Aerosol-Cloud Interactions

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

Graham Feingold

A Complex System with Myriad Feedbacks

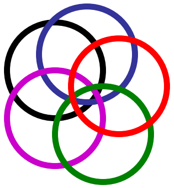
Cloud ←→ Aerosol

← 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

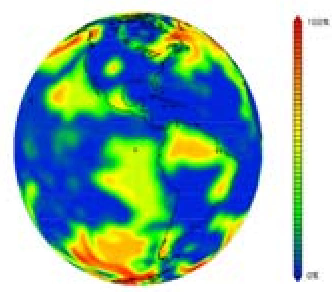
Aerosol-Cloud-Dynamics-Radiation-Chemistry-Land-use



What is NOAA ESRL's Role?

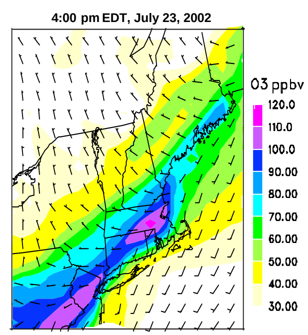
To understand the <u>fundamental processes</u> at the micro-to-cloud scale (μm – 10s km) and to improve representation of aerosol-cloud interactions in regional scale → GCM models

Predictive GCM
Regional/Global scale



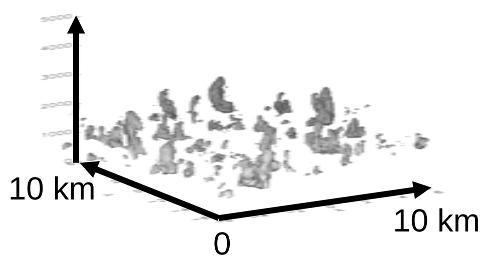
Forcing on regional and global scale (GFDL)

