Aerosol-Cloud-Precipitation Interactions in warm clouds

Graham Feingold

NOAA Earth System Research Laboratory Boulder, Colorado USA

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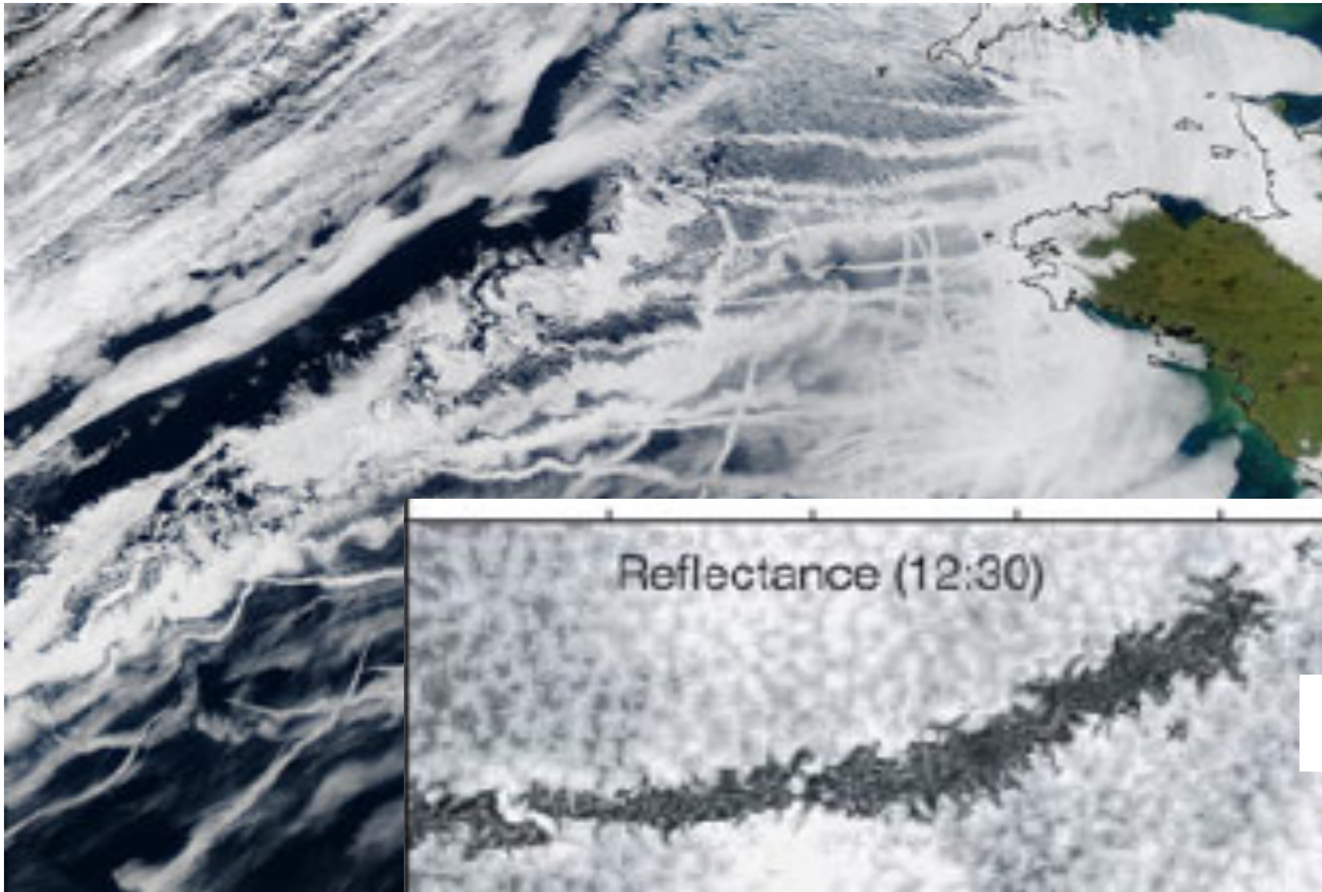
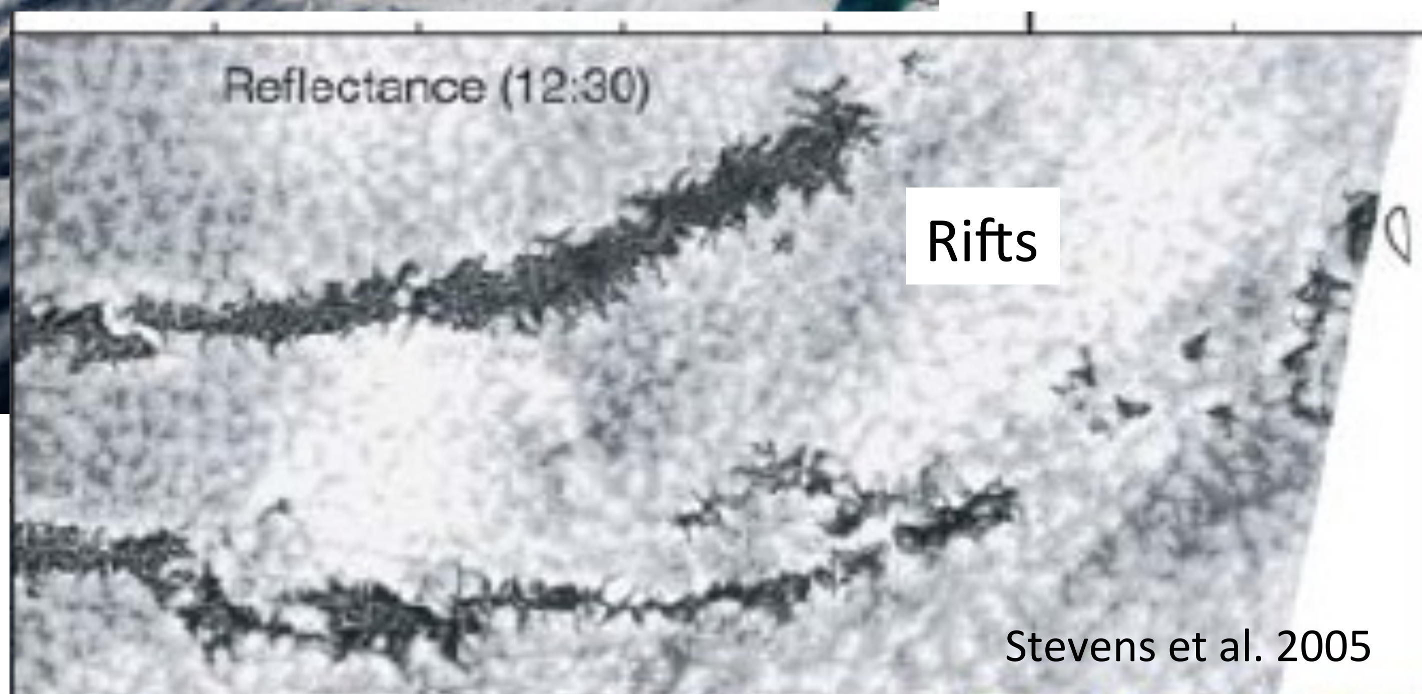
Aerosol Effects on Clouds



Shiptracks

(Courtesy, NASA)



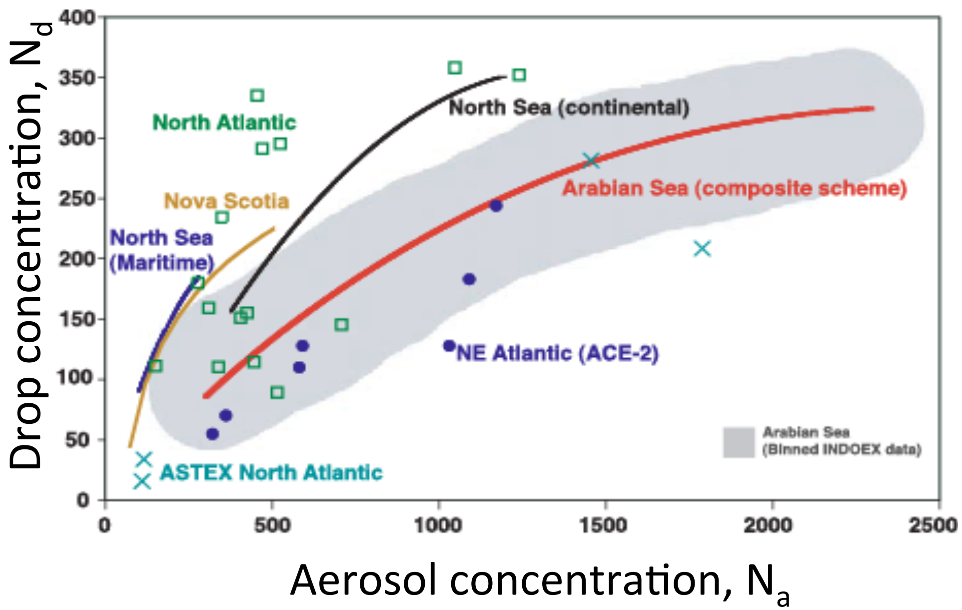
Outline

- Simple constructs that may have outlived their usefulness
  - Albedo effect
  - Lifetime effect
  - n^{th} indirect effect
- Anticipated and unanticipated responses
- Correlation vs. Causality
- Self-organizing systems
- Bistability and the role of Aerosol
- Numerical Ship track experiments

Some simple cloud physics

- Clouds are dynamical entities and the characteristics of the cloud field depend on the meteorological regime
  - To first order, cloud fraction and depth or LWP dictate albedo

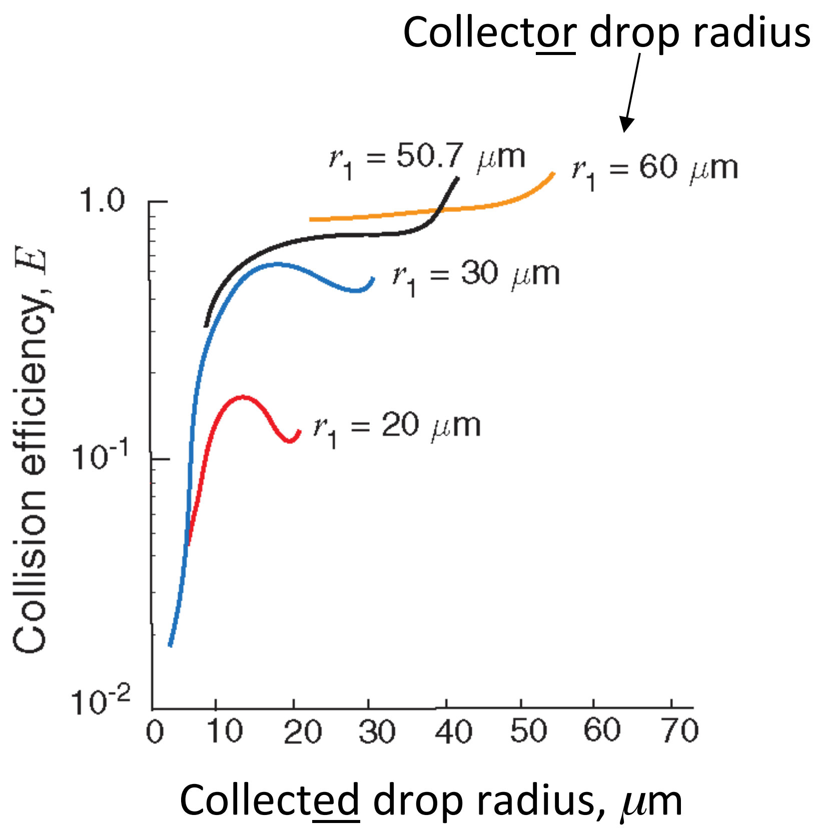
- More aerosol → more drops (almost always)
  - But drop size response is unpredictable



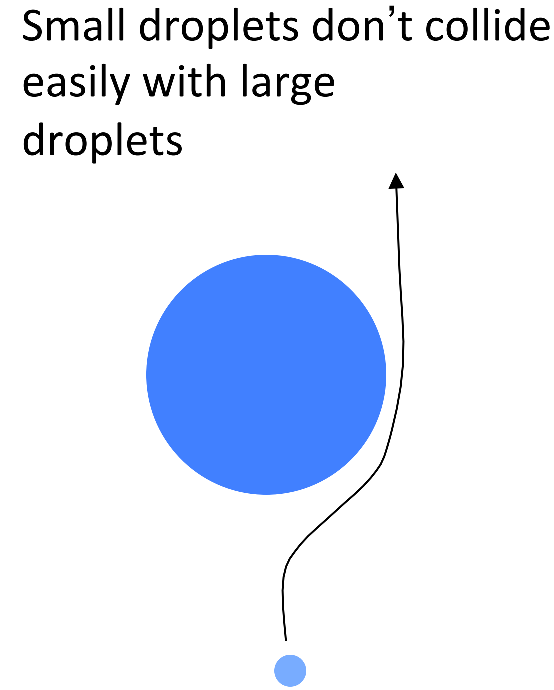
$$N_d \propto N_a^{\alpha}$$

Ramanathan et al. 2001

Some simple cloud physics



Wallace and Hobbs 2006

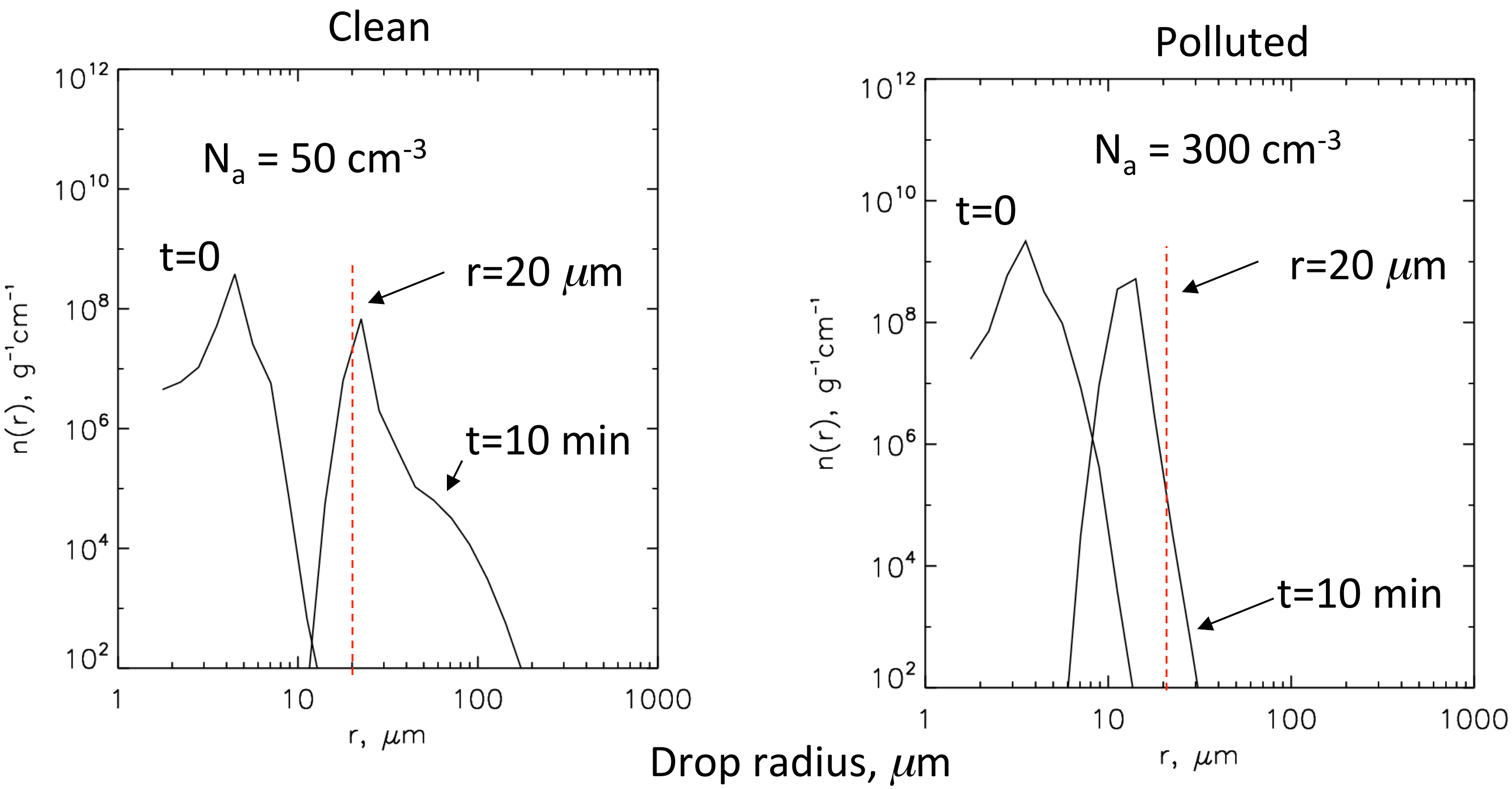


$$K(x,y) \propto (r_x^2 + r_y^2)\left|V_x - V_y\right|E(x,y)$$

$E(x,y)$ = collection efficiency

- Smaller drops are less likely to collide and coalesce; need ~ 20 μm radius drops to initiate the process

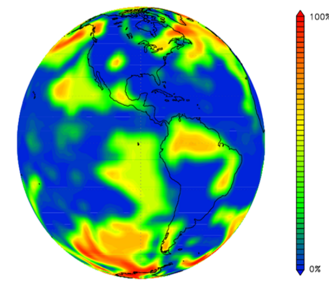
Some simple cloud physics

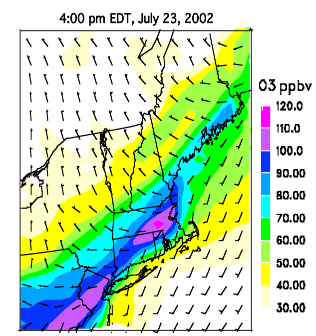


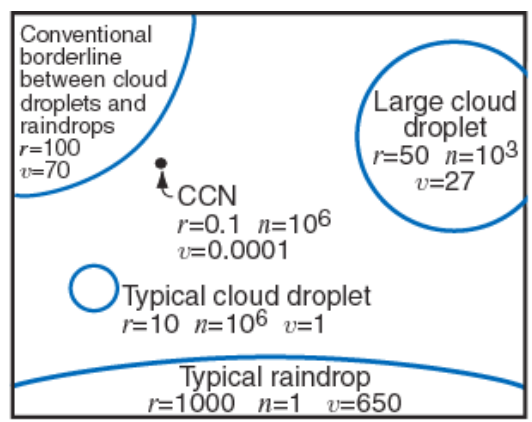
- Smaller drops are less likely to collide and coalesce; need ~ 20 μm radius drops to initiate the process

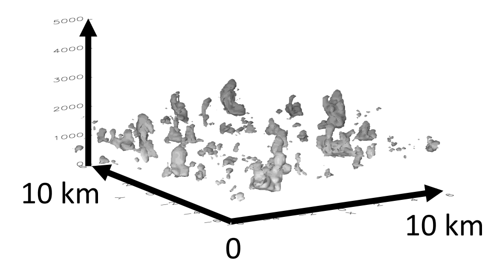
Spatial/Temporal scales

- Involves complexity in both aerosol and clouds
- Range of spatial scales
  - Aerosol particles 10s – 1000s nanometres
  - Cloud drops/ice particles: μm – cm
  - Cloud scales: ~ 10 m – 10^3 km
- Range of temporal scales
  - Activation process (aerosol→ droplet): < sec
  - Time to generate precipitation ~ 20 min
  - Cloud systems: days
- Coupled System
  - Scale interactions









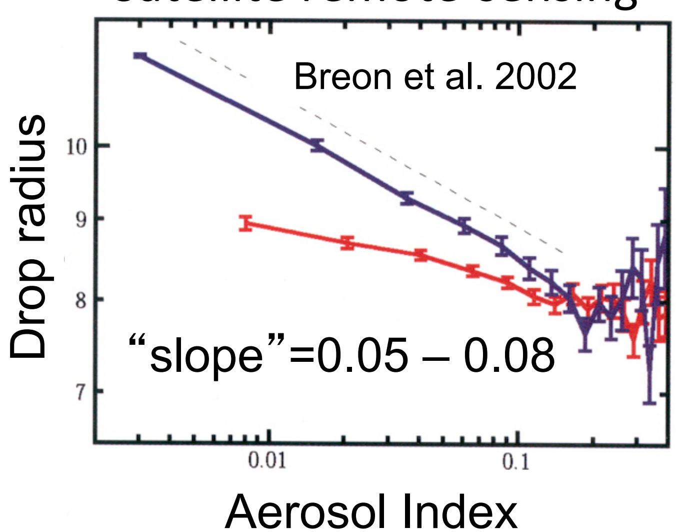
Some pitfalls

Correlation vs Causation

Most satellite studies show correlations between cloud and aerosol

Increasingly, model reanalysis is being used to separate aerosol from meteorological influences

Satellite remote-sensing



Ice cream causes shark attacks

Some pitfalls contd..

Remote sensing of aerosol-cloud interactions from space is hard!

- *Adjacency*

- *"Cloud contamination"*

- *3-D effects*

Photo credit: International Space Station

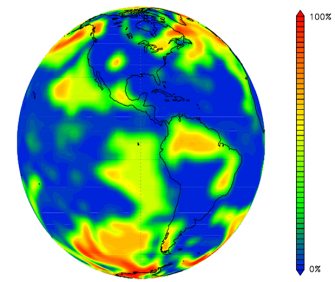
Some pitfalls contd..

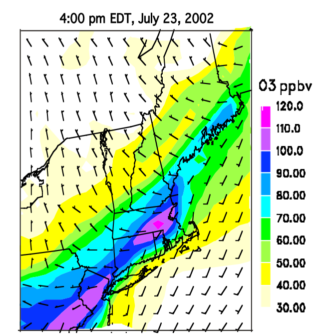
Models are imperfect!

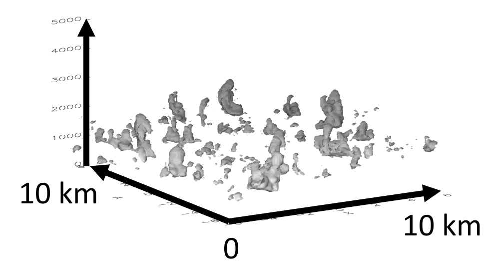
- *Range of scales is a huge challenge*

- *"All models are wrong: some are useful"*

  George Box







What controls cloud albedo?

$$\tau \sim N_d^{1/3} LWP^{5/6}$$

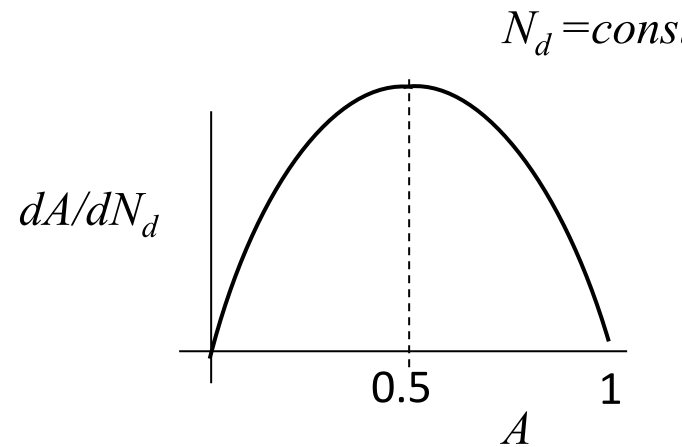
$$A \sim \tau \qquad \text{(for low } \tau\text{)}$$

- Cloud Optical depth is 2.5 x more sensitive to changes in LWP than changes in N_d
- LWP has a much stronger control on cloud optical depth than N_d

A useful metric

Albedo Susceptibility

Which clouds are most sensitive to increases in N_d (vis-à-vis albedo)?

