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

Colin Tully, David Neubauer, Nadja Omanovic, and Ulrike Lohmann
8th July 2022

Author Responses

Dear Prof. Liu

On behalf of all coauthors, thank you once again for taking the time to handle our manuscript for publication in ACP. I have quoted your comments below with our responses. You will see our changes in the tracked changes PDF.

Sincerely,
Colin Tully

Main Text & Abstract:

1. **Comment:** Line 13: "artificial ice-cloud expansion upon ice nucleation". it is unclear, what you mean "ice-cloud expansion upon ice nucleation". ice cloud fraction increase?
    a. **Response:** Agreed, this is unclear for an abstract, we amended the text in the manuscripts to make this clearer
    b. **Changes in the text at line 13:**

"The most notable response from our extreme case is the reduction of the maximum global-mean net top-of-atmosphere (TOA) radiative anomalies from overseeding by about 50%, from 9.9 Wm^{-2} with the original cloud fraction approach, down to 4.9 Wm^{-2} using the new cloud fraction RH thresholds that allow partial gridbox coverage of cirrus clouds above ice saturation, unlike the original approach."

2. **Comment:** Line 20. "In response, we examined the TOA responses..." There are two "respone" in this sentence. please improve.
    a. **Response:** Thank you for finding this. We changed the second "responses" to "anomalies".
    b. **Changes in the text at Line 20:**

"In response, we examined the TOA anomalies regionally and found that specific regions only show a small potential for targeted CCT, which is partially enhanced by using the larger $S_{i,seed}$."

3. **Comment:** Lines 124-127, 145-146, and 772-774. The large differences in the outcome of CCT studies between ECHAM and CESM-CAM5 is mainly due to the treatment of ice nucleation in cirrus clouds in the two models. While the manuscript introduces the ice nucleation scheme and preexisting ice treatment in ECHAM, the authors may need to refer the related cirrus schemes in CESM-CAM5 to help understanding. For example, the ice

nucleation in CAM5 is based on Liu and Penner (2005) which treats both homogeneous and heterogeneous ice nucleation, and also includes the preexisting ice treatment (Shi et al., ACP, 2015). CAM5 has a high frequency of homogeneous ice nucleation. The authors may add some discussion of cirrus cloud states simulated in CAM5 to better explain the differences from ECHAM.

a. **Response:** Based on our search and a review of the literature, all CCT studies to date with CAM5 (Storelvmo et al. 2013; Storelvmo and Herger 2014; Storelvmo et al., 2014; Penner et al., 2015; Gasparini et al., 2020) used the cirrus ice microphysics scheme by Barahona and Nenes (2008, 2009). Only Storelvmo et al. (2013) "partly replaced" the older scheme by, as they quote, Liu et al. (2007) with the scheme by Barahona and Nenes (2008, 2009). Therefore, we based our discussion in the revised manuscript on the Barahona and Nenes (2008, 2009) scheme, with reference to Liu and Penner (2005). In addition, Penner et al. (2015) were the only ones using CAM5 with pre-existing ice in some of their simulations, following Shi et al. (2015) as you cite above. This made a difference in the outcome of CCT compared to CAM5 simulations that did not include pre-existing ice. As Gasparini et al. (2020) state CAM5, being part of the wider CESM1 that was used for studying CCT to date, does not include pre-existing ice, whereas CESM2 does. We agree that some more detail can be provided about the differences in cirrus microphysics in CAM5 and ECHAM6, as this is a large point of uncertainty in determining CCT efficacy. The largest difference between the two models is the inclusion of pre-existing ice as we describe above. Moreover, in studies using ECHAM6, the impact of cirrus seeding is to produce some new cirrus clouds, whereas this does not appear to be the case with CAM5. We also argue that a full review of the specific parameterizations governing homogeneous and heterogeneous nucleation within cirrus clouds in the two models is beyond the scope of this specific study, but some short reference to this was added. Therefore, for brevity, we added this discussion only to the discussion section and moved some related text from the conclusions to avoid repetition.
b. **Changes made in the text from Line 770 in the Discussion and Line 837 in the Conclusions:**

