Where, Why, and How on Earth does Aerosol affect Clouds and Precipitation?

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Based on:

Feingold and Siebert (2009): *Cloud–Aerosol Interactions from the Micro to the Cloud Scale*, Ernst Strüngmann Forum, Chapter 14, MIT Press.

Stevens and Feingold (2009): *Untangling aerosol effects on clouds and precipitation in a buffered system*, Nature, October 1.

With Acknowledgement to:

Bjorn Stevens, Hongli Jiang, Huiwen Xue, Hailong Wang, Jan Kazil, Allison McComiskey, Armin Sorooshian, Patrick Chuang, Jen Small, Barbara Ervens, Holger Siebert, Ilan Koren

Why do aerosol-cloud interactions matter?

1. Clouds have a significant impact on Earth's radiation budget

   Shallow clouds significantly increase the SW reflectance relative to the dark underlying ocean but radiate in the LW at approximately the surface temperature

2. Aerosol may influence albedo and precipitation

   Enhanced cloud reflectance

   Suppression of warm rain

   Aerosol effects on deep convection ??

Simple Constructs

We have (somewhat artificially) separated aerosol effects on clouds into:

Albedo effect (more aerosol → smaller droplets → brighter clouds; ceteris paribus)

Lifetime effect (more aerosol → smaller droplets → less coalescence less rain → longer lifetime)

Semi-direct effect (more absorbing aerosol → stabilization → less cloud)

Glaciation effect

Riming effect

……

Despite decades of research, we still do not have a robust understanding of aerosol effects on clouds and precipitation

This is at least in part due to our imperfect observational tools…

but,

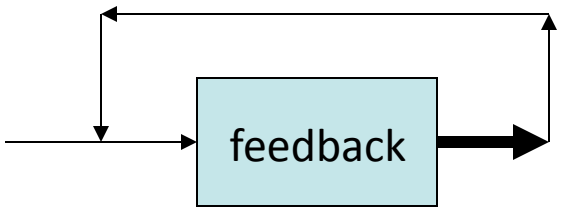
Hypothesis

- *Aerosol effects are hard to detect and quantify because the aerosol-cloud system is buffered*
  - Microphysical buffering
  - Macrophysical buffering
  - Strong responses

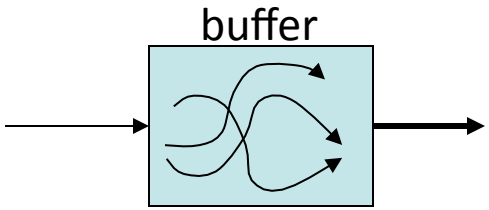
Focus here is on shallow convection (warm clouds)

Buffering

Feedback: output of a system modifies the input



Buffering: Response of a system to a forcing is weaker than would have been expected had internal mechanisms not been accounted for

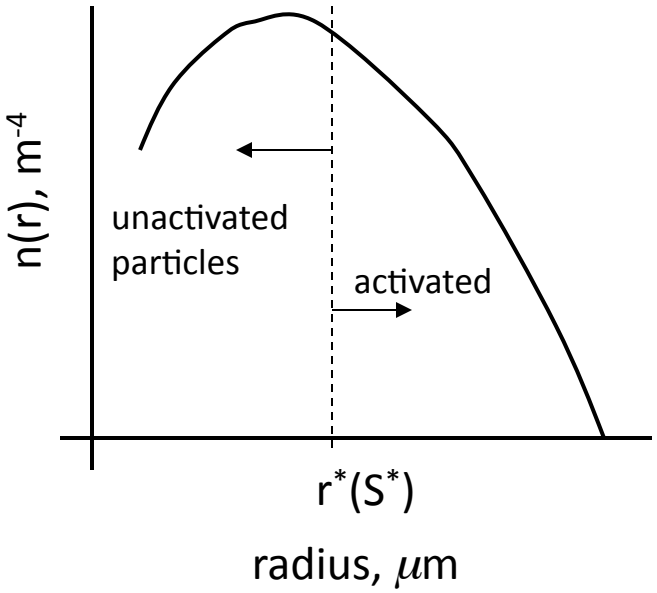


Microphysical Buffering

- More aerosol → more drops → lower S → less activation
- More soluble aerosol → more drops → lower S

E.g.: a factor of 2x in the [CCN] at $S = S^*$ yields ~ 15% change in drop concentration N_d in a dynamically adjusting system

Self-regulating or "buffered" system



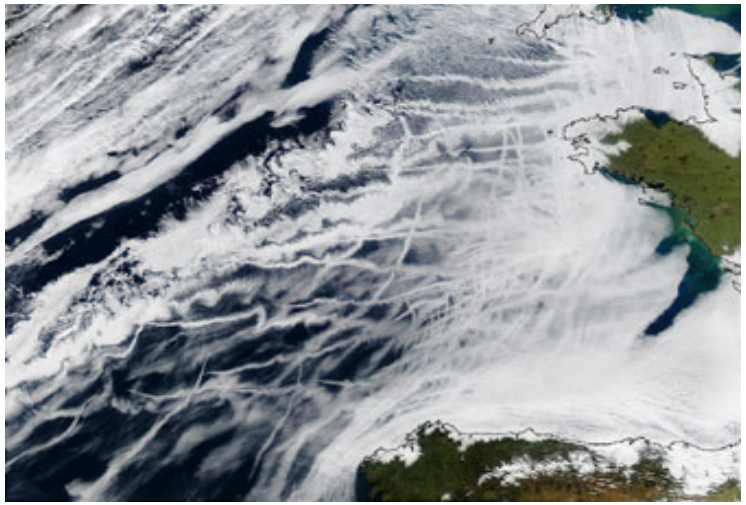
Microphysical Buffering contd..

