Dynamics vs. aerosol induced warm-phase microphysics and orographic precipitation

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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 fixed liquid water content (LWC), 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 controlled by prescribing different number concentrations of CCN which are then available for the cloud drop nucleation.

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

Throughout this study the focus is put on warm phase clouds and the microphysical processes are treated within a sophisticated two-moment (bulk) microphysics scheme.

1. Introduction

One of the major uncertainty in todays efforts of climate prediction is to estimate the role of aerosol particles which interact with clouds and radiation 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 (e.g. Peng et al., 2002) 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 perturbations at the top of atmosphere range from -0.5 to -1.9 W m^{-2} due to cloud albedo effect, and

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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 time series 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 and the evaporation 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 non-hydrostatic limited-area 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).

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 dimensionless mountain height $\hat{h} = \frac{Nh}{u}$ characterizes the flow regime depending on the windspeed u, the maximum 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 potential temperature field for 3 different simulations after 6 h. For these simulations the maximum mountain height h varies from 1000 m (A), 750 m (B) to 500 m (C) and the flow regime changes from a hydraulic jump (A,B) to a smooth mountain wave (C).

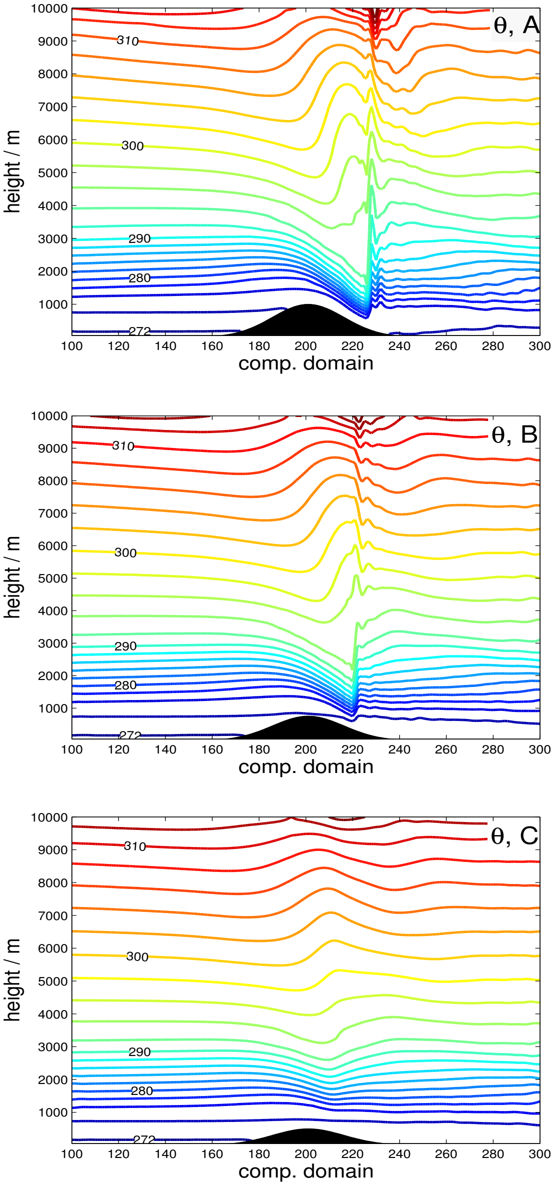

Figure 1: Potential temperature field for 3 different simulations (A-C) after 6 h. The mountain height h varies from 1000 m (A), 750 m (B) to 500 m (C). θ is in units of K.

