P 2.2 CCC
Global climate processes: Role of cirrus clouds for present and future climate

PI: Ulrike Lohmann
Co-PI: Thomas Peter
ETH Zurich, Institute for Atmospheric and Climate Science

1. Three research questions of the project

- How do number densities and composition of natural and anthropogenic ice nuclei affect cirrus clouds in the present and future climate?
- Does mineral dust lead to cirrus clouds with fewer and larger or more and smaller ice crystals? Does that depend on their chemical aging and active sites?
- How will aerosol-induced perturbations of cirrus clouds affect the surface energy budget and the hydrological cycle?

2. Research Summary

Aerosol-cloud interactions constitute one of the biggest uncertainties in climate prediction. Cloud feedbacks have been confirmed as a primary source of differences between climate model estimates of the equilibrium climate sensitivity, i.e. the global mean surface temperature increase, for a doubling of carbon dioxide (Solomon et al., 2007). While much work has been directed towards aerosol effects on liquid water clouds, aerosol effects on cirrus and mixed-phase clouds should receive more attention. These effects may change in uncertain ways when homogeneous freezing in sulphate-containing aerosols will compete with natural ice nuclei, such as mineral dust particles. While higher aerosol number densities normally lead to more cloud droplets, the situation in cirrus clouds is more complex, as the competition between homogeneous and heterogeneous freezing can lead to cirrus clouds with more or less ice crystals whereby fewer ice crystals are more likely (e.g. Kärcher et al., 2006). Clouds containing fewer particles have a smaller cross-sectional area for the same water content and thus reflect less solar radiation back to space. For cirrus clouds a decrease in crystal concentration would also impact the longwave radiation and could lead to a net cooling. Thus, it is important to better understand the role of ice nuclei for cirrus clouds in order to estimate the response of cirrus clouds to increasing levels of anthropogenic aerosols.

Besides nucleation effects, ice growth impedances were recently found to lead potentially to high supersaturations within cirrus clouds (e.g. Peter et al., 2006). The role of physico-chemical processes affecting the deposition of water vapour on ice and of water vapour on aerosols is presently unclear. These effects could be related to unknown intrinsic properties of the ice substance at the lowest temperatures of cirrus clouds close to the tropopause, or due to natural or anthropogenic species on the ice surface.

The effects of these nucleation and growth effects on regional and global cirrus properties and on the radiation balance will be investigated by means of process-based or parameterization-based trajectory models in task 1 and in the global climate model (GCM) ECHAM5 in task 2.

3. Data and methods

The following work is planned:

Task 1: Develop a heterogeneous ice nucleation parameterization based on trajectory-box model runs for competing homogeneous and dust-induced heterogeneous ice nucleation and impeded ice particle growth.

The trajectory model will be a generalization of the model used by Hoyle et al. (2005) for purely homogeneous nucleation studies. This will enable us to study the nucleation of ice crystals using realistic mesoscale temperature fields. This is an important ingredient of nucleation modelling, as higher instantaneous cooling rates lead to favouring homogeneous over heterogeneous nucleation and results in higher ice number densities. While Hoyle et al. (2005) used exclusively the mesoscale temperature fields obtained from the SUCCESS field campaign, we will here acquire an overview over published temperature fluctuation measurements (e.g. Gary, 2006) in an attempt to obtain climatologically realistic fields for various altitude levels.

Mineral dust aerosols will be investigated as the arguably most important category of heterogeneous ice nuclei (IN). We will focus on the issue how natural mineral dust particles are processed physically (e.g. in deep convection) and chemically (e.g., by HNO_3), and develop refined parameterizations. For the heterogeneous freezing mechanism we will start with the efficiency of immersion mode ice nucleation on surrogates of mineral dust, which we derived recently from our laboratory measurements (Marcolli et al., 2007). A model for the freezing has been developed, which describes the ice nucleation on active sites and which currently comprises the most advanced treatment of the freezing process. From this a parameterization for dust induced ice nucleation to be applied in Task 2 will be developed.

