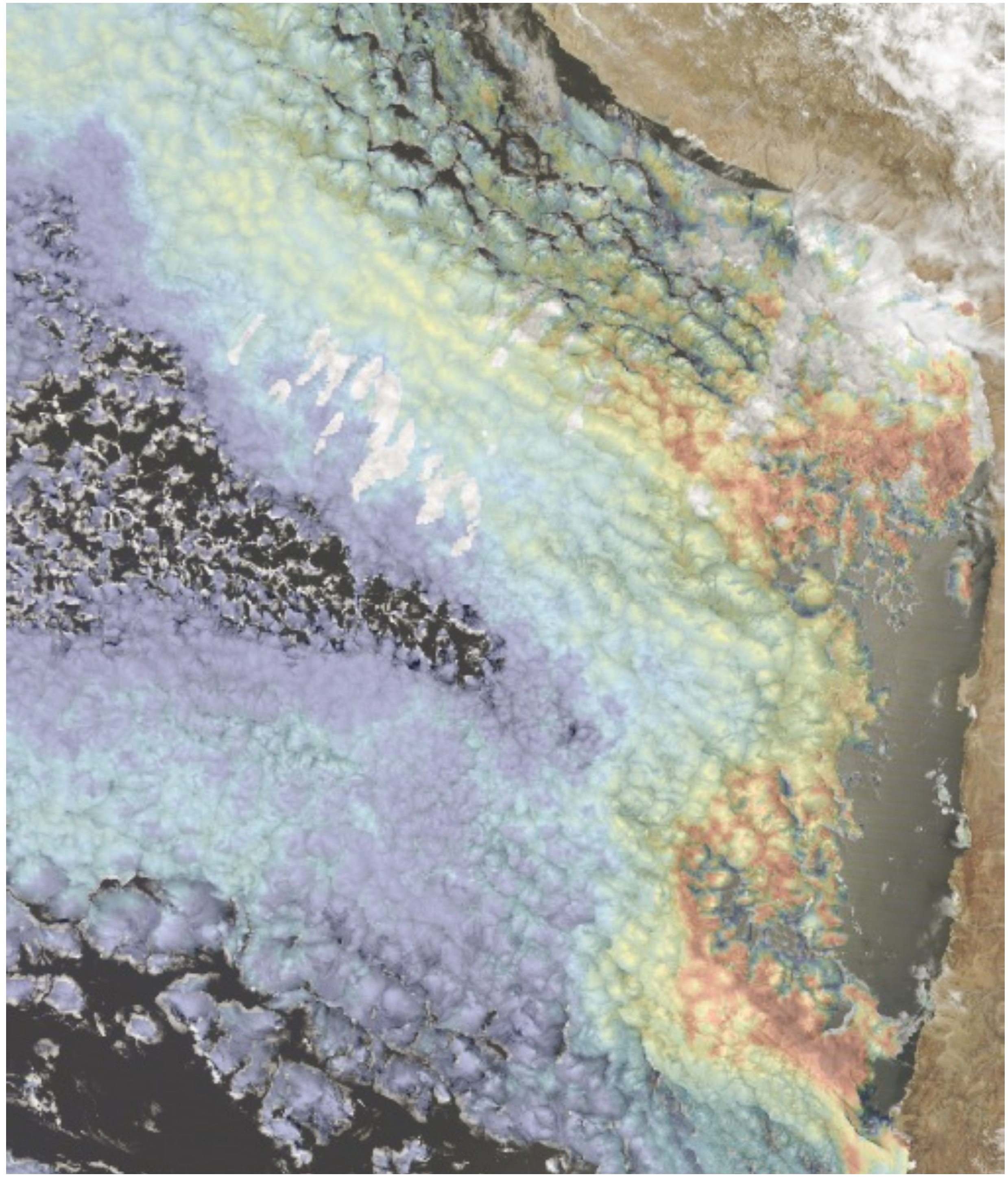
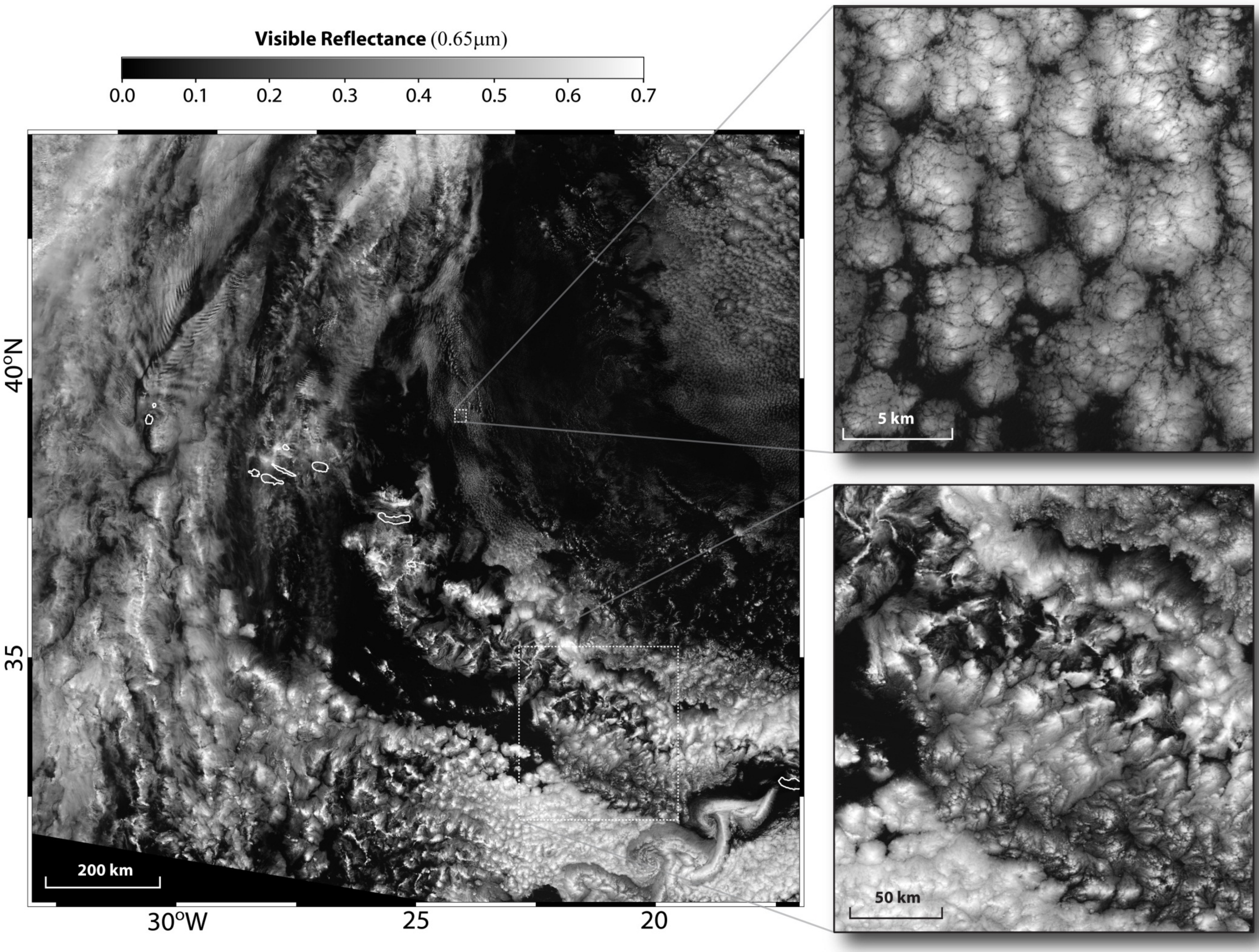
What processes control diversity in the sensitivity of warm low clouds to aerosol perturbations?



Robert Wood
Graham Feingold
Dave Turner

Warm cloud responses to aerosols

- Microphysical, structural, and dynamical properties of low, liquid-phase clouds show sensitivity to aerosol loading, **but** the responses are not uniform
- Increase in aerosol concentration increases cloud droplet concentration
  - droplet size response may depend on LWP response
- The magnitude and even the sign of the response of various cloud-field characteristics (depth, liquid water path, cloud fraction) appear to depend upon
  - cloud type and meteorological regime
  - Precipitation
  - cloud field organization (itself a function of precipitation)
  - aerosol loading in the unperturbed clouds



Visible Reflectance (0.65μm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
40°N
35
30°W
25
20
200 km
5 km
50 km

A formalism

- The response of albedo α to a perturbation in some aerosol property (*N*, nominally CCN concentration) can be written

$$\frac{d\alpha}{dN} = \left(\frac{d\alpha}{dN}\right)_{h,f} + \left(\frac{d\alpha}{dh}\right)_N \left(\frac{dh}{dN}\right)_{W_x} + \left(\frac{d\alpha}{df}\right)_N \left(\frac{df}{dN}\right)_{W_x}$$

