Aerosol-cloud Interactions, drizzle, and the self-organization of clouds

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Acknowledgements

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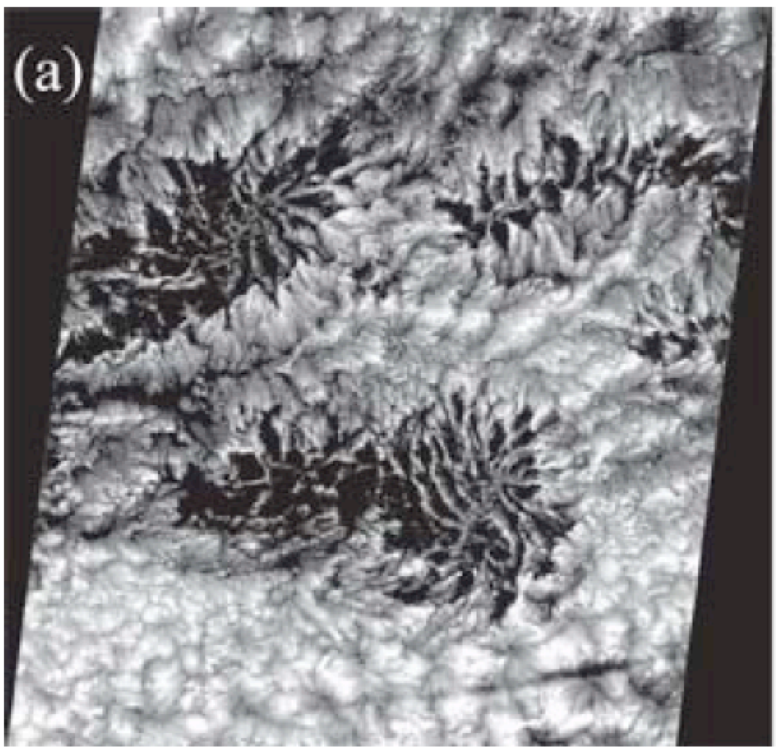
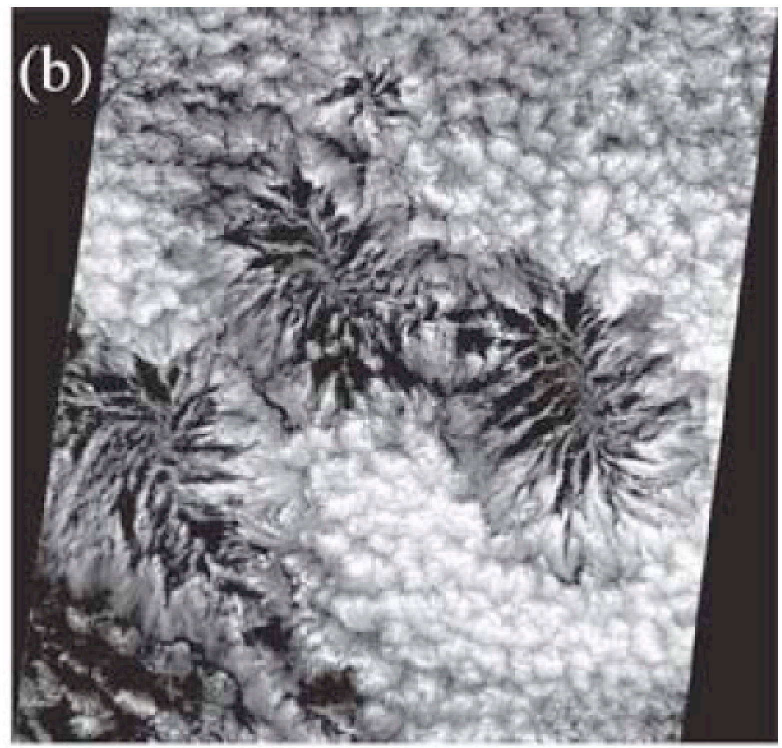
Clouds are complex and sometimes exhibit intricate structure

The strongest aerosol effects on albedo are likely those that change both the macroscale and microphysical cloud properties

Northern Hemisphere

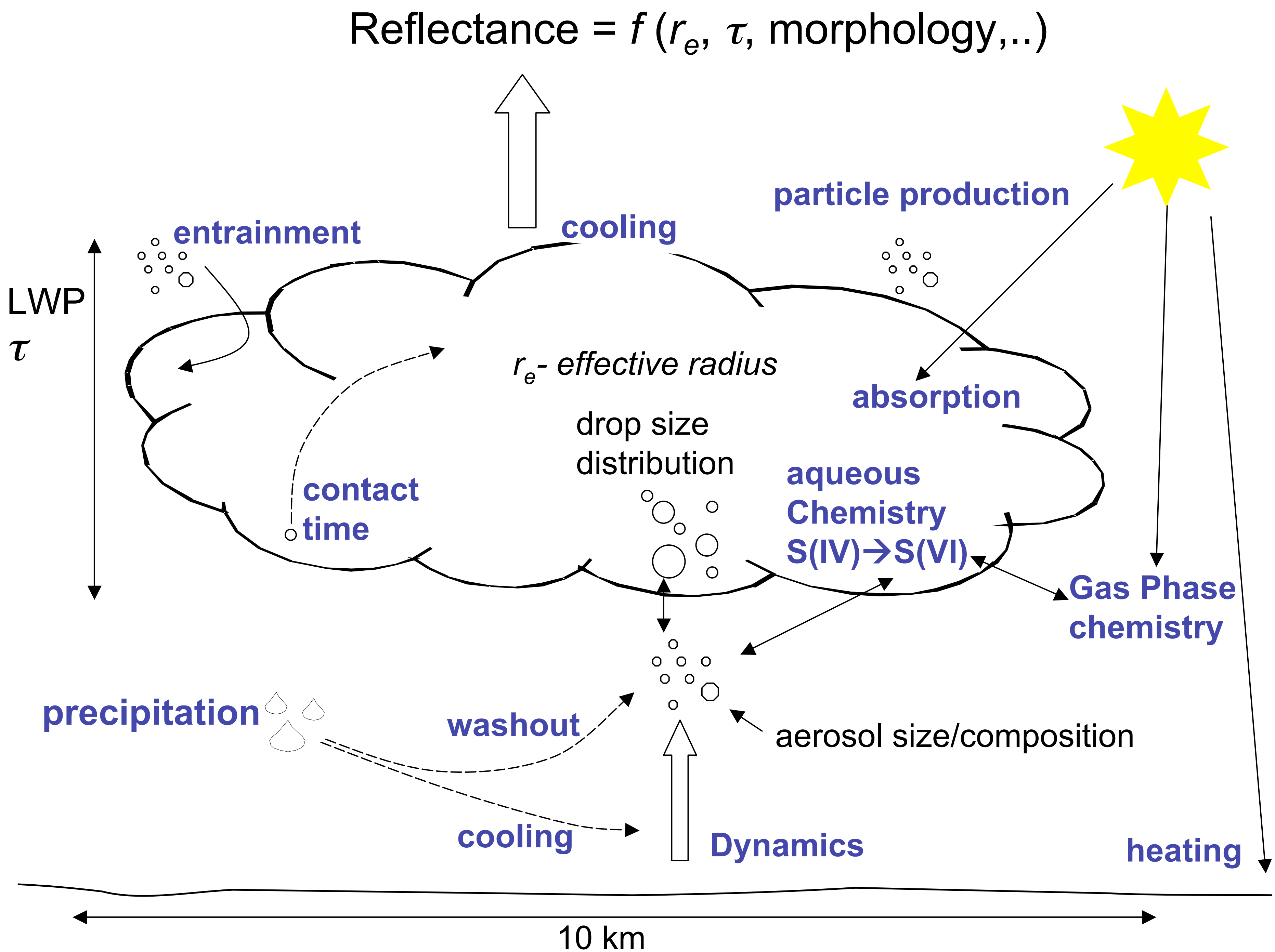


Southern Hemisphere



MISR Images

Garay et al., 2004



Reflectance = f (r_e, τ, morphology,..)
particle production
entrainment
cooling
LWP
τ
r_e- effective radius
absorption
drop size
distribution
contact
time
aqueous
Chemistry
S(IV)→S(VI)
Gas Phase
chemistry
precipitation
washout
aerosol size/composition
cooling
Dynamics
heating
10 km

Outline

Aerosol-Cloud Interactions in a Coupled System

Aerosol Indirect Effects

1. Survey of some remote sensing observations of aerosol and clouds: *conflicting results*

2. Precipitation in warm boundary layer clouds
   – Aerosol-cloud-precipitation-<u>dynamical</u> feedbacks

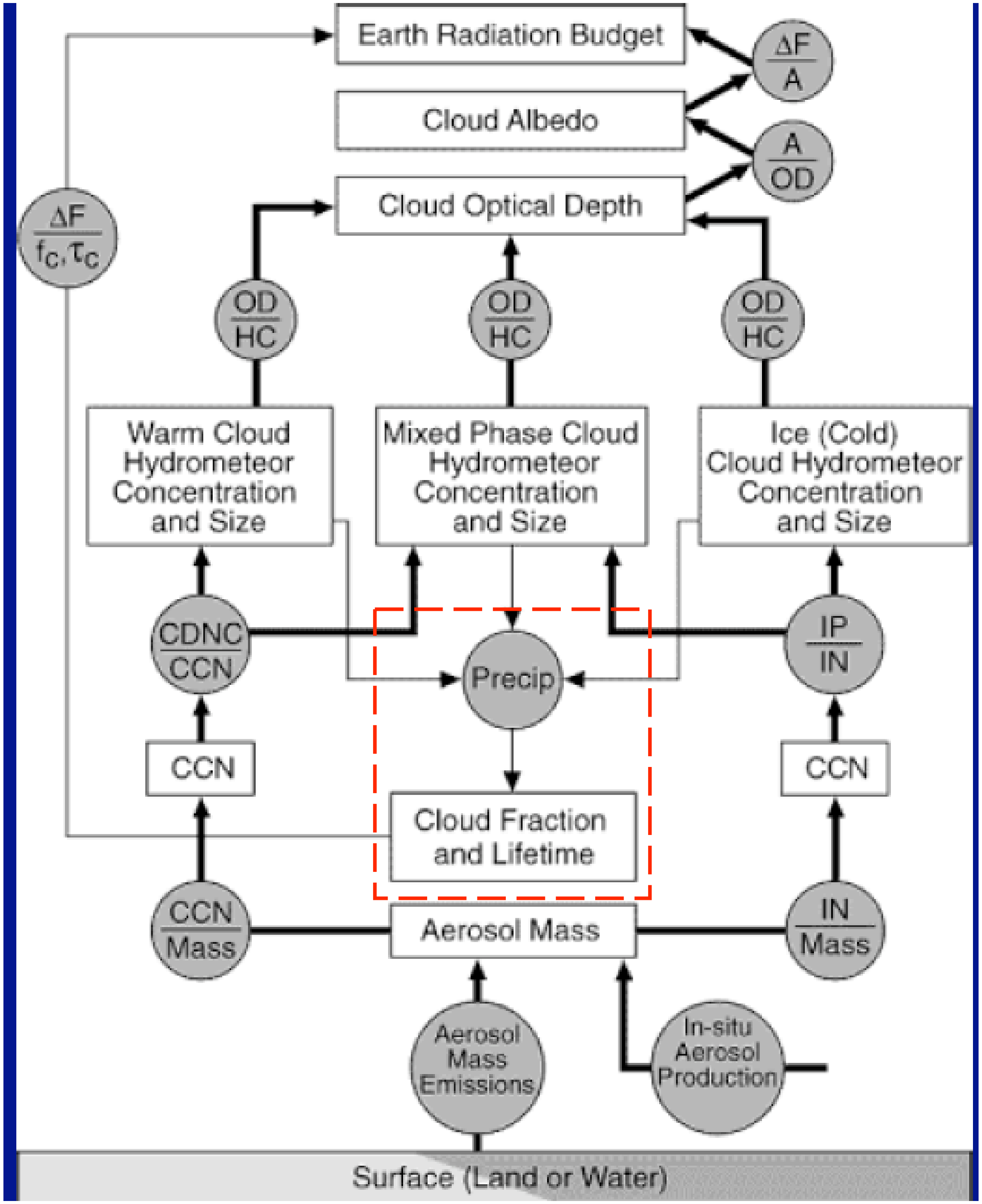
3. Cloud lifetimes
   – Do enhanced aerosol concentrations increase cloud lifetime?

4. Cloud Albedo
   – Cloud brightening vs changes associated with changes in cloud spatial distribution

The “Second” Aerosol Indirect Effect

More aerosol → more CCN → more drops → suppressed coalescence→ less rain → <u>larger LWP, cloud fraction</u> → <u>longer lifetime</u>

A construct that needs to be revisited

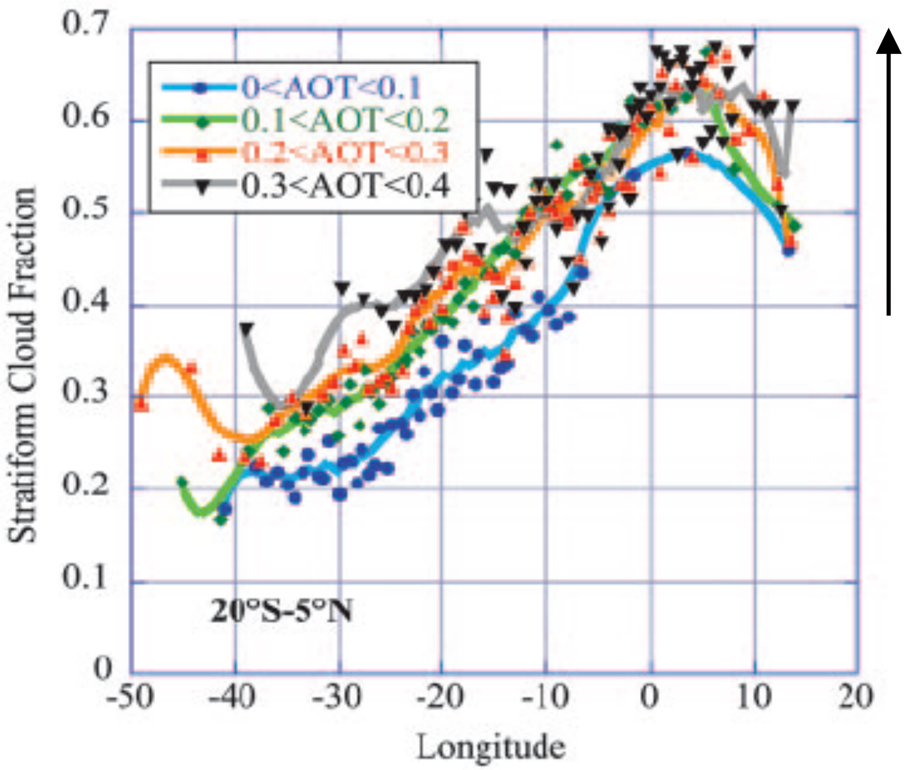


GCMs

Investigation of
"Cloud Lifetime Effect"
is equivalent to changing
autoconversion scheme

IPCC 2001
Penner et al.

