Aerosol-Cloud Interactions

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

Graham Feingold

Hongli Jiang, Allison McComiskey, Hailong Wang
Huiwen Xue

Contributions from many divisions in ESRL

A Complex System with Myriad Feedbacks

Cloud ←→ Aerosol

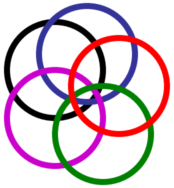
← Aerosol affects cloud radiative properties, precipitation
← Absorbing aerosol reduces cloud “aerosol absorption effect” (semi-direct)
→ Scavenging by rain
→ Aqueous chemistry (inorganic + organic)

Cloud ←→ Dynamics

← Convection
→ Evaporation, precipitation

Cloud ←→ Radiation

← Longwave cooling, absorption
→ Indirect Effects

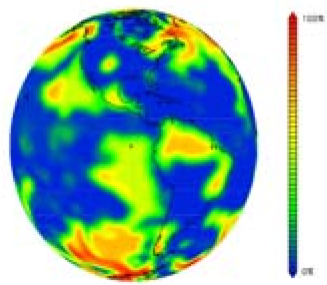


Aerosol-Cloud-Dynamics-Radiation-Chemistry-Land-surface

What is NOAA ESRL's Role?

To understand the <u>fundamental processes</u> at the micro-to-cloud scale (μm – 10s km) and to improve representation of aerosol-cloud interactions in regional scale → GCM models

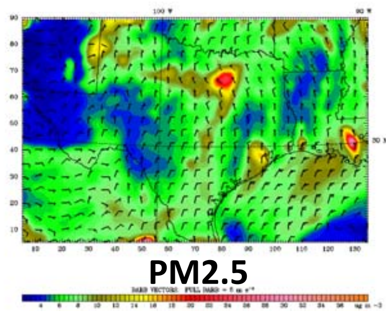
Predictive GCM
Regional/Global scale



Forcing on regional and global scale (GFDL, ESRL)

↑

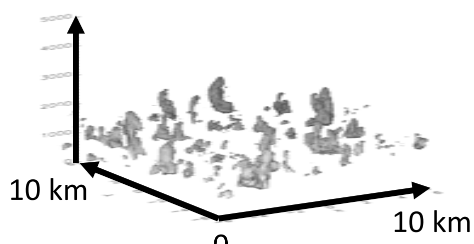
Mesoscale Models
Cloud resolving Models
Regional Models
10s km – 1000s km



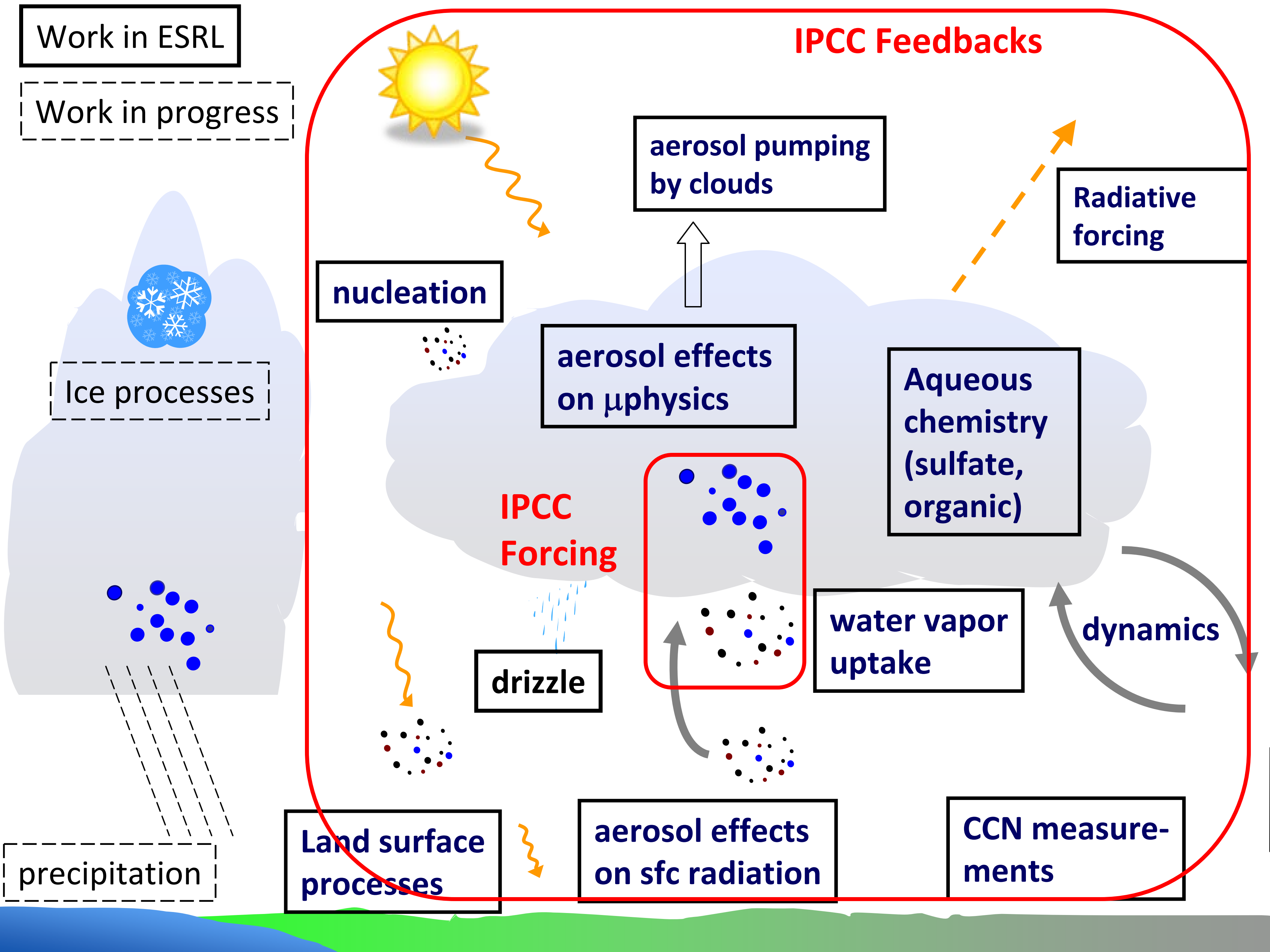
Aerosol transport and its effect on clouds (ESRL)