Twomey Response | Cloud thickness Response | Cloud cover Response

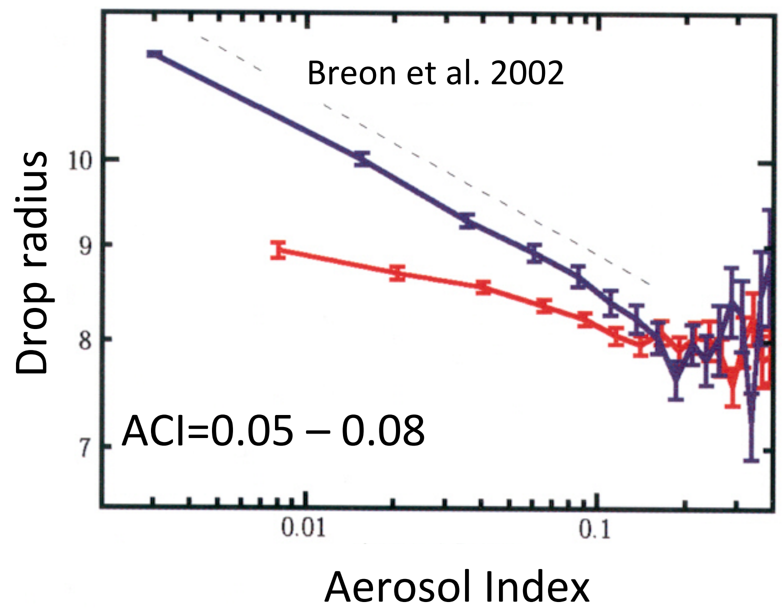
W_x = meteorology

Twomey

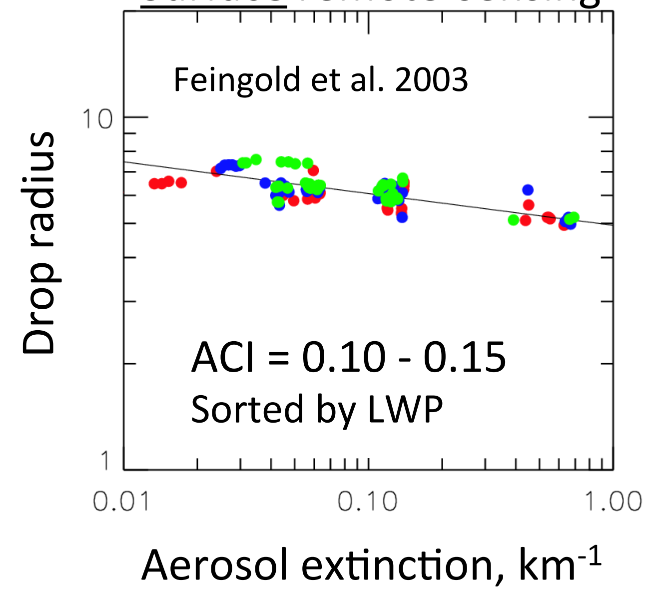
- Twomey responses (at fixed LWP) are most simple to understand
  - But is it an activation problem or the net effect of all microphysical processes (at constant LWP)?
- A diverse response of albedo dependent upon
  - cloud albedo (susceptibility maximum at α=0.5)
  - N_d before perturbation
  - aerosol/dynamical properties affecting activation
  - spatial scales of aerosol and cloud variability
  - etc..

Measurements of Aerosol-Cloud Interactions

Satellite remote-sensing



Surface remote-sensing



Critical 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

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

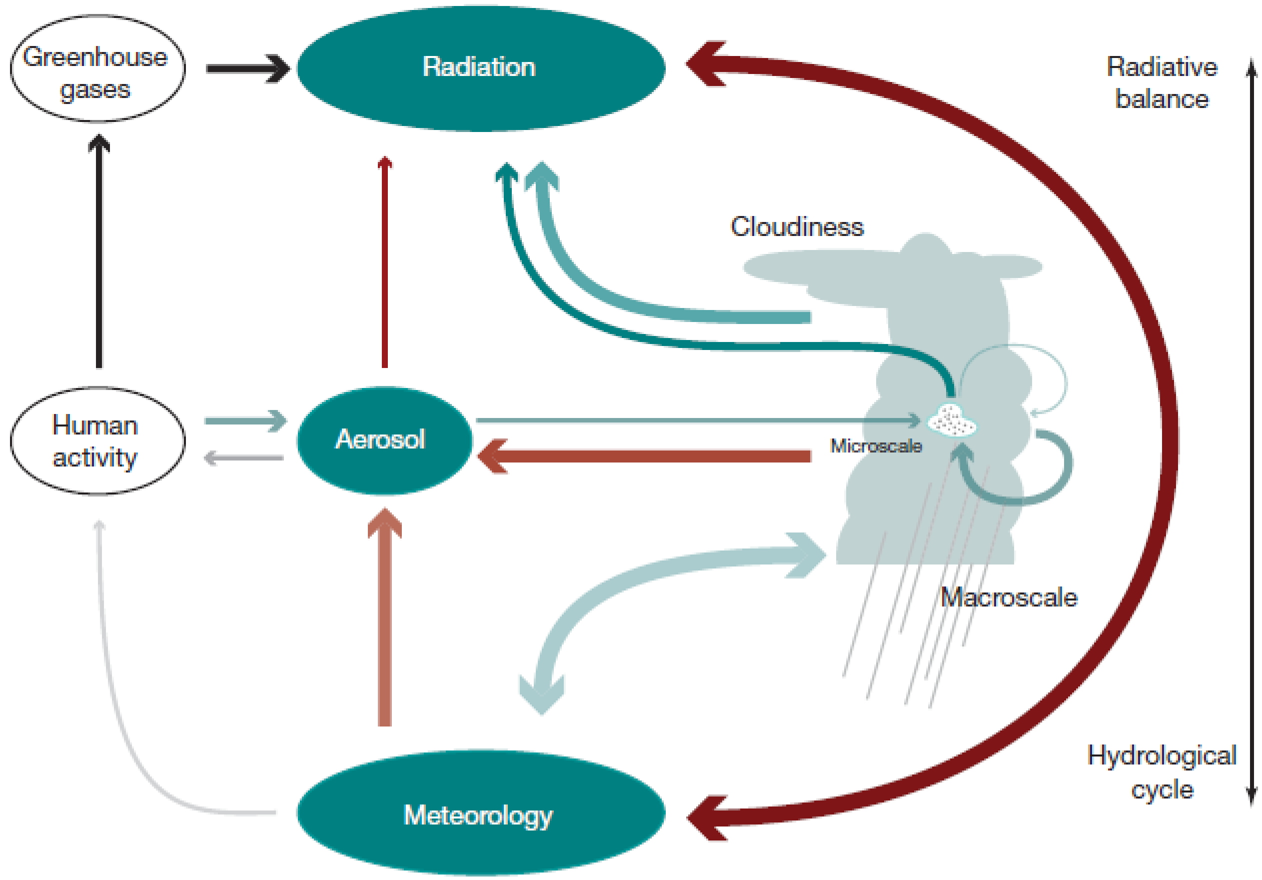
$$= -\left.\frac{\partial \ln r_e}{\partial \ln \alpha}\right|_{LWP}$$

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

α = aerosol

Beyond Twomey

- All else is not equal........



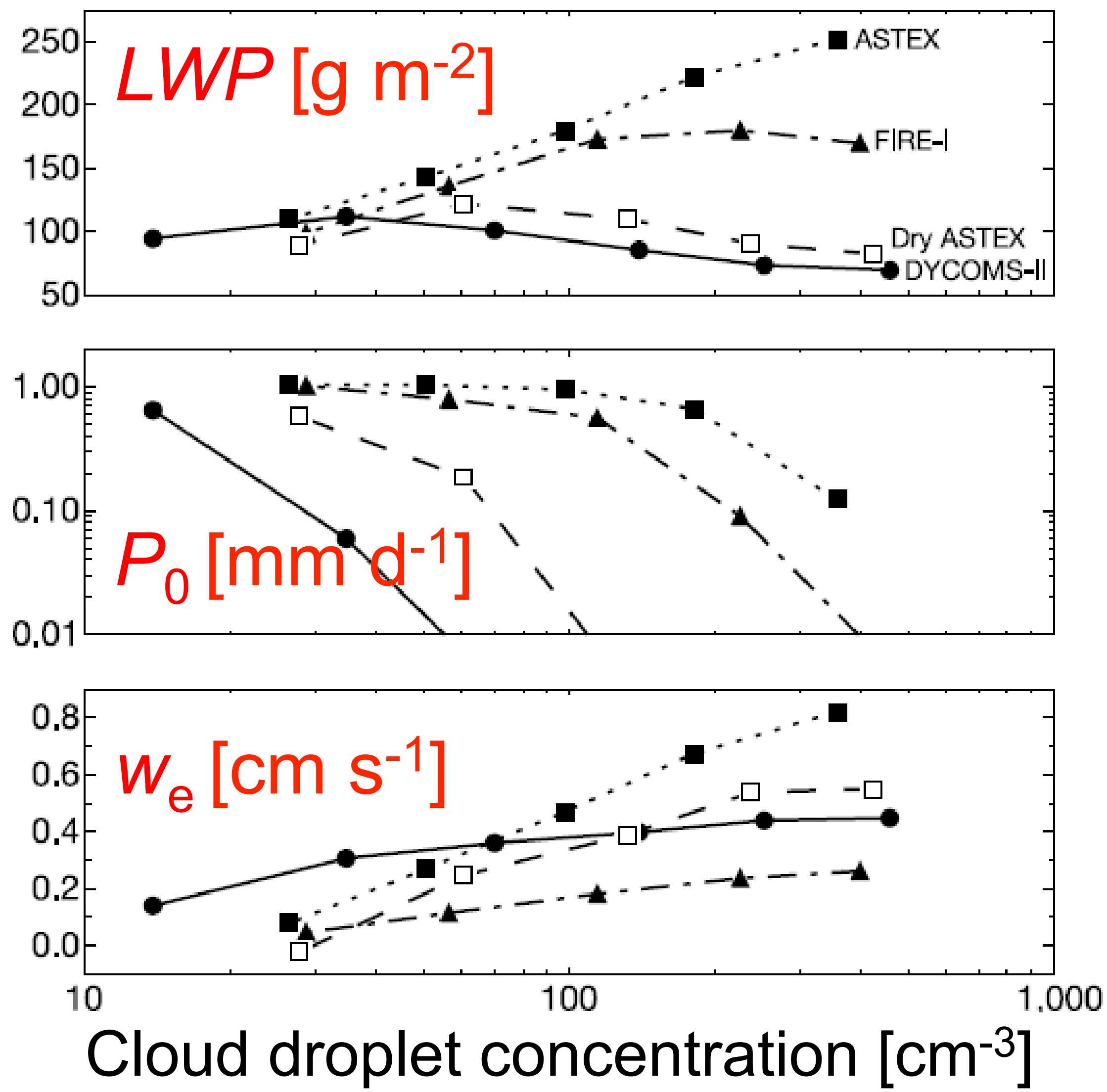
How does precipitation respond to aerosol perturbations?