1. Observations of Aerosol Effects on Cloud Fraction



Increasing
Aerosol Optical
Thickness (AOT)

(Kaufman et al., PNAS, 2005)

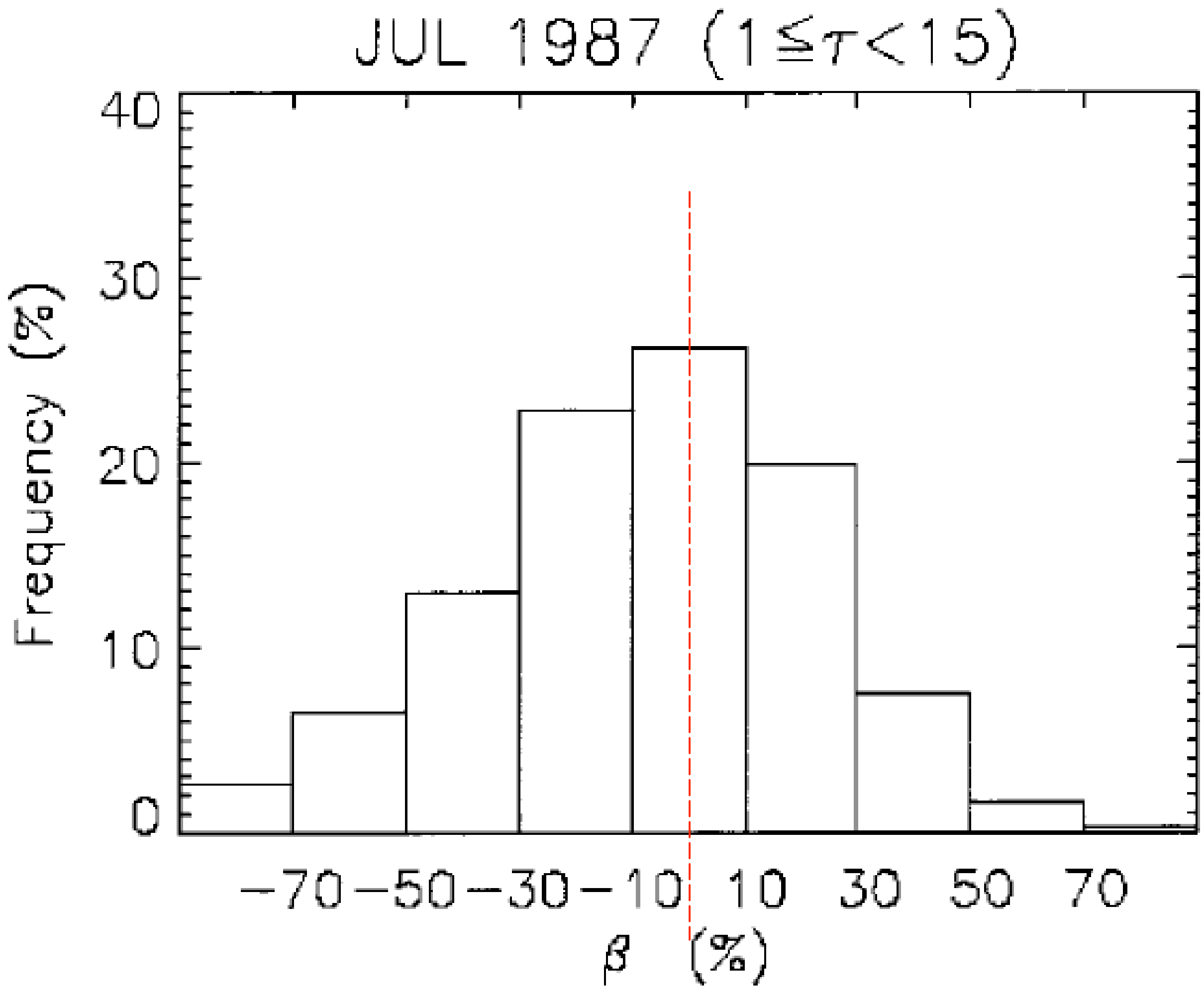
Cloud Fractions: ~ 20% to 70%

Cloud Fraction <u>increases</u> with increasing aerosol

Note: Longitudinal changes are much larger than aerosol perturbations

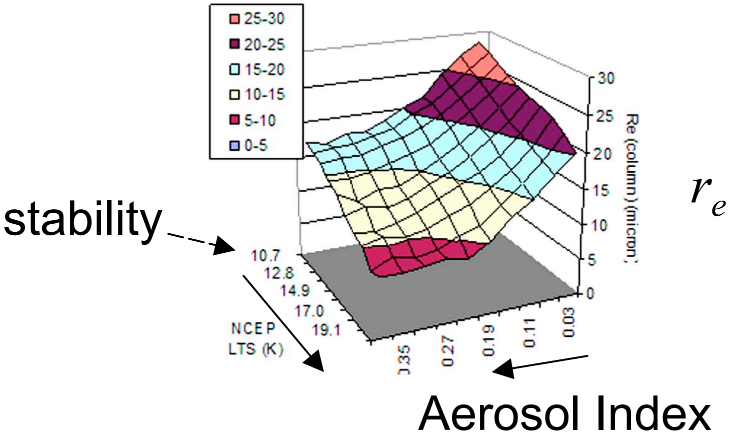
$$\beta = \frac{\Delta \ln LWP}{\Delta \ln N_d}$$

Sign of the change is uncertain!

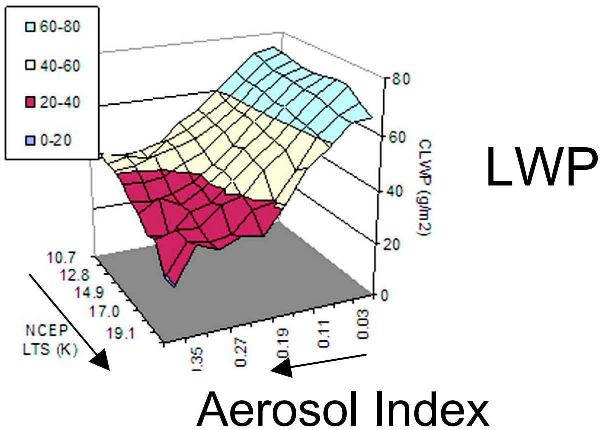


Han et al. 2002: ISCPP Data

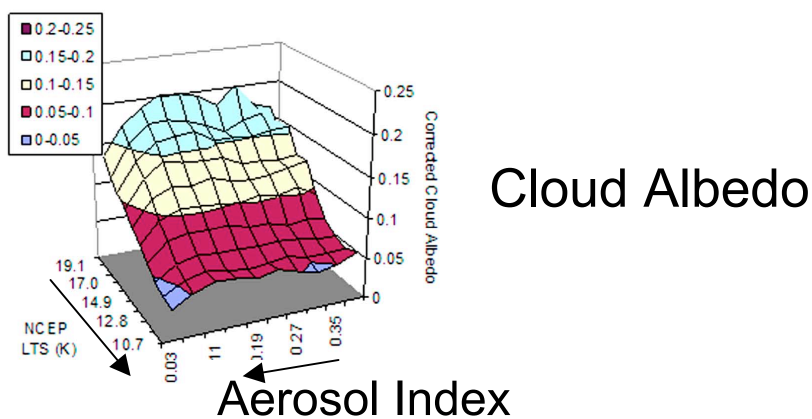
Global low cloud satellite measurements and reanalysis



Drop size decreases with aerosol



LWP <u>decreases</u> with aerosol



Albedo ~ constant
(competing effects)

Matsui et al. 2006

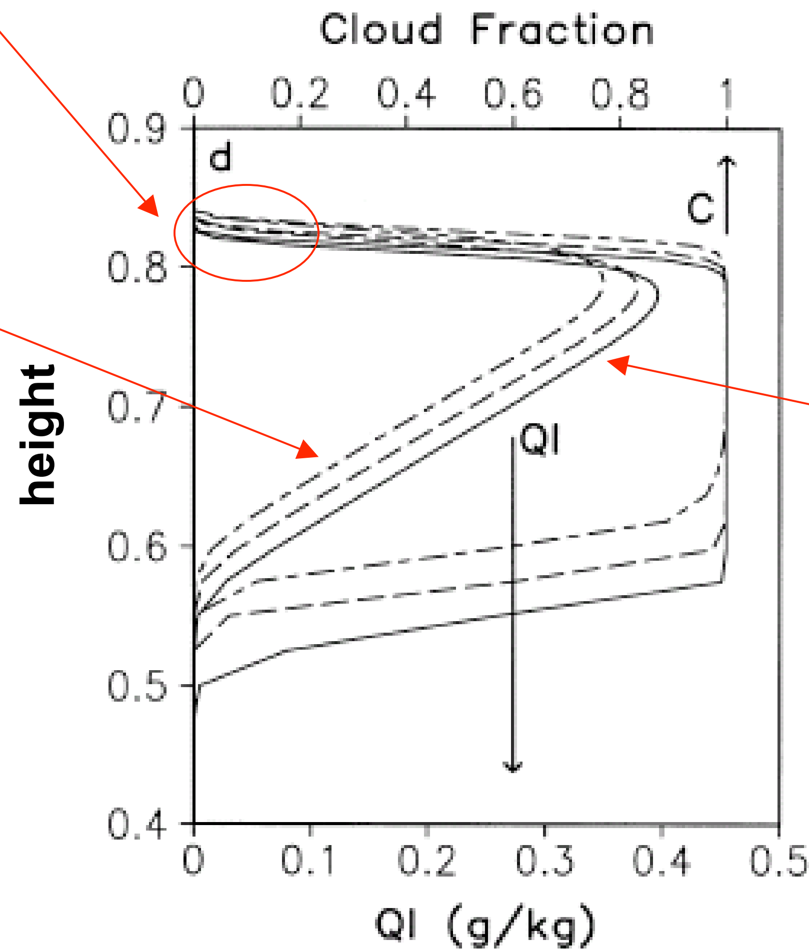
Correlation ≠ Cause-and-effect

Can we use models to understand the mechanisms

Modeling of Aerosol effects on stratocumulus in LES

Pollution elevates cloud tops

polluted



LWC

clean

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

Evaporation rates

Small droplets evaporate faster than large ones

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

Timescale for condensation/evaporation:

$$\tau_{c/e} \propto \left[\int r n(r) dr\right]^{-1} \propto 1/(N\bar{r})$$

$$\left.\begin{array}{l}\text{E.g., polluted case, } N = 1000\ \text{cm}^{-3};\ r = 5\ \mu\text{m} \\ \qquad\quad \text{clean case, } N = 100\ \text{cm}^{-3};\ r = 10\ \mu\text{m}\end{array}\right\} \quad \frac{\tau_{c/e}\,(\text{clean})}{\tau_{c/e}\,(\text{polluted})} = 5$$

Evaporation vs Mixing vs Sedimentation

$$\tau_{c/e} \sim \left(\int r n(r) dr\right)^{-1}$$

Evaporation (phase relaxation time)

