Aerosol-Cloud-Precipitation Interactions: Some lessons from Large Eddy Simulations

Exploring observational constraints on the “lifetime effect”

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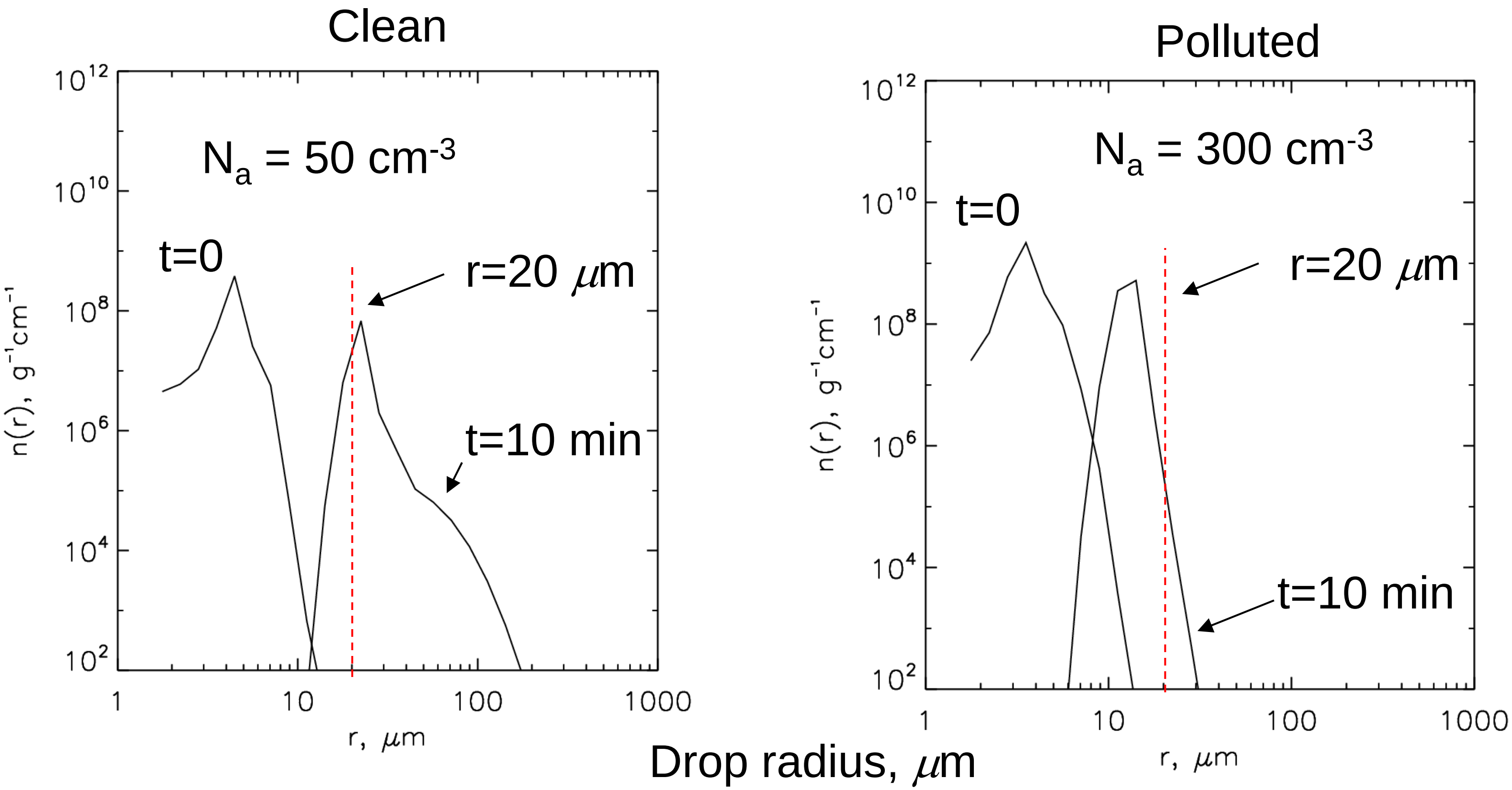
Effect of Aerosol on Precipitation Formation

Aerosol reduces the ability of a warm cloud to generate precipitation (all else equal) (Gunn and Phillips 1957; Warner 1967)



Autoconversion vs. Accretion

Autoconversion: cloud droplets interact to form rain

$$\left(\frac{\partial q_r}{\partial t}\right)_{\text{auto}} = 1350 q_c^{2.47} N_c^{-1.79}$$

depends on drop concentration and cloud water c

Accretion: rain drops collect cloud droplets to form rain

$$\left(\frac{\partial q_r}{\partial t}\right)_{\text{accr}} = 67(q_c q_r)^{1.15}$$

no drop concentration dependence

N_c cloud drop # conc
q_c cloud water mixing ratio
q_r rain water mixing ratio

Khairoutdinov and Kogan 200
See also
Berry, 1967, 1968
Berry and Reinhardt 1970s

Bulk parameters controlling the rate of rain formation

Rainrate R
Liquid water path LWP
Drop concentration N_d
time available for collision-coalescence t_c

Parameterization (empirically and theoretically based)

