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Atmospheric Chemistry and Physics
Discussions

# *Interactive comment on* "Influence of heterogeneous freezing on the microphysical and radiative properties of orographic cirrus clouds" *by* H. Joos et al.

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Anonymous Referee #1

This manuscript aims to better understand the influence of heterogeneous freezing on the microphysical and radiative properties of cirrus using idealized cloud resolving model simulations of orographic cirrus clouds. The approach is to perform a set of 38 simulations where the homogeneous and heterogeneous nucleation mechanisms are tested individually and allowed to compete. In addition, the impact of ice nuclei concentrations, temperature, supersaturation threshold for heterogeneous nucleation



initiation, and solar zenith angle on the microphysical properties are examined. The ultimate goal is to improve the representation of cirrus in climate models through improved understanding of cirrus processes, though that is not specifically addressed in this study.

In general, the representation of cirrus in climate models is improving though there continues to be some areas of improvement needed primarily related to the representation of sub-grid scale processes. This study aims to partially address this issue by examining the variation in cirrus properties with different sub-grid processes. However, the findings are not really tied back to climate models but instead are presented as a sensitivity study to show which parameters have the largest impact on the microphysical properties and hence the cloud radiative forcing.

-We think that in order to improve parameterizations for climate models, the first step is to understand in detail which parameters do have an influence on the microphysical properties and the radiative forcing. We have chosen this idealized setup in order to investigate the dependence of the cloud forcing on various parameters in order to find out which processes have to be taken into account in order to simulate a realistic cloud forcing in climate models. We think that it is justified to publish results of such an idealized sensitivity study because it might help to improve the basic understanding of the interaction between dynamics, microphysics and radiation.

They conclude that orographic cirrus will have either a warming or cooling effect depending on IN concentrations, the cloud temperature, and the time of day that the cloud forms. This type of study has been performed previously for synoptic type cirrus, but not necessarily for orographic cirrus so in that sense the results are "new".

-There are other studies investigating the competing effect of heterogeneous and homogeneous freezing in cirrus clouds (see also references in the Introduction pages 3,4). However, most of them put the focus on the influence on the ice crystal number concentration. In our study we additionally investigate the impact on the cirrus cloud forcing and examine systematically a parameter space (freezing threshold, temperature, zenith angle) which has not been investigated like this in other studies. Furthermore it has been stated in other studies that heterogeneous freezing mainly competes with homogeneous freezing only for small updraft velocities (e.g. Sassen and Benson (2000) or Kärcher et al. (2006)). For our study we have chosen a setup which is characterized by high updraft velocities (∼1 m/s). Our findings differ from previous ones in a way that we show that even in this dynamically dominated regime, heterogeneous freezing can strongly modify the clouds radiative and microphysical properties.

However, the results are not really all that surprising because it is well known that the cloud radiative forcing depends strongly on the cloud microphysical properties (i.e. extinction) and hence homogeneous and heterogeneous nucleation will certainly produce different radiative effects depending on the ice crystal number concentrations produced.

-Of course it is well known that the cloud forcing depends on the microphysical properties. However, we do not know studies where the effect of changes in the microphysical properties due the competition of homogeneous and heterogeneous freezing is systematically investigated. The studies we know investigate mainly the effects of heterogeneous freezing on cirrus formation in global climate models. However this approach clearly differs from our sensitivity study where a certain parameter space is investigated with a high resolution model with detailed ice microphysics. Therefore we think that it is justified to perform such a detailed analysis.

The importance of these results might have been elevated if the authors provided some context regarding how the climate modeling community might utilize their results or suggested a path forward with specific links to climate models. Otherwise, the study by itself may not represent a significant advancement.

-We agree that it would be helpful for the climate modeling community if we could directly propose how to improve cirrus parameterization in GCMs. However, we are



convinced that the first step is a detailed understanding of the processes determining whether a cloud is in a warming or cooling regime. The aim of our study is to gain insight in the complex interactions of dynamics, microphysics and radiation in an idealized framework. These results might at one point be useful to improve the parameterization of cirrus clouds and their impact on radiation. However we think that it is justified to publish the results of an idealized study without proposing how to use these results in the context of climate modeling.

The model simulations and approach are reasonable and the presentation of results is generally good, though the text is somewhat wordy and the figures require some improvements. I would not be inclined to accept this paper unless significant changes are made to the presentation and discussion of results, as well as improvements to the significance of the results as they relate to climate models. I have made some suggestions and specific comments that will hopefully help to improve the manuscript.

Specific Comments: 1) The study focuses on orographic cirrus clouds. How prevalent are orographic cirrus and what impact do they have on climate? Are they primarily a regional phenomena or more important than that?

Dean et al. 2005 showed that cirrus clouds are quite prevalent over and in the lee of big mountain ranges (see figure 1 and 3 in their paper). By comparing regions where the formation of orographic gravity waves is quite probable with the regions of frequent cirrus occurrence they could show that orographically induced cirrus clouds are more than only a regional phenomena. Furthermore, as the ice crystals formed in the wave can survive also in subsaturated air, the ice crystals can be advected relatively far away from the formation region and therefore contribute to the cirrus cloud occurrence also in the lee of mountains.