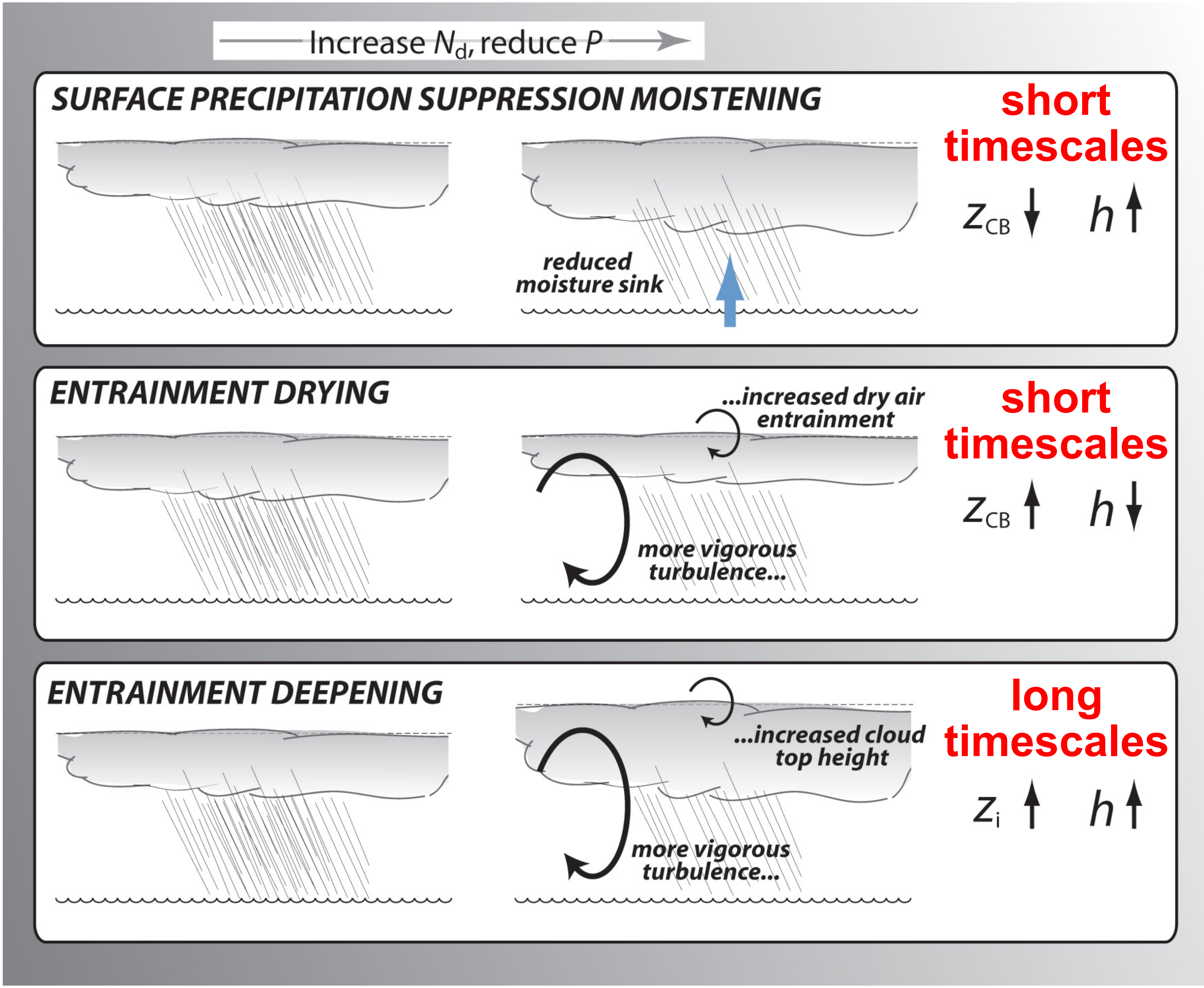
- Aerosol suppresses collision-coalescence but dynamical responses may counter
  - e.g. the clouds deepen allowing more precip
- What are the appropriate timescales?
  - Aerosol perturbations timescales vs. adjustment timescales
- Do albedo and "lifetime" effects work in unison?
- Precipitation susceptibility $-d\ln R/d\ln N$ as a means of quantifying aerosol influence on precipitation

Marine stratocumulus: LES results

- Impact of aerosols simulated by varying N_d
- Increased $N_d \Rightarrow$ Reduced precipitation $\Rightarrow$ increased TKE $\Rightarrow$ increased entrainment w_e
- Changes in w_e can sometimes result in cloud thinning (reduced *LWP*)
- Also noted by Jiang et al. (2002)

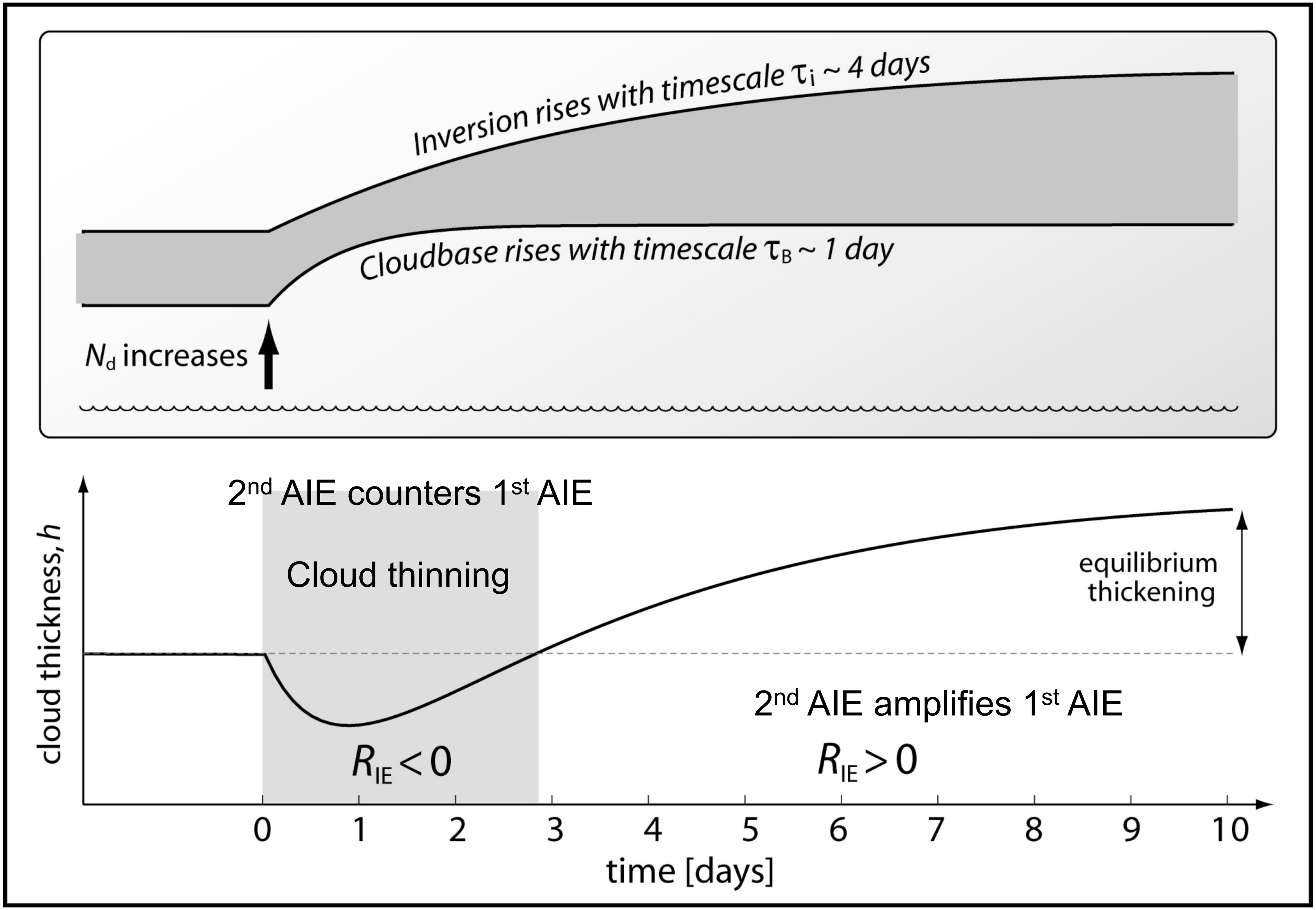
Ackerman et al. (2004)





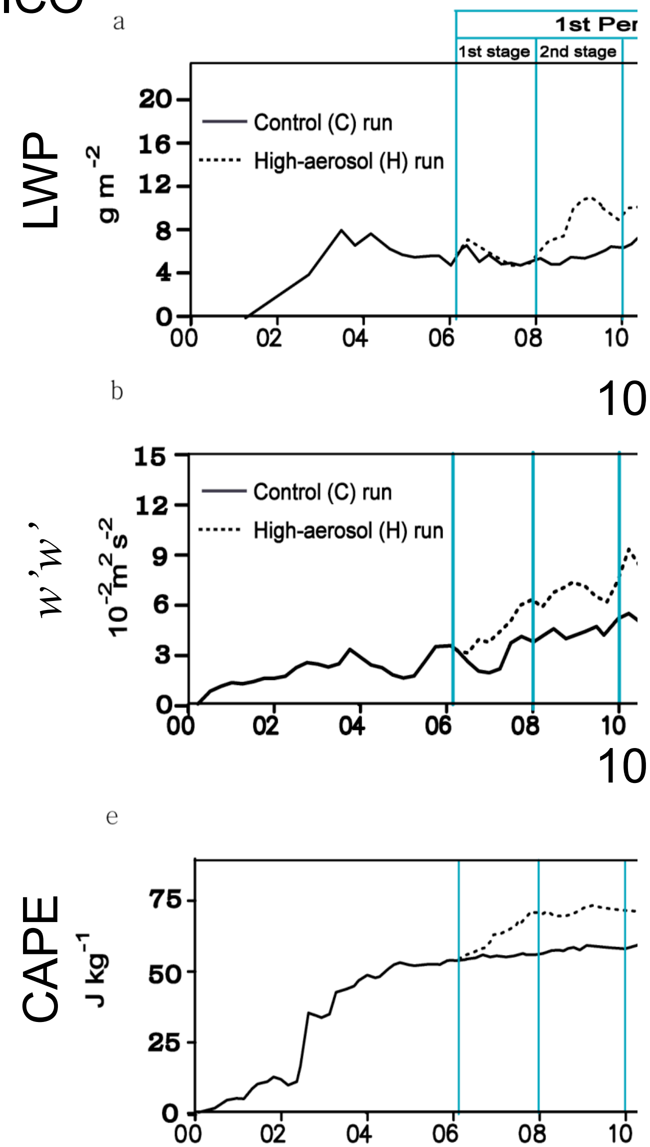
Increase N_d, reduce P
SURFACE PRECIPITATION SUPPRESSION MOISTENING
reduced moisture sink
short timescales
z_{CB} ↓ h ↑
ENTRAINMENT DRYING
...increased dry air entrainment
more vigorous turbulence...
short timescales
z_{CB} ↑ h ↓
ENTRAINMENT DEEPENING
...increased cloud top height
more vigorous turbulence...
long timescales
z_i ↑ h ↑