$$\tau_{mix} = \left(\frac{L^2}{\varepsilon}\right)^{1/3}$$

mixing

$$\tau_{sed} = L / v_r$$

sedimentation

$$v_r = \int v(r) n(r) dr / N$$

Drop fall velocity

Pollution suppresses collision-coalescence

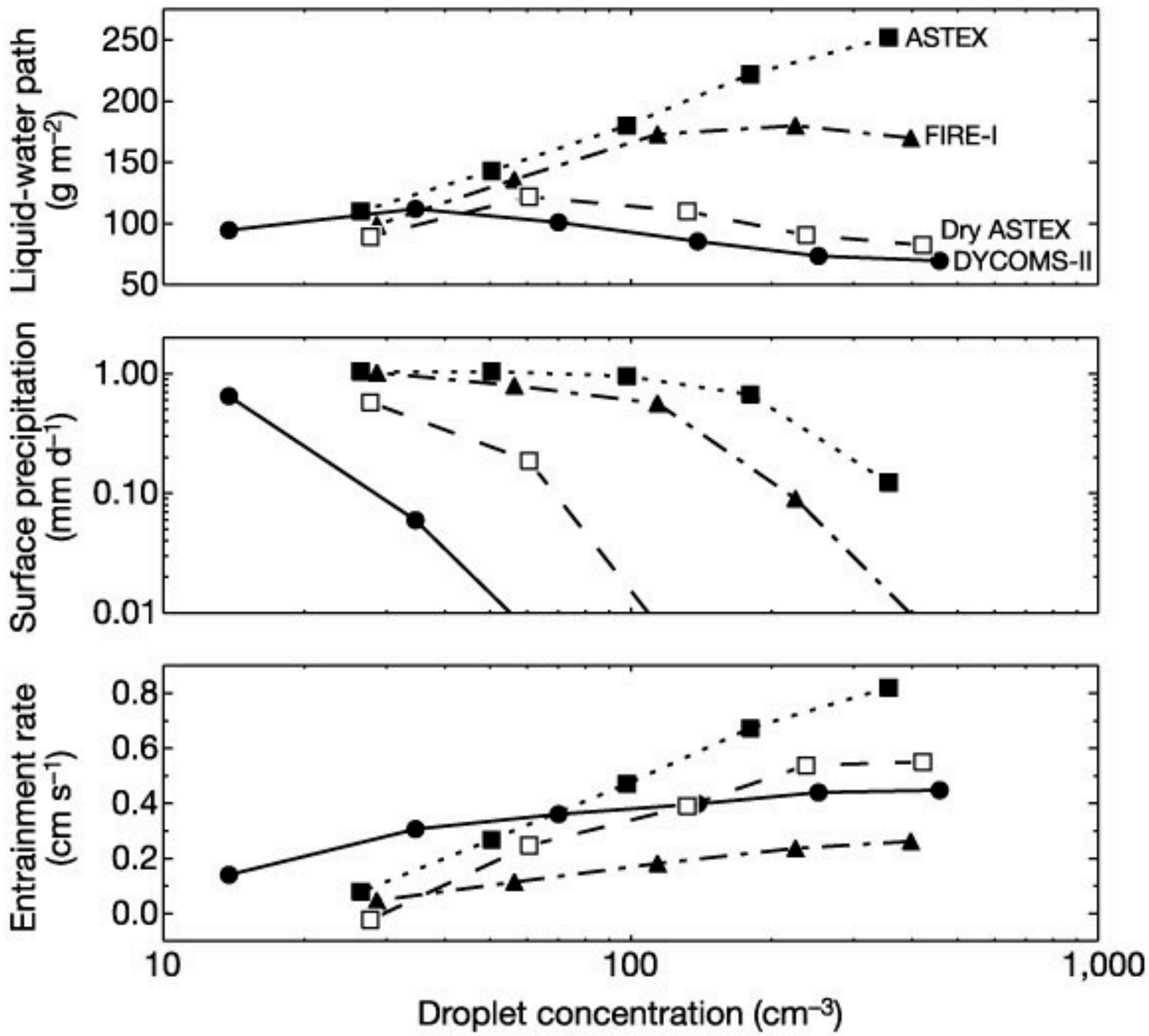
-

Pollution reduces fall velocities

-

Pollution enhances evaporation

Humidity of air above stratocumulus is important



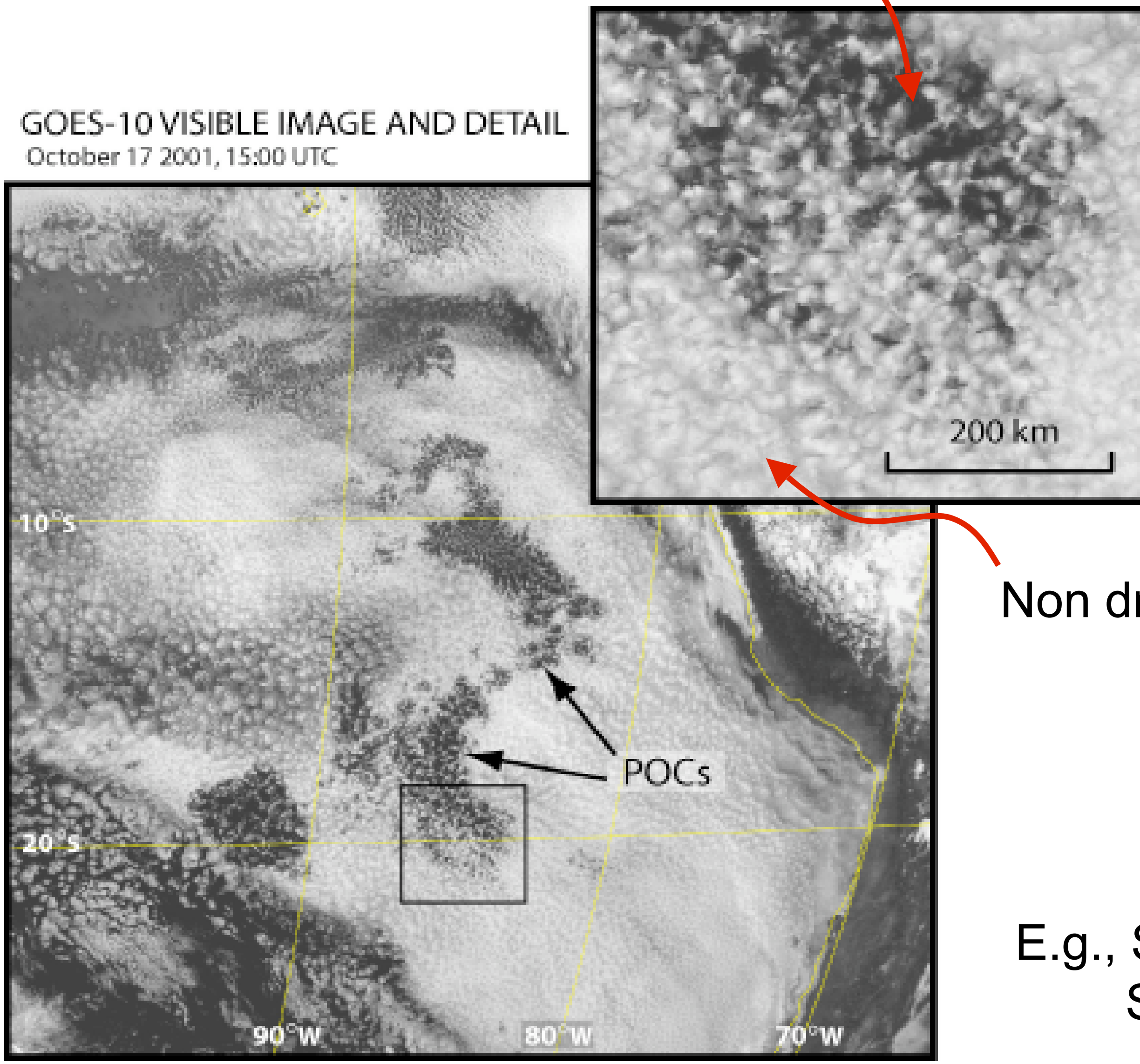
$$\frac{dLWP}{dN_d} \begin{matrix} >0 \\ <0 \end{matrix} ?$$

LWP = liquid water path

Ackerman et al. 2004

2. Precipitation in warm boundary layer clouds: Aerosol-cloud-precipitation-dynamical feedbacks

Drizzling patches: open cells
(POCS; pockets of open cells)

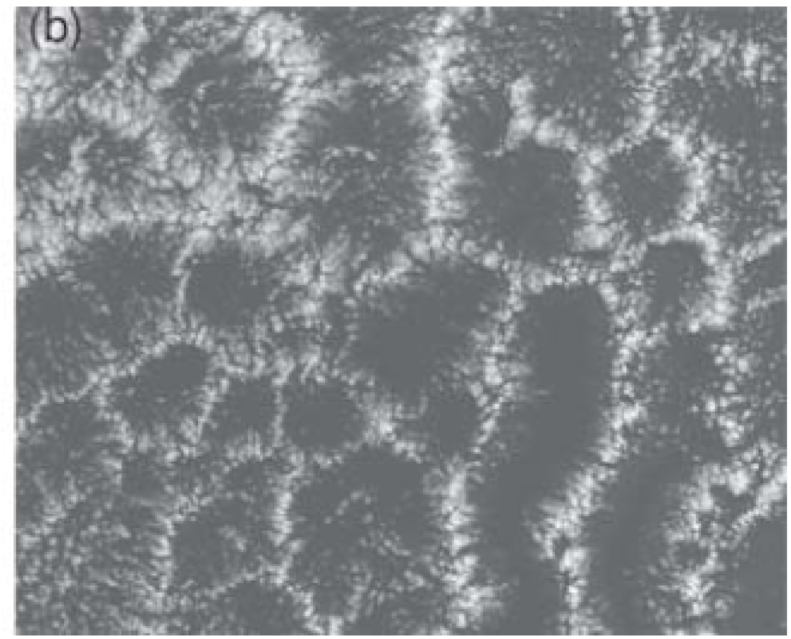


Non drizzling closed cells

E.g., Stevens et al. 2005
Sharon et al. 2006

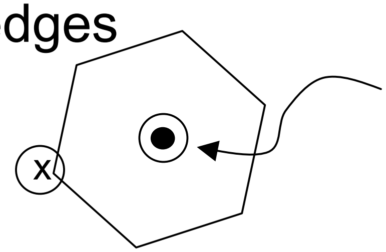
Self Organization of Clouds

Closed cell convection
98W, 15S



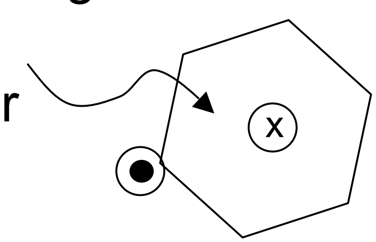
Open cell convection
30S, 0E

Descending motion around edges



Ascending motion in center

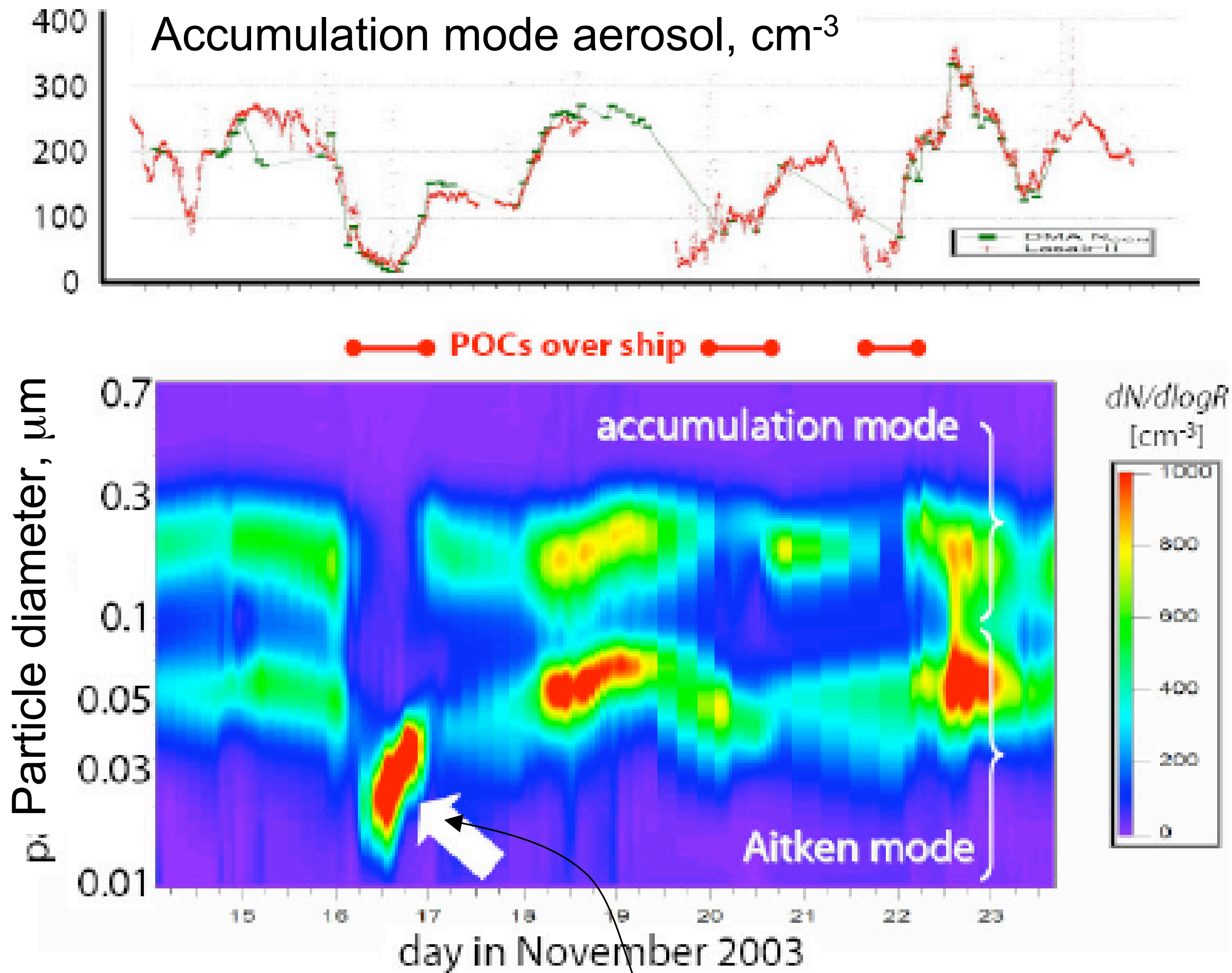
Descending motion in center



Ascending motion around edges

MISR images: Garay et al. 2004

Nucleation of New particles in Clean Open Cell Regions

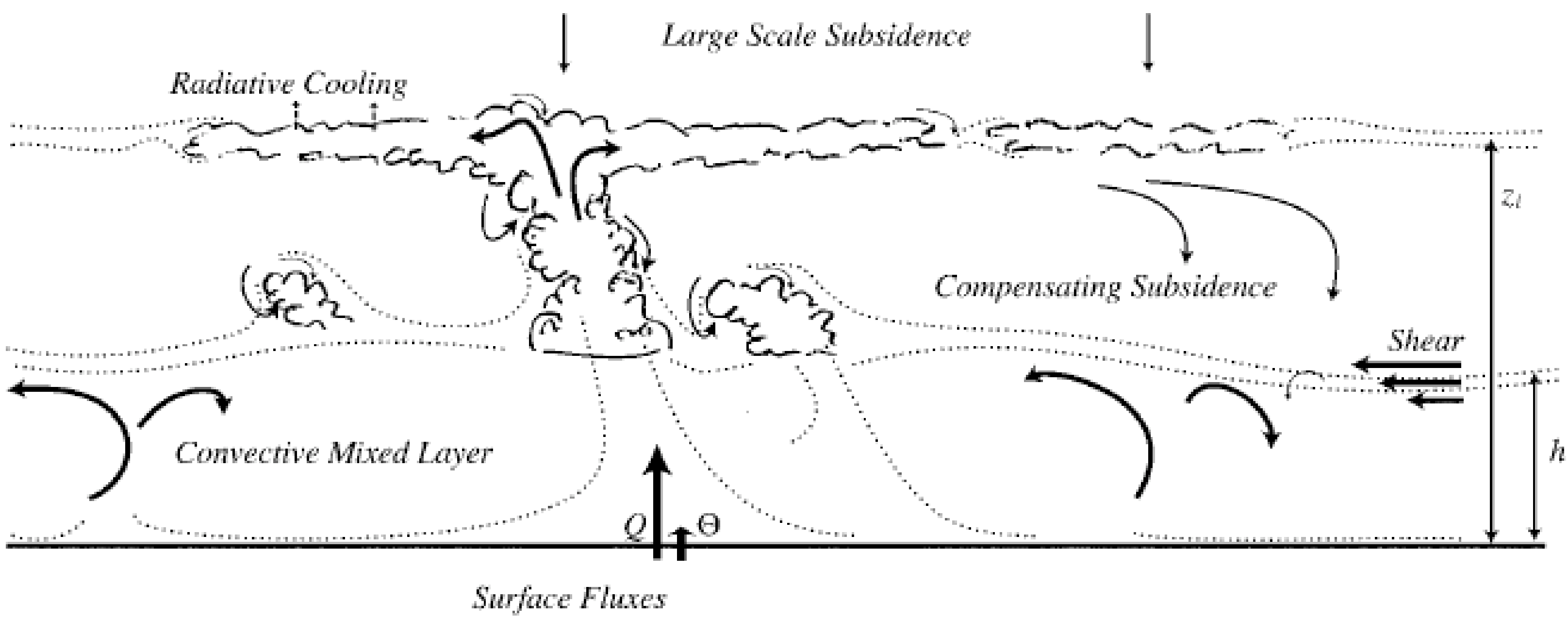


Nucleation of new particles

Kollias et al. 2004

Large Eddy Simulations

- Atlantic Trade Wind Experiment (ATEX, 1969) sounding
- Cumulus penetrating into stratus
- GCSS intercomparison case



Bjorn Stevens

Numerical Model

Large Eddy Simulation (LES)

