Cirrus cloud thinning using a more physically-based ice microphysics scheme in the ECHAM-HAM GCM (acp-2021-685)

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Referee #2 Author Response

Thank you for taking the time to review our manuscript and for providing useful comments on improving this study. We have quoted each of your comments below with our response.

1. **Comment:** Line 197-199: If you are using the Karcher et al 2006 method to represent ice nucleation, which includes water vapor consumption, why is there a need to add a downdraft to update the water vapor consumption? More explanation is needed here.
    a. **Response:** The cirrus model works such that changes to the ice saturation ratio (S_i) only occur by the updraft. Therefore, we need some way of altering this variable to account for the effect of water vapor consumption during ice formation events or onto pre-existing ice crystals in a single cirrus model timestep. We calculate an updated updraft velocity every cirrus model timestep, with the deposited water vapor accounted for by the fictitious downdraft. Although the amount of water vapor consumption in one cirrus timestep may not completely deplete ice supersaturation (and therefore shut off further ice formation/growth), the consumption will alter the way the updraft evolves and therefore how the S_i evolves in subsequent cirrus model timesteps. We altered the text to make this clearer for readers.
    b. **Changes in the text at lines 191-194, and 196-198:**

"… The scheme uses a sub-stepping approach to simulate the temporal evolution of ice saturation during the formation-stage of a cirrus cloud. This is achieved by calculating the balance between the adiabatic cooling of rising air, with the associated saturation increase, and the diffusional growth of ice particles that consume the available water vapor. …

As the magnitude of the ice saturation ratio is determined only by the vertical velocity, a fictitious downdraft is introduced at the end of each timestep of the cirrus scheme to quantify the effect of water vapor consumption during new ice formation events or onto pre-existing ice particles (Kuebbeler et al., 2014). The updated vertical velocity therefore determines the evolution of the ice saturation ratio in sub-sequent sub-timesteps. …"

2. **Comment:** Line 219-220: What is the time step in the cirrus scheme that is referred to here? Is it the 7.5 min time step or the sub-stepping time step? The latter would be more accurate.
    a. **Response:** The cirrus model uses variable sub-stepping that is based on the 7.5 minutes of the model timestep but is calculated according to how S_i will evolve with the input updraft velocity such that changes in S_i equate to 1% for each cirrus model timestep. The cirrus timestep is

updated to 1 second after a threshold freezing process, like homogeneous nucleation, to better "capture the details after the nucleation event" (Münch, 2020) and then readjusted back to a longer timestep after the next cirrus timestep.

We added the detail of the dynamic sub-stepping to the text for clarity.

b. **Change in the text at line 220:**

"The sub-stepping approach in the cirrus scheme is computed dynamically based on a 1.0 % rate of change of the ice saturation ratio between each sub-timestep."

3. **Comment:** Lines 221-240: It would be useful to add a table summarizing the different ice nucleating properties, the sizes included, their ice saturation for nucleation and whether the AF treatment is used.
   a. **Response:** This is a great idea. Please find an example of the proposed table below that we will include in the revised manuscript, with the last column indicating whether freezing occurs using active fraction (continuous) or through a threshold process, which is explained in more detail in the text.

Particle Type	Radius	Critical S_i	Freezing Mechanism	Freezing Method
Insoluble dust	0.05 – 0.5 μm	Temperature-dependent, but > 1.1	Deposition nucleation	Continuous
	> 0.5 μm	Temperature-dependent, but > 1.2		
Soluble dust	> 0.05 μm	1.3	Immersion freezing	Threshold
Aqueous Sulphate	All size modes from < 0.005 μm to > 0.5 μm	~1.4	Homogeneous nucleation	Threshold

4. **Comment:** Lines 253-255: Can you explain a bit more here? What is RHi becomes 100% under a heterogeneous ice simulation?
   a. **Response:** This refers to the default saturation adjustment approach, where any ice supersaturation used to form new ice particles is adjusted down to ice saturation (RH_i = 100%) for the cloud fraction parameterisation and a cirrus cloud is assumed to fully cover a gridbox. With D19, this is no longer the case, as it allows for partial cirrus cloud fractions above ice saturation. We changed the example in the text to explain the difference between the two schemes more clearly. We also added text that provides more description in line with Figure 1 to make it clearer for readers.
   b. **Changes in the text at lines 244-246, 251-255, and 256-258:**

