and not total CRE) anomalies at the top of the atmosphere for increased sedimentation velocity setup, SEED1r50, and SEED1r50N in section 3.2.2, on page 9.

The switch between higher than net to lower than net, as observed in SEED and SEEDr50 simulations (Fig. 2 b,c) is interesting and can most likely be explained by additional cloud responses, as discussed for the VEL2, SEED1r50, and SEED1r50N simulations in the text.

Table 1: please write out what MLO means within the table (as well as in text).

Added to the table in addition to the main text on page 5, line 10.

Table 5: Please add a description of how ΔmpCRE, ΔcCRE, ΔliqCRE are computed within text.

Included in text, in the experimental setup, on page 5, lines 3-8.

In addition to the standard model radiative fluxes, we separately diagnosed the cloud radiative effect contribution of clouds at temperatures colder than -35°C (cirrus cloud radiative effect, cCRE) with the help of the double call of the radiation routine. Similarly, we diagnosed mixed-phase cloud radiative effects (mpCRE) for all clouds at temperatures between -35°C and 0°C independent of their cloud phase, and liquid cloud radiative effects (liqCRE) for clouds at temperatures above the freezing level.

REVIEWER 2

This is a nice and straightforward, if not exactly Earth shattering, modeling study of geoengineering in the form of cirrus seeding. The study includes highly relevant testing of the usefulness of the approach of mimicking cirrus seeding by increasing ice crystal fall speed. The latter has been proposed as an experiment in a new set of GeoMIP simulations, so it is important to understand in what respects this is a useful proxy for explicitly simulating the shift from homogeneous to heterogeneous nucleation that (at least in theory) occurs in response to seeding with INP.

I have a few major/substantial comments, and numerous minor comments which are listed below, and which are intended to help the authors improve the readability of the manuscript. Once the major/minor comments have been addresses, I believe the manuscript will be suitable for publication in ACP.

Major comments:
- The authors conclude that the simulation that includes seeding at nighttime only is the most "appealing". To me, that simulation is a purely academic exercise, because in practice it would be impossible to only seed during night-time. It would take time to build up the right seeding INP concentration, and obviously one could not make the particles magically disappear at sunrise. I understand the desire to minimize the SW radiative effect, as well as the effects of increased convection, but I don't understand why the study doesn't include simulations with only high-latitude seeding (and fall speed increases).

Seeding only high latitudes would, as opposed to the entire globe at night-time, potentially be possible in practice, and should achieve many of the same advantages. Considering the very large particles that appear to be most favorable seeding INP in this model, it would also be advantageous to seed much smaller areas to reduce the total mass required.

We didn't want to expand the manuscript too much beyond the comparison of seeding with increased sedimentation velocity setup, which represents the core of this study. We do have a few simulations where seeding/increased sedimentation velocity has been applied only over high latitudes, with the same zenith angle dependent seeding scenarios as in Storelvmo and Herger, 2014.

Our cirrus clouds respond differently to seeding compared to what described in Storelvmo and Herger, 2014 publication. A solar zenith angle dependent seeding scenario Y1 leads to only about half of the radiative flux anomaly compared with the seeding over the whole world. The difference to Storelvmo and Herger's publication probably lies in the radiative effects of our cirrus clouds, which show a peak over the tropics and a large proportion of tropical cirrus clouds being formed by homogeneous freezing, as shown by Gasparini et al., 2016.

Similarly, increasing sedimentation velocity using the solar zenith dependent scenario Y1 also leads to only about half as large radiative anomaly effects compared to the globally uniform sedimentation velocity increase simulation VEL2.

Added also in the text on page 6/7, lines 31-34/1-2:

Interestingly, our cirrus clouds respond differently to seeding compared to what has been described in Storelvmo and Herger, 2014. A solar zenith angle dependent seeding scenario which seeds about 40% of the earth's surface leads, unlike the cited study, to only about half of the radiative flux anomaly compared with the globally uniform seeding strategy SEED1r50. The difference probably originates from the zonally different radiative effects of cirrus clouds in ECHAM-HAM, which show a peak over the tropics (Fig. 3) and, differently from Storelvmo and Herger, 2014, a large proportion of tropical cirrus clouds is formed by homogeneous freezing (Gasparini et al., 2016).

We will revisit limited seeding scenarios in a future publication.

The night seeding scenario is indeed less realistic compared with other experiments (added a comment on that in the manuscript, page 13, line 6: "…not considering its unlikely technical implementation,…". But we would argue that none of our experiments is much more than an academic exercise. We seed at every model timestep at all locations where the cirrus formation scheme is called (i.e. at T<-35°C, in conditions of updraft, at RH_{ice} > 100%). That indeed is not a very plausible scenario either.

Yet, in defence of the night seeding scenario, we want to point out that such large INP forming large ICs can sediment out of the atmosphere (or at least out of upper troposphere) in only a few hours time. Large particle seeding could in this case instead of building up a permanent aerosol layer be used to target specific regions, in which one would forecast conditions favourable for homogeneous ice nucleation.

Considering the very large particles that appear to be most favorable seeding INP in this model, it would also be advantageous to seed much smaller areas to reduce the total mass required.

This is a good point and we also started to explore it, by limiting seeding for example to areas of prevalent homogeneous freezing, globally non-uniform seeding INP concentrations, etc. It will be subject to a future publication.

Again, we avoided including that in the manuscript to prevent it from becoming too large and to keep the focus on the main scientific question of this manuscript – the comparison of sedimentation velocity increase to cirrus seeding.

We added a sentence to conclusions, page 13, lines 8-10.

We note that a seeding strategy limited to areas of highest seeding effectiveness (where the cCRE anomalies after seeding are the largest as shown by Fig. 7a), might significantly decrease the mass of seeded material while exerting a roughly similar climatic forcing.

- The simulations with increased fall speed are, while in some respects useful, deeply unphysical. I missed a discussion of this in the manuscript. Specifically, I have problems with the sudden drop in fall speed that all ice crystals will experience as soon as they fall through the -35 degree isotherm. This would naturally lead to an accumulation of ice at mixed-phase levels, which is exactly what can be seen in Fig. 4. The authors seem to attribute this to mid-level convection. This is one important reason why increased fall speed is an imperfect proxy for actually simulating cirrus cloud microphysics.

We totally agree on the sudden drop in fall speed as the main reason for the increase in IC number concentration and IWC in the model. We revised the text to make it clearer.

In addition, we still argue that increases in convection (or more specifically, mid-level convection) do contribute towards part of the ICNC increase and RH signal. Mid-level convection in our model has an upper limit of 400 hPa, with the detrainment occurring in the 2 levels above it, that is between 400 and 300 hPa. This is exactly the level where the RH increases, in particularly in the VEL2 and VEL2all simulations. Moreover, an increase in convective precipitation in VEL2 by about 1.5% in global average additionally indicates a likely convective strength increase.

Please see also changes in text, which better point out the problem of the drop in IC velocity, for instance in conclusions, page 12, lines 9-11.
However, in VEL2 the IC sedimentation velocity is abruptly set back to the standard one computed by the model at temperatures warmer than -35°C, leading to a redistribution of ICs and IWC from cirrus to underling mixed phase clouds, which is not observed in SEED1r50.

Minor comments:
- Make sure you're consistent in your use of the abbreviations IC and INP - they are used to represent both the plural and singular forms of the nouns.

Thanks, we corrected it and tried to be more consistent in its use now.

- Page 4, Line 20: "precipiation"–>"precipitation"
- Page 5, "for"–>"by"
- Page 5, Line 31-31: inappropriate referencing
- Page 7, Line 11: suggest replacing "affects also part of" with "to some extent also affects"
- Page 7, Line 19: suggest replacing "temperature decrease anomaly" with

"negative temperature anomaly"
- Page 11, Line 15: "twice larger"–> "twice as large"

Changed in text

- Figure 4: Why are ice crystal numbers and sizes not included in this figure? They seem like very important microphysical variables to include.

We did not include IC number concentration and size to prevent increasing the complexity of the figure. The message however does not change when adding the additional plots. Yet, as the change in ICNC and IC radius do matter when trying to interpret the climatic responses to seeding, we decided to add them nevertheless to the manuscript.

Please note also changes to the text on pages 7, 10, 11 related to the inclusion of ICNC and IC radius in Figure 4 (now Figure 5).

- Figure 5: Are these in-cloud or grid-box values?

all-sky values, added to the figure caption

REVIEWER 3

This is a manuscript on evaluating a simplified geo-engineering simulation strategy against the more comprehensive microphysical model treatment. The authors performed both fixed-SST and mixed-layer ocean simulations and investigated the changes in cloud properties for both ice and liquid phases, and the associated changes in cloud radiative forcing, surface temperature, and precipitation, due to using different geo-engineering model setups.
The manuscript is clearly written and well organized. The designed experiments and analysis are comprehensive. The conditionally sampled/calculated CRE changes are interesting and informative. I only have several questions that need clarification and some minor suggestions for better readability. Below please find my specific comments:

1. Page 2, Line 20: Cirrus seeding affects the sedimentation of ice crystals from cirrus clouds to mixed phase/warm clouds, the cloud glaciation, and therefore the ice supersaturation. Maybe change it to "cannot directly influence"?

Thanks, changed in the text.

2. Page 3, Line 12: What is the model time step? This is related to the question below about the numerical treatment of ice sedimentation.

It's 6 minutes.

3. Page 3, Line 26-27: If the model time step is about 20min, an ice crystal with a sedimentation velocity larger than 1m/s will fall through a 800m thick model layer (800m/1200s=0.67m/s). How does the model treat this (violation of CFL condition)?

We use a time step of 6 min, i.e. 360 sec so CFL is not violated.
Added also to the text, page 3, line 25.
…and a model timestep of 6 minutes.

4. Page 4, Line 5-6: What is the initial size of the nucleated ice particles? If not the size of the seeded INP, is it determined by the parameterization or by explicit microphysical calculation?

The aerosol both nucleates an ice crystal as well as experiences the initial growth by deposition within the same model timestep. Therefore the ice crystals rapidly grow beyond their initial sizes.
The size of the newly nucleated ICs is limited by the INP size and/or a minimum allowable IC size of 1 μm (Kärcher and Lohmann 2002, Kärcher and Lohmann 2003, Kärcher et al., 2006).

5. Page 4, Line 12: Does the seeded INP immediately freeze at RHi=105% when T<-35C? How do you consider the competition between the homogeneous freezing of solution droplets, heterogeneous freezing of natural dust, and heterogeneous freezing of the seeded INP?

It can nucleate if the RH_{ice} exceeds 105% at the moment the cirrus scheme is called by the model.
After the cirrus scheme is called (always when RH_{ice} > 100% and in presence of an updraft) the scheme verifies whether cirrus conditions were met, in the following order (from the most effective INP onwards):

1.) seeding by deposition
2.) heterogeneous nucleation – deposition
3.) heterogeneous nucleation – immersion
4.) homogeneous freezing

In case of pre-existing ice crystals, the cirrus scheme first computes the depositional growth of water vapor onto these pre-existing ice crystals, decreasing the RH_{ice}.
If the RH_{ice} is still high enough, the freezing proceeds as mentioned above, starting from the most effective freezing mechanism (in our case seeding). If no seeding INP are present, the scheme tries to freeze ice crystals heterogeneously, and finally, homogeneously. After each freezing (and initial growth) step, the RH_{ice} is decreased accordingly.