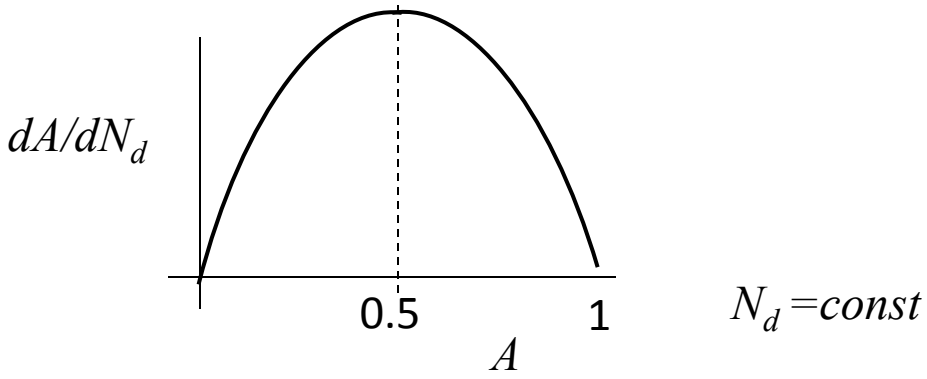
- Albedo Susceptibility

$$\frac{dA}{dN_d} = \frac{A(1-A)}{3N_d}$$

Clouds with A=0.5 are most susceptible to aerosol perturbations

(vis-à-vis albedo)



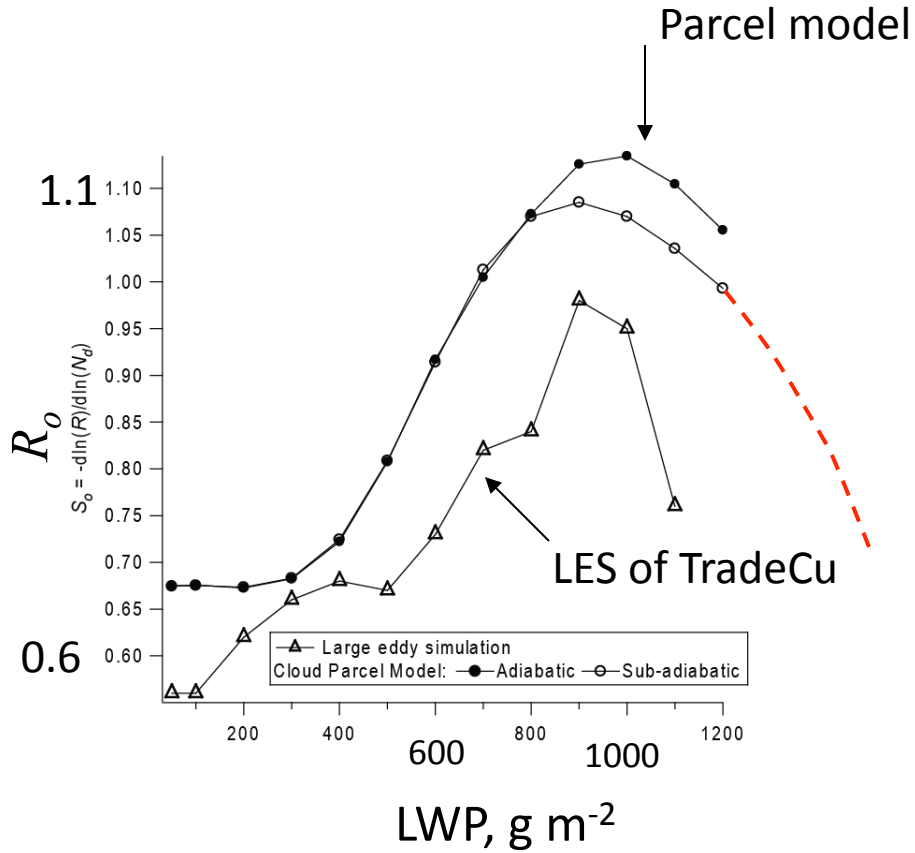


Microphysical Buffering contd..

- Precipitation Susceptibility

$$R_o = -\frac{d \ln R}{d \ln N_d}$$

Clouds within a limited range of LWP are susceptible to aerosol (vis-à-vis precipitation)