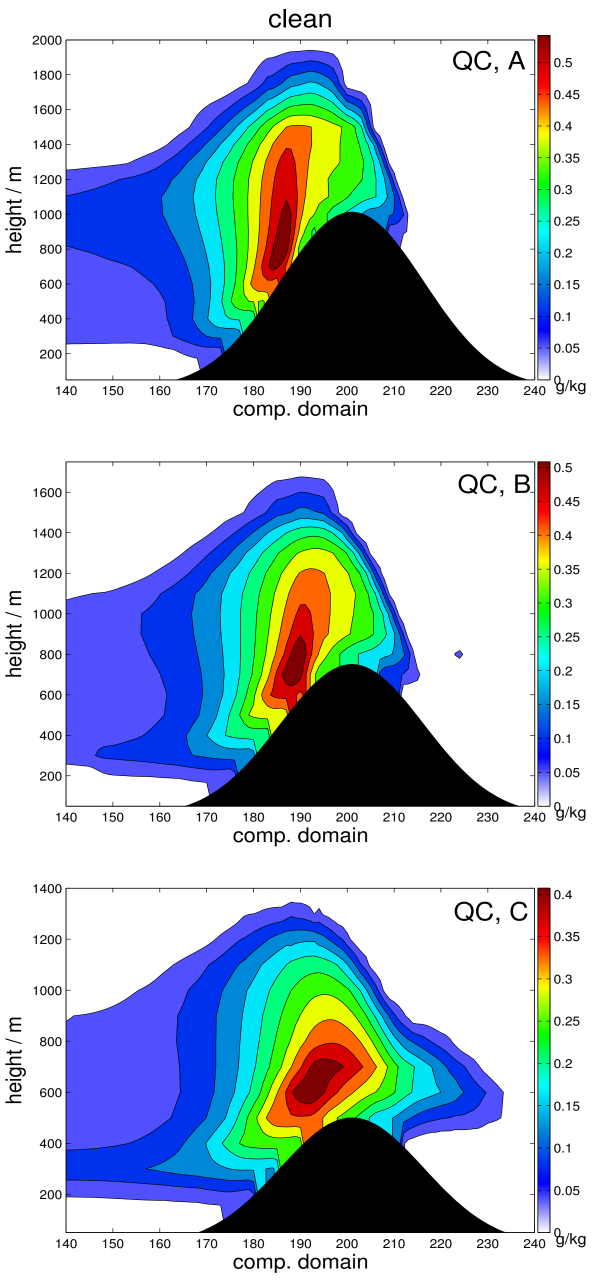

Figure 2: QC for the orographic clouds in the clean case simulations (A-C) after 6 h. QC is in units of g/kg.

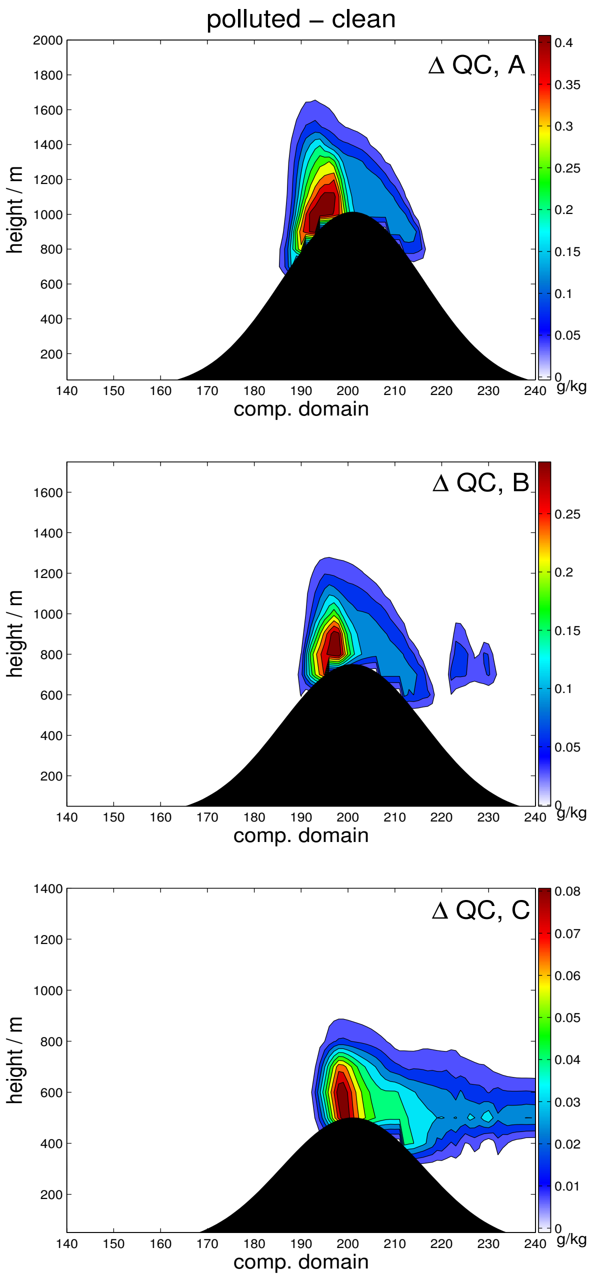

Figure 3: Difference fields of QC (polluted case minus clean case) for the orographic clouds after 6 h. Units are g/kg.