Technically, the RH_{ice} is represented by the so-called 'fictitious updraft'. More information about its details can be found in Kuebbeler et al., 2014 and Kärcher et al., 2006.

6. Page 4, Line 13-14: Do you avoid the INP seeding in anvil clouds? Or in-situ ice nucleation doesn't happen in anvil clouds?

We seed in the described setup also anvil clouds. Yet, the in-situ nucleation occurs rarely under such conditions.
Added in the text, page 4, lines 33-34.
It is important to note that we only modify in situ formed cirrus and not the convective anvil clouds as in situ deposition nucleation does not occur in anvils.

7. Page 5, Line 24-25: I don't quite understand this. Do you mean with the same amount of ice crystal mass?

The freezing probability increases with the surface area of particle, which quadratically depends on its radius. The sedimentation velocity of INP increases quadratically with the radius too. The two effects cancel out each other.

Rephrased in text on page 6, line 15-18.
On the other hand, the probability P of one INP to freeze in a given time as described by the classical nucleation theory depends on the INP's surface area, which

increases quadratically with particle size. Quadratic fallspeed velocity and freezing probability increases cancel out each other leading to no change in the concentration of ICs formed on geoengineered INPs when they increase in size.

8. Page 8, Line 27: The signal over topography seems pretty strong. Does the model consider the impact of orographic waves on ice nucleation?

Yes – we follow the Joos et al., 2008 formulation, as mentioned in the referenced studies with the current cirrus scheme (Gasparini and Lohmann, 2016 and Kuebbeler et al., 2014). We added the following 2 sentences in the manuscript on pages 3/4, lines 34/1-2.

The formulation of vertical velocity used for cirrus formation considers the large-scale velocity field and a sub-grid scale contribution derived from the turbulent kinetic energy. The latter is replaced by a gravity wave parametrization by Joos et al., 2008 over mountain regions.

9. Page 9, Line 28-29: This result is very interesting, but it's very likely model-dependent. Do you have extinction output as well? Would be nice to show the forcing efficiencies (&CF/&EXT) in table 3 as well.

Unfortunately we do not have the extinction or cloud optical depth output for the performed analysis. Yet, we expect the efficiency to be the largest at the coldest cirrus clouds, despite its absolute forcing being very small.

10. Conclusion: Many points are made in the conclusion part and to me, they are a little bit scattered (very useful information though). I would recommend the authors to make it more compact and concise.

Maybe in the order of 1) statement of general findings;
2) differences in microphysical responses;
3) differences in CREs;
4) differences in temperature and precipitation response; . . .?

Thanks for the suggestion, we tried to modify the conclusions according to your suggestion. The reviewed conclusions section has now the following order:

-general findings (with microphysical responses, 1 paragraph)
-differences in CRE (2 paragraphs)
-differences in temperature and precipitation response (2 paragraphs)
-general conclusions (last 2 paragraphs)

References

Boudala et al., 2002: Parametrization of effective ice particle size for high-latitude clouds

Cahalan et al, 1994: The albedo of fractal stratocumulus clouds

Gehlot and Quaas, 2012: Convection-climate feedbacks in the ECHAM5 general circulation model: Evaluation of cirrus cloud life cycles with ISCCP satellite data from a lagrangian trajectory perspective

Jensen et al., 2011: Impact of radiative heating, wind shear, temperature variability, and microphysical processes on the structure and evolution of thin cirrus in the tropical tropopause layer

Gu and Liou, 2006: Cirrus cloud horizontal and vertical inhomogeneity effects in a GCM

Joos et al., 2008: Orographic cirrus in the global climate model ECHAM5

Kärcher and Lohmann, 2002: A parameterization of cirrus cloud formation: Homogeneous freezing including effects of aerosol size

Kärcher and Lohmann, 2003: A parameterization of cirrus cloud formation: Heterogeneous freezing

Kärcher et al., 2006: Physically based parameterization of cirrus cloud formation for use in global atmospheric models

Kuebbeler et al., 2014: Dust impact on ice nuclei

Luo and Rossow, 2004: Characterizing Tropical Cirrus Life Cycle, Evolution, and Interaction with Upper-Tropospheric Water Vapor Using Lagrangian Trajectory Analysis of Satellite Observations

Mauritsen et al., 2012: Tuning the climate of a global model

Politovich and Bernstein, 1995: Production and Depletion of Supercooled Liquid Water in a Colorado Winterstorm

Spichtinger et al., 2009: Modelling of cirrus clouds – Part 1a: Model description and validation

Sundqvist et al., 1989: Condensation and Cloud Parametrization Studies with a Mesoscale Numerical Weather Prediction Model

Storelvmo and Tan, 2015: The Wegener-Bergeron-Findeisen process – its discovery and vital importance for weather and climate

[1]

Is increasing ice crystal sedimentation velocity in geoengineering simulations a good proxy for cirrus cloud seeding?

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Abstract. The complex microphysical details of cirrus seeding with ice nucleating particles (~~INP~~INPs) in numerical simulations are often mimicked by increasing ice crystal sedimentation velocities. So far it has not been tested whether these results are comparable to geoengineering simulations in which cirrus clouds are seeded with ~~INP~~INPs. We compare simulations where the ice crystal sedimentation velocity is increased at temperatures colder than -35°C with simulations of cirrus seeding with ~~INP~~ INPs using the ECHAM-HAM general circulation model. The radiative flux response of the two methods shows a similar behaviour in terms of annual and seasonal averages. Both methods decrease surface temperature but increase precipitation in response to a decreased atmospheric stability. Moreover, simulations of seeding with ~~INP~~ INPs lead to a decrease in liquid clouds, which counteracts part of the cooling due to changes in cirrus clouds. The liquid cloud response is largely avoided in a simulation where seeding occurs during night only. Simulations with increased ice crystal sedimentation velocity, on the contrary, lead to counteracting mixed-phase cloud responses. The increased sedimentation velocity simulations ~~induce a 30% larger surface temperature response, due to their lower altitude of maximum diabatic forcing compared with simulations of seeding with INP particles. They~~ can counteract up to 60% of the radiative effect of CO_2 doubling with a maximum net top-of-the-atmosphere forcing of -2.2 W m^{-2}. They induce a 30% larger surface temperature response, due to their lower altitude of maximum diabatic forcing compared with simulations of seeding with INPs.

1 Introduction

Cirrus seeding is a proposed geoengineering method to decrease the occurrence of cirrus clouds by changing their optical properties~~to increase the amount of outgoing longwave (LW) radiation (?) and thereby cooling the climate~~. Cirrus clouds on average have a stronger ~~LW~~ longwave (LW) than shortwave (SW) effect on the radiative balance, leading to a positive net cloud radiative effect (CRE), as estimated from satellite data ~~(????)~~(?????), in situ lidar observations (**?**), and global modelling studies (**?**). Thus a reduced amount of cirrus clouds will increase the amount of outgoing longwave (LW) radiation (**?**) and thereby cool the climate. Cirrus CRE has a pronounced seasonal and daily cycle, with higher values in the winter hemisphere (or at night) where the reflection of SW radiation is limited by the lack of insolation. We define cirrus clouds as all clouds that form at temperatures lower than -35°C with no additional altitude criteria.

Two microphysical formation pathways of cirrus clouds exist:

- Homogeneous freezing of solution droplets occurs at high relative humidities with respect to ice (RH_{ice}) and can lead to a large number of ice crystals (~~IC~~ICs) depending on temperature ~~, updraft velocity , and relative humidity with respect to ice~~ and updraft velocity (**?**). If their concentration is large, their growth is limited, as they rapidly consume the available water vapour (**?**).
- Heterogeneous freezing can occur in the presence of effective ~~ice nucleating particles (INP)~~ INPs which lowers the freezing energy barrier, allowing droplets to freeze at lower RH_{ice} and/or smaller updraft velocities (**??**).

Heterogeneous ice nucleation can suppress homogeneous nucleation in conditions of slow updrafts, commonly found in the upper troposphere (**??**), resulting in optically thinner and shorter-lived cirrus clouds. A modelling study by **?** showed that the global net top-of-the-atmosphere (TOA) radiative balance can change by up to 2.8 $\mathrm{W\,m^{-2}}$ as a result of a complete shift from homogeneous to heterogeneous cirrus formation (the numbers are reported in **?**). As the upper tropospheric INP number concentrations ~~are~~ is limited (**?**), only few ~~IC~~ ICs can nucleate heterogeneously and consequently grow to larger sizes (**?**).

A large fraction of cirrus clouds at temperatures warmer than -60°C is found to have formed from homogeneous nucleation of cloud droplets in ~~the~~ convective clouds forming anvil cirrus ~~clouds~~ (**?**). These cannot be modified by seeding of ~~INP~~ INPs as their formation is dominated by ~~the dynamics~~ strong updraft velocities (**?**). In addition, ~~IC~~ ICs in warm cirrus in the extratropics often form by heterogeneous freezing of cloud droplets in mixed-phase clouds, which are subsequently advected to cirrus conditions (**???**). Cirrus seeding can perturb only the nucleation ~~and initial growth processes and therefore cannot influence the IC that nucleated at temperatures between 0°C and -35°C in the mixed-phase clouds~~of ice crystals in supersaturated cloud-free conditions (in-situ formed cirrus) and their subsequent initial growth.

Cirrus seeding tries to modify the competition between homogeneously and heterogeneously formed ~~IC~~ ICs by artificial injections of efficient ~~INP~~ INPs with the goal of cooling the climate. Modelling studies by **?** and **?** suggested that cirrus seeding can decrease the net TOA radiative balance by up to 2 $\mathrm{W\,m^{-2}}$ or decrease the surface temperature by up to 1.4 °C. On the other hand, a study by **?** showed no significant net radiative change as a result of seeding due to a larger concentration of upper tropospheric ~~INP~~ INPs in their reference climate, no upper limit on the subgrid-scale updraft velocities, and the inclusion of the competition of pre-existing ~~IC~~ ICs for the available water vapour. **?** also found an insignificant radiative response to cirrus seeding in their simulations. They attributed it to a decrease in IC radius and an increase in cirrus cloud cover by forming new cirrus in previously ~~cloud free~~ cloud-free ice supersaturated regions.

As it is computationally demanding to simulate the detailed cirrus microphysical processes, climatic responses of seeding are often represented by increasing the IC sedimentation velocity in cirrus clouds (**???**). Increasing the IC sedimentation velocity can, analogous to seeding, decrease the amount of cirrus cloud cover, ice water content (IWC), and ice crystal number concentration (ICNC). Such a modelling strategy was also selected by the Geoengineering Modeling Intercomparison Project (**?**). However, it has never been systematically analysed whether this method leads to results comparable to seeding with ~~INP~~INPs.

In this paper we compare the radiative, microphysical, and climatic responses between the increased sedimentation velocity and seeding simulations with the help of suitable ~~INP~~INPs. We point out differences between the two setups, examine liquid and mixed-phase cloud responses to changes in cirrus clouds, and show geographical areas where both ways of simulating cirrus geoengineering are most effective. We also evaluate the maximum effect of the increased sedimentation velocity schemes.