2) P. 18073, Line 16-22: It maybe more succinct to state your objective in this way: “To understand the important contributors to sub-grid processes related to the interaction between dynamics, microphysics, and radiation, we investigate the role of nucleation

mechanism, ice nuclei concentration, temperature, and diurnal cycle in modulating the simulation of cirrus microphysical properties."

We changed that according to your suggestion.

3) P. 18075, Line25-26: You state that the model represents (simulates?) well the INCA measurements and therefore is suitable for orographic clouds. However, I don't recall that the INCA campaign was dominated by orographic clouds and maybe more representative of synoptic cirrus rather than orographic generated cirrus. Orographic cirrus will certainly have different composite microphysical properties than synoptic cirrus. If your model is tuned to INCA measurements, then I am not sure that the simulations are representative of orographic cirrus. Can you please clarify your meaning in this sentence and state what the expected ice number concentrations might be in orographic vs synoptic cirrus?

The simulation has been compared to measurements of an orographic cirrus cloud taken during the INCA campaign on 5th of April 2000. The measurements have been taken between 18 and 19 UTC on a flight track at 53°S. The simulation is driven by wind, temperature and pressure fields extracted from the ECMWF Reanalysis data at 18 UTC to the West of the Chilean Cost and a realistic topography for 53°S has been implemented in the model. The simulated PDF of the vertical velocities, ice crystal number concentration and ice water path agree well with the measurements of the orographic cirrus cloud. We therefore concluded that the model is able to simulate realistically orographic gravity waves and orographic cirrus clouds. As this is not clear from the text we added additional information (see p.7, l.20 f).

4) Figure 2. You state reference temperatures for the specific temperature profiles (229, 220, and 210 K). Can you state what these values refer to? Are they where we expect cloud top to be? You reference Joos 2009, but would be nice to give one sentence about these temperature profiles so that the reader can have a quick understanding without digging up other references.



The temperatures refer to the temperature inside the ISSR for the different temperature profiles. For the warm profile, the temperature inside the ISSR in a height of 9000 m = 229.9 K, for the reference 220.7 K and for the cold 210.1 K. The temperature profiles are now also briefly described in the text. We added additional information in the text (see p. 8, line 8)

5) I find myself flipping back and forth to compare figures in order to interpret the results. I wonder if it might be more efficient to combine similar figures to make the comparisons easier. For instance, I would suggest combining Fig. 4 and 7 to show side by side the cloud forcing results between HOM and 10IN simulations (such as two columns with three rows, column 1 has HOM and column 2 has 10IN results). Something similar could be done with Figures 3 and 5.

We combined Fig. 4 and 7 and Fig 3 and 5 to make them better comparable.

6) P. 18084, Line 12-13: "Cold temperatures lead to a decreased crystal growth rate. . ." I don't really agree with this statement. There are many factors that determine the growth rate and an important factor is the total surface area available to uptake water vapor, which is determined by the total ice crystal number that is nucleated. In your simulations, the HOM case produces the largest number of ice crystals at the coldest temperatures (driven by the cooling rates), which is expected. So indirectly the cold temperatures are impacting the size of the crystals because more crystals formed initially, and hence the growth of crystals is less due to a larger total surface area available to collect water vapor. I would suggest rewording this section and discussing more about the physical mechanisms than the indirect causes.

We agree that there are many factors influencing the growth of ice crystals. The chain of arguments is as follows: Diffusion is quite slow at low temperatures because of the low water vapour concentration (due to Clausius-Clapeyron-equation). Thus, if the homogeneous nucleation threshold for large solution droplets is reached and they are freezing, they grow quite slowly. Therefore they cannot deplete the excess water vapour efficiently, and ice supersaturation still increases, leading to freezing of smaller, more numerous ice crystals. This behaviour is “repeated” until so many ice crystals are produced that the surface of all ice crystals leads to an efficient reduction of the ice supersaturation. This is the main reason for high ice crystal number concentrations at cold temperatures, assuming a constant updraft.

7) P. 18084-18085: I am not sure that I agree with your discussion concerning the role of temperature in changing the ICNB given the figures as they are presented (Fig. 8 and 9). I think that in order for you to demonstrate the amount of water vapor that is depleted you need to show figures of the ISSR, ice number concentration, and temperature evolution for each simulation (such as height vs time cross sections). You are making some assumptions about the causes of the changes in cloud forcing that I don’t feel are supported in the figures that you have presented. It is quite possible that your interpretation is correct, but the evidence is not presented. Please provide more specific examples to support your conclusions.

We added a figure which shows plots for the relative humidity with respect to ice (RHi), the heterogeneously and homogeneously frozen ice crystal number concentrations and the area where RHi exceeds the critical supersaturation (Scr) necessary for homogeneous freezing for the HOM and 10IN simulations for the cold and warm temperature profiles, respectively. It can be seen, that the difference in RHi and ICNC between the HOM and 10IN simulation in the cold temperature case is much smaller than in the warm temperature case. In the warm case, RHi is much smaller because it has been depleted by the existing ice crystals. As a result, RHi exceeds Scr only in a very small area and nearly no crystals form homogeneously. In contrast, in the cold case, the crystals which have been formed cannot deplete enough RHi in order to suppress the homogeneous freezing and many crystals can still form homogeneously. See Fig. 8 and explanations in the text (page.16, line 18 ff).

