SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Aerosol Cloud Interactions
Computer Project Account:	spchclai
Start Year - End Year :	2006 - 2011
Principal Investigator(s)	Prof. Ulrike Lohmann
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Other Researchers (Name/Affiliation):	Prof. Peter Spichtinger, University of Mainz, Germany Dr. Andreas Mühlbauer, University of Washington, USA Dr. Fabian Fusina, ETH Zurich, Switzerland Dr. Hanna Joos, ETH Zurich, Switzerland Prof. Trude Storelvmo, Yale University, USA

The following should cover the entire project duration.

Summary of project objectives
(10 lines max)

In this project the interaction between clouds and aerosols on different spatial and temporal scales were studied. The main objectives were the following:

1. Effect of aerosols on orographic precipitation
2. Impact of aerosols on mixed-phase clouds
3. Impact of dynamics vs. aerosols on cirrus clouds
4. Multiscale modelling of cirrus clouds

Summary of problems encountered
(If you encountered any problems of a more technical nature, please describe them here.)

none

Experience with the Special Project framework
(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

We are pleased that the administrative effort for Special Projects is low. It was always easy to apply for continuation of the project, to get additional computing resources, and to do the reporting.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

Orographic precipitation:

Warm phase orographic precipitation:

In a first study aerosol-cloud interactions and the possible impact on the orographic precipitation distribution are investigated for warm-phase clouds. Herein, simulations of moist orographic flow over topography are conducted and the influence of anthropogenic aerosols on the orographic precipitation formation is analyzed. The degree of aerosol pollution is prescribed by different aerosol spectra, which are characteristic and representative for remote-continental conditions in Switzerland. The simulations are performed with the Consortium for Small-Scale Modeling's mesoscale nonhydrostatic limited-area weather prediction model (COSMO) with a horizontal grid spacing of 2 km and a fully coupled two-moment aerosol-cloud microphysics parameterization.

It is found that an increase in the aerosol load leads to a downstream shift of the orographic precipitation distribution and to an increase in the spillover factor (i.e., the fraction of leeward precipitation to total precipitation). A reduction of warm-phase orographic precipitation is observed at the upslope side of the mountain.

The downslope precipitation enhancement critically depends on the width of the mountain and on the flow dynamics. In the case of orographic precipitation induced by stably stratified unblocked flow the loss in upslope precipitation is not compensated by leeward precipitation enhancement. In contrast, flow blocking may lead to leeward precipitation enhancement and eventually to a compensation of the upslope precipitation loss. However, the loss in upslope precipitation also depends on the geometry of the mountain, such as the half-width, and is most severe for narrow mountains where the orographic spillover factor is high. The simulations also indicate that latent heat effects induced by aerosol-cloud-precipitation interactions may considerably affect the orographic flow dynamics and consequently feed back on the orographic precipitation development.

The results of this part of the project are published in Muhlbauer and Lohmann (2008).

Mixed-phase orographic precipitation:

Based on the findings of Muhlbauer and Lohmann (2008) on warm-phase orographic clouds idealized 3D simulations are conducted to investigate aerosol-cloud interactions also in mixed-phase clouds and for various aerosol perturbations. For the microphysical initialization of the model typical and representative anomalies in the aerosol size distribution and aerosol compositions are taken from observations. Two different types of aerosol anomalies are considered which are naturally occurring mineral dust and anthropogenic black carbon.

In the simulations with dust aerosol anomaly the dust aerosols serve as efficient ice nuclei in the contact mode leading to an early initiation of the ice-phase in the orographic cloud.

As a consequence, the riming rates in the cloud are increased leading to increased precipitation efficiency and to an enhancement of orographic precipitation. The simulations with anthropogenic aerosol anomaly suggest that the mixing state of aerosols plays a crucial role since coating and mixing may cause the aerosols to initiate freezing in the less efficient immersion mode than by contact nucleation. It is found that externally mixed black carbon aerosols increase riming in orographic clouds and enhance orographic precipitation. In contrast, internally mixed black carbon aerosols decrease the riming rates, which in turn leads to a decrease in orographic precipitation.

The results of this part of the project are published in Muhlbauer and Lohmann (2009).

Microphysical uncertainties:

A further part of this project is to investigate the microphysical uncertainties of aerosol-cloud interactions with respect to the numerical representation of microphysical processes in models. The motivation for this type of work is that past studies show large impacts and sensitivities with respect to the numerical approach used in the models to treat microphysical processes. For example, bulk microphysical parameterizations typically rely on some assumed form of hydrometeor size distributions, which introduces additional uncertainties. In contrast, bin- resolving microphysical models explicitly calculate the particle size distributions without assumptions on the shape and slope parameter. However, for computing microphysical collection processes (i.e., coalescence, aggregation and riming) both modeling approaches rely on assumptions for the collection efficiencies, which are usually derived from either laboratory experiments or numerical simulations. Hence, it is necessary to analyze and inter-compare the sensitivities of different microphysical processes in mixed-phase orographic clouds and orographic precipitation to changes in the ambient aerosol conditions using several state-of-the-art numerical models and microphysical approaches. Special emphasis is given to the sensitivity of the riming process and the general role of heterogeneous ice nucleation.