$$R \sim LWP^{\alpha} N_d^{-\beta}$$

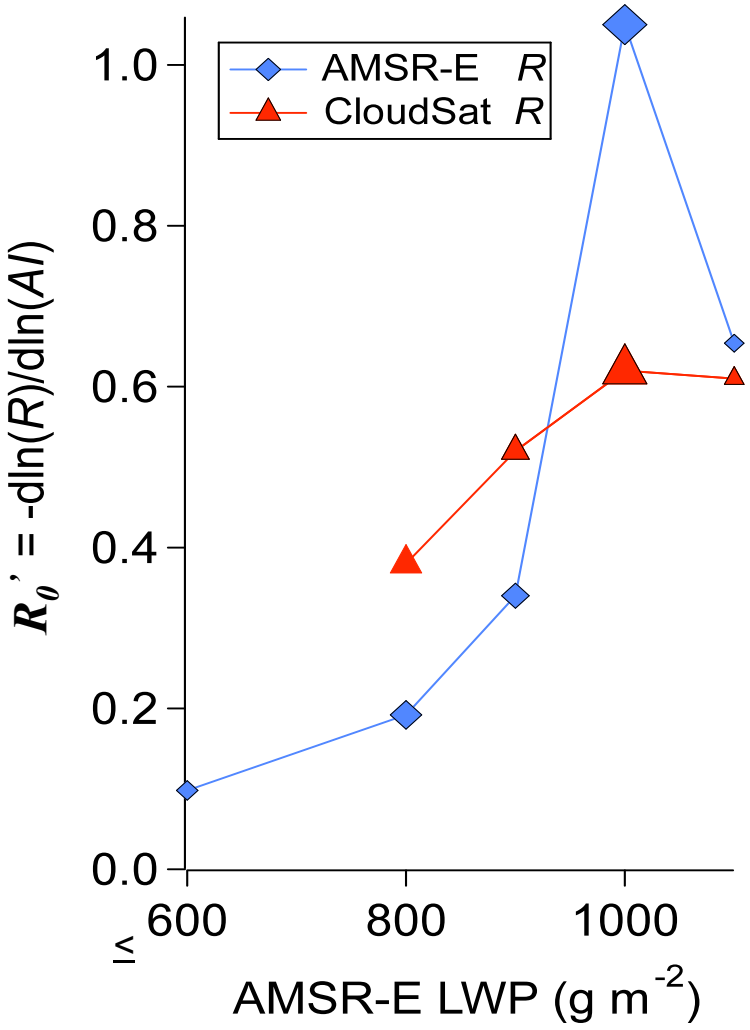
α ~ 1.50
β ~ 0.67

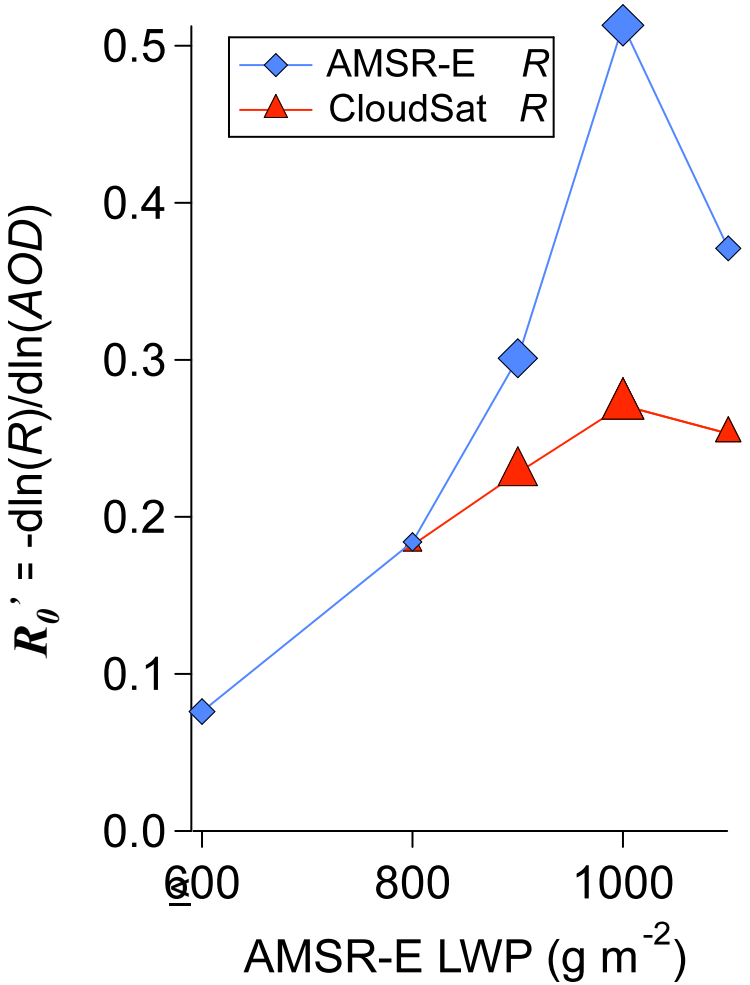
GCMs often assume $\beta = 2$

Feingold and Siebert 2009
Sorooshian et al. 2009

A-Train Results

Sorooshian et al. 2009

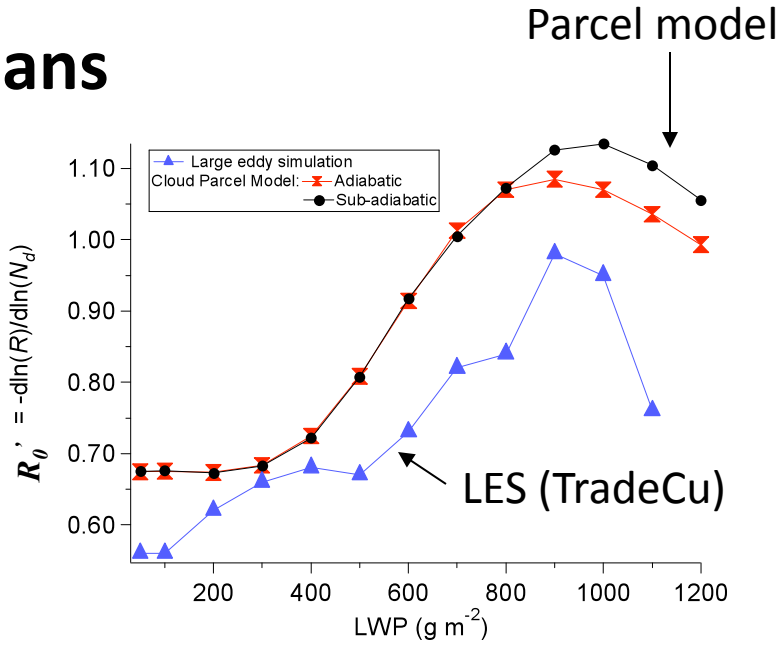


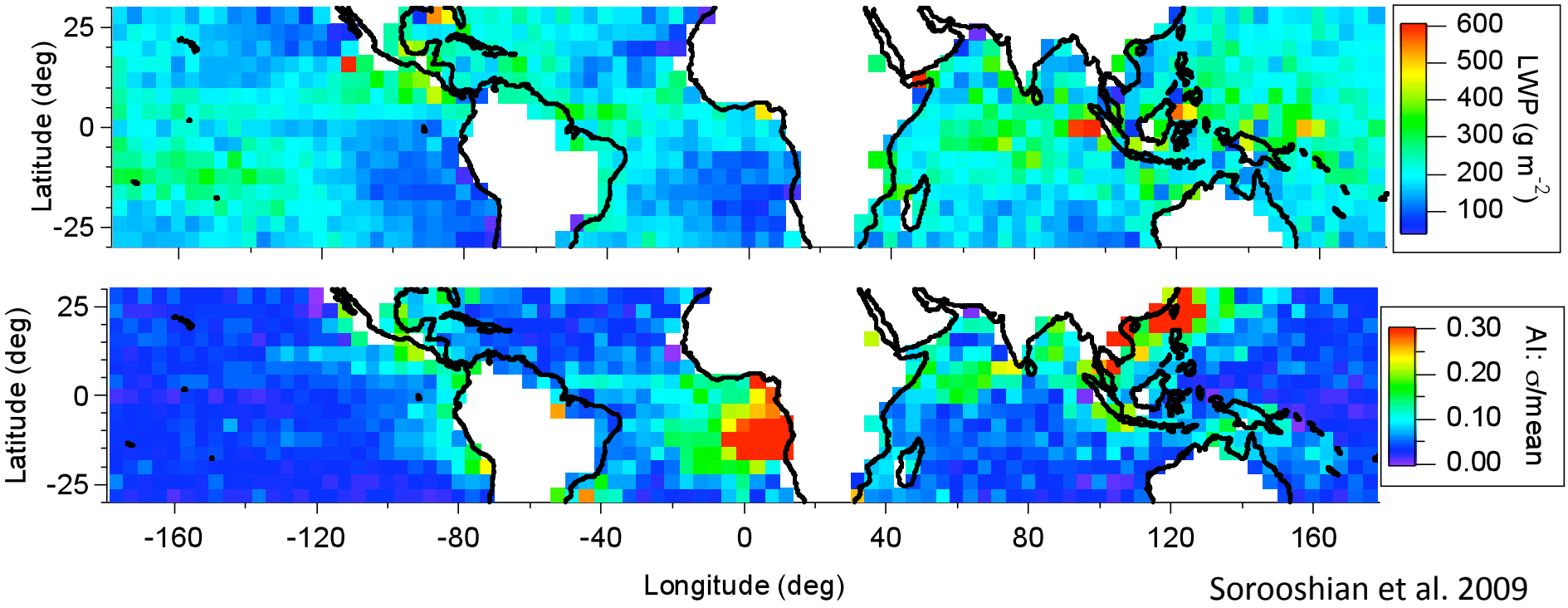


Extrapolation to Tropical Oceans

Calculate typical precipitation reduction in a given region

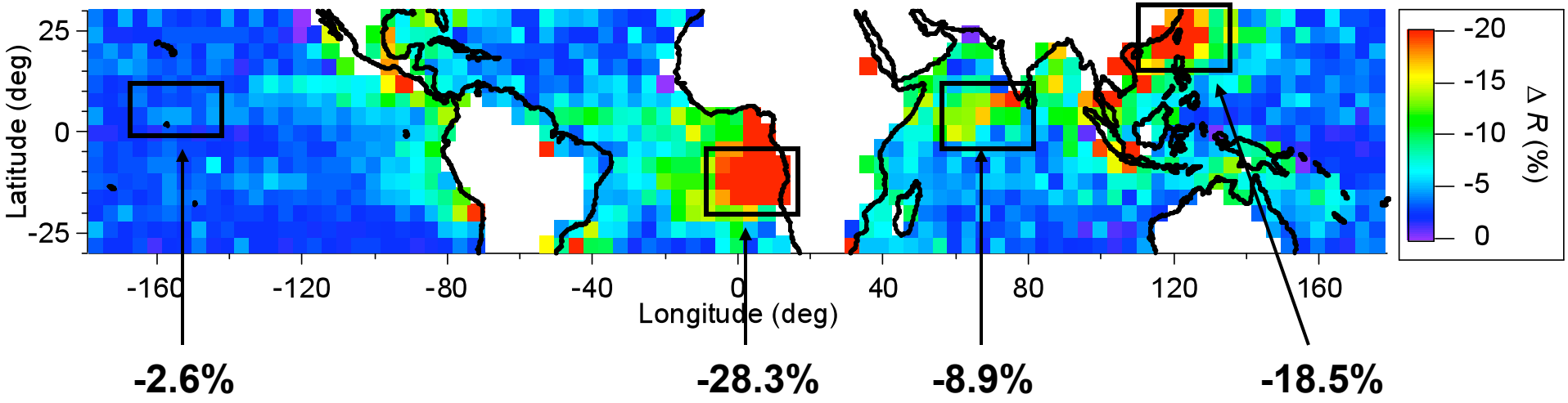
Input: LWP and aerosol perturbation →