8) Sec. 4.2.2 Cloud Forcing: What zenith angles are you considering? What latitude do your simulations represent? It seems obvious that the zenith angle will change the



cloud radiative forcing (assuming constant microphysical properties). But you seem to imply that zenith angle impacts the microphysical properties themselves. What are the physical processes? Increased heating/cooling in the atmosphere? I am wondering if I have misinterpreted your point. Please clarify how the simulations are different in this section than the previous sections. Are you just taking the simulated cloud properties from previous sections and changing the radiation calculations to represent a different time of day? Is the radiation just a diagnostic process in the model, or does it feedback to the cloud evolution?

The zenith angle is representative for 50°N and for 21 of March. It is calculated every 10 minutes, which is equal to the time resolution of the microphysical input data provided by the EULAG simulations. The simulations are always run for 6 h, either from 6 to 12 or 12 to 18 local time with always the same microphysical input data, thus no feedback from radiation to the microphysics is possible. This section only shows the summary of all simulations (HOM,5IN,10IN,50IN) for the different temperature profiles and times of day.The whole procedure is described in section “2.3 Simulation of cirrus radiative properties”.

9) P. 180087: Shortwave cloud forcing is mainly driven by the optical depth (extinction) of the cloud, which is a function of the ice crystal number concentration and size distribution primarily. The diurnal cycle impacts cloud formation in that it may inhibit cloud formation or increase buoyancy in the atmosphere. I think that it would be more interesting to know how these time of day simulations impact cloud lifecycle and microphysical properties (and hence the cloud radiative forcing). I think that the causal mechanisms related to your conclusions should be discussed in more detail.

With our setup it is not possible to investigate the feedback of radiation on the cloud lifecycle and the microphysical properties. However we think that it is justified to investigate how the CF of one and the same cirrus cloud depends on the time of day when it forms. Of course, investigating the feedback of the radiation on the microphysical properties is an important and interesting question but is beyond the scope of this study.

10) P. 18087 Line 3: ". . .ice water content of xx mg mËĘ-3. . ." Did you mean to put a specific number in for the "xx" ?

Sorry, we inserted the correct number. For this simulation 2 mg/m3 are used, according to Schiller et al. 2008.

11) P. 18088 Line 15-20: Your statements imply that the cloud evolves exactly the same (same microphysical properties) regardless of whether it started forming at 0600 or 1200 LT. This implies that the radiation has no impact on the cloud evolution and lifecycle. This seems unlikely and implies that you do not have a realistic representation of cloud-radiative-dynamical interactions in your model, but merely computing the radiative transfer on the same cloud with different zenith angles. Please clarify the related discussion.

Yes you are right. The radiation does not have an impact on the formation of the cloud. But as the focus of this study lies on the influence of heterogeneous freezing on the microphysical and optical properties we think that it is justified to use the setup as we did. Furthermore, as we investigate a situation with a strongly stable stratified atmosphere, the radiation feedback will probably not impact the underlying dynamics. Thus, the quality of the results should not change. A nice extension would be to investigate the feedback of radiation on the microphysics, however we think it is out of the scope of our Paper. We now mention in the text that there is no feedback. (p.20,l.18)

12) Section 5. Summary and Conclusions: The summary section is really a very long repeated account of the results that are already presented. I suggest shortening this section to present the most salient points and provide some discussion regarding the significance of those results.

Thanks for this suggestion. We restructured the Summary section and now emphasize the most important findings.



Minor editorial suggestions: Abstract (Line 19-21) "If a cloud produces a net warming or cooling depends on the IN concentration, the temperature and the time of day at which the cloud forms." Suggest minor word change: "A cloud will produce a net warming or cooling depending on the IN concentration, the temperature, and the time of day when the cloud forms."

done

Figure 2 seems to really be a table, not a figure, and Fig. 2 is mentioned before Fig. 1. Suggest renaming Figure 2 -> Table 1, present before Figure 1, and renumber the rest of the figures.

We would like to have exactly the same symbols and colors in the table as in the figures 6,8,10. The figures are produced with IDL and therefore we also produced the table with IDL. Therefore we decided to not change Fig. 2 to table 2, however now Fig.1 is mentioned before Fig.2.

P. 18077, Line 3: ". . .ice water content are used. . ." done P. 18081, Line 4: "...how these microphysical. . ." done P. 18082, Line 17 (and throughout the paper): "INs" -> suggest spelling out "ice nuclei" or use "IN" since ice nuclei is already in the plural form. done P. 18083, Line 14: ". . .rapid growth of ice crystals, which produces IWP values up to. . ." done P. 18084, Line 5: ". . .an overview of all simulations. . ." done Fig. 11 caption: solar not clear what we should change

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