In order to reduce the complexity of the problem, simulations are performed within an idealized setup of a 2D flow over a mountain (case 1a at http://www.rap.ucar.edu/˜gthompsn/workshop2008) introduced at the Seventh WMO International Cloud Modeling Workshop (Morrison et al. 2009). The results of this model inter-comparison are published in Muhlbauer et al. (2010).

Aerosol influence on clouds:

The objective is to introduce a sophisticated treatment of aerosol influence on clouds in the IFS model, to allow simulations of aerosol-cloud interactions and their implications for weather and climate on timescales ranging from weeks to centuries.

For climate simulations, this extended version of the IFS will be coupled to ocean, chemistry, sea-ice and vegetation components to form the Earth system model EC-Earth (http://ecearth.knmi.nl).

As no aerosol influences on clouds are currently included in the standard IFS cycles, we have started this process by implementing a relatively simple treatment of aerosol effects on warm (i.e, liquid) clouds. By introducing monthly mean aerosol concentrations for pre-industrial (PI, ~ year 1750) and present-day (PD) conditions, and by allowing the aerosols to influence cloud properties using 4 different empirical methods, we are now able to simulate aerosol effects on cloud albedo in a simple manner. As the four empirical methods applied correspond to those applied by various climate models for transient climate simulations for IPCC assessment report 4 (AR4), we could use this simple framework to estimate the spread in radiative forcings among these models introduced by the use of the different empirical methods. This resulted into the publication Storelvmo et al. (2009).

However, aerosols may affect Earth's radiative balance not only via clouds (so called indirect effects), but also directly by scattering and absorbing solar radiation. Based on the monthly mean aerosol fields described above, such effects were introduced in the IFS by another partner in the EC Earth consortium, namely Dr. Annica Ekman at Stockholm University. Although prescribed aerosol concentrations were already influencing radiation in the IFS model, the introduction of PD and PI aerosol fields enables simulations of the *anthropogenic* aerosol effects.

Using the new treatments of direct and indirect aerosol effects on the radiation balance, we participated in a model intercomparison comparing various radiative forcings (by CO_2, methane and direct and indirect aerosol effects) to the corresponding flux perturbations. While forcings are calculated by making several calls to a models radiation routine, and where the radiation driving the model evolution is the same in both PD and PI simulations, flux perturbations are calculated by allowing the PD/PI aerosols to influence the model evolution via the radiation, allowing for feedback responses like circulation changes between PD and PI simulations.

The model intercomparison resulted in the publication Lohmann et al. (2009).

Simulations for the two publications described above were carried out partly with resources from special project SPCHCLAI, partly from special project SPCHAERO, and also with some additional computing resources provided by MeteoSwiss.

Orographic cirrus clouds:

The cloud-resolving model (CRM) EULAG is used to investigate the formation of orographic cirrus clouds in the current and future climate.
First, the capability of the CRM in realistically simulating orographic cirrus clouds has been tested by comparing the simulated results to aircraft measurements of an orographic cirrus cloud. Due to the very good agreement we assume that the model is able to simulate realistic vertical velocities and microphysical properties of orographic cirrus and can be used for further investigations of orographic cirrus clouds.
In a future climate warmer temperatures and more moisture can be expected. In order to investigate how additional moisture and higher temperatures influence the formation of orographic cirrus clouds, idealized simulations have been performed where the temperature profiles have been varied. The results mainly show an increased ice water content with increasing temperatures as a constant relative humidity was assumed. Furthermore, higher temperatures lead to a faster growth of the ice crystals such that the supersaturation is depleted faster and less ice crystals nucleate. The net effect of higher ice water content and lower ice crystal number concentrations is an increasing optical depth with increasing temperatures.
The influence of a warmer climate on the microphysical and optical properties of cirrus clouds has been investigated by initializing the CRM with vertical profiles of horizontal wind, temperature and moisture from IPCC A1B simulations for the present climate and for the period 2090-2099 for two regions representative for North and South America. Furthermore, simulations for the corresponding summer and winter months have been performed. In a future climate, the increase in moisture dampens the vertical propagation of gravity waves and the occurring vertical velocities. The higher temperatures lead to a faster growth of the ice crystals such that the supersaturation is depleted faster and fewer crystals nucleate. Assuming that the relative humidity does not change in a warmer climate the specific humidity in the model is increased. This increase in specific humidity in a warmer climate results in a higher ice water content. In all simulations the dynamical changes are negligible and are strongly dominated by thermodynamical changes. The net effect of a reduced ice crystal number concentration which would lead to a decreased optical depth and a higher ice water content which would lead to an enhanced optical depth, is an increase of the optical depth in all cases. These results show that in order to predict realistic changes in the microphysical and optical properties of orographic cirrus clouds, the changes in moisture influencing the dynamics as well as the changes in temperature have to be taken into account. Furthermore a higher optical depth of orographic cirrus clouds might be expected in a future climate. These results were published in Joos et al. (2009).