<u>*Discussion*</u>
"Additionally, there are still large differences in the outcome of CCT studies between the two leading climate models that at the time of writing were used to study CCT globally, ECHAM6-HAM2 (ECHAM) and CESM1-CAM5 (CESM) (Storelvmo et al., 2013; Storelvmo and Herger, 2014; Storelvmo et al., 2014; Penner et al., 2015; Gasparini and Lohmann, 2016; Gasparini et al., 2017, 2020). Such differences can be partially attributed to a lack of reliable remote sensing measurements and in-situ observations of cirrus in order to constrain models, though this gap is starting to be closed with more recent studies (Krämer et al., 2016; Sourdeval et al., 2018; Gryspeerdt et al., 2018; Krämer et al., 2020).

Gasparini et al. (2020) were the first to present a comparative analysis of CCT between the two models. They noted a much higher cooling potential of CCT in CESM than in ECHAM

(−1.8 Wm^{-2} versus −0.8 Wm^{-2}). This is in part due to the different cirrus ice microphysics scheme used in either model. CCT studies using CAM5 to date follow the scheme by Barahona and Nenes (2008, 2009) that explicitly links the number of ice crystals formed from nucleation events to the dynamical environment as well as to the properties of the available INPs (i.e. number, size, freezing threshold). This scheme replaced an earlier one by Liu and Penner (2005) that was based on classical nucleation theory for ice formed by deposition or immersion freezing on mineral dust and soot particles, respectively (Liu et al., 2007; Barahona and Nenes, 2009; Liu et al., 2012). CCT studies using ECHAM6, including this study, also use a cirrus ice nucleation scheme that resolves ice number dependence on aerosol properties that is based on the time integration of S_i by Kärcher et al. (2006), following updates made by Kuebbeler et al. (2014) and Muench and Lohmann (2020), (Section 2).

A notable difference between the two models is the inclusion of pre-existing ice particles in ECHAM, which are not included in the default version of CESM (Gasparini et al., 2020) nor in any CCT study using this latter model. The one exception is the study by Penner et al. (2015), who included pre-existing ice particles in some of their simulations, following Shi et al. (2015). They found no significant cooling by CCT in any of their cases where pre-existing ice particles were included in CESM, despite better agreement with observations of ICNC in the temperature range relevant for CCT than the cases without pre-existing ice particles (Penner et al., 2015). The inclusion of pre-existing ice acts to decrease the frequency of homogeneous nucleation in all cirrus clouds as more water vapor is consumed on these particles and prevents the development of high ice supersaturation. Therefore, the potential homogeneous-to-heterogeneous nucleation shift as a result of CCT is also reduced when pre-existing ice particles are considered. This is the case in ECHAM and explains why the "optimal" seeding particle concentration differs between the two models (1 L^{-1} for ECHAM versus 18 L^{-1} for CESM), (Gasparini et al., 2020). Almost any amount of cooling that was found in ECHAM as a result of CCT is smaller in magnitude than in CESM (Storelvmo et al., 2013; Gasparini and Lohmann, 2016; Gasparini et al., 2020), (with the notable exception of Penner et al. (2015), see above), or, as is this case with our results, is not evident (Figure 3). Moreover, for similar seeding particle concentrations (> 10 L^{-1}) ECHAM produces more numerous ice crystals, which contribute to new cirrus cloud formation or cirrus lifetime prolongation (i.e. an overseeding response) that lead to positive TOA anomalies (Figures 5 and 6, and Gasparini and Lohmann (2016)). In CESM, CCT in general leads to a reduction in cirrus frequency (Storelvmo et al., 2013; Storelvmo and Herger, 2014; Storelvmo et al., 2014; Gasparini et al., 2020) that is not present in ECHAM (Gasparini and Lohmann, 2016; Gasparini et al., 2020). While our results show a reduction in the frequency of the lowest cirrus clouds, we also find new cloud formation in previous clear-sky regions (Figure 4). Cloud fraction anomalies in our study are amplified by the slower ice removal when using the P3 scheme (as discussed above). This highlights differences between the cloud fraction approaches used in CESM (Slingo, 1987; Gettelman et al., 2010) and ECHAM (Sundqvist et al., 1989; Dietlicher et al., 2018, 2019), (Section 2).