↑

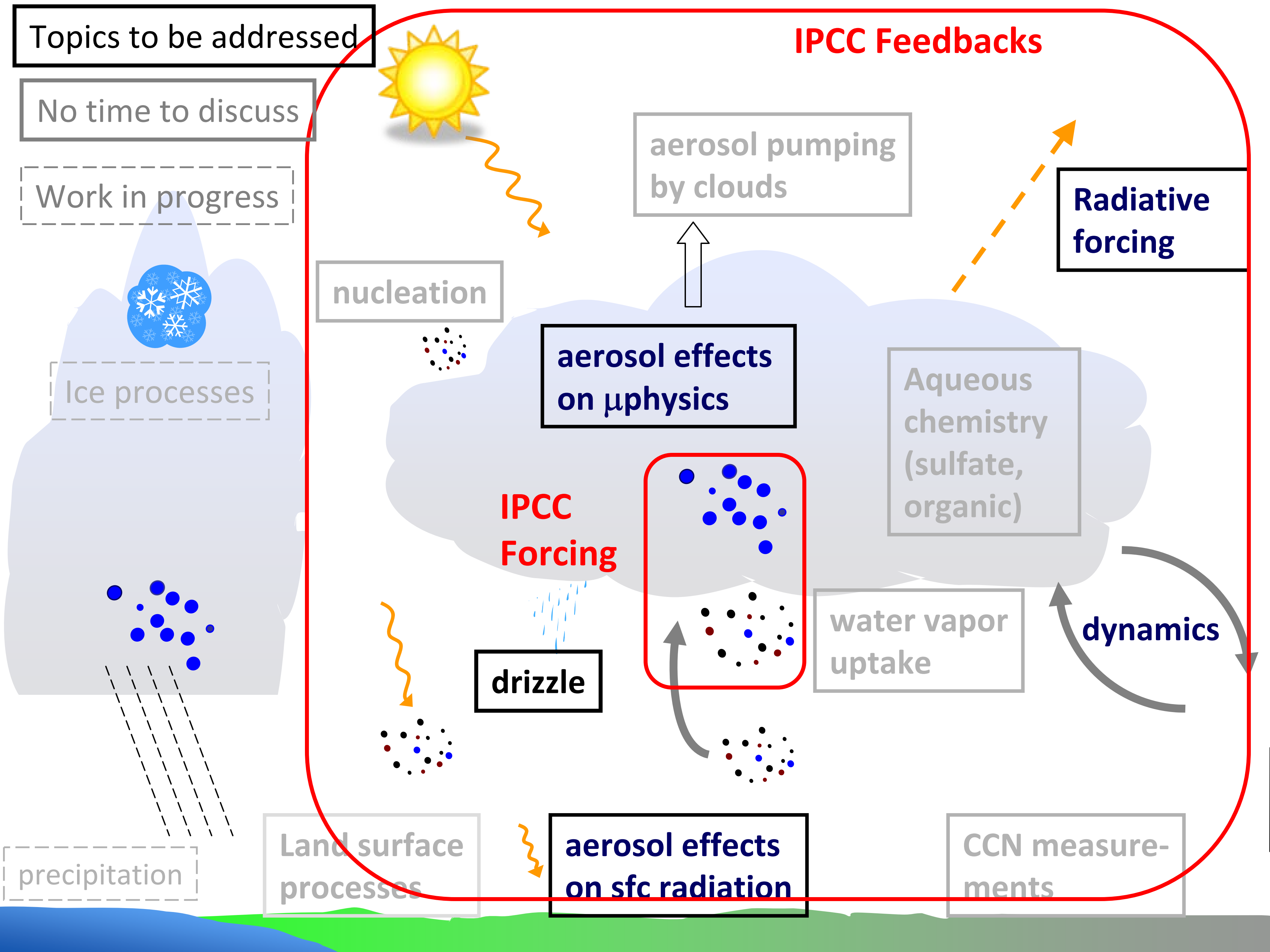
Process Models
~ 10s km



Large Eddy Simulations; microphysical models; Aerosol ←→ cloud interactions (ESRL)



Work in ESRL
Work in progress
IPCC Feedbacks
aerosol pumping by clouds
Radiative forcing
nucleation
aerosol effects on μphysics
Aqueous chemistry (sulfate, organic)
Ice processes
IPCC Forcing
drizzle
water vapor uptake
dynamics
precipitation
Land surface processes
aerosol effects on sfc radiation
CCN measure-ments