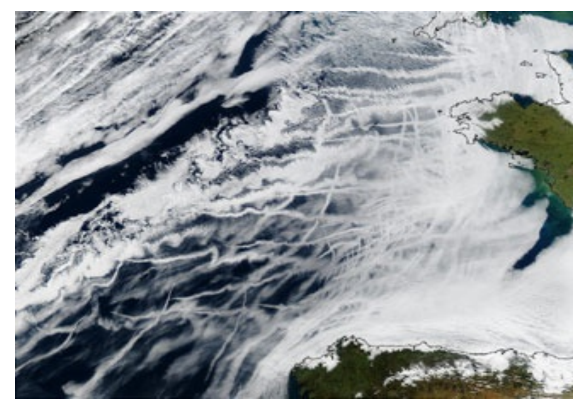


$$S_0 = \left.\frac{dA}{dN_d}\right|_{LWP,...} = \frac{A(1-A)}{3N_d}$$

$$N_d \propto N_a^{\alpha}$$

$$S'_{0,LWP,...} = S'_0\left[1 + \frac{5}{2}\frac{d\ln LWP}{d\ln N_d} + \frac{d\ln k}{d\ln N_d}\right]$$

LWP response — breadth response

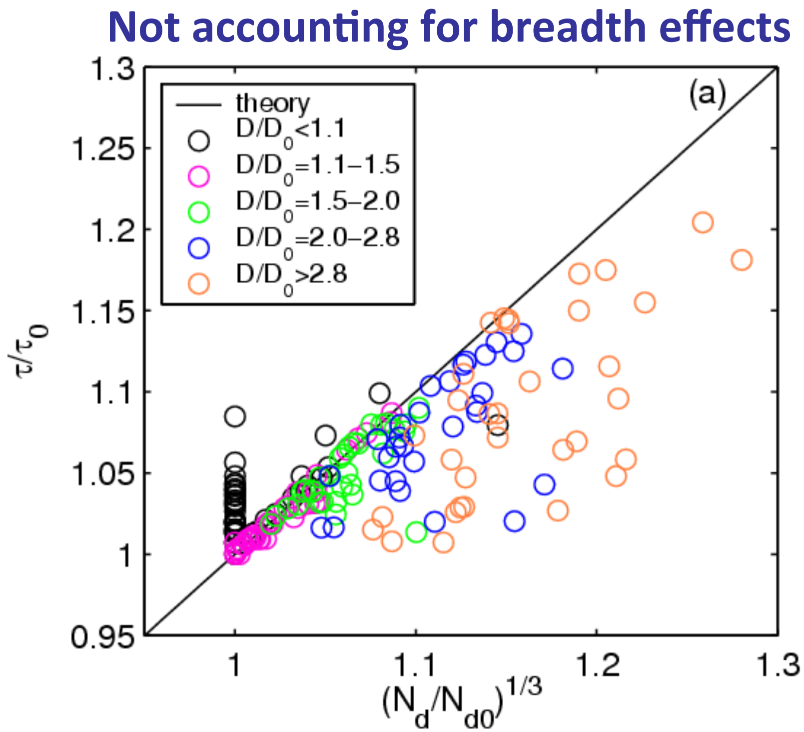


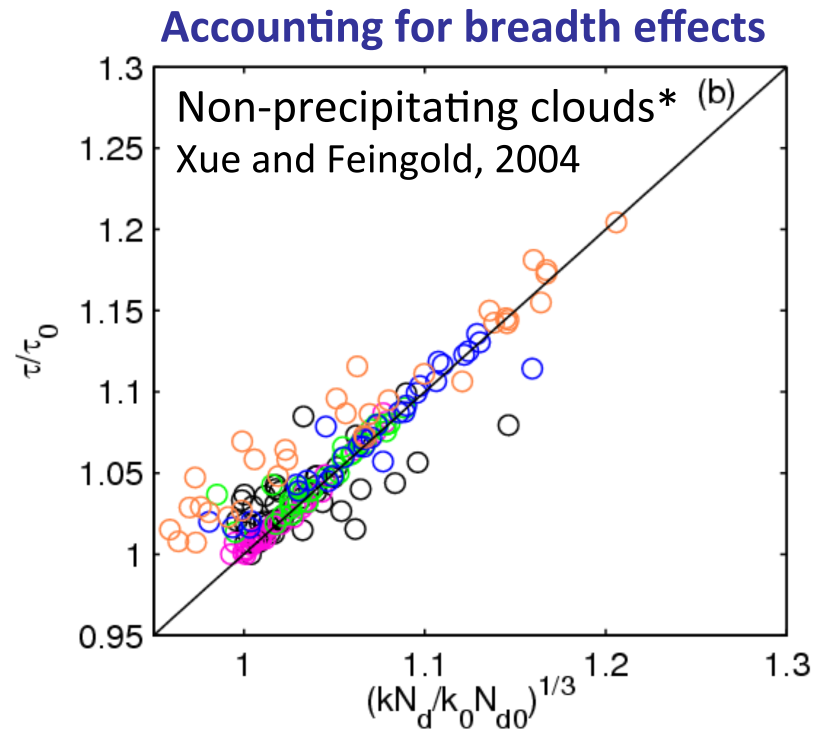
Platnick and Twomey 1994

Note: $k \propto 1/$ breadth

Feingold and Siebert 2008

Influences of aerosol on distribution breadth $\frac{d \ln k}{d \ln N_d}$





At constant LWP: $\tau / \tau_0 = (N_d / N_{d0})^{1/3}$

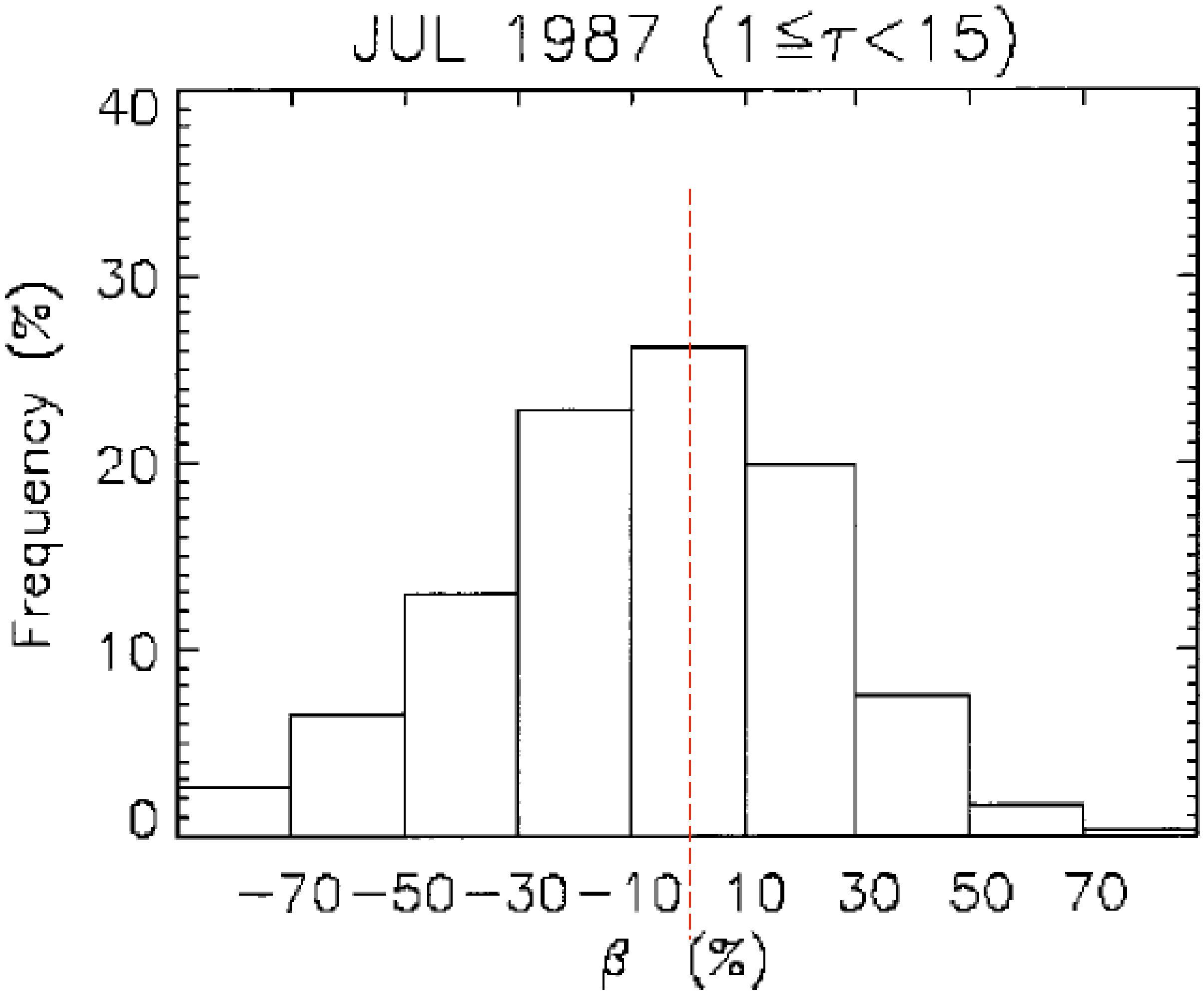
- Non precipitating clouds: breadth effects *reduce* albedo susceptibilty
- Precipitating clouds: breadth effects *enhance* albedo susceptibilty

*For precipitating clouds see Feingold et al. JGR 1997

How does LWP respond to aerosol?

Sign of the change is uncertain!

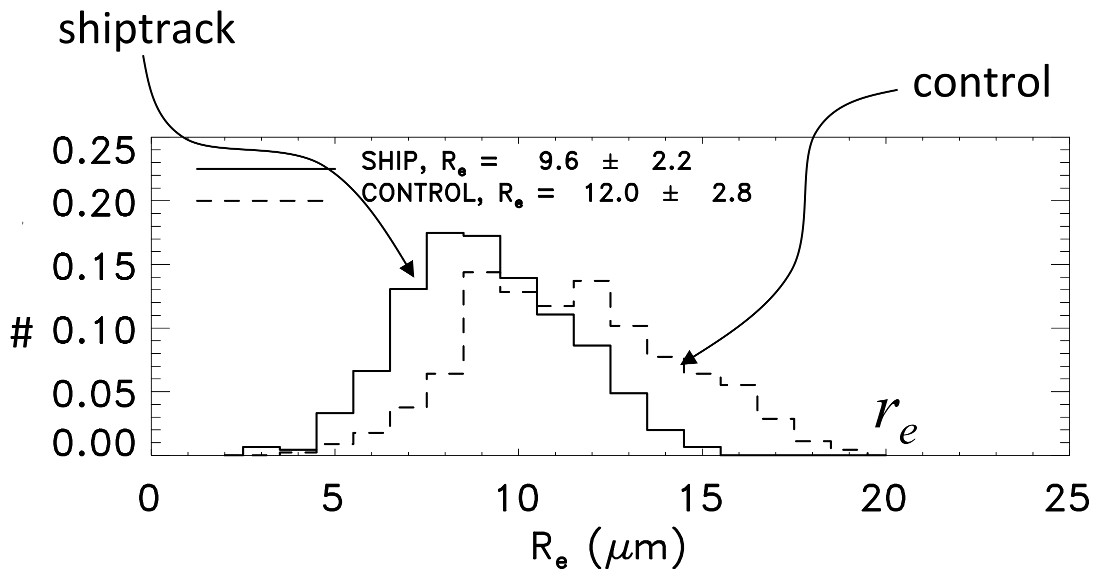
$$S'_{0,LWP,...} = S'_0\left[1+\frac{5}{2}\frac{d\ln LWP}{d\ln N_d}+..\right]$$



$$\beta = \frac{\Delta \ln LWP}{\Delta \ln N_d}$$

Han et al. 2002: ISCPP Data

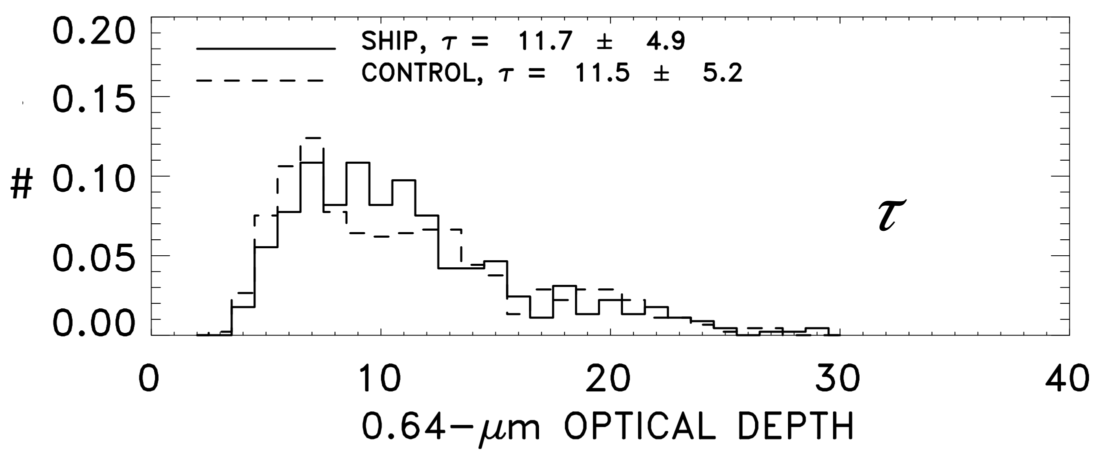
Shiptracks

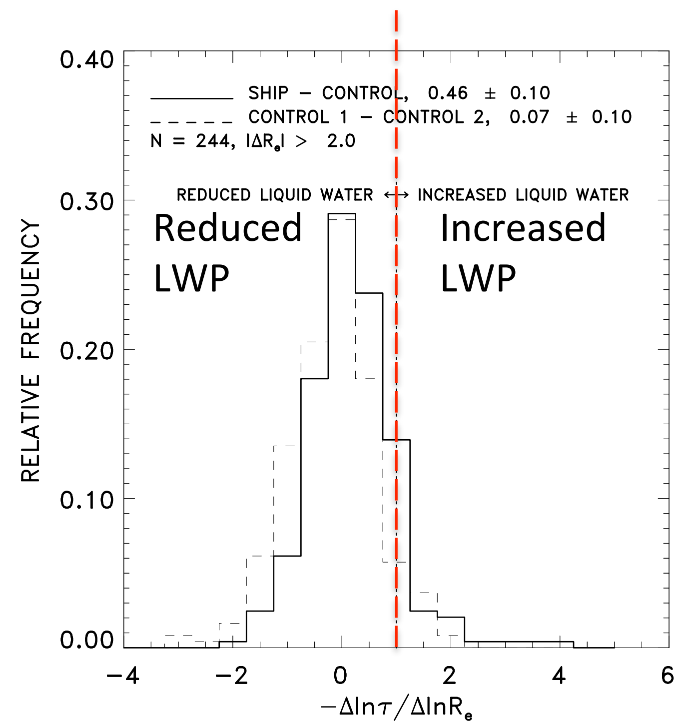


r_e is smaller in ship tracks

Cloud optical depth is ~ constant

LWP tends to decrease

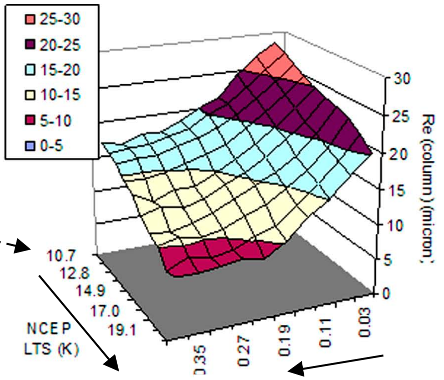




Coakley and Walsh, 2002

Global low cloud satellite measurements and NCEP reanalysis

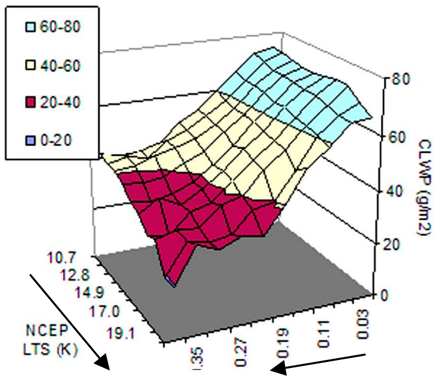
stability



r_e

Aerosol Index

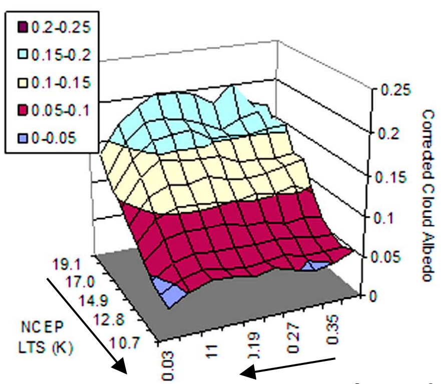
Drop size decreases with aerosol



LWP

Aerosol Index

LWP <u>decreases</u> with aerosol



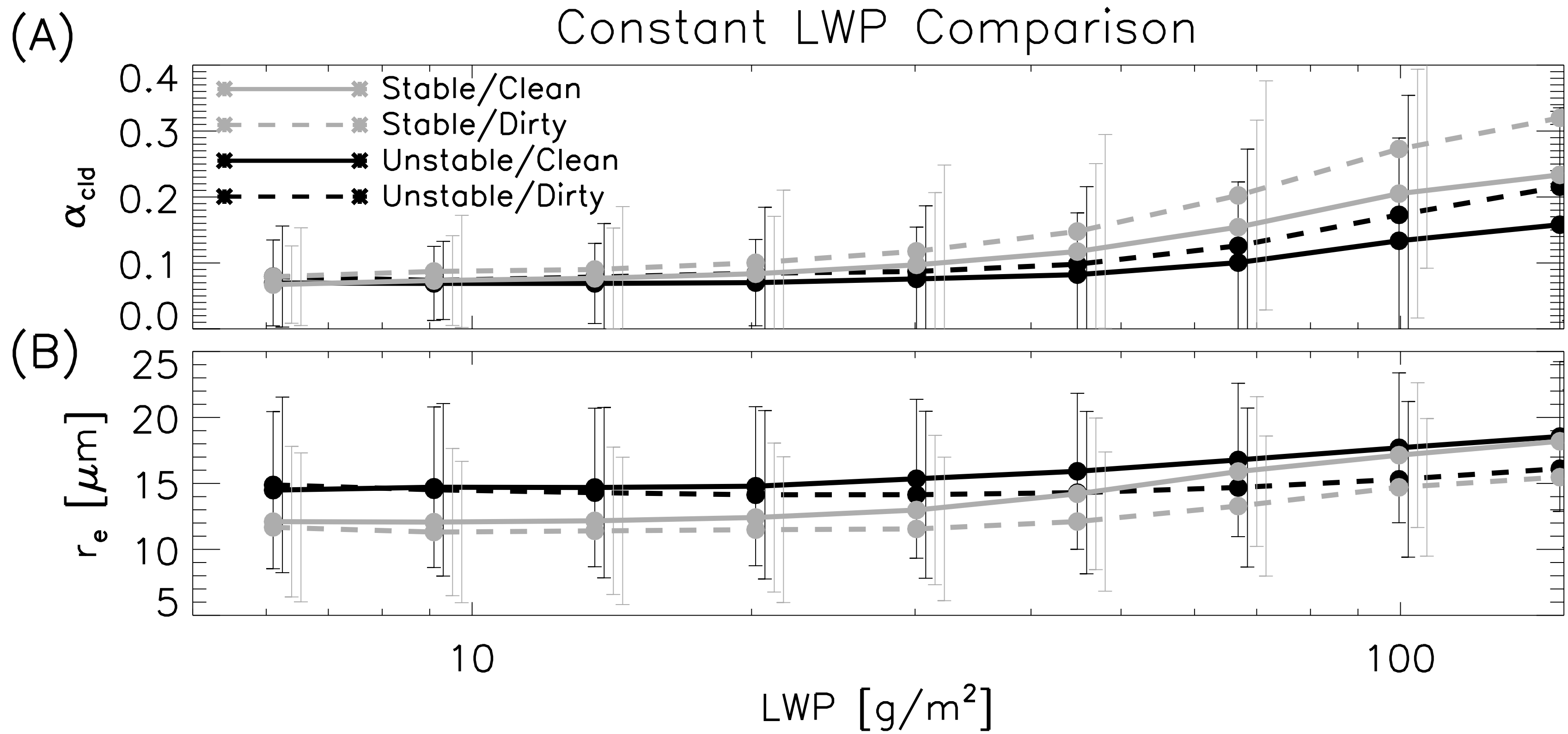
Cloud Albedo

Aerosol Index

Albedo ~ constant
(competing effects)

Matsui et al. 2006

Meteorological context for aerosol influences



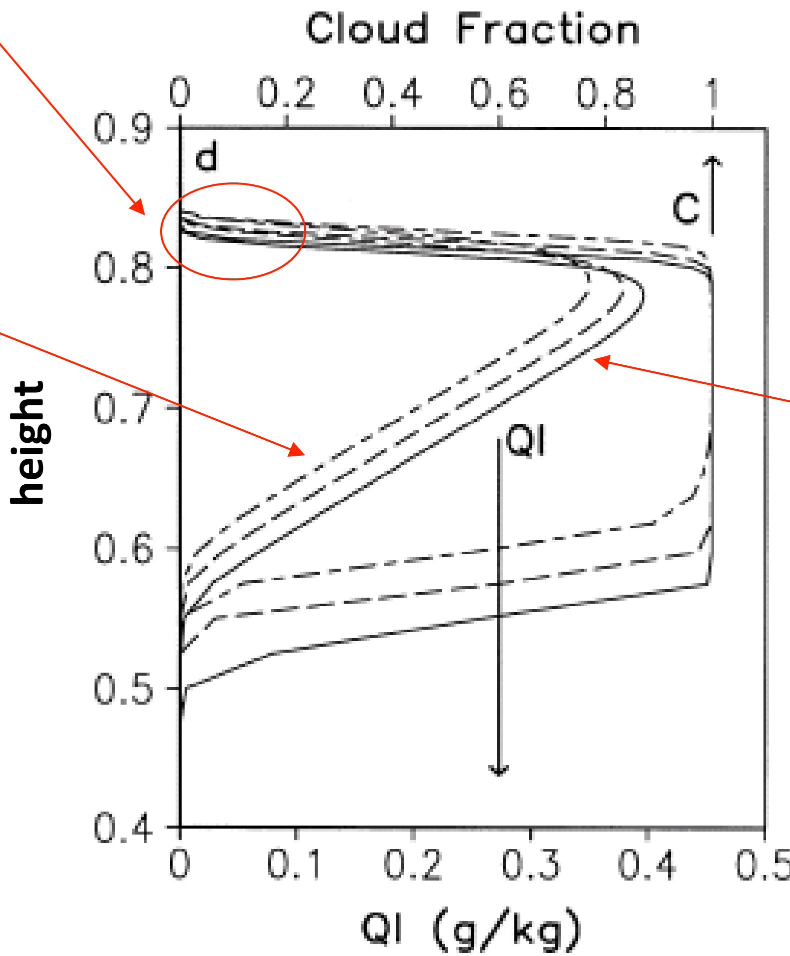
α_{cld} = A = albedo

Lebsock et al. 2008
A-Train data

Modeling of Aerosol effects on Stratocumulus in LES

Models help determine causality

Pollution elevates cloud tops



polluted

clean

LWC

LWP *decreases*
with increasing aerosol:

Evaporation-entrainment feedback

100/cc

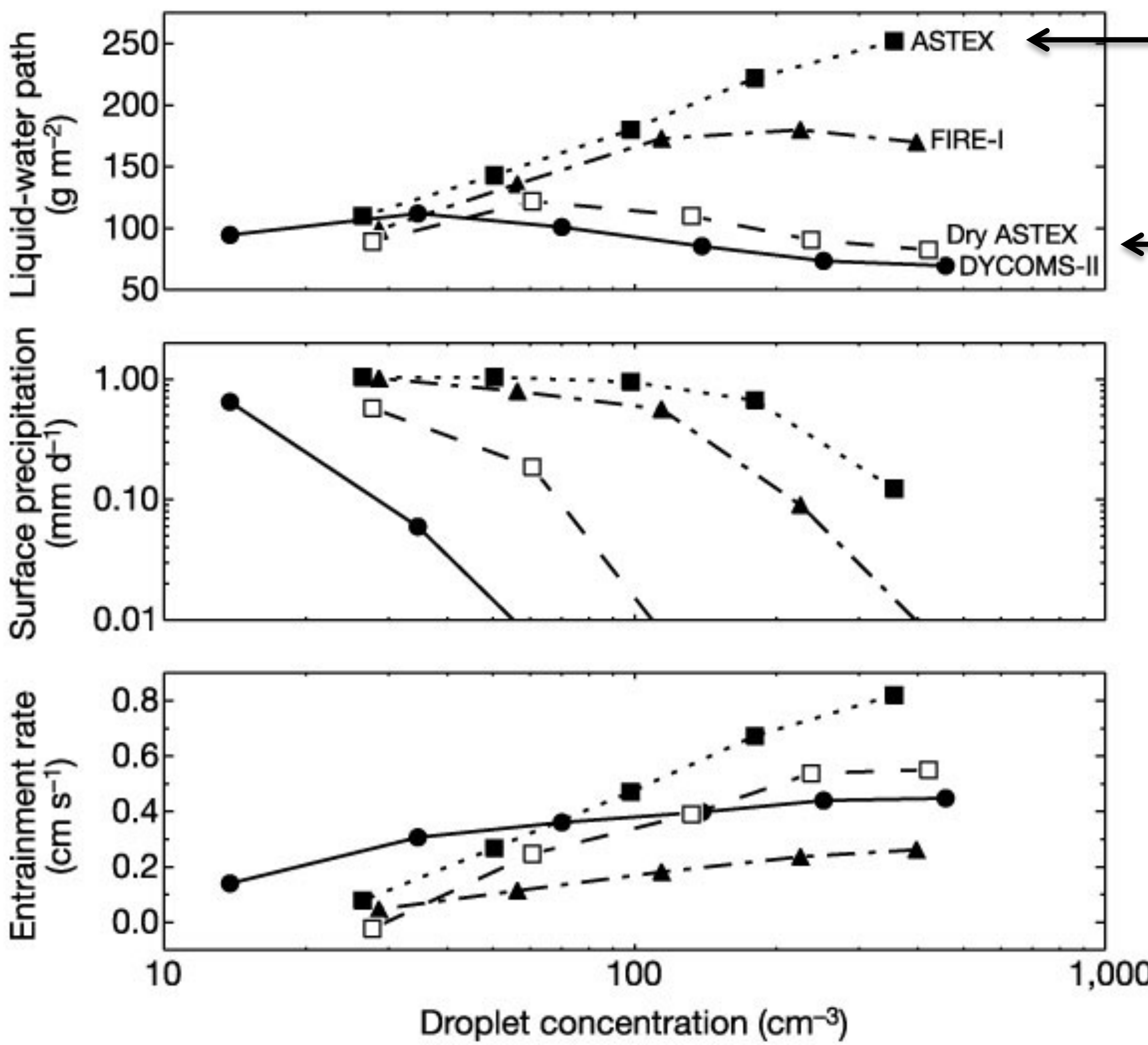
1000/cc

Bulk microphysics

Wang, Wang, Feingold, 2003

Also, Xue and Feingold 2006
for cumulus

Modeling of Aerosol effects on Stratocumulus in LES



Relatively moist above inversion

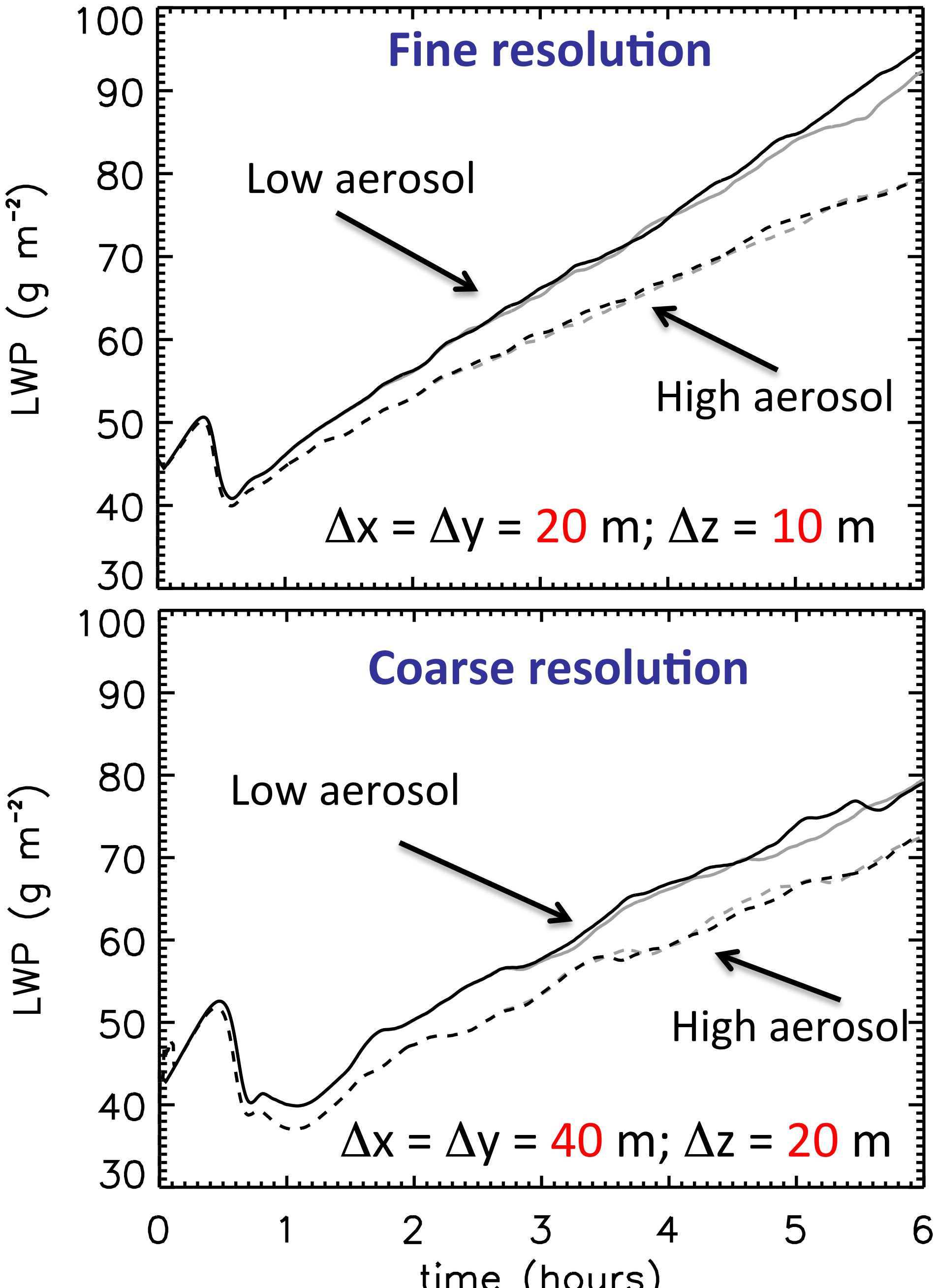
Very dry above inversion

$$\frac{d\mathrm{LWP}}{dN_d} \begin{matrix} >0 \\ <0 \end{matrix} \;?$$

Humidity of air above stratocumulus is important

Ackerman et al. 2004

Modeling of Aerosol effects on Stratocumulus in LES



FIRE-I Scu, non precipitating

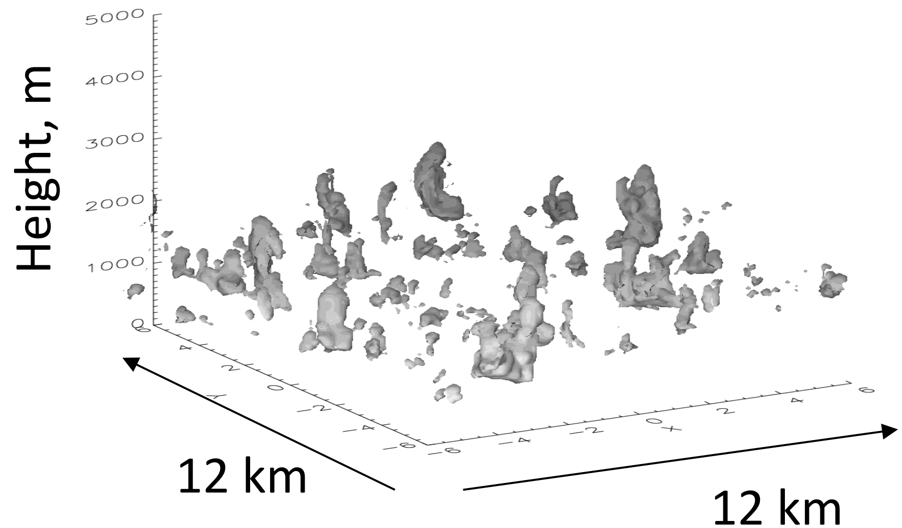
- *Coarse resolution has lower LWP*
- *Reduction in LWP with increasing aerosol*
- *Effect of representation of mixing (homogeneous vs. inhomogeneous; black vs grey) is small*

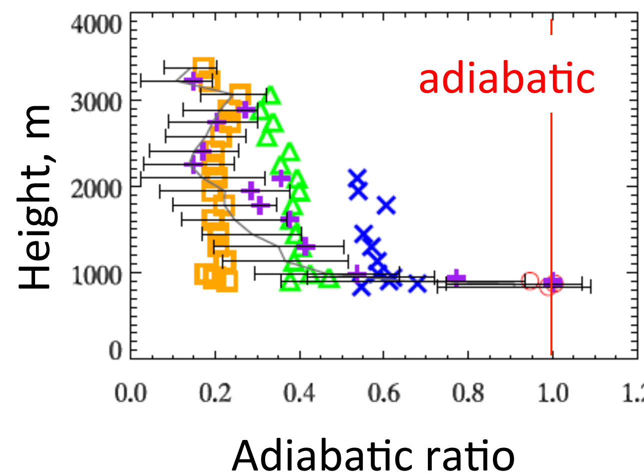
Hill et al. 2009

Cumulus Clouds

Cumulus Clouds

Houston, GoMACCS 2006: Mike Hubbel





- Large variation in cloud depth
- Significant entrainment
- *Subadiabatic liquid water
- Cloud Fraction ~ 10%
- Frequent in trade wind regime
- Precipitation common

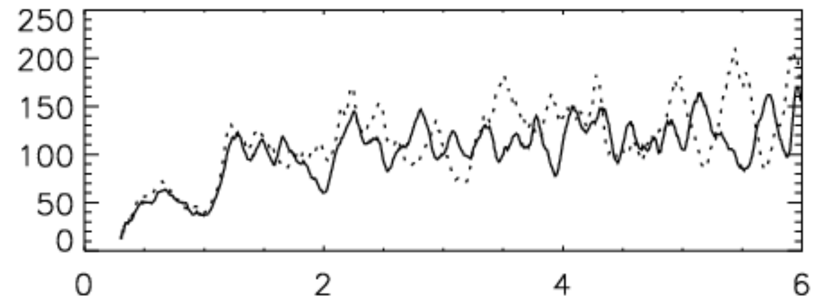
*Warner et al. 1955

Lu et al. 2008

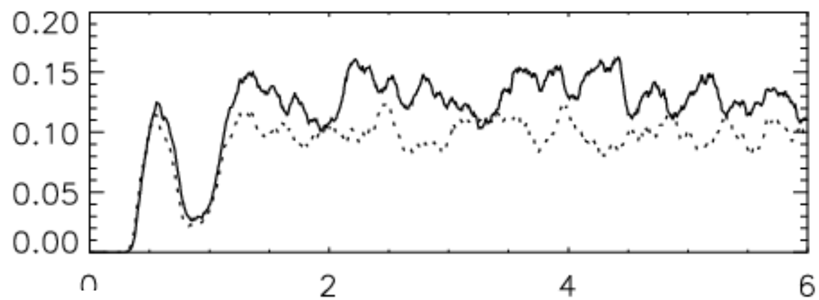
Time series

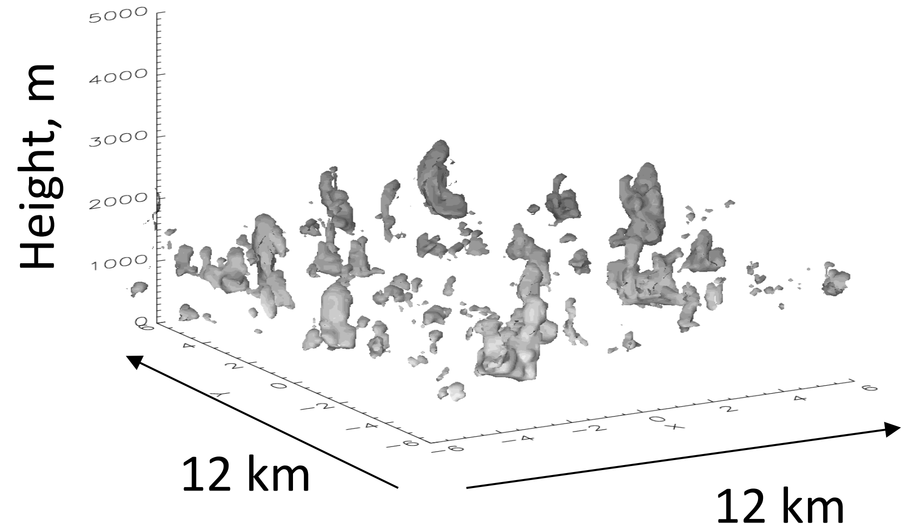
——	clean (N_a = 25 cm^{-3})
- - - - - -	polluted (N_a = 2000 cm^{-3})

LWP_cloud (g m^{-2})

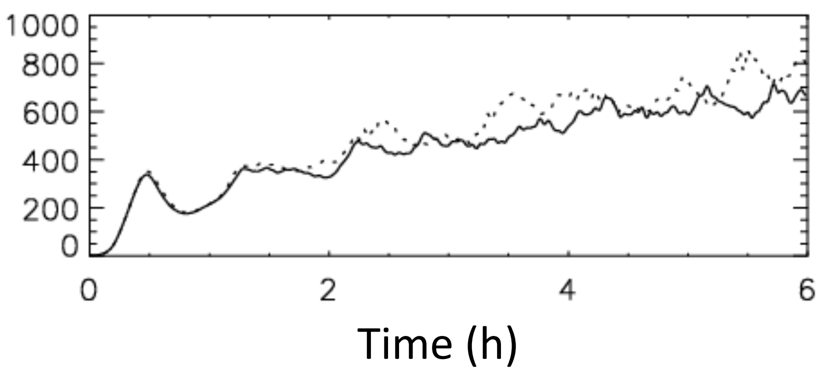


cloud fraction

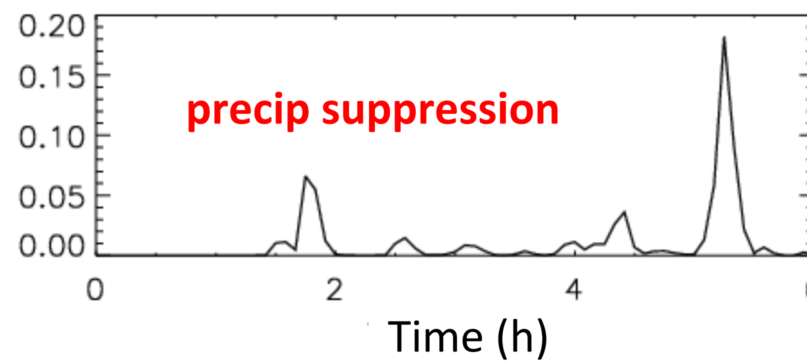




TKE (kg s^{-2})



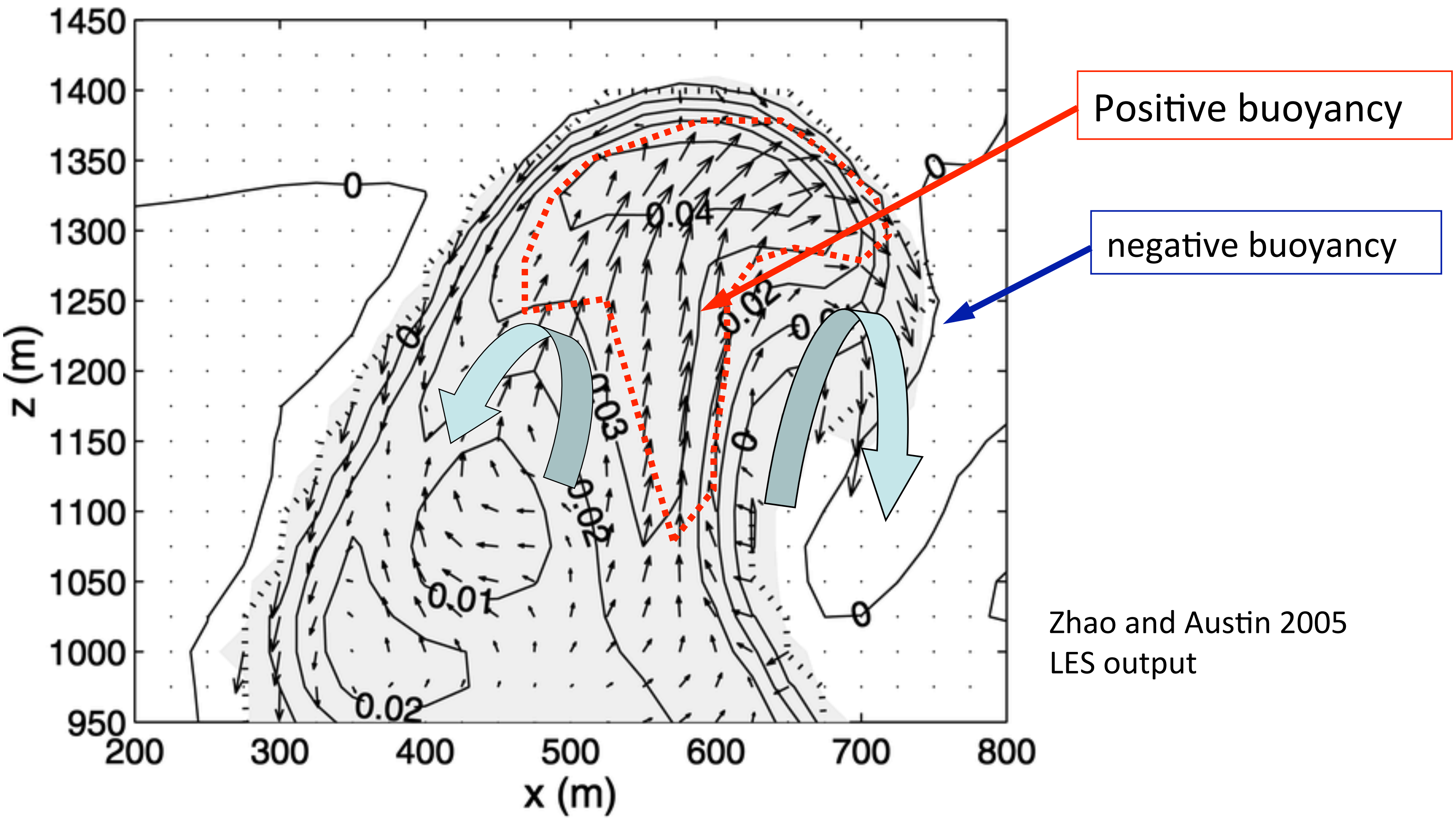
surface drizzle rate (mm day^{-1})



Xue and Feingold, JAS 2006

Model of a Cumulus Cloud

Contours: buoyancy
Arrows: wind vectors



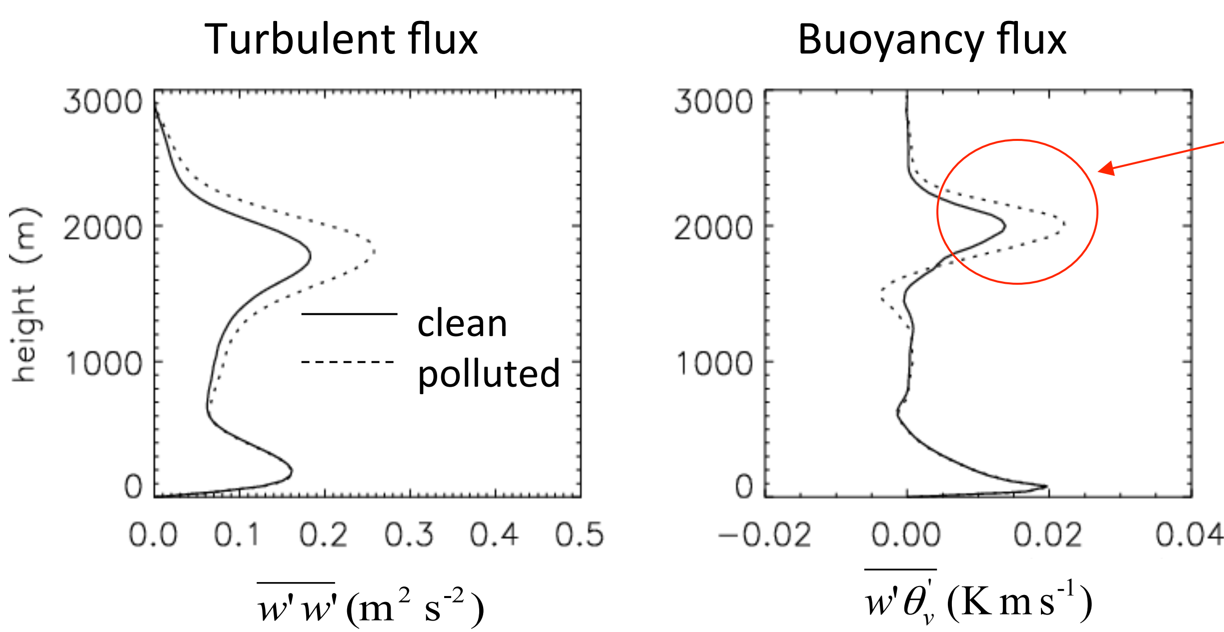
Zhao and Austin 2005
LES output

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

ω = vorticity
B = buoyancy

The link between smaller droplets, faster evaporation and dynamics: Turbulent flux and buoyancy flux

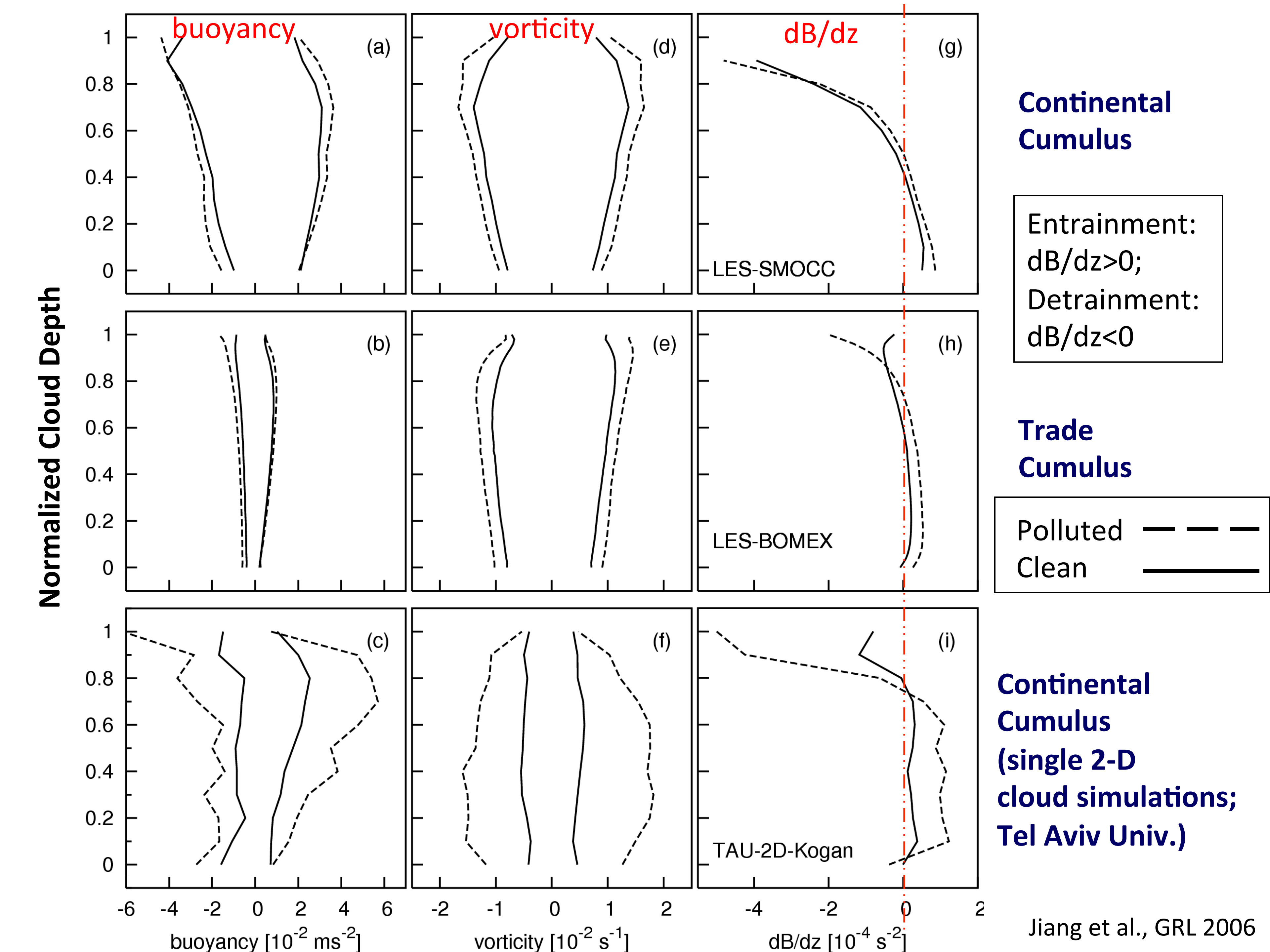
Downdraft regions



evaporative cooling is larger for polluted clouds

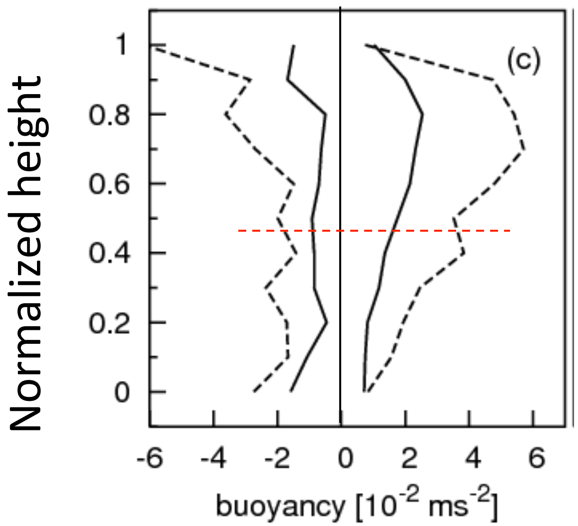
evidence of enhanced evaporative cooling & higher turbulence due to aerosol: Smaller drops evaporate faster