$R = C\,\mathrm{LWP}^{\alpha}\,N_d^{-\beta}$
$\alpha \sim 1.5$
$\beta \sim 0.5$

time is not included in these parameterizations

Pawlowska et al. 2003; van Zanten et al. 2005; Kostinski 2008

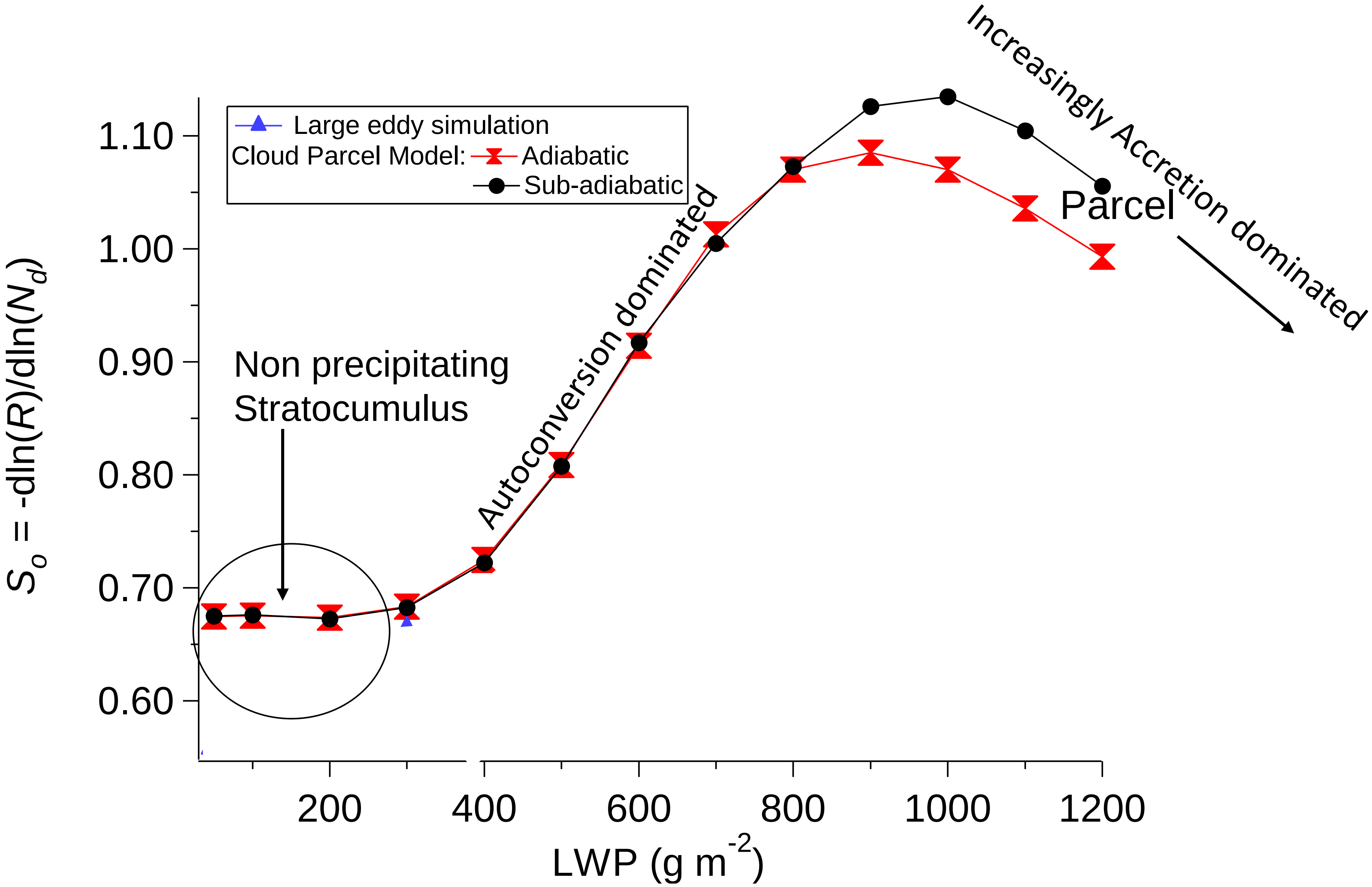
Precipitation Susceptibility

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

- S_o aims to identify cloud conditions for which the aerosol may suppress precipitation