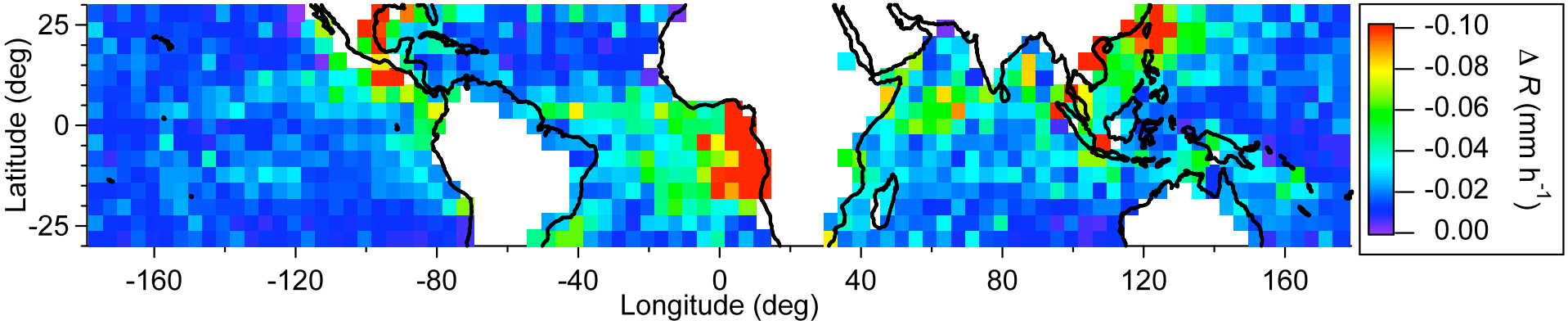


Sorooshian et al. 2009

Where on Earth will aerosol reduce precipitation?



What about the ABSOLUTE reduction in precipitation?



Note: R_o may be biased in certain regions characterized by persistent above-cloud aerosol layers (CALIPSO can help with this).

Sorooshian et al. 2009

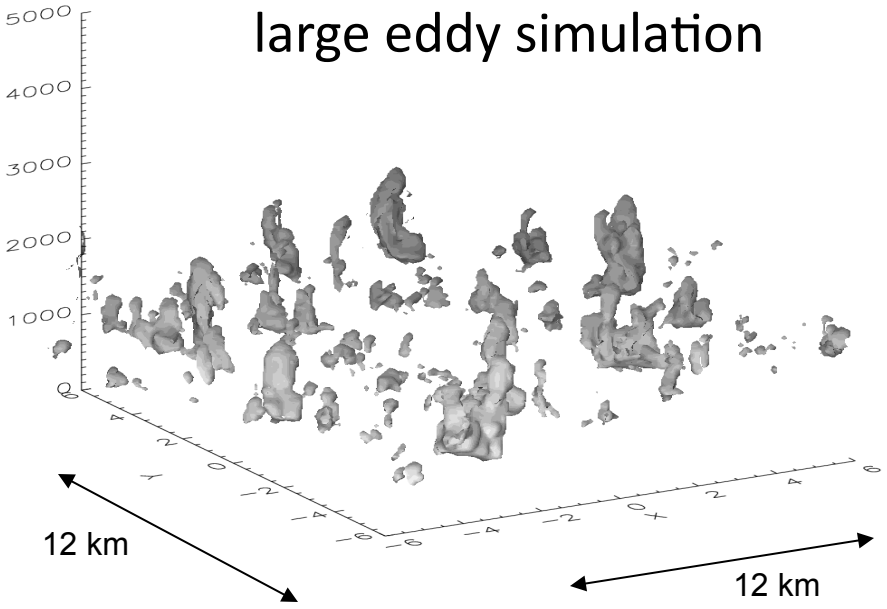
Macrophysical Buffering

- Cloud Lifetime
- Cloud Deepening
- Absorbing Aerosol
- Entrainment drying vs. precipitation moistening