"… This formulation works well for warm clouds, but as Kuebbeler et al. (2014) and Dietlicher et al. (2018, 2019) note, it breaks down for mixed-phase clouds (T < 273 K) that may or may not include ice, presenting a difficult choice between RH with respect to liquid (RH_l) or ice (RH_i) to determine cloud fraction. …

… Dietlicher et al. (2019) updated the cloud fraction formulation for pure ice clouds to differ from liquid clouds by updating the RH conditions in which an ice cloud can partially cover a gridbox. In this new scheme (hereafter, D19) that we use in this study, ice saturation (S_i= 1.0) is set as the lower boundary condition for partial ice cloud fractions. The upper boundary condition for full gridbox coverage for ice clouds is set following the theory for homogeneous nucleation of solution droplets by Koop et al. (2000). …

… As a contextual example, if ice were to form at 233 K in an environment with S_i = 1.2, then D19 would calculate an ice cloud fraction <1.0, whereas S89 would adjust the ice supersaturation down to ice saturation and would produce a cloud fraction of 1.0."

5. **Comment:** Lines 265-267: This sentence needs more explanation. As it is now, I cannot understand what is being said.
    a. **Response:** This refers to the scaling introduced to the available aerosol concentrations. The sentence was changed to make it clear that we apply scaling to the available aerosol concentration for each freezing mode to account for the aerosol particles that already nucleated ice crystals in previous time steps. This is necessary as no in-cloud aerosol tracers are available. The scaling was updated to account for only the fraction of each mode out of the total pre-existing ice. Previously the scaling was applied such that the total pre-existing ice concentration was removed from all modes, which resulted in an overestimation of the in-cloud aerosol concentration and an underestimation of the interstitial aerosol concentration.
    b. **Change in the text at lines 265-269:**

"… The implementation of these tracers highlighted an error when accounting for the number of aerosols that previously nucleated ice. The aerosol concentration of each freezing mode of the cirrus scheme was scaled by the total amount of pre-existing ice. This approach overestimated the concentrations of in-cloud aerosols and underestimated the interstitial aerosol concentration. We updated the scaling of each mode aerosol concentration to account for the fraction of each mode out of the total pre-existing ice concentration. …"

6. **Comment:** Line 279: Here you say you have a fractional ice cover scheme, but Lines 253-255 states that there is no fractional cover. When and where do you have fractional ice cover?
    a. **Response:** Agreed. This is an inconsistency in the text, and it leaves out some important detail. The new D19 cloud fraction scheme allows for fractional cirrus coverage under ice formation conditions, as supersaturation is required. The default ECHAM S89 scheme would not allow this, where ice forming above ice saturation would be part of a cloud that would fully cover the gridbox. The manuscript was changed to clarify the description of the fractional ice-cloud cover

scheme related to your Comment 5 above. We also edited this line to remove ambiguity.

b. **Change in the text at line 279:**

"We performed cirrus seeding simulations using P3 with the cirrus scheme coupled to the new ice-cloud fraction approach (D19) described above."

7. **Comment:** Lines 316-318: It appears to me that the model is too high from 190-205K by about the same factor as too high from 230-240. Please correct.
   a. **Response:** We would argue that the disagreement between the model and the observations is not as consistent between 190-205K than it is between 230-240K. However, there is a noticeable difference and we amended the text to reflect that. In line with your next comment, we edited the text as well to note that the agreement above 240 K is better than the two temperature ranges quoted here but is slightly underpredicted.
   b. **Change in the text at lines 316-318:**

"… Model-median ICNC values agree rather well with the observational median at temperatures between roughly 205K and 230K. …"