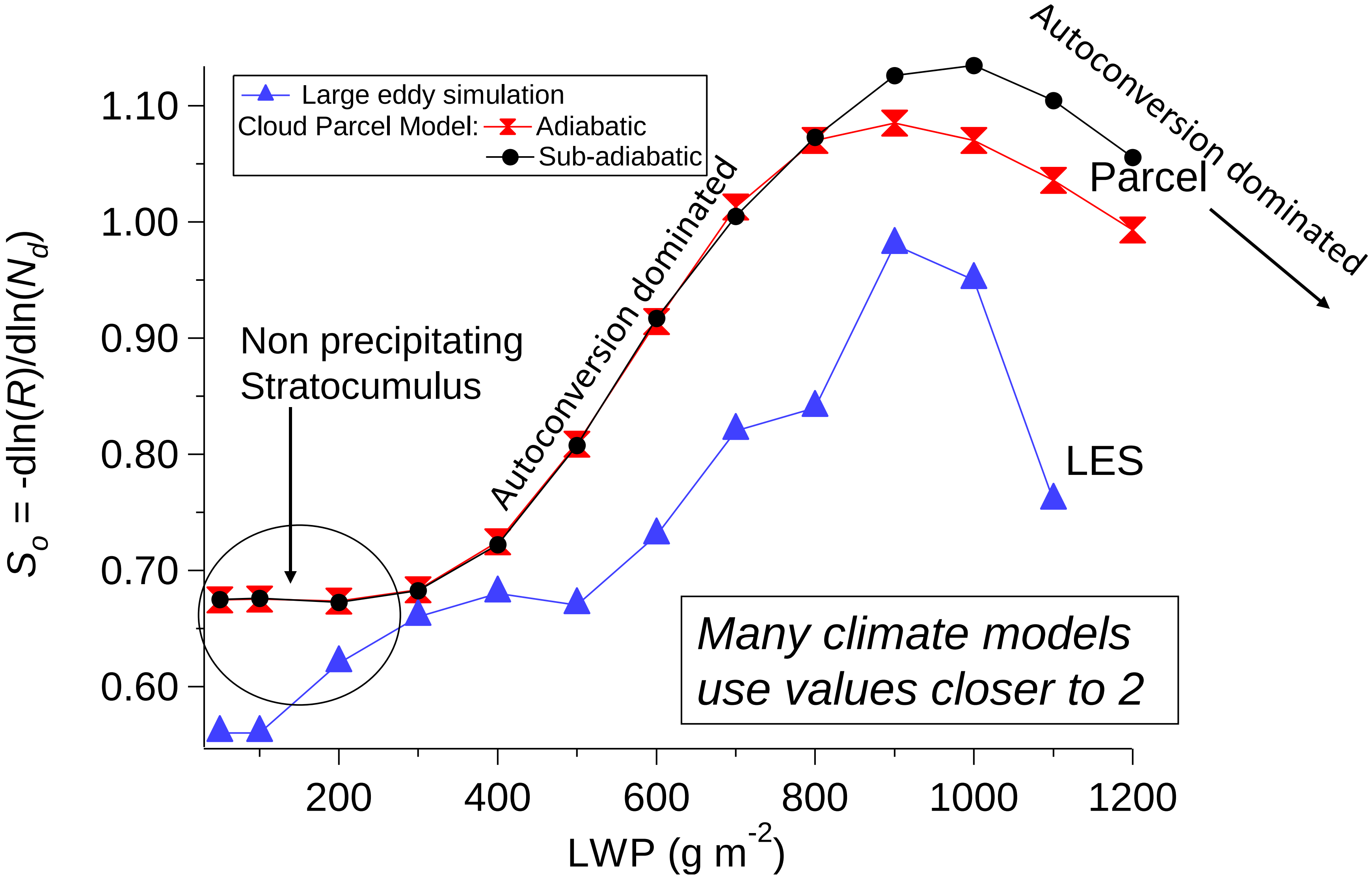
- S_o is related to GCM representation of “lifetime effects”
  - S_o is equivalent to β in Autoconversion ~ $N_d^{-\beta}$ parameterizations
- *S_o* is a measure of the potential for suppression (not the actual suppression)

Feingold and Siebert (2009); Sorooshian et al. (2009)



Finite range over which clouds exhibit significant precipitation suscepti

Feingold and Siebert (2009); Sorooshian et al. (2009)