Bin-microphysics: activation, condensation, collision-coalescence, and sedimentation

Fixed surface fluxes

Radiation: simple function of LWP

Domain size: 12.4 km × 12.4 km × 3.0 km

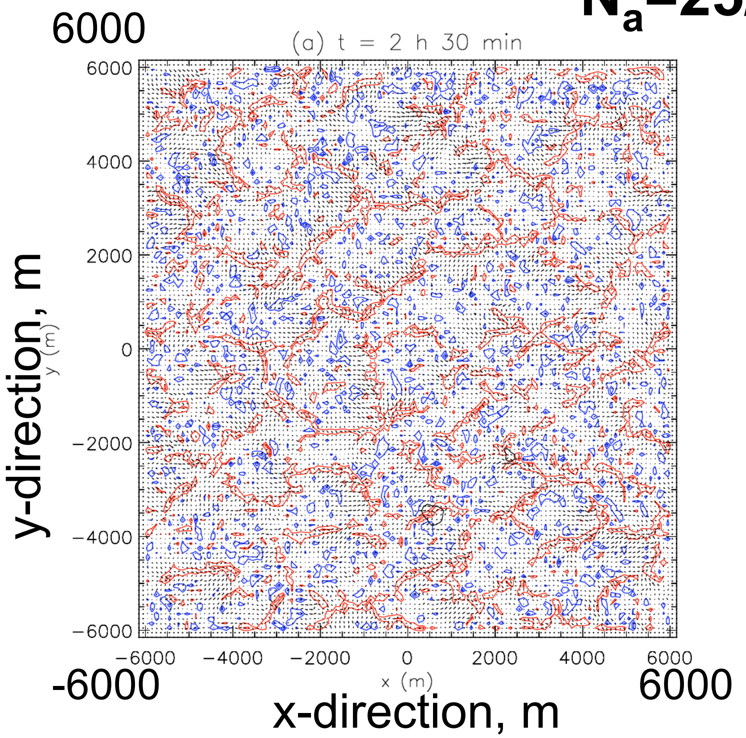
Grid size: $\Delta x = \Delta y = 100$ m, $\Delta z = 20$ m

Time step : $\Delta t = 1$ s

Range of Aerosol inputs: clean (25/cc) to extremely polluted (2000/cc)

(25, 50, 100, 500, 2000/cc)

N_a=25/cc - precipitating

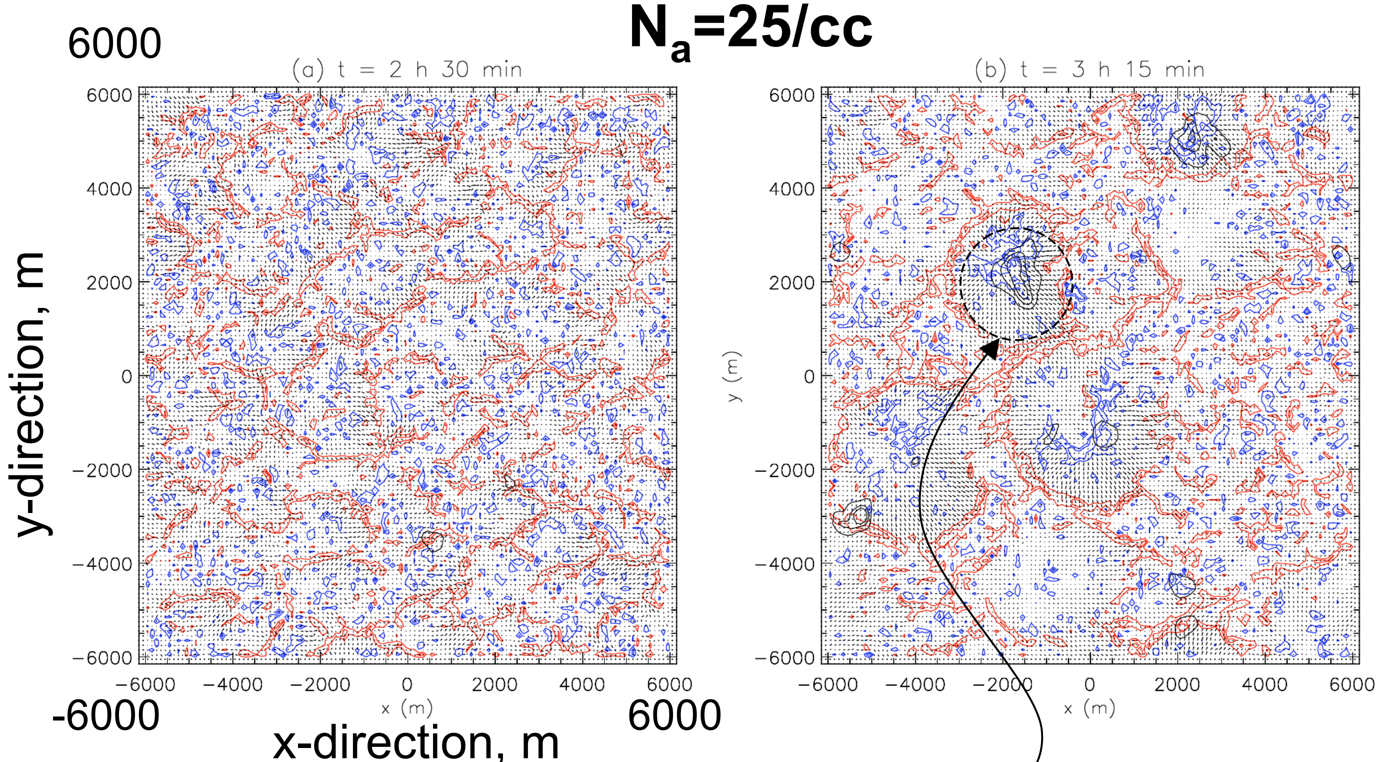


Red: convergence (surface)
Blue: divergence (surface)
Black: surface rainrate

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

Xue, Feingold, Stevens, JAS 2007, in press

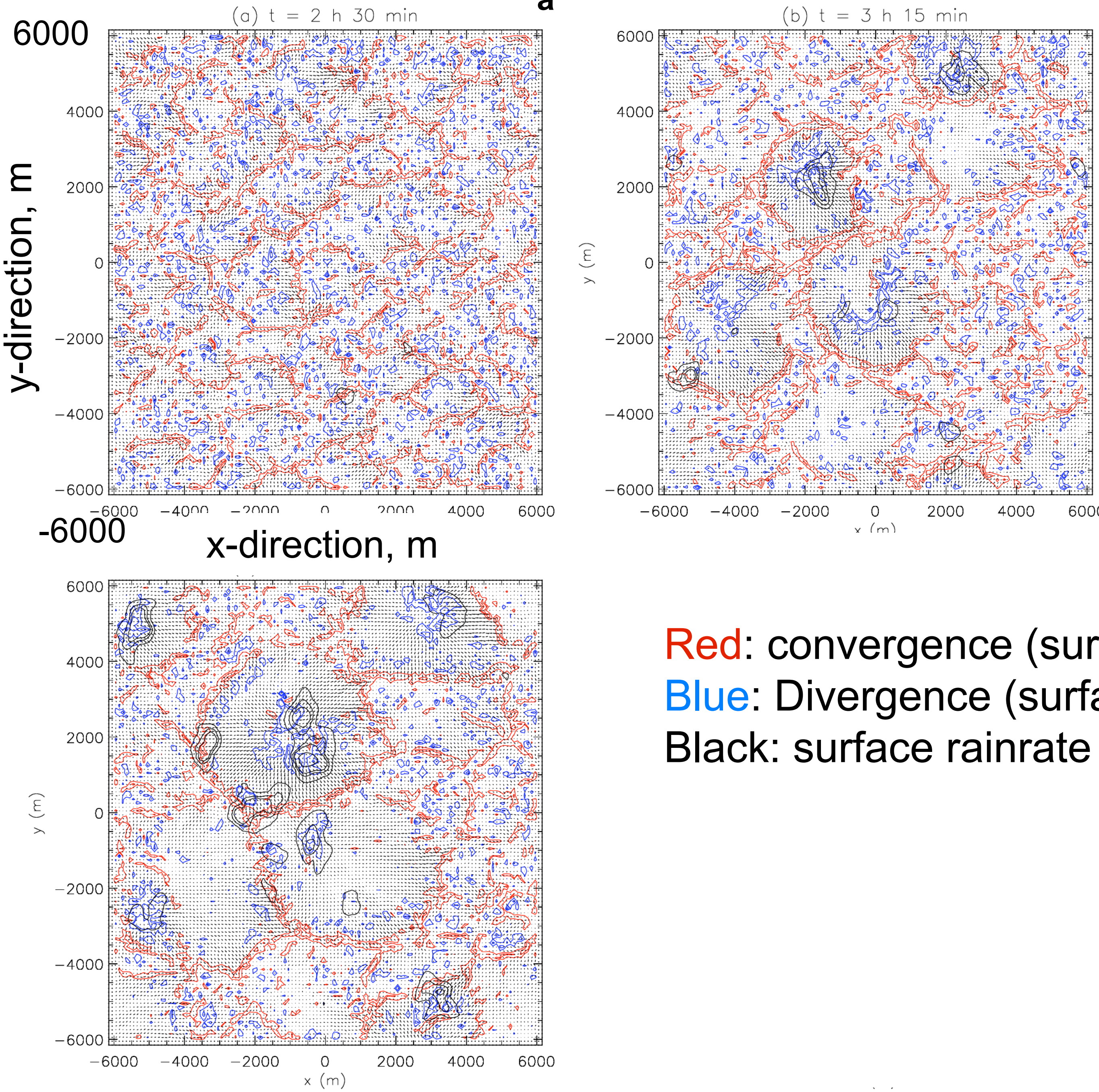
N_a=25/cc



Red: convergence (surface)
Blue: Divergence (surface)
Black: surface rainrate

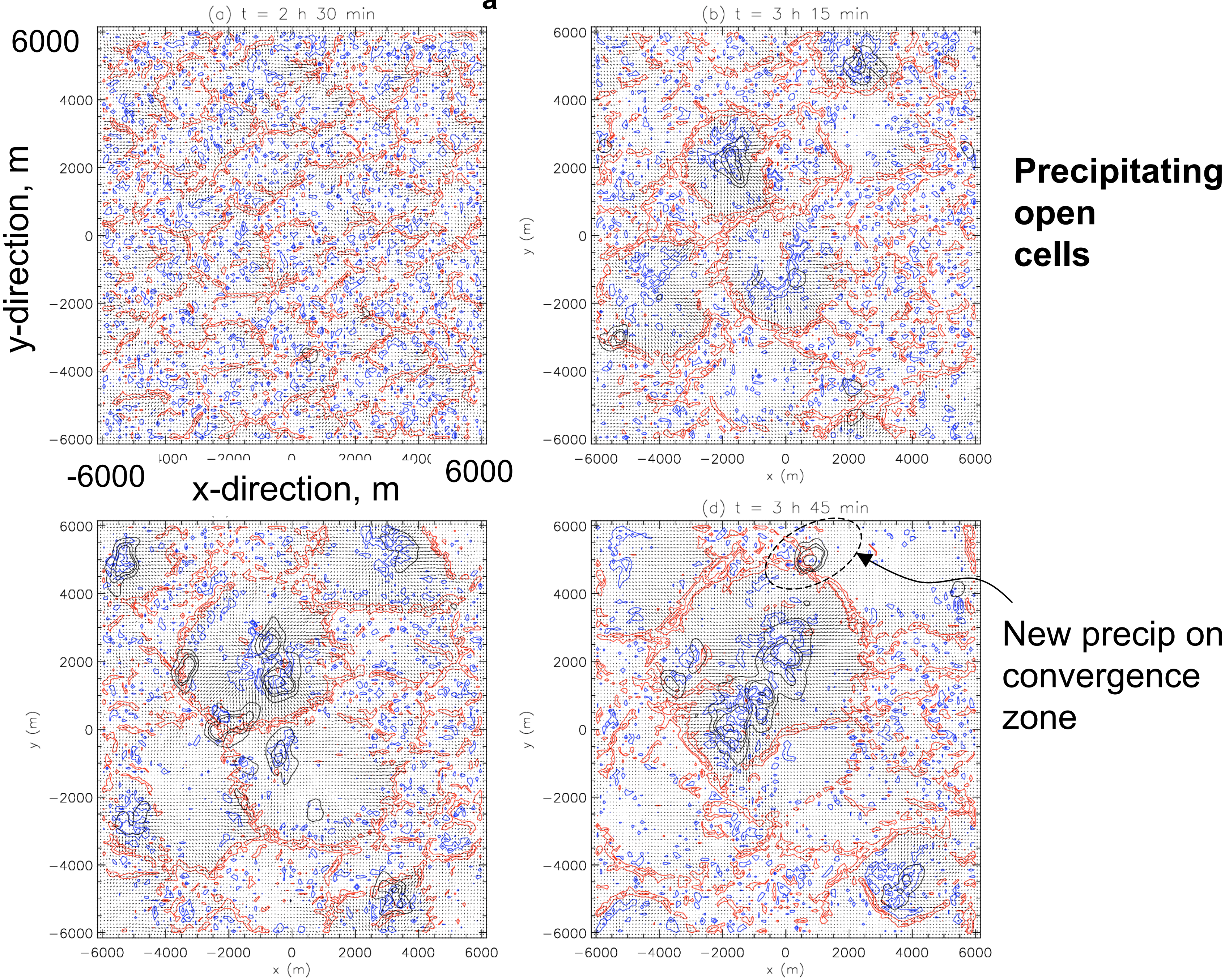
Precip in centre of cell generating downdraught and divergence