Finally, inconsistent approaches also exist between studies using the same model. For example, in our study, we excluded the orographic gravity-wave vertical velocity parameterization by Joos et al. (2008, 2010), unlike Gasparini and Lohmann (2016). Verification of this approach is presented in Appendix A. In summary, we found that the orographic gravity wave paramaterization in its current form is incompatible with ECHAM6.3 when using the P3 scheme, and leads to worse agreement of median ICNC values between the model and the in-situ observations by Krämer et al. (2020). As gravity waves were found to be an influential component for cirrus ice nucleation competition (Jensen et al., 2016a), we argue that this incompatibility when using the parameterization by Joos et al. (2008, *2010) with the P3 cloud microphysics scheme should be investigated in greater detail in future work.”*

Conclusions

“Finally, based on our discussion, we extend the assertion by Gasparini et al. (2020) that a consistent CCT approach among climate modeling groups is needed, especially if the desire amongst the scientific community is to critically assess this proposed method as a feasible climate intervention strategy.”

4. **Comment:** Line 205. "updated cirrus ice nucleation schemes". do you mean "updated cirrus ice fraction scheme"?
    a. **Response:** That is a typo. Thank you for finding that. We meant only the scheme that simulates in-situ ice nucleation within cirrus, as quoted on Lines 187-188, with updates following Muench and Lohmann (2020). We amended the text to make this clearer.
    b. **Change in the text at line 205:**

“In summary, by using the new P3 ice microphysics with the in-situ cirrus ice nucleation scheme (Muench and Lohmann, 2020), including orographic effects acts to drastically increase cirrus ICNC while reducing spatial heterogeneity, in worse agreement with observations.

Appendix:

1. **Comment:** Line 812: Figure A2. why the model ICNC is so low (<10 L-1) in SH? this is different from Figure A3 (for homogeneously nucleated ice).
    a. **Response:** Thank you for finding this inconsistency in our appendix. The ICNC diagnostics we were using to compare to the DARDAR data were not prescribed correctly and, therefore, lacked some ice number data. We fixed this issue and re-ran our simulations and find much better agreement not only with the DARDAR data in Figure A2, but also with our cirrus ice number tracers in Figure A3.

2. **Comment:** Figure A1. Where and when the ice number in P3 Oro increases substantially near 202 K in Figure A1. Is this strong increase a result of increased vertical velocity?
    a. **Response:** Yes, this is due to the strong increase in vertical velocity that is used as input to our cirrus scheme, as shown in Figure A4 of the Appendix. Our cirrus model is based on the fundamental theoretical work by Kärcher and Lohmann (2002) on homogeneous nucleation. Their study found a strong link between the strength of the vertical velocity and the number of ice crystals formed following a homogeneous nucleation event. We find the same behavior in our model when activating the orographic vertical velocity parameterization by Joos et al. (2008, 2010), with a noticeable increase in ICNC at cold temperatures (Figure A2) that consists mostly of ice formed by homogeneous nucleation (Figure A3).

Minor comments:

1. Line 828. change "due" to "due to".
2. Line 843. two "terrain" here.
3. **Combined response:** thank you for finding these typos. These are amended in the text.