Xue and Feingold, JAS 2006


buoyancy
vorticity
dB/dz
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
LES-SMOCC
LES-BOMEX
TAU-2D-Kogan
Normalized Cloud Depth
buoyancy [10^-2 ms^-2]
vorticity [10^-2 s^-1]
dB/dz [10^-4 s^-2]
Continental Cumulus
Entrainment: dB/dz>0;
Detrainment: dB/dz<0
Trade Cumulus
Polluted
Clean
Continental Cumulus (single 2-D cloud simulations; Tel Aviv Univ.)
Jiang et al., GRL 2006

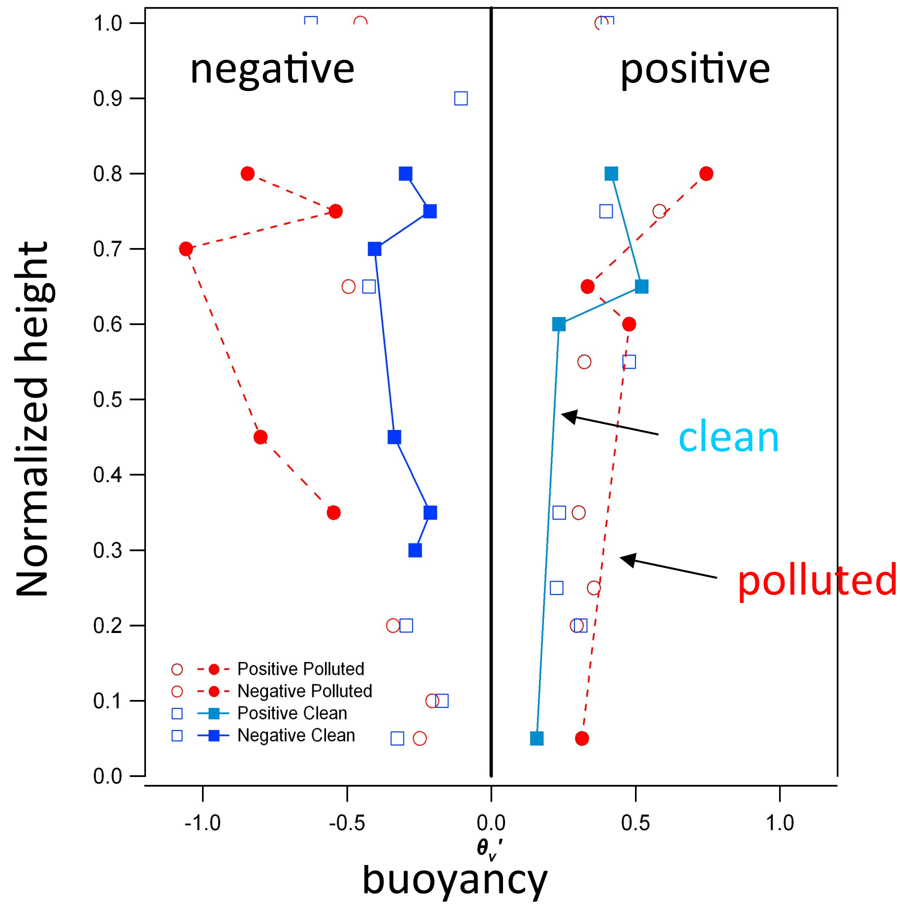
Evidence from Observations: GoMACCS (Houston 2006)

Model



Jiang et al. 2006

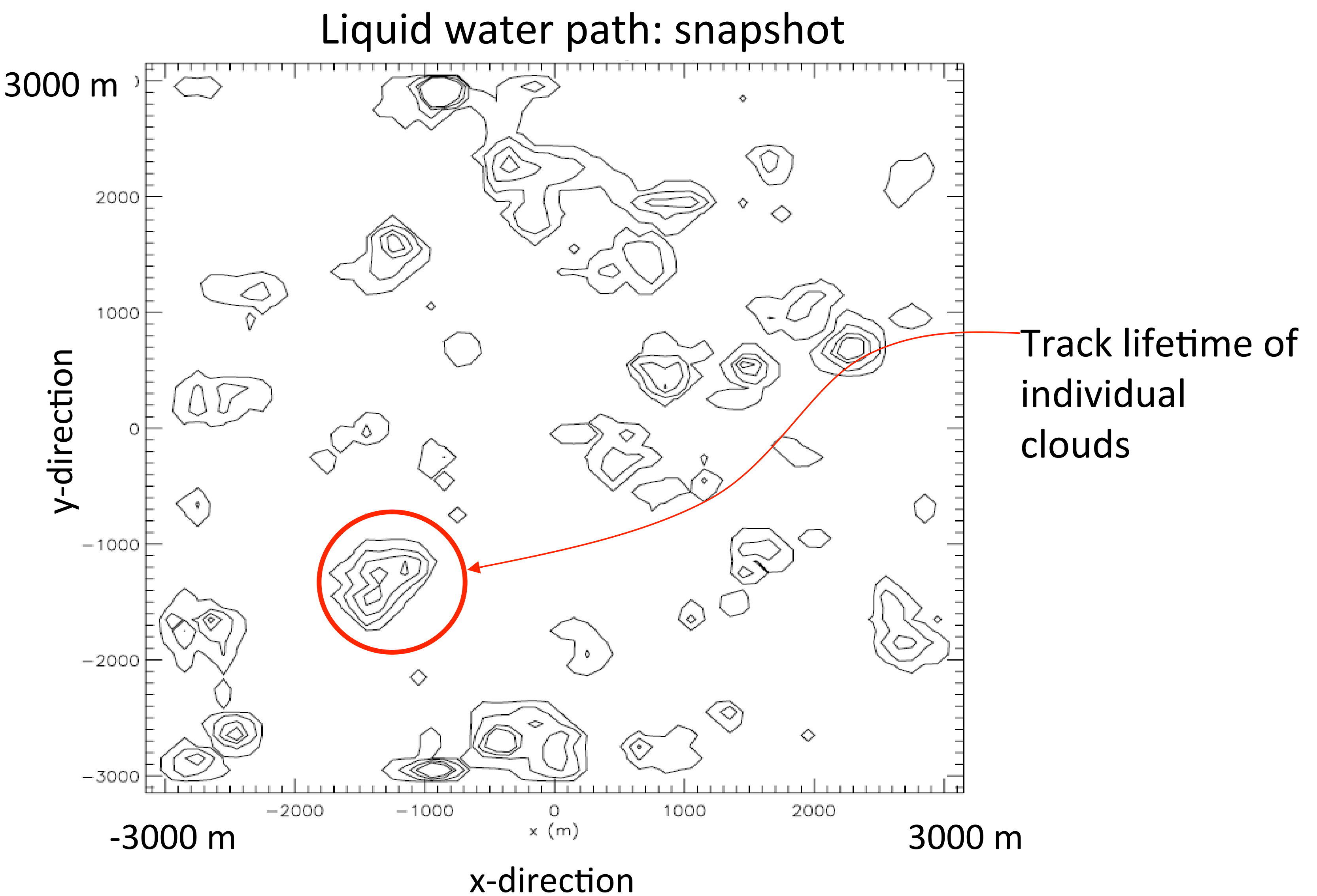
Observations



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

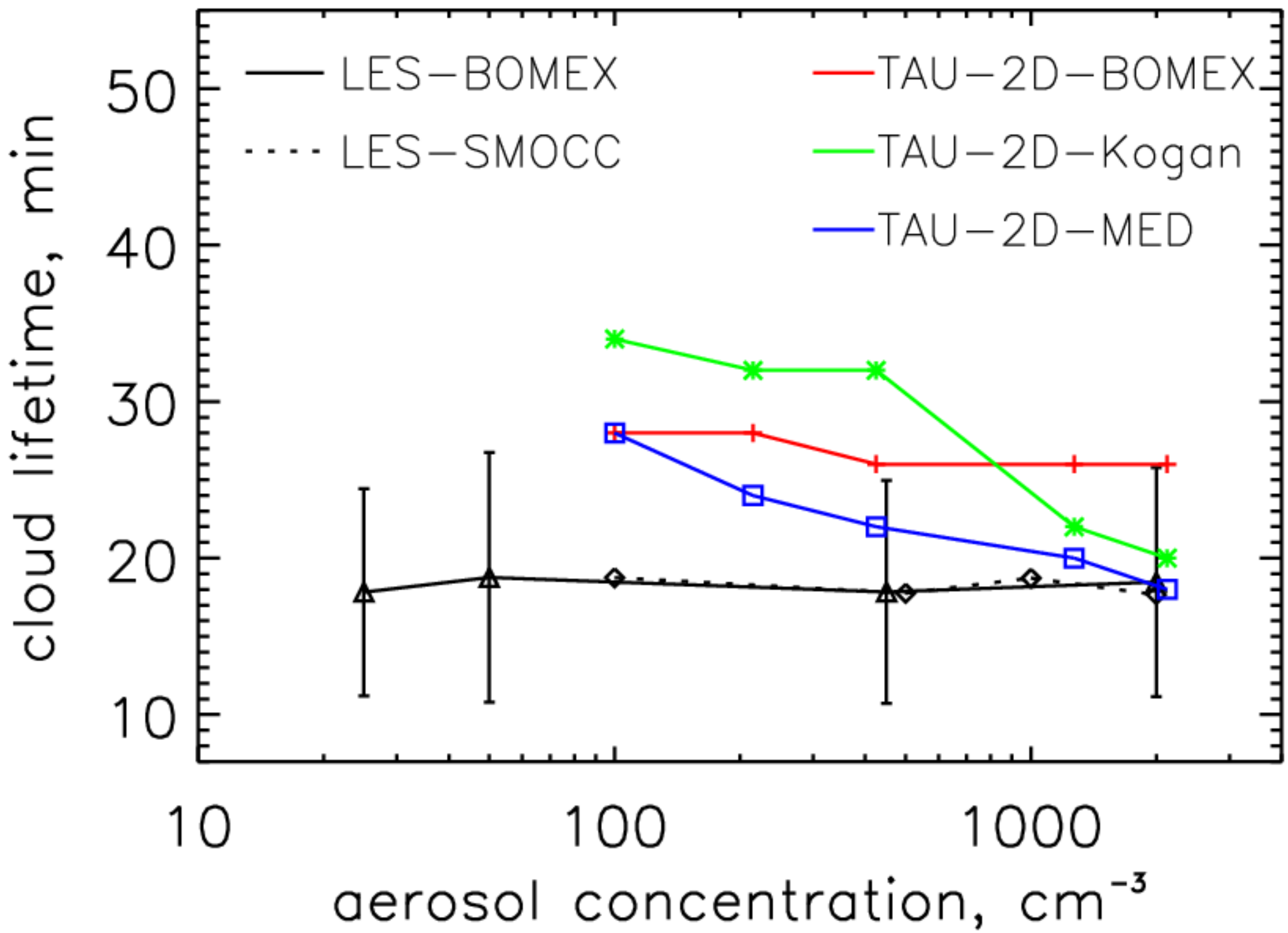
Small et al., GRL 2009

Aerosol Effects on Cloud Lifetime



Aerosol Effects on Cloud Lifetime

Based on analysis of 100s of individual clouds using object oriented cloud tracking tools



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

Why? Competing Aerosol effects on Cloud Microphysics

- *Small droplets do not coalesce efficiently → less rain*

vs.

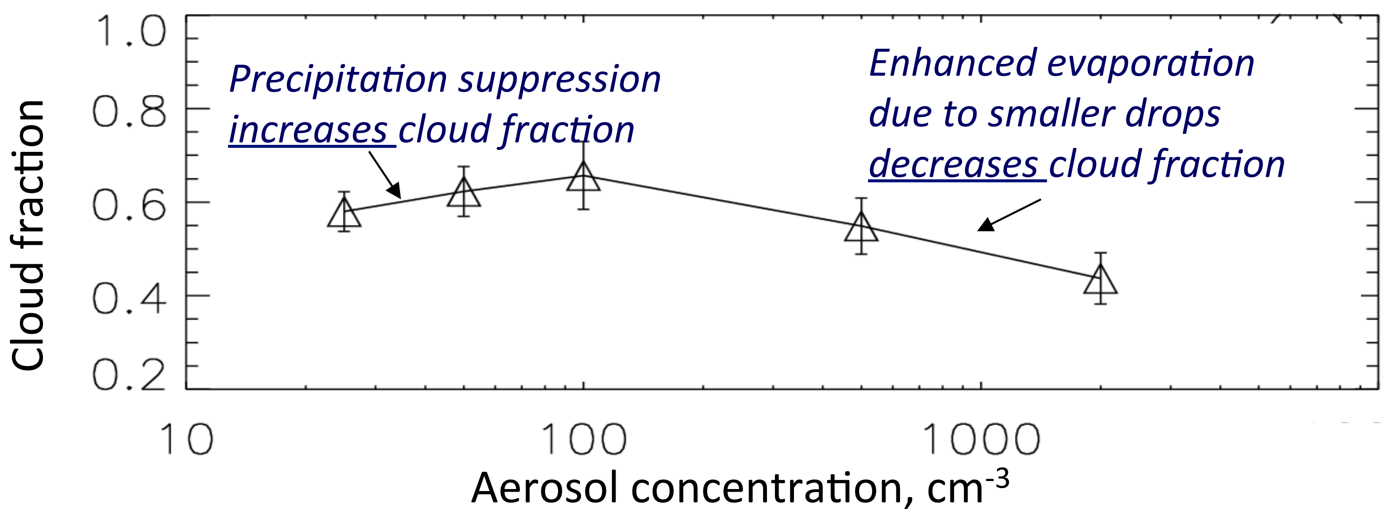
- *Small droplets evaporate faster than large ones*
  Ratio of timescales for evaporation (clean vs polluted) may be a factor of 5-10

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

Beware of simple constructs

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

A non monotonic response…



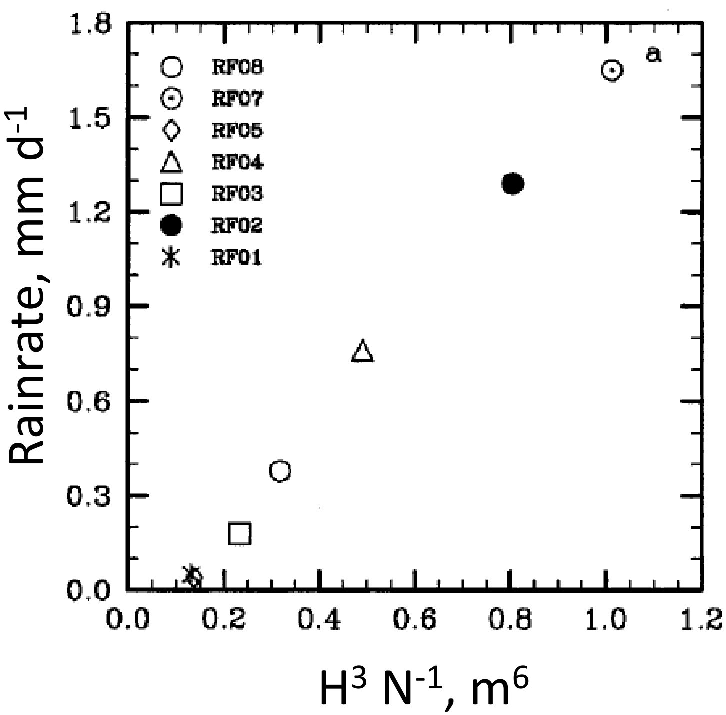
ATEX
Xue, Feingold, Stevens, 2008

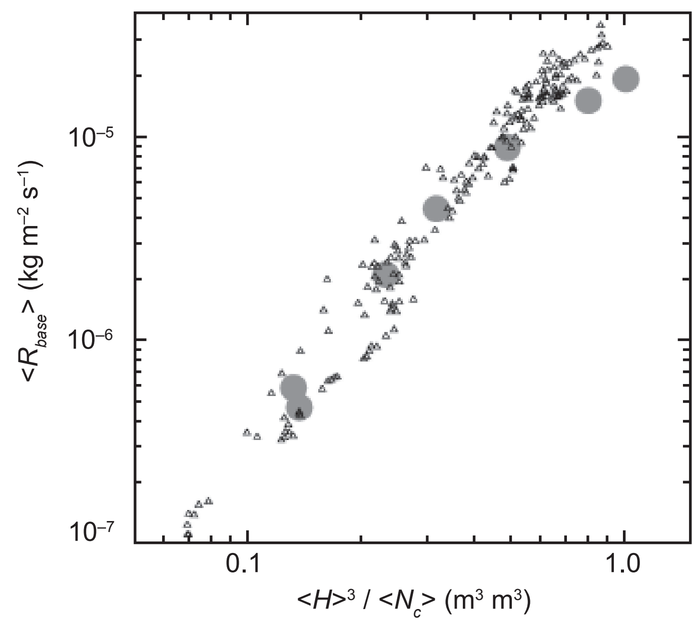
- *Microphysical feedbacks complicate the simple monotonic response*
- *Rain, LWP, cloud fraction and lifetime responses are not necessarily connected*

Precipitating Warm Clouds

Macrophysics vs Microphysics

- Measurements show that Rainrate $R \sim H^3/N$ or $R \sim \mathrm{LWP}^{1.5}/N$
- Rain production is 1.5 -2.5 x more sensitive to changes in LWP than changes in N
- H *or* LWP is a much stronger control of rainrate than N
  - For accretion, R is independent of N





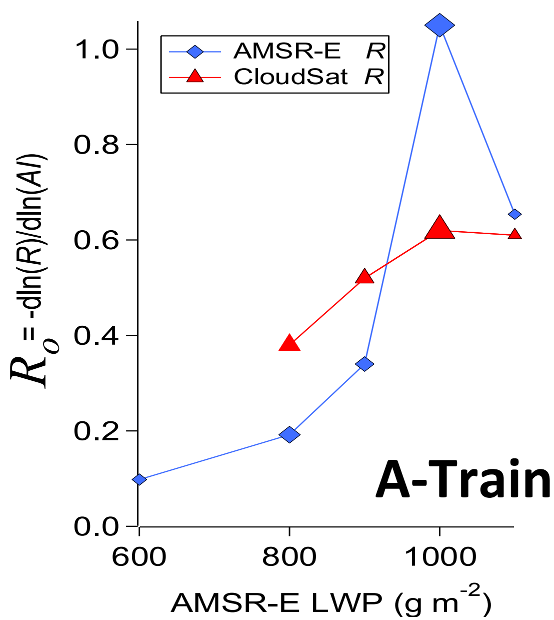
Van Zanten et al. 2005; Wood and Brenguier, 2008

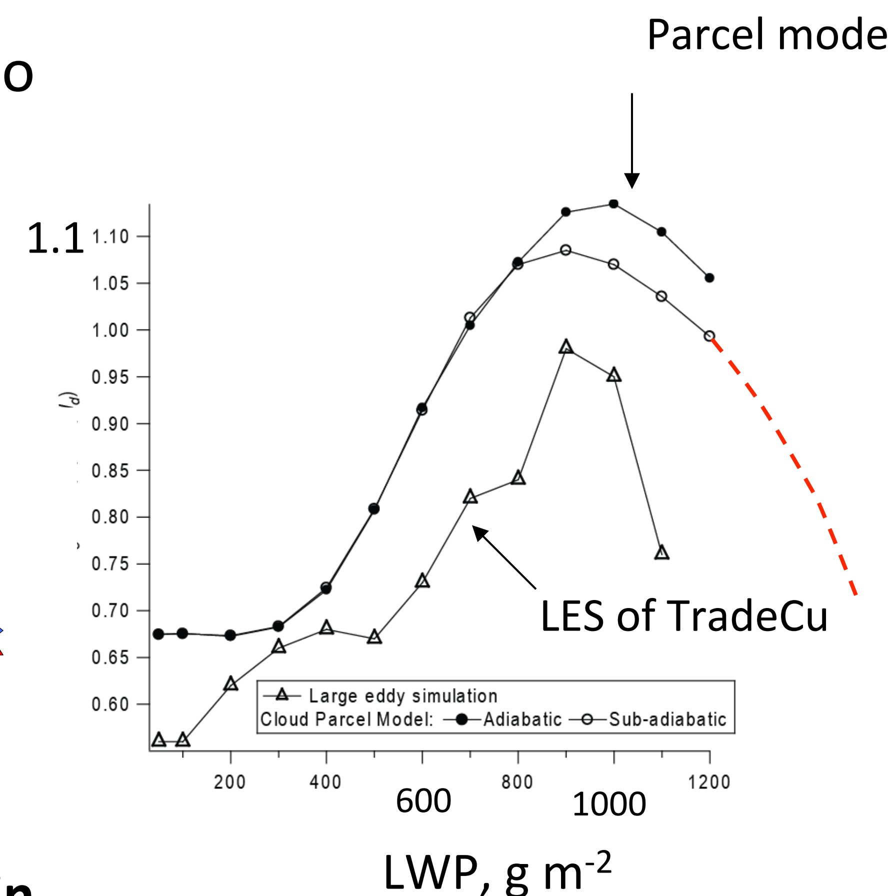
Another useful metric

Precipitation susceptibility

Which clouds are most sensitive to increases in N_d (vis-à-vis precip)?