N_a=25/cc



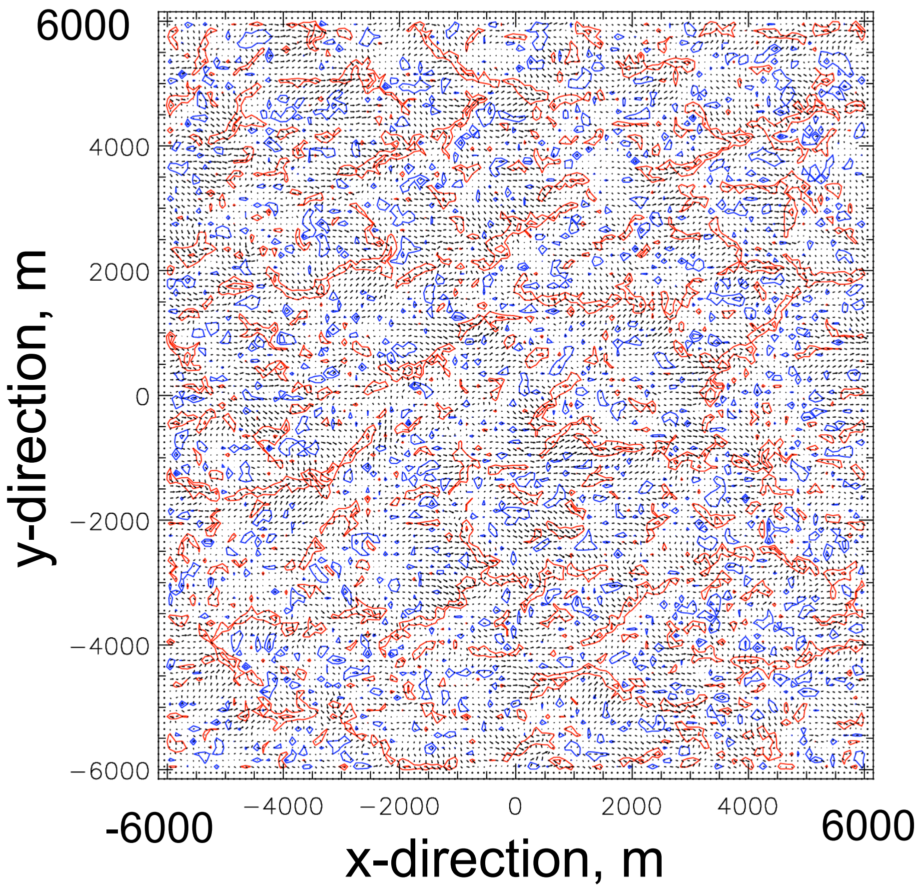
Red: convergence (surface)
Blue: Divergence (surface)
Black: surface rainrate

N_a=25/cc



(a) t = 2 h 30 min
(b) t = 3 h 15 min
(d) t = 3 h 45 min
6000
-6000
y-direction, m
x-direction, m
y (m)
x (m)
Precipitating
open
cells
New precip on
convergence
zone

N_a=100/cc (non precipitating)

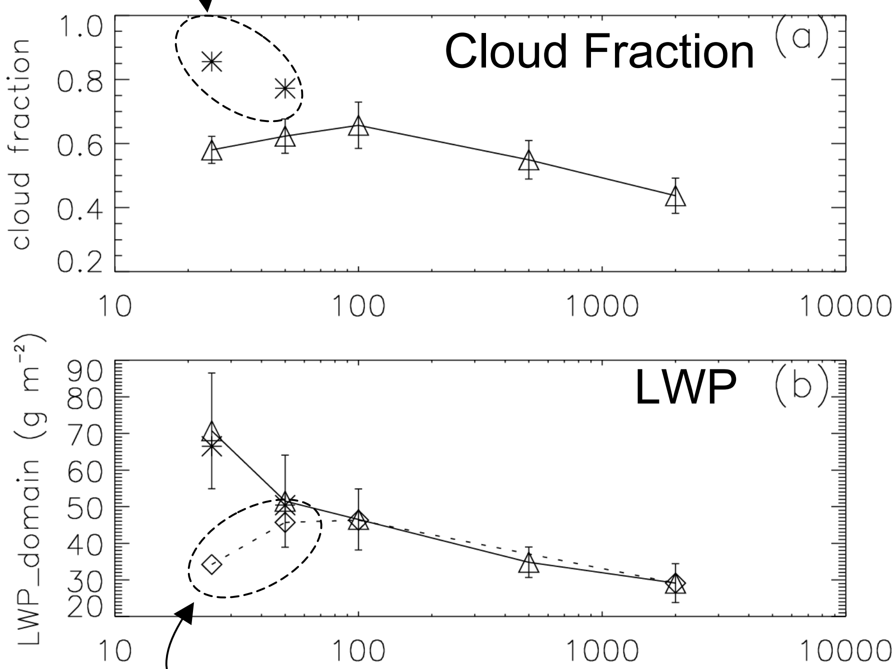


~ no evolution with time
no cellular structure

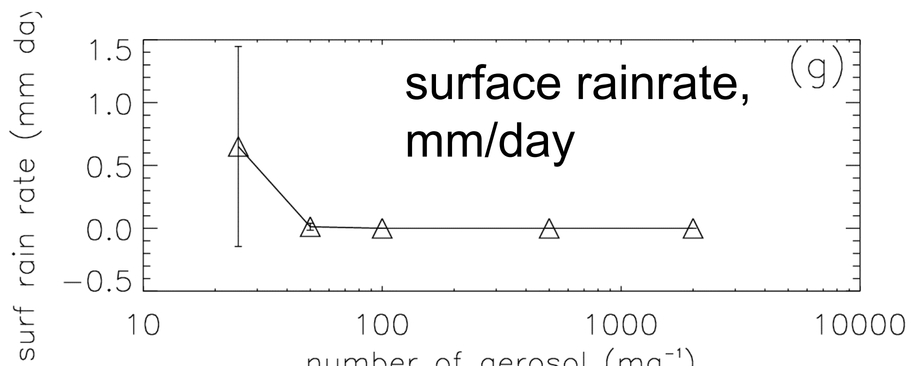
Xue, Feingold, Stevens, JAS 2007, in press

Closed cell convection

No precip allowed

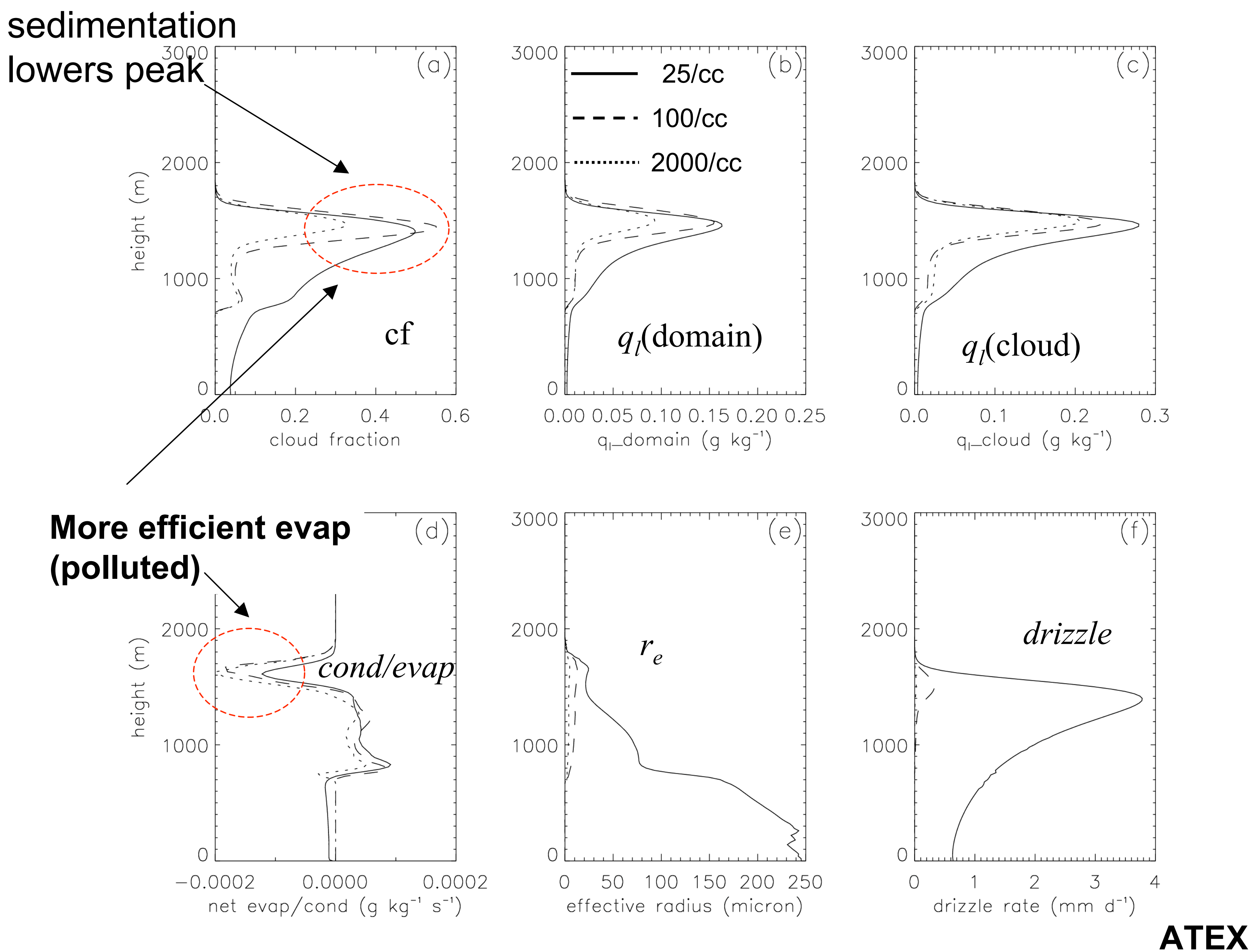


Number of aerosol, mg^{-1}



Only count cloud drops (exclude rain drops)

$\tau_{sed} > \tau_{evap}$



sedimentation
lowers peak
More efficient evap
(polluted)
25/cc
100/cc
2000/cc
(a)
cf
cloud fraction
height (m)
(b)
q_l(domain)
q_l_domain (g kg^{-1})
(c)
q_l(cloud)
q_l_cloud (g kg^{-1})
(d)
cond/evap
net evap/cond (g kg^{-1} s^{-1})
(e)
r_e
effective radius (micron)
(f)
drizzle
drizzle rate (mm d^{-1})
ATEX

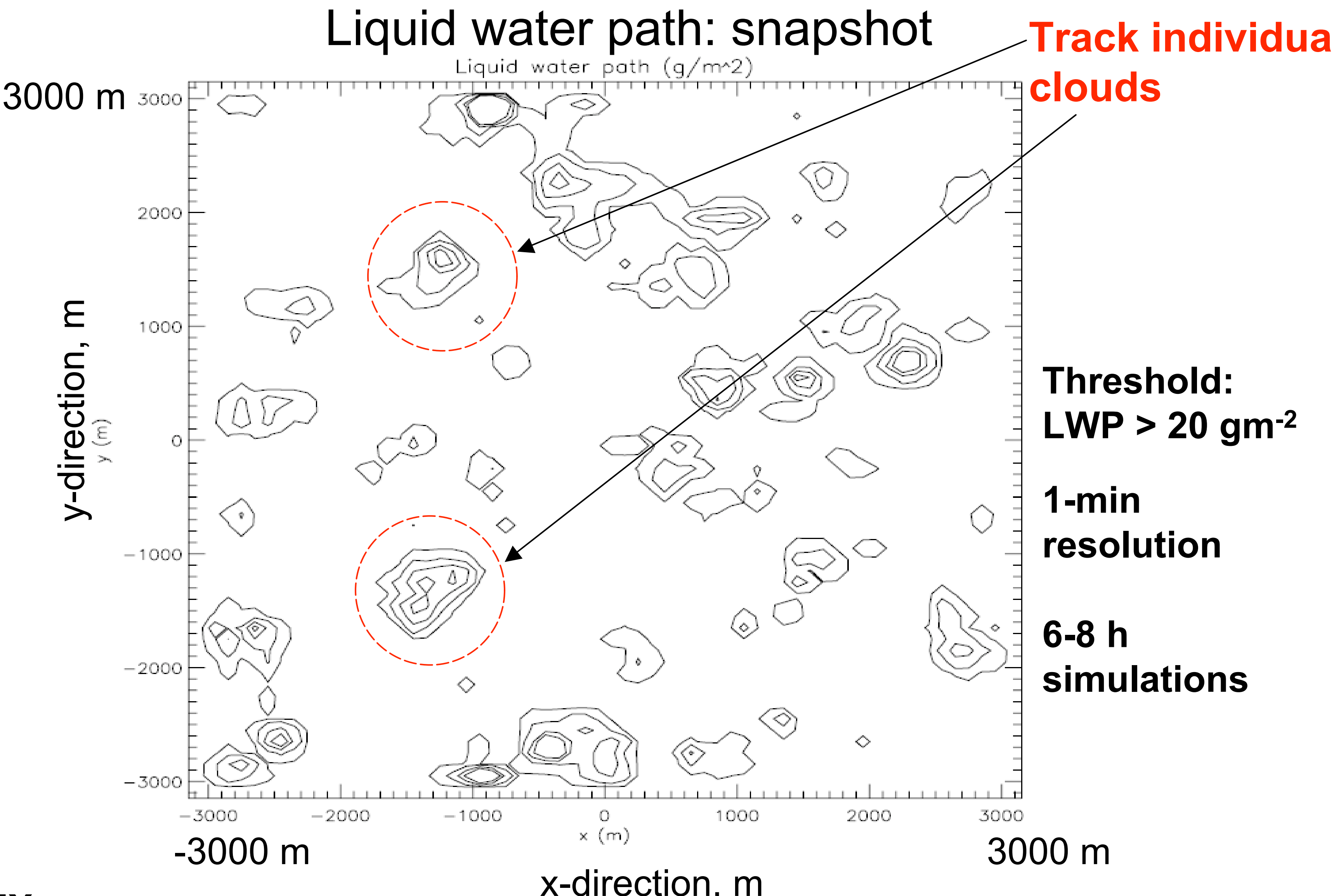
3. Aerosol Effects on Cloud Lifetime

Houston, Aug/Sept 2006: Photo from CIRPAS Twin Otter (Mike Hubbell)

Modeling Aerosol Effects on the Lifetime of Warm Cumulus

Model	Domain	Resolution	Δt; T	Other
RAMS-LES (NOAA) 3-D	6.4 x 6.4 km	100 x100 x 50m	2s; 8h	- Bin μphysics - surface model - radiation (cloud/ aerosol) **SMOCC continental sounding (Brazil)**
UCLA-LES 3-D	6.4 x 6.4 km	100 x100 x 40m	1.5s; 6h	- Bin μphysics - Simple surface/ radiation models **BOMEX Trade-Cu sounding**
Tel Aviv Univ. 2D; x,z		40 x 40 m	2s; 1.5h	- Single cloud - Bin μphysics **BOMEX, Kogan, Med. Sea soundings**

Analysis of Cloud Lifetimes (LES)