Lifetime of Shallow Cumulus

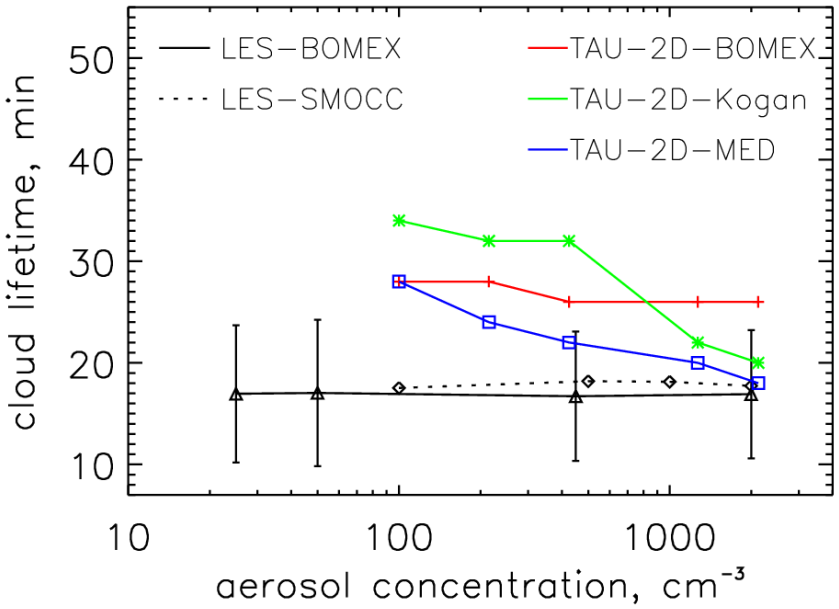
Clouds in Houston sampled by aircraft; CIRPAS/CalTech/NOAA

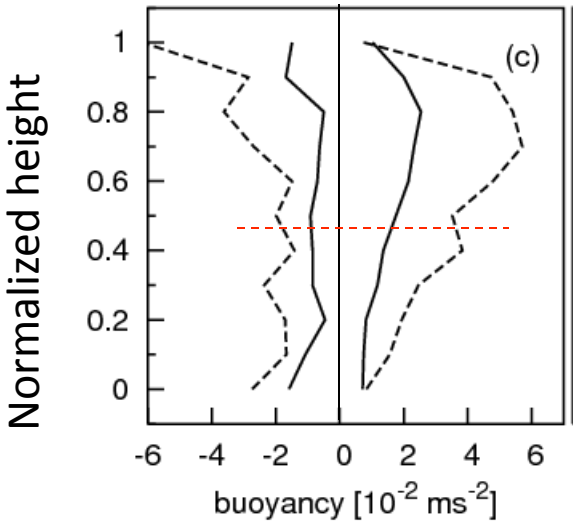
Clouds modeled by large eddy simulation



Jiang, Feingold, et al. 2008

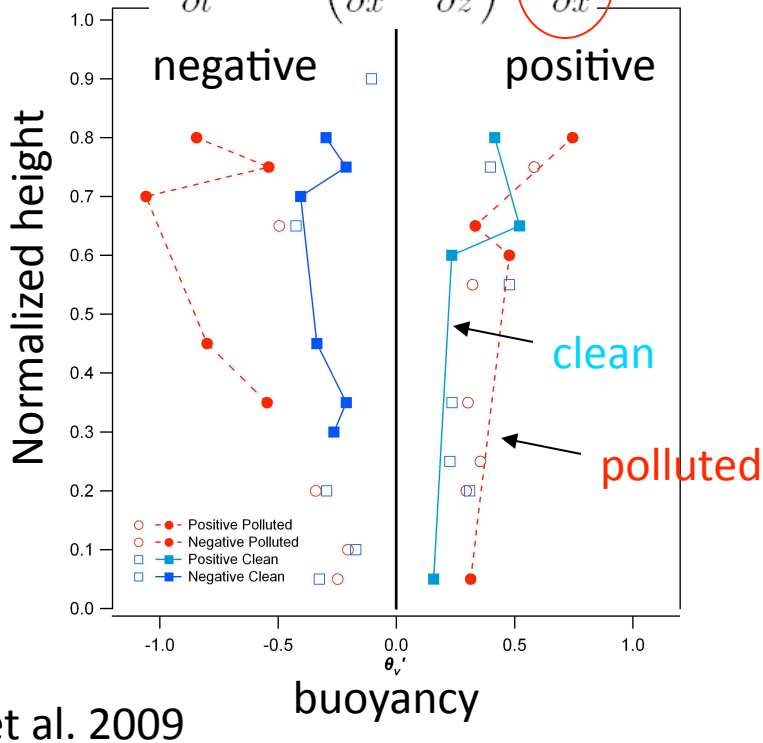
Cloud Lifetime





Jiang et al 2006

$$\frac{\partial \omega}{\partial t} = -\omega\left(\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z}\right) - \frac{\partial B}{\partial x}$$



Small et al. 2009

The lifetime effect:

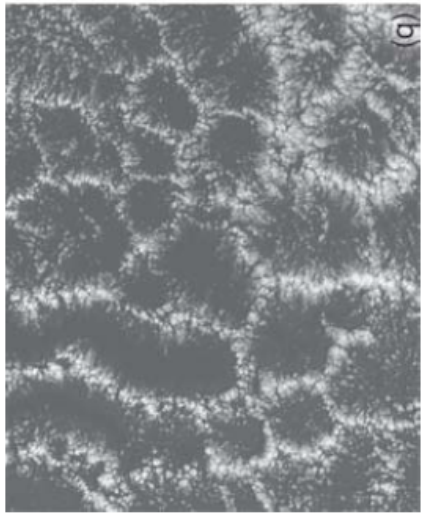
- Aerosol does not appear to have any effect on cloud lifetime;
- Enhanced evaporation may even <u>decrease</u> lifetime

Strong Response

Albedo

Closed-cell
Albedo ~ 0.6
(non-
precipitating)

→ **high aerosol**

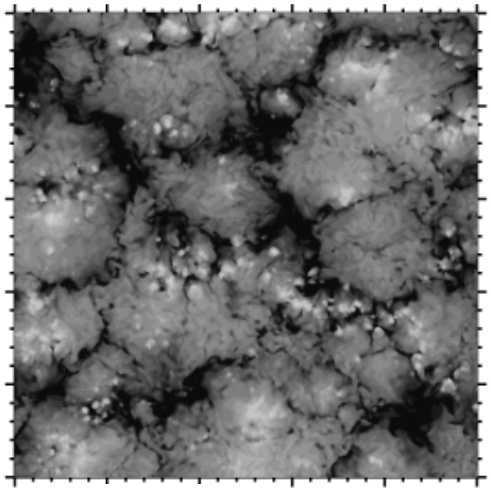


Open-cell
Albedo ~ 0.2
(precipitating)