Multiscale modelling of cirrus clouds:

Impact of radiation and small-scale dynamics on cirrus clouds

The influence of radiative cooling and small eddies on cirrus formation has been investigated, using idealized profiles with high supersaturations up to 144% and weak stable stratification. Due to the radiative cooling at the top of the ice-supersaturated region (ISSR) with cooling rates down to -3.5 K/d, the stability of the ISSR stratification decreases with time. At a critical point, small eddies induced by Gaussian temperature fluctuations start to grow and trigger first nucleation. The effects of increasing local relative humidity by cooling due to radiation and adiabatic lifting lead to the formation of a cirrus cloud with IWC up to 33mg/m3 and optical depths up to 0.82. Only the interaction of a small scale (eddies due to Gaussian temperature fluctuations) and a large scale (radiation) effect leads to the formation of a cirrus in these particular cases, i.e. the cirrus only can be formed by a superposition of processes on different scales. The main goal of this study was to obtain deeper insights in the different environmental conditions (relative humidity, stratification, wind shear), which allow the formation of this type of cirrus clouds. The results were published in Fusina and Spichtinger (2010)

Transient environmental states for modelling cirrus clouds

In model investigations of clouds formed by orographic waves usually the stratified flow is evaluated in almost steady state conditions, i.e. after a long time until quasi-equilibrium has been reached. However, in nature the flow conditions often change with time, e.g. wind fields are time dependent. It is unknown how a time-dependent flow will influence or even change the formation and evolution of clouds, in our case cirrus clouds in the upper troposphere; this is a multiscale problem, involving cloud microphysics and dynamics on different scales.

In this model study we investigate a stable stratified flow over an isolated mountain, exciting gravity waves, which trigger ice formation. In a second step we investigate the impact of a time-dependent wind, i.e. the impact of a developing jet in the tropopause region on the further cirrus cloud evolution. For this kind of simulations we apply a new method, which allows us to prescribe the environmental time-dependent 2D wind fields in the anelastic non-hydrostatic model EULAG including ice microphysics. Using this method we are able to investigate the impact of motion on a larger scale on motion and microphysical processes on smaller scales. The results are currently summarized and will be submitted as a publication soon.

List of publications/reports from the project with complete references

Fusina, F. and P. Spichtinger, 2010: Cirrus Clouds triggered by Radiation, a Multiscale Phenomenon. Atmos. Chem. Phys., 10, 5179-5190, doi:10.5194/acp-10-5179-2010.

Joos, H., P. Spichtinger, U. Lohmann, 2009: Orographic cirrus in a future climate. Atmos. Chem. Phys., 9, 7825–7845.

Lohmann, U., L. Rotstayn, T. Storelvmo. A. Jones, S. Menon, J. Quaas, A. Ekman, D. Koch and R. Ruedy, 2010: Total aersol effect: radiative forcing or radiative flux perturbation? Atmos. Chem. Phys., 10, 3235-3246.

Morrison, H., G. Thompson, M. Gilmore, W. Gong, R. Leaitch, and A. Muhlbauer, 2009: Seventh WMO cloud modeling workshop. Bull. Amer. Meteor. Soc., 90, 1683-1686.

Muhlbauer, A. and U. Lohmann, 2008: Sensitivity studies of the role of aerosols in warm-phase orographic precipitation in different dynamical flow regimes. J. Atmos. Sci., 65, 2522–2542.

Muhlbauer, A. and U. Lohmann, 2009: Sensitivity Studies of Aerosol-Cloud Interactions in Mixed-Phase Orographic Precipitation. J. Atmos. Sci., 66, 2517-2538.

Muhlbauer, A., T. Hashino, L. Xue, A. Teller, U. Lohmann, R.M. Rasmussen, I. Geresdi and Z. Pan, 2010: Intercomparison of aerosol-cloud-precipitation interactions in stratiform orographic mixed-phase clouds. Atmos. Chem. Phys., 10, 8173-8196.

Storelvmo, T., U. Lohmann and R. Bennartz, 2009: What governs the spread in shortwave forcings in the transient IPCC AR4 models? Geophys. Res. Lett., doi:10.1029/2008GL036069.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

No future plans for projects at ECMWF