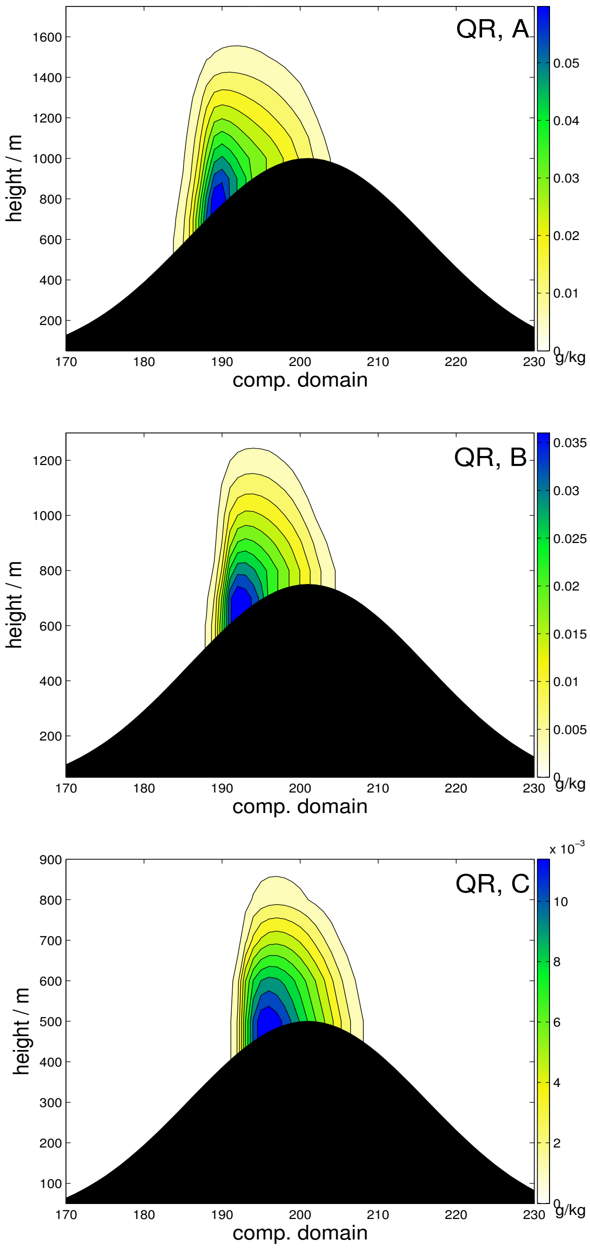

Figure 4: QR for the orographic clouds in the clean case simulations (A-C) after 6 h. QR is in units of g/kg.

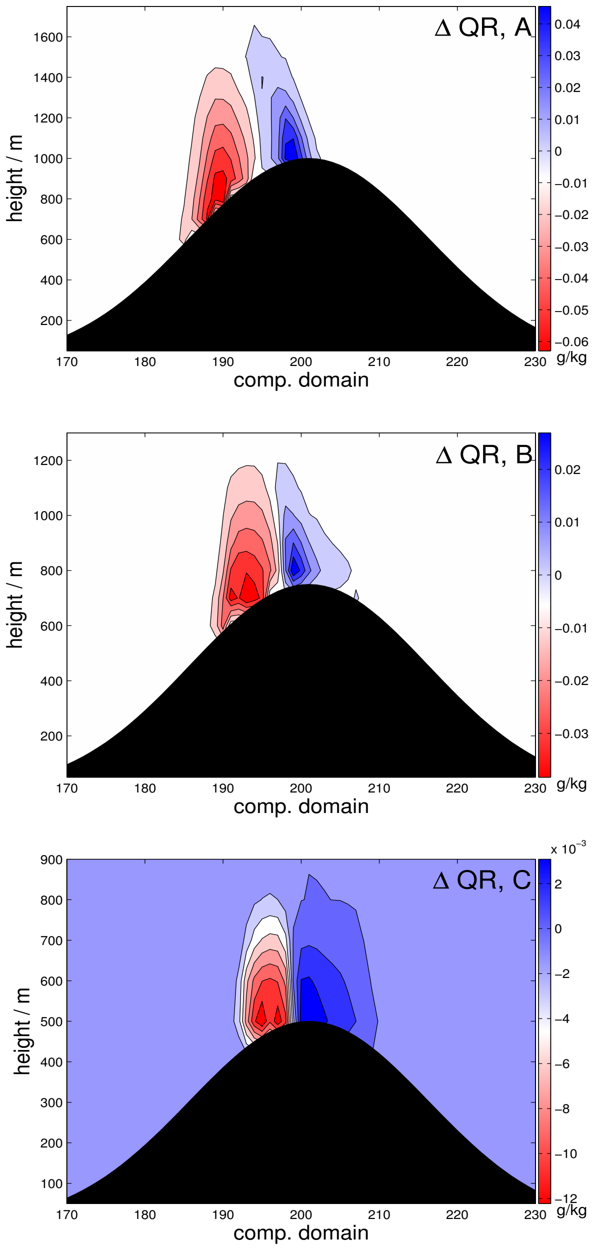

Figure 5: Difference fields of QR (polluted case minus clean case) for the orographic clouds after 6 h. Units are g/kg.

