Aerosol-Cloud Interactions

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

Graham Feingold
A Complex System with Myriad Feedbacks

*Cloud ↔ Aerosol*

← Aerosol affects cloud radiative properties, precipitation
← Absorbing aerosol causes “cloud burning” (semi-direct)
→ Scavenging and wet deposition
→ Aqueous chemistry (inorganic + organic)

*Cloud ↔ Dynamics*

← Convection
→ Evaporation, precipitation

*Cloud ↔ Radiation*

← Longwave cooling, absorption
→ Scattering, absorbing

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

To understand the fundamental processes at the micro-to-cloud scale (\(\mu m \rightarrow 10s \ km\)) 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**
\(~ 10s \ km\)

Forcing on regional and global scale (GFDL)

Effect of aerosol transport on clouds

Large Eddy Simulations of aerosol \(\leftrightarrow\) cloud interactions;
Observations (in-situ and remote)
Aqueous chemistry (sulfate, organic)

aerosol effects on μphysics

Radiative forcing

IPCC Forcing

aerosol pumping by clouds

water vapor uptake

nucleation

drizzle

Land surface processes

aerosol effects on sfc radiation

CCN measurements

IPCC Feedbacks

Radiative forcing

Ice processes

Work in progress

Work in ESRL
Remote Sensing of Aerosol-Cloud Interactions: Satellite vs Surface

Surface remote sensing avoids ambiguity of aerosol/cloud interface

Satellite
- drop size, reflectance
- aerosol optical depth

Surface
- drop size
- aerosol optical depth

Column measurements of aerosol and cloud properties

the small box
**Measurements of Aerosol-Cloud Interactions**

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

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

Define slopes as ACI:

\[
ACI = \left. \frac{\partial \ln \tau_d}{\partial \ln \alpha} \right|_{\text{LWP}} = \left. -\frac{\partial \ln r_e}{\partial \ln \alpha} \right|_{\text{LWP}} = \frac{1}{3} \frac{d \ln N_d}{d \ln \alpha}
\]

\( \alpha = \text{aerosol} \)
Modeling: Sensitivity of drop size $r_e$ to various parameters

$$S_i = \frac{d \ln r_e}{d \ln X_i}$$

<table>
<thead>
<tr>
<th>$X_i$</th>
<th>All</th>
<th>Clean</th>
<th>Polluted</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWC</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>updraft</td>
<td>-0.10</td>
<td>-0.06</td>
<td>-0.17</td>
</tr>
<tr>
<td>number</td>
<td>-0.28</td>
<td>-0.30</td>
<td>-0.12</td>
</tr>
<tr>
<td>size</td>
<td>-0.09</td>
<td>-0.11</td>
<td>-0.11</td>
</tr>
<tr>
<td>dispersion</td>
<td>0.16</td>
<td>0.11</td>
<td>0.26</td>
</tr>
<tr>
<td>Soluble fraction</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

- Number and size matter most
- Updraft more important when polluted
- Composition relatively unimportant

$r_e \propto \left( \frac{LWC}{N_d} \right)^{1/3}$

$\Rightarrow S_{LWC} = 0.33$

Feingold, GRL 2003
Relating Aerosol-Cloud Interactions to TOA Radiative Forcing: Modeling

- GCMs use ACI to represent aerosol effects on clouds
- Errors in ACI translate to large errors in forcing

1. Perturbation of 500 cm\(^{-3}\) vs. 100 cm\(^{-3}\)
2. 2500 cm\(^{-3}\) vs. 100 cm\(^{-3}\)

\[ ACI = \left. \frac{\partial \ln \tau_d}{\partial \ln \alpha} \right|_{LWP} = \left. \frac{\partial \ln r_e}{\partial \ln \alpha} \right|_{LWP} = \frac{1}{3} \frac{d \ln N_d}{d \ln \alpha} \]

McComiskey and Feingold, GRL, 2008
Topics to be addressed

No time to discuss

Work in progress

Aqueous chemistry (sulfate, organic)

Radiative forcing

aerosol effects on μphysics

IPCC Forcing

nucleation

drizzle

Land surface processes

precipitation

aerosol effects on sfc radiation

CCN measurements

IPCC Feedbacks

aerosol pumping by clouds

water vapor uptake

dynamics
Higher-order Indirect Effects

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 contd..

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…

- Microphysical feedbacks complicate the simple linear response

- Rain, LWP, cloud fraction and lifetime responses are not necessarily connected
Aerosol Effects on Cloud Lifetime: modeling

- There are no observations of aerosol effects on cloud lifetime!
- Modeling: No statistical signal for aerosol effect on cloud lifetime

Based on analysis of 100s of individual modeled cumulus clouds

Jiang, Xue, Teller, Feingold, Levin: GRL 2006
Aerosol Effects on Cloud Morphology via Drizzle

Time
Δt ~ 60 min

Onset of drizzle results in transition to open-cell convection

Garay et al. 2004, MISR
Xue, Feingold, Stevens 2008
Comparison between Model and In-situ Observations

Clouds in Houston sampled by aircraft; CIRPAS/CalTech/NOAA

Clouds modeled by large eddy simulation

Jiang, Feingold, et al. 2008
Statistical Comparisons

Generally good comparison between model and in-situ measurements: LWC, \(N_d\), updraft; Irradiance (aerosol + cloud)

Comparison of 100s of clouds

Jiang, Feingold, et al. 2008
Absorbing aerosol: modeling of the semi-direct effect

Absorbing aerosol suppresses clouds

The importance of coupling aerosol radiative properties in dynamical models

- Non monotonic response of cloud optical depth to increase in smoke aerosol
- Reduction in surface fluxes due to smoke is primary reason for cloud “burning”

Jiang and Feingold 2006
Summary

Albedo Effect

- Significant improvement in understanding of processes through observations and modeling;
- GCMs that use satellite 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.
The Future

*More aerosol-cloud-climate work*
- Modeling, observations, bridging the scale gap

*Ice Modeling*
- Aerosol-cloud interactions in Arctic Stratus

*Aerosol Effects on Precipitation in Deep Convective Clouds*
- Water resources are in increasingly short supply
  (population pressures and climate change)

A bright future for cloud studies!