2 Methods

2.1 Model setup

We use the ECHAM6-HAM2 aerosol-climate model (**???**) with a horizontal resolution of 1.875° × 1.875°~~and~~, 31 vertical levels, and a model timestep of 6 minutes. The model top is at 10 hPa. The level thickness at typical cirrus altitudes varies between 500 and 1000 m. The ~~two moment~~ two-moment aerosol scheme (**??**) interactively simulates aerosol emissions, their growth, coagulation and sink processes in terms of their number and mass mixing ratios. The model uses a ~~two moment microphysics cloud scheme (?)~~ two-moment cloud microphysics scheme with prognostic equations for cloud liquid and ice mass mixing ratios as well as cloud droplet and ice crystal number concentrations (**?**). The cirrus nucleation scheme by **?** simulates the competition between homogeneous freezing, heterogeneous freezing, and deposition of water vapour on pre-existing ~~IC~~ICs. Heterogeneous freezing occurs via deposition nucleation of insoluble coarse and accumulation mode dust aerosols or immersion freezing of internally mixed (coated) dust aerosols based on laboratory measurements by **??**. The formulation of vertical velocity used for cirrus cloud formation considers the large-scale velocity field and a subgrid-scale contribution derived from the turbulent kinetic energy. The latter is replaced by a gravity wave parametrization by **?** over mountain regions. The detailed implementation of the cirrus formation scheme in the ECHAM-HAM general circulation model has been described in **?** and **?**. We use the convective mass flux scheme of **?** with modifications for deep convection from **?**, which is an important source of detrained cloud ice leading to frequent anvil cirrus formation. The model gridboxes are considered partially cloudy above a certain relative humidity threshold, and fully cloud covered when relative humidity reaches 100%, following **?**.

2.2 Experimental setup

For the idealized seeding scenario we perform simulations where the sedimentation velocity of all ~~IC~~ ICs at temperatures below -35°C is increased by ~~a factor~~ factors of 2 (simulation VEL2), 4 (VEL4), and 8 (VEL8), and two simulations where the sedimentation velocity is either always set to 2 m s^{-1} (VELmax) or only during night (VELmaxN). 2 m s^{-1} is the maximum sedimentation velocity ~~IC~~ ICs can achieve in our model. The sedimentation velocity increase applies for all the cirrus ICs, regardless of their microphysical origin. We always show anomalies with respect to the ~~reference, unperturbed~~ unperturbed reference simulation (REF). Fig. 1 shows the relation of IC size and their sedimentation velocity following the formulation by **?** for typical upper tropospheric conditions in the tropics. The upper sedimentation velocity limit of 2 m s^{-1} used in ECHAM-HAM does not significantly influence our results, as ~~IC with a radius~~ ICs with radii smaller than 90 μm in atmospherically relevant conditions do not sediment faster than approximately 0.3 m s^{-1}. ~~Ice~~ Only an IC of about 1 mm radius would fall with a velocity of about 2 m s^{-1}. Moreover, ice crystals larger than 90 μm are transferred from ice into snow (**?**) and precipitate out of the atmosphere within one model timestep.

For the realistic seeding scenarios, we performed 5 simulations of globally uniform continuous seeding in areas with ~~temperature~~ temperatures colder than -35°C as decribed by **?**. In ~~SEED we use INP~~ our simulations we either increase the cirrus IC sedimentation velocity or seed with geoengineered INPs, which sediment with the size dependent sedimentation velocities (**?**). In SEED simulations we use INPs with the modal radius of 0.5 μm, while in SEEDr50 simulations the radius is increased to 50 μm. In this way we overcame the ~~problem of a~~ cloud cover increase and IC radius decrease that we see when seeding with 0.5 μm particles (**?**). We do not go beyond a radius of 50 μm despite using even larger INP sizes would likely result in larger climatic impacts~~; as~~. As the injected particle mass increases cubically with particle size, its practical use will be limited due to the needed delivery into the upper troposphere and shorter atmospheric residence time. We seed all areas supersaturated with respect to ice at temperatures below -35°C with 0.1, 0.3, 1, 3, 10, 30, and 100 ~~INP~~ INPs L^{-1} (consequently we name the simulations as SEED0.1r50, SEED0.3r50, SEED1r50, etc., see Table 1), which ~~freeze~~ nucleate in deposition mode at RH$_{ice}$ as low as 105% (**?**). In addition, we simulate a scenario where ~~seeding with large INP~~ 50 μm INP of 1 INP L^{-1} is applied only during night (SEED1r50N). It is important to note that we only modify in situ formed cirrus and not the convective anvil clouds as in situ deposition nucleation does not occur in anvils. Furthermore, the injected ~~INP~~ INPs do not interact with radiation and cannot directly influence mixed-phase or liquid clouds.

In addition to the standard model radiative fluxes, we separately diagnosed the cloud radiative effect contribution of clouds at temperatures colder than -35°C (cirrus cloud radiative effect, cCRE) with the help of the double call of the radiation routine. Similarly, we diagnosed mixed-phase cloud radiative effects (mpCRE) for all clouds at temperatures between -35°C and 0°C independent of their cloud phase, and liquid cloud radiative effects (liqCRE) for clouds at temperatures above the freezing level.

All simulations are after a 3-month model spin-up run for 5 years with fixed sea surface temperatures (SST) to study radiative flux anomalies and fast responses to seeding. Simulations SEED1r50 and VEL2 are extended to 10 years to increase the statistical robustness of the results. They are additionally simulated in the mixed layer ocean (MLO) setup in order to study long term microphysical and climatic responses, especially temperture and ~~precipiation~~precipitation. The MLO simulations are run for 50 years, but we only assess the anomalies of the last 30 simulated years, after the model has reached an equilibrium. A list of all simulations and their specifications can be found in the Table 1. The significance is calculated based on a double-sided Welch's t-test at the 95% significance level.

3 Results

3.1 Cirrus geoengineering

3.1.1 Increased sedimentation velocity

The radiative effects decrease exponentially with the increase in sedimentation velocity (Fig. 2a) as already noted by **?**. This is because the cirrus CRE always decreases ~~for~~ by about 30% when doubling the IC sedimentation velocity, i.e. comparing REF ~~and~~ with VEL2, VEL2 ~~and~~ with VEL4, or VEL4 ~~and~~ with VEL8 (Table 2). In the VELmax simulation increasing IC sedimentation velocities in cirrus to 2 m s^{-1} leads to a negative net TOA radiative balance anomaly of -2.20 W m^{-2} $\pm$ 0.26 W m^{-2} which corresponds to about 60% of the radiative forcing induced by the doubling of the CO_2 concentrations (**?**).

In VELmaxN we only increase the IC sedimentation velocity in cirrus during night, which leads to an overall (considering day and night) 15-20% smaller radiative effect decrease compared with VELmax . The result is consistent with the cirrus CRE diurnal cycle diagnosed from the model, which reaches 8 W m^{-2} in the global annual average at night and 1 W m^{-2} during day, when cirrus reflect part of the incoming SW radiation ~~. Even though the fall velocity in the VELmax simulationcorresponds to an unrealistically large IC at typical cirrus levels~~ (Fig. 3). The VELmax simulation, which sets the cirrus IC sedimentation velocity to the unrealistically high value (Fig. 1), ~~the simulation~~ shows that globally uniform cirrus cloud thinning ~~cannot~~ can reduce the cirrus CRE by ~~more than~~ about 3.3 W m^{-2} which is equivalent to $\sim$~~50%~~ 75% of its full value (Table 3).

3.1.2 Cirrus seeding with ice nucleating particles

In the SEED simulations we inject seeding ~~INP~~ INPs of 0.5 μm radius at every model timestep in areas with temperatures colder than -35°C. We see no significant radiative response for concentrations of up to 1 INP L^{-1} (Fig. 2b), while a net TOA positive radiative anomaly develops ~~for~~ by seeding with more than 3 ~~INP~~ INPs L^{-1} (overseeding) as explained in detail in **?**. With an increased radius of 20 and 50 μm (simulations SEEDr20 and SEEDr50) and a seeding concentration of 1 INP L^{-1}, we achieve a significant negative TOA radiative anomaly of -0.46 $\pm$ 0.14 W m^{-2} and -0.85 $\pm$ 0.40 W m^{-2}, respectively (Fig. 2c and Table 4). Seeding with large ~~INP particles~~ INPs leads to larger newly formed heterogeneous ~~IC~~ ICs and therefore avoids their decrease in size as observed in **?**. Moreover, the initial increase in cloud cover by seeding of ice supersaturated clear sky regions with ~~very efficient INP particles~~ efficient INPs is outweighted by the large increase in the IC sedimentation velocities, which leads to a net cirrus cloud cover decrease (Fig. 5a).

Large ~~INP~~ INPs have a shorter atmospheric lifetime because of the quadratic dependence of particle fallspeed on its radius where the impact of turbulence can be neglected as we are in Stokes regime. For instance, the vertical velocity of a 0.5 μm aerosol particle (considering a density of 2500 kg m^{-3}, similar to dust aerosols) in the upper troposphere is $\sim$10^{-4} m s^{-1}, while a 50 μm particle falls with a velocity of 1 m s^{-1}. On the other hand, the ~~freezing probability P~~ probability of one INP to freeze in a given time as described by the classical nucleation theory ~~(Eq. **??**), remains roughly similar, because it~~ depends on the INP's surface area ~~A~~ which increases quadratically with particle size. ~~We consider a constant nucleation rate J where Δt represents the time a particle spends in conditions favourable for freezing:~~

$$\cancel{P = 1 - e^{-JA\Delta t}}$$

Quadratic fallspeed velocity and freezing probability increases cancel out each other leading to no change in the concentration of ICs formed on geoengineered INPs when they increase in size.

The large size of seeding ~~INP~~ INPs also increases the deposition flux of water vapour onto the INP leading to a more effective drying of the upper atmosphere. The largest disadvantage of seeding with large ~~INP~~ INPs is the cubic dependence of particle mass on its radius: an increase in radius from 0.5 to 50 μm increases its mass by a factor of 10^{6}, making the transport of the seeding material to the upper troposphere much more challenging. Additionally, the seeding frequency of the large ~~INP~~ INPs would probably need to be larger compared with the small ~~INP~~ INPs seeding, due to their faster sedimentation.

The radiative anomalies obtained by injecting 0.3 or 3 ~~INP~~ INPs L^{-1} of 50 μm radius are -0.66 $\pm$ 0.35 W m^{-2} and -0.77 $\pm$ 0.27 W m^{-2} and thus are not significantly different from those with injecting 1 INP L^{-1} (Fig. 2~~b~~c). The effective seeding range with similar results thus spans over about an order of magnitude of INP concentrations. The response from a simulation with large particle seeding ~~at night only~~ only at night (SEED1r50N) with a net TOA radiative anomaly of -0.91 W m^{-2} is similar to the one from SEED1r50.