Figure 2 shows the cloud water mixing ration (QC) for the orographic clouds in the clean case simulations A-C after 6 h. The orographic cloud forms a result of the forced smooth ascent of the moist ambient air along the upslope mountain side. As the mountain height decreases the maximum values of QC shift towards the mountain peak. Note that the prevailing wind direction is from left to right in all figures.

In figure 3 the difference fields (polluted case minus clean case) for QC are shown. The fact that the differences are positive implys that the LWC is higher in the polluted case than in the clean case. Furthermore, the cloud water in the polluted case is much more advected to the leeward side which suggests that the conversion process of cloud droplets into rain is prolongated. In contrast to simulation C, the dry downslope winds in the simulations A and B evaporate the cloud water on the leeward side and the downstream advection of cloud water is less pronounced.

The figures 4 and 5 show the mixing ratio of rain water (QR) and the difference fields (polluted case minus clean case) of rain water (ΔQR), respectively. Generally, as the mountain height decreases the pattern of QR shifts further downstream and the maximum values of QR occur close to the mountain peak. The difference fields ΔQR show the development of a dipole structure in the rain water mixing ratio. In the polluted case the rain water content decreases at the upslope mountain side and increases further downstream on the mountain top and on the leeward side. This shift in QR directly translates into the spatial orographic precipitation pattern which is shown in figure 6.

In these simulations the total domain precipitation is always higher in the clean case than in the polluted case but the opposite holds true for the maximum precipitation. which suggests that the spatial precipitation pattern is changed. 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. Relative to the clean case the precipitation distribution narrows in the polluted case and the maximum of the precipitation distribution is shifted upslope towards the mountain peak and the leeward side. Note that the mountain peak is located at gridpoint 201 in the computational domain as indicated by the black triangle in figure 6.

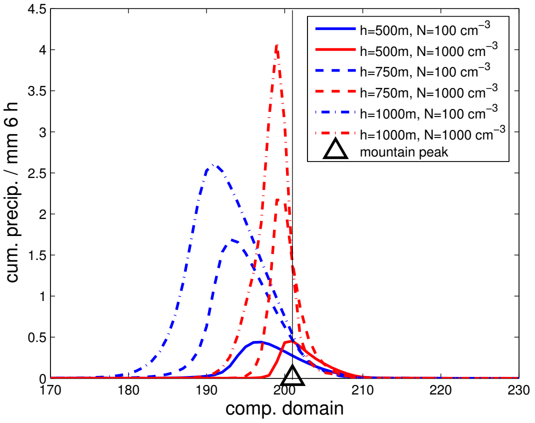

Figure 6: Spatial distribution of the orographic precipitation for the clean case (blue) and the polluted case (red) as a function of the mountain height h. The gridpoint precipitation is shown in units of mm after 6 h. Note that the mountain peak is located at gridpoint 201 in the computational domain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

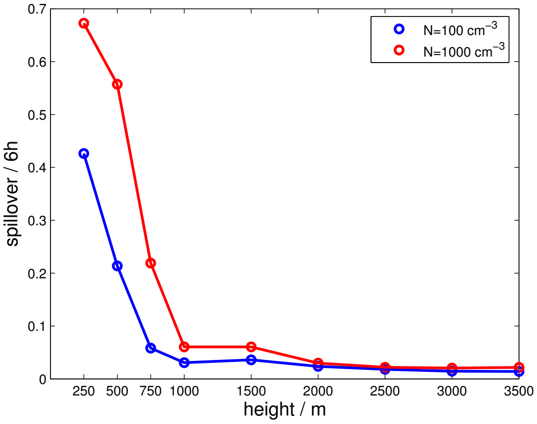

Figure 7: Spillover factor for the clean case (blue) and the polluted case (red) for various mountain heights h ranging from 250 m to 3500 m and after 6 h.

Due to the downstream shift of the precipitation distribution the spillover factor (SP) is higher in the polluted case than in the clean case. SP 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 is increasing due to the increased SP 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 which might indicate that optimum conditions for aerosol-cloud interactions influencing orographic precipitation may exist.

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 (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 obtained from idealized simulations suggest that aerosol-cloud interactions 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 and the precipitation distribution is changed. 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 goal of further experiments is to investigate the role of aerosol particles on the different orographic precipitation formation processes in more detail. From the microphysical point of view aerosols may prolongate the rain drop development 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.

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