Topics to be addressed
No time to discuss
Work in progress
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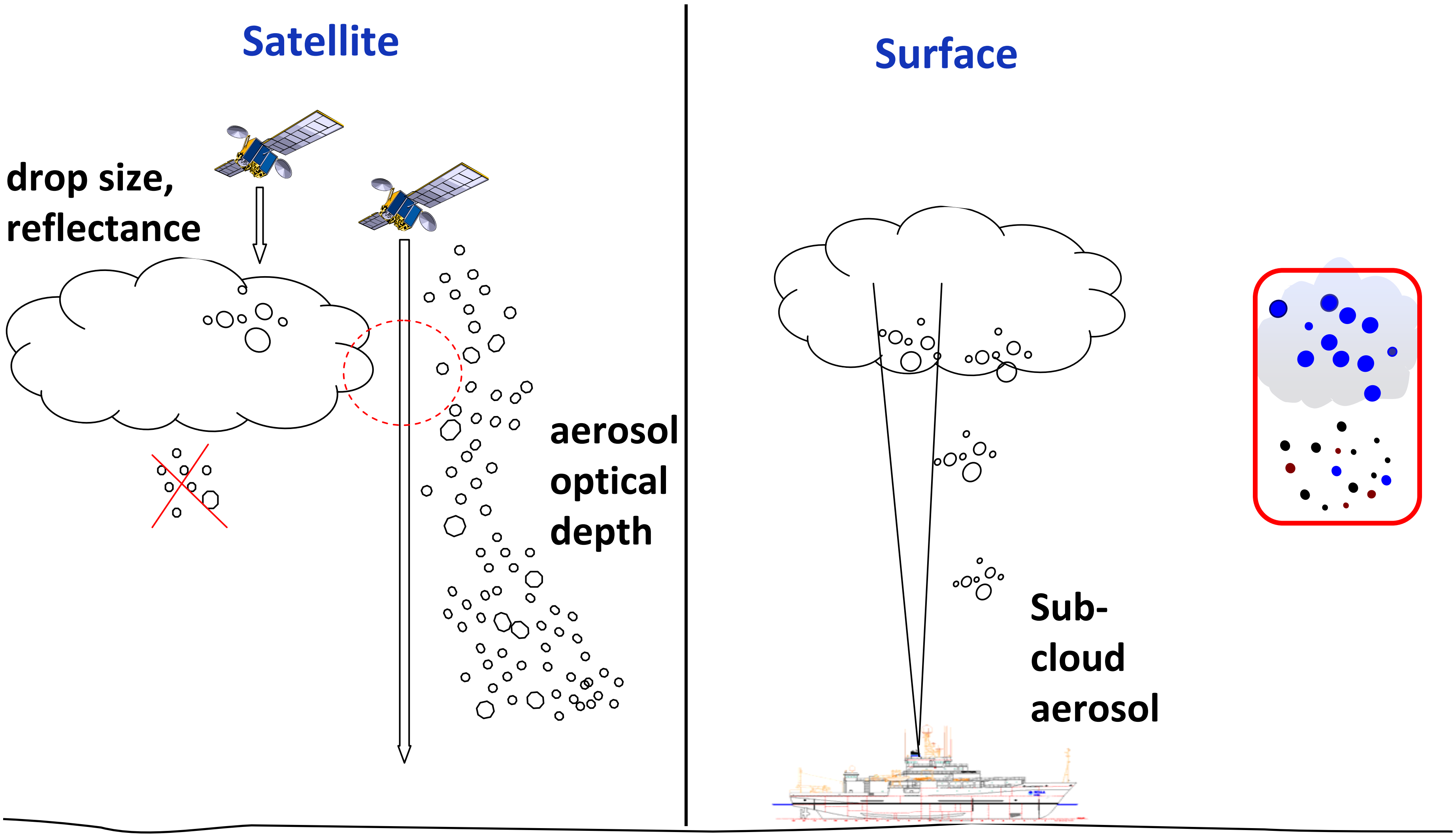
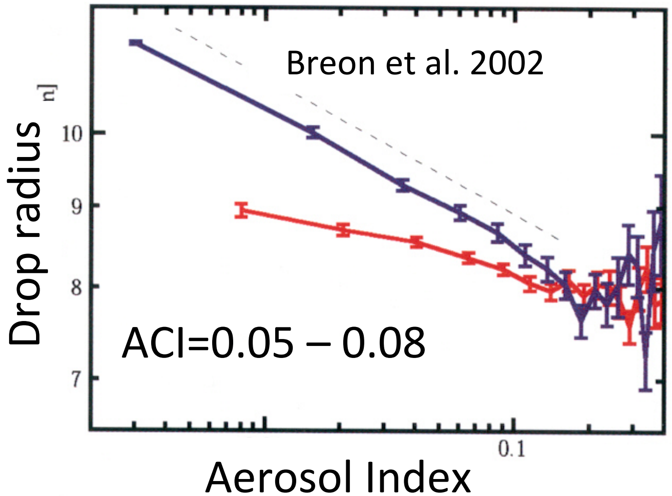
Remote Sensing of Aerosol-Cloud Interactions: Satellite vs Surface