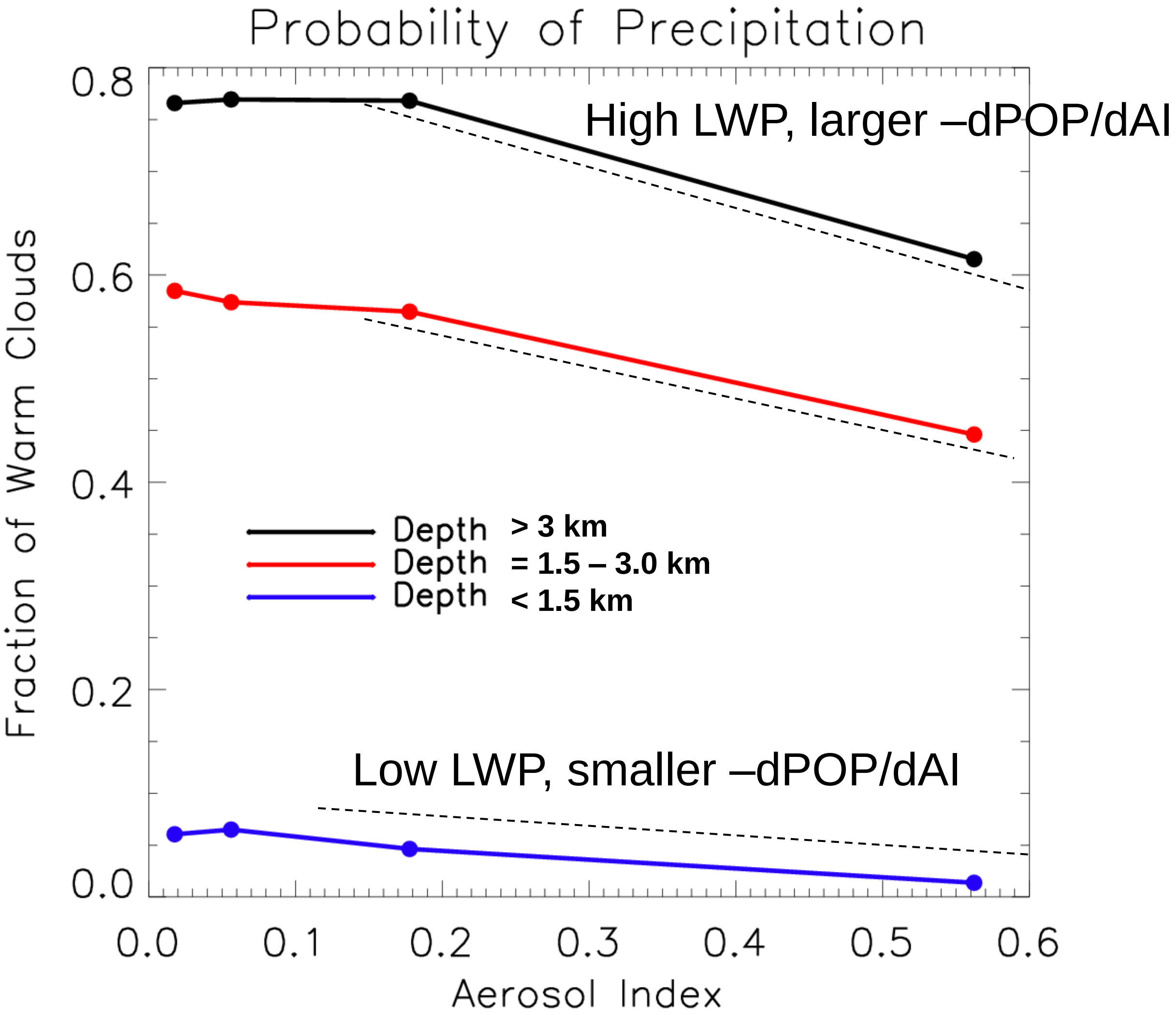


Many climate models use values closer to 2

Finite range over which clouds exhibit significant precipitation suscepti

Independent Satellite Work

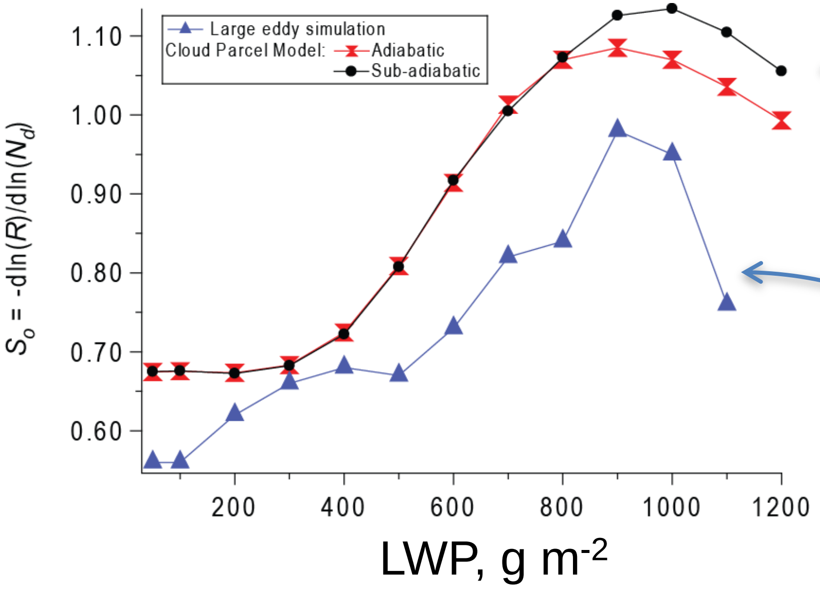
Increasing Probability of Precipitation (POP)



High LWP, larger –dPOP/dAI

Low LWP, smaller –dPOP/dAI

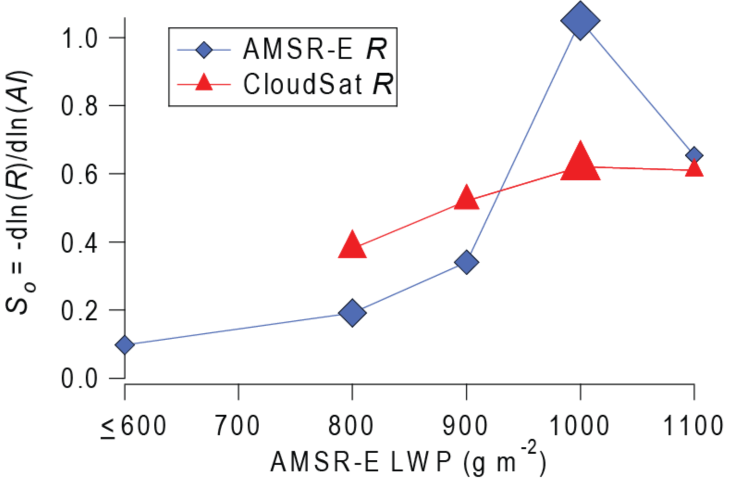
CloudSat and MODIS Data: M. Lebsock et al.



Single parcel models (entraining and adiabatic)

