Aerosol-Cloud Interactions

- Small-scale modeling
- In-situ measurements
- Surface-based remote sensing

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Contributions from many divisions in ESRL
A Complex System with Myriad Feedbacks

Cloud $\leftrightarrow$ Aerosol

$\leftarrow$ Aerosol affects cloud radiative properties, precipitation
$\leftarrow$ Absorbing aerosol reduces cloud “aerosol absorption effect” (semi-direct)
$\rightarrow$ Scavenging by rain
$\rightarrow$ Aqueous chemistry (inorganic + organic)

Cloud $\leftrightarrow$ Dynamics

$\leftarrow$ Convection
$\rightarrow$ Evaporation, precipitation

Cloud $\leftrightarrow$ Radiation

$\leftarrow$ Longwave cooling, absorption
$\rightarrow$ Indirect Effects

Aerosol-Cloud-Dynamics-Radiation-Chemistry-Land-surface
What is NOAA ESRL’s Role?

To understand the fundamental processes at the micro-to-cloud scale ($\mu m - 10s \ km$) and to improve representation of aerosol-cloud interactions in regional scale $\rightarrow$ GCM models

- **Predictive GCM**
  - Regional/Global scale

- **Mesoscale Models**
  - Cloud resolving Models
  - Regional Models
  - $10s \ km - 1000s \ km$

- **Process Models**
  - $\sim 10s \ km$

- **Forcing on regional and global scale**
  - (GFDL, ESRL)

- **Aerosol transport and its effect on clouds**
  - (ESRL)

- **Large Eddy Simulations; microphysical models; Aerosol $\leftrightarrow$ cloud interactions**
  - (ESRL)
Precipitation
Water vapor uptake
Aqueous chemistry (sulfate, organic)
Aerosol effects on μphysics
Aerosol pumping by clouds
Radiative forcing
Nucleation
Drizzle
Land surface processes
IPCC Forcing
IPCC Feedbacks
Cloud dynamics
CCN measurements
Work in progress
Work in ESRL
Ice processes
Work in progress
Radiative forcing
Drizzle
Water vapor uptake
Aerosol effects on sfc radiation
Ice processes
IPCC Forcing
IPCC Feedbacks
Cloud dynamics
CCN measurements
Work in progress
Work in ESRL
Ice processes
Topics to be addressed:

- Work in progress
- No time to discuss

IPCC Feedbacks:

- Radiative forcing
- Aerosol pumping by clouds
- Aqueous chemistry (sulfate, organic)
- Water vapor uptake
- CCN measurements

IPCC Forcing:

- Nucleation
- Drizzle
- Aerosol effects on μphysics
- Land surface processes
- Precipitation

Ice processes:

- Ice processes
- IPCC Forcing

No time to discuss:

- Topics to be addressed
Remote Sensing of Aerosol-Cloud Interactions: Satellite vs Surface

Surface remote sensing avoids ambiguity of aerosol/cloud interface
**Measurements of Aerosol-Cloud Interactions**

**Slope (ACI) is a measure of the magnitude of the cloud response to aerosol**

**Slope determined by:**
- aerosol number conc.,
- size/composition, updraft, etc.

**Important to sort data by liquid water (Twomey)**

\[
ACI = \frac{\partial \ln \tau_d}{\partial \ln \alpha} \bigg|_{LWP}
\]

\[
ACI = -\frac{\partial \ln r_e}{\partial \ln \alpha} \bigg|_{LWP}
\]

\[
ACI = \frac{1}{3} \frac{d \ln N_d}{d \ln \alpha}
\]

\[\alpha = \text{aerosol}\]

Breon et al. 2002

McComiskey et al. 2008, SCu

ACI = 0.10 - 0.15

Sorted by LWP
Aerosol-Cloud microphysical response and TOA Radiative Forcing

- Some GCMs use satellite-derived “slope” to represent aerosol effects on clouds
- Errors in slope yield large errors in forcing
- Weakest indirect forcing in IPCC (2007) is associated with satellite-derived slopes

Flux change resulting from CCN changing from 100 to 1000 cm⁻³; Diurnal average based on 100% cloud cover
Topics to be addressed

No time to discuss

Work in progress

Ice processes

Precipitation

Land surface processes

Aerosol effects on \( \mu \)physics

Drizzle

Aerosol pumping by clouds

Radiative forcing

IPCC Forcing

IPCC Feedbacks

Aqueous chemistry (sulfate, organic)

Water vapor uptake

CCN measurements

Particulate physics

No time to discuss
Higher-order Indirect Effects (IPCC feedback)

More aerosol $\rightarrow$ more drops $\rightarrow$ less coalescence $\rightarrow$ less rain $\rightarrow$ higher LWP $\rightarrow$ higher cloud fraction $\rightarrow$ longer lifetime

A monotonic response...
Higher-order Indirect Effects  (IPCC feedback)

More aerosol $\rightarrow$ more drops $\rightarrow$ less coalescence $\rightarrow$ less rain $\rightarrow$ higher LWP $\rightarrow$ higher cloud fraction $\rightarrow$ longer lifetime

A non monotonic response...

Some satellite observations and our models suggest the sign of these responses may not always be positive

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Xue, Feingold, Stevens, 2008
Why? Competing Aerosol effects on Cloud Microphysics

- Small droplets do not coalesce efficiently $\rightarrow$ less rain

vs.

- Small droplets evaporate faster than large ones
  
  Ratio of timescales for evaporation (clean vs polluted)
  
  may be a factor of 5-10

\[
\frac{dr}{dt} \propto \frac{S}{r}
\]

- Microphysical feedbacks complicate the simple monotonic response

- Rain, LWP, cloud fraction and lifetime responses are not simply connected
Absorbing aerosol: the semi-direct effect

Non-monotonic response of cloud optical depth to increase in smoke aerosol

Modeling: Jiang and Feingold 2006

Observations: Koren et al. 2008
Aerosol → Cloud → Radiation: Model-Measurement Comparisons during Houston 2006

- Generally good comparison between LES model and in-situ measurements: LWC, $N_d$
- Also good comparison for irradiance (provided aerosol and cloud are included!)

Schmidt, Pilewskie et al., 2008

Comparison of 100s of clouds

NOAA, CalTech, CIRPAS, Univ. of Colorado collaboration
Aerosol Effects on Cloud Morphology via Drizzle

Onset of drizzle results in transition to open-cell convection.

Closed-cell Albedo $\sim 0.6$ (non-precipitating)

Open-cell Albedo $\sim 0.2$ (precipitating)

WRF Model + 2-moment $\mu$-physics; 60 km domain; $\Delta x = \Delta y = 300$ m, $\Delta z = 30$ m

Garay et al. 2004, MISR

Wang and Feingold, 2008
Summary

**Albedo Effect**
- Significant improvement in understanding of processes through observations and modeling;
- GCMs that use remote-sensing estimates of aerosol-cloud interactions likely underestimate the albedo effect.

**Higher-Order Indirect Effects**
- Improved understanding of complexity of feedbacks in the coupled aerosol-cloud system;
- GCM representation of the higher order indirect effects is inadequate since it *prescribes* an increase in cloud lifetime and cloud fraction responses.
Future

Small Clouds

Further verification that small clouds behave differently from large clouds

Exploration of Self-Regulation Mechanisms

Mixed-Phase Clouds

Precipitation