Role of aerosols for warm-phase orographic precipitation in different dynamical flow regimes

A. Mühlbauer and U. Lohmann

ETH Zurich
Institute for Atmospheric and Climate Science

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Introduction

Anthropogenic and natural aerosols affect radiation and precipitation processes on a local scale:

- Aerosols serve as cloud condensation nuclei
- Aerosols change microphysical properties of clouds

Indirect aerosol effect: Increased aerosol number leads to

- more numerous but smaller cloud droplets (Twomey, 1977; Albrecht, 1989)
- smaller collision efficiency for cloud droplets (Pruppacher and Klett, 1997)
- deceleration of cloud drop coalescense process and rain drop development

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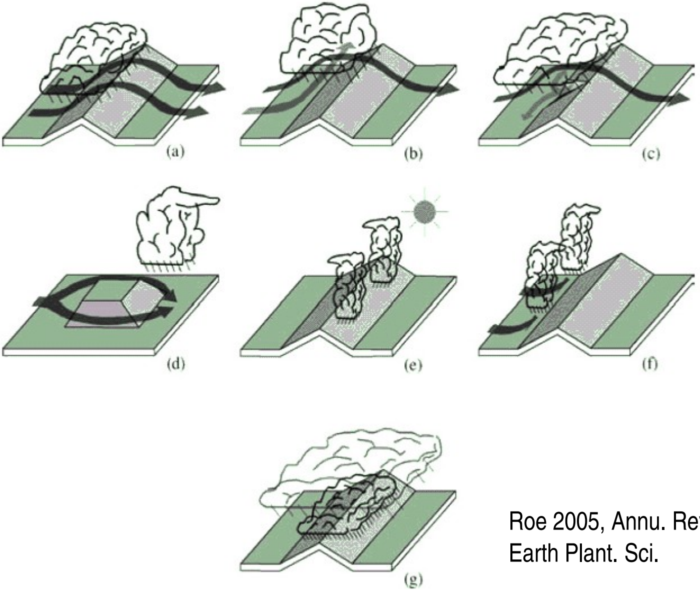
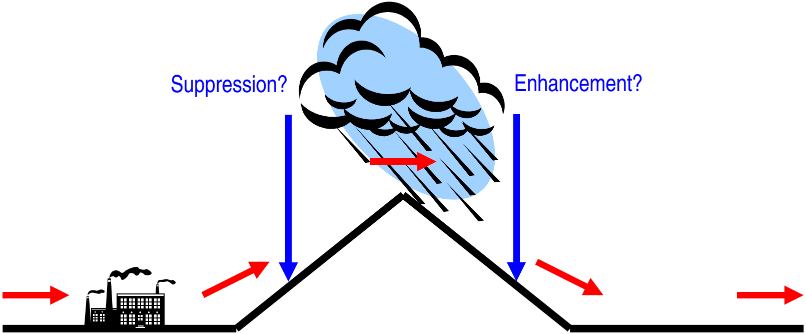
Mechanisms of orographic precipitation



Roe 2005, Annu. Rev. Earth Plant. Sci.

Motivation: Rosenfeld-Hypothesis



Hypothesis:

Suppression of orographic precipitation on the upslope side of the mountain and possible enhancement on the downslope side of the mountain (e.g. Givati and Rosenfeld, 2004; Jirak and Cotton 2006)

Questions:

- Can we observe such an effect in model simulations?
- How does the aerosol load affect the orographic precipitation pattern?
- Which atmospheric flows are most sensitive to the aerosol modification?