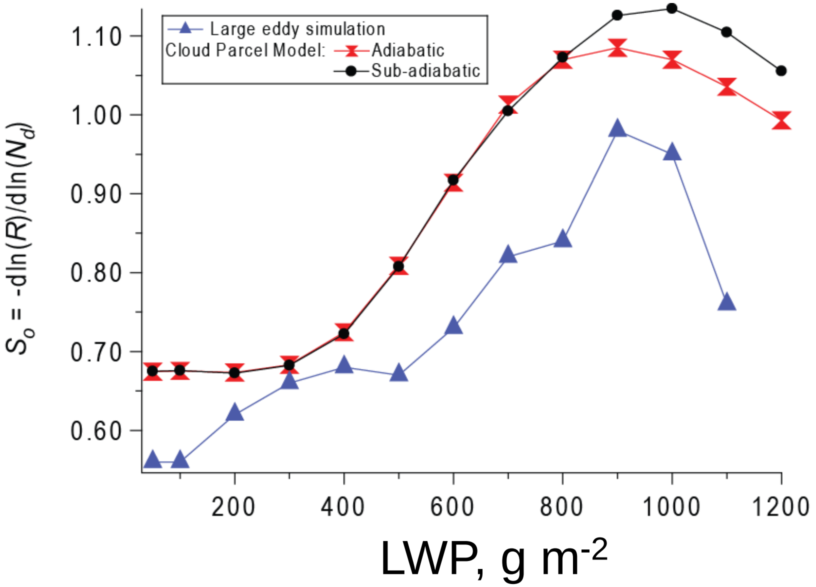
LES of RICO trade cumulus

Satellite retrievals

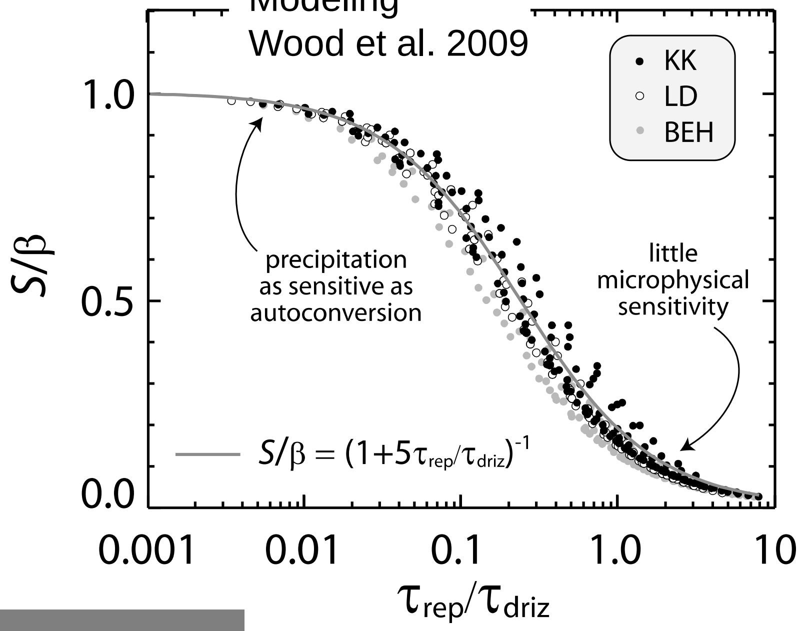


$$S_o = -\frac{d\ln R}{d\ln N_d}$$

Sorooshian et al. 2009

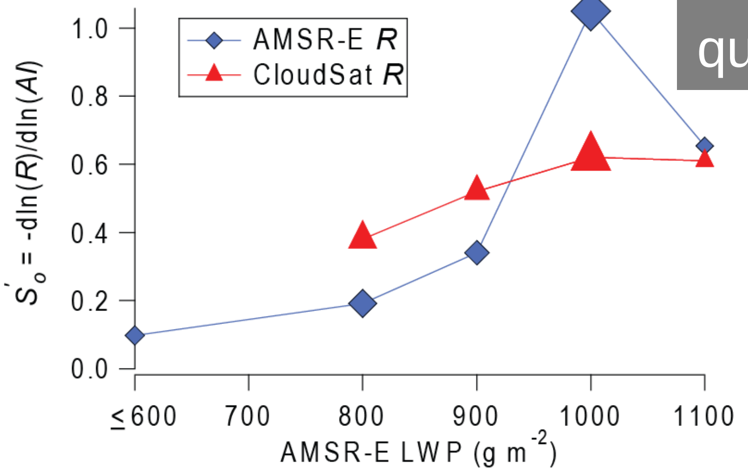


Modeling
Wood et al. 2009



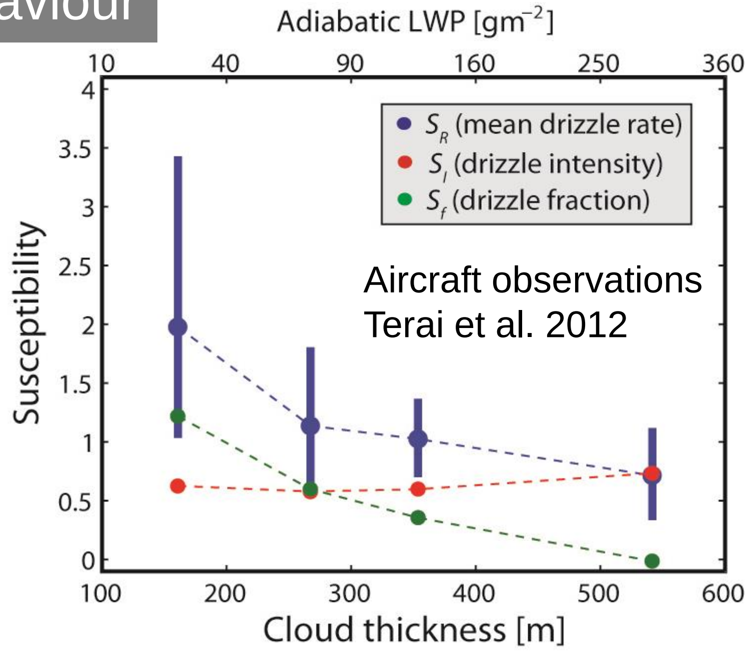