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

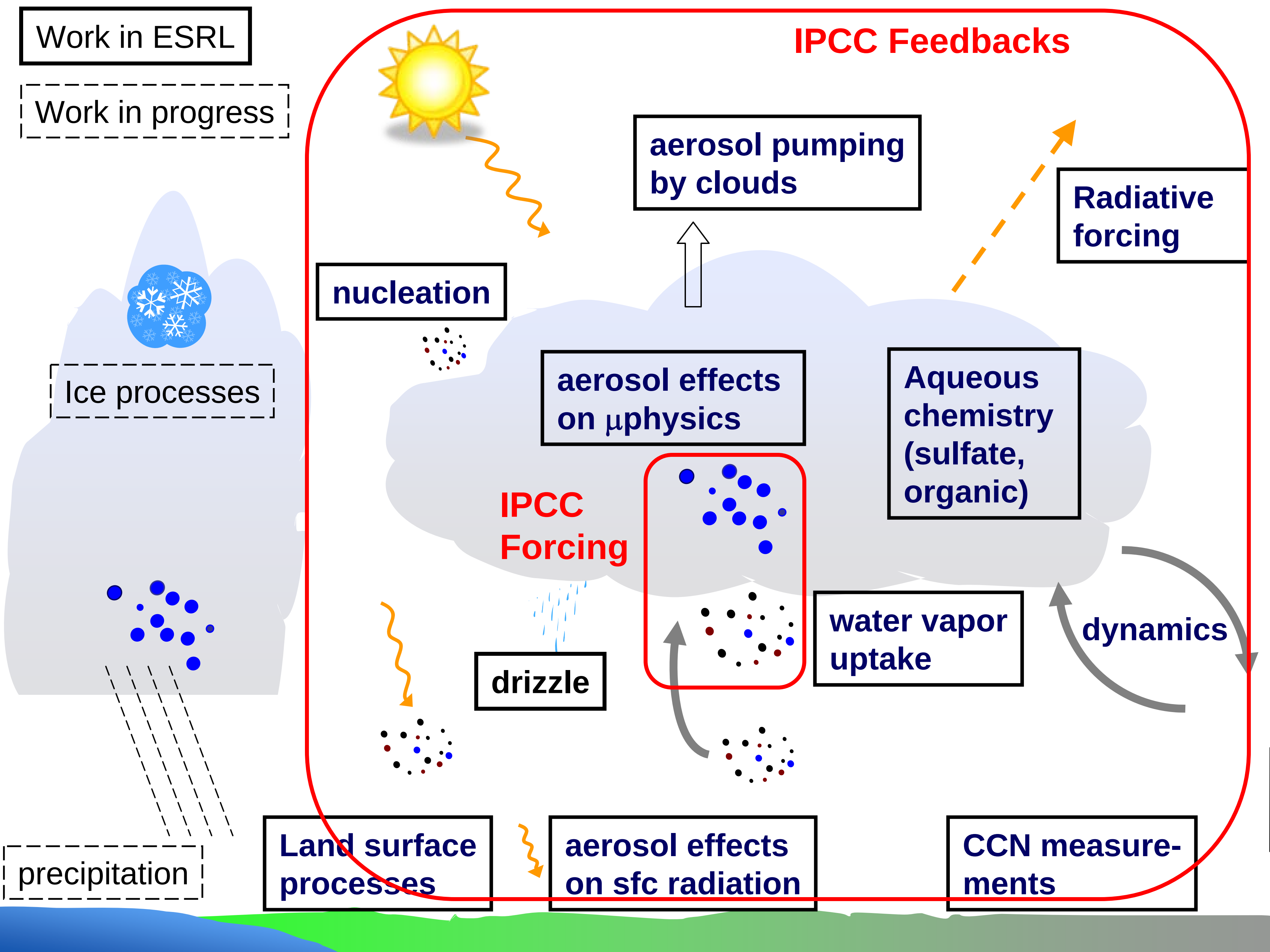


Effect of aerosol transport on clouds

Process Models
~ 10s km

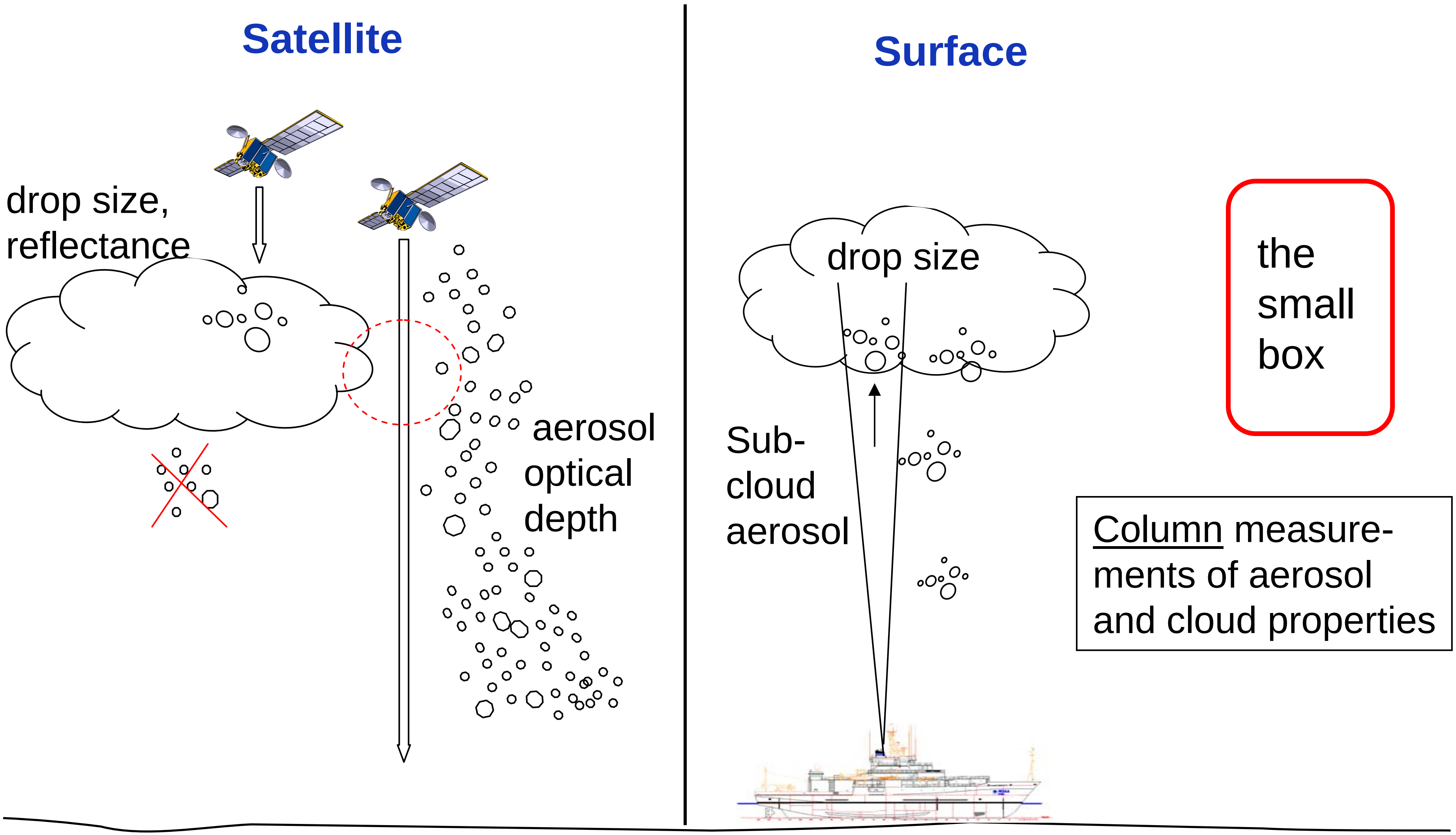


Large Eddy Simulations of aerosol ←→ cloud interactions; Observations (in-situ and remote)



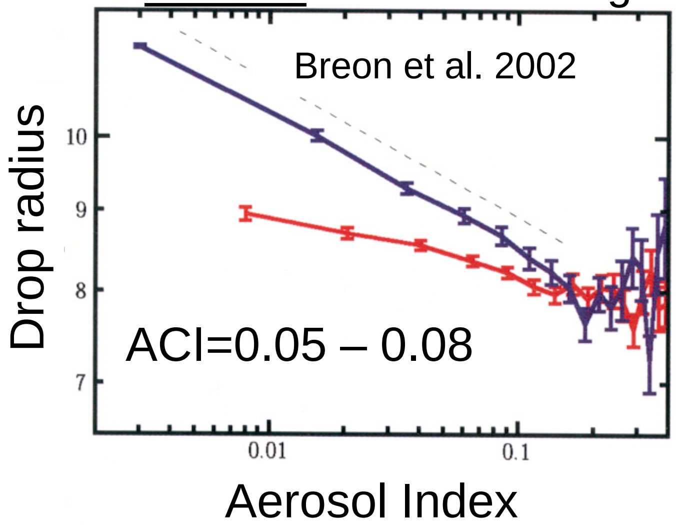
Work in ESRL
Work in progress
IPCC Feedbacks
aerosol pumping by clouds
Radiative forcing
nucleation
Ice processes
aerosol effects on μphysics
Aqueous chemistry (sulfate, organic)
IPCC Forcing
drizzle
water vapor uptake
dynamics
precipitation
Land surface processes
aerosol effects on sfc radiation
CCN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