Interestingly, our cirrus clouds respond differently compared to what has been described in **?**. A solar zenith angle dependent seeding scenario which seeds about 40% of the earth's surface leads, unlike the cited study, to only about half of the radiative flux anomaly compared with the globally uniform seeding scenario SEED1r50. The difference probably originates from the radiative effects of the cirrus clouds in ECHAM-HAM, which show a peak over the tropics (Fig. 3) and, differently from **?**, a large proportion of tropical cirrus clouds is formed by homogeneous freezing (**?**).

3.2 Response comparison

3.2.1 Radiative and microphysical responses

We now focus on the climatic and microphysical responses of the seeding with 1 INP L^{-1} (SEED1r50) and increased sedimentation velocity (VEL2) scenarios due to their similar TOA net radiative flux anomalies ($\sim$ -0.8 W m^{-2}, Fig. 4a) in 10-year fixed SST simulations. Both geoengineering simulations show a positive anomaly in net SW TOA fluxes, due to a smaller SW CRE, i.e. less SW radiation reflected by cirrus clouds. The LW radiation budget, on the other hand, is more negative due to the increased outgoing LW radiation in response to a decrease in cirrus cloud cover. The radiative changes result in increased tropospheric cooling, decreasing the atmospheric stability, increasing convection, and leading to a precipitation increase of about 1% for both VEL2 and SEED1r50 (Fig. 4b).

Interestingly, the simulation SEED1r50N leads to a slightly larger net TOA radiative anomaly, which is different from the comparison of VELmaxN and VELmax simulations and counterintuitive as the cirrus cloud radiative effects (cCRE) in ECHAM-HAM on average is positive also during the day. However, while the impact of increasing the sedimentation velocity only during night ceases immediately when the sun appears above the horizon, the seeding of ~~INP particles can have~~ INPs has some inertia. The effective cirrus cloud lifetime is in the range of ~~a couple of~~ several hours as diagnosed from our model~~; we~~ , with values around 6 hours in the tropical tropopause region. This is shorter compared with available studies which estimated it to 12-30 hours (**???**). We therefore expect the seeded clouds to prevent the formation of homogeneous cirrus also some hours after sunrise, when the sun is low on the horizon and the cirrus LW warming effect significantly outweighs the cooling by the scattering of the SW radiation. Moreover, the simulation SEED1r50N avoids the warming effect induced by a response of liquid clouds to seeding during the day, as described in the Sect. 3.2.2.

From now on we focus only on the 30-year MLO simulation anomalies. The surface temperature decrease in response to changes in the atmosphere results in a more stable lower troposphere compared with fixed SST simulations. This overcompensates the fast (surface temperature independent) precipitation response in Fig. 4b, leading to a small decrease in global average precipitation for both scenarios (Fig. 4d).

Cirrus cloud cover decreases in both simulations (Fig. 5 a,b) with maximum anomalies between 7 (extratropics) and 15 km (tropics) altitude. The maximum decrease occurs at about 11 km altitude amounting to 4% in SEED1r50, whereas the decrease is about 3-4 times smaller in the VEL2 scenario (Fig. 5e). Both simulations show an IWC anomaly of about -0.2 to -0.5 mg kg^{-1} in the upper troposphere, corresponding to about 20-50% of the total IWC there (Fig. 5 ~~k,l,o~~p,q,t). However, the IWC decrease in VEL2 is followed by an increase of IWC of a similar magnitude in the mixed-phase cloud regime at temperatures warmer than -35°C, where the IC sedimentation velocity is restored to the reference value.

The IWP and ICNC pattern in VEL2 ~~is~~ are a result of an unrealistic redistribution of ice mass and number concentration to lower levels ~~,~~ (Fig. 5 q,v), while in SEED1r50 (Fig. 5z) the large, newly formed ~~IC quickly precipitate and are~~ ICs quickly grow by vapour deposition to sizes large enough to precipitate and be removed from the atmosphere. ~~Therefore, the~~ Moreover, the convectively detrained ICs dominate ICNC at locations below about 250 hPa in our model (**?**). Including new freezing INP in the environment by either convection or heterogeneous IC nucleation only redistributes the same amount of vapour between more particles as explained in **?**, leading to a decrease in IC radii. The ice water path (IWP) decreases by about 7% in SEEDr50 but only by about 1.5% in the VEL2 simulation (Fig. 4e). In SEED1r50 the effect of quickly sedimenting large ~~IC~~ ICs from cirrus levels ~~affects also part of the IC~~ to some extent also affects the ICs in mixed-phase clouds, leading to a small IWC decrease also at temperatures warmer than -35°C (Fig. 5k).

On the other hand, ~~the IWC in mixed-phase clouds increases in~~ in VEL2 ~~, leading to~~ the redistribution of IWC and ICNC from the cirrus levels to warmer temperatures leads additionally to a mixed-phase cloud glaciation effect~~, which is responsible for the total~~ : the cloud droplet number concentration (CDNC) at temperatures between -35°C and 0°C therefore decreases at the expense of the additional increase in ICNC. This leads to a globally averaged liquid water path decrease by about 3%~~and the cloud droplet number concentration (CDNC)~~ , CDNC drop by 1%, and ICNC increase by 7% (Fig. 4e and Fig. 6b). In VEL2 the ICs at cirrus levels fall faster and have therefore less time available for depositional growth, leading to a decrease in their size (Fig. 5aa), confirming the results of **?**

The decrease in cirrus cloud cover changes the atmospheric diabatic heating, leading to an upper tropospheric cold anomaly of about 1°C in both simulations (Fig. 5 ~~p,q,t~~k,l,o). Interestingly, the location of the maximum anomaly and its vertical extent differ significantly between SEED1r50 and VEL2. The peak temperature decrease in SEED1r50 is concentrated in the tropical tropopause region, while VEL2 shows an elongated ~~temperature decrease~~ negative temperature anomaly extending to about 7 km altitude. The reason for this 5 km difference in the altitude of peak cooling is most likely related to the inability of seeding to influence the convectively formed and other liquid origin cirrus clouds, which dominate at temperatures warmer than -50°C (**?**). On the contrary in the simulation VEL2 all cirrus ~~IC sediment~~ ICs are affected by the increased sedimention regardless of their origin. Considerably larger TOA SW and LW radiative flux anomalies in SEED1r50 compared to VEL2 ~~also indicate~~ occurs at a higher altitude ~~of~~ as well as the maximum radiative forcing anomaly ~~in SEED1r50~~ (Fig. 4c). Moreover, in SEED1r50 the destabilisation of the upper troposphere leads to increased vertical velocities and increased tropical tropopause and stratospheric specific humidities. ~~That~~ This implies higher cooling rates dominated by the LW emissivity of water vapour (**?**), and explains part of the tropical tropopause and the stratospheric temperature signal.

3.2.2 Other cloud responses to seeding

The anomalies of cCRE are almost a factor of two larger than the net TOA balance anomalies (Fig. 2) or net TOA CRE anomalies (Fig. 4) as evaluated from the fixed SST setup, where the TOA radiative fluxes do not reach a new equilibrium. The additional diagnostics of liquid and mixed-phase CRE (Table 5) point at additional cloud responses to cirrus geoengineering that exert a positive radiative forcing and thus weaken the effect of cirrus geoengineering. We note that the additional CRE decomposition is performed in fixed SST simulation setup which, however, leads to very similar cloud responses as in the corresponding MLO simulations.

The VEL2 simulation leads to a redistribution of ice from the cirrus to the lower lying mixed-phase regime, exerting a positive mixed-phase cloud forcing of about 0.5 W m^{-2} (Fig. 5~~l~~ q and Table 5). Changes in vertical stability ~~most likely~~ lead to an increase in midlevel convection and additionally contribute to the redistribution of ice. These changes are responsible for part of the increases in ICNC ~~due to detrainment~~ burden associated with the convectively detrained ICs (Fig. 4e and Fig. 5 v). The positive anomaly in RH at 5-10 km (Fig. 5g) is concentrated in and just above areas of vertical velocity increase (not shown), driven by changes in vertical temperature gradients (Fig. 5~~t~~o).

Furthermore, in SEED1r50 an increase ~~in~~ or intensification of convective activity, expressed by an 1.2% increase in globally averaged convective precipitation, leads to a drying of the tropical planetary boundary layer and lower troposphere and a decrease in liquid cloud cover (Fig. 5a)~~,~~. The cloud cover is directly related to RH (**?**); its decrease therefore leads to a cloud cover decrease, which decreases also the all-sky water content and CDNC (Fig. 6 a,c and Fig. 4e). This ~~leads to~~ exerts a positive liquid CRE anomaly (Table 5), similarly to what was found in studies by **?** and **?**. Interestingly, the shift from homogeneous to heterogeneous ~~nucleation of IC~~ ice nucleation leads to higher RH in the upper troposphere (Fig. 5f). The heterogeneous nucleation and growth timescale is several times longer than the homogeneous one (**?**), leading to slower vapour consumption by ~~deposition on IC~~ depositional growth on ICs at our optimal seeding concentration of 1 INP L^{-1}.~~Moreover, the IWC in~~

The sedimentation of ICs into mixed-phase ~~clouds is replaced by an increased liquid water content and a higher CDNC~~ clouds leads to the IC growth by riming of supercooled cloud droplets, also known as the seeder-feeder mechanism (**?**). The seeder-feeder mechanism, reinforced by the additional growth of ice crystals at the expense of supercooled cloud droplets (Wegener-Bergeron-Findeisen process (**?**)) leads to a depletion of CDNC and LWC. A decrease of ICs sedimenting flux from cirrus in SEED1r50 compared to REF therefore leads to an increase in CDNC and LWC in mixed-phase cloud regime. In the tropics, this process is contrasted by the large RH decrease (Fig. 5f), leading to a decrease in cloud cover (Fig. ~~6 a,c), in particular in the extratropics, where the convective activity is less frequent.~~ 5a), and consequently also a small and not significant decrease in all-sky CDNC and LWC in Fig. 6a.

By seeding cirrus clouds only at night (simulation SEED1r50N) we target their warming LW CRE and obtain a similar net TOA flux anomaly (-0.88 $\pm$ 0.36 W m^{-2}) without significantly perturbing the SW balance as in other simulations (Table 5). Despite obtaining a smaller annually averaged cCRE, the net radiative decrease at the TOA is similar to the one in the simulation SEED1r50 (Fig. 2c). SEED1r50N triggers only a small increase in convective activity (0.8% increase in convective precipitation compared with 2.8% in SEED1r50) and thus limits the drying of the boundary layer and the decrease of the liquid CRE (Table 5).

3.2.3 Cirrus cloud radiative effects and temperature

We separately diagnose ~~radiative effects of clouds at temperatures below -35°C~~ cirrus cloud radiative effects from the two MLO simulations (SEED1r50, VEL2) to evaluate the regions of highest seeding effectiveness. Both scenarios produce similar net cCRE anomalies, which follow the climatological pattern of cirrus cloudiness and their radiative impacts at the TOA, having the largest ~~impact~~ effect in the warm pool region, in storm tracks, and over orographic barriers (Fig. 7 a,b). In SEED1r50 the anomaly pattern shows an even more pronounced impact over mountain regions and the tropical warm pool than in VEL2, corresponding to regions dominated by homogeneously nucleated ~~IC~~ ICs (**?**).