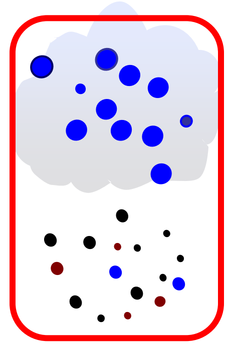


Surface remote sensing avoids ambiguity of aerosol/cloud interface

Measurements of Aerosol-Cloud Interactions

Satellite remote-sensing





Define slopes as ACI:
Aerosol-Cloud-Interactions

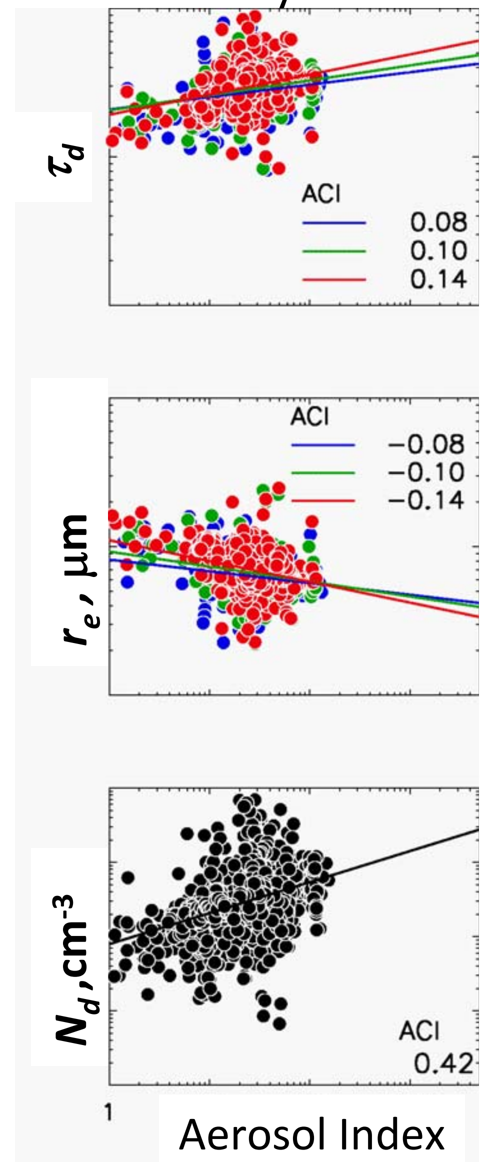
$$ACI = \left.\frac{\partial \ln \tau_d}{\partial \ln \alpha}\right|_{LWP}$$

$$ACI = -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_{LWP}$$

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

α = aerosol

ACI = 0.10 - 0.15
Sorted by LWP



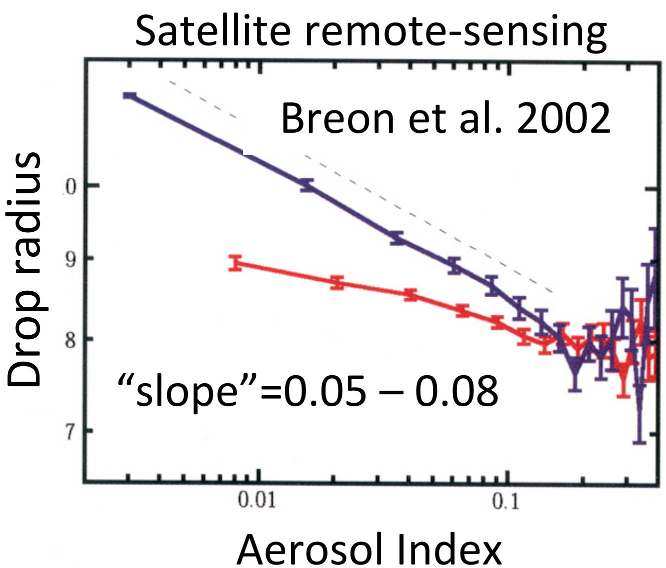
McComiskey et al. 2008, SCu

Slope (ACI) is a measure of the <u>magnitude</u> of the cloud response to aerosol

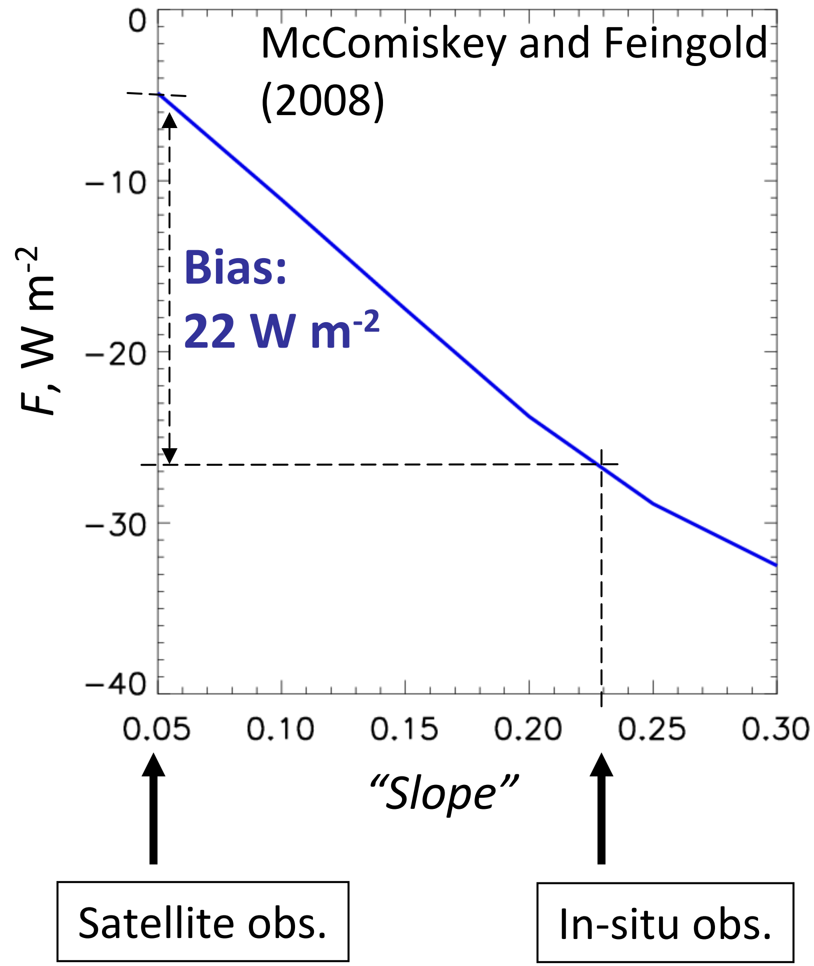
Slope determined by:
aerosol number conc., size/composition, updraft, etc.