8. **Comment:** Lines 319-321: Can you explain this statement better? Why do you think the finding is due to the dust immersion freezing rate? What aspect could cause this?
   a. **Response:** In Figure 2a we see that between 230 and 240 K the model overpredicts ICNC, whereas above 240 K the model slightly underpredicts ICNC. We declare the cirrus regime at 238 K. Therefore, the disagreement in these two temperature ranges could be linked to a mixed-phase process. The Villanueva et al. (2021) study we cite looked into one such process in ECHAM, mixed-phase dust immersion freezing. In that study they compared the ECHAM-default rate-based parameterization for dust immersion freezing to a new active fraction (AF) approach. They note that using the new AF approach in combination with a higher dust-INP efficiency leads to better agreement with satellite observations, as the default rate-based approach underpredicts the amount of ice formation by dust immersion freezing in the mixed-phase regime. This leads to weak ice formation and a higher availability of cloud droplets from the mixed phase regime to be advected into the cirrus regime where they can freeze homogeneously, leading to a high ICNC just below the homogeneous temperature limit (238 K). We believe that the ICNC patterns we find in the model compared to the Krämer et al. (2020) observations reflect this issue. Model ICNC is slightly underpredicted above 240 K due to a too-slow mixed-phase dust immersion freezing rate that allows more cloud droplets to be advected into the cirrus regime and form excess ice at temperatures between 230 and 240 K.
   b. **Change in the text at lines 319-327:**

"… The small disagreements in these two temperature ranges may be linked to the default parameterization for heterogeneous nucleation on mineral dust particles in mixed-phase clouds in ECHAM. The results by Villanueva et al. (2021) offer an explanation in this regard. In their study, they conducted several sensitivity tests with ECHAM-HAM using the default rate-based immersion freezing scheme by Lohmann and Diehl. (2006) and a newer AF approach based on dust particle surface area and active site density. They found better agreement with satellite-based observations using the AF approach in combination with higher dust particle freezing efficiency as compared to the default rate-based approach, and noted an under-prediction of mixed-phase ice with the latter that led to a higher abundance of cloud droplets being transported into the cirrus regime where they could undergo homogeneous nucleation. …"

9. **Comment:** Lines 394-395: How can the change in ICNC (200 / L) be larger than the seeding number of 100?
    a. **Response:** The zonal anomalies we are presenting are the ICNC tracers we implemented into the model. The anomaly value can exceed the concentration of seeding particles for two reasons. Firstly, we use a simplified uniform seeding method in our model that does not include seeding-INP budgeting. This means that at every cirrus model timestep the same number of INPs is available and will activate if the S_i value is sufficient. This means we can achieve much higher ICNC values out of the cirrus scheme than the number of available seeding particles. Secondly, the ICNC variables are passed from the cirrus model to the microphysics scheme where they can be advected and/or undergo growth/shrink processes. With the anomaly value being so high, this also indicated that seeding at this concentration leads to more and smaller ice crystals that do not sediment out of the cirrus regime, but rather remain and increase the total ICNC. The combination of these two factors feeds into the overseeding response we find. We added a description related to the first point to the Experimental Setup section in the text to make this clearer for readers.
    b. **Change in the text at Line 286-288:**

"… For both model configurations (see Table 2) we implemented seeding particles as an additional heterogeneous freezing mode in the cirrus ice-nucleation scheme continuously at every timestep, following on from previous approaches (i.e. without accounting for those that already formed ice). Only gridboxes that are supersaturated with respect to ice (i.e. $S_i > 1.0$) are seeded. …"

References

1. Münch, S., Development of a two-moment cloud scheme with prognostic cloud fraction and investigation of its influence on climate sensitivity in the global climate model ECHAM., *Doctoral Thesis*, https://doi.org/10.3929/ethz-b-000454801, 2020.
2. Villanueva, D., Neubauer, D., Gasparini, B., Ickes, L., and Tegen, I.: Constraining the Impact of Dust-Driven Droplet Freezing on Climate Using Cloud-Top-Phase Observations, Geophysical Research Letters, 48, https://doi.org/https://doi.org/10.1029/2021GL092687, 2021.