Aerosol-cloud interactions and the effects on orographic precipitation

A. Mühlbauer and U. Lohmann[*]
Institute for Atmospheric and Climate Science, ETH Zurich
8092 Zurich, Switzerland

Abstract

Anthropogenic and natural aerosols serve as a source of cloud condensation nuclei (CCN) and influence the microphysical properties of clouds. An increase of the aerosol load leads to an increase of the cloud droplet number concentration and, for a given liquid water content, to a decrease of the average cloud droplet size. Since the collision efficiency is small for small droplets, the increased aerosol load induces a deceleration of the cloud drop coalescense process in warm phase clouds. Furthermore, the rain drop development through the (auto-)conversion process is prolongated. This prolongation effect extends the cloud lifetime and leads to a modification of the precipitation formation. Furthermore, the spatial distribution of precipitation at the surface may be altered.

In the case of low-level orographic clouds the aerosol-cloud interactions are suspected to reduce the amount of precipitation on the upslope side of the mountain and to enhance the precipitation on the downslope side of the mountain. The net effect may lead to a shift of the precipitation distribution towards the leeward side of mountain ranges which affects the hydrological cycle on the local scale.

The main purpose of this study is to investigate aerosol-cloud interactions in warm phase clouds and to quantify the aerosol indirect effect on the hydrological cycle. Herefore, simulations of moist orographic flows over topography are conducted and the influence of aerosol particles on the orographic precipitation formation is analyzed by comparing a polluted case against a clean reference case. The degree of aerosol pollution is simulated by prescribing different number concentrations of CCN which are then available for the cloud drop nucleation.

The simulations are performed with the shortrange Local Model (LMK) which is currently developed at the German weather service (DWD) for the purpose of short-range weather prediction and the horizontal resolution of the model is 2.8km.

Throughout this study the focus is put on warm phase clouds. The considered microphysical processes are the nucleation of cloud droplets, the selfcollection, the accreation and the autoconversion of cloud droplets into rain. These warm phase processes are treated within the framework of a two-moment microphysics scheme.

1. Introduction

One of the major uncertainties in todays efforts of climate prediction is to estimate the role of aerosol particles which interact with clouds and precipitation in several ways and are in contrast to the greenhouse gases more confined to the local scale. Besides radiative effects aerosols serve as cloud condensation nuclei (CCN) and are considered to alter the cloud droplet size spectrum towards smaller radii which directly translates into a change of the microphysical properties of clouds. For a fixed liquid water content (LWC) the change in the cloud droplet spectrum implies also a change in the cloud albedo (Twomey et al. 1984) as well as the cloud lifetime (Albrecht 1989). In a recent review on aerosol indirect effects, Lohmann and Feichter (2005) summarize that GCM estimates of global annual mean radiative per-

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[*] andreas.muehlbauer@env.ethz.ch

turbations at the top of atmosphere range from -0.5 to -1.9 W m^{-2} due to cloud albedo effect, and from -0.3 to -1.4 W m^{-2} due to cloud lifetime effect. However, the confidence in the given values is very low and no estimate is given for the possible implications of the aerosol-cloud interaction on precipitation formation.

Based on remote observations from TRMM (Tropical Rainfall Measuring Mission) Rosenfeld (1999) proposed that organic and black carbon emissions from vegetation fires may lead to a total shutoff of convective precipitation. Although an increased aerosol load may initially inhibit convective precipitation Khain et al. (2005) showed in model simulations that precipitation may also be enhanced by aerosols due to increased latent heating and higher updraft velocities in deep convective clouds.

Based on records of rain gauge measurements, different authors tried to quantify the indirect aerosol effect on orographic precipitation formation (Givati and Rosenfeld 2004, 2005; Jirak and Cotton 2006). Givati and Rosenfeld (2004) employ a linear trend analyses to timeseries of annual precipitation data from several stations in the US and in Israel. Herefore, they analyse the ratio of annual rainfall which is the ratio of the precipitation measured at a mountain station divided by the precipitation measured at the upstream located lowland station. Givati and Rosenfeld (2004) hypothesise that this ratio of annual rainfall, which reflects the orographic precipitation enhancement, shows a decreasing trend in areas with air pollution (polluted case) whereas it is constant in areas without air pollution (clean case).