Temperature anomalies in general follow the anomalies in cCRE and are about 30-40% larger over land than over the ocean (Fig. 7 d,e). Yet, the temperature anomaly in the Pacific warm pool area is an exception to this general trend, which needs to be addressed in future studies. Moreover, both scenarios have larger responses in high latitudes, with a cooling of almost 2°C in the annual average, similar to findings of **?** and **?**. The globally average surface temperature decrease is about 30% larger in VEL2 (-0.68 $\pm$ 0.13°C) compared with SEED1r50 (-0.49 $\pm$ 0.09 °C). The difference is likely explained by the larger surface forcing in VEL2 compared to SEED1r50 (-0.86 and -0.74 W m^{-2}, respectively), which is the result of a lower altitude of the maximum diabatic cooling anomaly in VEL2 (Fig. 5~~t~~o). The radiative response is further amplified by changes in precipitable water, acting primarily in the tropics (Fig. 4e), and the sea ice feedback in high latitudes (not shown).

Both cCRE and temperature anomalies have a strong seasonal cycle (Fig. 7 c,f). The cooling is particularly pronounced in the winter hemisphere, and can exceed 3°C in the Arctic or 2°C in the Antarctic winter. The high-latitude cooling is a combination of atmospheric geoengineering and the ice-albedo feedback. The two scenarios exhibit remarkably similar zonally averaged temperature responses with no significant differences.

Interestingly, the SEED1r50N scenario leads to a 0.1°C larger globally averaged surface temperature cooling effect with a similar seasonality (Fig. 8a). The SEED1r50N scenario is more effective in the tropical deep convective areas, which probably originates from differences in the response of liquid clouds (in SEED1r50 the liquid clouds have a positive CRE anomaly, Table 5). The mid and high latitude temperature anomaly pattern likely ~~reflects~~ reflect changes in extratropical interannual climate variability modes. Most notably, we observe a significant Arctic cooling and warming in the northern hemispheric midlatitudes (Fig. 8 b,c), associated with a pressure decrease over the Arctic and increase over most of the midlatitudes (not shown), resembling a positive Northern Annular Mode temperature signal (**?**).

3.3 Alternative modelling strategies to increased sedimentation velocity

The INP seeding setup, as opposed to the increased sedimentation velocity setup, does not allow modifications of lower lying liquid origin cirrus clouds, which are mainly dynamically controlled anvils of convective clouds (**?**). Such clouds most likely cannot be influenced by seeding as they are less sensitive to changes in microphysics. The temperature of the boundary between liquid origin and in situ cirrus is also latitudinally dependent: a study by **?** suggested this boundary to be rather close to -70°C in the tropics, with -50°C being more representative for the midlatitudes (**??**).

In order to bridge the gap between increased sedimentation velocity and seeding simulations we performed an additional simulation using a lower temperature threshold of -50°C to modify prevalently in situ formed cirrus (VELmax-50). However, a large proportion of cirrus clouds that strongly influence the global radiative budget resides in the temperature range between -35°C and -50°C. The CRE of cirrus clouds colder than -50°C is only 1.7 W m^{-2} as compared to the 4.4 W m^{-2} for all cirrus clouds according to our model (Table 3). Therefore, we need to set the sedimentation velocity of ~~IC~~ ICs at temperatures lower than -50°C to the maximum allowed by the model (2 m s^{-1}) to obtain a similar, but still with -0.4°C significantly smaller globally averaged cooling effect. Simulation VELmax-50 approximately reproduces the SEED1r50 cloud cover anomaly pattern (Fig. 5 a,d,e) and upper tropospheric temperature anomalies (Fig. 5 ~~p,s,t~~k,n,o). However, in simulation VELmax-50 the IWC at temperatures warmer than -50°C increases substantially (Fig. 5~~n~~s), leading to an increase in the ICNC and IWP (Fig. 4e). The ICNC increases even at the tropical tropopause (Fig. 5 x), which is a microphyiscal response to a decrease of temperature for up to 2°C in the same region (Fig. 5 n) and can be eliminated by nudging the temperature in the seeded simulation to the reference simulation values (not shown).

Interestingly, VELmax-50 exerts a smaller radiative flux and temperature perturbation but a fast precipitation response comparable to the one in the VEL2 simulation (Fig. 4 a,b). Both the large fast precipitation response and the smaller temperature decrease lead to an overall net small and not statistically significant precipitation increase in the MLO simulation setup, differently from other simulations (Fig. 4d).

We additionally performed ~~a test~~an arguably more physical simulation, in which the IC sedimentation velocity is increased for ~~all IC~~ both ICs at temperatures warmer and colder than -35°C (VEL2all, see Table 1). VEL2all leads to strikingly similar radiative and precipitation responses as in the VEL2 and SEED1r50 simulations, inducing a slightly larger surface cooling effect (Fig. 4d). Interestingly, in VEL2all IWC decreases throughout the atmosphere only in the extratropics. Its tropical mid-tropospheric IWC increase is likely caused by a convective activity increase (convective precipitation ~~increase of~~ increases by 1.4%), resulting in a similar RH anomaly peak at 7-10 km altitude as in the VEL2 simulation (Fig. 5 g,h). These changes in ~~tropical~~ deep and mid-level convection, which lead to a large number of small ~~IC (?)~~ ICs are also responsible for an 8% increase in ICNC burden despite a 6% decrease in IWP. ~~Yet,~~ The surprising result can be explained by the parametrization of the size of the detrained ICs, which assumes an IC radius of about 10-20 μm (**?**), distributing the detrained IWC over a large number of ICs and is part of the reason for the ICNC increase pattern in mixed-phase cloud conditions (Fig. 5w). Moreover, the freezing in mixed-phase clouds in our model occurs only rarely in situ onto dust or black carbon aerosols and is largely affected by the sedimented ICs from cirrus levels, initiating a seeder-feeder type of IC growth.

Yet, neither VEL2all ~~cannot reproduce the same~~ nor any other cirrus geoengineering method with increased IC sedimentation velocity can reproduce the magnitude of cloud cover and temperature changes induced by seeding with effective ~~INP~~INPs. Our simulations show that idealised cirrus seeding simulations by means of increased sedimentation velocity are not a good proxy for cloud macro- and microphysical changes. Nevertheless, simulations with increased IC sedimentation velocities can still provide useful information ~~on~~ for some climatic responses (e.g. surface temperature, precipitation) to cirrus seeding.

4 Conclusions

We studied the climatic responses to cirrus seeding and to increased sedimentation velocity of ice crystals in cirrus clouds. In general, the increased sedimentation velocity simulation (VEL2) leads to qualitatively similar responses compared to cirrus seeding with large ~~INP~~ INPs (SEED1r50): a decrease in cloud cover and ice water content at cirrus levels, and a temperature decrease throughout the troposphere. ~~Ice cloud radiative effects and temperature responses are larger over land than over oceans. The pattern is particularly pronounced in the simulation SEED1r50.~~

~~The mean climatic responses of both the SEED1r50 and~~ However, in VEL2 ~~simulations in terms of radiative fluxes are also similar. However, seeding by INP interacts with clouds and cloud microphysics differently compared with the increase in sedimentation velocity, implying a different atmospheric temperature response. The different vertical cooling patterns lead to a 30% larger surface temperature response in the VEL2 simulation. As the surface temperature response pattern in the annual and seasonal averages is similar, we expect to achieve the same amount of surface cooling by a smaller increase of~~ the IC sedimentation velocity ~~. Moreover, precipitation responds to both geoengineering strategies in a similar way. The fast responses to seeding yield a ∼1% increase in precipitation, while the slow, temperature driven response in the mixed layer ocean simulations leads to a 0.5% decrease.~~

~~A large part of the cirrus induced negative CRE is counteracted by decreases in liquid clouds in the SEED1r50 simulation in response to increased convective activity. In addition, the redistribution of ice to lower levels in VEL2 leads to a positive~~ is abruptly set back to the standard one computed by the model at temperatures warmer than -35°C, leading to a redistribution of ICs and IWC from cirrus to underlying mixed-phase ~~cloud CRE anomaly.~~ clouds, which is not observed in SEED1r50. Our general findings therefore indicate that increasing sedimentation velocity is a good proxy for cirrus seeding surface climate responses, while it cannot reproduce the complex cloud macro- and microphysical responses. The additional simulations with increased sedimentation velocity for all ice crystals (VEL2all) or only for those at T<-50°C (VELmax-50) also cannot reproduce all the seeding signals from the seeding scenario. An accurate evaluation of atmospheric changes of cirrus thinning therefore requires the implementation of a cirrus microphysics scheme that is able to simulate the competition between homogeneous and heterogeneous ice crystal nucleation.

~~Our work moreover shows the non-negligible positive liquid CRE response, counteracting~~

The maximum impact on TOA radiative fluxes by the increase of ice crystal sedimentation velocity is -2.2 $\mathrm{W\,m^{-2}}$, which corresponds to about half of the ~~original cirrus CRE signal.~~ cirrus CRE and half of the radiative forcing of doubling of CO_2. The maximum impact of seeding with effective INPs is, on the other hand, only about -1 $\mathrm{W\,m^{-2}}$ or 20-25% of cirrus CRE, which is achieved by injecting large ice nucleating particles of 50 μm radius in the SEED1r50 simulation.

A large part of the cirrus geoengineering induced negative CRE is counteracted by decreases in liquid clouds in the SEED1r50 simulation in response to increased convective activity. In addition, the redistribution of ice to lower levels in VEL2 leads to a positive mixed-phase cloud CRE anomaly. As shown in Fig. 2, implementing seeding only during night leads to a comparable cirrus CRE and net radiative anomaly signal, without any significant counteracting effect from liquid or mixed-phase clouds (Table 5). Interestingly, such a seeding strategy leads to no significant fast precipitation response and smaller changes in IWP, ICNC, LWP, and CDNC compared to SEED1r50. ~~Despite seeding only half of the time, we obtain a slightly~~

The mean climatic responses of both the SEED1r50 and VEL2 simulations in terms of radiative fluxes are roughly similar. Yet, the microphysical differences between the two setups lead to a different vertical cooling patterns and a 30% larger surface temperature response in ~~its MLO simulation,~~ the VEL2 simulation. As the surface temperature response pattern in the annual and seasonal averages is similar, we expect to achieve the same amount of surface cooling by a smaller increase of IC sedimentation velocity. Moreover, precipitation responds to both geoengineering strategies in a similar way. The fast responses to seeding yield a ~1% increase in precipitation, while the slow, temperature driven response in the mixed layer ocean simulations leads to a 0.5% decrease.

The SEED1r50N strategy shows, despite seeding only in the night, a slightly larger surface temperature response and a twice ~~larger~~ as large precipitation decrease which follows more closely the temperature dependence of the Clausius-Clapeyron relation (7% precipitation decrease per 1°C cooling). SEED1r50N therefore seems to be, not considering its unlikely technical implementation, our most appealing seeding simulation due to minimal climatic and microphysical responses outside the cirrus regime~~, our most appealing seeding simulation.~~

~~The maximum impact on TOA radiative fluxes by the increase of ice crystal sedimentation velocity is -2.2 W m^{-2}, which corresponds to about half of the cirrus CRE and half of the radiative forcing of doubling of CO_2. The maximum impact of seeding with effective INP is, on the other hand, only about -1 W m^{-2} or 20-25% of cirrus CRE, which is achieved by injecting large ice nucleating particles of 50 μm radius in the SEED1r50 simulation~~. We note that a seeding strategy limited to areas of highest seeding effectiveness (where the cCRE anomalies after seeding are the largest, as shown by Fig. 7a), might significantly decrease the mass of seeded material while exerting a roughly similar climatic forcing.