Threshold: LWP > 20 gm^{-2}

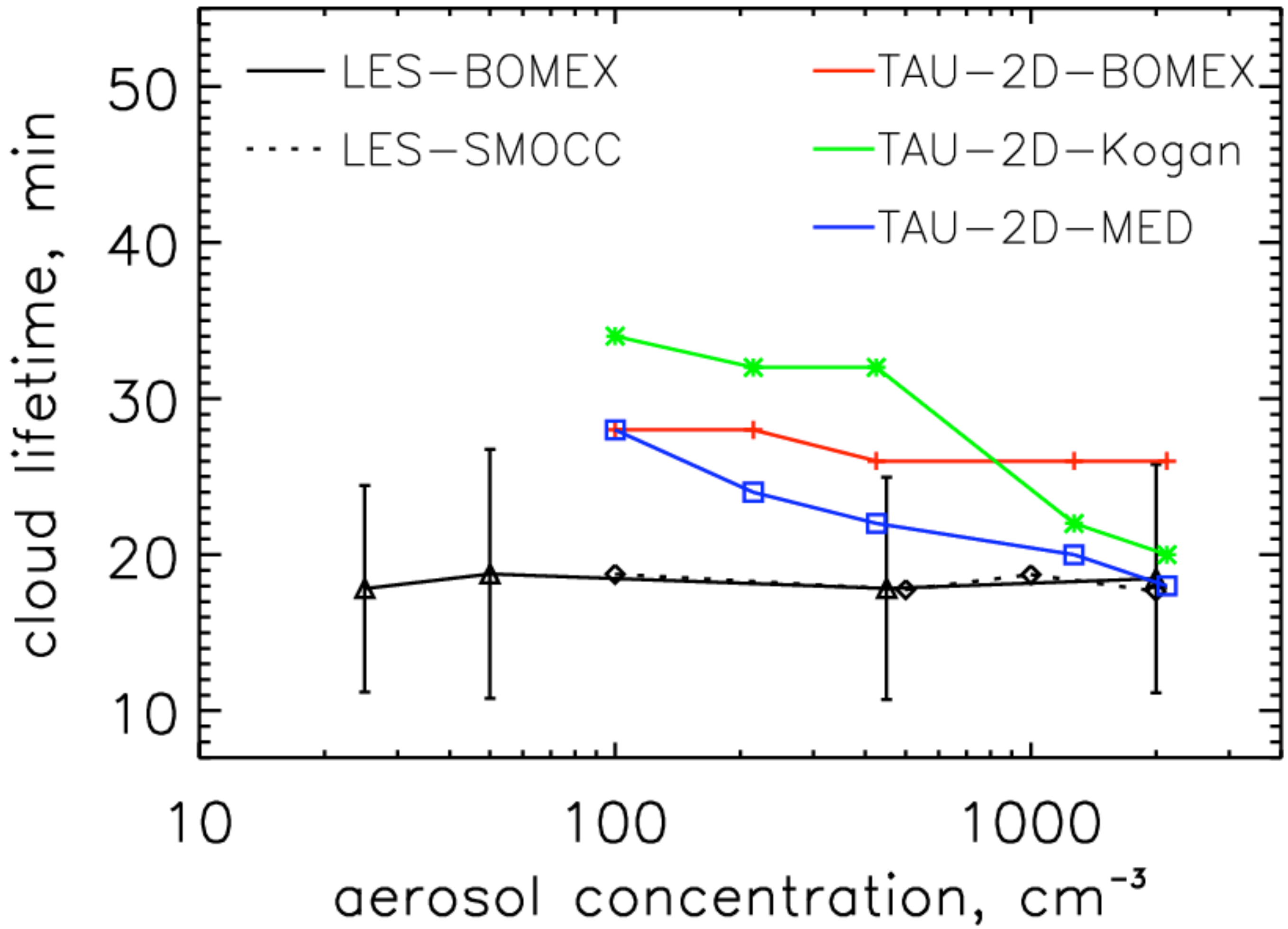
1-min resolution

6-8 h simulations

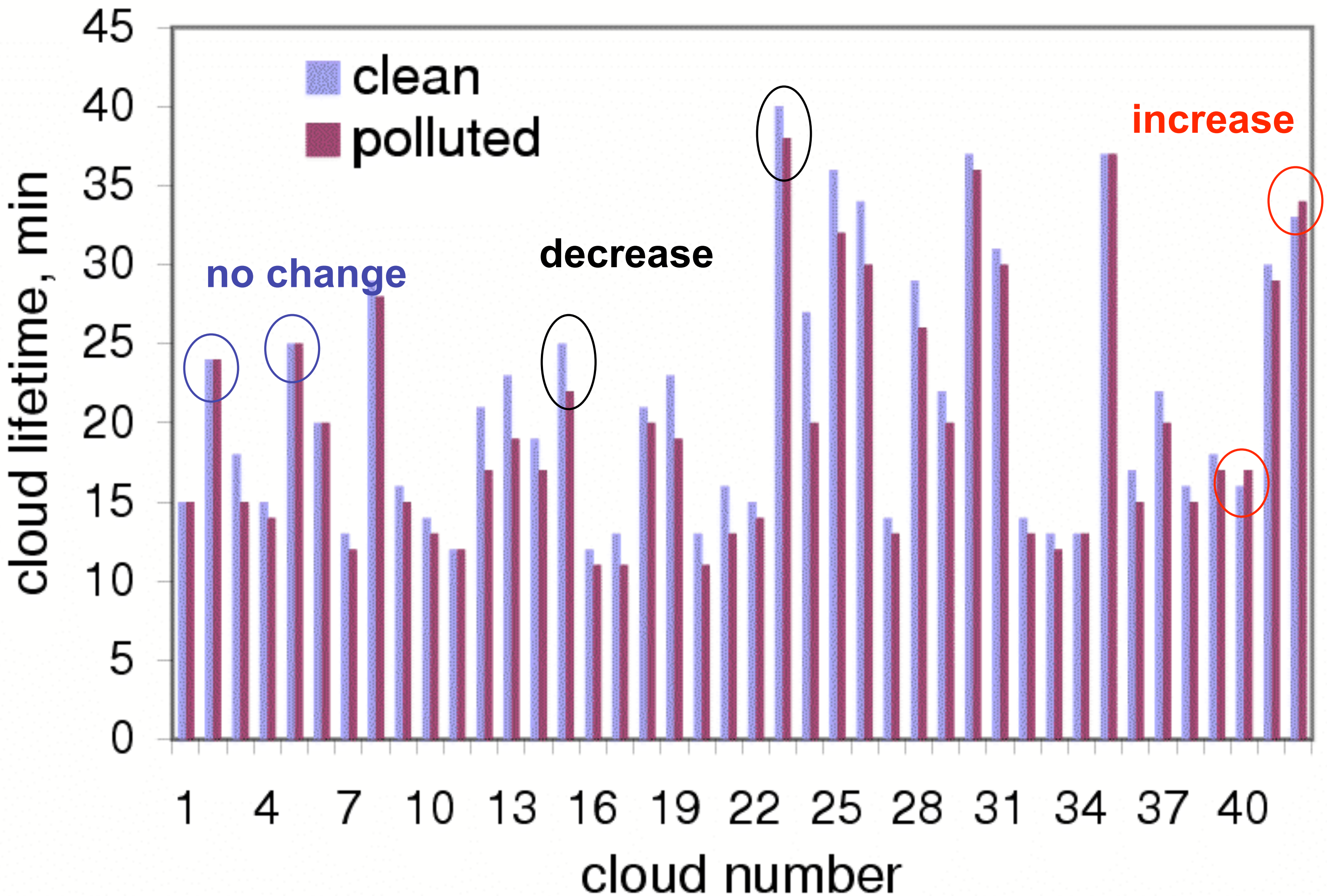
BOMEX

Aerosol Effects on Cloud Lifetime

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



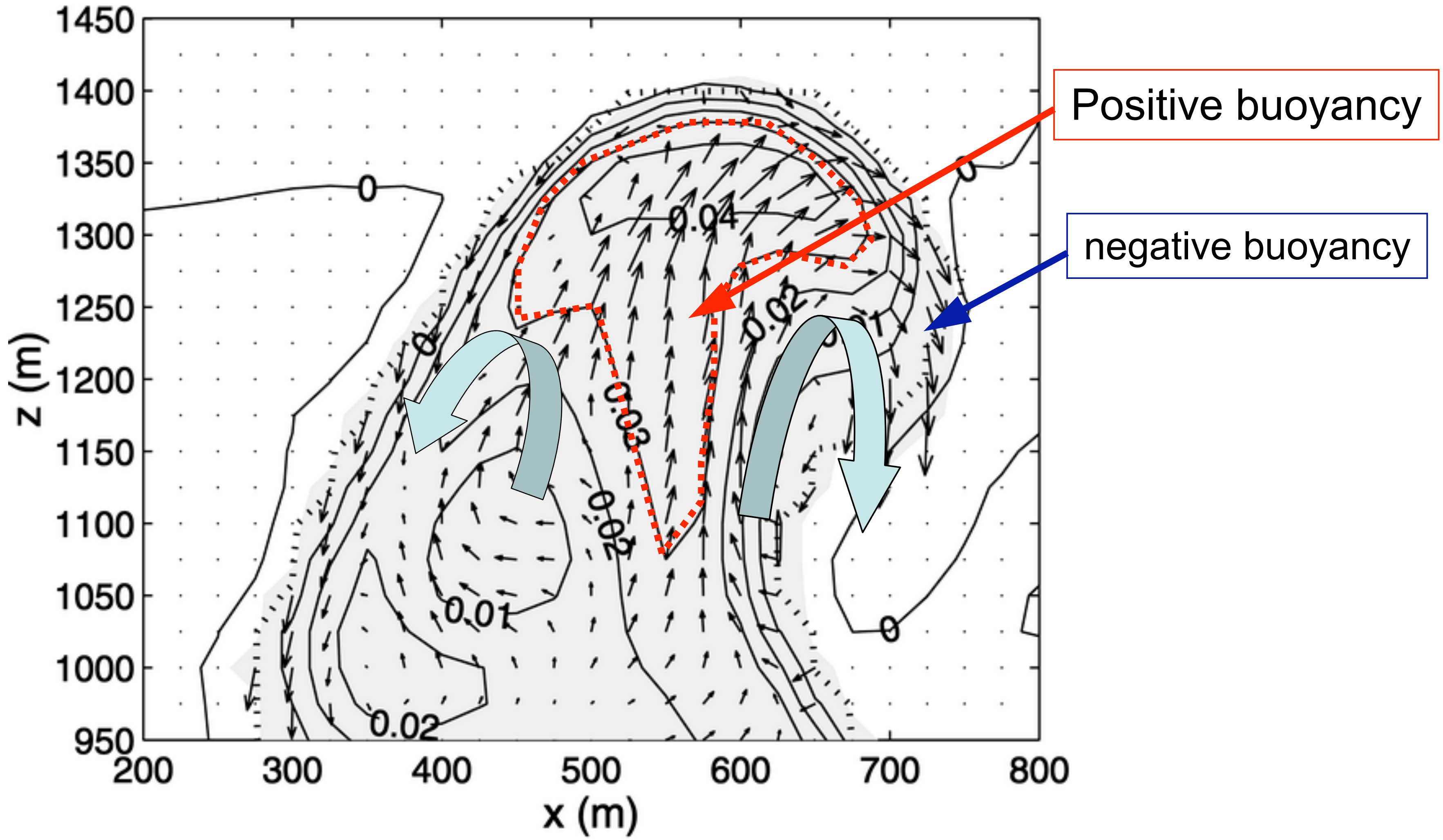
Jiang, Xue, Teller, Feingold, Levin: GRL 2006



LES simulations spawned from common dynamical point at 2-h
BOMEX Trade Cumulus clouds

Buoyancy gradient and entrainment

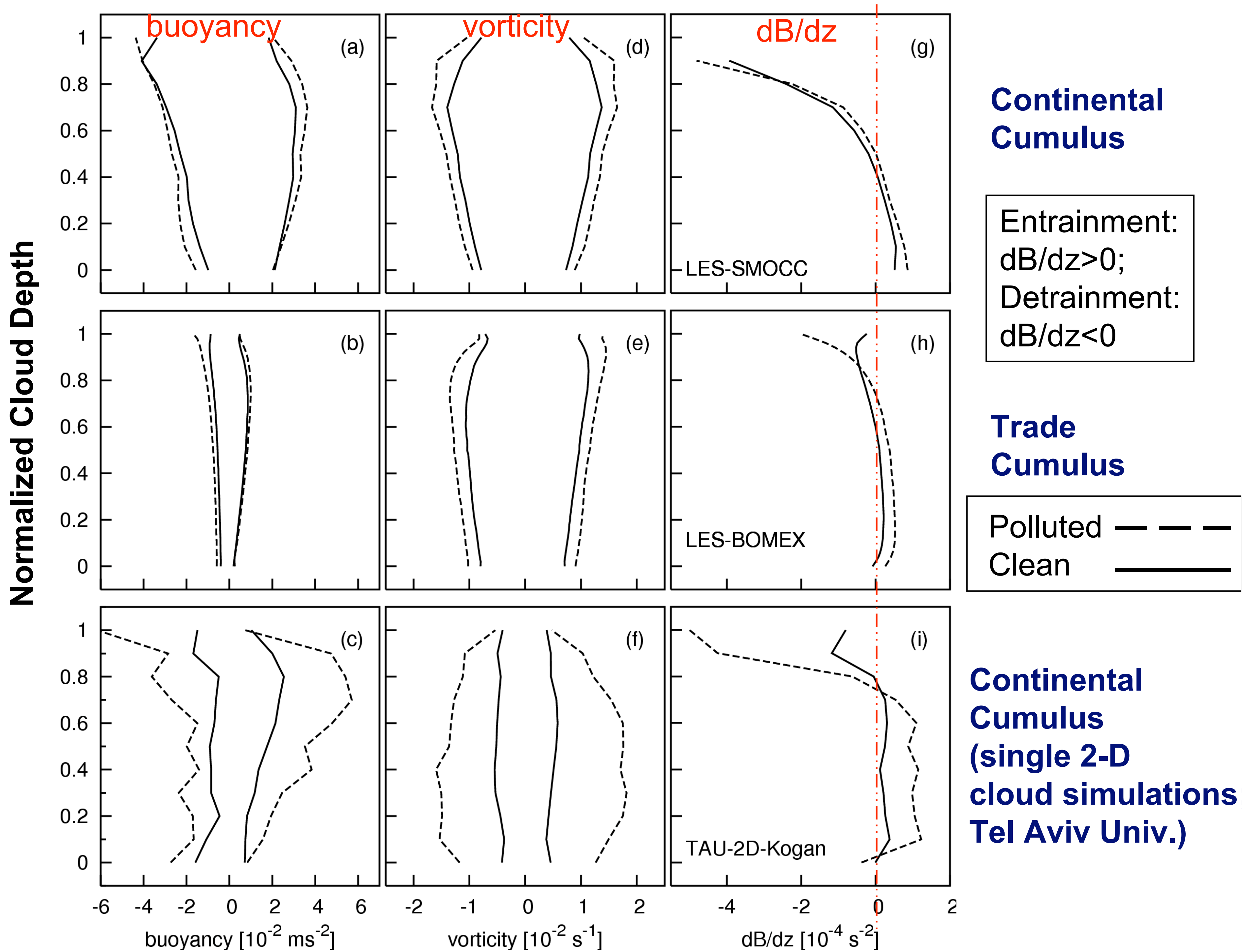
Contours: buoyancy
Arrows: wind vectors



Strength of horizontal buoyancy gradient contributes to vorticity.