Model

- LMK 3.19 with Runge-Kutta dynamics
- 200 gridpoints ($\Delta x \approx 2$ km), 50 vertical levels, timestep 10 s
- 4th order positive definite advection scheme for moisture variables and aerosol tracer (Bott 1989)
- LES turbulence parameterization (Herzog et. al 2002)
- Aerosol-microphysics:
  - Aerosol dynamical module M7 of Vignatti et. al (2004)
- Cloud-microphysics:
  - Two-moment bulk microphysics scheme of Seifert and Beheng (2006)
  - Explicit calculation of condensation/evaporation for cloud droplets (similar to Lohmann and Kärcher, 2002)
  - Aerosol activation scheme based on Lin and Leaitch (1997) and Lohmann (2002)

Processes considered in M7

MODES IN M7	SOLUBLE/MIXED	INSOLUBLE
NUCLEATION (r < 0.005 μm)	1 N_1, M^1_{SO4}	
AITKEN (0.005 μm < r < 0.05 μm)	2 N_2, M^2_{SO4}, M^5_{BC}, M^9_{OC}	5 N_5, M^8_{BC}, M^{12}_{OC}
ACCUMULATION (0.05 μm < r < 0.5 μm)	3 N_3, M^3_{SO4}, M^6_{BC}, M^{10}_{OC}, M^{13}_{SS}, M^{15}_{DU}	6 N_6, M^{17}_{DU}
COARSE (0.5 μm < r)	4 N_4, M^4_{SO4}, M^7_{BC}, M^{11}_{OC}, M^{14}_{SS}, M^{16}_{DU}	7 N_7, M^{18}_{DU}

- Assuming lognormal size-distribution with fixed width
- Prognostic equations for aerosol number-/mass densities
- Source/sink terms include
  - Homogeneous nucleation of sulfuric acid
  - Coating of black/organic carbon by sulfuric acid
  - Condensation of sulfuric acid on insoluble/mixed modes
  - Intra-/intermodal coagulation

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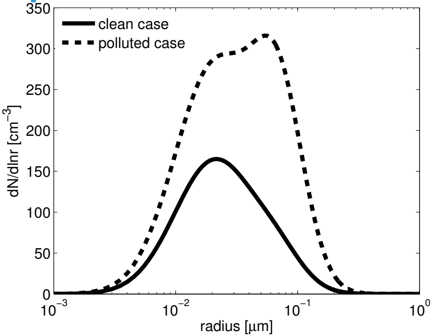
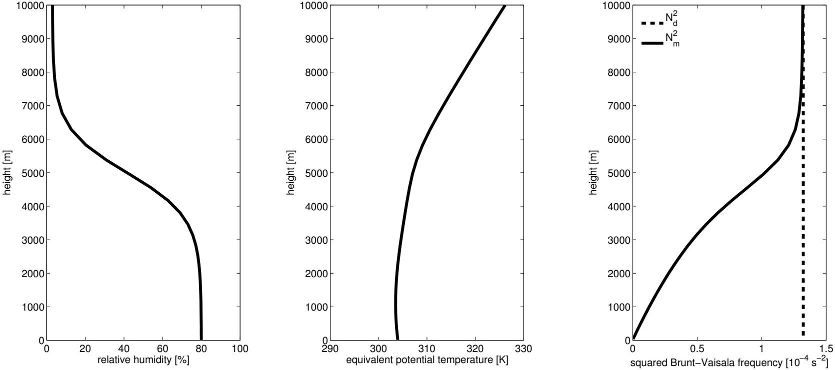
Initial aerosol spectra



- 2D-simulations of idealized flows (Experiment A, B) over an idealized topography (h=1000 m, a=10,30 km)
- Prescription of aerosol spectra (Weingartner et al. 1999), background (gasphase) sulfuric acid concentration and sulfate nuc. mode aerosols (Lohmann et al. submitted)
- Comparison of polluted case simulation against a clean case reference simulation by varying the aerosol size distribution