$$R_0' = -\frac{d\ln R}{d\ln N_d}$$



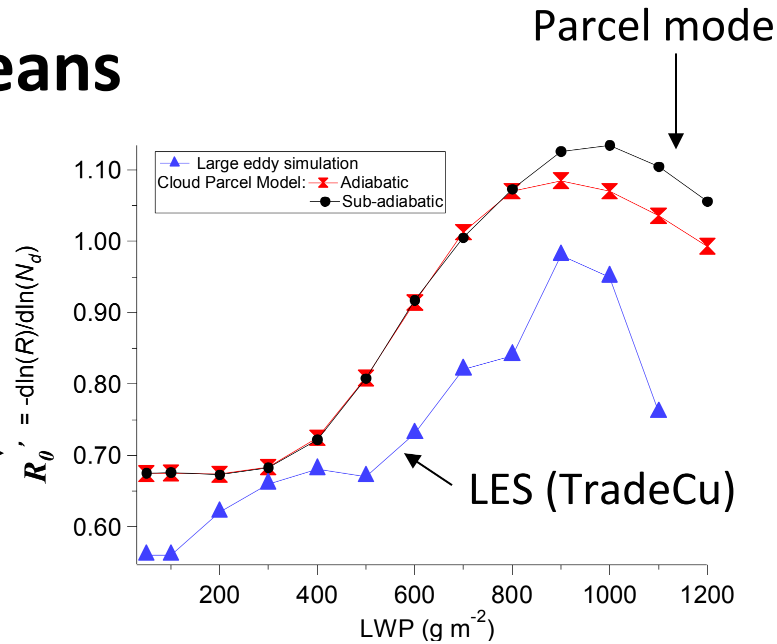


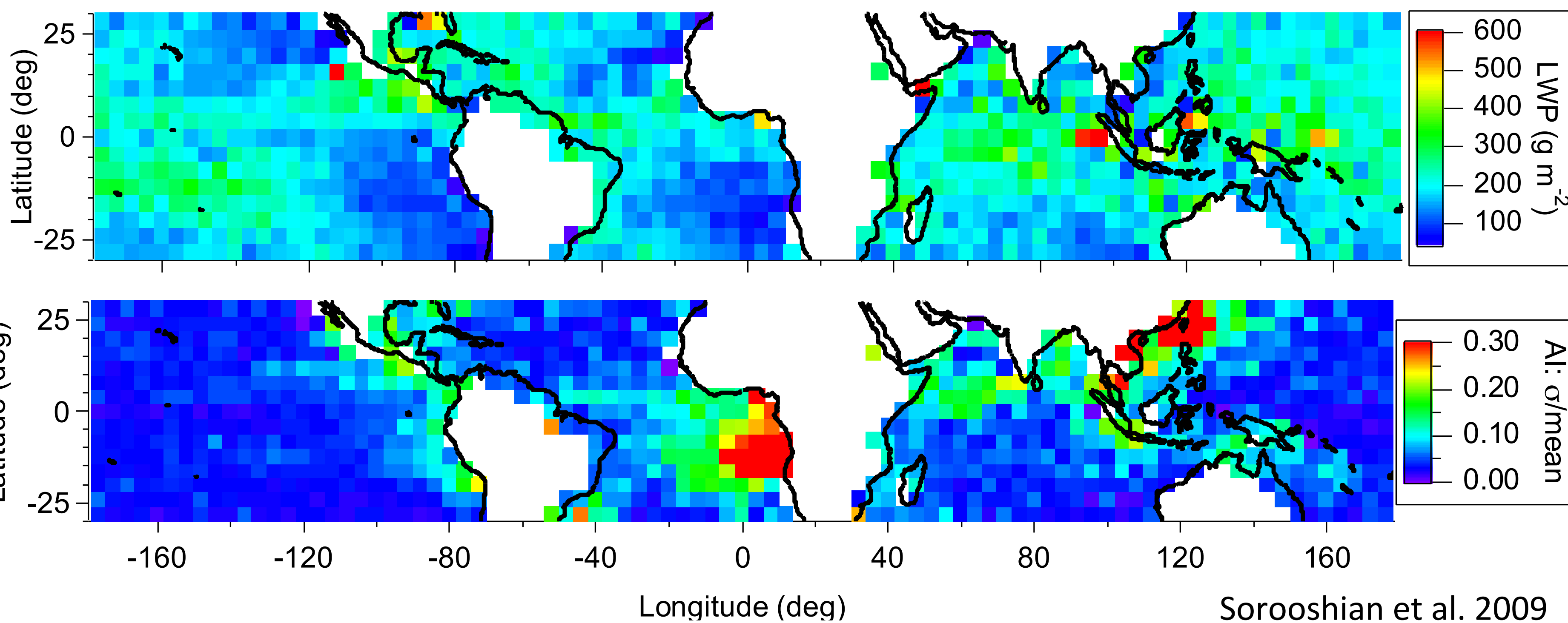
Feingold and Siebert 2008;
Sorooshian et al., 2009

Extrapolation to Tropical Oceans

Calculate expected precipitation reduction in a given region

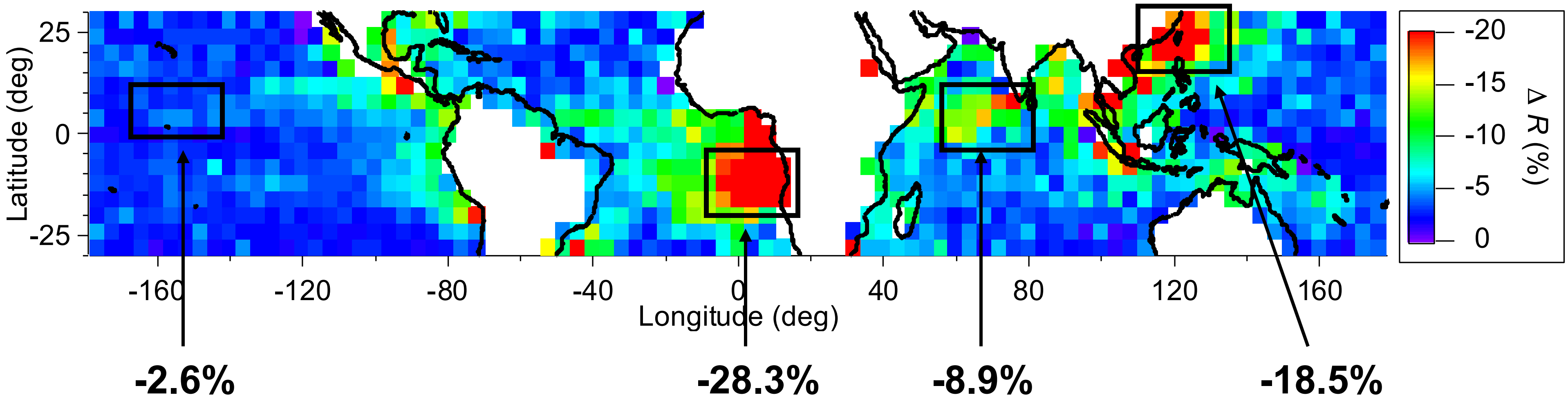
Input: LWP and aerosol perturbation



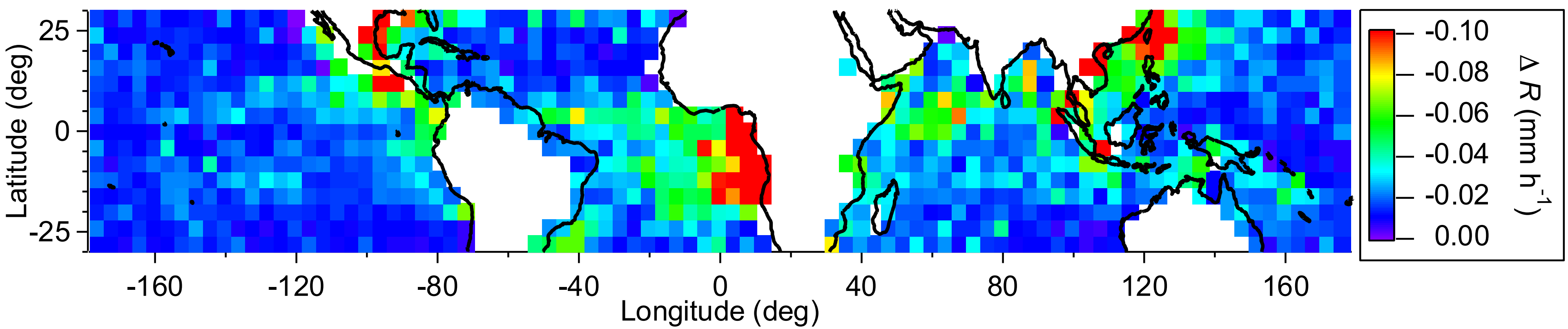


Sorooshian et al. 2009

Where on Earth might aerosol reduce precipitation?



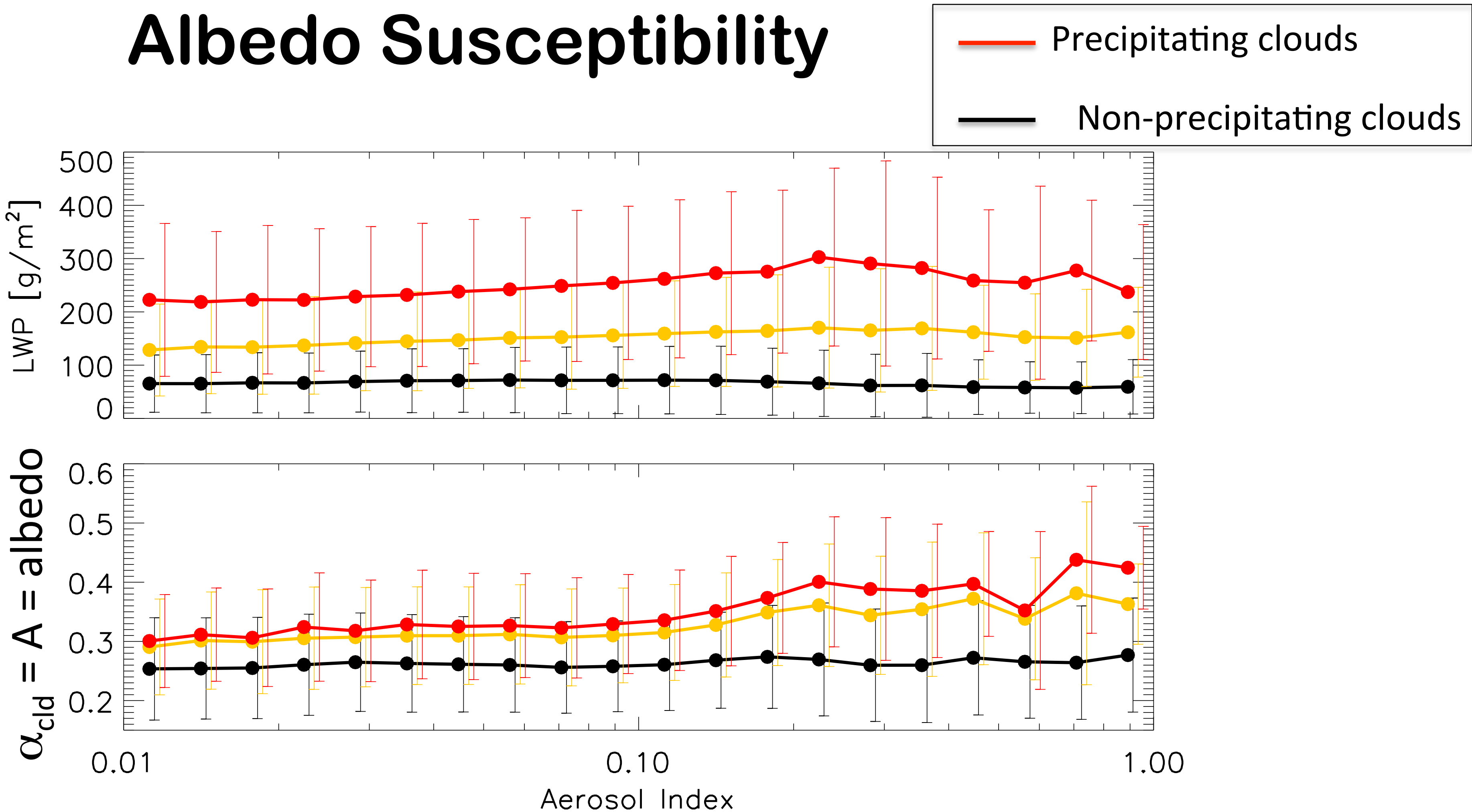
What about the ABSOLUTE reduction in precipitation?



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

Albedo Susceptibility



$$S_0' = \frac{d \ln A}{d \ln N_d}$$

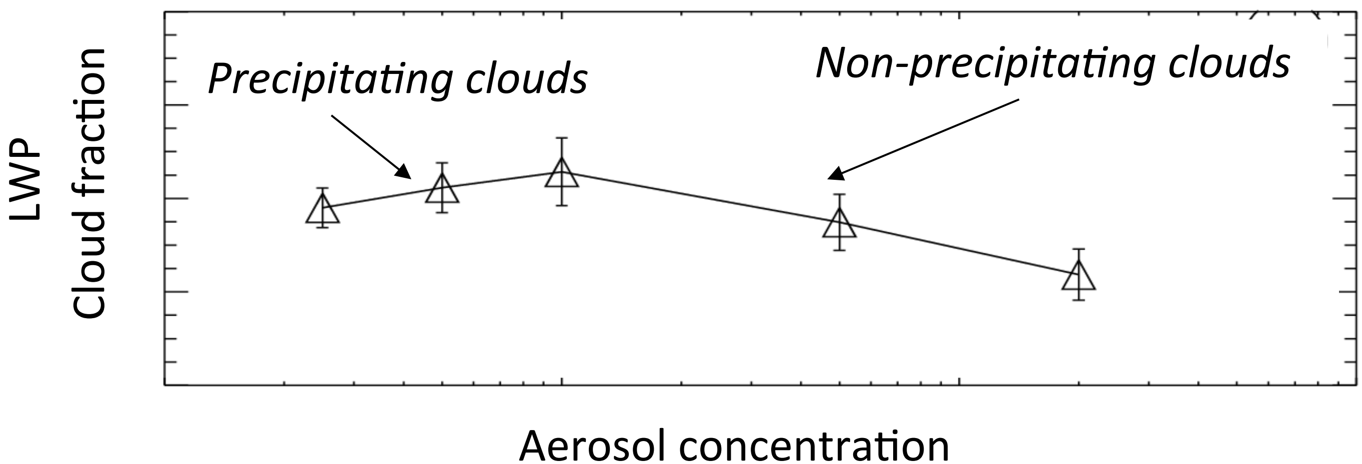
$$S'_{0,LWP,...} = S'_0 \left[1 + \frac{5}{2} \frac{d \ln LWP}{d \ln N_d} + \frac{d \ln k}{d \ln N_d} \right]$$

LWP response — breadth response

Lebsock et al. 2008

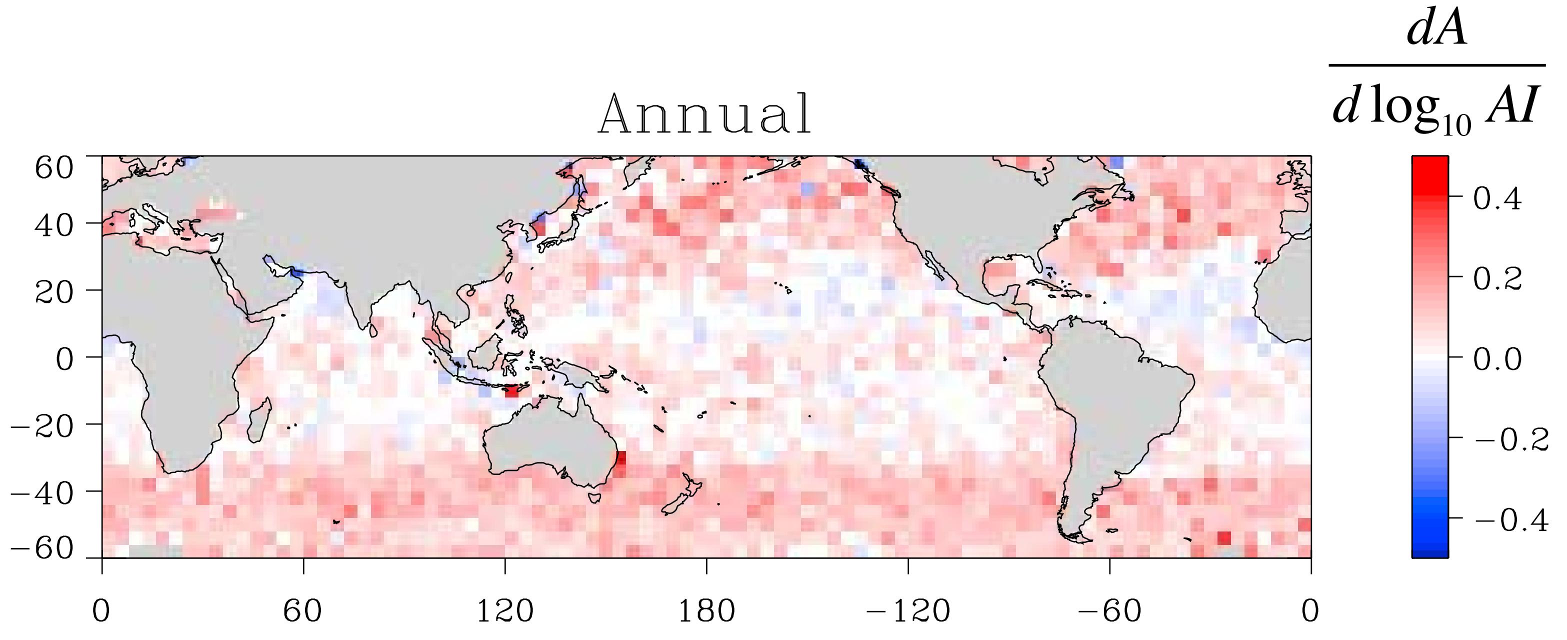
A picture seems to be emerging…

A non monotonic response…



Based on Wang et al. 2003, Ackerman et al. 2004, Lu and Seinfeld 2005, Matsui et al. 2006, Xue et al. 2008, Lebsock et al. 2008, Wang et al. 2011

The global picture

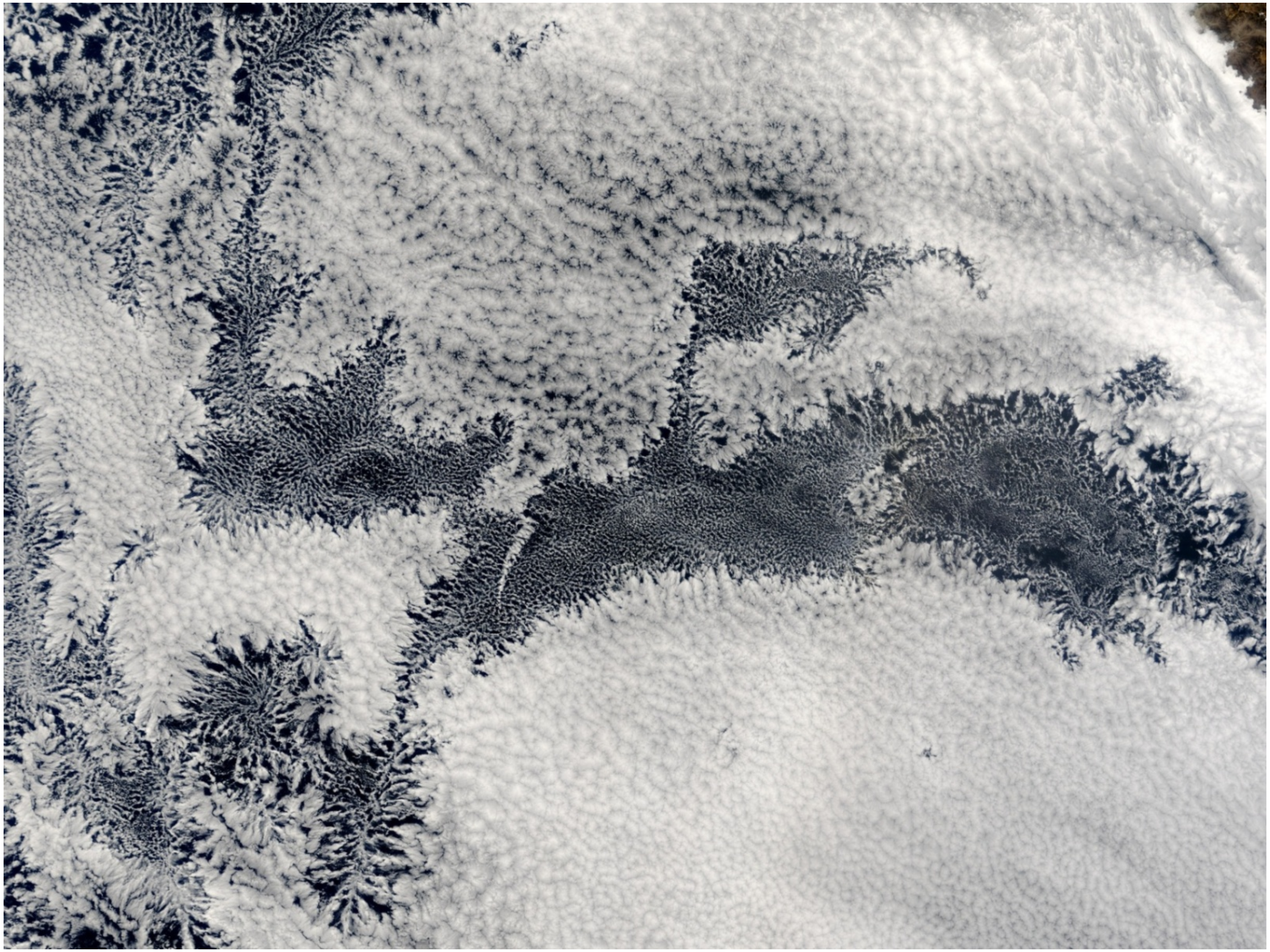


Strongest in: extratropics, subtropical stratus
winter
strongly capped MBL
regions less apt to show decreases in LWP

Lebsock et al. 2008

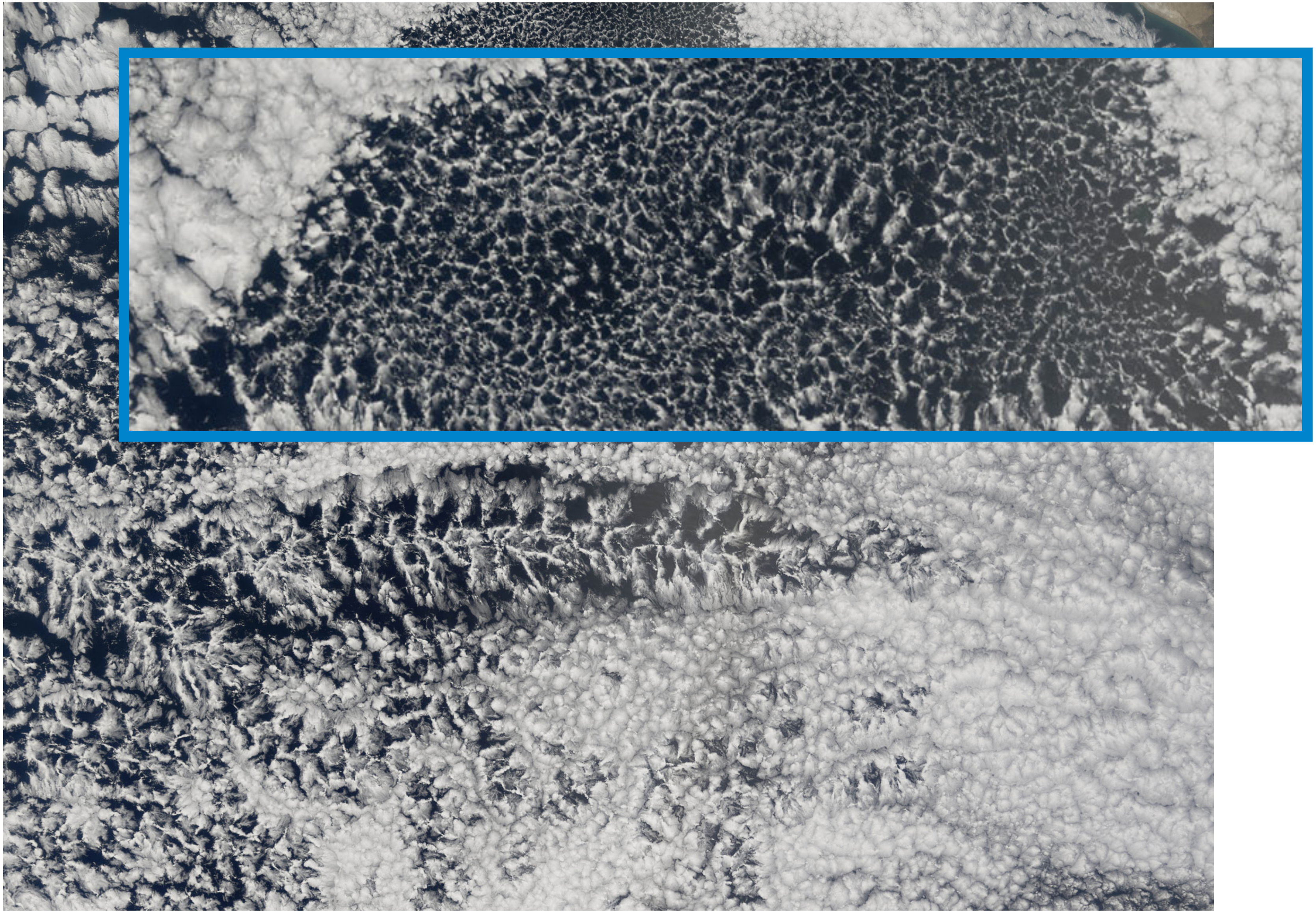
Self-organization in the aerosol-cloud-precipitation system

Mesoscale Cellular Convection



MODIS image, South East Pacific

- *Radiative forcing of the ocean-cloud system*
- *Fundamental understanding of closed/open-cell evolution*



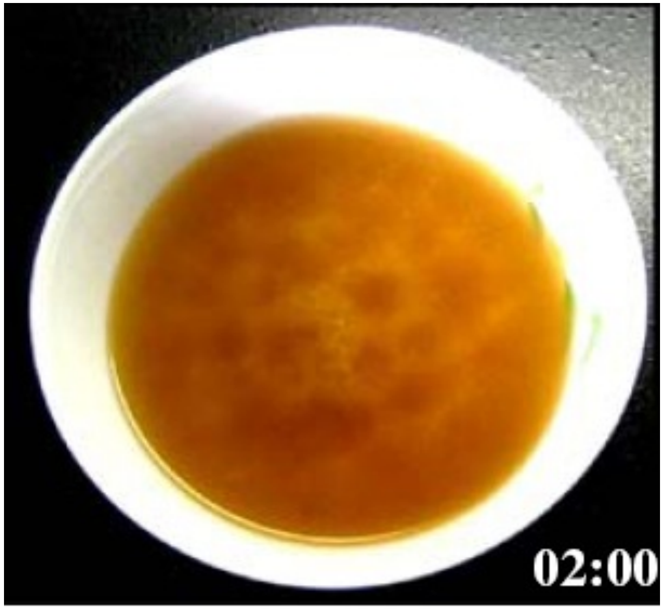
MODIS image, South East Pacific

Self-Organization in a Bowl of Soup

Warm currents rise; Cold surface currents sink; Opposite movements cannot take place at the same time without self-organization;