→ **low aerosol**

More aerosol → more cloudiness ***+ self-organization***

60 km x 60 km

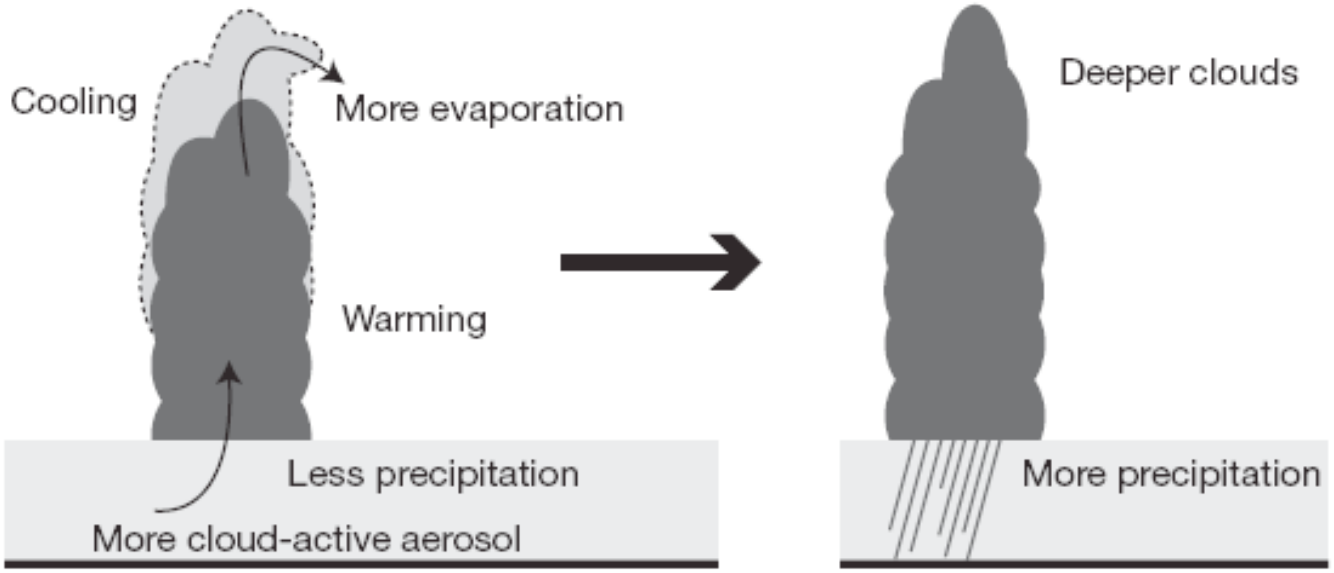


WRF LES simulations:
Wang and Feingold 2009

Garay et al. 2004, MISR Satellite images

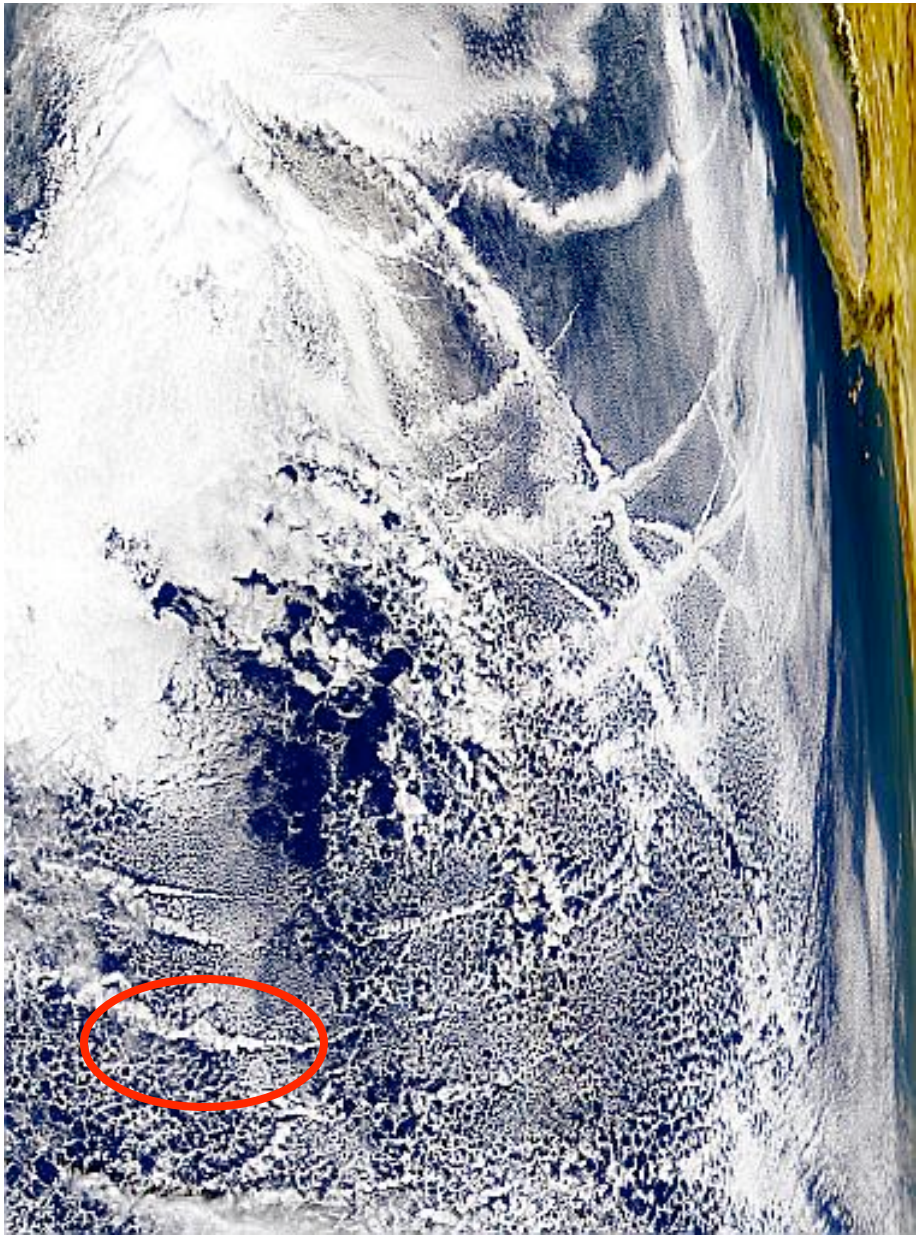
Cloud Deepening

High aerosol concentration



The deepening effect: local inhibition of precipitation helps precondition the environment for deeper convection;
→ Clouds rain more

Stevens and Feingold, 2009
Nuijens and Stevens, 2009



Are ship tracks converting open cells to closed cells?