AIEs may reverse in sign



Trade cumulus responses

RICO



10 h

10 h

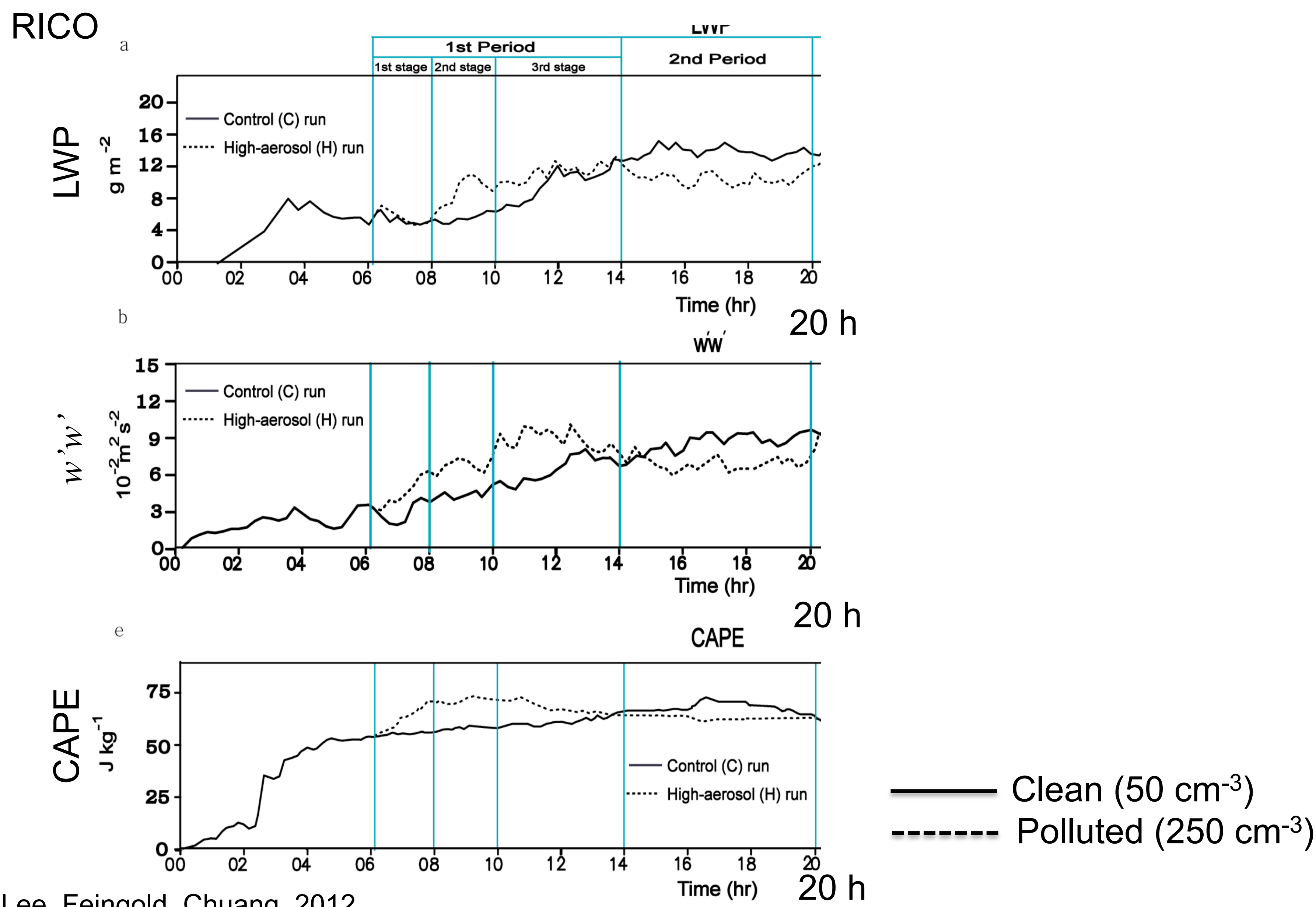
10 h

Lee, Feingold, Chuang, 2012

Clean (50 cm^{-3})

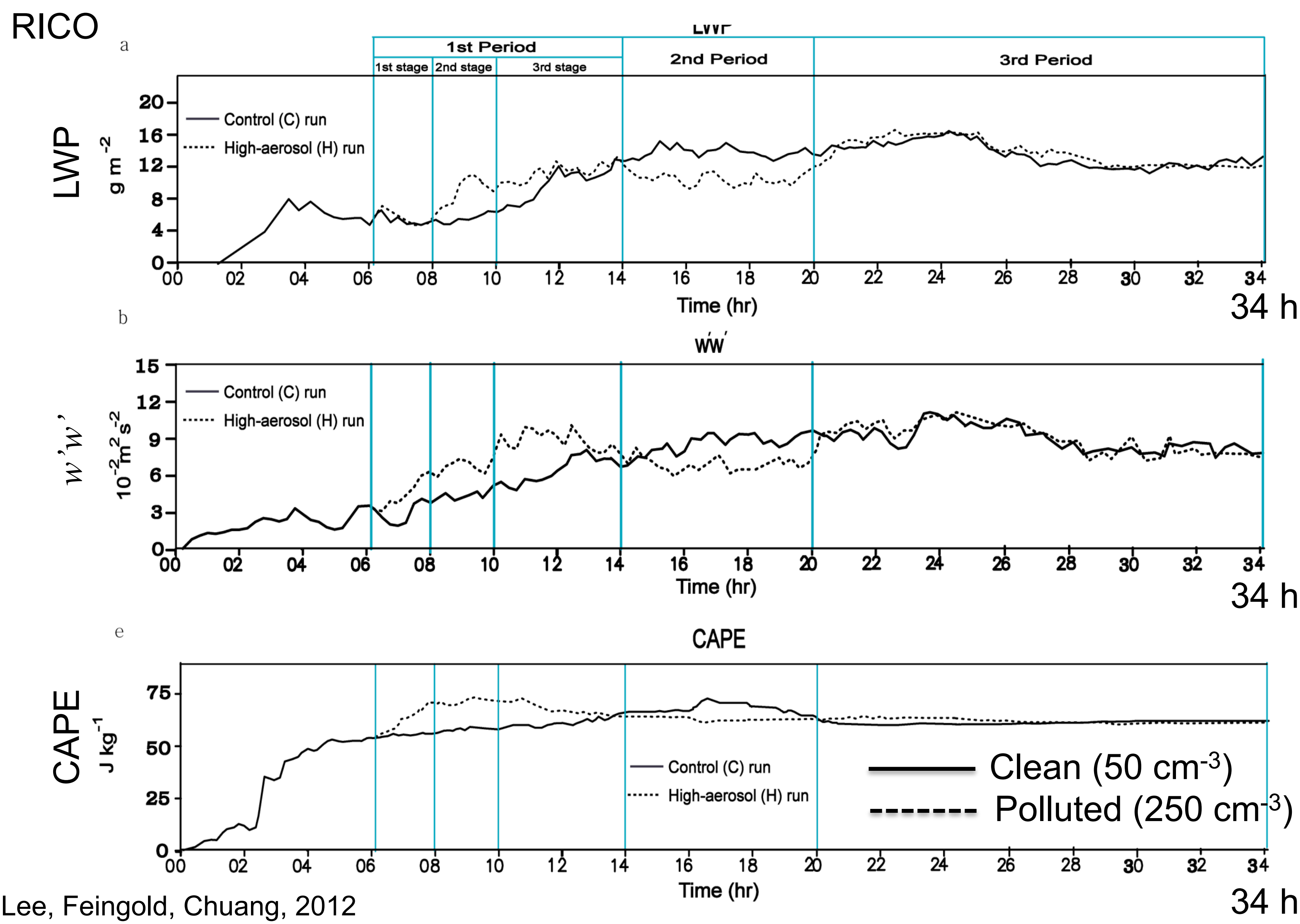
Polluted (250 cm^{-3})