Remote Sensing of Aerosol-Cloud Interactions: Satellite vs Surface

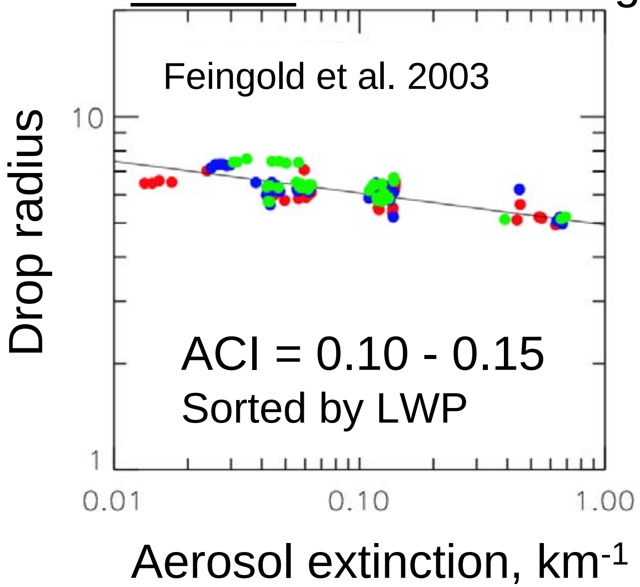


Surface remote sensing avoids ambiguity of aerosol/cloud interface

Measurements of Aerosol-Cloud Interactions



the small box



Important to sort data by liquid water (Twomey)

Slope determined by:

aerosol number conc., size/composition, cloud turbulence, etc.

Define slopes as ACI:
Aerosol-Cloud-Interactions

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

α = aerosol

Modeling: Sensitivity of drop size r_e to various parameters

$$S_i = d \ln r_e / d \ln X_i$$

	X_i	All	Clean	Polluted
dynamics	LWC	**0.33**	**0.33**	**0.33**
	updraft	-0.10	-0.06	**-0.17**
aerosol	number	**-0.28**	**-0.30**	**-0.12**
	size	-0.09	**-0.11**	**-0.11**
	dispersion	**0.16**	**0.11**	**0.26**
	Soluble fraction	-0.03	-0.03	-0.03

	ACI
Modeling	0.12 – **0.30**
In-situ	0.15 – 0.30
Surface remote	0.10 – 0.15
Satellite remote	0.05 – 0.10

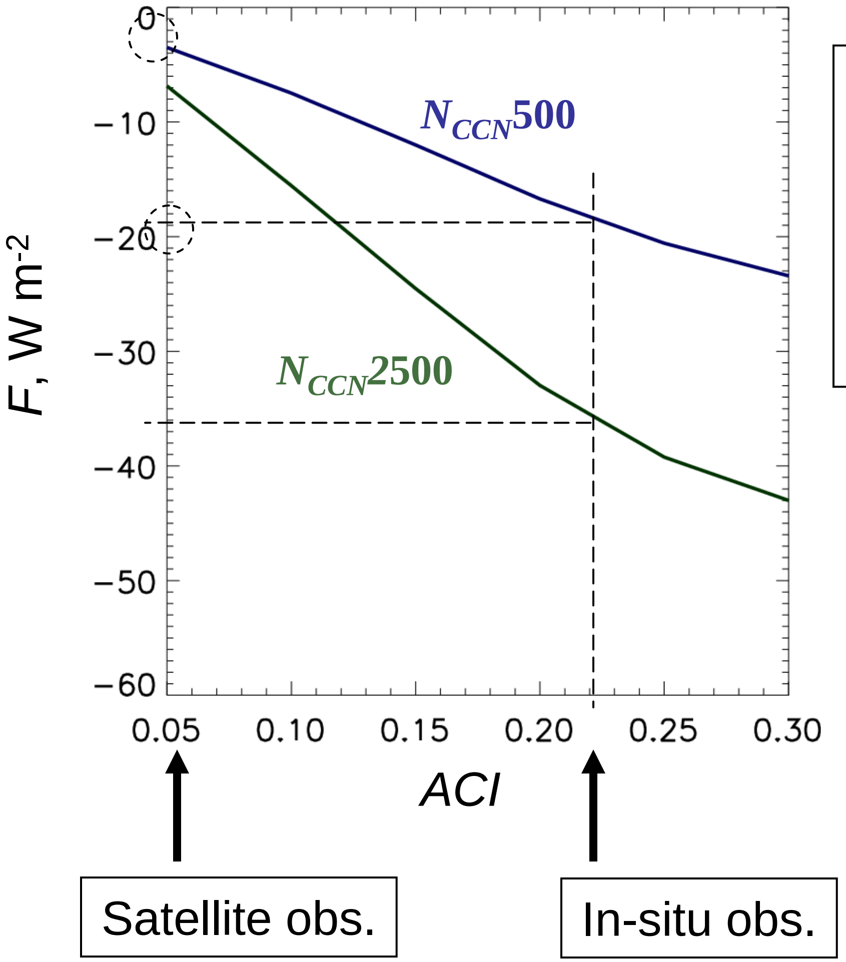
$$r_e \propto \left(\frac{LWC}{N_d} \right)^{1/3}$$