Geo-engineering implications

Stevens and Feingold 2009

Conclusions

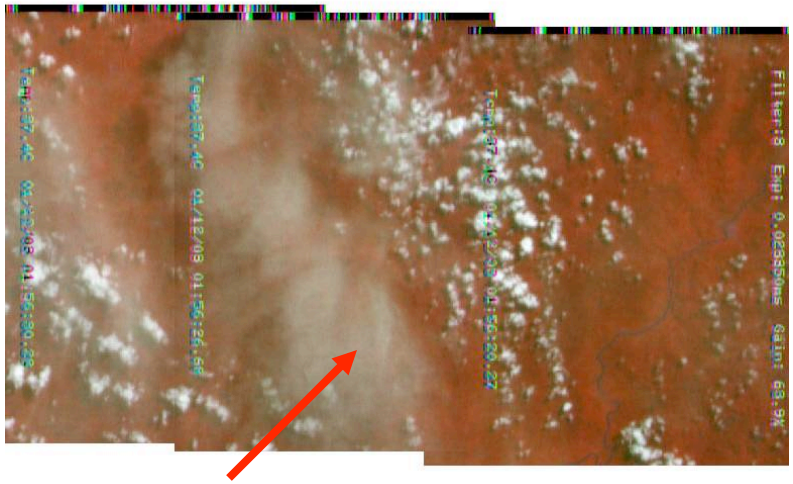
The Aerosol-Cloud-Precipitation system is often buffered

- Strong perturbations are "absorbed" by the system
- Aerosol effects on clouds are nuanced
- Responses are regime-dependent

The best chance of observing aerosol effects is in well-defined dynamical regimes where meteorological "noise" is reduced

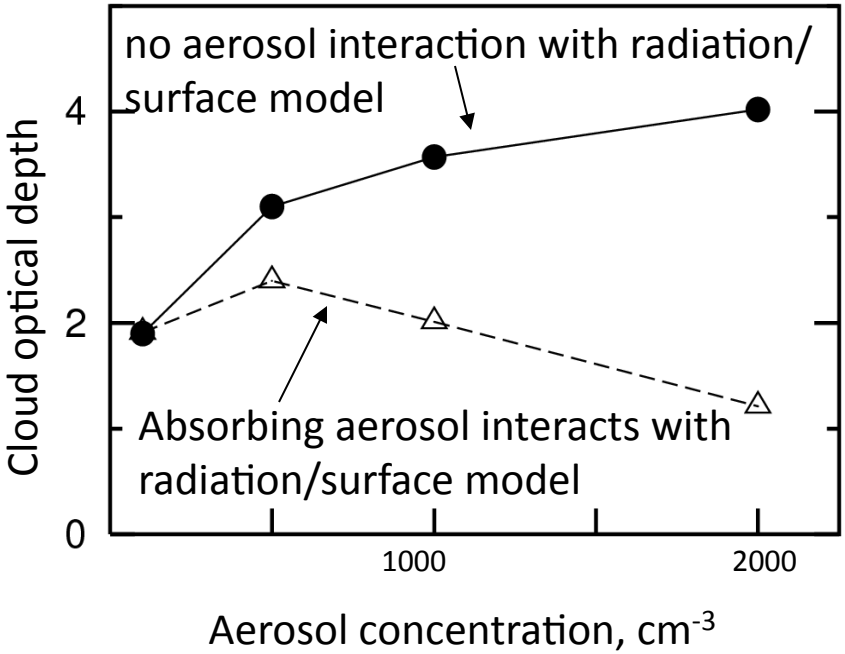
Absorbing Aerosol

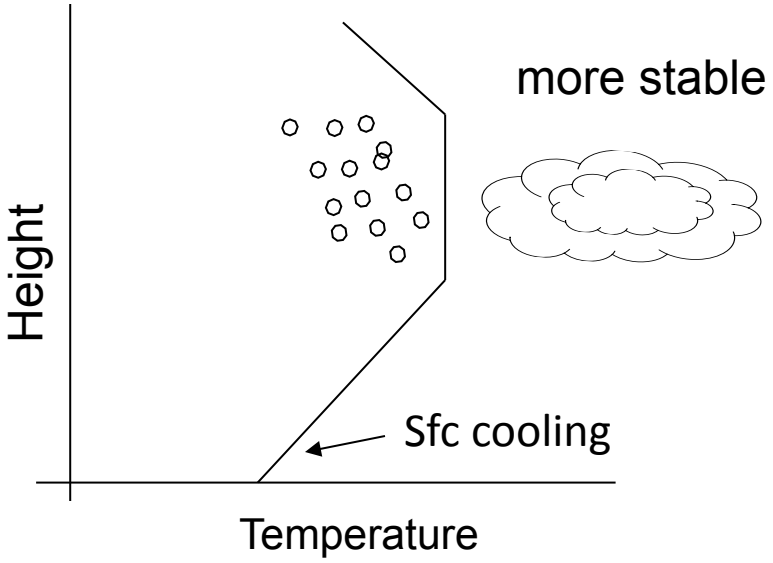
Non-monotonic response of cloud optical depth to increase in smoke aerosol



Absorbing aerosol suppresses clouds

Columbia Shuttle





Modeling: Jiang and Feingold 2006

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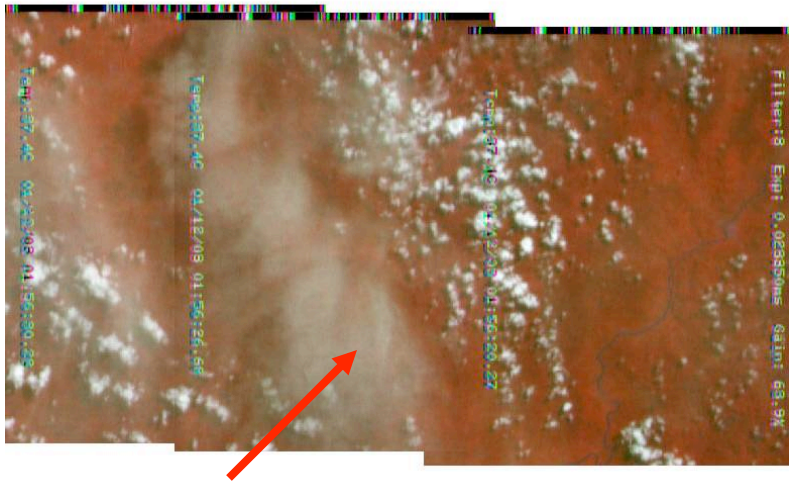