The seeding effectiveness does not only depend on the seeding INP properties, but also on the relative frequency between both the in situ and liquid origin cirrus and homogeneously vs. heterogeneously in situ formed cirrus, which may differ between the model and observations and between different models. We also expect the cirrus seeding effectiveness to be dependent on the amount of background aerosol available for both homogeneous or heterogeneous freezing (**?**). Furthermore, the effectiveness of cirrus seeding measured in terms of radiative anomalies is highly dependent on the cirrus CRE and consequently also on model parameters that have a large effect on cirrus optical properties~~(e.g. inhomogeneity parameter for ice clouds).~~.

Ice cloud radiative effects are poorly constrained by observations on the global scale and rarely explicitly diagnosed from modelling studies. We suggest to invest more resources in understanding the cirrus cloud formation mechanisms and radiative effects at high temporal resolutions in order to better constrain CRE effects. Until then, we propose to not only state the radiative impact in terms of W m^{-2} achieved by cirrus geoengineering simulations (either by injection of seeding ~~INP~~ INPs or by increasing ice crystal sedimentation velocities) but also ~~to which~~ the fraction of the total cirrus ~~CRE this radiative anomaly corresponds~~cloud radiative effect that is eliminated by cirrus geoengineering.

5 Code availability

6 Data availability

The data from the model simulations are available from the authors upon request.

Author contributions. TEXT

Competing interests. TEXT

Disclaimer.

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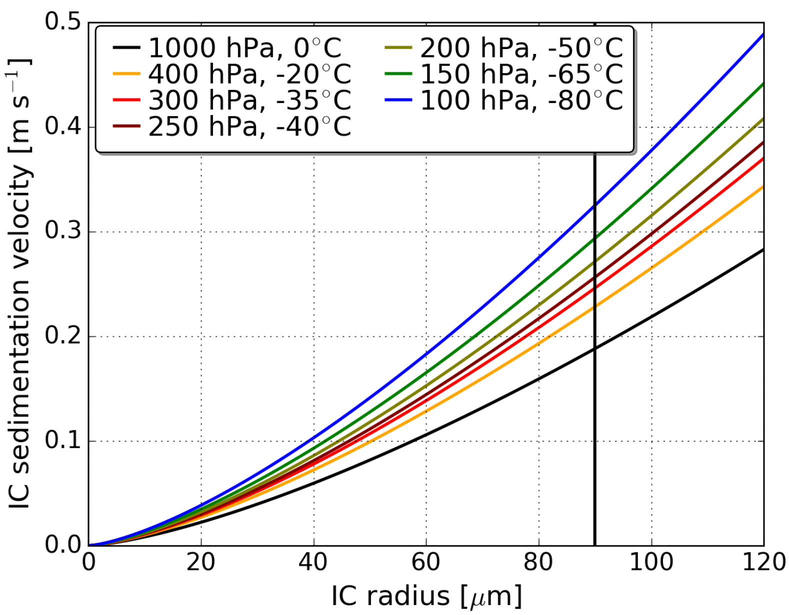

Figure 1. Ice crystal sedimentation velocities as a function of IC radius for the selected atmospherically relevant conditions in ECHAM-HAM (**?**). The black vertical line represents the maximum radius ice crystals can have before they are transferred to the precipitating snow category.

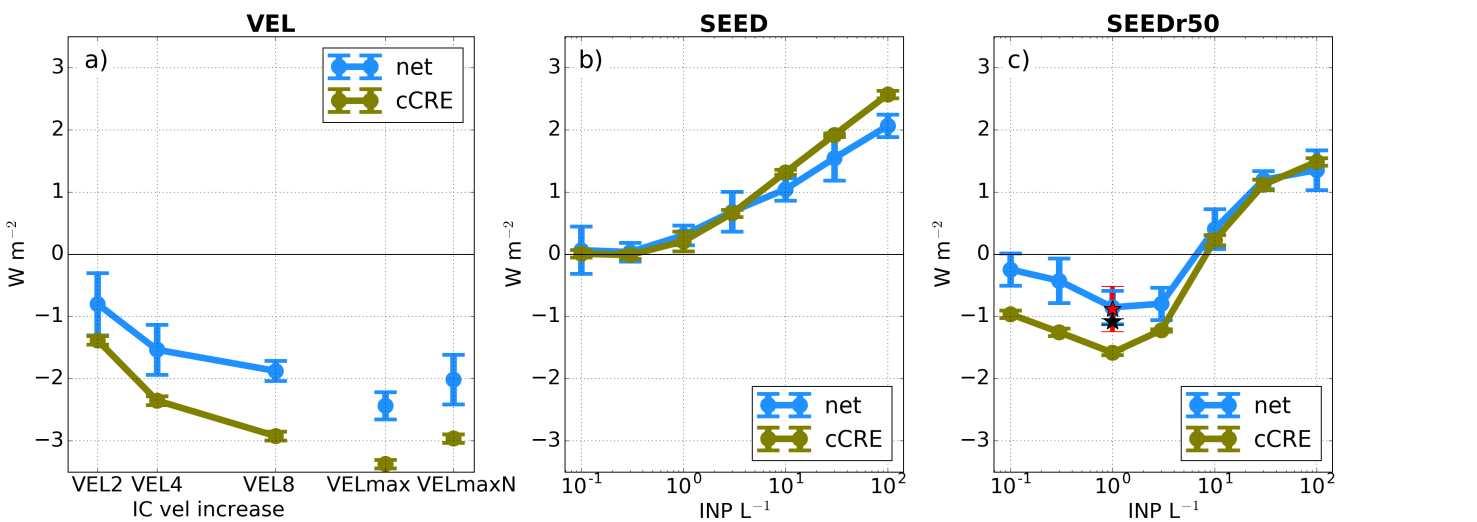

Figure 2. 5-year TOA anomalies of net radiative fluxes (NET) and net cirrus cloud radiative effects (cirrus CRE) ~~for~~ from fixed SST simulations of seeding with increased sedimentation velocities (a). b) shows net radiative fluxes and cirrus CRE for seeding simulations with different 0.5 μm sized ~~INP~~INPs, while c) shows the equivalent for seeding with 50 μm ~~INP~~INPs. The stars in c) show results from the SEED1r50N simulation with seeding performed only at night where the red star represents the net ~~anomalies~~ anomaly and the black one cirrus CRE ~~anomalies~~anomaly. The error bars represent $\pm$ 2 standard deviations.

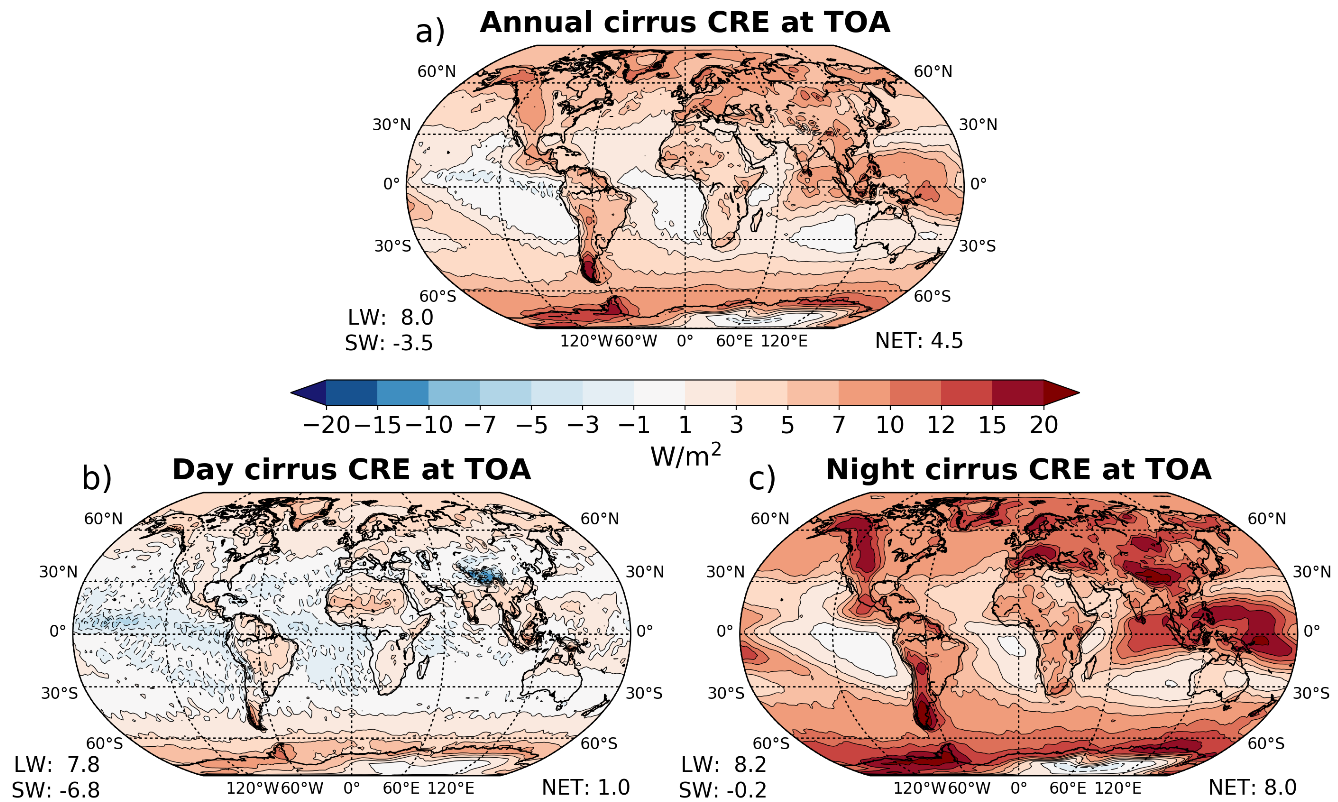

Figure 3. ~~Annually averaged~~ 5-year all-sky TOA anomalies of net cirrus cloud radiative effects (cirrus CRE) for ~~top-of-the-atmosphere~~ the reference (~~TOA~~unseeded) ~~energy fluxes~~ fixed SST simulation in annual average (a~~,c~~) ~~,~~ and ~~precipitation~~ when computed only during day ~~(P), temperature (T) (~~b~~,d~~) and ~~the selected microphysical quantities~~ night (~~e~~c)~~: liquid water path (LWP)~~. The day/night definition is based on the solar zenith angle, ~~ice water path (IWP), precipitable water (PWAT), ice crystal number concentration (ICNC), cloud droplet number concentration (CDNC)~~where day includes all gridboxes with the sun above the horizon. Panel (a) ~~and b) show anomalies of fixed SST simulations, c), d), and e) are~~ is reproduced with slight modifications from ~~mixed layer ocean (MLO) simulations~~**?**~~.The error bars represent the ± 2 standard deviation range.~~

