Aerosol effects on warm-phase and mixed-phase orographic clouds and precipitation

Andreas Muhlbauer

Joint Institute for the Study of the Atmosphere and Ocean (JISAO)
University of Washington, Seattle, WA

Orographic Precipitation and Climate Change Workshop
NCAR
March 13-15 2012
Outline

- Introduction
- Aerosol effects on warm-phase orographic clouds & precipitation
- Aerosol effects on mixed-phase orographic clouds & precipitation
- Variability of aerosol effects
- Role of aerosol mixing state (aerosol chemistry)
- Key uncertainties for modeling aerosol effects on precipitation
- Conclusions
Some microphysics terminology

Auto-conversion:
\[ c + c = r \]

Accretion:
\[ r + c = r \]

Aggregation:
\[ i + i = s \]

Riming:
\[ i + c = g \]
Cloud droplet nucleation

- Aerosol activation depends on supersaturation, aerosol size and composition
- Once cloud droplets form, remaining aerosols and cloud droplets compete for supersaturated water vapor
Heterogeneous freezing mechanisms relevant for orographic precip. at mid-latitudes are condensation/immersion and contact freezing.
Microphysical collection efficiencies

Collision/coalescence efficiencies

Riming efficiencies

- Collision efficiency decreases with decreasing cloud droplet size
- Riming efficiency decreases with decreasing cloud droplet size (Lew et al. 1986)
Indirect aerosol effects on clouds and precipitation

A conceptual picture (IPCC, Ch. 7, Denman et al. 2007):

Cloud albedo and lifetime effect (negative radiative effect for warm clouds at TOA; less precipitation and less solar radiation at the surface)

More reflection → higher albedo

Clean

Polluted

Glaciation effect (positive radiative effect at TOA and more precipitation), thermodynamic effect (sign of radiative effect and change in precipitation not yet known)

Delays freezing → higher (and colder) clouds

Clean

Polluted

More ice crystals → more precipitation
Aerosol indirect effect on riming and snowfall?

Borys et al. 2003, GRL:

- Cases resemble the Twomey effect
- Observations indicate lower degree of riming and lower snowfall rates in case of smaller cloud droplets

**Caveat:** Role of dynamics is unclear for both cases and precipitation measurements are from two stations only
Problem of competing time scales

Time scale problem:

- Time available to form precipitable hydrometeors is constrained by the flow over the mountain
- Competition between microphysical time scale $\tau_m = \frac{q}{dq/dt}$ and dynamical time scale $\tau_d = \frac{a}{U}$

Two limits:

- $\tau_d \ll \tau_m \rightarrow$ high aerosol susceptibility of orographic precipitation
- $\tau_d \gg \tau_m \rightarrow$ low aerosol susceptibility of orographic precipitation
Do we know what the time scales are?

- Dynamical time scale is relatively straightforward
  (e.g., $U=10 \text{ m s}^{-1}$, $a=50 \text{ km} \rightarrow \tau_d=5000 \text{ s}$)

- Unfortunately, knowledge of microphysical time scale $\tau_m$ is very limited and relatively unconstrained from observations (factor 10)
  - Oregon Cascades: $\tau_m$ ranges from 500 s to 5000 s (Smith et al., 2005)
  - Andes: $\tau_m \approx 1700 \text{ s}$ (Smith and Evans, 2007)

- Assuming $\tau_m \approx 2100 \text{ s}$ gives $a_c < 20 \text{ km}$ as a “critical“ spatial scale where we should be able to measure an aerosol effect on orographic precipitation (if there is any)
Stably stratified flow and warm-phase microphysics

Mühlbauer and Lohmann 2008, JAS
Microphysical processes and sensitivities

In polluted case: Decrease in auto-conversion and accretion leads to less orographic rainfall and high aerosol susceptibility of orographic precipitation
Strong precipitation loss for narrow mountain range

Increasing the width of the mountain range reduces the loss of orographic rainfall (in agreement with time scale argument)
Blocked flow and warm-phase microphysics

Clean case:  
Polluted case:

[Graphs showing differences between clean and polluted cases]
Microphysical processes and sensitivities

In polluted case: Decrease in auto-conversion but increase in accretion leads to low aerosol susceptibility of orographic precipitation.
Advantages of a clean burning economy:

- 0% emissions of particulate matter
- 0% emissions of nitrogen oxides
- 0% emissions of sulfur dioxide
- 0% emissions of carbon monoxide
- 0% emissions of volatile organic compounds
Model intercomparison of aerosol-cloud interactions

Muhlbauer et al. 2010, ACP
Model intercomparison of aerosol-cloud interactions
Orographic precipitation distribution (Case 1)

(a) Rain (mm/10h)
(b) Snow (mm/10h)
(c) Graupel (mm/10h)
(d) Total precipitation (mm/10h)
Microphysical processes and sensitivities

- Collision/coalescence process is of minor importance
- Decrease in riming is *not* found robustly among the models
Importance of the ice phase

- WRF is the model with lowest IWP and highest sensitivity
- UWNMS is the model with highest IWP and lowest sensitivity
Orographic precipitation distribution (Case 2)

(a) Rain (mm/10h)

(b) Snow (mm/10h)

(c) Graupel (mm/10h)

(d) Total precipitation (mm/10h)
Microphysical processes and sensitivities
Variability of aerosol effects on orographic precip.
166 2D ensemble simulations over Swiss Alps (Zubler et al. 2011, JAS)
Aerosol effects on precipitation: Rain vs. snow

Empirical cumulative distribution of relative precip. difference (RPD)

\[
\text{RPD} = \frac{P_{\text{polluted}}}{P_{\text{clean}}} - 1
\]
Aerosol effects on precipitation: Rain vs. snow

25% of cases with largest aerosol effect on precip.: Warmer T, more LWC, less IWC, larger horizontal wind speeds → less orographic blocking
Role of aerosol mixing state and freezing properties

Mühlbauer and Lohmann 2009, JAS
**IN effect overwrites CCN effect?**

BC serves as contact IN

BC serves as immersion IN

▶ Case 1: Externally mixed black carbon acts as IN in contact freezing mode at warmer temperatures
→ IN effect outweighs CCN effect → increase in precipitation

▶ Case 2: Sulfuric acid coating/internal mixture *deactivates* IN
→ CCN effect dominates → decrease in precipitation
What are the key uncertainties in numerical models and microphysical parameterizations?

- Ice initiation by heterogeneous ice nucleation (strength of ice-phase is important for sign and magnitude of the aerosol indirect effect on precipitation)
- Number of ice crystals. Many past studies in mixed-phase clouds have shown high ice number conc. \((100-1000 \ \text{l}^{-1})\). However, many of these studies may be affected by particle shattering on cloud probes.
- Efficiency of ice aggregation process (temperature, crystal shape) as an important sink of ice crystals
- Artificial categorization in numerical models. Treatment of snow and graupel in numerical models and modeling the degree of riming
Conclusions

Dynamics point of view:

- The flow dynamics over/around the mountain are crucial and can significantly alter the aerosol sensitivity/susceptibility of orographic precipitation.
- Aerosol susceptibility may be lower (inverted?) for high mountain ranges (e.g., Alps, Rocky Mountains) and higher for small and narrow hills.
- Only a subset of the possible orographic precipitation mechanisms have been investigated and climatology of the mechanisms may strongly dependent on geography (e.g., orographically induced convection).
Conclusions

Microphysics point of view:

- In many cases collision/coalescence is not the dominant process for orographic precipitation formation (temperature dependence)
- Accretion can compensate for loss in auto-conversion
- Melting of sedimenting ice hydrometeors is a source for rain and can increase accretion rates in mixed-phase clouds
- Riming is found to increase as well as decrease with increasing aerosol number concentrations and, thus, is not a robust result
- Neither a loss in coalescence nor a loss in riming implies a loss in precipitation due to compensating microphysical pathways (e.g., increased aggregation)
- High uncertainty because many microphysical processes are not well constrained (e.g., ice aggregation, heterogeneous nucleation)
Thank you!

Questions?