Trade cumulus responses



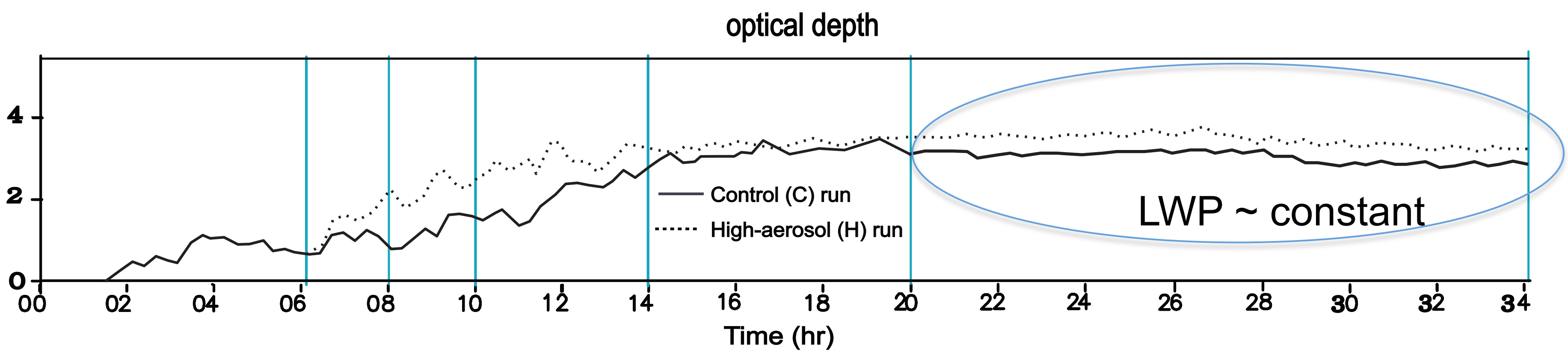
Lee, Feingold, Chuang, 2012

Trade cumulus responses



Lee, Feingold, Chuang, 2012

Influence on cloud optical depth



Only about 75% of the Twomey increase in albedo is realized because of horizontal and vertical spatial variability in microphysical properties

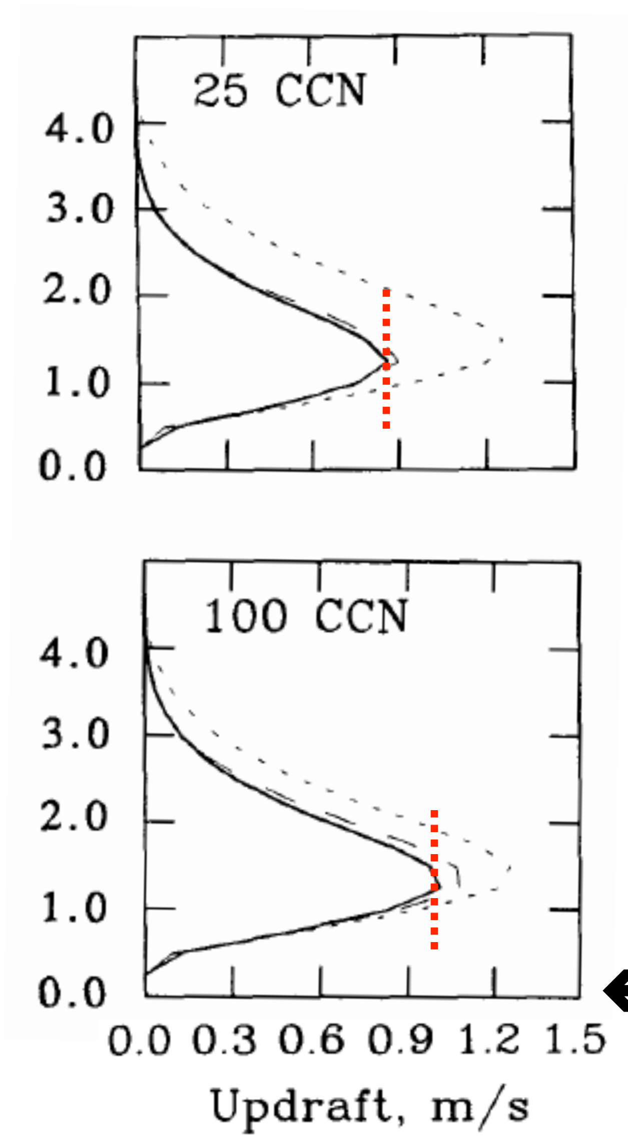
Clean (50 cm^{-3})
Polluted (250 cm^{-3})

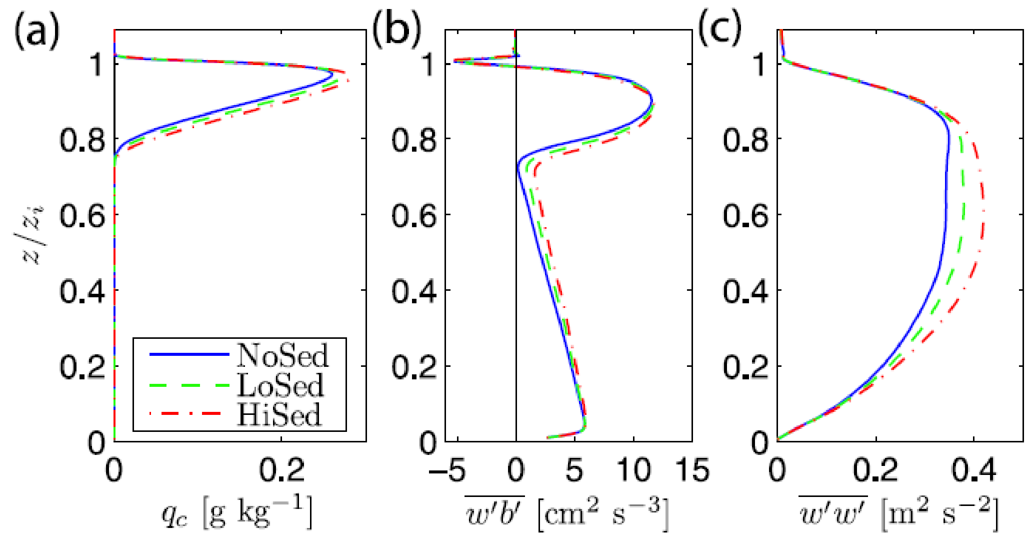
i.e., 3/4 x $(N_{d,H}/N_{d,C})^{1/3}$

Resilience, buffering and multiple timescales

- To what extent are aerosol perturbations "absorbed" by the cloud system? ("buffering")
  - Feedbacks via precipitation, evaporation, sedimentation
  - Aerosol perturbations imprint cloud morphological responses (e.g. depth, fraction, inversion height)
  - How do these compare with slower time scale drivers?
  - How stable is the aerosol-cloud system?

Aerosol effects on cloud dynamics





🡅 Smaller droplets ⇒ slower sedimentation ⇒ more evaporative cooling at inversion ⇒ more entrainment ⇒ drier PBL with less LWP

(Bretherton et al. 2007)

🡄 More CCN ⇒ higher condensation ⇒ stronger w

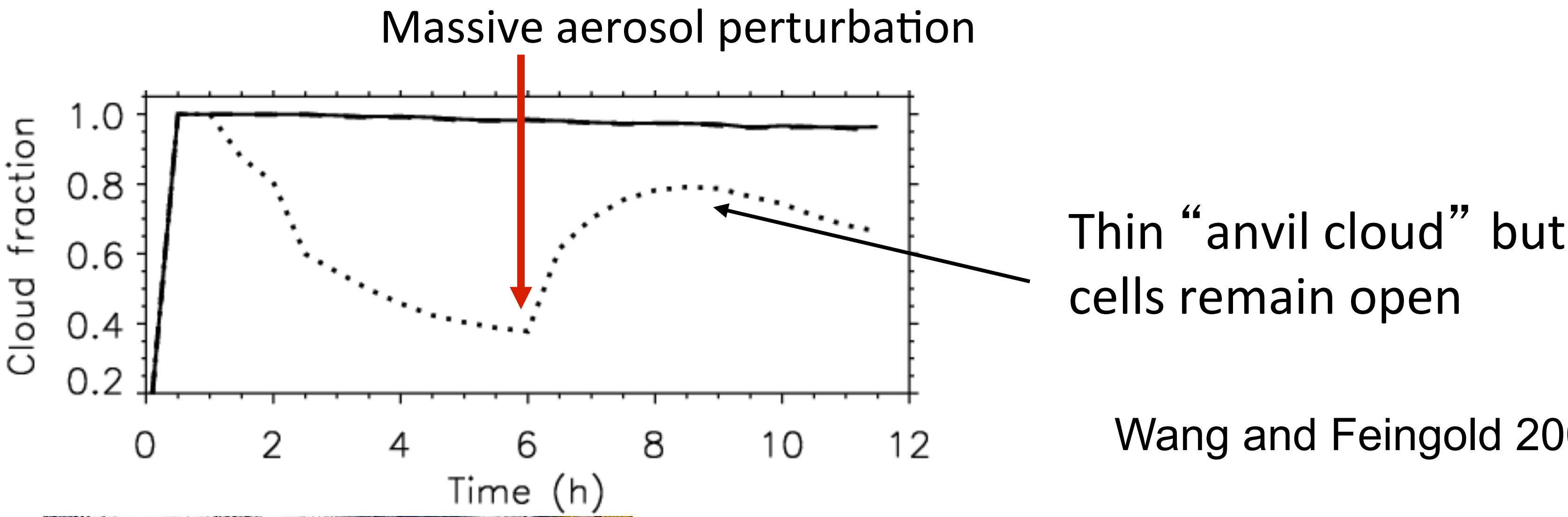
Kogan and Martin (1994)