Important to sort data by liquid water (Twomey)

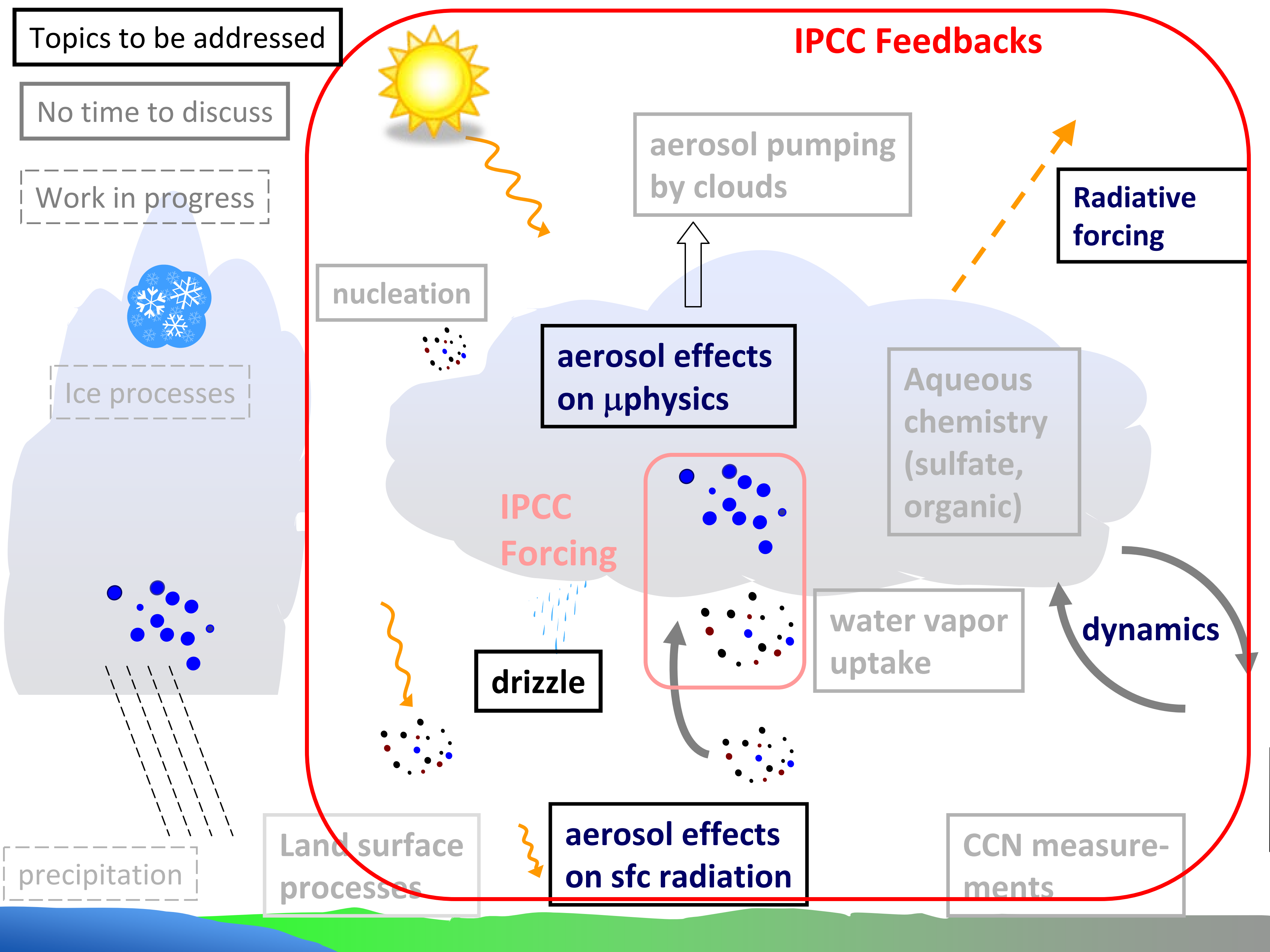
Aerosol-Cloud microphysical response and TOA Radiative Forcing



- ***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



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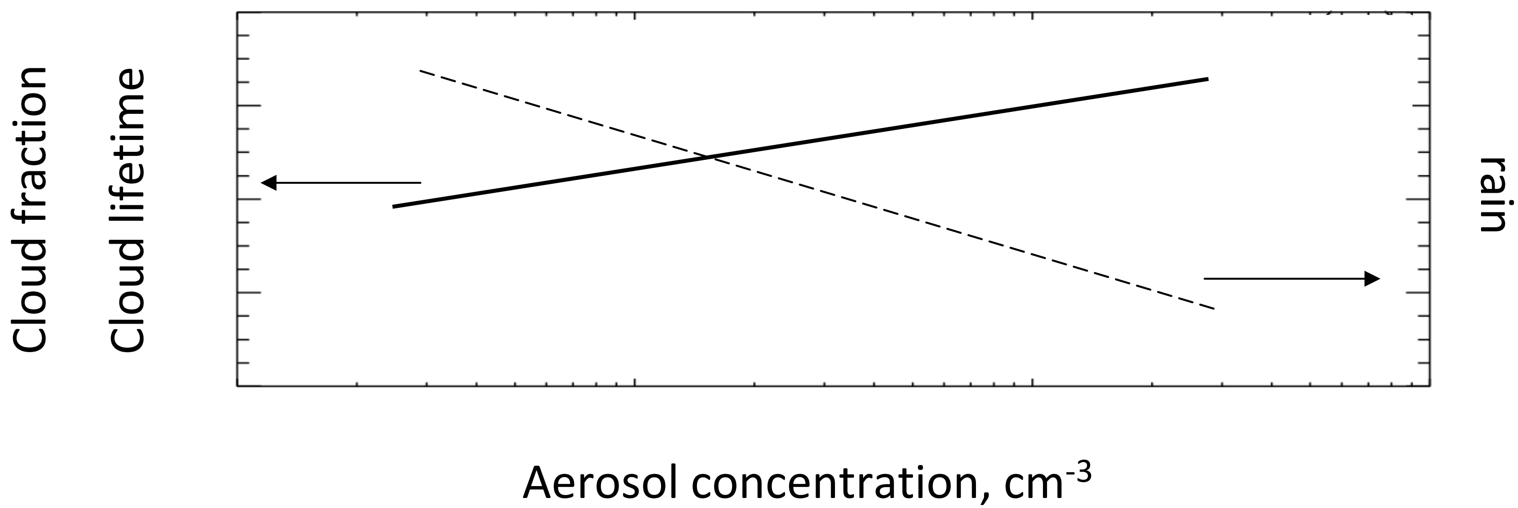
Higher-order Indirect Effects (IPCC feedback)