While this parameterization will first be constrained to the freezing process of mineral dust immersed in pure water, in a second step this will be generalized to various kinds of solutions (ammoniated sulphate solutions, organics-containing solutions). Measurements for this are currently on the way in our laboratory. From the literature we will collect data on the deactivation of sites due to chemical aging, e.g. by HNO_3.

Task 2: Analyse the role of cirrus clouds formed by heterogeneous vs. homogeneous freezing for current and future climate with implications for the surface energy budget.

Contrails have been shown to reduce the diurnal temperature range in the United States (Travis et al., 2002). On the contrary a shift from cirrus clouds formed by homogeneous freezing of solution droplets to cirrus clouds formed by a combination of homogeneous and heterogeneous freezing would lead to cirrus clouds with a reduced optical depth. These clouds would allow more solar radiation to reach the Earth surface with implications for the surface energy budget and the hydrological cycle. Previous climate model simulations did not investigate this issue because these simulations were conducted with climatological sea surface temperature (Lohmann et al., 2004). In these simulations only the land surface temperature could react to changes in cirrus cloud properties. In order to analyze effects of cirrus on the surface energy budget, it is appropriate to couple a GCM to a mixed-layer ocean model (MLO) (e.g., Feichter et al., 2004). Thus we suggest studying the effect of cirrus on the surface energy budget in coupled GCM-MLO studies. This also allows us to study the importance of cirrus clouds on climate sensitivity.

Moreover, previous cirrus studies were conducted with the ECHAM4 GCM that only predicted the mass mixing ratios of the major aerosol compounds (sulphate, organic and black carbon, dust and sea salt). In the meantime, the newest version of the ECHAM GCM, the ECHAM5 is coupled to the two-moment aerosol scheme ECHAM5-HAM that predicts the aerosol mixing state in addition to the aerosol mass and number concentrations (Stier et al. 2005). The size distribution is represented by a superposition of log-normal modes including the same major aerosol compounds. Also the two-moment cloud microphysical scheme has been improved in terms of the ice crystal fall velocity and ice crystal shape and a simple treatment that allows both homogeneous freezing and heterogeneous freezing by immersed dust aerosols in cirrus clouds has been developed (Lohmann et al., 2008).

However, chemical aging of dust aerosols, the role of the water uptake and active sites have not been considered so far. Task 2 will focus on adapting and applying the parameterization that considers these effects and was developed in task 1 in coupled GCM-MLO simulations with ECHAM5-HAM. It will then investigate the importance of homogeneous and heterogeneous freezing on cirrus clouds with implications for future global and regional scenarios, the surface energy budget and for the hydrological cycle.

4. Milestones and deliverables

After 18 months:

- Cirrus box model runs for close intercomparison with aircraft and balloon-based observations, yielding basic information for parameterization development.
- A parameterization considering active sites of mineral dust aerosols for use in large-scale models.

- Analysis of the importance of cirrus clouds formed by heterogeneous vs. homogeneous freezing in the present and future climate with the present cirrus scheme.

After 36 months:

- Generalization of the active-site/nucleation parameterization for a wide range of solutions including chemical aging during aerosol transport.
- Implementation of the heterogeneous freezing parameterization developed in task 1 in ECHAM5-HAM; comparisons with observations and implications for future climate.
- Make the new cirrus module available for P2.1, in particular, for high-resolution GCM scenarios in collaboration with M. Wild and Ch. Schär.

5. Contribution to the WP1 and collaboration with other NCCR projects and 3rd parties

The improved parameterization will be used to assess the impact of mineral dust versus sulphate aerosols on cirrus clouds, with implications for future global and regional scenarios (P2.1 HyClim Wild/Schär) and for the hydrological cycle (P2.3 PreClim Appenzeller/Liniger/Knutti and P3.3 ECOWAT Bugmann/Seneviratne).

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