Why is the qualitative behaviour

Satellite retrievals



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

Sorooshian et al. 2009

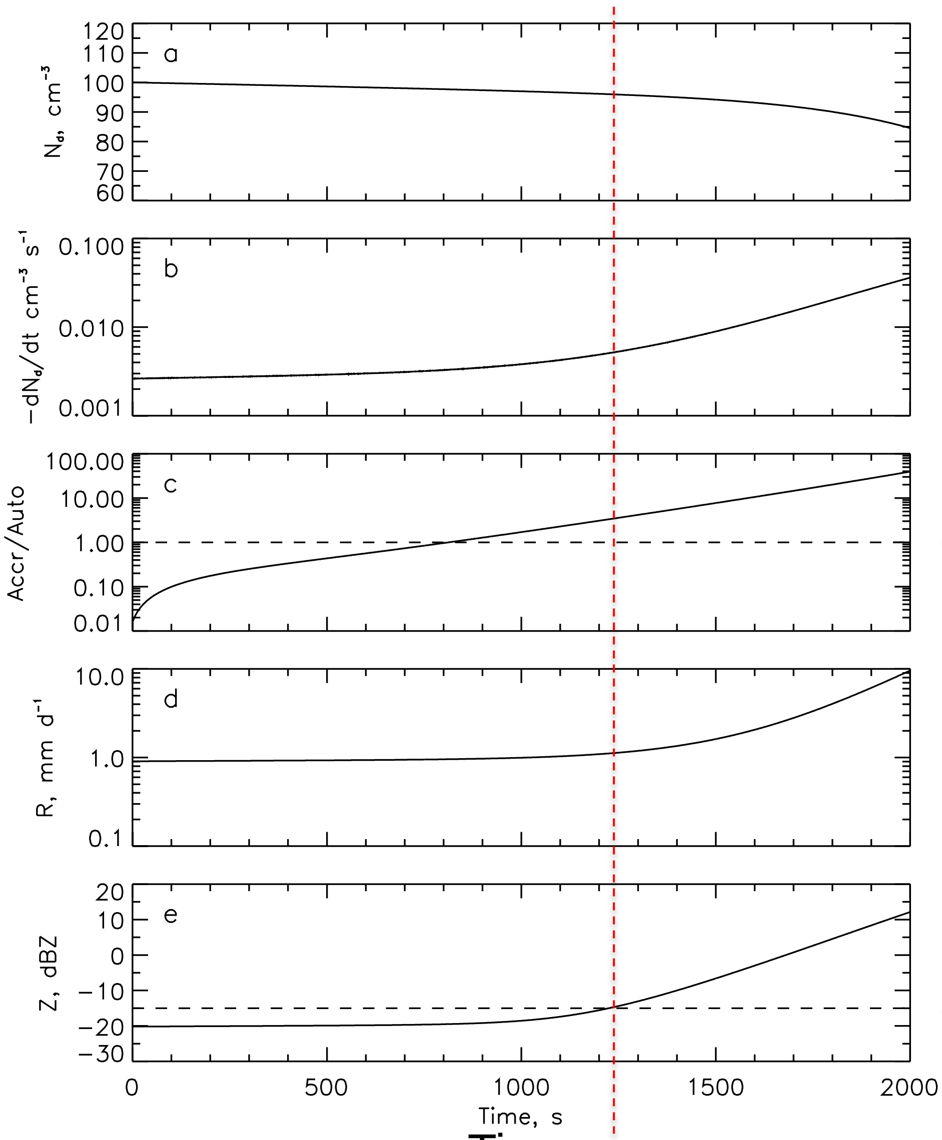


Aircraft observations
Terai et al. 2012

Simple Models

Box model of collision-coalescence (bin microphysics); <u>constant LWC</u>