More aerosol → more drops → less coalescence → <u>less rain</u>
→ higher LWP → higher cloud fraction → longer lifetime

A monotonic response…

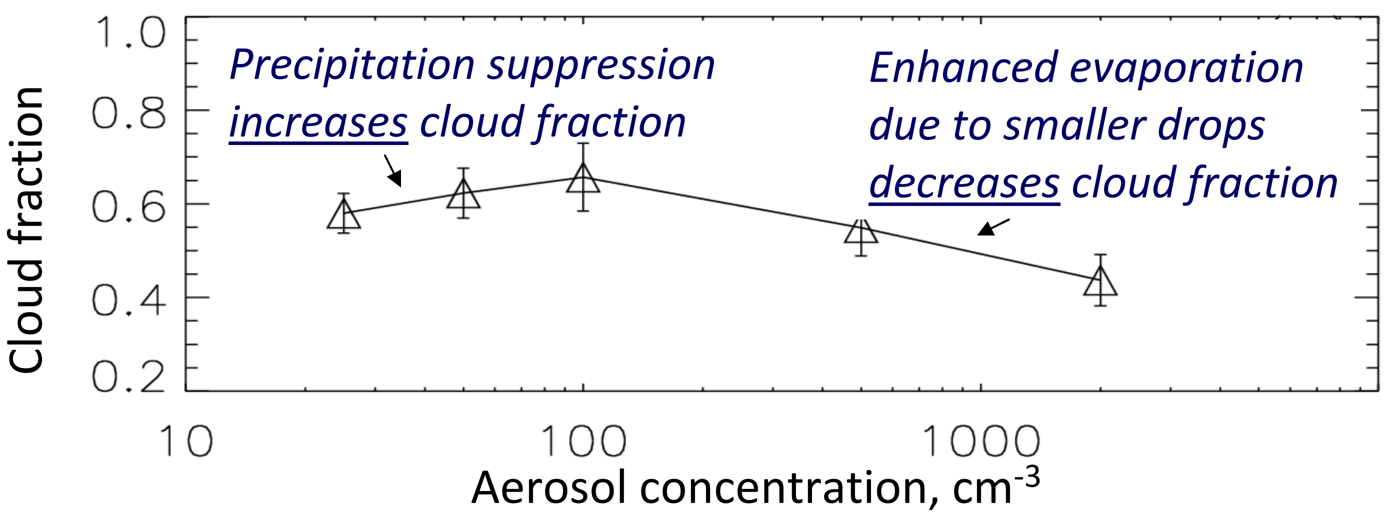


Higher-order Indirect Effects (IPCC feedback)

More aerosol → more drops → less coalescence → less rain → higher LWP → higher cloud fraction → longer lifetime
? **?** **?**

A non monotonic response…

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



Xue, Feingold, Stevens, 2008

Why? Competing Aerosol effects on Cloud Microphysics

- *Small droplets do not coalesce efficiently* → *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

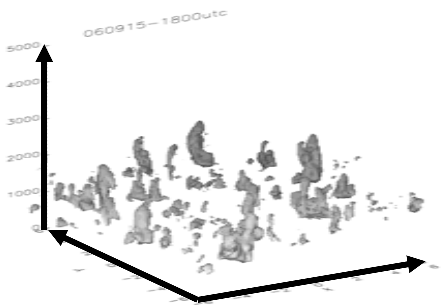
$$\frac{dr}{dt} \propto \frac{S}{r}$$

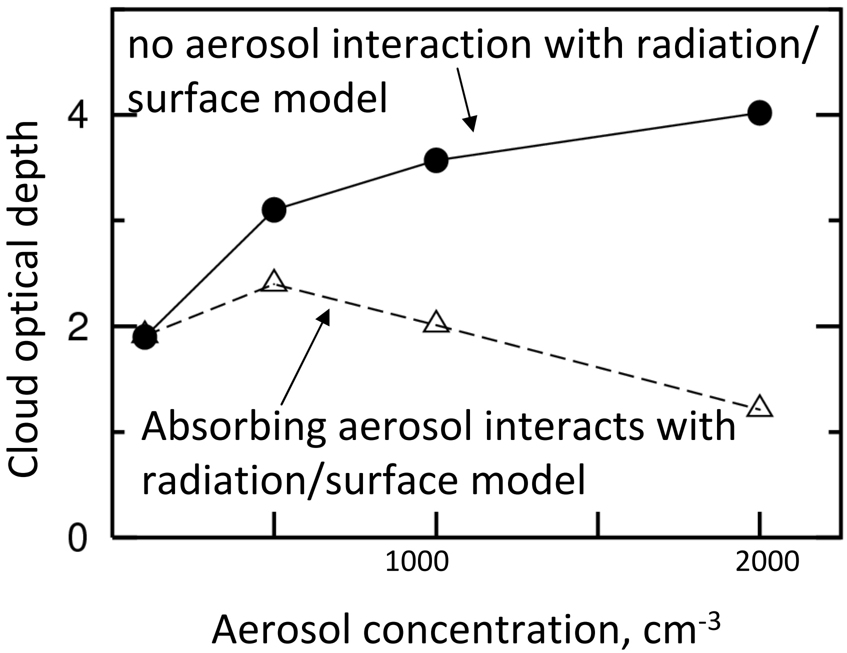
- Microphysical feedbacks complicate the simple monotonic response