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

Zhao and Austin 2005
LES output

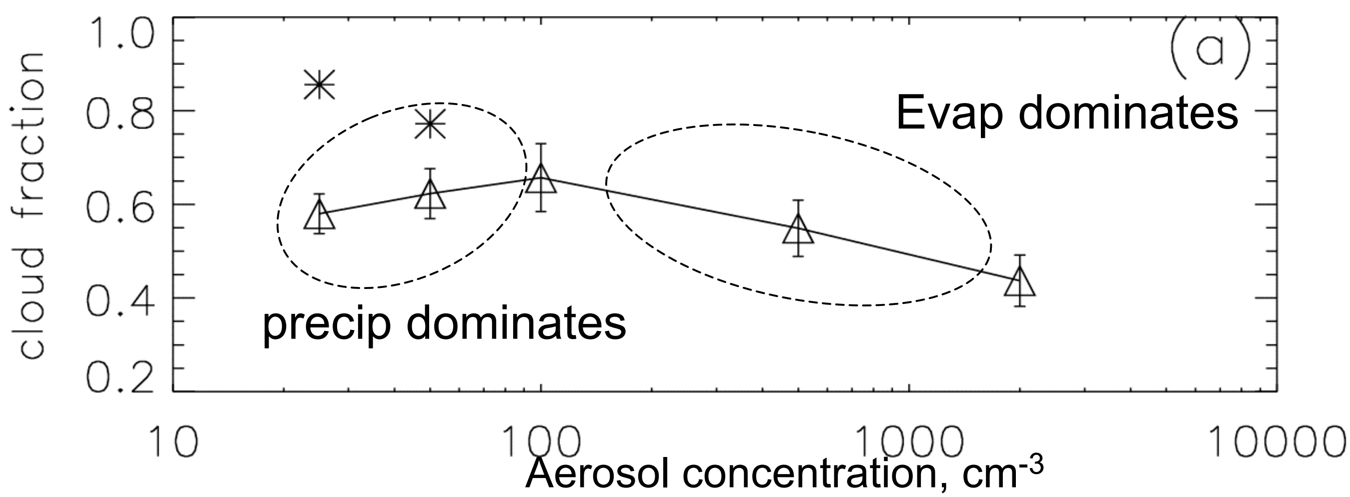


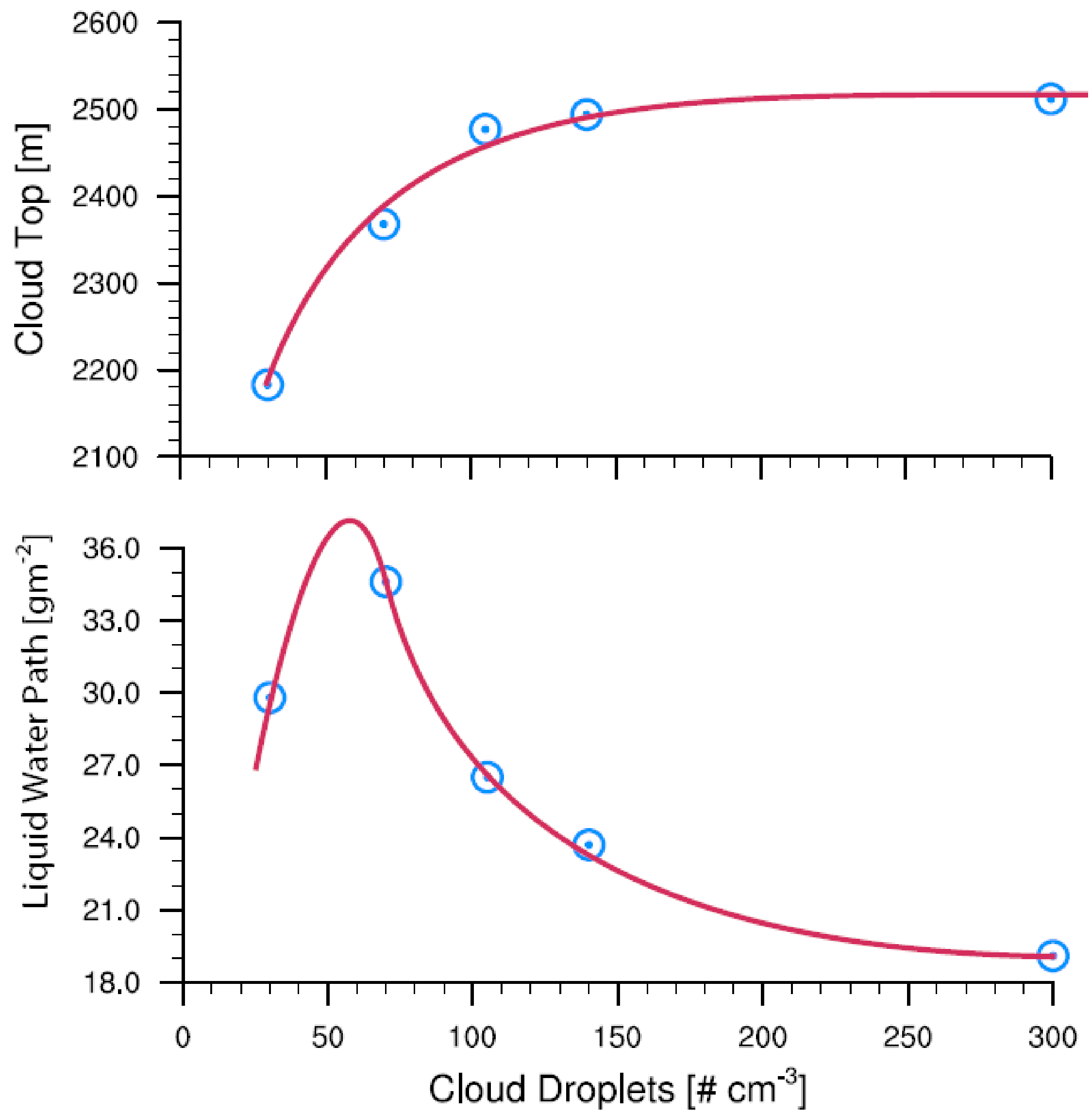
buoyancy
vorticity
dB/dz
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
LES-SMOCC
LES-BOMEX
TAU-2D-Kogan
Normalized Cloud Depth
buoyancy [10^-2 ms^-2]
vorticity [10^-2 s^-1]
dB/dz [10^-4 s^-2]
Continental Cumulus
Entrainment: dB/dz>0;
Detrainment: dB/dz<0
Trade Cumulus
Polluted
Clean
Continental Cumulus (single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

More aerosol → more drops → <u>less coalescence</u>→ less rain

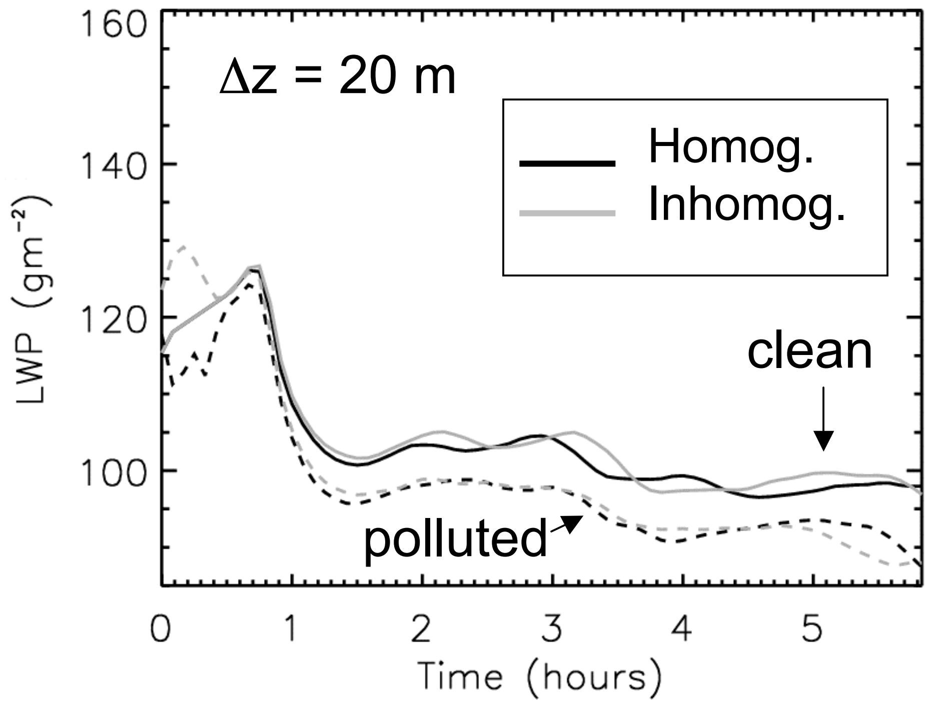
vs.

More aerosol → more drops → smaller drops → <u>more efficient evaporation</u>



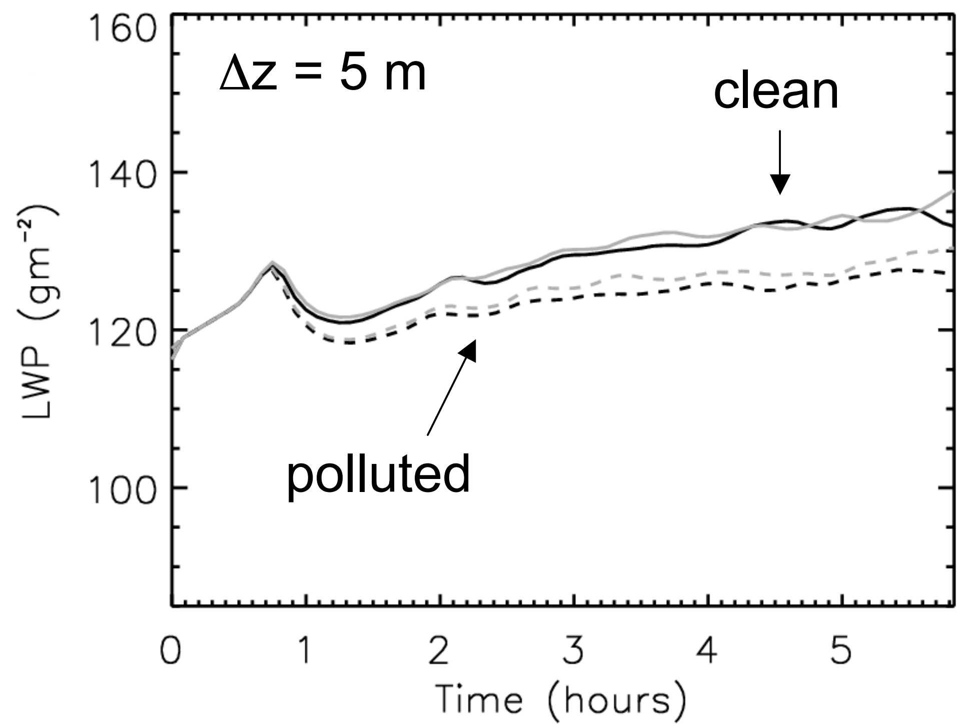


Stevens and Seifert: RICO case study, LES + two moment bulk microphysics



Reduction in LWP robust to changes in
- resolution
- mixing scenario (homog vs. inhomog.)

Stratocumulus simulations (non precipitating)