$$\rightarrow \quad S_{LWC} = 0.33$$

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

Feingold, GRL 2003

Relating Aerosol-Cloud Interactions to TOA Radiative Forcing: <u>Modeling</u>



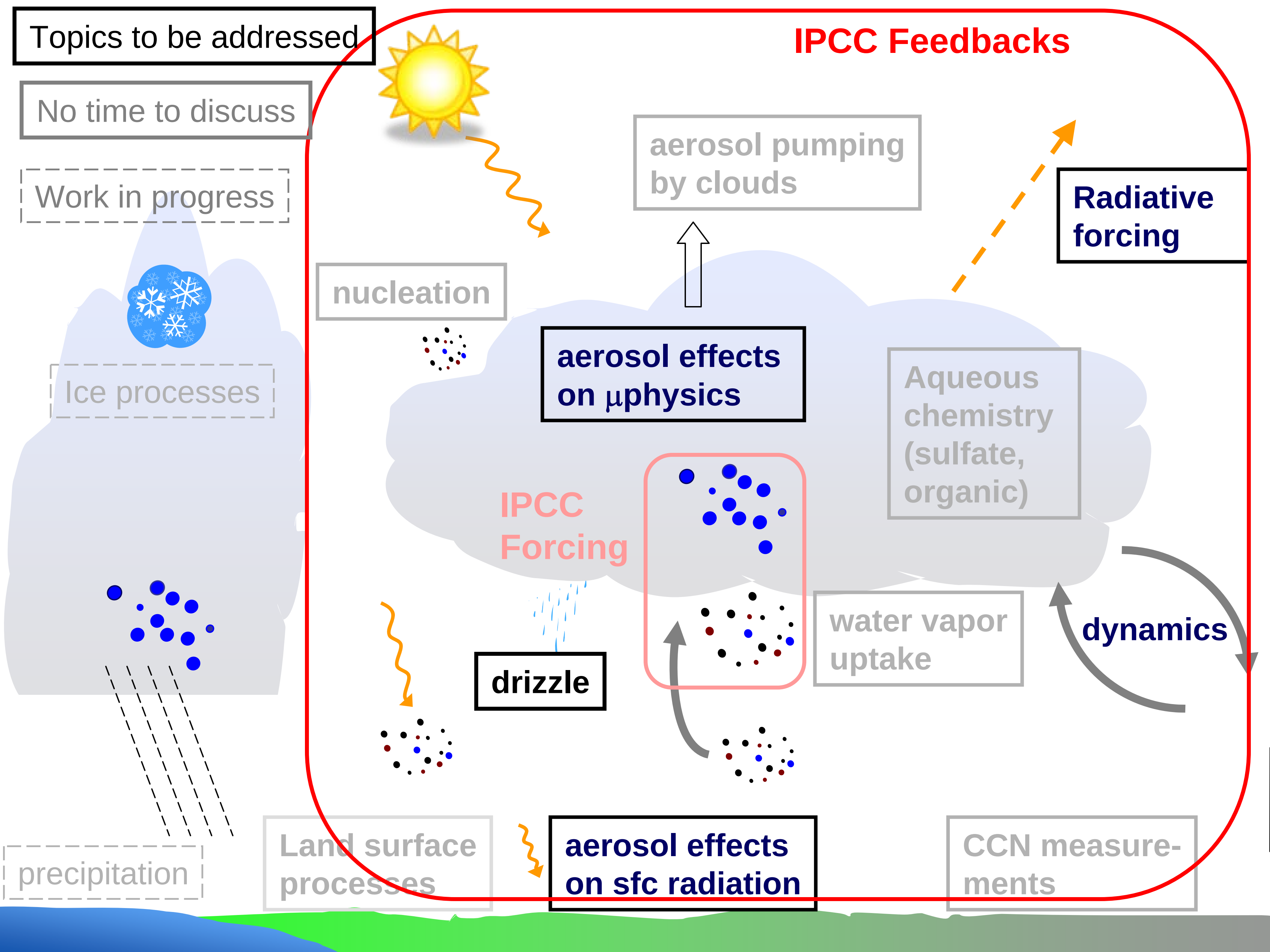
(Diurnal average based on100% cloud cover)

- ***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

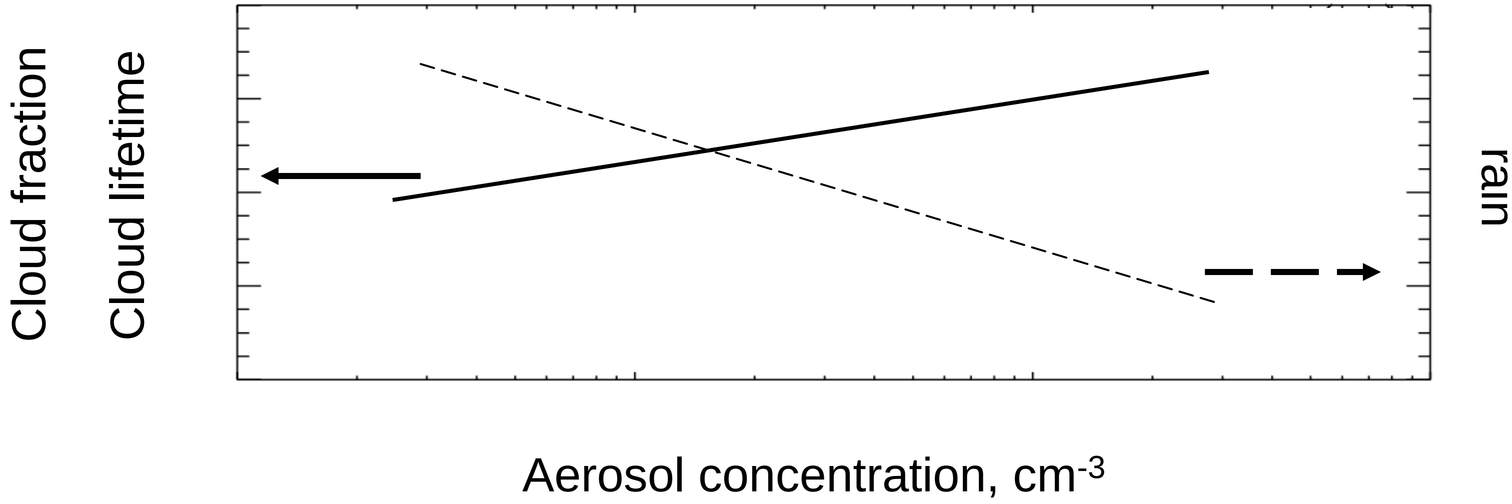


Topics to be addressed
No time to discuss
Work in progress
IPCC Feedbacks
aerosol pumping by clouds
Radiative forcing
nucleation
aerosol effects on µphysics
Ice processes
Aqueous chemistry (sulfate, organic)
IPCC Forcing
water vapor uptake
dynamics
drizzle
precipitation
Land surface processes
aerosol effects on sfc radiation
CCN measure-ments