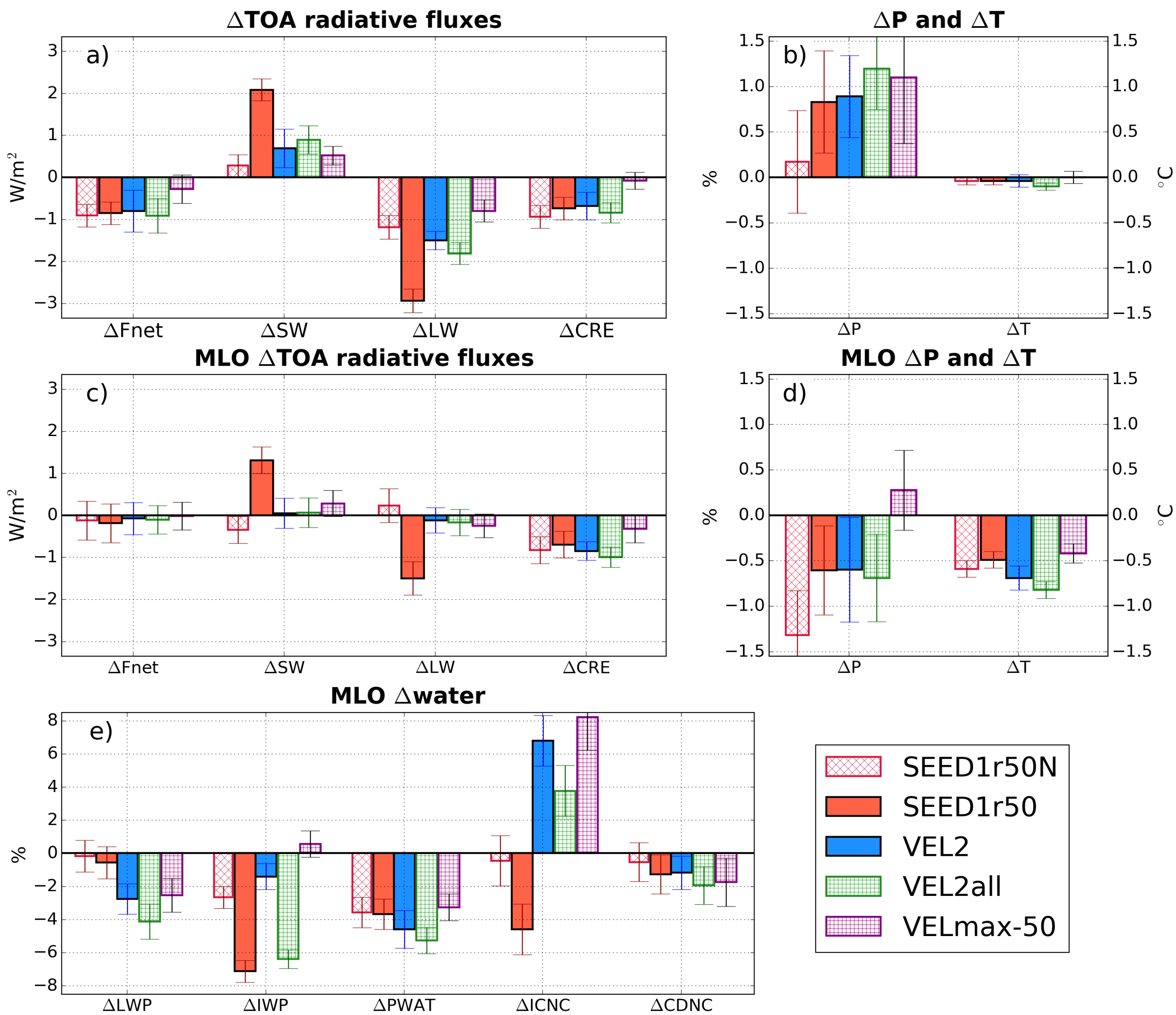

Figure 4. Annually averaged anomalies for top-of-the-atmosphere (TOA) energy fluxes (a,c), precipitation (P), and temperature (T) (b,d) and selected quantities of the hydrological cycle (e): liquid water path (LWP), ice water path (IWP), precipitable water (PWAT), ice crystal number concentration (ICNC), cloud droplet number concentration (CDNC). a) and b) show anomalies from fixed SST simulations, c), d), and e) from mixed layer ocean (MLO) simulations. The error bars represent the $\pm$ 2 standard deviation range.

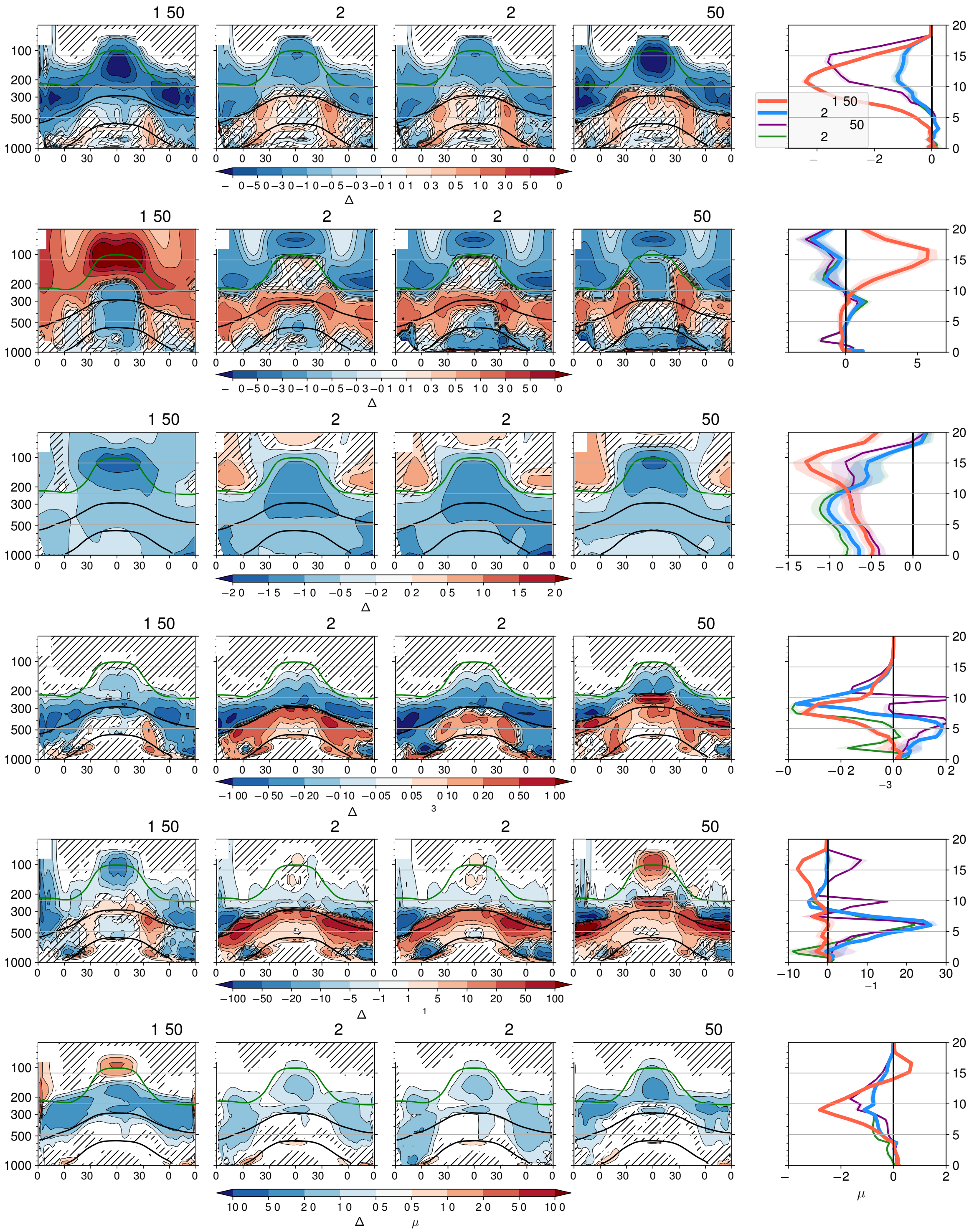

Figure 5. Annually averaged anomalies of cloud cover (Cldcov, a-e), relative humidity with respect to liquid water (RH, f-j), temperature (Temp, k-o), all-sky ice water content (IWC, ~~k-o~~p-t), all-sky ice crystal number concentration (ICNC, u-y), and ~~temperature~~ all-sky ice crystal effective radius (~~Temp~~REFFI, ~~p-t~~z-dd) for the SEED1r50 and VEL2 MLO simulations (see Table 1). The green curve represents the tropopause, ~~while~~ and the black curves ~~are~~ the -35°C and the 0°C isolines. The hatching is applied for anomalies not significant at the 95% confidence level. On the right hand the anomalies are averaged over latitude and longitude.

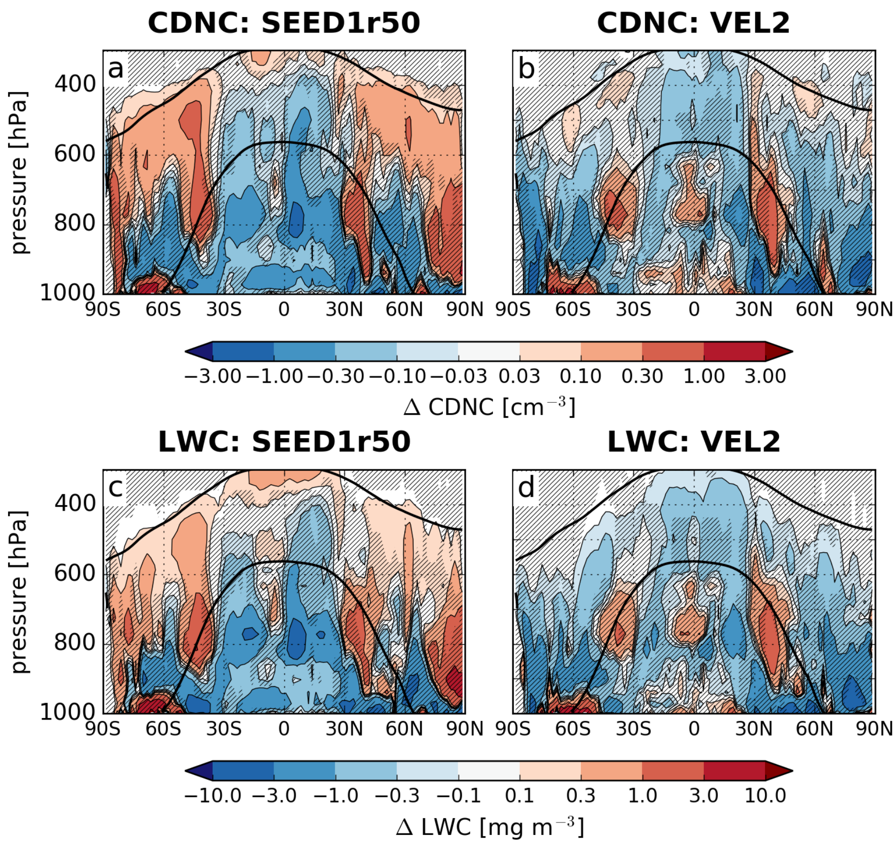

Figure 6. Annually averaged all-sky anomalies of the cloud droplet number concentration (CDNC, a,b) and liquid water content (LWC, c,d) for the SEED1r50 and VEL2 fixed SST simulations (see Table 1). The black curves are the -35°C and the 0°C isolines. The hatching is applied for anomalies not significant at the 95% confidence level.