Resilience and dynamical systems

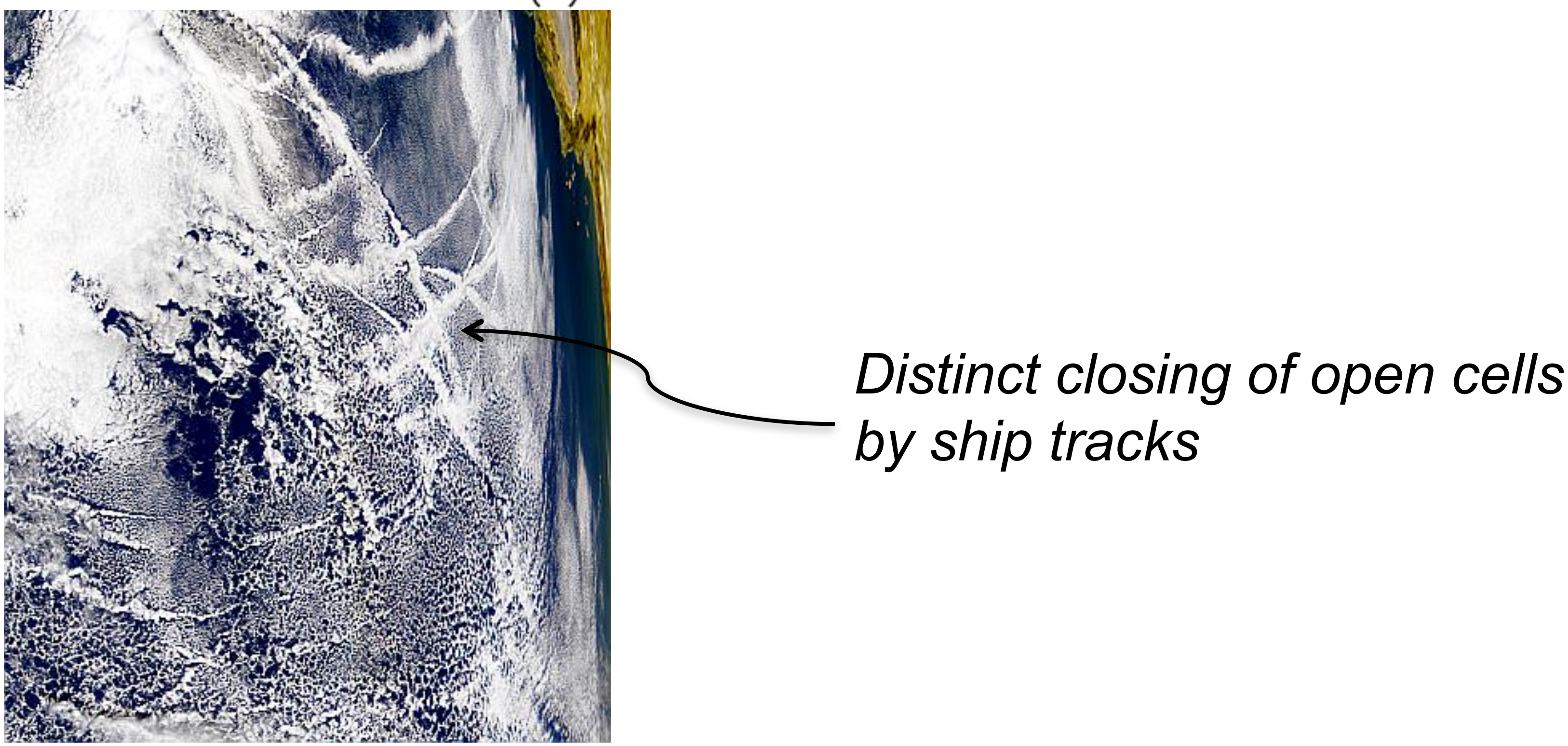
- In the beginning….
  - We saw the world in terms of 1^{st}, 2^{nd}, n^{th} indirect effects
  - Clouds tended to be thought of in a box
- Time to shift focus from individual microphysical processes to a dynamical system view of myriad interacting dynamical/microphysical components
  - Systems are often characterized by self organization
  - Self-organizing systems are resilient and even benefit from small perturbations (aerosol and other)

Aerosol-driven shifts in organization

- POCs and other closed to open cell transitions
  - Collapsed boundary layers, ultraclean, highly sensitive to aerosol (e.g. shiptracks)
  - But not all open cells are necessarily aerosol-sensitive….



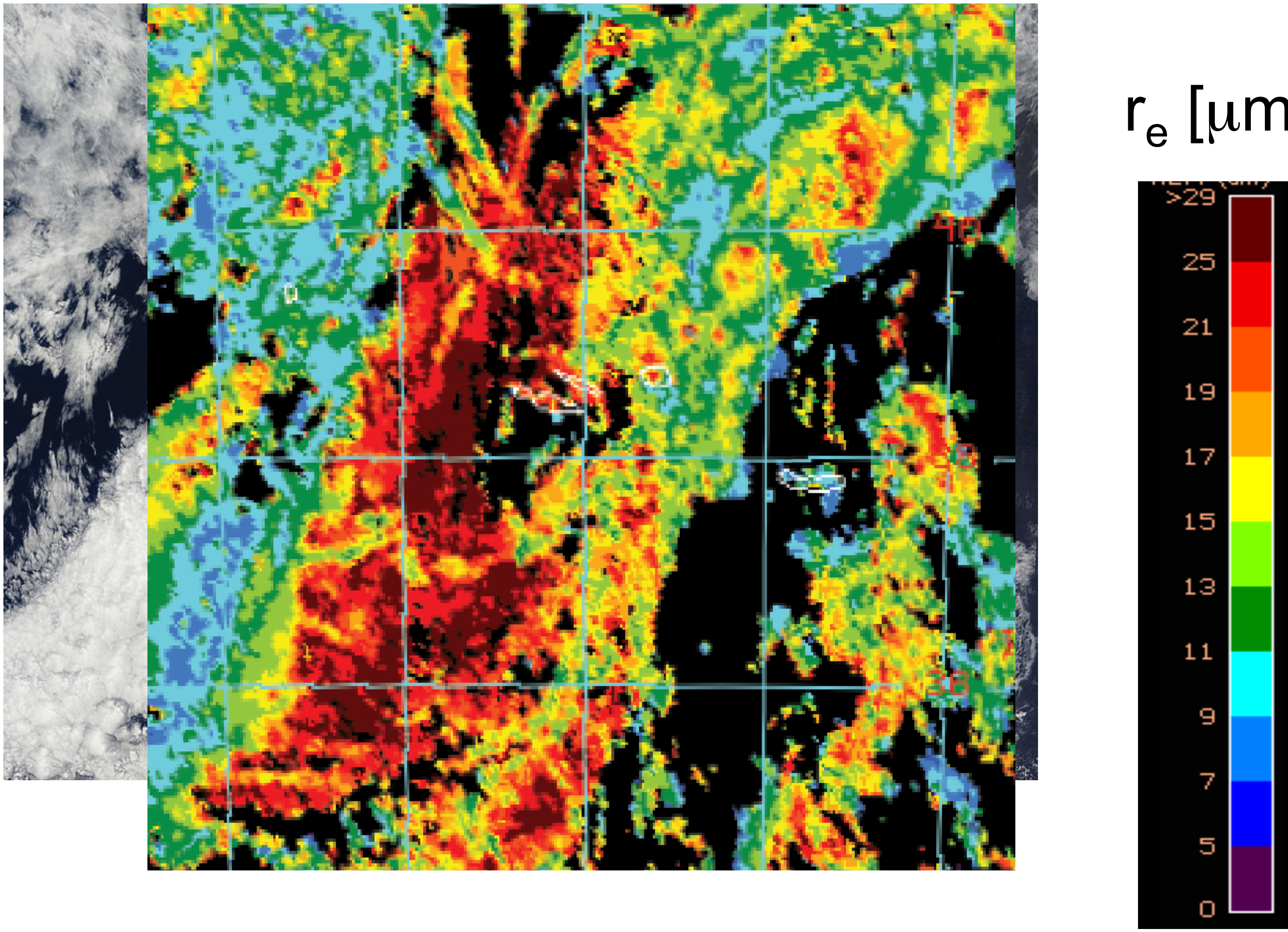
Wang and Feingold 2009



MODIS image courtesy NASA

Collapsed boundary layer at the Azores

r_e [μm]



Action plan
Beyond aerosol indirect effects?

- Consider the aerosol-cloud system as a whole with the following key properties
  - Dynamically evolving
  - Aerosols are an integral component and a "dynamic" variable (cloud effects on aerosols, aerosol effects on clouds)
  - Aerosols are more relevant to some systems than to others

Action plan

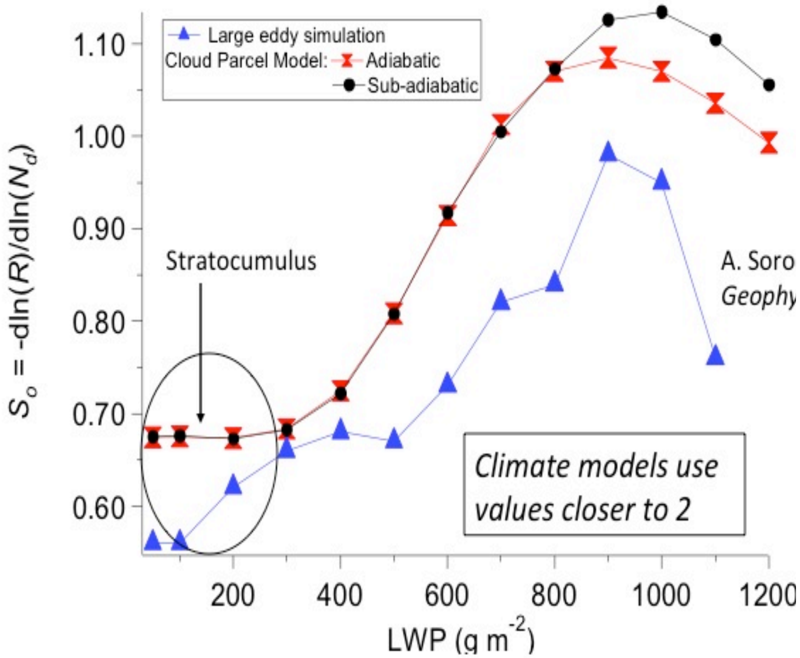
What processes control diversity in the sensitivity of warm low clouds to aerosol perturbations?

Guiding subquestions:

- What factors control the susceptibility of warm rain to aerosol perturbations?
- Why do different approaches to quantifying the Twomey effect yield such diverse estimates?
- How do aerosol perturbations change the dynamics of marine and continental low clouds?
- How sensitive are cloud transitions to aerosol perturbations?
- Can we move beyond the aerosol-cloud microphysical component of the Twomey effect and make progress on the radiative forcing aspect?