Borys et al. (2003) and Givati and Rosenfeld (2004) suggest that a tendency of decreasing precipitation with increasing anthropogenic aerosol load may exist due to a change of the microphysical properties of the hydrometeors in warm-phase and in mixed-phase clouds. More specifically, in warm phase clouds the collision efficiency is smaller for smaller cloud droplets and in mixed-phase clouds the riming process is considered to be less efficient for small cloud droplets (Pruppacher and Klett 1997). Since collision and riming are very efficient processes in producing precipitation, an inhibition of these cloud microphysical processes is assumed to yield a prolongation of the precipitation development which then potentially leads to a precipitation suppression.

The hypothesized implications of the aerosol-cloud interactions on orographic precipitation are the tendency towards a loss of precipitation on the upslope side of the mountain and a possible gain of precipitation on the downslope side of the mountain. This shift of the precipitation pattern towards the leeward side of mountain ranges may alter the hydrological cycle on a local scale and is a further aspect of climate change.

In warm phase clouds the deceleration of the cloud drop coalescense process may prolongate the raindrop development through the (auto-)conversion process. Furthermore, the mean raindrop size may be smaller in polluted clouds than in clean clouds which in turn also affects the sedimentation velocity of raindrops. Especially in situations where precipitation is initiated due to forced ascent along the upstream mountain slopes, the orographic precipitation pattern depends on the different timescales of hydrometeor advection, sedimentation and evaporation (Hobbs et al. 1973; Jiang and Smith 2003). Hence, the aerosol interaction with low-level orographic clouds may also be an interesting aspect for quantitative precipitation forecasting and runoff modelling in mountainous regions.

A first goal of this study is to quantify the indirect aerosol effect on the amount and the distribution of orographic precipitation with a restriction on warm-phase microphysical processes.

2. Model

The model simulations are performed with the nonhydrostatic shortrange Local Model (LMK) which is currently developed at the German weather service (DWD) for the purpose of shortrange numerical weather prediction. The computational domain is two-dimensional with 400 gridpoints in the horizontal and 38 vertical levels. The horizontal resolution of the model is 2.8 km and the timestep is 10 s.

Idealized two-dimensional simulations of moist orographic flows over topography are conducted and the influence of aerosol particles on the orographic precipitation formation is analyzed by comparing a polluted case against a clean reference case. The degree of aerosol pollution is simulated by prescribing different number concentrations of CCN which are then available for the cloud drop nucleation. The initial number concentration of CCN in the clean case is 100 cm^{-3} whereas it is 1000 cm^{-3} in the polluted case.

The microphysical processes are treated within the two-moment scheme of Seifert and Beheng (2006). Since the emphasis is put on warm-phase clouds the considered microphysical processes are the nucleation of cloud droplets, the selfcollection, the accreation and the autoconversion of cloud droplets into rain.

For the initial condition an idealized vertical sounding is used which prescribes the vertical distribution of pressure, temperature and moisture similar to Thompson et al. (2004). The horizontal wind profile is constant with height and the lateral boundary conditions are open.

3. Simulations and preliminary results

Orography contributes to the small scale precipitation in several ways. Topography enhances precipitation by lifting unsaturated air mechanically along the upsloping terrain up to the condensation level where the water vapor starts condensating and latent heat is released. Depending on the atmospheric stratification this latent heat release may also initiate orographically induced convection. A brief review of all the possible mechanisms which may lead to orographically induced or enhanced precipitation can be found in Smith (1989) or Roe (2005).

For the generation of orographic precipitation dynamical as well as microphysical processes are considered to be most dominant. In the following experiments the emphasis is put on aerosol impacts on the microphysical evolution of orographic precipitation and the dynamics of the flow.

For orographic flows the Froude number $Fr = \frac{u}{Nh}$ characterizes the flow regime depending on the windspeed u, the mountain height h and the Brunt-Väisälä frequency N. In moist flows the dry Brunt-Väisälä frequency N_d is replaced by the moist Brunt-Väisälä frequency N_m to account for the effect of moisture on the atmospheric stability (Durran and Klemp 1982).

In a first experiment we compare the orographically induced precipitation patterns for a polluted case ($N_{CCN} = 1000$ cm^{-3}) and a clean reference case ($N_{CCN} = 100$ cm^{-3}) as function of mountain height h. The initial horizontal windspeed u is prescribed with 15 m s^{-1} constant with height during all simulations. For the idealized topography a Gaussian mountain with a half-width of $a = 50$ km is chosen.

Figure 1 shows the domain total precipitation together with the maximum precipitation as a function of mountain height and after 6 h of simulation.