References

- Barahona, D. and Nenes, A.: Parameterization of cirrus cloud formation in large-scale models: Homogeneous nucleation, Journal of Geo-physical Research: Atmospheres, 113, https://doi.org/10.1029/2007JD009355, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/9002007JD009355, 2008. Barahona, D. and Nenes, A.: Parameterizing the competition between homogeneous and heterogeneous freezing in cirrus cloud formation – monodisperse ice nuclei, Atmospheric Chemistry and Physics, 9, 369–381, https://doi.org/10.5194/acp-9-369-2009, https://acp.copernicus.org/articles/9/369/2009/, 2009.
- Gasparini, B. and Lohmann, U.: Why cirrus cloud seeding cannot substantially cool the planet, Journal of Geophysical Research: Atmospheres, 121, 4877–4893, https://doi.org/10.1002/2015JD024666, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015JD024666, 2016.
- Gasparini, B., McGraw, Z., Storelvmo, T., and Lohmann, U.: To what extent can cirrus cloud seeding counteract global warming?, Environmental Research Letters, 15, 054 002, https://doi.org/10.1088/1748-9326/ab71a3, https://doi.org/10.1088%2F1748-9326%2Fab71a3, 2020.
- Joos, H., Spichtinger, P., and Lohmann, U.: Orographic cirrus in the global climate model ECHAM5, *Journal of Geophysical Research*, 113, https://doi.org/10.1029/2007JD009605, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JD009605, 2008.
- Joos, H., Spichtinger, P., and Lohmann, U.: Influence of a future climate on the microphysical and optical properties of orographic cirrus clouds in ECHAM5, *Journal of Geophysical Research: Atmospheres,* 115, https://doi.org/https://doi.org/10.1029/2010JD013824, https: //agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD013824, 2010.
- Kärcher, B. and Lohmann, U.: A parameterization of cirrus cloud formation: Homogeneous freezing of supercooled aerosols, Journal of Geophysical Research: Atmospheres, 107, AAC 4–1–AAC 4–10, https://doi.org/10.1029/2001JD000470, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001JD000470, 2002.
- Liu, X. and Penner, J. E.: Ice nucleation parameterization for global models, Meteorologische Zeitschrift, 14, 499–514, https://doi.org/10.1127/0941-2948/2005/0059, http://dx.doi.org/10.1127/0941-2948/2005/0059, 2005.
- Liu, X., Penner, J. E., Ghan, S. J., and Wang, M.: Inclusion of Ice Microphysics in the NCAR Community Atmospheric Model Version1035 3 (CAM3), Journal of Climate, 20, 4526 – 4547, https://doi.org/10.1175/JCLI4264.1, https://journals.ametsoc.org/view/journals/clim/20/18/jcli4264.1.xml, 2007.
- Muench, S. and Lohmann, U.: Developing a Cloud Scheme With Prognostic Cloud Fraction and Two Moment Microphysics for ECHAM- HAM, *Journal of Advances in Modeling Earth Systems*, 12, e2019MS001 824, https://doi.org/10.1029/2019MS001824, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS001824 , e2019MS001824 2019MS001824, 2020.

- Penner, J. E., Zhou, C., and Liu, X.: Can cirrus cloud seeding be used for geoengineering?, Geophysical Research Letters, 42, 8775–8782, https://doi.org/10.1002/2015GL065992, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015GL065992, 2015.
- Shi, X., Liu, X., and Zhang, K.: Effects of pre-existing ice crystals on cirrus clouds and comparison between different ice nucleation parameterizations with the Community Atmosphere Model (CAM5), Atmospheric Chemistry and Physics, 15, 1503–1520, https://doi.org/10.5194/acp-15-1503-2015, https://acp.copernicus.org/articles/15/1503/2015/, 2015.
- Storelvmo, T. and Herger, N.: Cirrus cloud susceptibility to the injection of ice nuclei in the upper troposphere, Journal of Geophysical Re-search: Atmospheres, 119, 2375–2389, https://doi.org/10.1002/2013JD020816, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JD020816, 2014.
- Storelvmo, T., Kristjansson, J. E., Muri, H., Pfeffer, M., Barahona, D., and Nenes, A.: Cirrus cloud seeding has potential to cool climate, Geophysical Research Letters, 40, 178–182, https://doi.org/10.1029/2012GL054201, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.11551029/2012GL054201, 2013. Storelvmo, T., Boos, W. R., and Herger, N.: Cirrus cloud seeding: a climate engineering mechanism with reduced side effects?, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 372, 20140 116, https://doi.org/10.1098/rsta.2014.0116, https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2014.0116, 2014.