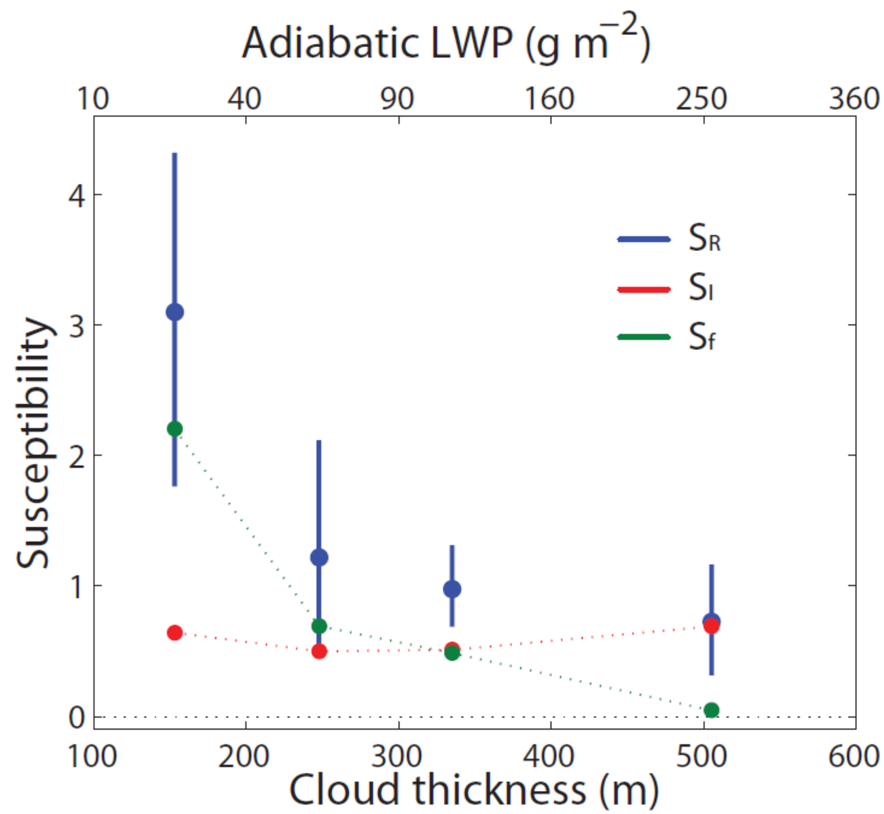
1. What factors control the susceptibility of warm rain to aerosol perturbations?

Example 1:
Parcel and LES models



Sorooshian et al. (GRL, 2009)

Example 2:
Marine Stratocumulus (VOCALS, aircraft data)



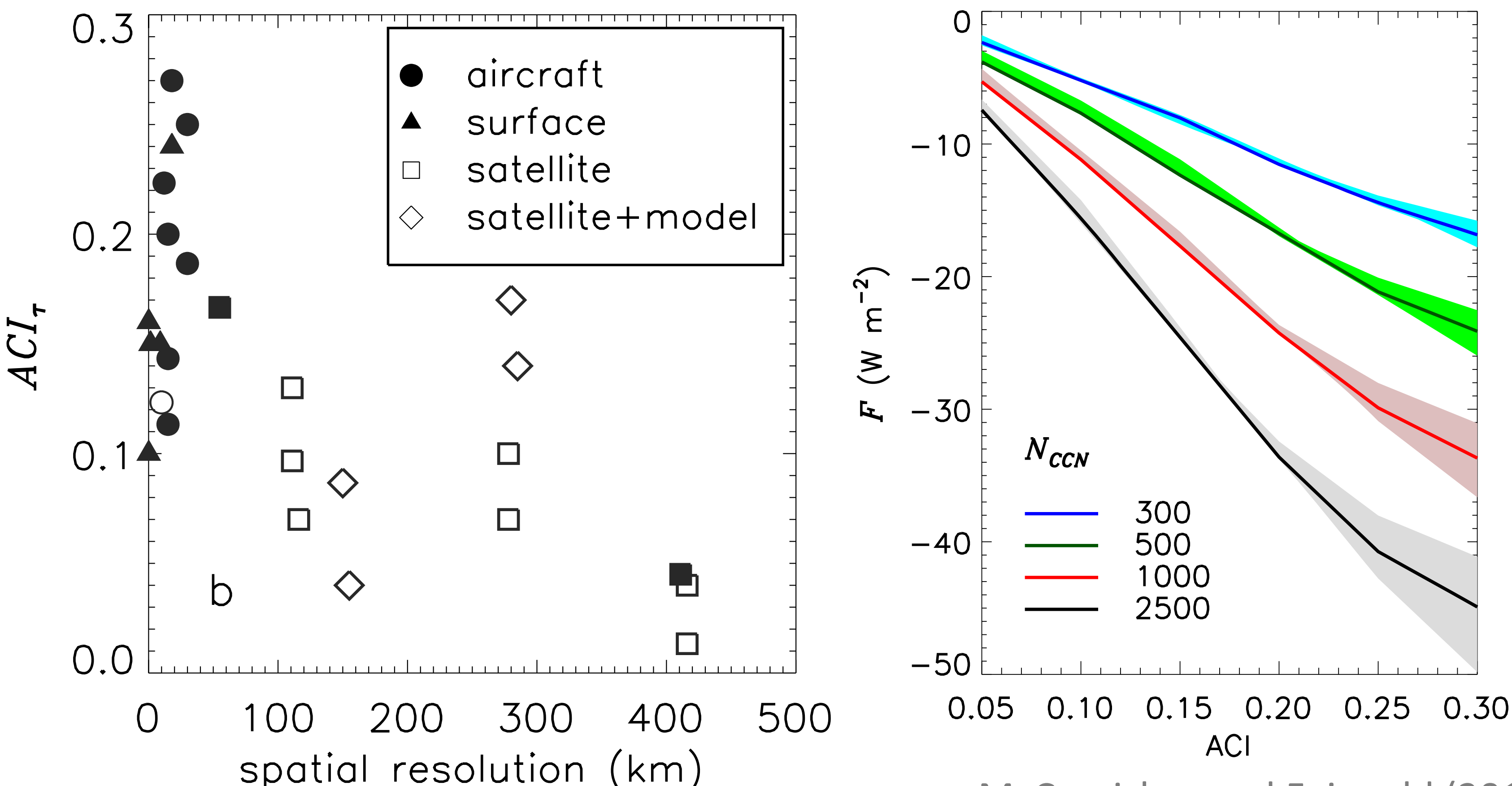
Terai et al. [*Atmos. Chem. Phys.* 2012]

1. What factors control the susceptibility of warm rain to aerosol perturbations?

- Ideas for moving forward:
  - Estimate precipitation susceptibility metrics for existing ARM low cloud datasets (e.g. Azores, MASRAD, MAGIC)
  - Use high resolution and simple process models to explore key controlling factors and attempt to composite observations using these factors
- Data needs:
  - Improved quantification of light drizzle, cloud liquid water path, microphysical retrievals, CCN measurements

2. Why do different approaches to quantifying the Twomey effect yield such diverse estimates?

- ACI is scale dependent. Constant LWP matters!
- Averaging method matters!



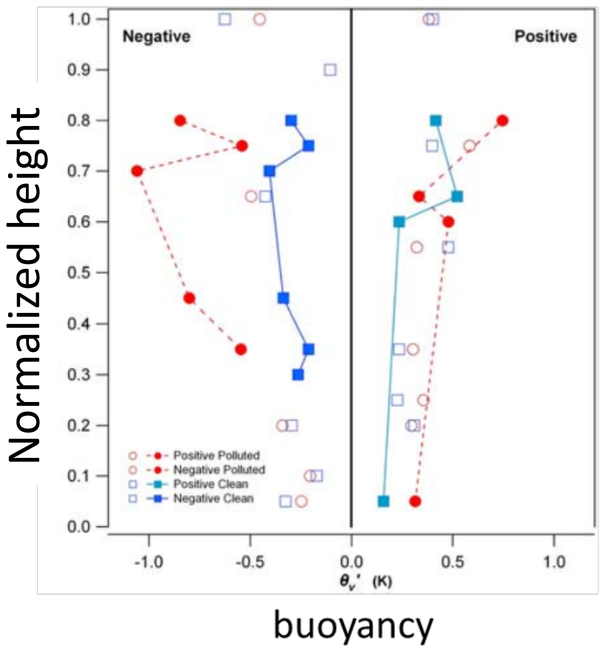
McComiskey and Feingold (2012)

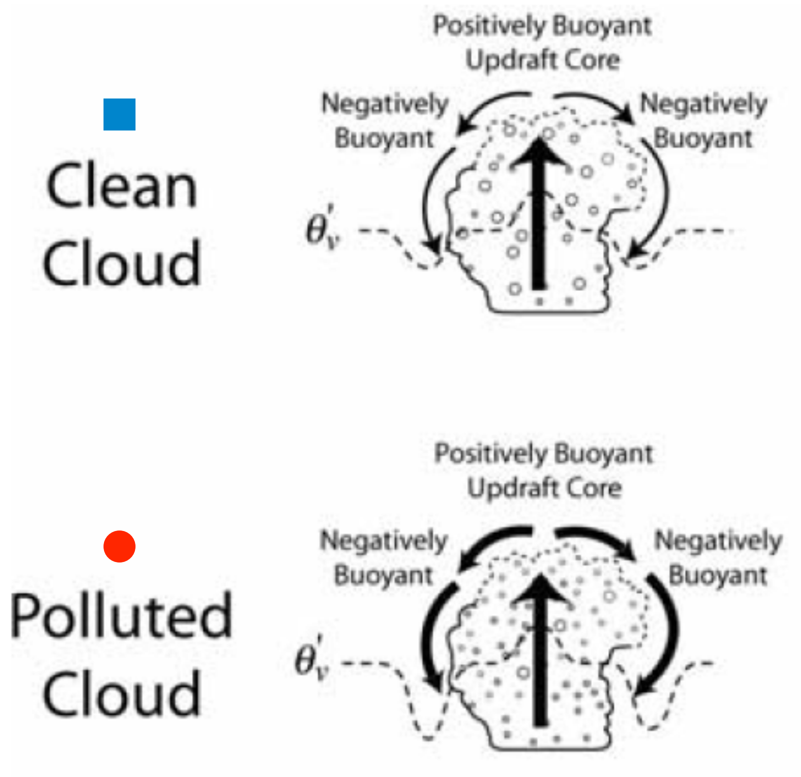
2. Why do different approaches to quantifying the Twomey effect yield such diverse estimates?