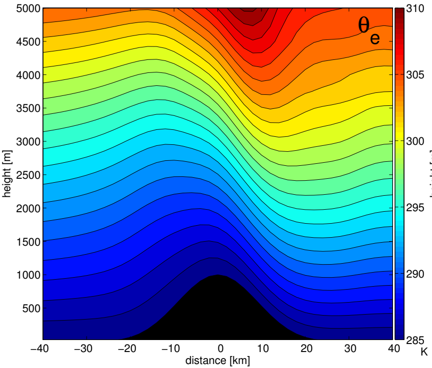
Initial condition



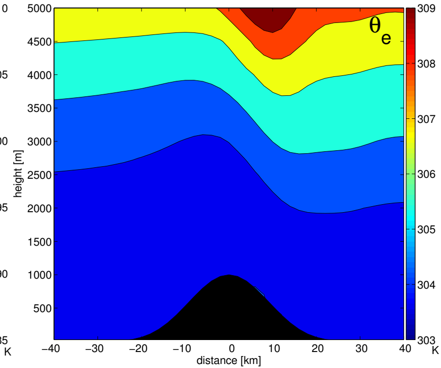
- $N_d = 0.0115\ \mathrm{s}^{-1}$, $p_{SL} = 1000$ hPa, $T_{SL} = 285$ K (Clark and Farley 1984)
- $RH_{SL} = 80$ % decaying with height (mod. Fermi-function after Spichtinger 2004)
- Lifting condensation level (LCL) at $z_{LCL} \approx 425$ m

Mountain wave after 6 h

Dry simulation:



Moist simulation:



$h = 1000$ m, $a = 10$ km, $U = 20$ m s^{-1}

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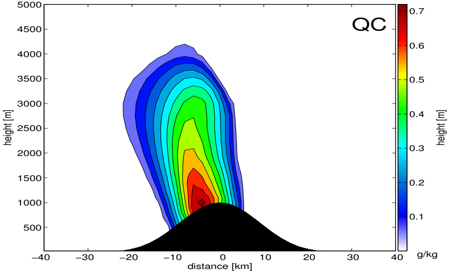
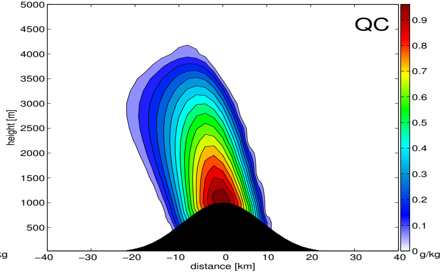
Cloud/rain water mix. rat. after 6 h

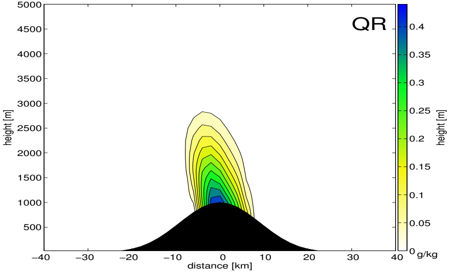
Clean case:



Polluted case:



Clean case:



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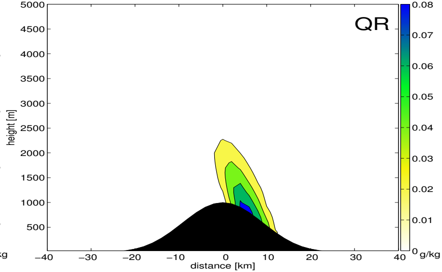

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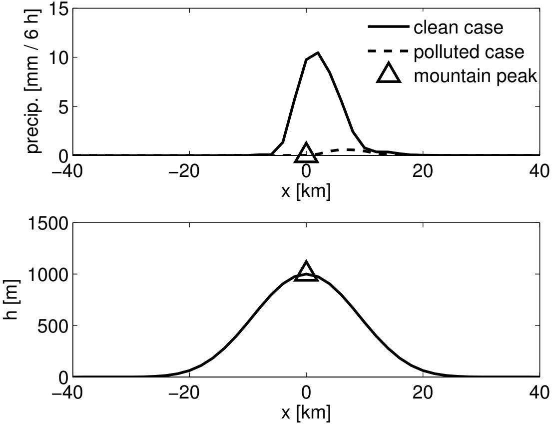
Orographic precipitation pattern after 6h