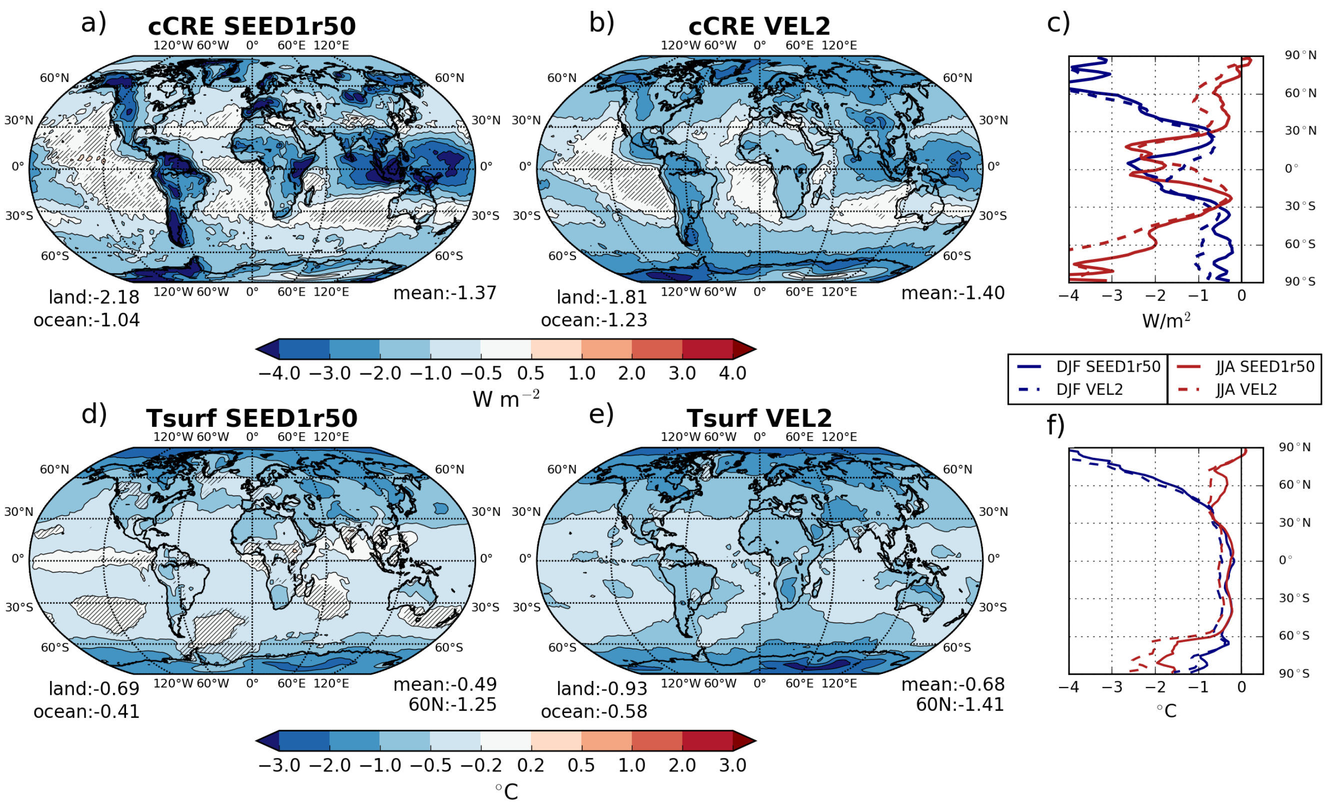

Figure 7. Annually averaged anomalies of cirrus cloud radiative effect (cCRE, a,b) and surface temperature (Tsurf, c,d) from the SEED1r50 and VEL2 MLO simulations. The hatching is applied for anomalies not significant at the 95% confidence level. Panels c) and f) show the respective annual zonal averages for DJF (blue) and JJA (red).

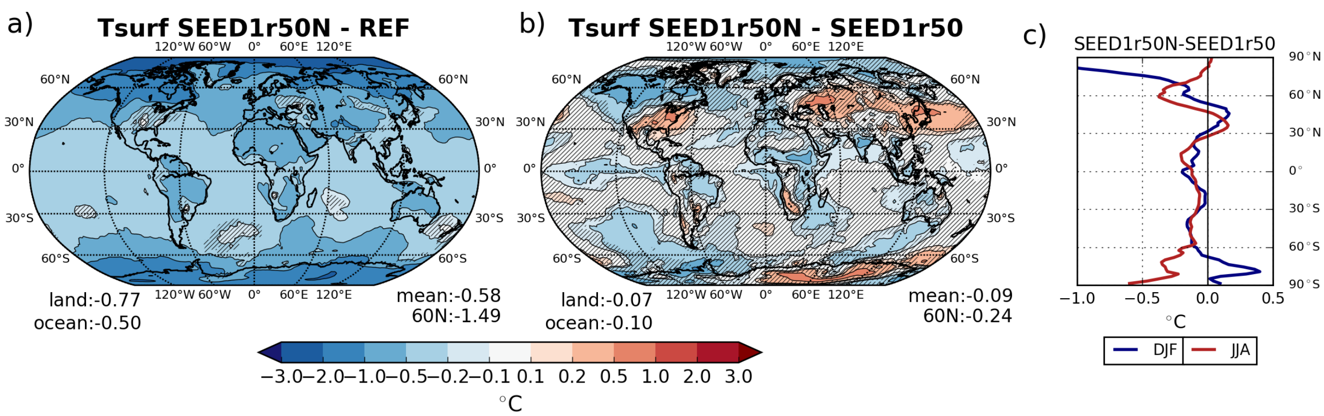

Figure 8. Annually averaged anomalies of surface temperature (Tsurf) for the SEED1r50N simulation ~~plotted in anomaly~~ with respect to REF (a) or SEED1r50 (b). The hatching is applied for anomalies not significant at the 95% confidence level. Panel c) shows the respective annual zonal average anomalies of SEED1r50N with respect to SEED1r50 for DJF (blue) and JJA (red). All simulations are performed in the MLO setup.

Table 1. Simulation terminology and their respective cirrus geoengineering method.

Simulation	Sim. length [y]	IC sedimentation	seed INP conc. [L^{-1}]	seed INP radius [μm]
fixed SST				
REF	10	/	/	/
VEL2	10	2 x ref	/	/
VEL4	5	4 x ref	/	/
VEL8	5	8 x ref	/	/
VELmax	5	set to 2 m/s	/	/
VELmaxN	5	set to 2 m/s at night	/	/
VEL2all	5	2 x ref (all ~~IC~~ICs)	/	/
VELmax-50	5	2 x ref (at T<-50°C)	/	/
SEED0.1	5	/	0.1	0.5
SEED0.3	5	/	0.3	0.5
SEED1	5	/	1	0.5
SEED3	5	/	3	0.5
SEED10	5	/	10	0.5
SEED30	5	/	30	0.5
SEED100	5	/	100	0.5
SEED0.1r50	5	/	0.1	50
SEED0.3r50	5	/	0.3	50
SEED1r50	10	/	1	50
SEED3r50	5	/	3	50
SEED10r50	5	/	10	50
SEED30r50	5	/	30	50
SEED100r50	5	/	100	50
SEED1r50N	10	/	1 at night	50
SEED1r5	5	/	1	5
SEED1r10	5	/	1	10
SEED1r20	5	/	1	20
Mixed layer ocean (MLO)				
REF	50	/	/	/
SEED1r50	50	/	1	50
SEED1r50N	50	/	1 at night	50
VEL2	50	2 x ref	/	/
VEL2all	50	2 x ref (all ~~IC~~ICs)	/	/
VELmax-50	50	2 x ref (at T<-50°C)	/	/

Table 2. Cirrus geoengineering CRE anomalies in W m^{-2} with respect to REF (first column) or with respect to the simulation with two times smaller ~~IC~~ ICs sedimentation velocities (second column) for fixed SST simulations. The last column represents the relative fraction of the cirrus cloud radiative effect (cCRE) anomaly with respect to the remaining cCRE.

	ΔcCRE [W m^{-2}]	**Δ remaining cCRE [W m^{-2}]**	**Δ remaining cCRE [%]**
VEL2	-1.43	-1.43	-33%
VEL4	-2.40	-0.97	-33%
VEL8	-2.98	-0.58	-30%

Table 3. Net cirrus cloud radiative effects (cCRE) from the fixed SST REF simulation of all clouds at temperatures colder than the one stated in the left column. The right column represents the percentage contribution to the total cCRE.

Temp [$^\circ$C]	**cCRE [W m^{-2}]**	**percentage [%]**
-35	4.35	100
-40	3.42	79
-45	2.49	57
-50	1.73	40
-55	1.22	28
-60	0.83	19
-65	0.53	12
-70	0.34	8

Table 4. Top-of-the-atmosphere net radiative balance (F_{net}) anomalies in W m^{-2} for cirrus seeding with 1 INP L^{-1} with varying INP radius and the $\pm$ 2 standard deviation range for fixed SST simulations.

	SEED1	**SEED1r5**	**SEED1r10**	**SEED1r20**	**SEED1r50**
ΔF_{net} [W m^{-2}]	0.30 ± 0.30	0.01 ± 0.44	-0.03 ± 0.41	-0.46 ± 0.14	-0.85 ± 0.40

Table 5. Top-of-the-atmosphere net cloud radiative effect anomalies of cirrus geoengineering with the individual contributions from cirrus clouds (cCRE, for temperatures <-35°C), mixed-phase clouds (mpCRE, -35°C $<$ T $<$ 0°C), and liquid clouds (liqCRE, T $>$ 0°C) for the VEL2, SEED1r50, and SEED1r50N fixed SST simulations. The radiative anomalies are further divided into their LW and SW components (shown in parenthesis).

simulation	**ΔliqCRE** (LW, SW) [W m^{-2}]	**ΔmpCRE** (LW, SW) [W m^{-2}]	**ΔcCRE** (LW, SW) [W m^{-2}]	**ΔtotCRE** (LW, SW) [W m^{-2}]
VEL2	0.09 ± 0.38 (0.02, 0.07)	0.41 ± 0.12 (0.82, -0.42)	-1.43 ± 0.06 (-2.02, 0.60)	-0.84 ± 0.41(-1.47, 0.63)
SEED1r50	0.96 ± 0.25 (0.00, 0.96)	0.15 ± 0.10 (0.24, -0.10)	-1.63 ± 0.03 (-2.47, 0.84)	-0.82 ± 0.31 (-2.90, 2.08)
SEED1r50N	0.15 ± 0.14 (0.01, 0.14)	0.18 ± 0.18 (0.13, 0.04)	-1.06 ± 0.03 (-1.07, 0.02)	-0.95 ± 0.20 (-1.21, 0.26)