Cloud contact time = simulation time



N_d

$-dN_d/dt$

Accr/Auto

R

Z

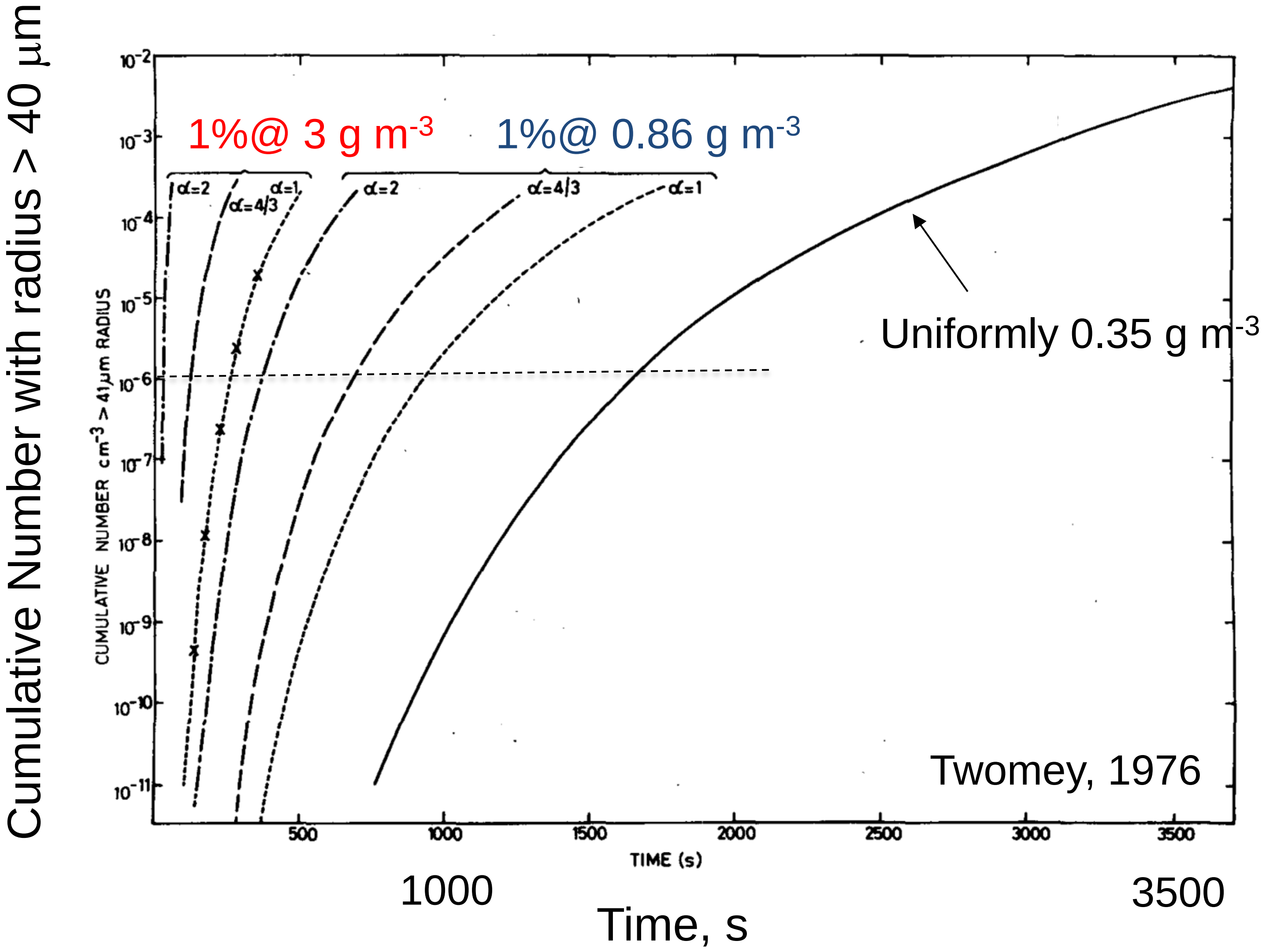
Accr=Auto

Z=-15dBZ

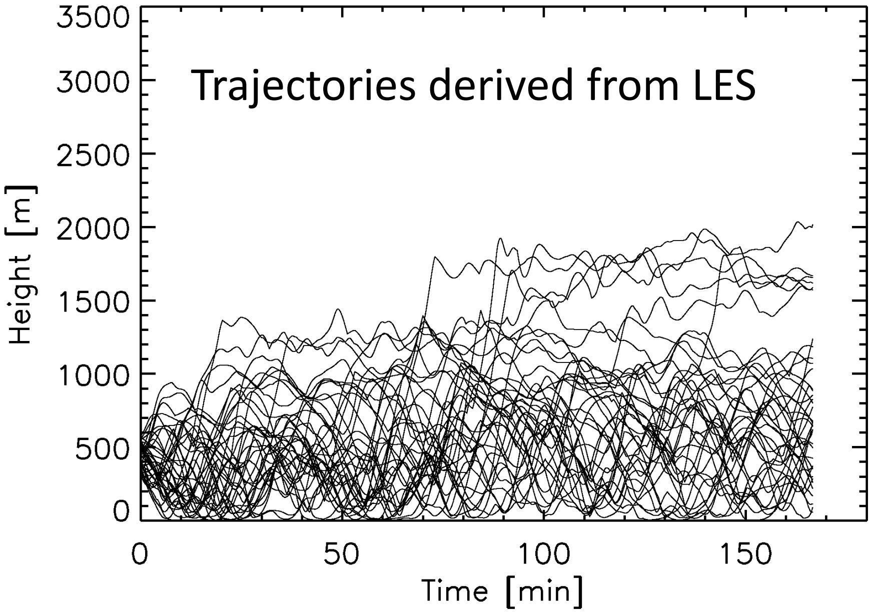
Time, s

Feingold et al. 2013

Brief contact with regions of high LWC has an inordinately strong effect on collision-coalescence