Narrow mountain ($a = 10$ km):



- Reduction in total (domain) precip. of almost 43 mm (94%)
- Shift of max. precip. of 4 km further towards leeward side
- $SP(clean) = 0.63$, $SP(polluted) = 0.99$, $\Delta SP = 0.36$

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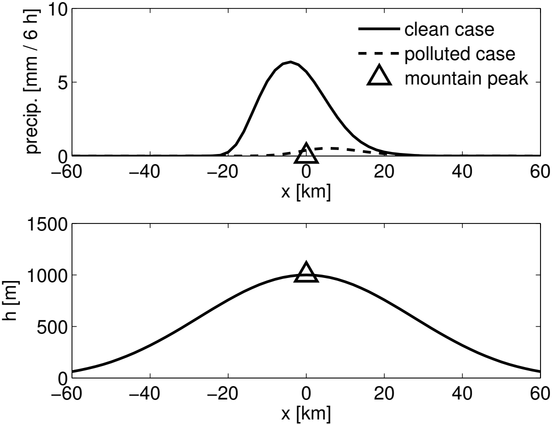
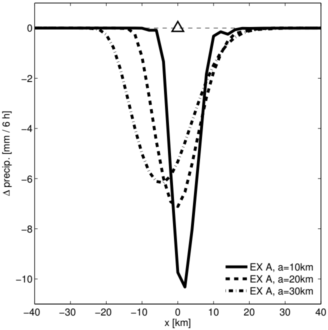
Orographic precipitation pattern after 6h

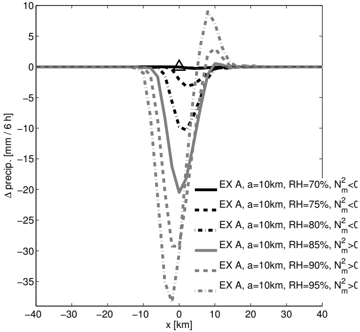
Wide mountain ($a = 30$ km):



- Reduction in total (domain) precip. of 61 mm (92%)
- Shift of max. precip. of 10 km towards leeward side
- $SP(clean) = 0.32$, $SP(polluted) = 0.78$, $\Delta SP = 0.46$

Surface precipitation differences after 6 h

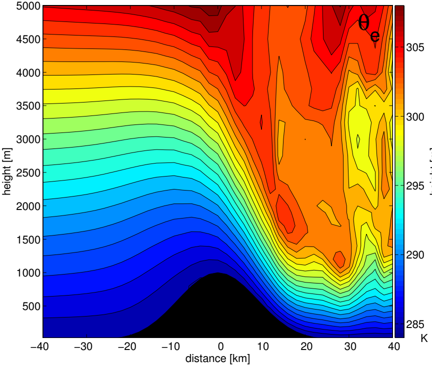




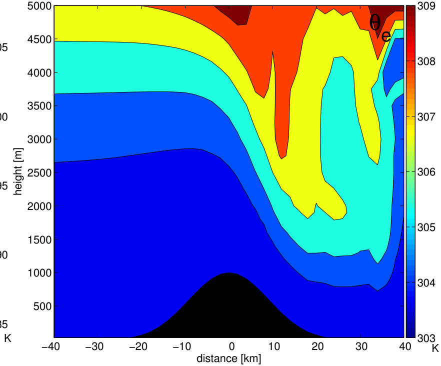
- Windward loss in orographic precipitation is not compensated by a leeward gain
- Evaporation of precipitation in downdraft region of mountain wave
- Only statically unstable upstream soundings lead to leeward precip. enhancement

Flow field after 6 h

Dry simulation:



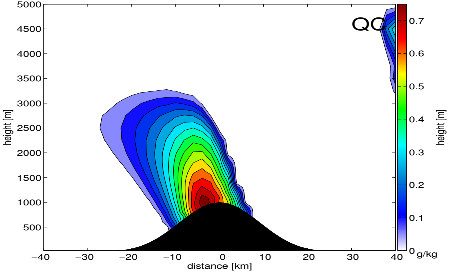
Moist simulation:



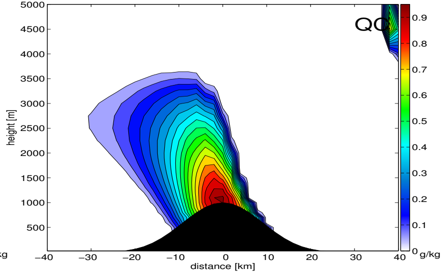
$h = 1000$ m, $a = 10$ km, $U = 14$ m s^{-1}

Cloud/rain water mix. rat. after 6 h

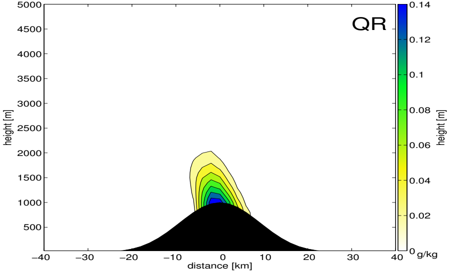
Clean case:



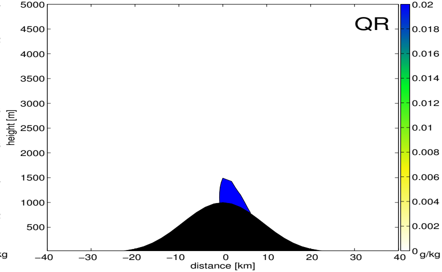
Polluted case:



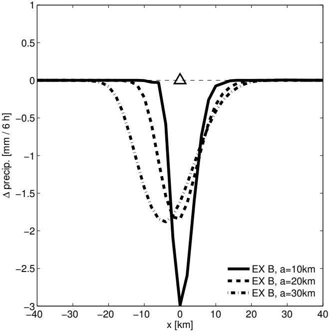
Clean case:

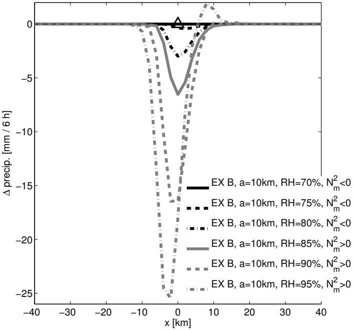


Polluted case:



Surface precipitation differences after 6 h





- Windward loss in orographic precipitation is not compensated by a leeward gain
- Strong downdrafts evaporate rain on the leeward side (barrier)
- Only the most unstable sounding produces very weak leeward precip. enhancement

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Conclusion

- 2D-simulations under idealized dynamical conditions
- Prescription of characteristic aerosol spectra
- Experiments with single low-level orographic clouds and isolated mountains
- Only warm phase microphysics considered

Suppression of orographic precipitation on the upslope side of the mountain...

Yes (aerosol-cloud-precipitation interaction)

...and possible enhancement on the downslope side of the mountain **depends on the flow regime (dynamics) and the stability of upstream sounding (thermodynamics). These parameters govern the role of hydrometeor advection, evaporation and sedimentation on the leeward side**

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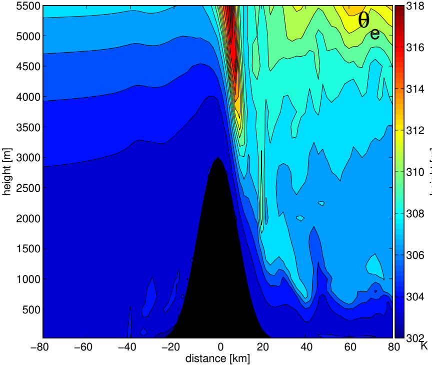
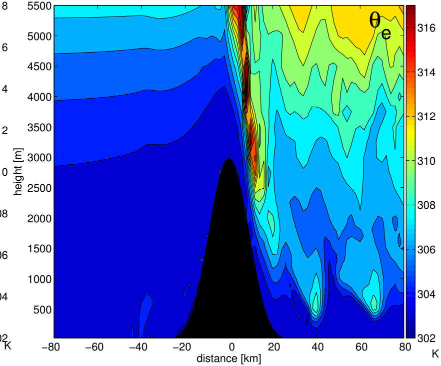
Thank you!