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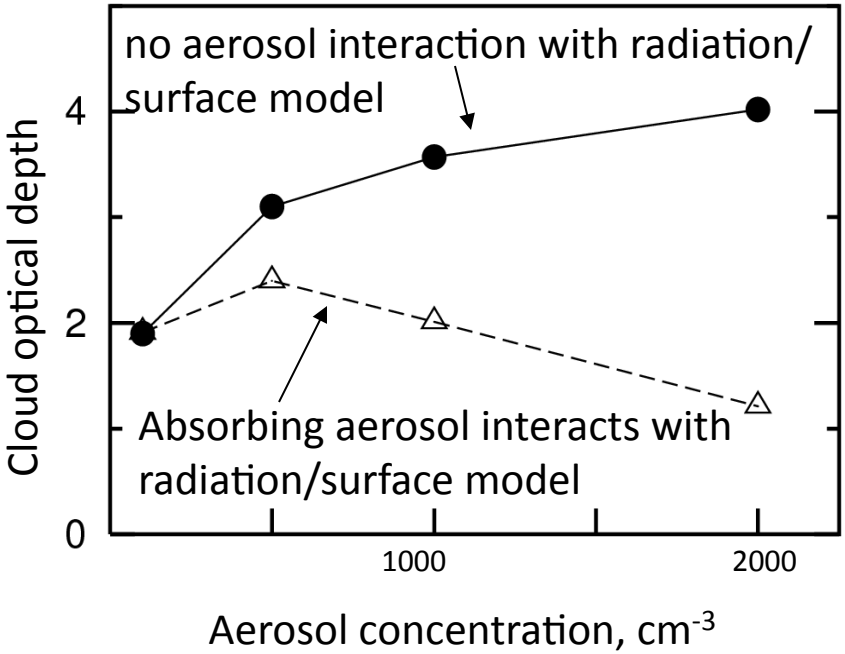

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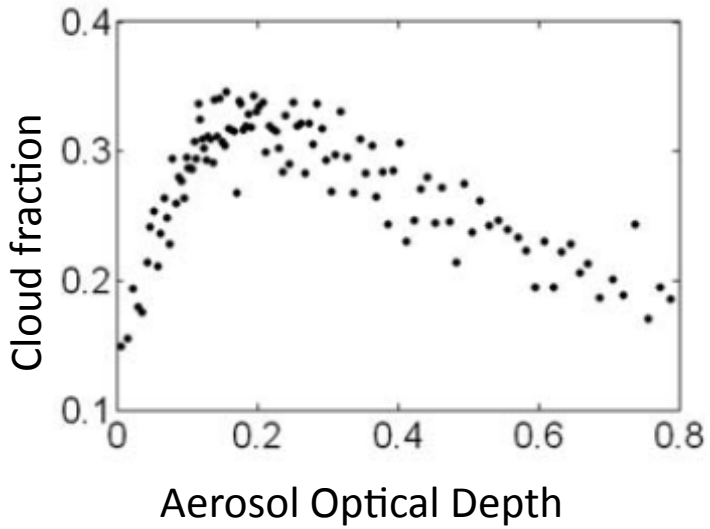
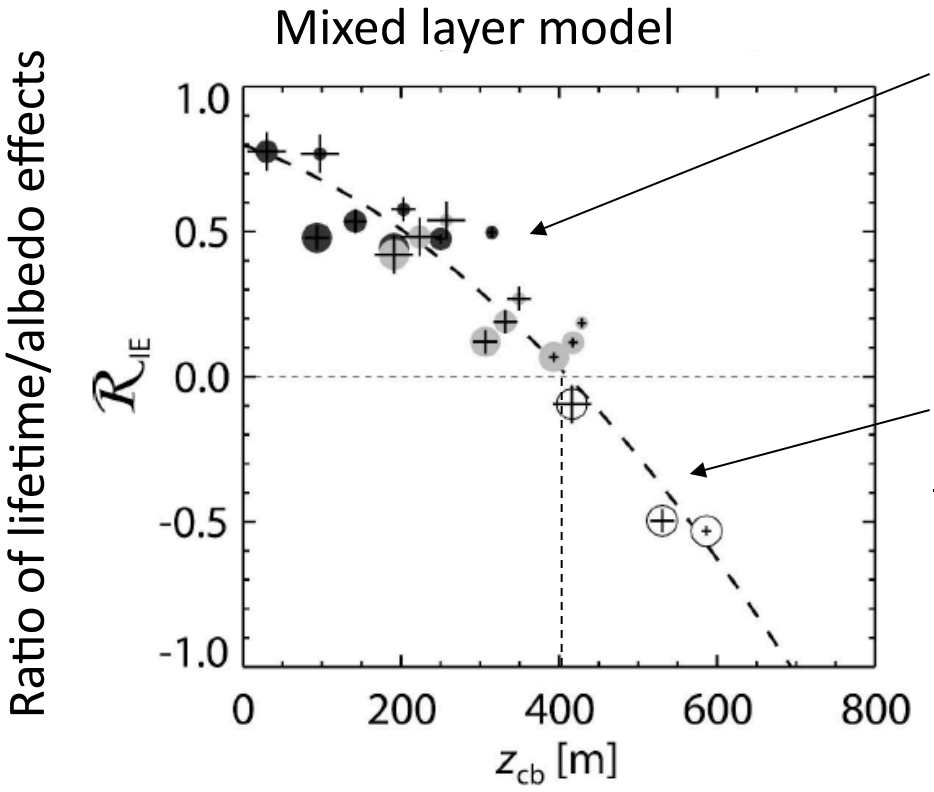


Observations: Koren et al. 2008 (Science)

Ambiguous Responses from Models

Stratocumulus Regime



"lifetime effect" enhances albedo effect

"lifetime effect" increasingly cancels albedo effect

Robert Wood, JAS 2007