Cellular structures emerge; Rayleigh-Benard cells

Spontaneous creation of globally coherent patterns out of local interactions



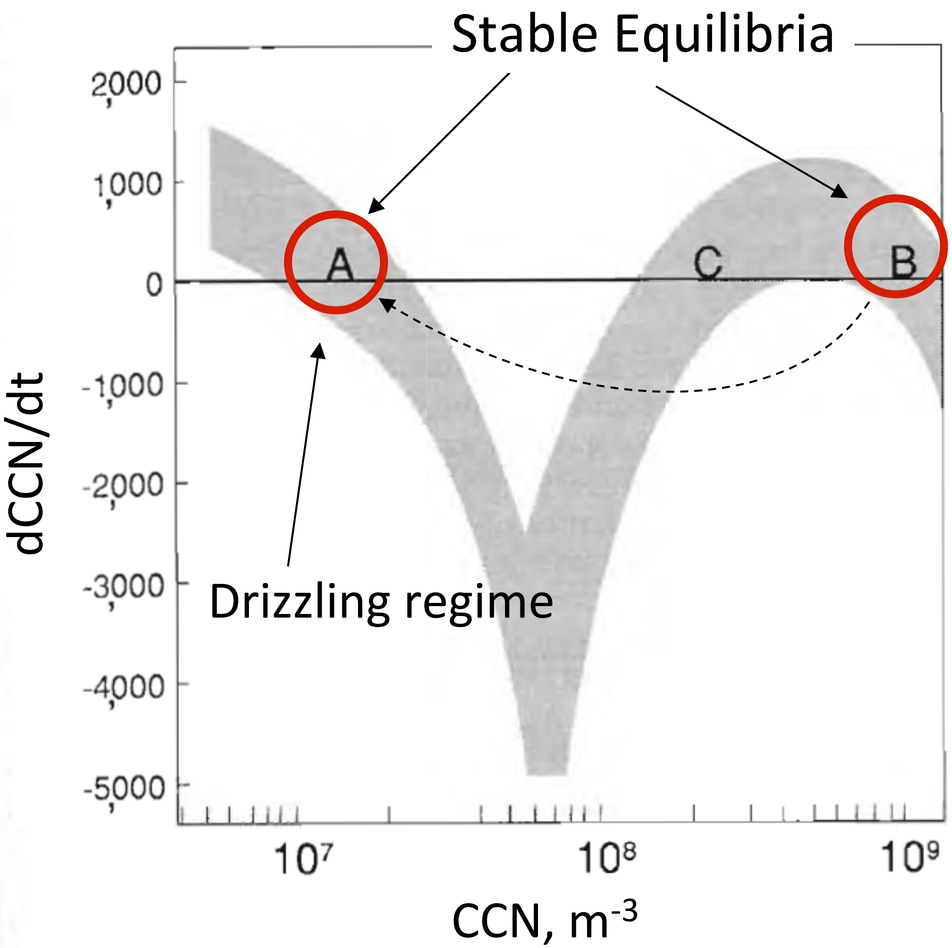
Convectional and sedimentation dissipative patterns of Miso soup Tsuneo Okubo.
Colloid Polym Sci (2009) 287:167–178

System Equilibria

$$\frac{dx}{dt} = \sigma(y - x)$$

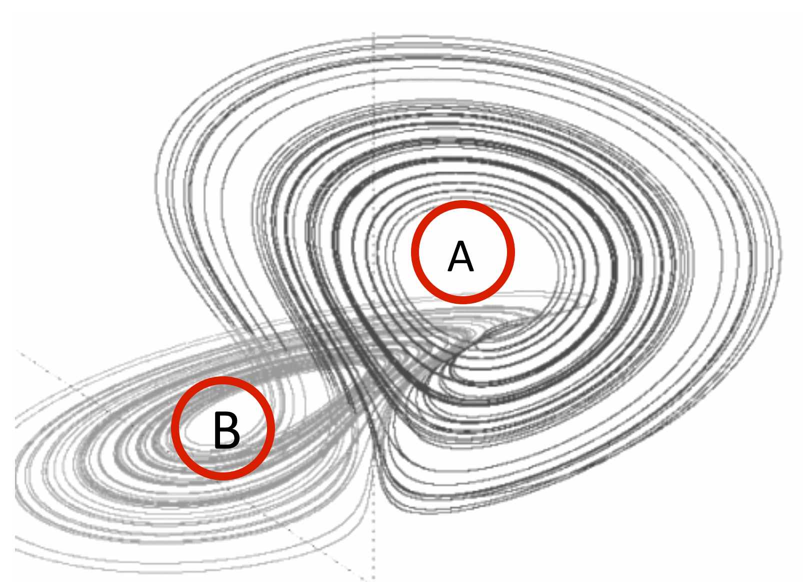
$$\frac{dy}{dt} = x(\rho - z) - y$$

$$\frac{dz}{dt} = xy - \beta z$$



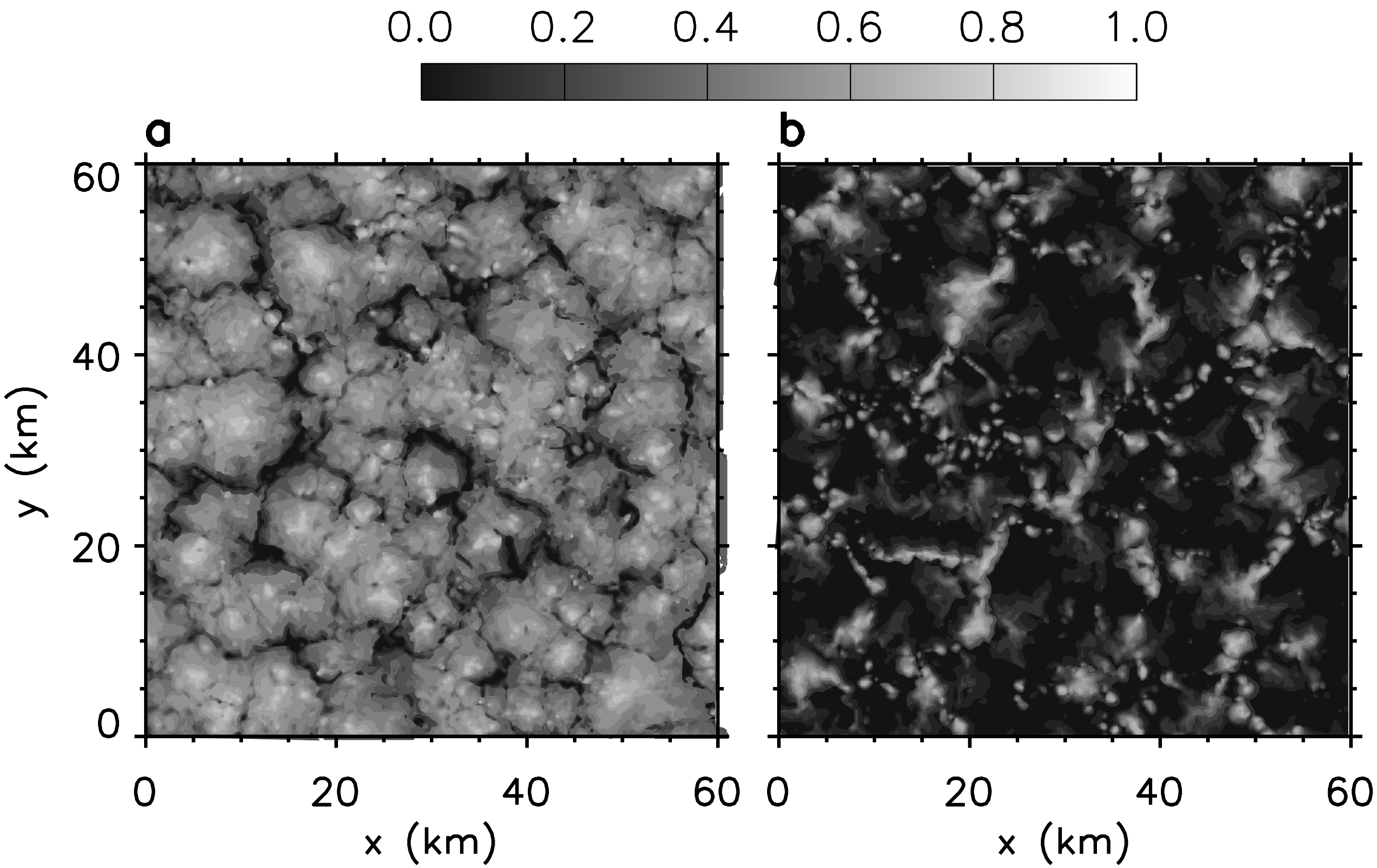
Baker and Charlson, 1990

Attractors



Lorenz, 1954

Large eddy simulation of open and closed-cells



Feingold, Koren, Wang, Xue, Brewer (2010)

See also Stevens et al. 2005; Savic-Jovcic and Stevens 2008; Xue et al. 2008; Wang and Feingold 2009

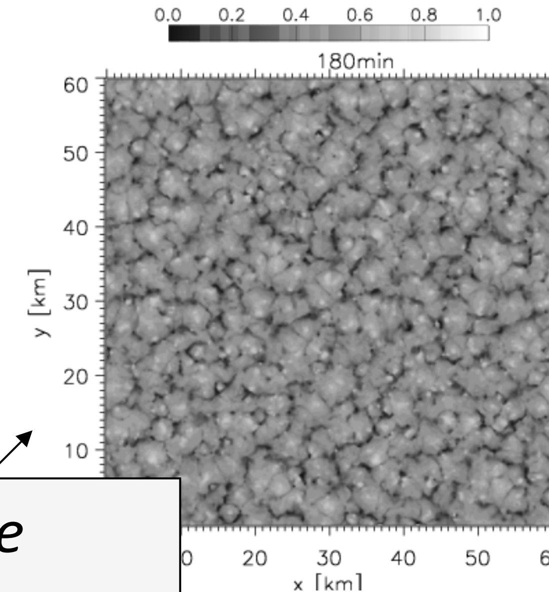
Aerosol/drizzle selects the state

Albedo

Closed-cell
Albedo ~ 0.6

→ <u>**high aerosol**</u>
(non-precipitating)

Albedo

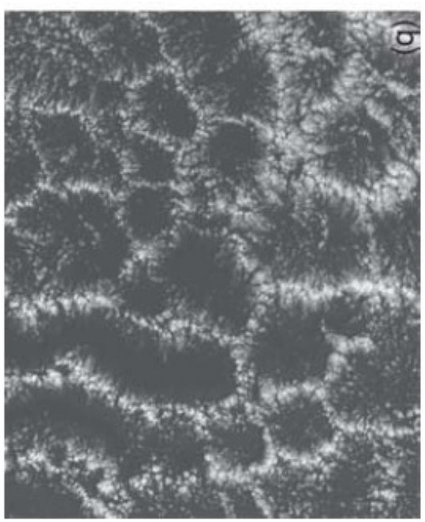


Onset of ***drizzle*** *results i*
transitio
to open-
convecti

WRF Model
+ 2-moment

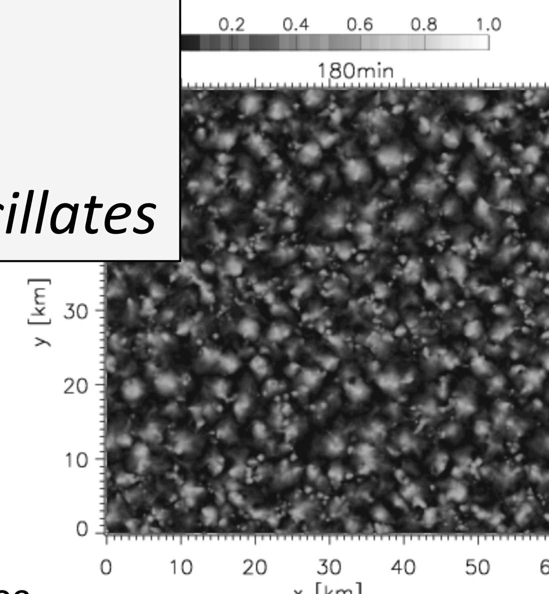
(i) Aerosol "selects" the state of the system
(same meteorology)

(ii) The stable state oscillates



Open-cell
Albedo ~ 0.2

→ <u>**low aerosol**</u>
(precipitating)

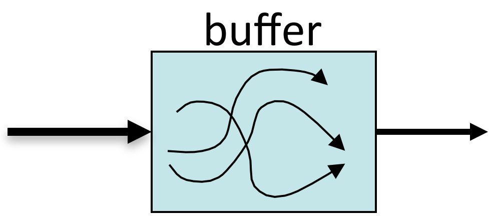


Garay et al. 2004, MISR

Wang and Feingold, 2009a

Buffering

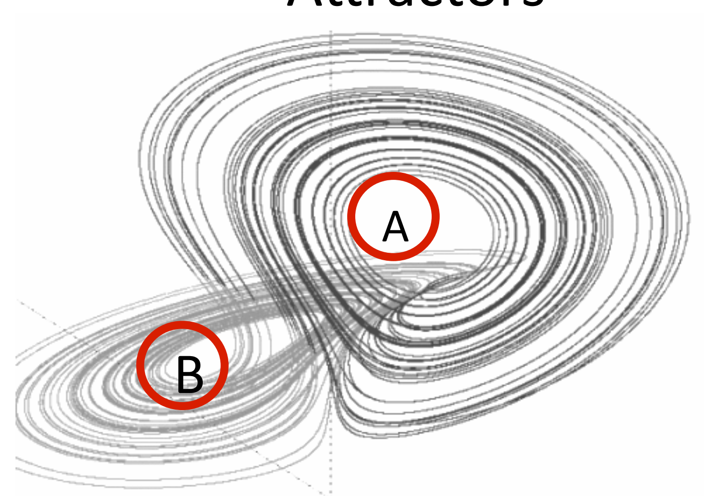
Buffering: different paths to a specific end buffer the system against disruptions to any particular path



Stable states A and B are stable and self-sustaining

Small perturbations strengthen the resilience of the state

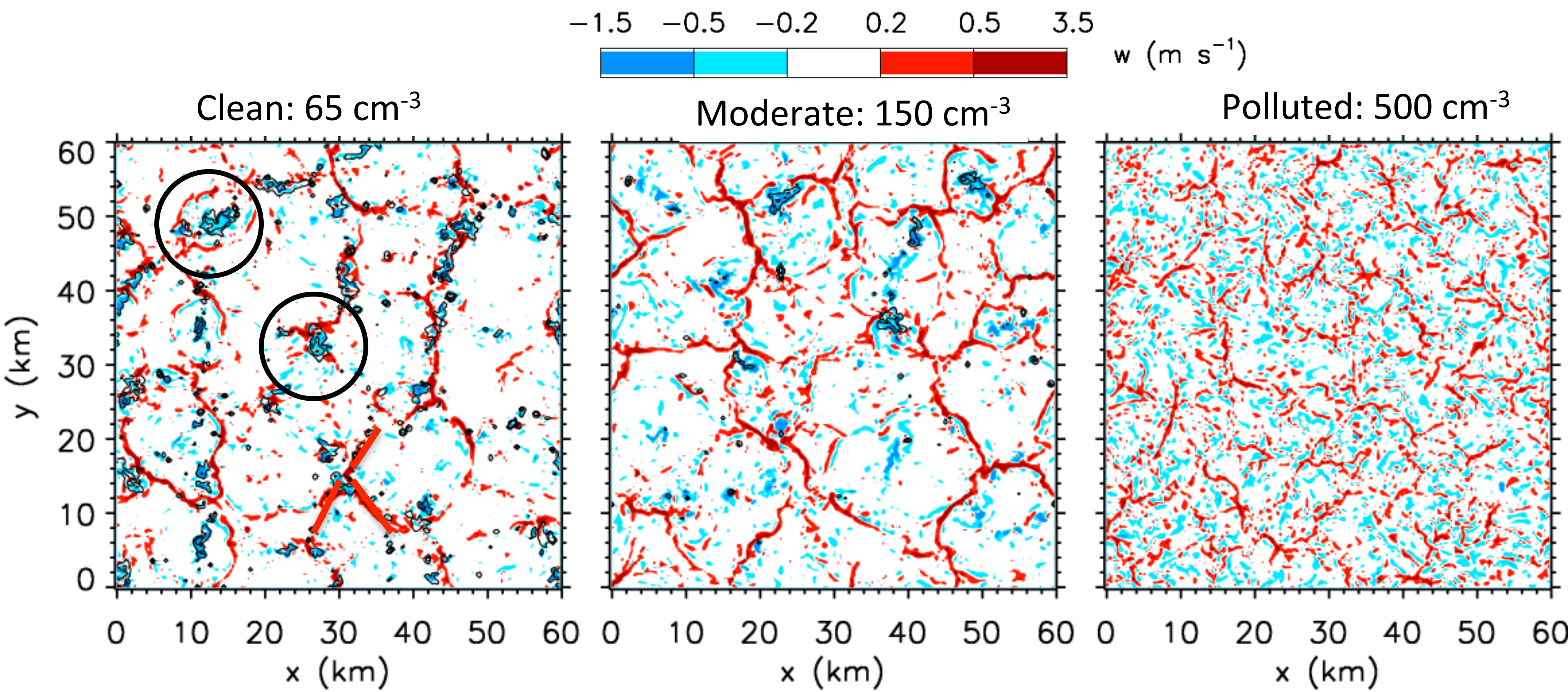
Attractors



Lorenz, 1954

Stevens and Feingold, 2009

Precipitation and convergence patterns



Near-surface vertical velocity

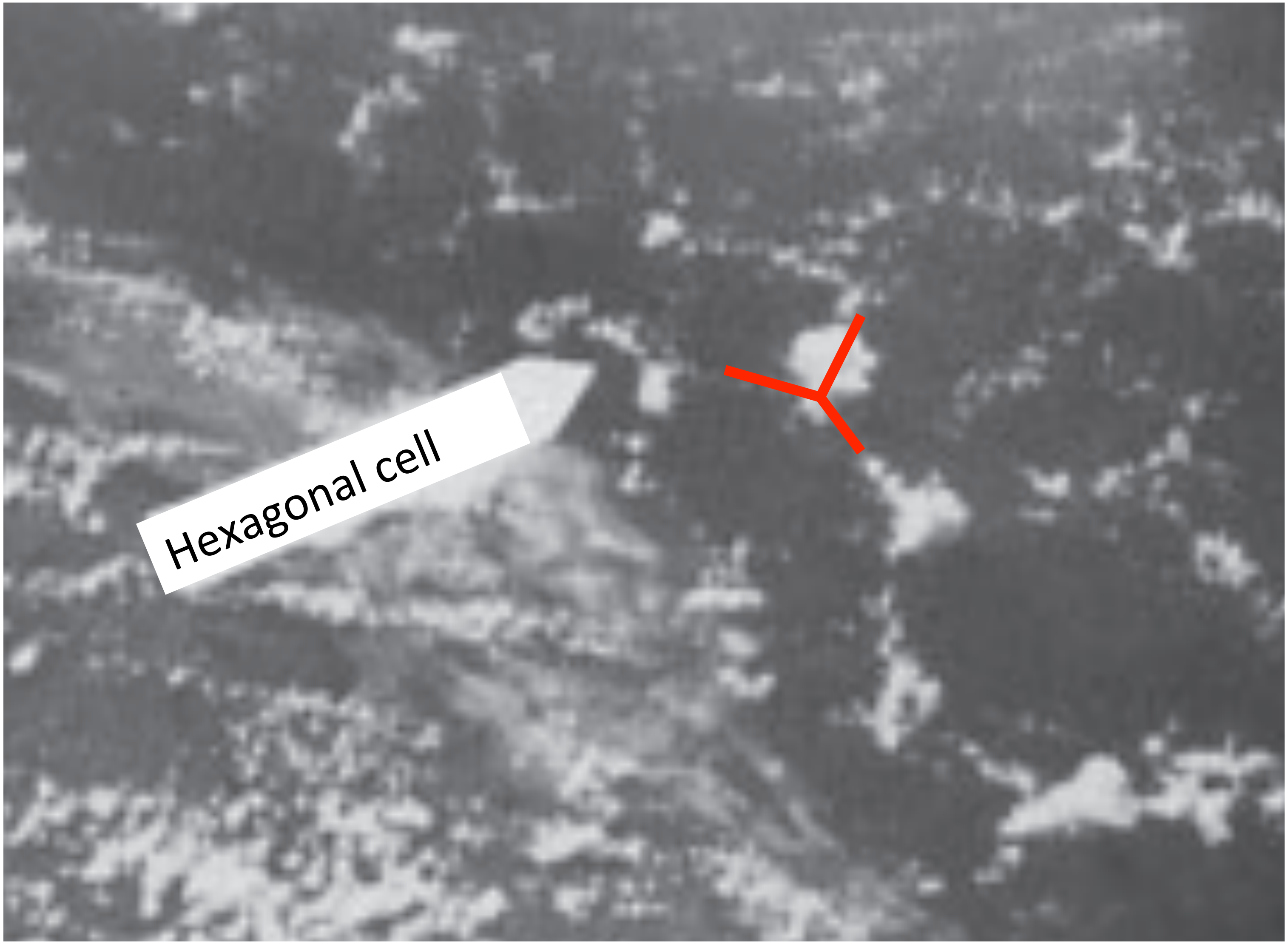
Red: Updrafts/surface convergence

Blue: Downdrafts/surface divergence

Black contours: Drizzle

DYCOMS-II
Model simulations

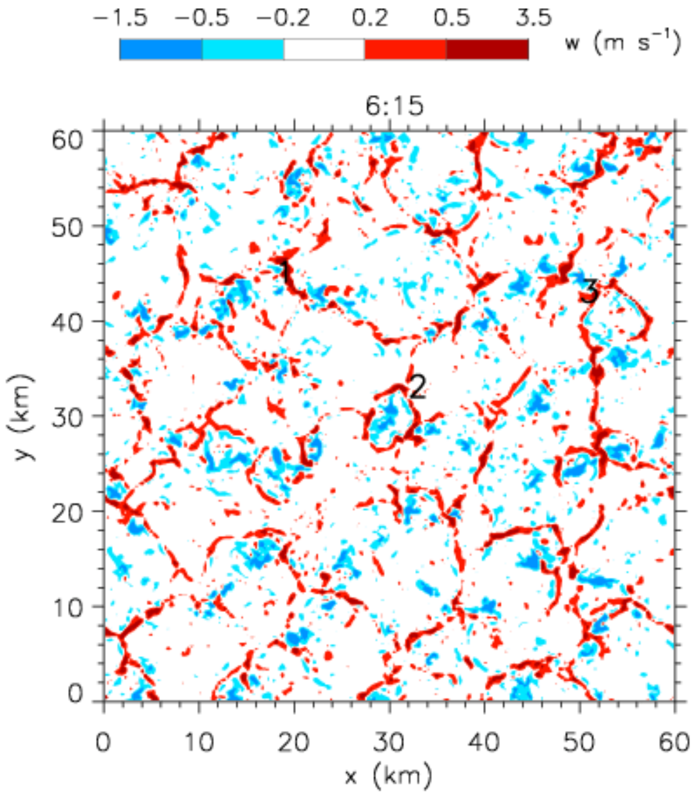
Wang and Feingold (2009a)