- Rain, LWP, cloud fraction and lifetime responses are not simply connected

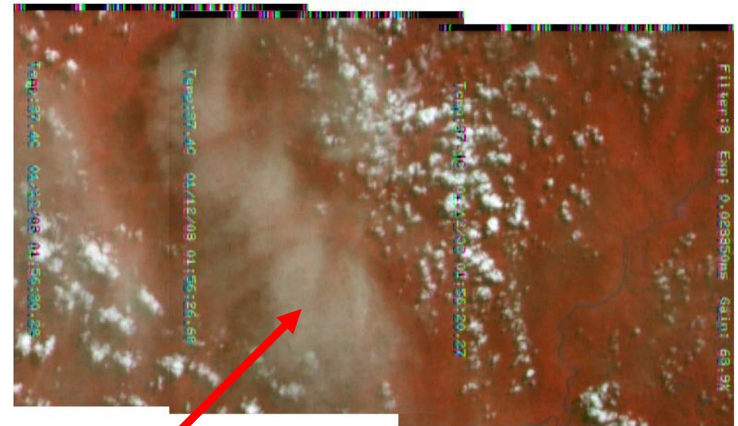
Absorbing aerosol: the semi-direct effect

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



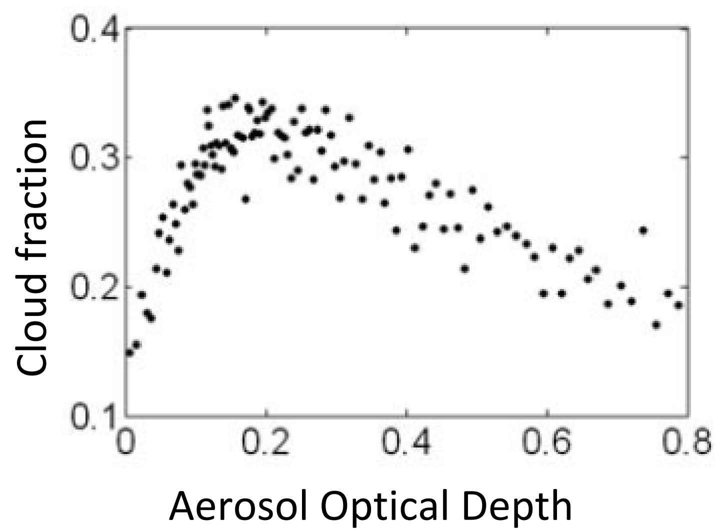


<u>Modeling</u>: Jiang and Feingold 2006



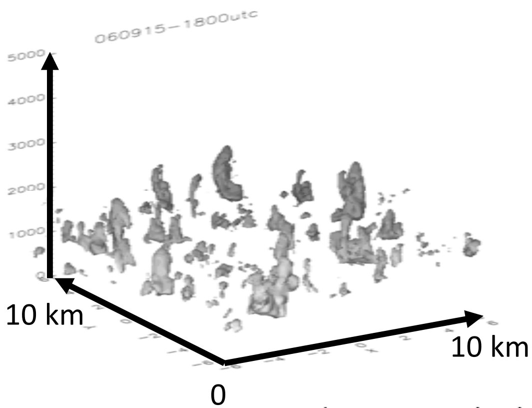
Absorbing aerosol suppresses clouds

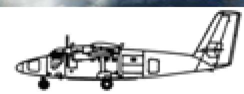
Columbia Shuttle

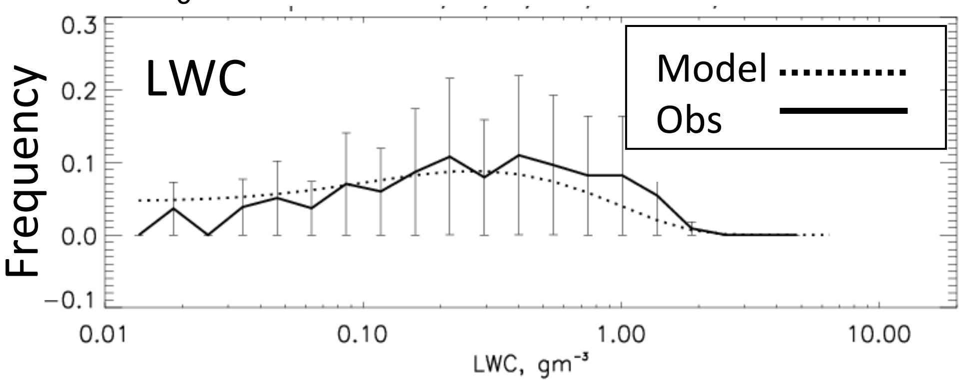


<u>Observations</u>: Koren et al. 2008

Aerosol→Cloud→Radiation: Model-Measurement Comparisons during Houston 2006

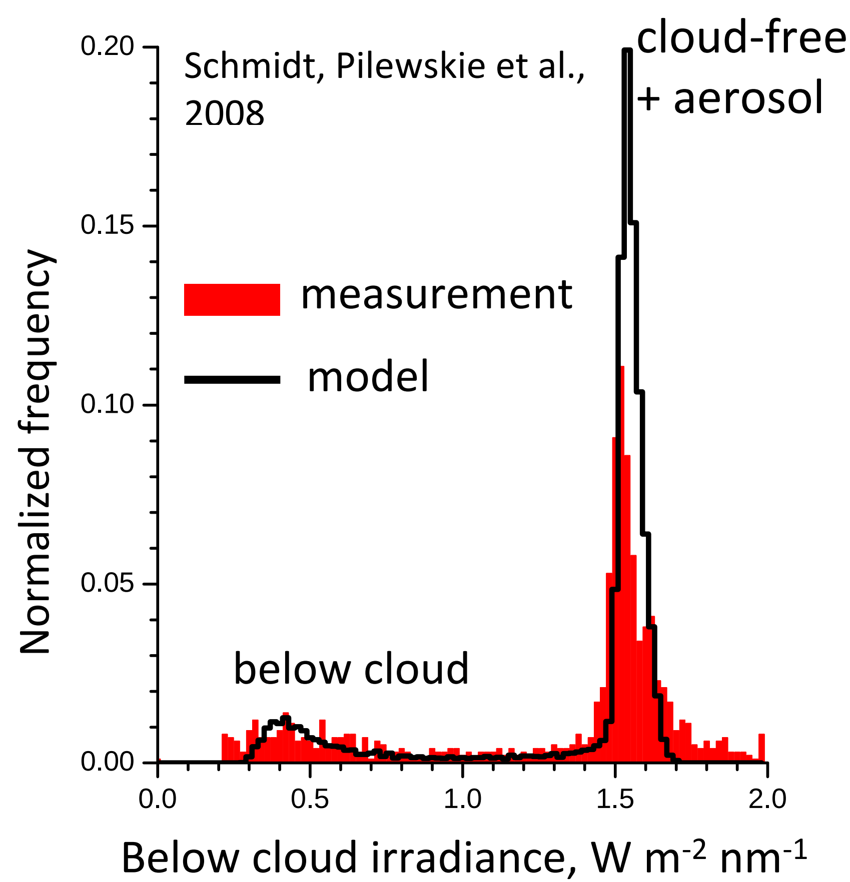






- ***Generally good comparison between LES model and in-situ measurements: LWC, N_d***