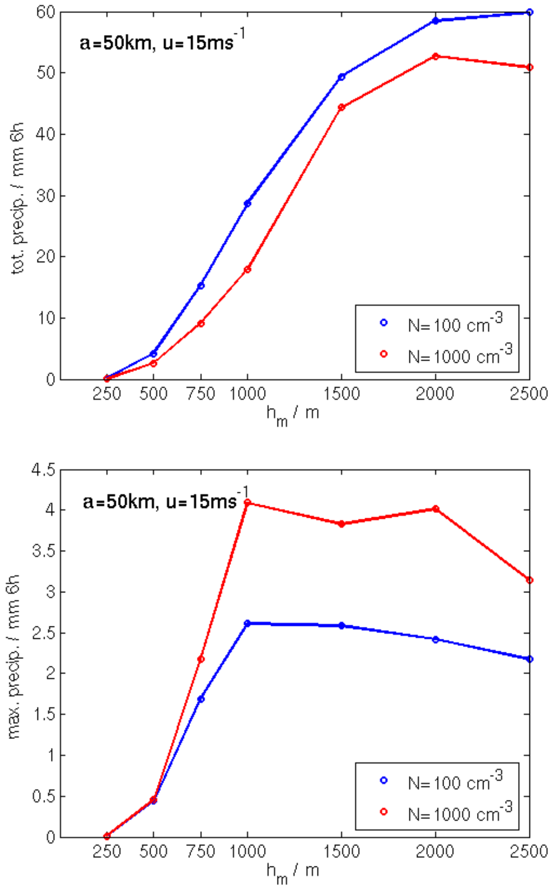

Figure 1: The left panel shows the domain total precipitation for the clean case (blue) and the polluted case (red) as a function of mountain height h. In the right panel the maximum precipitation is depicted for both cases. Note that in both panels the precipitation is shown in units of mm after 6 h and that the windspeed u and the mountain half-width a are constant for all simulations.

The total precipitation is increasing similarly in the polluted and in the clean case but the clean case produces always more precipitation than the polluted case which might be an indication for a precipitation reduction effect of aerosol particles. Contrary, the maximum value of orographic precipitation after 6 h is larger in the polluted case than in the clean case which suggests that the orographic precipitation distribution is changed.

In figure 2 the spatial orographic precipitation pattern is shown as a function of mountain height after 6 h. Note that the mountain peak is located at gridpoint 201 in the computational domain (indicated by the black triangle).

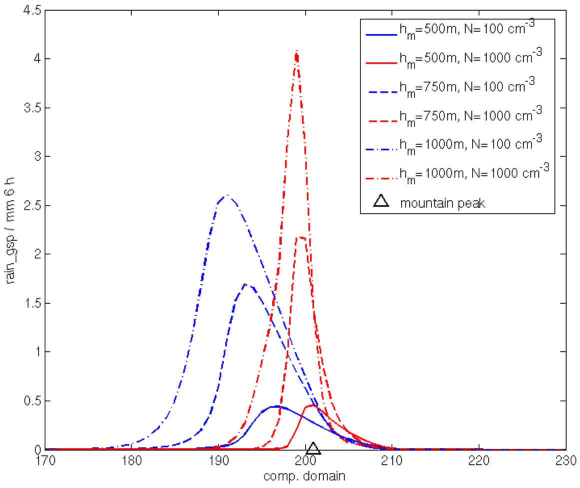

Figure 2: Spatial distribution of the orographic precipitation for the clean case (blue) and the polluted case (red) as a function of the mountain height h. The gridpoint precipitation in shown in units of mm after 6 h. Note that the mountain peak is located at gridpoint 201 in the computational domain which is indicated by the black triangle.

A comparison of the precipitation distributions for the clean and the polluted case reveals that the spatial precipitation pattern is influenced by the prescribed number of aerosols for all mountain heights. As the mountain height increases the precipitation increases as well and the maximum of the precipitation distribution is shifted upstream in both cases. In the polluted case the precipitation distribution narrows and the maximum precipitation is shifted upslope towards the mountain peak. Furthermore, the difference in the precipitation distribution is increasing with mountain height. Due to the downstream shift of the precipitation distribution the spillover factor is higher in the polluted case than in the clean case. The spillover factor is defined as the ration of precipitation over the lee side of the mountain to the total precipitation (Jiang and Smith 2003). Although the total precipitation is decreasing in the polluted case the leeward precipitation may increase due to the increased spillover which is summarized in table 1. Interestingly, the difference in the spillover factor (polluted case minus clean case) peaks at mountain heights of 500 m for the given flow conditions.

h_m	SP (clean)	SP (poll.)	Δ SP
250	0.43	0.67	0.25
500	0.21	0.56	0.34
750	0.06	0.22	0.16
1000	0.03	0.06	0.03
1500	0.04	0.06	0.02
2000	0.02	0.03	0.01
2500	0.02	0.02	0

Table 1: The spillover factor (SP) as a function of mountain height h_m (in units of m) for the clean case and the polluted case. The difference in the spillover factor (polluted case minus clean case) is shown in the last column.