See also Willis and Deardorff 1979

Agee, 1984; Gemini V image

Global Order from Local Interactions



200-m vertical velocity from
t = 6:15 to 9:15

Y-shaped surface convergence zone is region favoured for new convection

↓

Precipitation is initiated

↓

Downdrafts, opening of cell

↓

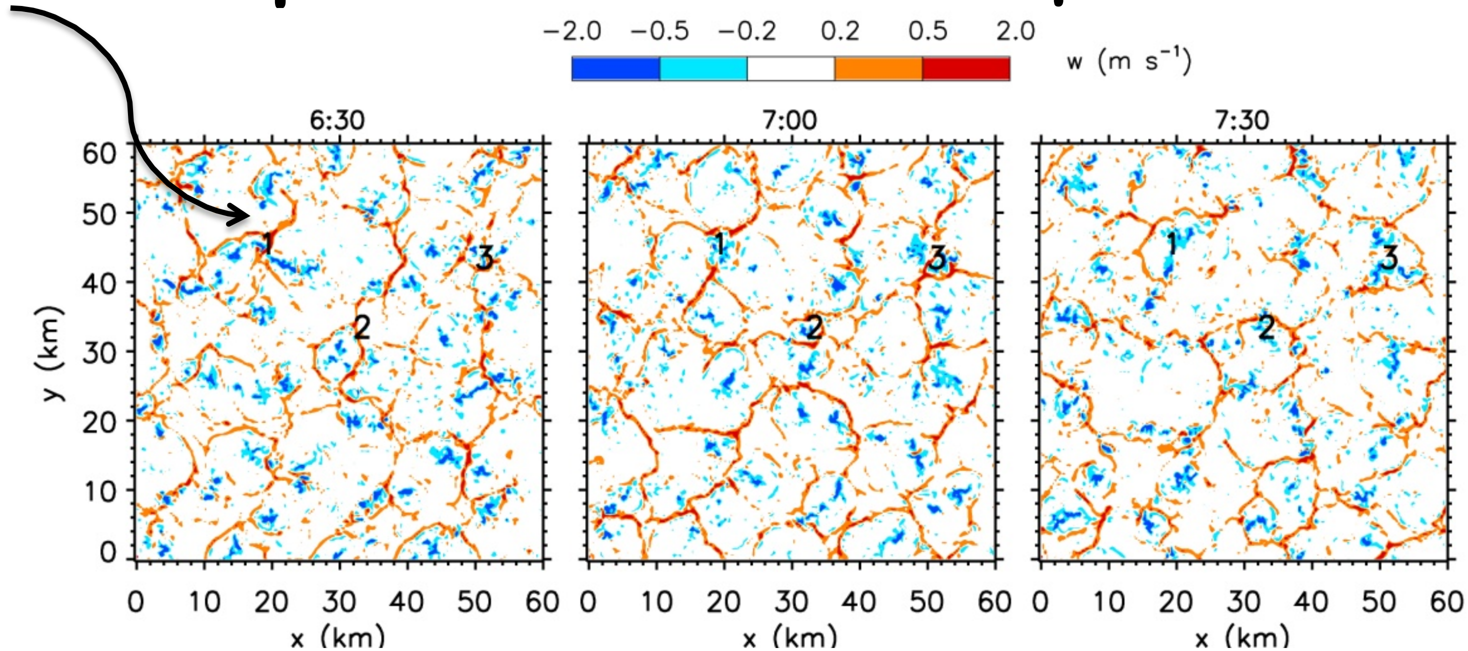
Surface divergence

Red: Updrafts

Blue: Downdrafts/precipitation

Cells compete or cooperate while interacting with their shared physical environment

Open Cells: Surface updrafts



Red: Updrafts
Blue: Downdrafts/precipitation

Feingold, Koren, Wang, Xue, Brewer (2010)

Y-shaped surface convergence zone is region favored for new convection

↓

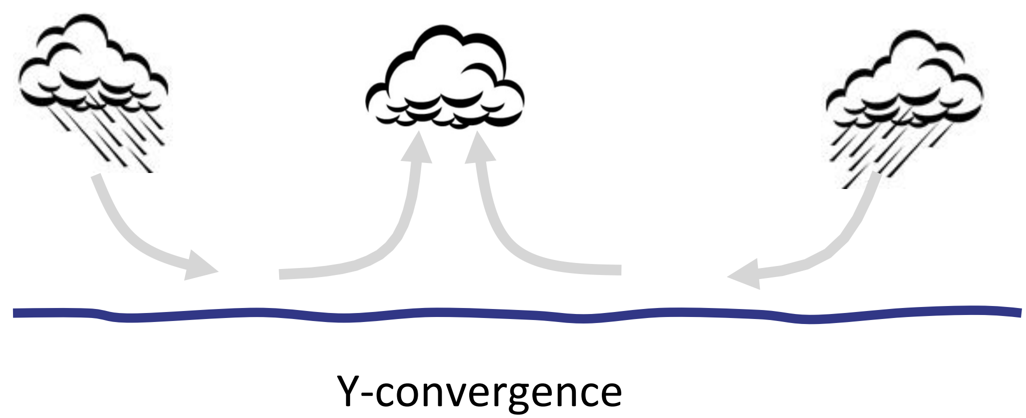
Precipitation is initiated

↓

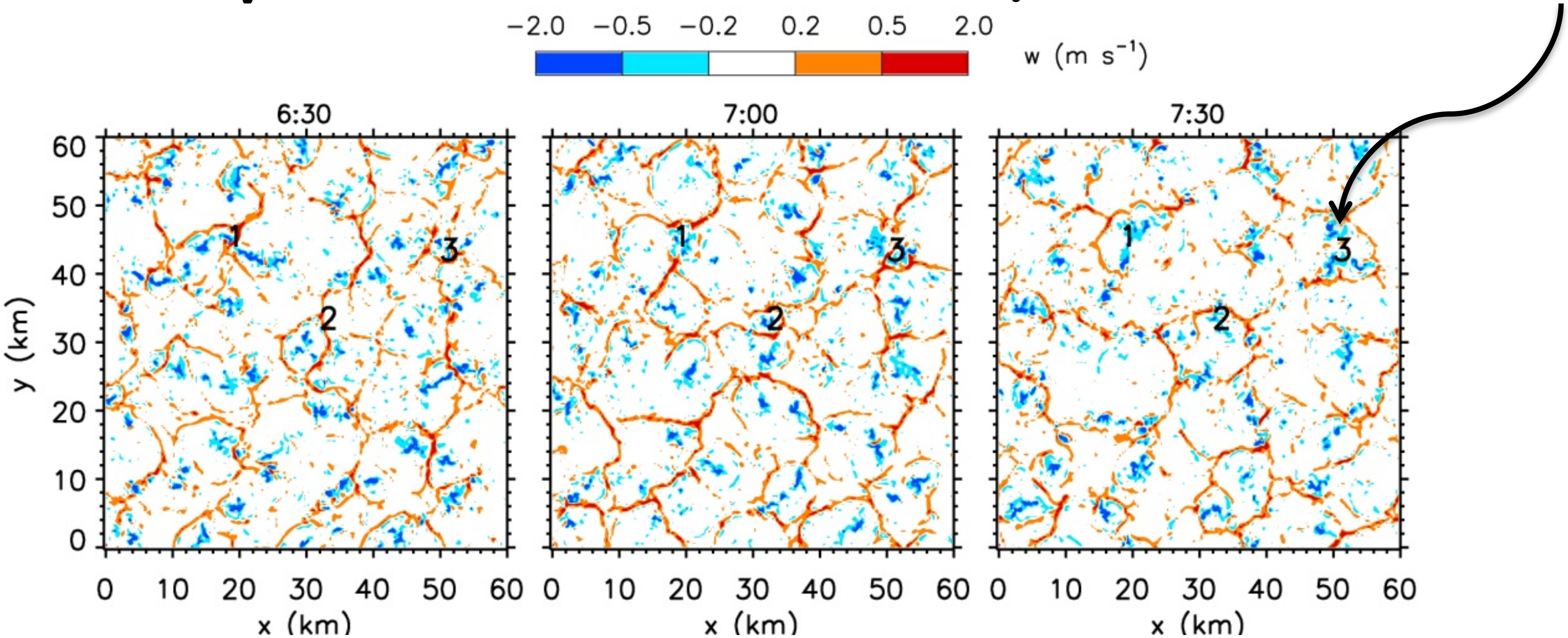
Downdrafts, opening of cell

↓

Surface divergence



Open Cells: Surface updrafts



Red: Updrafts
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Feingold, Koren, Wang, Xue, Brewer (2010)

Y-shaped surface convergence zone is region favored for new convection

↓

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↓

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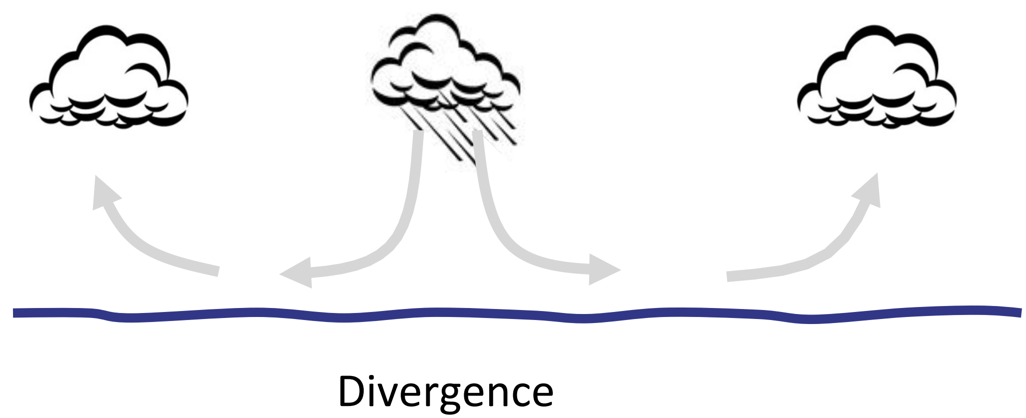
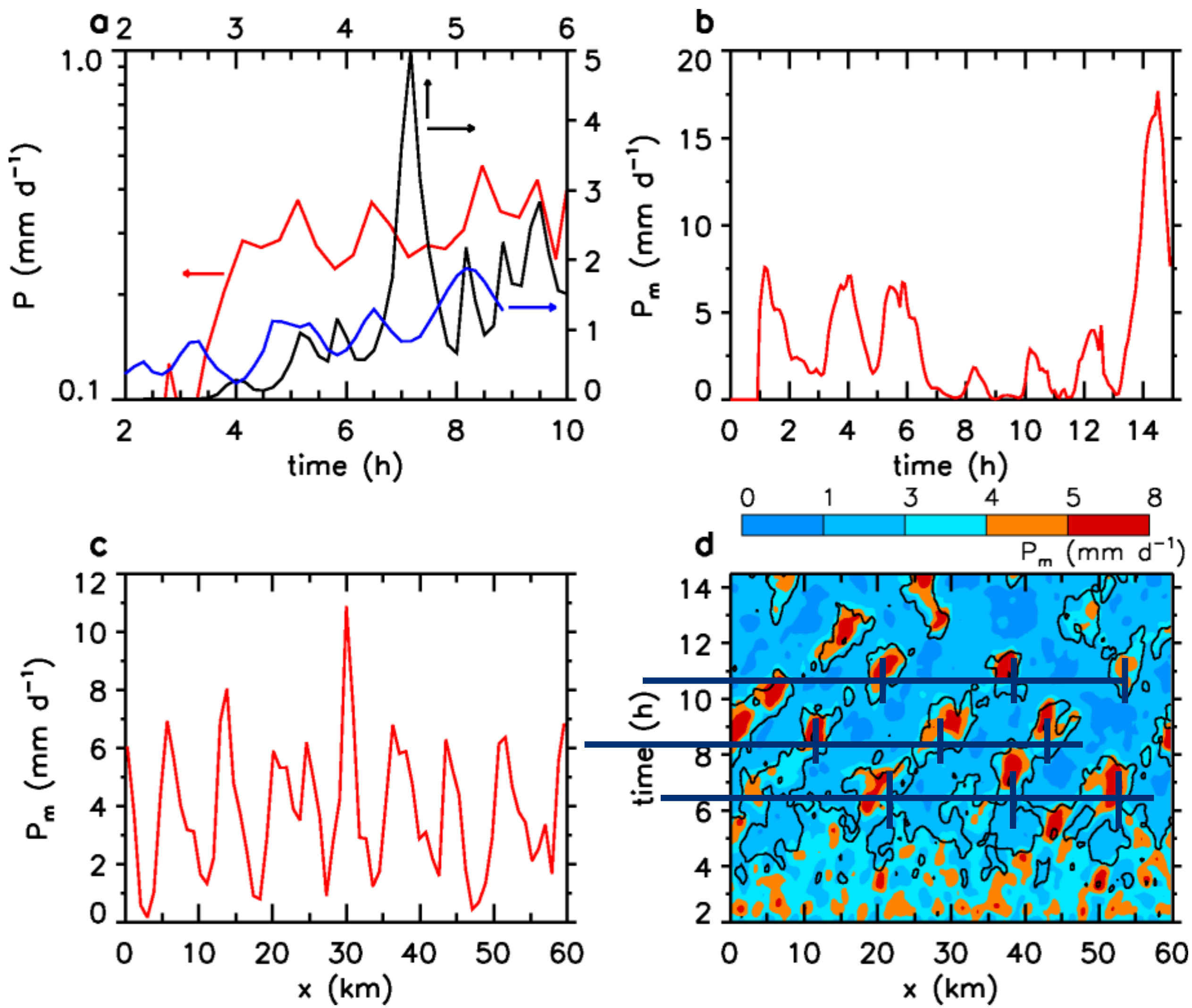
↓

Surface divergence



Synchronization: Oscillations in Precipitation



3 cases:
DYCOMS
ATEX
VOCALS

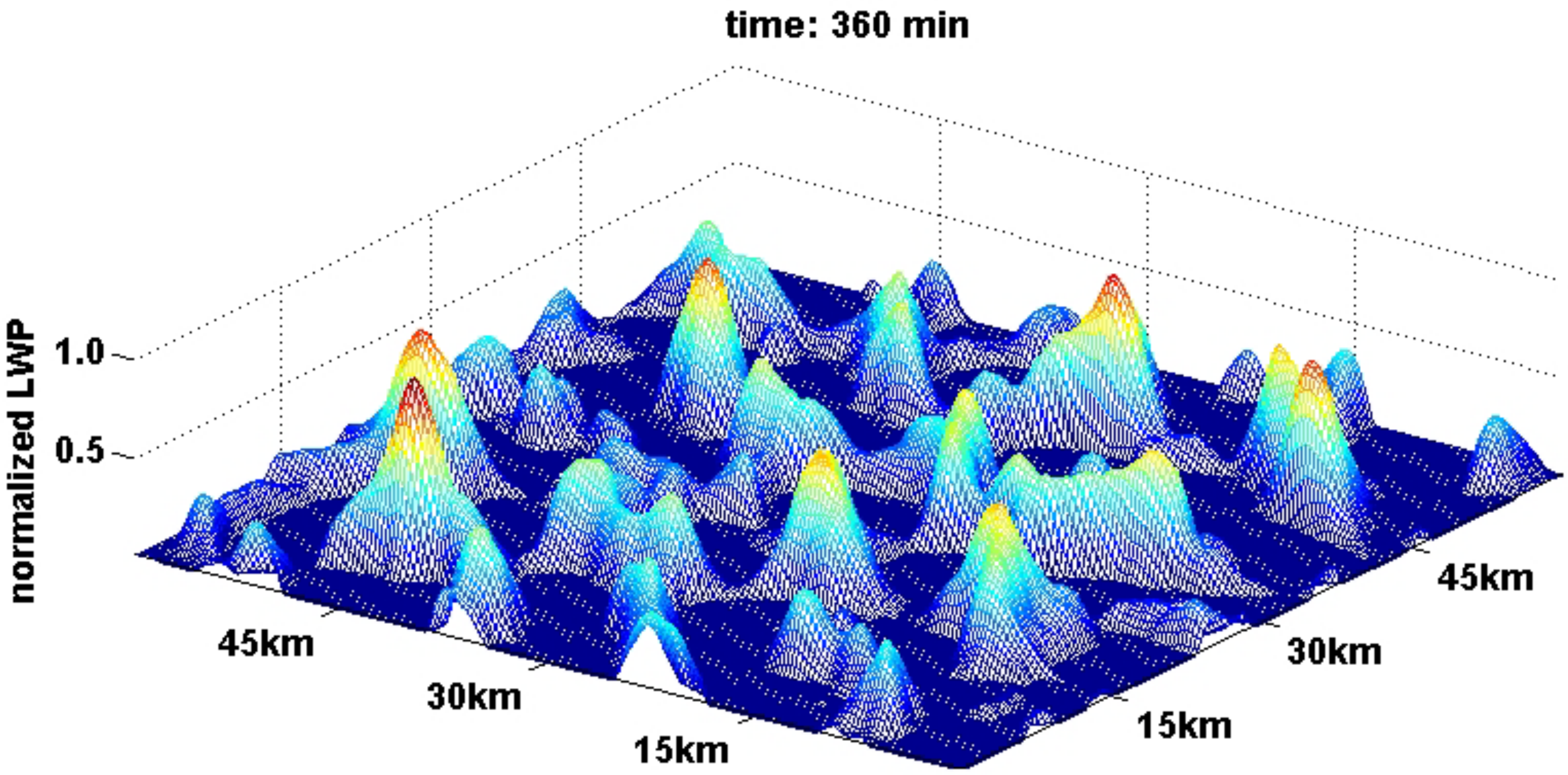
Hovmuller diagram

Shift in rain "grid"

Colored contours: rain
Contours: updraft

Feingold, Koren, Wang, Xue, Brewer (2010)

Synchronization

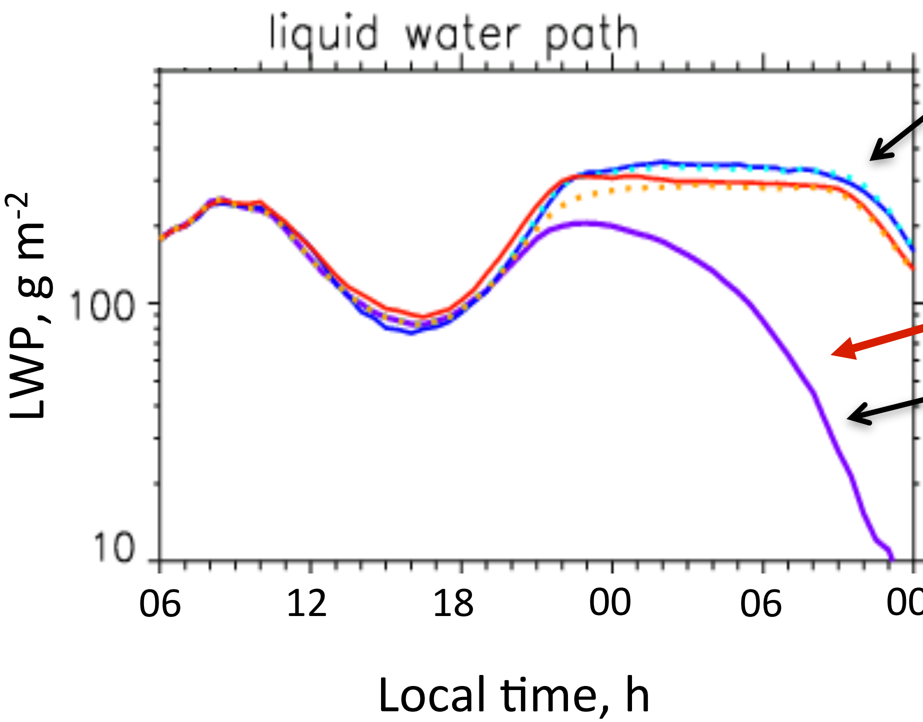


Feingold, Koren, Wang, Xue, Brewer (2010)

How important is the Aerosol?

Stability of the open-cell state: Role of Aerosol

VOCALS October 28th

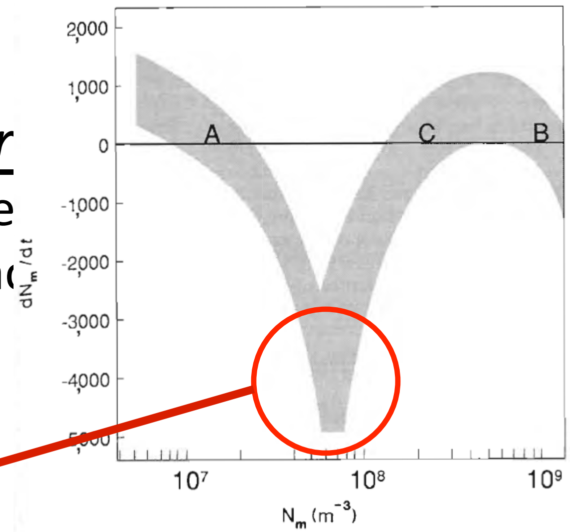


Wang et al. 2010 ACP

__Natur__

- Nucle
- Surfa

on



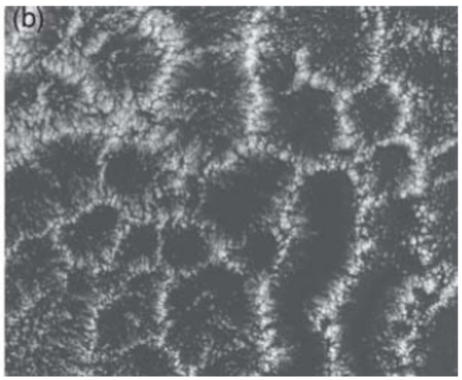
No aerosol source

runaway (un-buffered) reduction in drop concentration

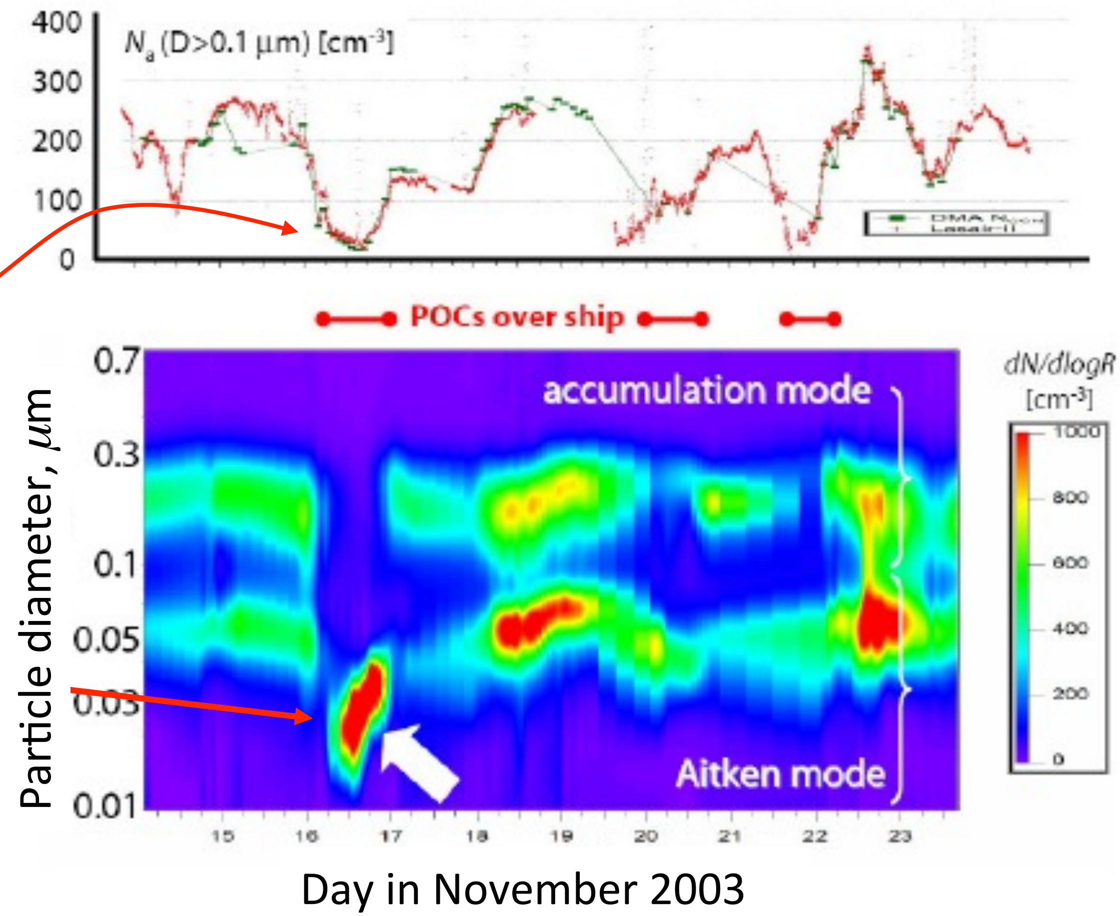
→ Collapse of cloud

See also Ackerman et al. (1993)
Kazil et al. ACPD (2011)