Higher-order Indirect Effects

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

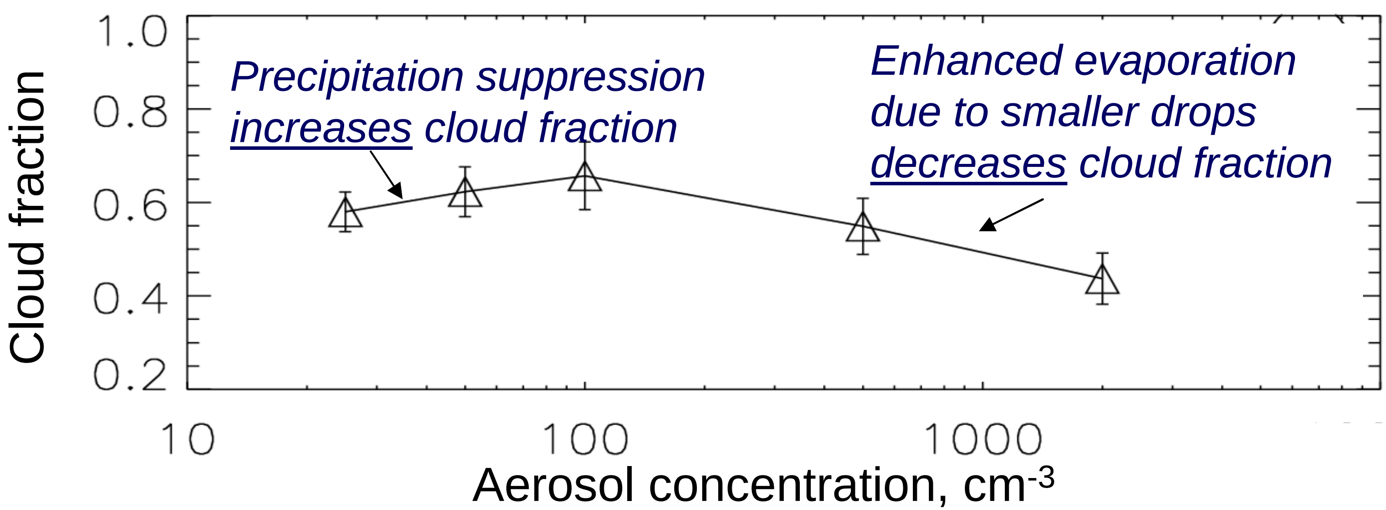
A monotonic response…



Higher-order Indirect Effects contd..

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

A non monotonic response…



Modeling of warm clouds
Xue, Feingold, Stevens, 2008

- Microphysical feedbacks complicate the simple linear response

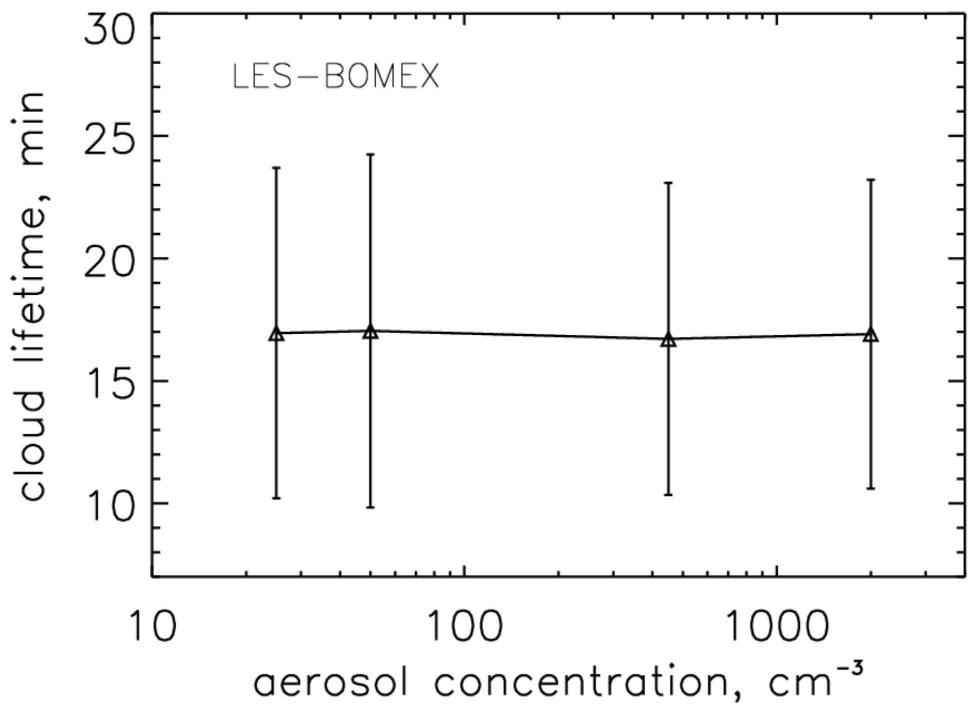
- Rain, LWP, cloud fraction and lifetime responses are not necessarily connected

Aerosol Effects on Cloud Lifetime: modeling

-There are no observations of aerosol effects on cloud lifetime!

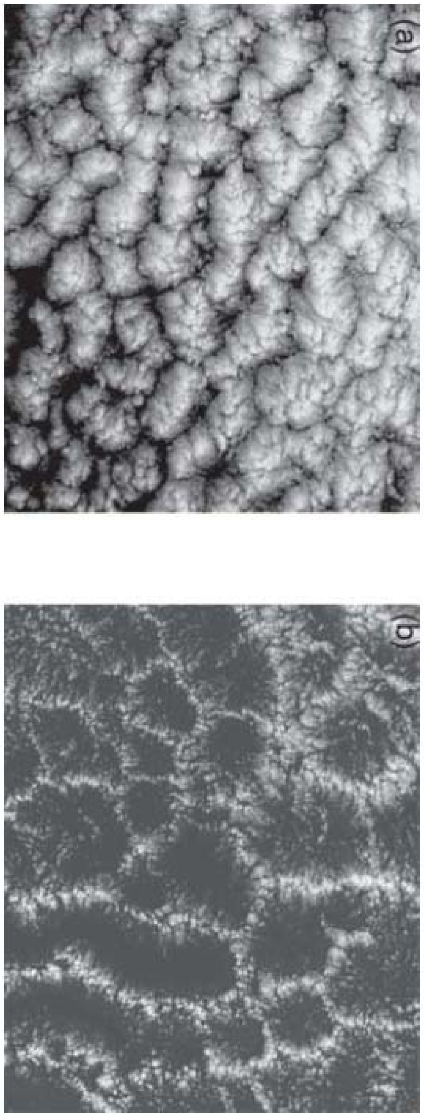
- Modeling: No statistical signal for aerosol effect on cloud lifetime