4. Discussion and outlook

The preliminary results suggest that the aerosol-cloud interaction may translate into a change of the orographic precipitation pattern. The total precipitation is decreasing with increasing aerosol load whereas the maximum precipitation is increasing. In the polluted case the precipitation distribution is shifted upslope towards the mountain peak and the leeward precipitation is increasing which might be an indication that the precipitation development is initially inhibited due to the larger amount of small cloud droplets.

The goals of the further experiments are to investigate the role of aerosol particles on the orographic precipitation formation processes in more detail. From the microphysical point of view aerosols may prolongate the autoconversion process in polluted clouds which might affect the microphysical timescale. Since the sedimentation time scale might also be altered, a further question which will be addressed in this investigation is whether the downstream advection of hydrometeors becomes more important. If the downstream advection of rain droplets becomes more dominant the leeward precipitation might be increasing due to an increased spillover factor. From the dynamical point of view, we want to analyze which atmospheric flow conditions are most sensitive towards aerosol modification and how this modification translates into the orographically produced precipitation pattern.

References

Albrecht, B., 1989: Aerosols, cloud microphysics, and fractional cloudiness. *Science*, **245**, 1227–1230.

Borys, R., D. Lowenthal, S. Cohn, and W. Brown, 2003: Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate. *Geophys. Res. Lett.*, **30**, 1538–1542.

Durran, D. and J. Klemp, 1982: On the effects of moisture on the Brunt-Väisälä frequency. *J. Atmos. Sci.*, **39**, 2152–2158.

Givati, A. and D. Rosenfeld, 2004: Quantifying precipitation suppression due to air pollution. *J. Appl. Meteor.*, **43**, 1038–1056.

— 2005: Separation between cloud-seeding and air-pollution effects. *J. Appl. Meteor.*, **44**, 1298–1314.

Hobbs, P., R. Easter, and A. Fraser, 1973: A theoretical study of the flow of air and fallout of solid precipitation over mountainous terrain: Part II. Microphysics. *J. Atmos. Sci.*, **30**, 813–823.

Jiang, Q. and R. Smith, 2003: Cloud timescales and orographic precipitation. *J. Atmos. Sci.*, **60**, 1543–1559.

Jirak, I. L. and W. R. Cotton, 2006: Effect of air pollution on precipitation along the front range of the Rocky Mountains. *J. Appl. Meteor.*, **45**, 236–245.

Khain, A., D. Rosenfeld, and A. Pokrovsky, 2005: Aerosol impact on the dynamics and microphysics of deep convective clouds. *Q. J. R. Meteorol. Soc.*, **131**, 2639–2663.

Lohmann, U. and J. Feichter, 2005: Global indirect aerosol effects: a review. *Atmos. Chem. Phys.*, **4**, 7561–7614.

Pruppacher, H. and J. Klett, 1997: *Microphysics of Clouds and Precipitation*. Kluwer Academic Publishers, second edition, 954 pp.

Roe, G. H., 2005: Orographic precipitation. *Annu. Rev. Earth Planet. Sci.*, **33**, 645–671.

Rosenfeld, D., 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.*, **26**, 3105–3108.

Seifert, A. and K. D. Beheng, 2006: A two-moment cloud microphysics parameterization for mixed-phase clouds. Part I: Model description. *Meteorol. Atmos. Phys.*, **92**, 45–66.

Smith, R., 1989: Mechanisms of orographic precipitation. *Meteorol. Mag.*, **119**, 85–88.

Thompson, G., R. Rasmussen, and K. Manning, 2004: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part I: Description and sensitivity analysis. *Mon. Weather Rev.*, **132**, 519–542.

Twomey, S., M. Piepgrass, and T. Wolfe, 1984: An assessment of the impact of pollution on global cloud albedo. *Tellus, Ser. B*, **36**, 356–366.