- Ideas for moving forward:
  - Determine ACI metrics across ARM low cloud datasets
  - Systematically examine how ACI changes with cloud dynamics, aerosol loading, spatiotemporal scale
- Data needs:
  - Robust cloud microphysical retrievals (r_e, N_d), LWP (especially for thinner clouds); vertical velocity measurements

3. How do aerosol perturbations change the dynamics of marine and continental low clouds?

Aircraft Observations





al. 2006)

GoMACCS
(Small et al. 2009)

Entrainment vs Twomey

$$\left.\frac{d\ln\tau}{d\ln L}\right|_{\text{inhomog}} = 1$$

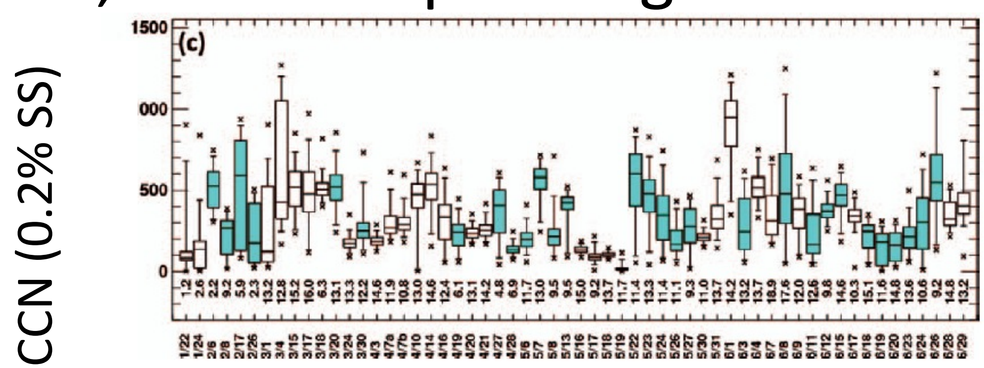
$$\left.\frac{d\ln\tau}{d\ln L}\right|_{\text{homog}} = \frac{2}{3};$$

$$\left.\frac{d\ln\tau}{d\ln N}\right|_{L} = \frac{1}{3}$$

3. How do aerosol perturbations change the dynamics of marine and continental low clouds?

- Ideas for moving forward:
  - Use existing ARM datasets to explore relationships between aerosols and cloud dynamics (updraft speed, entrainment rates)
- Data needs
  - Cloud dynamical properties (updraft speed)
  - Entrainment properties, moisture profiling

RACORO (Vogelman et al. 2012)



4. How sensitive are cloud transitions to aerosol perturbations?

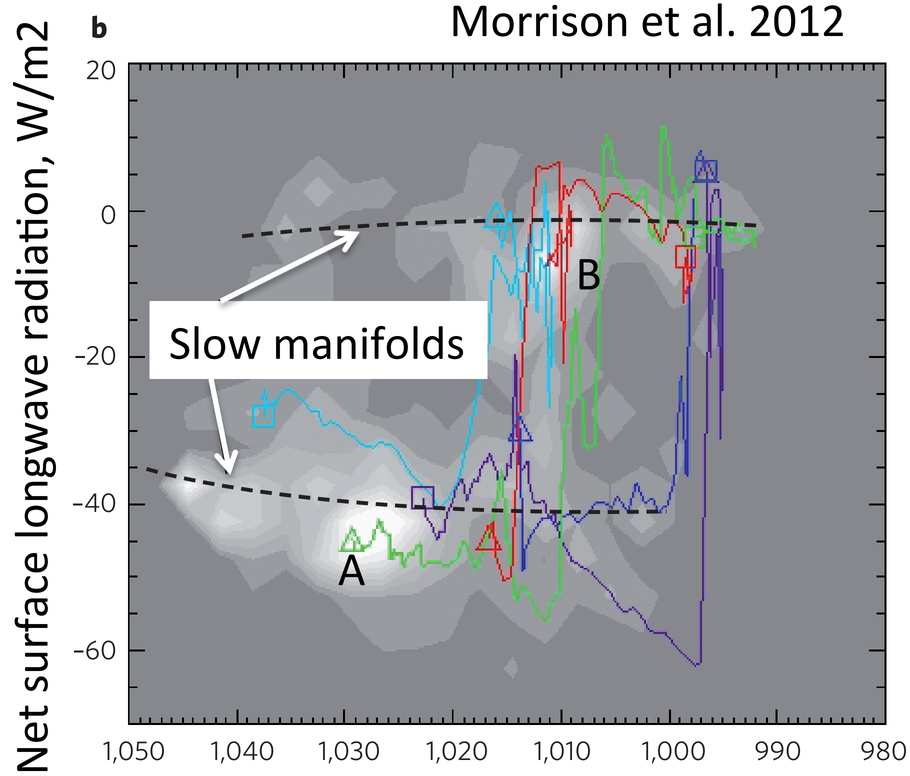
Fast processes: local interactions

Slow processes: broad meteorological environment

Fast processes “slave” system to the slow manifold

Transitions are dependent on changes to the largescale environment and/or μphysics

Morrison et al. 2012



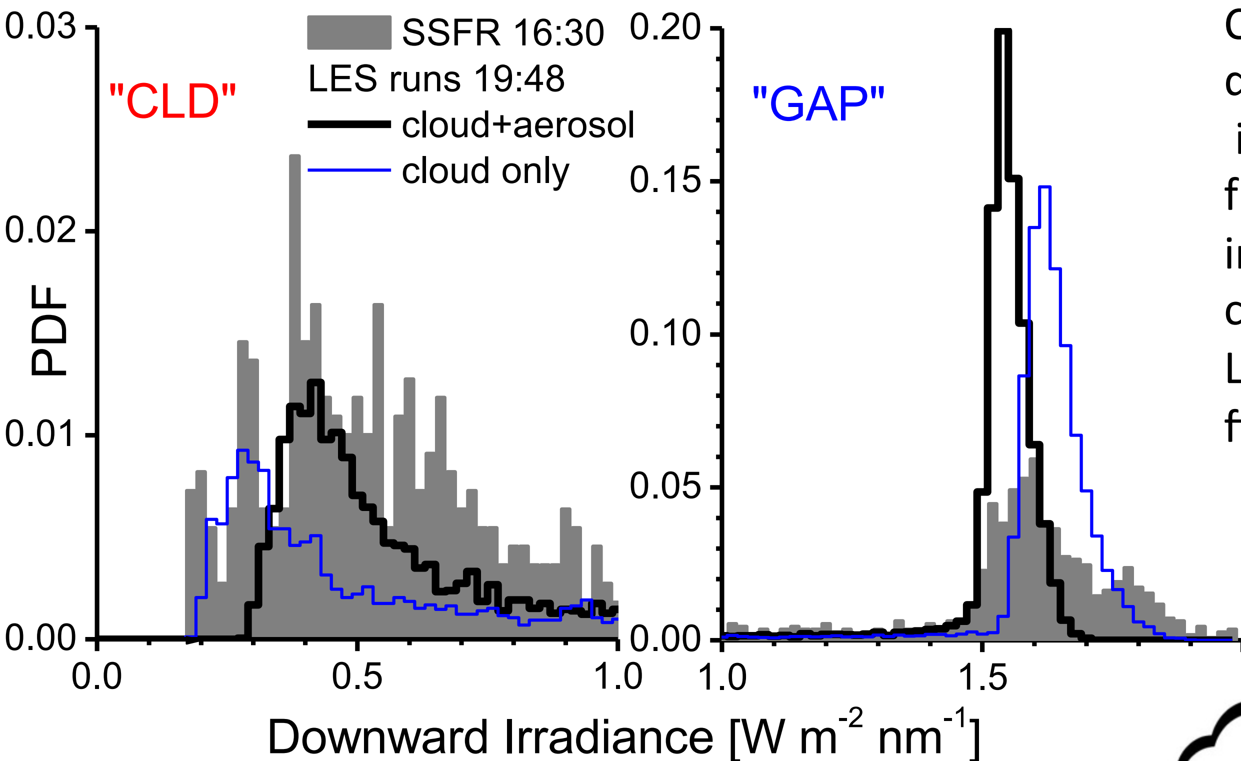
Colored trajectories: transition between states
Triangle = start; square = end

A = Radiatively clear
B = Cloudy

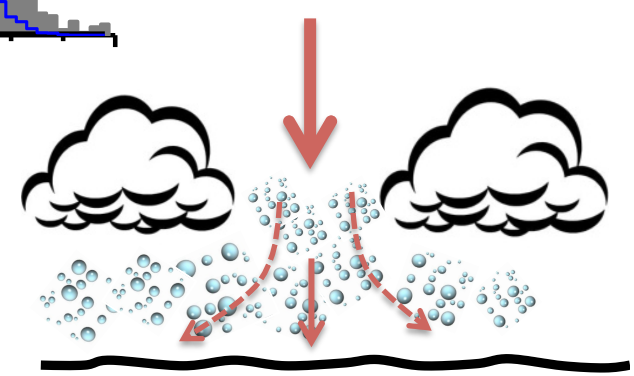
4. How sensitive are cloud transitions to aerosol perturbations?

- Ideas for moving forward:
  - Identify cloud organizational "states" and the transitions between them
  - How different are aerosol properties within states and between states
- Data needs
  - Meteorological controls on cloudiness
  - Microphysical data during transitions

5. Can we move beyond the aerosol-cloud microphysical component of the Twomey effect and make progress on the radiative forcing aspect?



Comparison of downward irradiance measured from aircraft with irradiance calculated from LES-generated cloud fields



CLD: below clouds

GAP: below gaps in clouds

Schmidt et al. 2009 GRL

5. Can we move beyond the aerosol-cloud microphysical component of the Twomey effect and make progress on the radiative forcing aspect?

- Ideas for moving forward:
  - Characterize the statistical nature of the radiation of cloud fields
- Data needs
  - Downward irradiance or radiance
  - Surface and/or airborne measurements