Based on analysis of 100s of individual
<u>modeled</u> cumulus clouds



Jiang, Xue, Teller, Feingold, Levin: GRL 2006

Aerosol Effects on Cloud Morphology via Drizzle



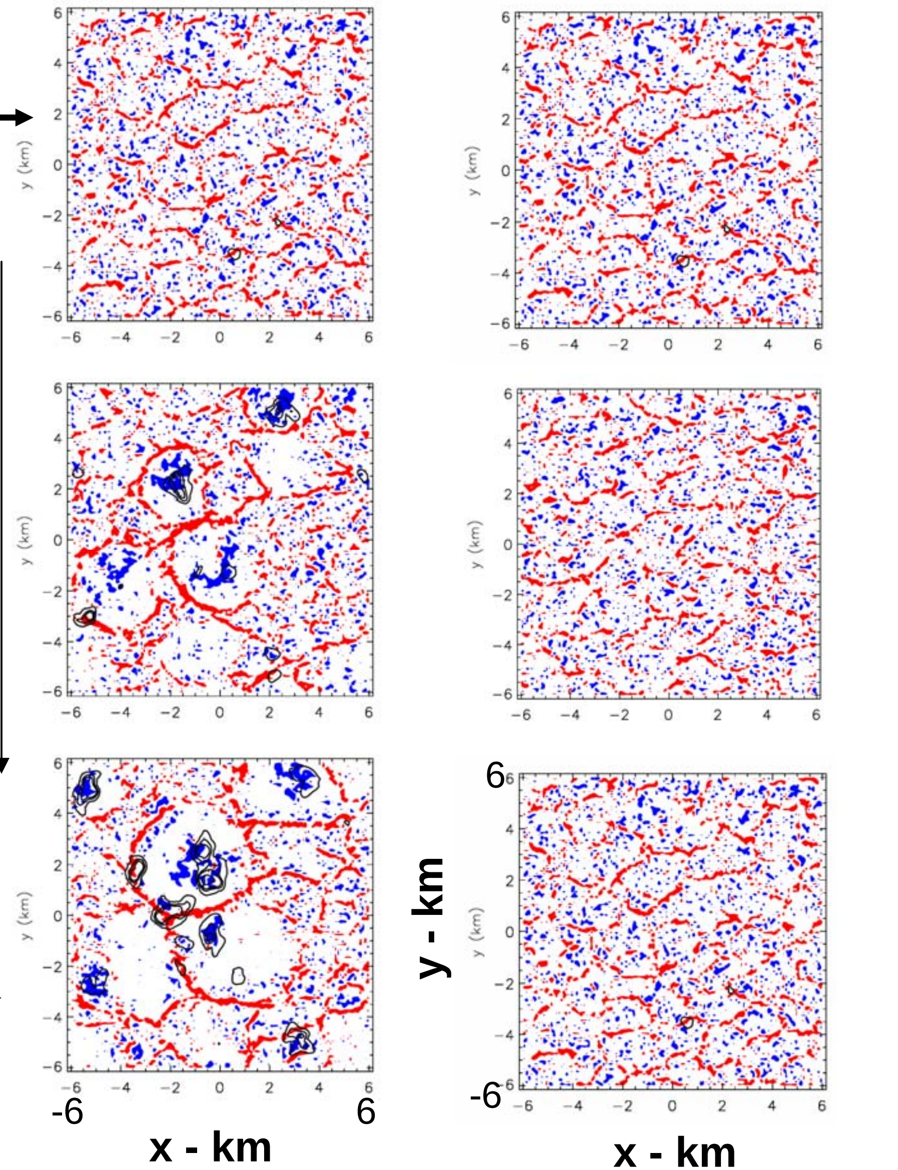
Closed-cell
Albedo ~ 0.6
(non-precipitating)

Time
Δt ~ 60 min

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

Open-cell
Albedo ~ 0.2
(precipitating)