Flow field after 6 h (θ_e)

Clean simulation:



Poll. simulation:



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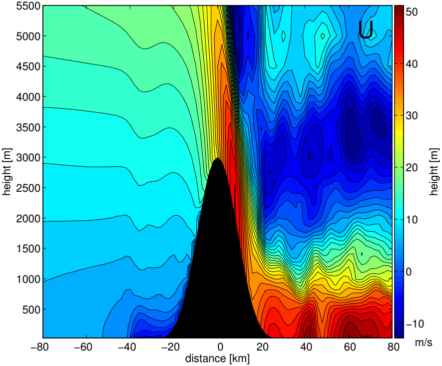
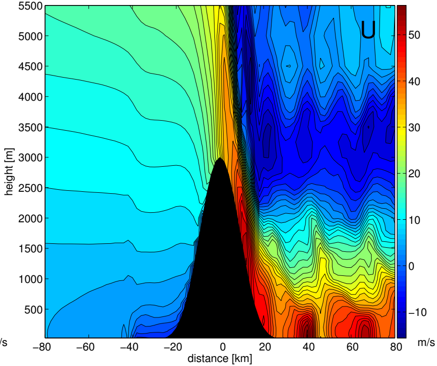
Flow field after 6 h (U)

Clean simulation:



Poll. simulation:



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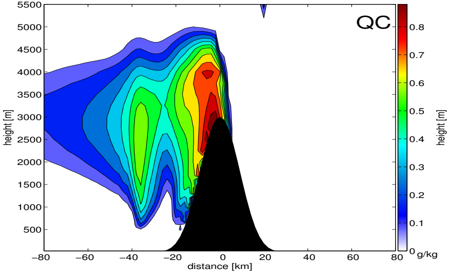
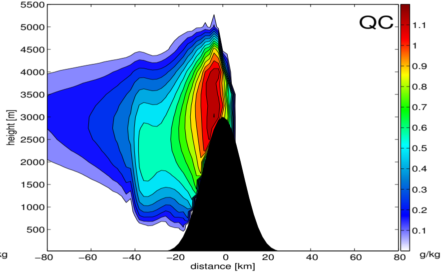
Cloud/rain water mix. rat. after 6 h

Clean case:



Polluted case:



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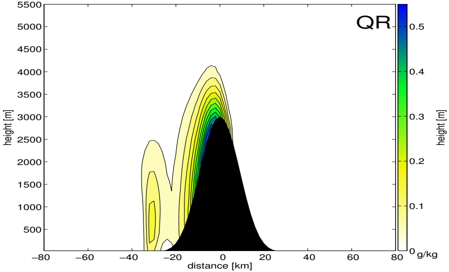

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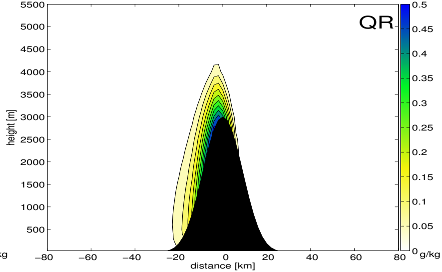

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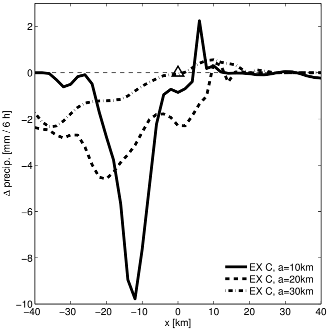
Surface precipitation differences after 6 h



Aerosol dynamics