Project: 1114

Project title: Development and evaluation of cloud glaciation processes in ECHAM-HAMMOZ

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Aerosol-cloud interactions are the main source of uncertainty in current climate models. In particular, the impact of Ice Nucleating Particles (INP) in the climate is poorly understood [1]. Therefore, we looked to improve the parameterization for immersion freezing of mineral dust in the ECHAM-HAM model. We evaluated different freezing schemes against the cloud ice frequency retrieved from satellite instruments. Specifically, we compared the simulated hemispheric and seasonal contrasts in cloud ice frequency against the observations.

We used the COSP simulator to relate the modelled droplet freezing rate to the frequency of ice cloud tops. In this way, we could link the large-scale satellite observations to the different assumptions in the microphysical scheme responsible for cloud glaciation. We used the CALIPSO-GOCCP cloud-phase product and an A-Train product combination as constraints for the model [2].

In the standard parameterization in ECHAM-HAM, the fraction of activated dust aerosols and the Turbulent Kinetic Energy (TKE) may limit the droplet freezing rate. Thus, we evaluated the impact of these limiting factors using simpler formulations for the freezing rate. In the simplest scheme, only the surface concentration of dust aerosol determines the freezing rate. In the standard parameterization, all dust aerosol is assumed to have the freezing efficiency of the dust mineral Montmorillonite. To assess the sensitivity of the model to different minerals, we assumed different efficiencies ranging from low- (e.g., Illite) to high-efficient (e.g., K-feldspar) dust minerals (Fig. 1a).

The last resources allocation allowed us to test numerous configurations for the different freezing schemes. From these simulations, we learned that simpler formulations for droplet freezing and higher dust INP efficiencies result in a more realistic ice cloud fraction. Additionally, we studied several factors related to the cloud phase partitioning (e.g., aggregation and sedimentation). However, only by changing the droplet freezing scheme could we modify the cloud phase partitioning without altering the total water path and the radiative balance in the model. Using satellite observations as a reference, we could improve key features related to cloud glaciation, such as the hemispheric and seasonal contrast in cloud phase.

The simplest scheme, which considers only dust concentration, resulted in a higher hemispheric contrast. On the other hand, increasing the efficiency of dust resulted in a shift of the contrast towards warmer temperatures (Fig. 1b). Consequently, assuming a higher efficiency of dust INP in the northern relative to the southern hemisphere, the hemispheric contrast increases as well. By using the simplest freezing scheme and a higher dust INP efficiency for the northern hemisphere (simulation A1B0 in Fig. 1b), we could replicate the observed hemispheric contrast with the model.

Currently, there is great uncertainty as to which INP efficiency can be considered atmospheric relevant. Therefore, we estimated a theoretical threshold for the Ice Nuclei Active Site (INAS) concentration for which dust aerosol may impact cloud glaciation. This threshold is about $10^{10}$ and $10^{11}$ $m^{-2}$ for the northern and southern hemisphere, respectively.

Furthermore, we could estimate a range of INAS concentration, for which the maximum rate of cloud glaciation is found. Over a certain INAS concentration threshold, higher efficiencies result in only small marginal increments in ice cloud frequency. We estimate this threshold to be about $10^{11}$ and $10^{12}$ $m^{-2}$ for the northern and southern hemisphere, respectively. This information may be of great interest in future cloud-seeding studies and geoengineering approaches.

We repeated the analysis also for the seasonal contrast between Spring and Fall in the northern hemisphere. Similar to the hemispheric contrast, using the simplest parameterization and a higher INP efficiency improved the agreement with observations. Furthermore, assuming a higher efficiency in Spring compared to Fall also improved the agreement to observations. This suggests that higher efficiencies may be associated not only with the northern hemisphere but with higher emission fluxes in general. For example, coarser particles (such as feldspar grains) are mostly emitted by high wind speeds. Similarly, other factors associated with higher emission rates, such as low precipitation and low vegetation, may affect the composition of the aerosol (e.g., biogenic material mixed with dust).

Currently, we are working on a manuscript presenting these results, which should be submitted this year [3]. For the next allocation period, we plan further test simulations focusing on the effects of black carbon as INP. After this first evaluation phase, we plan to focus on the effects of INP on radiation and precipitation. In this phase, we plan to apply the model to assess a series of geoengineering scenarios based on cloud seeding.

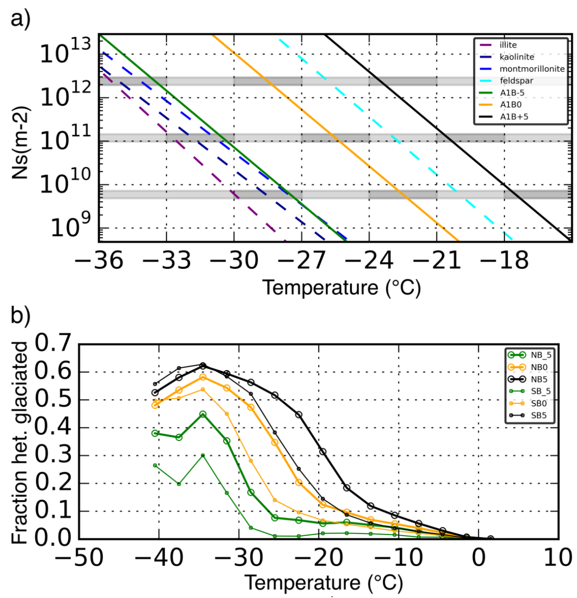


Figure 1: (a) Ice Nuclei Active Site (INAS) concentration for different dust minerals (dashed) and idealized simulations (continuous). The idealized simulations are coded as A$x$B$y$, were $x$ and $y$ are the slope and offset coefficient for each mineral ($N_s = e^{[-AT+B]}$). (b) Fraction of heterogeneously glaciated clouds for the different idealized simulations. This fraction is calculated as the difference in ice cloud frequency between each simulation and the no-freezing simulation. The difference is normalized by the frequency of liquid clouds in the no-freezing simulation. The curves represent the 30-60°N (thick lines) and the 30-60°S (thin lines) latitude bands.

# References

[1] D. Villanueva, B. Heinold, P. Seifert, H. Deneke, M. Radenz, and I. Tegen. The day-to-day co-variability between mineral dust and cloud glaciation: a proxy for heterogeneous freezing. *Atmospheric Chemistry and Physics*, 20(4):2177–2199, 2020.

[2] D. Villanueva. The seasonal and hemispheric contrast in cloud phase from a-train. In preparation.

[3] D. Villanueva. Climate models glaciate too few clouds in the mixed-phase regime. In preparation.