low aerosol, drizzle | high aerosol, no drizzle



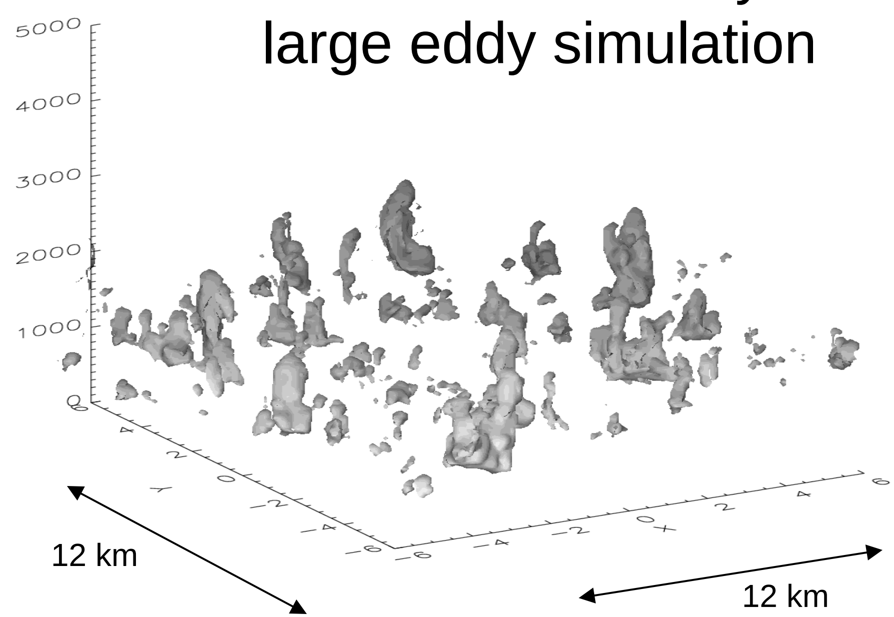
Garay et al. 2004, MISR

Xue, Feingold, Stevens 2008

Comparison between Model and In-situ Observations

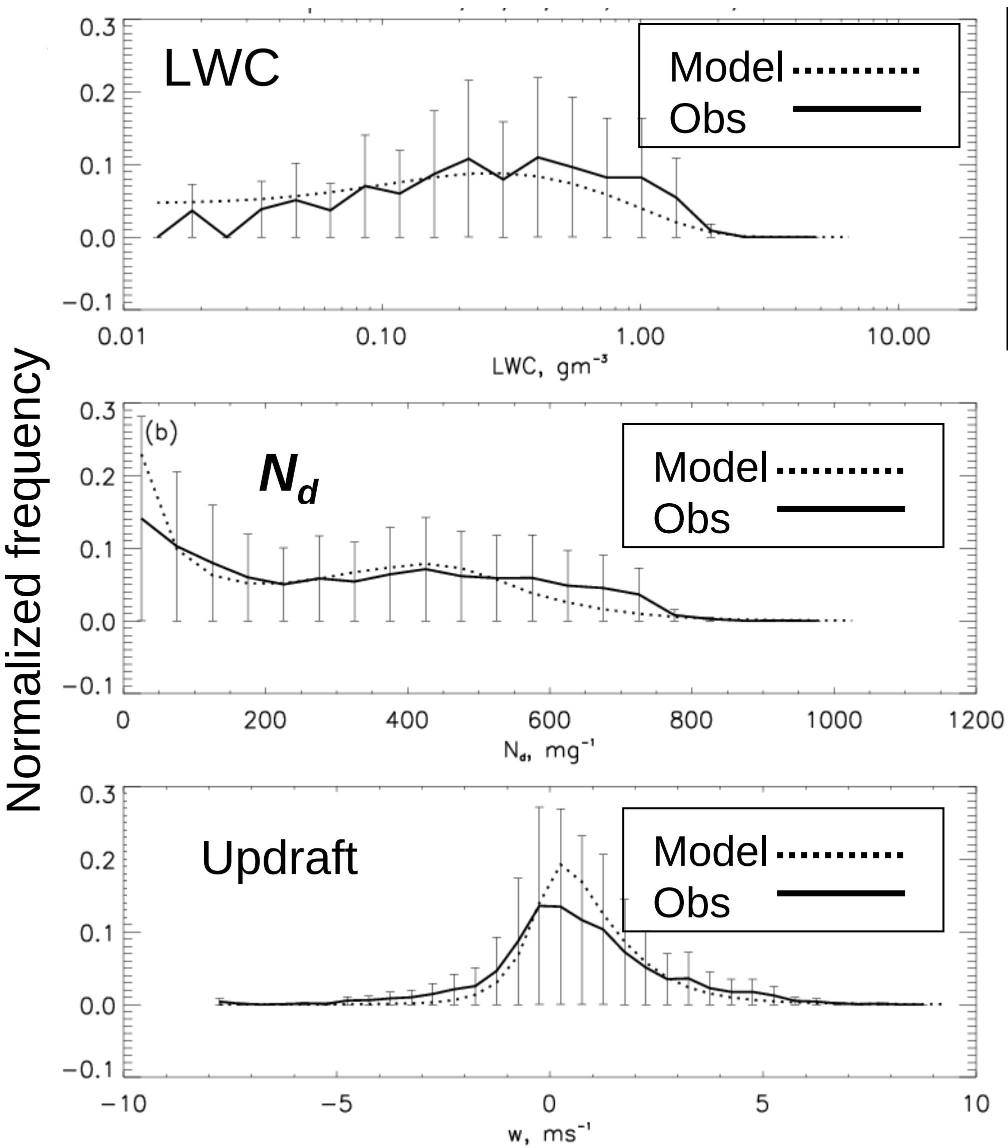
Clouds in Houston sampled by aircraft; CIRPAS/CalTech/NOAA