New Particle Formation in the Clean Marine Boundary Layer



Accumulation mode number conc

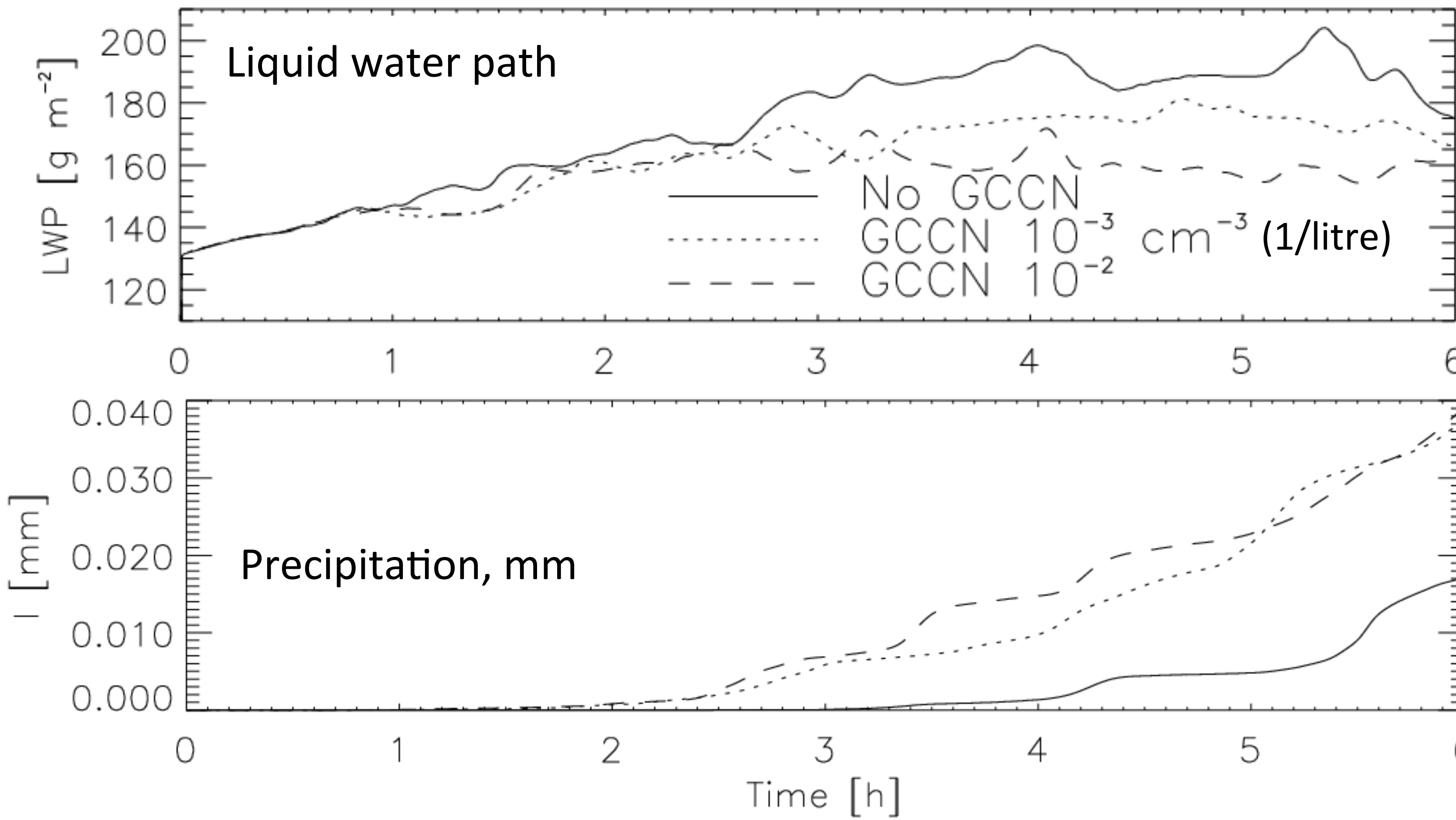


Pockets of open cells: Scavenging of accumulation mode;

New particle formation (from gasphase)

Tomlinson et al. 2007

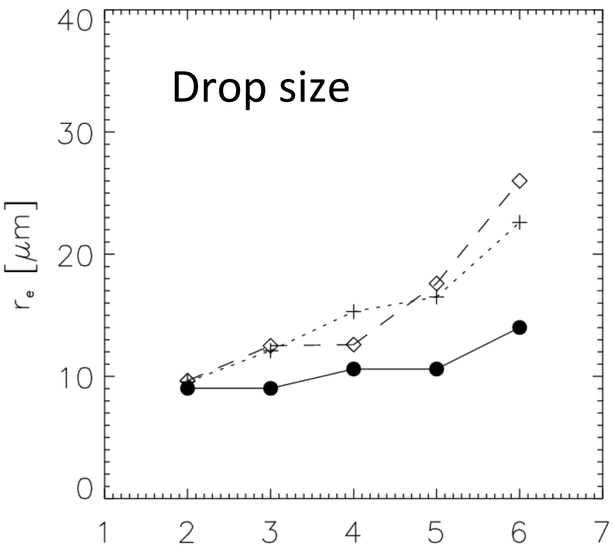
Influence of Giant CCN on precipitation in Stratocumulus

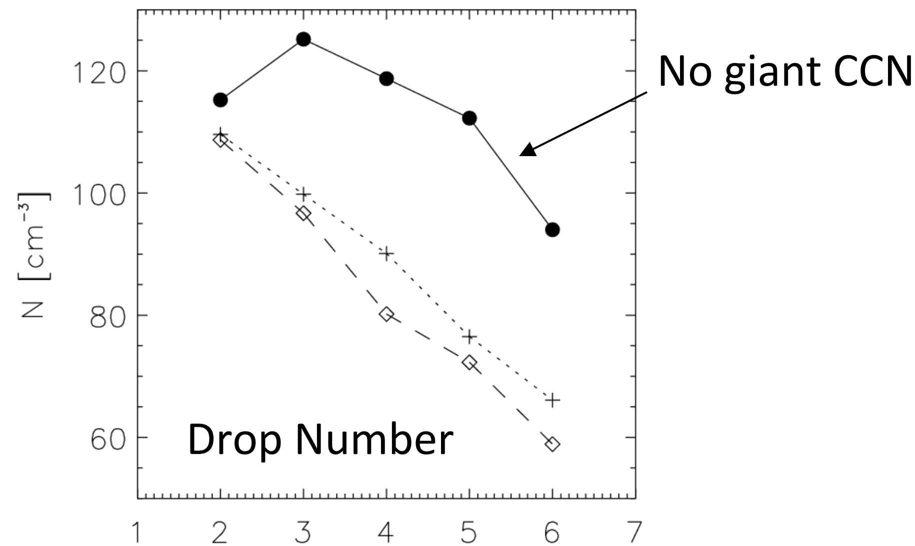


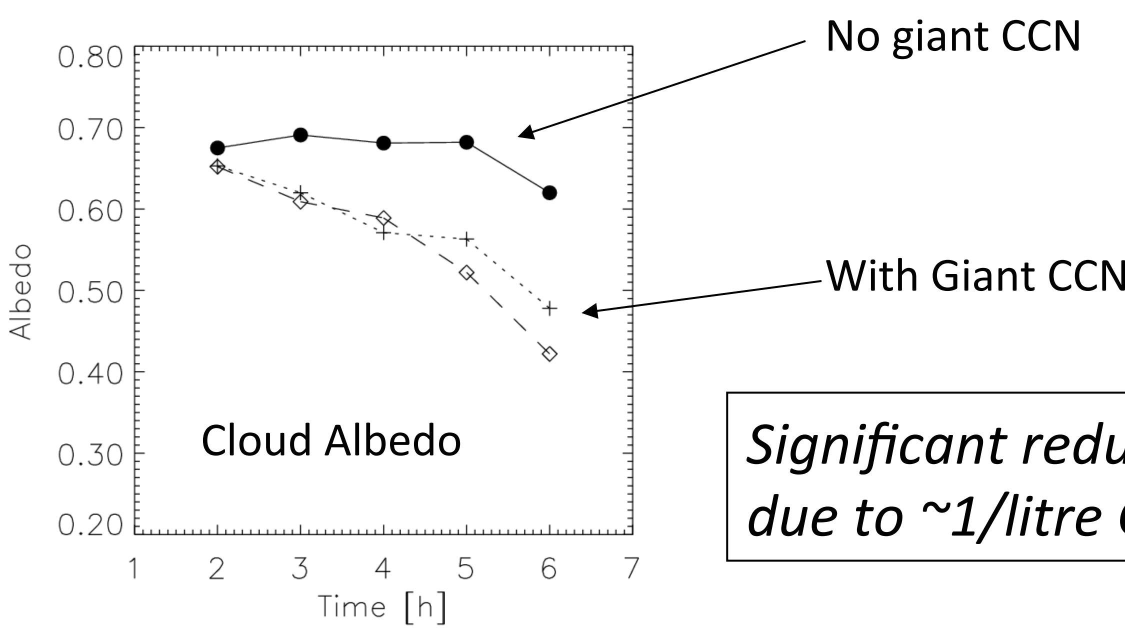
- Significant increase in precip due to ~1/litre Giant CCN
- More particles does not always mean smaller drops

Feingold et al. 1999

Influence of Giant Nuclei on μphysics and Cloud Albedo



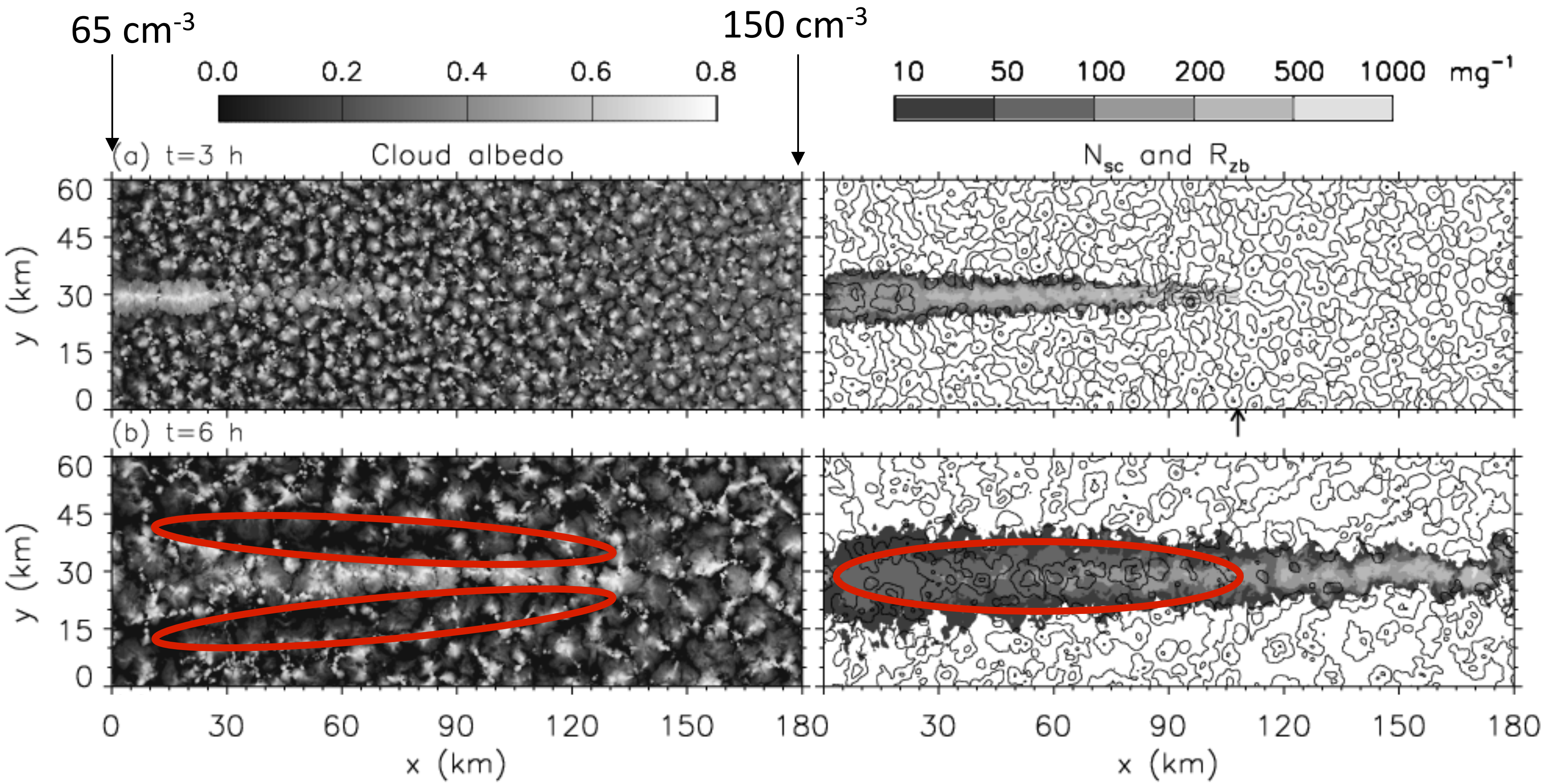




Significant reduction in cloud albedo due to ~1/litre Giant CCN

Feingold et al. 1999

Strong aerosol source: shiptrack

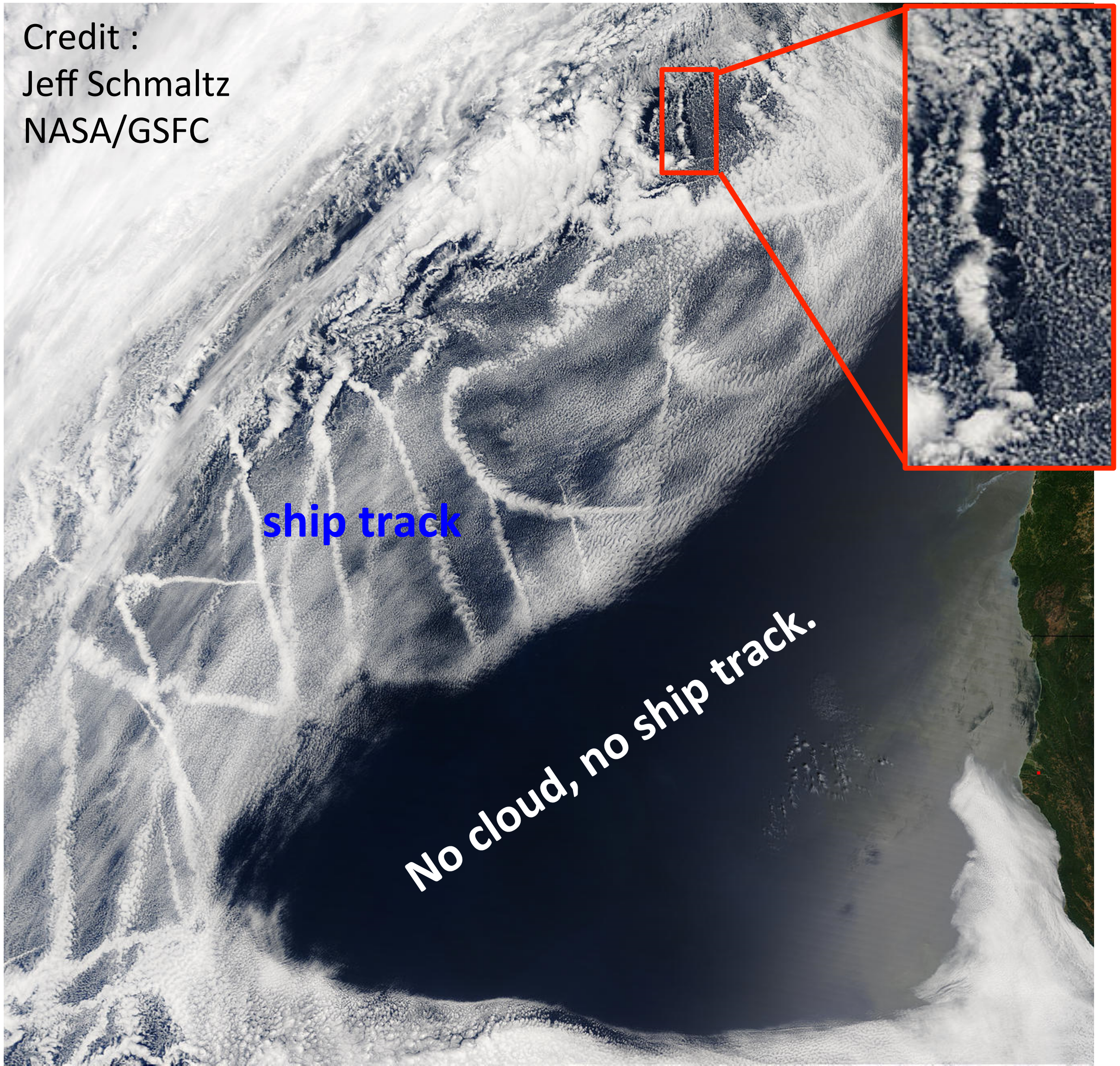


Contours: rain
Shading: ship particles

- *Mesoscale circulation transverse to track*
- *Strengthens LWP in track*
- *Clearing on either side of track*

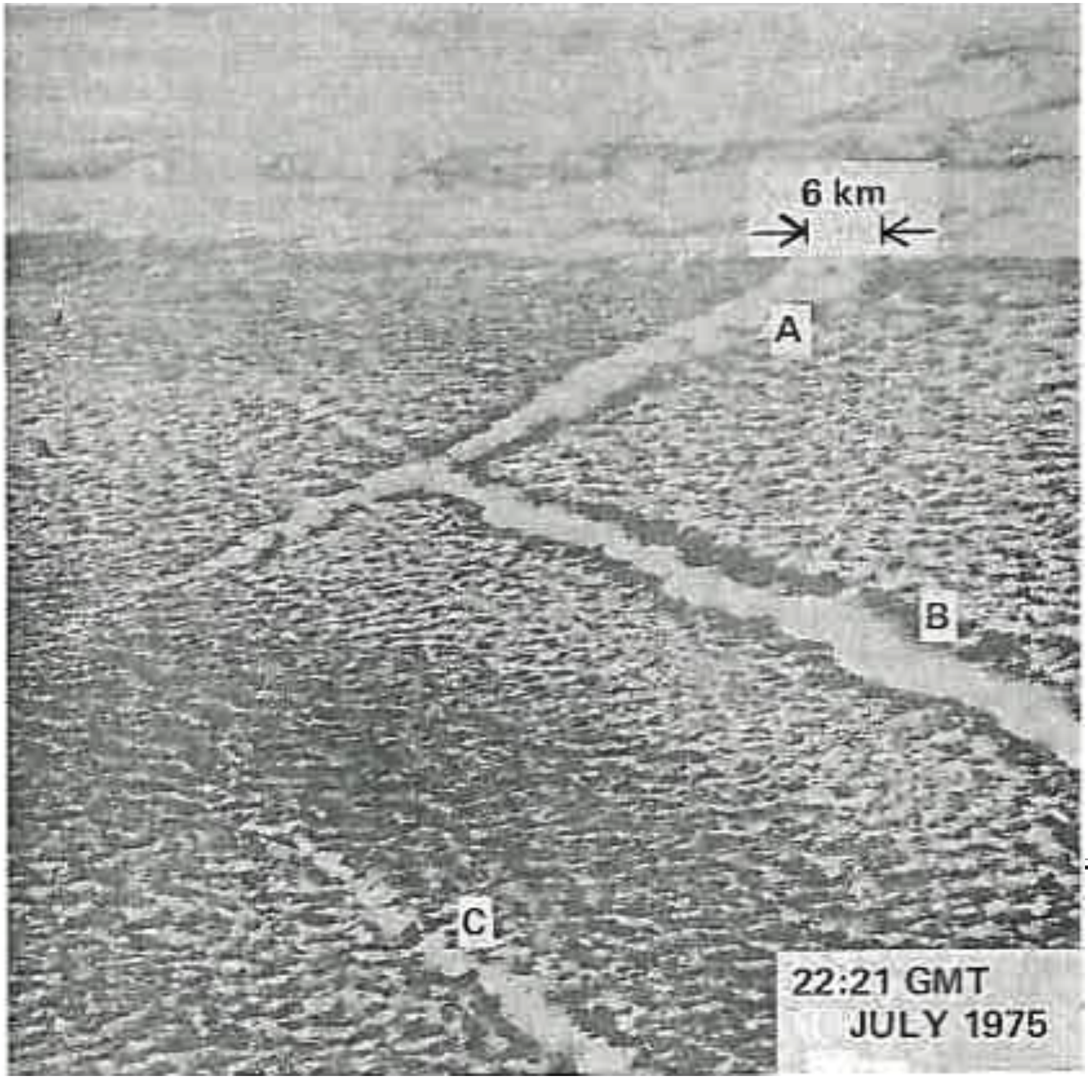
Wang and Feingold, 2009b

The Shiptrack Shadow

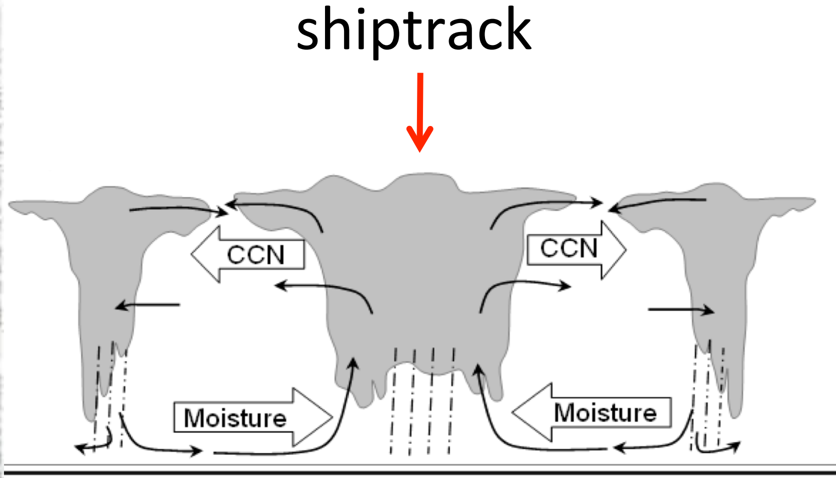


Unpredictable!

Clearing on either side of shiptracks



W. Porch et al. Apollo-Soyuz, July 1975

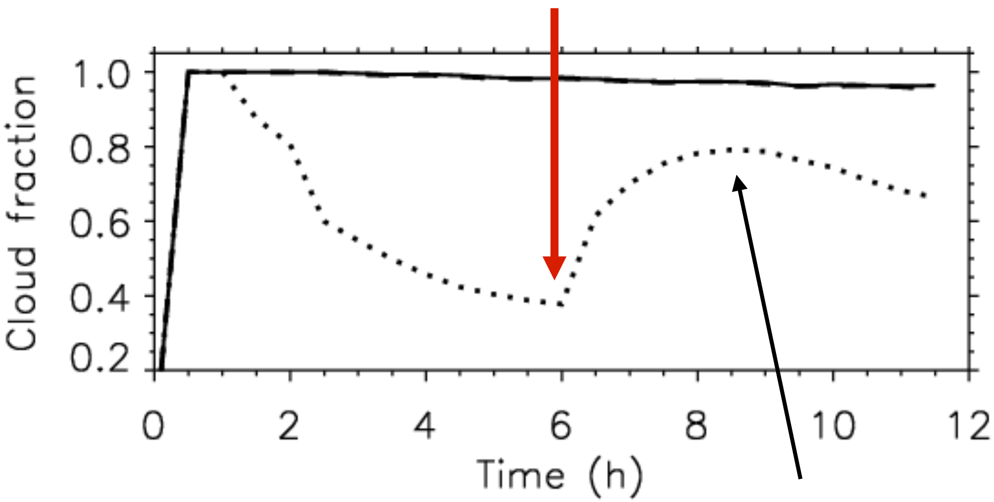


Wang and Feingold, 2009b

Massive aerosol source:

Self organising systems are resilient to change

Massive aerosol perturbation

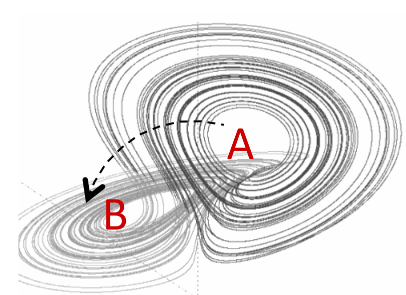


Polluted case

Clean case with massive aerosol perturbation (65 → 300 cm^{-3})

-Thin "anvil cloud" lacks dynamical support

Cells remain open



...ndom perturbation will facilitate rather
...ization
...or geoengineering

Stevens and Feingold 2009

Wang and Feingold, 2009b

Main Themes/Conclusions

- Aerosol-Cloud Interactions are seldom simple;
  - even shiptracks are complex

- Aerosol-Cloud-Precipitation System is often self-organizing or buffered

  - Identifying times when it is not would appear to be most fruitful
  - Aerosol influences may trigger changes in self-organization that are much more complex/interesting than the original microphysical perturbation

- Geoengineering ship track experiments may yield unintended consequences
  - Ship track "shadows" due to mesoscale circulations