Statistical Evaluation of the Indirect Aerosol Effect on Warm-Phase Orographic Precipitation

Elias M. Zubler
Andreas Mühlbauer, Ulrike Lohmann

ETH Zurich
Institute for Atmospheric and Climate Science

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Why a statistical (ensemble) approach?

1. Statistics potentially provide a more reliable estimate of the aerosol effect on warm-phase orographic precipitation compared to case studies (narrow down the uncertainty/quantify the uncertainty)

2. Since we apply a large range of different initial conditions for the model, we are able to study the sensitivity of the aerosol effect on orographic precipitation to changes in e.g. moisture, temperature
Outline

1. Introduction
2. Methodology
3. Results
4. Conclusions
Cloud lifetime effect

- Aerosols act as CCN and alter the microphysical properties of clouds
- In a cloud with constant LWC increasing the aerosol load leads to more numerous but smaller cloud droplets due to mass conservation (e.g. Twomey et al. 1984, Ferek et al. 2000)
- Small droplets have lower collision efficiencies than larger droplets (Pruppacher and Klett 1997)
- Consequently, hydrometeor growth is decelerated (cloud lifetime effect: Albrecht 1989)
Rosenfeld-Hypothesis

- Cloud lifetime effect leads to a loss of precipitation on the windward side of a ridge due to the slow-down of hydrometeor formation
- Possible precipitation enhancement on the drier lee side (downstream advection of precipitable water), shift in the precipitation pattern
Results from former studies

- Givati and Rosenfeld (2004): 15-25% loss of upslope precipitation in Israel and California, 15% gain on the drier lee side in polluted areas; no change in precipitation pattern in pristine surroundings (annual rain gauges)

- Jirak and Cotton (2006): 30% reduction of upslope precipitation in the Rocky Mountains (Denver region), rain gauges only from precipitation events with upslope rainfall

- Rosenfeld and Givati (2006): 24% reduction of upslope precipitation, 14% lee enhancement

- Lynn et al. (2007): 30% loss of precipitation on the windward side of the Rockies (2D modelling study), very cold sounding applied, bin cloud microphysics
Model setup

- COSMO 3.19, TVD-3rd order Runge-Kutta, 5th order advection
- 2D simulations, \( \Delta t \) 20s, \( \Delta x \) 2.2km, 12h integration, 50 vertical levels (Gal-Chen)
- 2nd order Bott scheme (Bott 1989): moisture variables, aerosol tracers
- 2-moment bulk cloud-microphysics (Seifert and Beheng 2006)
- No parameterization for large-scale convection, no soil model, radiation scheme is switched off
- Initialization: horizontally homogeneous fields of \( T, p, RH, u \), aerosol size distribution
Aerosol microphysics (Vignati et al. 2004)

Considered processes:

- Sulfuric acid: homogeneous nucleation, coating, condensation
- Intra-/ intermodal coagulation
- Water vapor uptake
Aerosol activation parameterization

For the activation of the soluble/mixed aerosols and cloud droplet nucleation, the following parameterization is used (Leaitch et al. 1996, Lin and Leaitch 1997, Lohmann 2002):

\[
N_c^t = \frac{N_a^t \omega}{\omega + \alpha N_a^t} \quad (1)
\]

\[
N_a^t = N_{COA} + N_{ACC} + \int_{\ln(r_{activ})}^{\infty} N_{AIT}(\ln r) \, d \ln r \quad (2)
\]

\[
r_{activ} = 35 \, \text{nm} \quad (3)
\]
Study setup - Ensemble range

- 178 00UTC soundings from Payerne, Switzerland
- Night soundings to avoid unstably stratified conditions
- Mean RH in the lowest 3000 m 80-90% (in order to yield precipitating orographic clouds)
Study setup - Topography

- Transect from operational COSMO2-topography
- The Jungfraujoch is the highest elevation in the domain
Study setup - Aerosol

- Climatology derived from measurements at Jungfraujoch (Weingartner et al. 1999)
- Typical winter (clean) and summer aerosol (polluted)
- Polluted case: more aerosols will be activated → more cloud droplets
Spillover precipitation

- Spillover factor, \( SP = \frac{P_{Lee}}{P_{Total}} \)
- \( SP \) decreases with mountain height (precipitation efficiency)
- Generally more spillover precipitation in polluted cases
Accumulated precipitation

Flow direction → → → →

- Accumulated precipitation reduced in polluted cases
- No complete shift in precipitation patterns
Relative differences in total domain precipitation (RPD = $\frac{P_{PC}}{P_{CC}} - 1$)

- Average: -14% (remember: 15-30% in previous studies)
- Std. dev.: 10%
- Median of RPD significantly differs from 0 ($p=0.00$, Wilcoxon signed-rank test).
Annual cycle (monthly means, 2002-2006)

- Percentiles (25, 50, 75) of RPD (black), monthly mean initial surface temperature (red solid) and mean 2m temperature in Payerne (2002-2006, red dashed)
- Aerosol effect on precipitation is subject to interseasonal variability
- Warmer/moister soundings yield smaller differences in total-mean domain precipitation than colder conditions
Conversion processes

- Conversion rates (here: accretion + autoconversion) = f(LWC)
- Since RH is between 80-90%, temperature mostly determines $q_v$ and LWC
Drying Ratio (DR)

DR = \frac{P}{F}, \ P = \text{precipitation rate}, \ \ F = \text{initial incoming moisture flux}

• DR decreases in polluted cases by 2% on average (mean clean case DR = 13%)
Limitations

- 2D simulations
- Different parameterizations of autoconversion and accretion may yield different results (size, but not the sign): Andreas Mühlbauer, Huang et al. (2007)
- Warm-phase microphysics (mixed-phase results could be different in case of large numbers of coarse aerosols which potentially serve as IN)
Conclusions

- There is statistical evidence for the cloud lifetime effect on orographic precipitation in 2D simulations.
- In general windward precipitation is suppressed, leeward rainfall is slightly enhanced.
- Earlier studies may have overestimated its magnitude (for a clear statement, climatological or NWP studies are required).
- The aerosol effect on precipitation may be subject to interseasonal variability: in summer, the effect of increasing aerosol loads on orographic precipitation was found to be smaller than in the colder seasons.
Thank you!
Aerosol activation parameterization

For the activation of the soluble/mixed aerosols and cloud droplet nucleation, the following parameterization is used (Leaitch et al. 1996, Lin and Leaitch 1997, Lohmann 2002):

\[
\left( \frac{\partial N_c}{\partial t} \right)_{NUC} = \max \left\{ \frac{1}{\Delta t} \left[ 0.1 (N_c^t)^{1.27} - N_c^{t-1} \right], 0 \right\} \quad (4)
\]

\[
\left( \frac{\partial L_c}{\partial t} \right)_{NUC} = m_{c,\text{min}} \left( \frac{\partial N_c}{\partial t} \right)_{NUC} \quad (5)
\]

\[
N_c^t = \frac{N_{a,w}^t}{w + \alpha N_a^t} \quad (6)
\]

\[
N_{a}^t = N_{COA} + N_{ACC} + \int_{\ln(r_{\text{activ}})}^{\infty} N_{AIT}(\ln r) \, d\ln r \quad . \quad (7)
\]
Feedback on dynamics

Average difference between polluted and clean cases

- left: cloud water (shaded) and rain water content (contours) in g/kg
- right: water vapor mass fraction (shaded) in g/kg and T (contours) in K