Clouds modeled by large eddy simulation

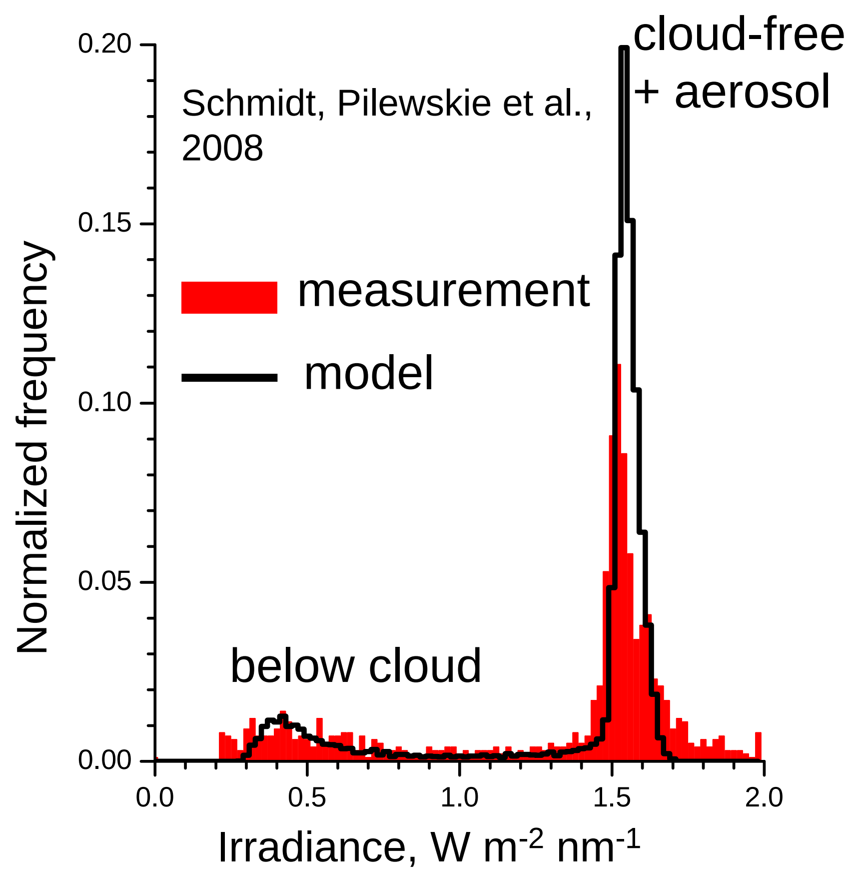


Jiang, Feingold, et al. 2008

Statistical Comparisons



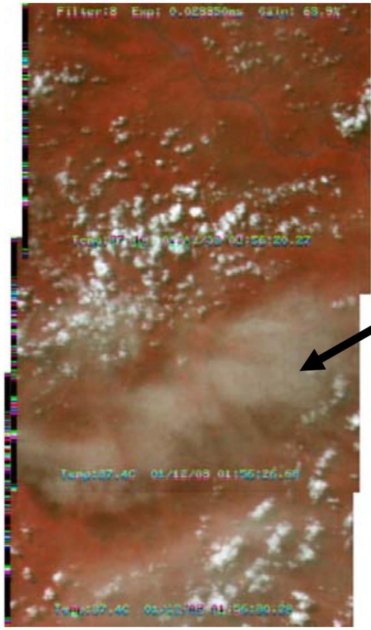
Generally good comparison between model and in-situ measurements: LWC, N_d, updraft; Irradiance *(aerosol + cloud)*



Comparison of 100s of clouds

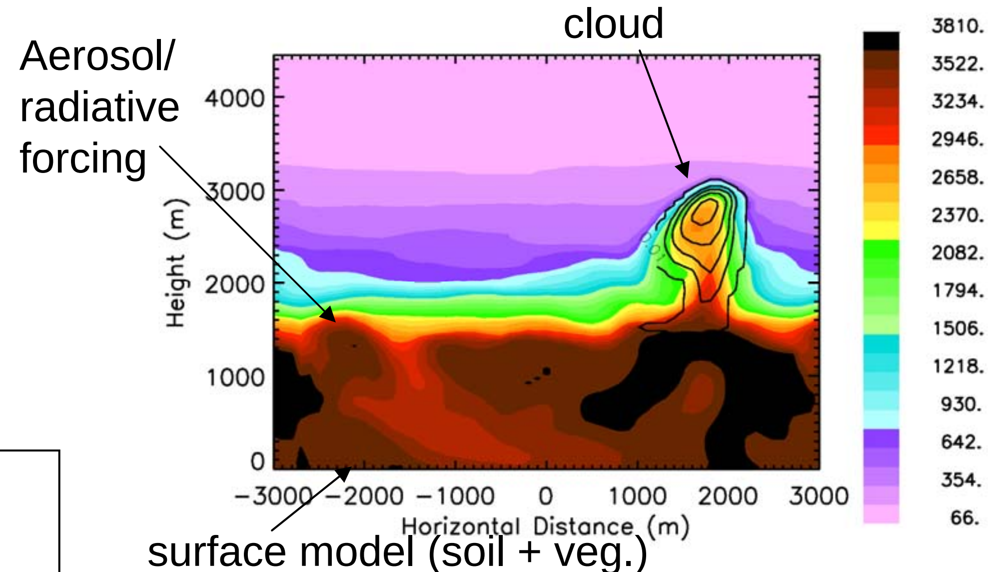
Jiang, Feingold, et al. 2008

Absorbing aerosol: modeling of the semi-direct effect

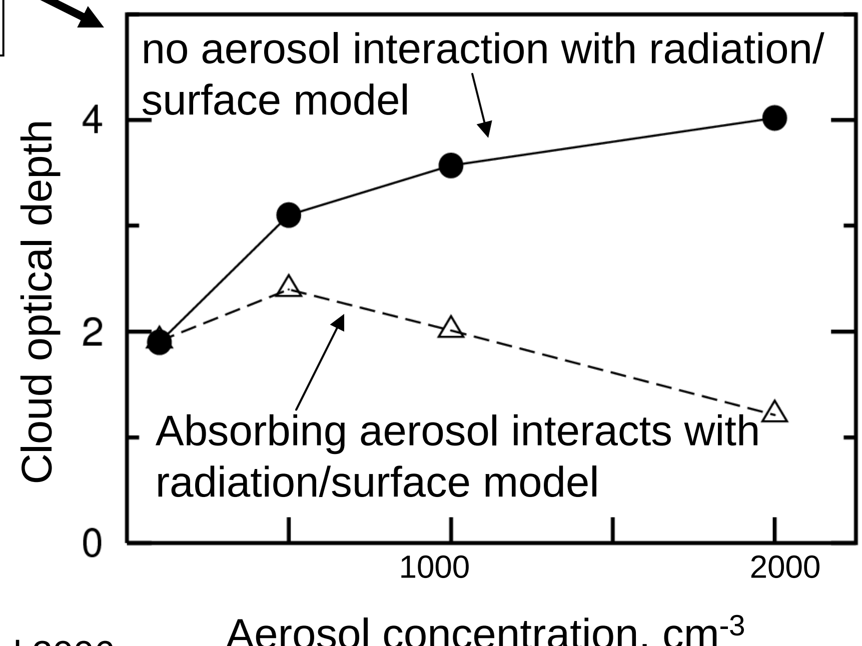


Columbia Shuttle image

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 <u>prescribes</u> 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 <u>Deep</u> Convective Clouds

- Water resources are in increasingly short supply (population pressures and climate change)

A bright future for cloud studies!