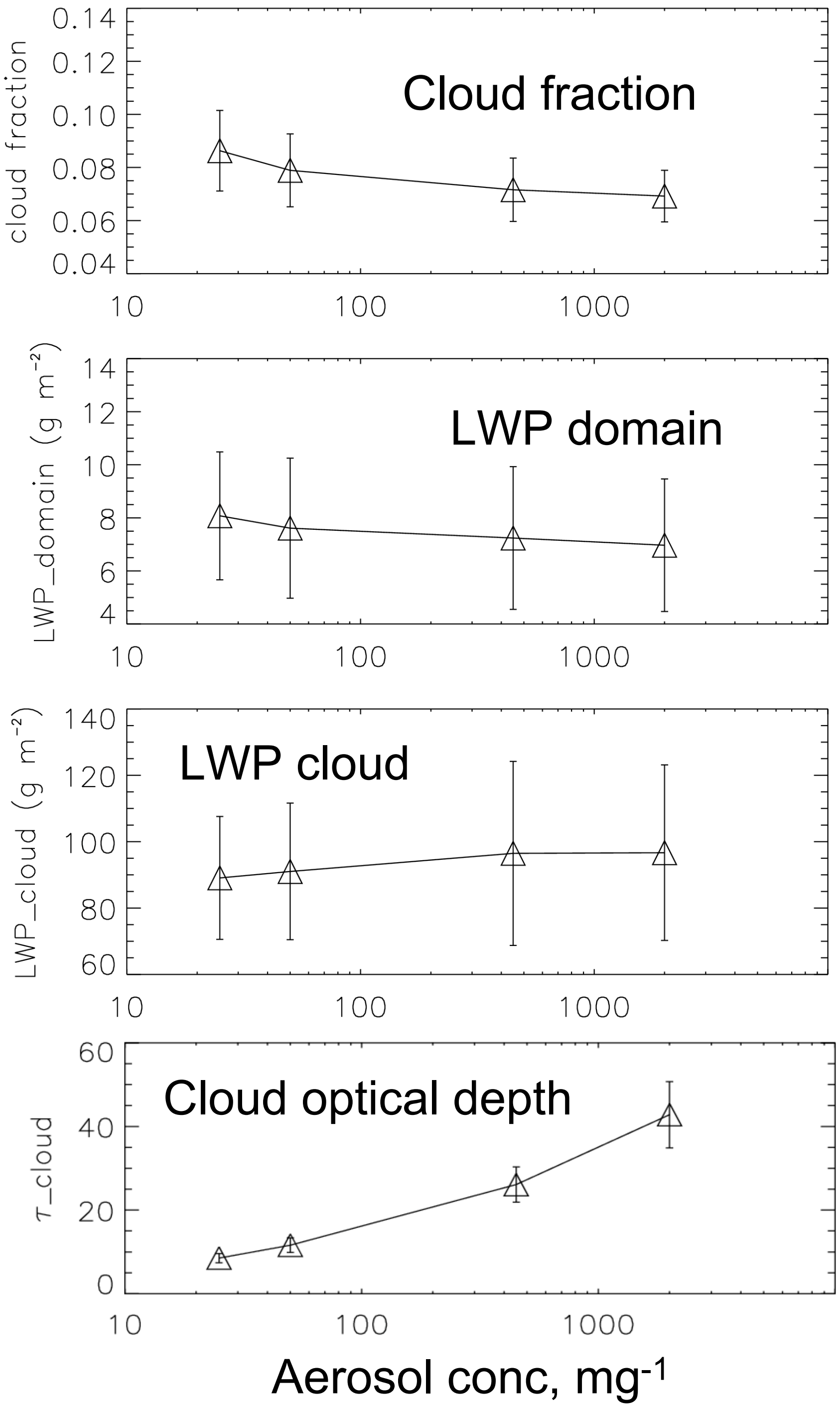
Hill, Feingold, Jiang, 2007

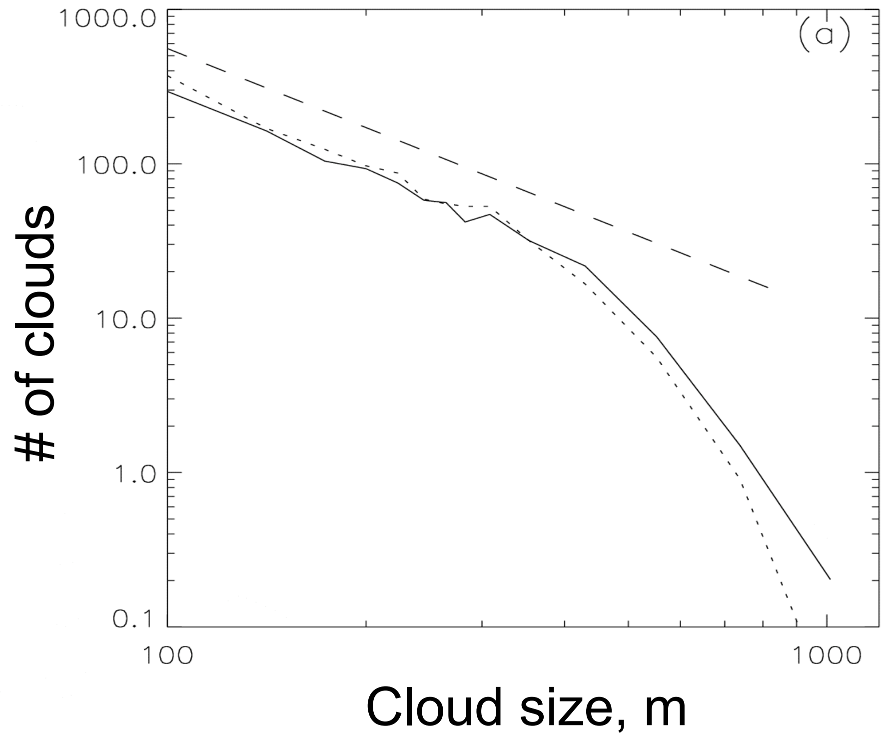
4. Aerosol Effects on Cloud Albedo

Cloud brightening vs changes in cloud spatial distribution

Subtext: Aerosol effect on cloud microphysics ≠ Aerosol Indirect effect

BOMEX trade Cumulus simulations





Perform 3-D RTM on modeled cloud fields

Aerosol Effects on Cloud Albedo: Microphysics vs Macroscale

- Aerosol brightens clouds
- Aerosol changes size distribution of clouds
- Aerosol changes cloud fraction

How does the albedo susceptibility respond?

Susceptibility calculations based on 3-D RTM for LES simulated cloud fields

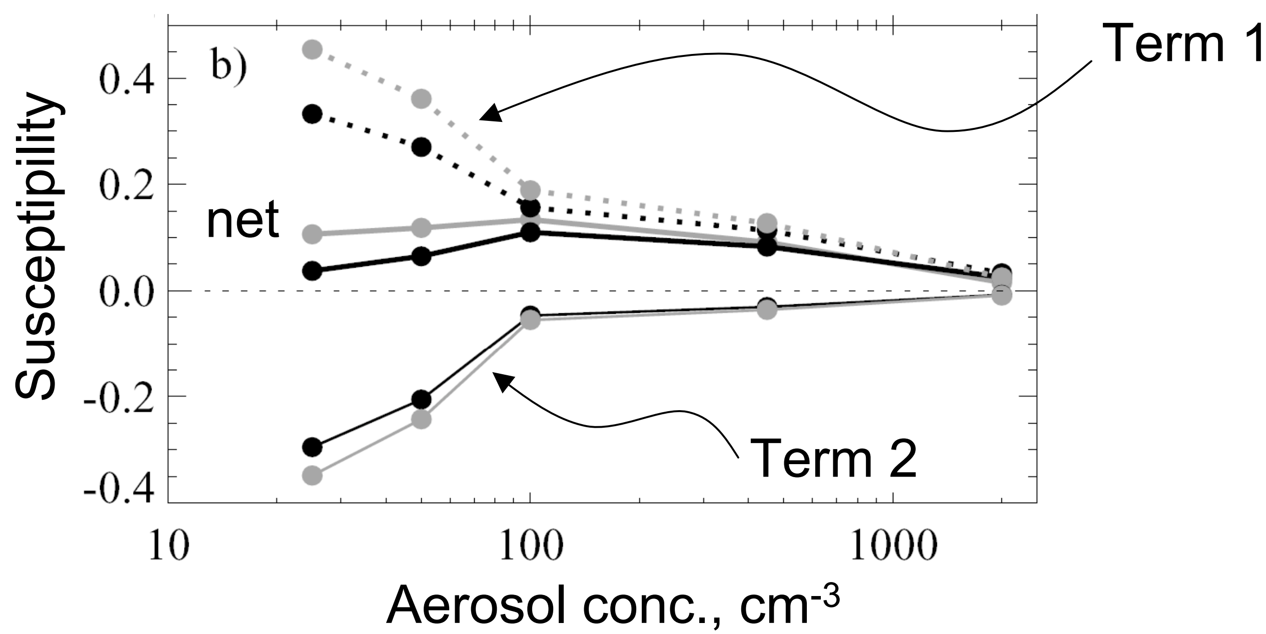
$$A_{dom} = CF \times A_{cld}$$

$$\frac{\partial A_{dom}}{\partial N_d} = \underbrace{\overline{CF}\,\frac{\partial A_{cld}}{\partial N_d}}_{\text{Term 1}} + \underbrace{\overline{A_{cld}}\,\frac{\partial CF}{\partial N_d}}_{\text{Term 2}}$$

$$S_0 = \left.\frac{\partial A_{cld}}{\partial N_d}\right|_{\text{Const LWP}}$$

$$S_0 = \frac{A_{cld}(1 - A_{cld})}{3N_d}$$

Overhead sun, λ =0.64 μm



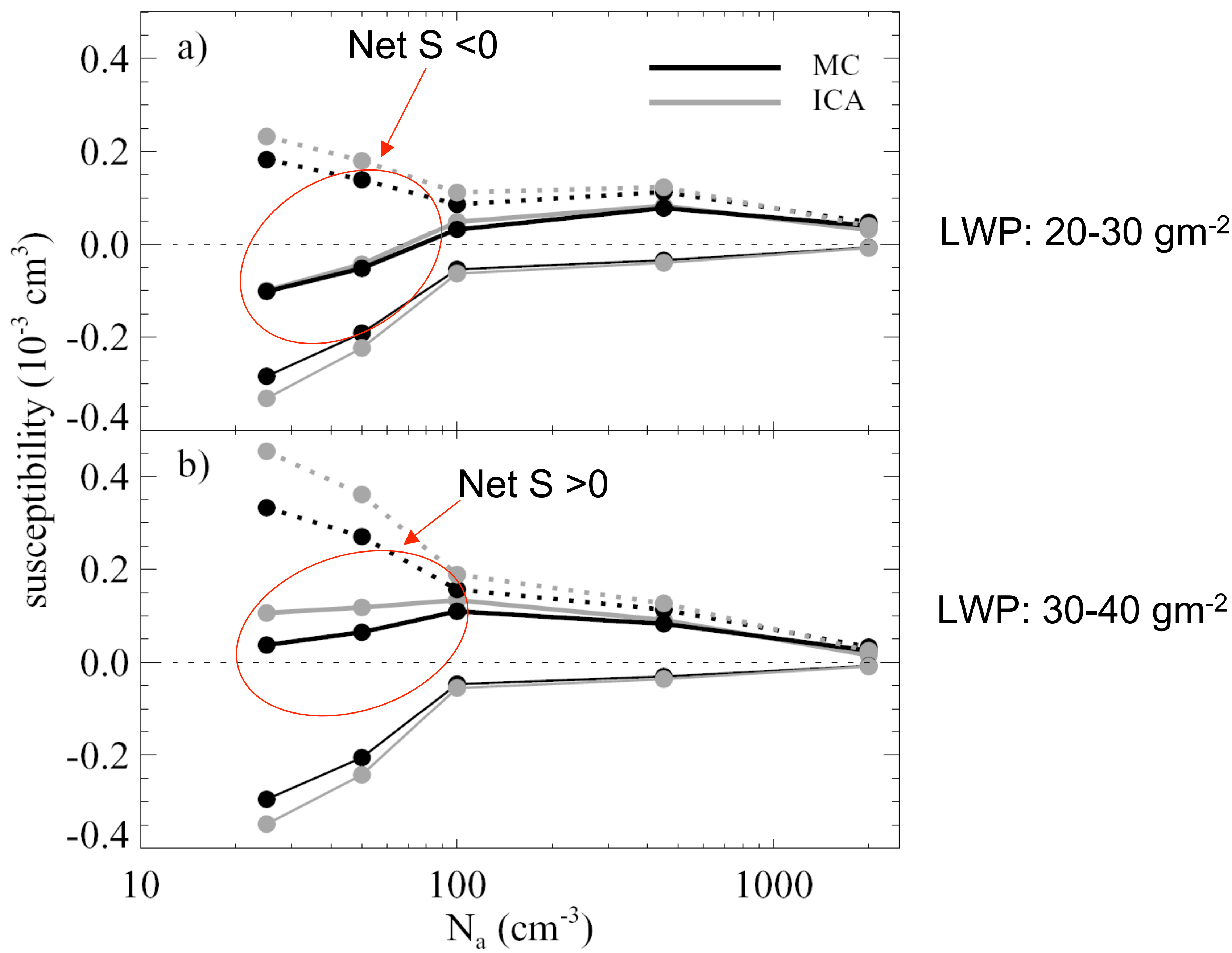
Black: Monte Carlo
Grey: ICA

LWP: 30-40gm^{-2}

Zuidema, Xue, Feingold, in press 2007

BOMEX

Susceptibility calculations at overhead sun, λ=0.64 μm



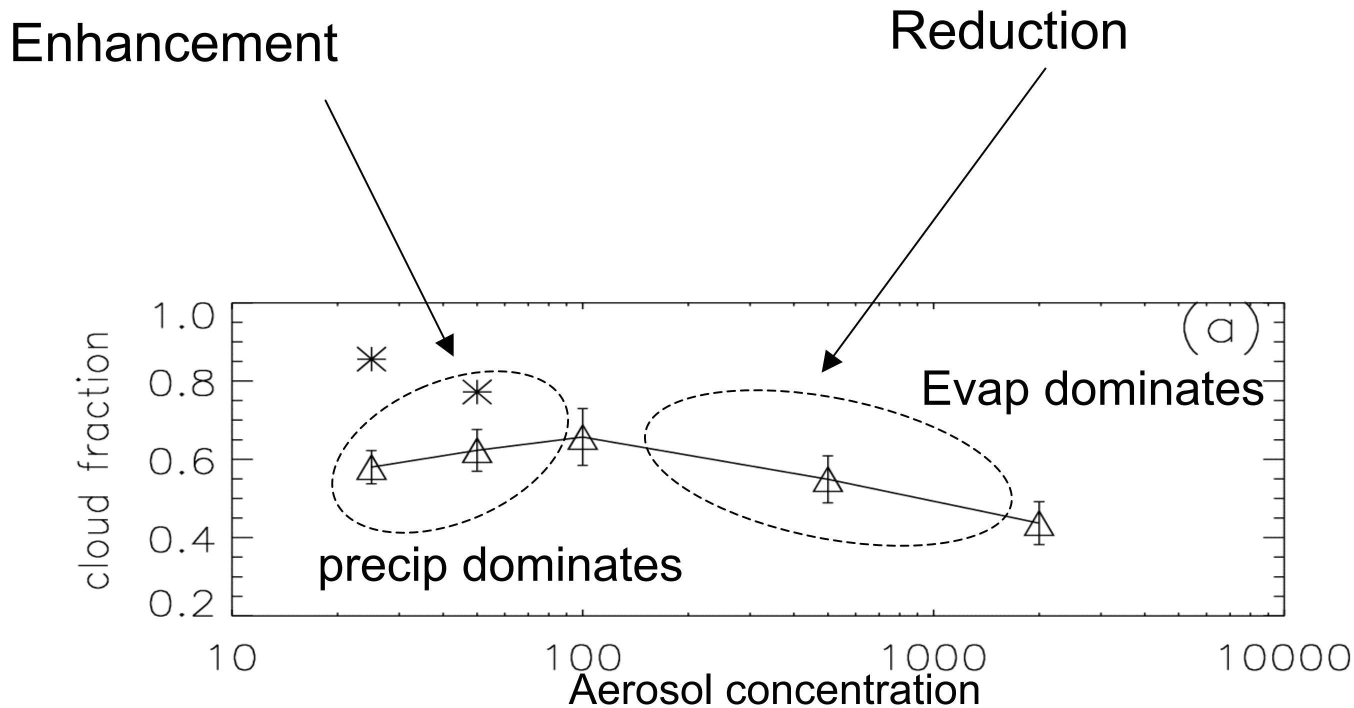
Susceptibility calculations based on 3-D RTM for LES simulated cloud fields

$$A_{dom} = CF \times A_{cld}$$

$$S_0 = \left.\frac{\partial A_{cld}}{\partial N_d}\right|_{\text{Const LWP}}$$

$$\frac{\partial A_{dom}}{\partial N_d} = \underbrace{\overline{CF}\,\frac{\partial A_{cld}}{\partial N_d}}_{\text{Term 1}} + \underbrace{\overline{A_{cld}}\,\frac{\partial CF}{\partial N_d}}_{\text{Term 2}}$$

$$S_0 = \frac{A_{cld}(1 - A_{cld})}{3N_d}$$



ATEX

Summary

- Observations of aerosol effects on clouds are ambiguous; modeling attempts to show why
- Aerosol effects on precipitation generate significant changes to cloud morphology
  - Self-organizing properties of clouds
  - Opposing effects of precip/sedimentation and evaporation
- Aerosol does not appear to modify shallow cumulus cloud lifetime in our large eddy simulations
  - Faster evaporation in polluted cases → entrainment feedback that dilutes clouds
- Aerosol effects on albedo
  - Cases where effects counter one another (BOMEX)
  - Case where effects work in unison (closed to open cell transition - ATEX)