- ***Also good comparison for irradiance** (provided aerosol <u>and</u> cloud are included!)*

Comparison of 100s of clouds



NOAA, CalTech, CIRPAS,
Univ. of Colorado collaboration

Aerosol Effects on Cloud Morphology via Drizzle

Albedo

Closed-cell
Albedo ~ 0.6
(non-precipitating)

→ **high aerosol**

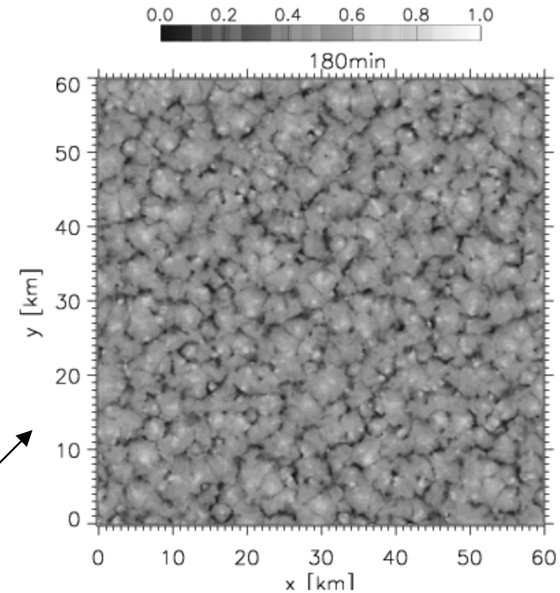
Onset of ***drizzle*** *results in transition to open-cell convection*

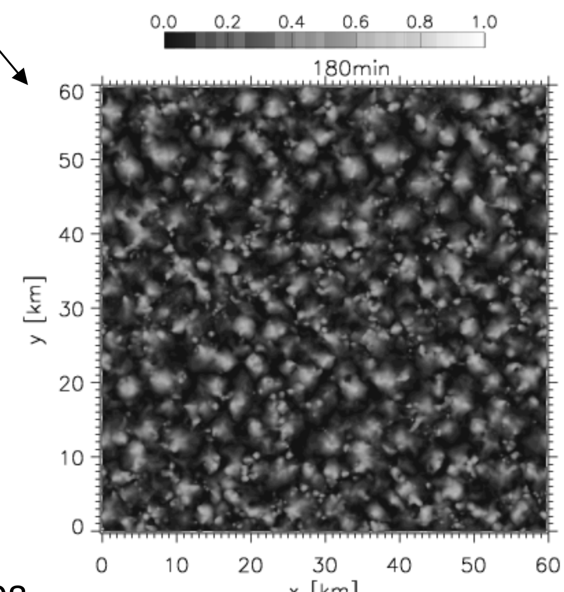
WRF Model
+ 2-moment μphysics;
60 km domain;
$\Delta x = \Delta y = 300$ m
$\Delta z = 30$ m

Open-cell
Albedo ~ 0.2
(precipitating)

→ **low aerosol**

Albedo





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 <u>prescribes</u> 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