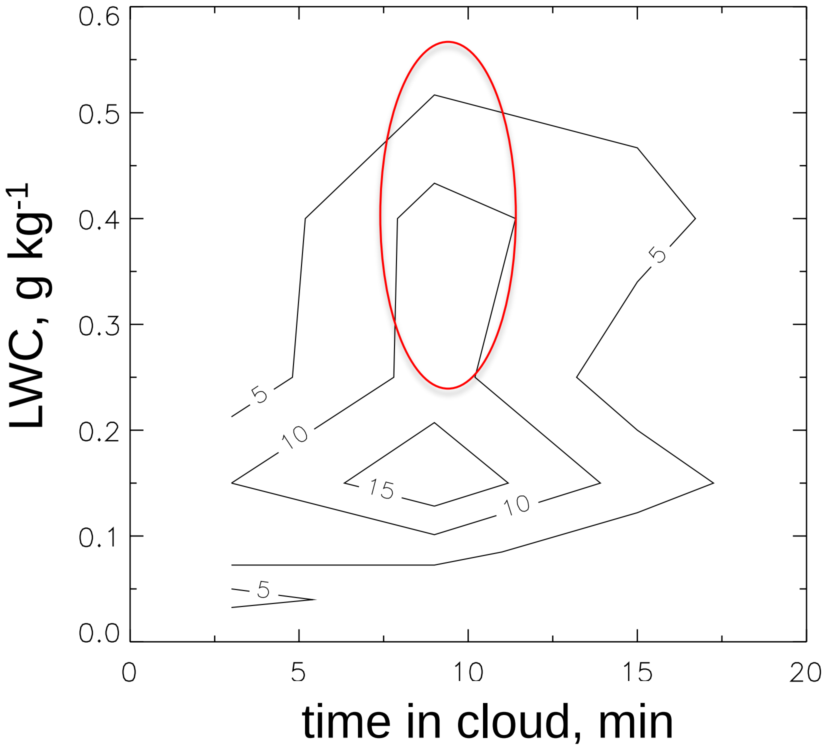


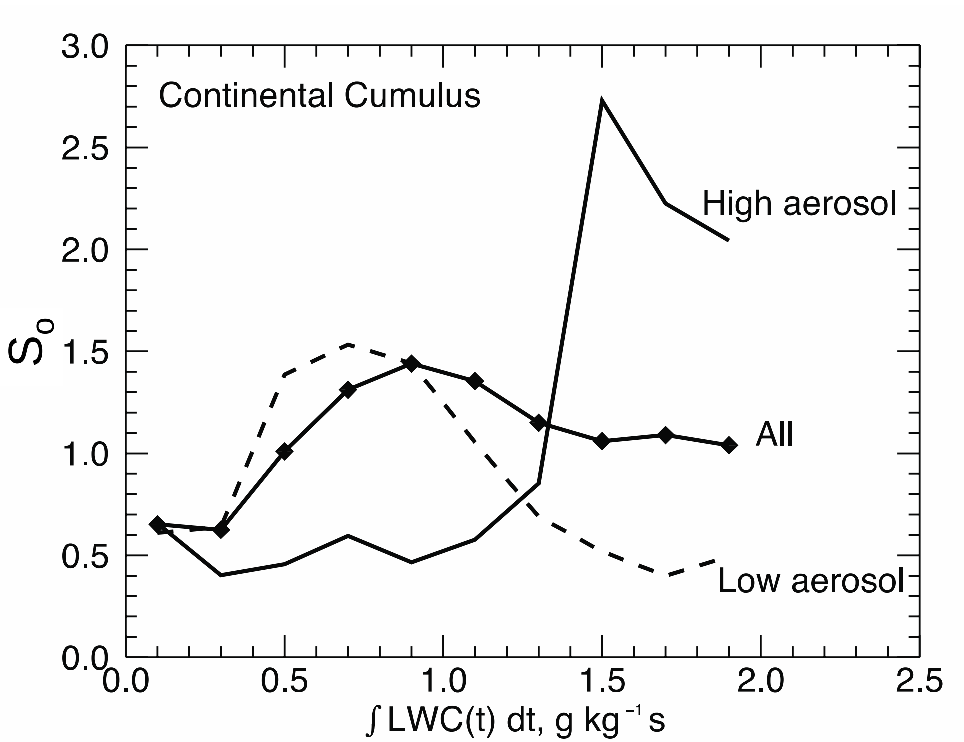
Twomey, 1976



Continental Cumulus

Convective boundary layer: Infrequent contact time but often at high LWC





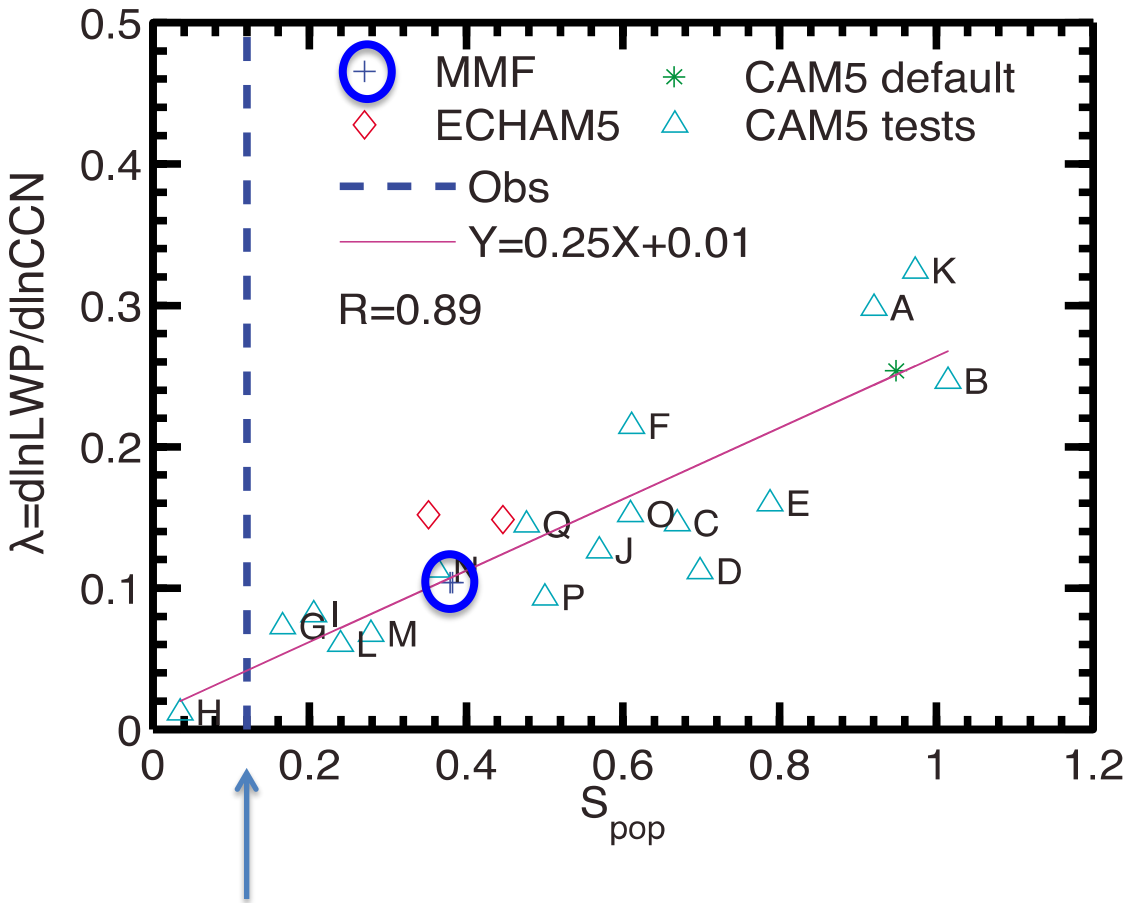
Feingold et al. 2013

Constraining Liquid Water Responses to changes in Aerosol (dL/dN)

L = Liquid Water Path

Constraining dL/dN

Climate Model Output



Satellite observations

Analysis over Global Oceans

$$S_{pop} = -\frac{dln\mathrm{POP}}{dlnN}$$

Minghuai Wang et al. 2012

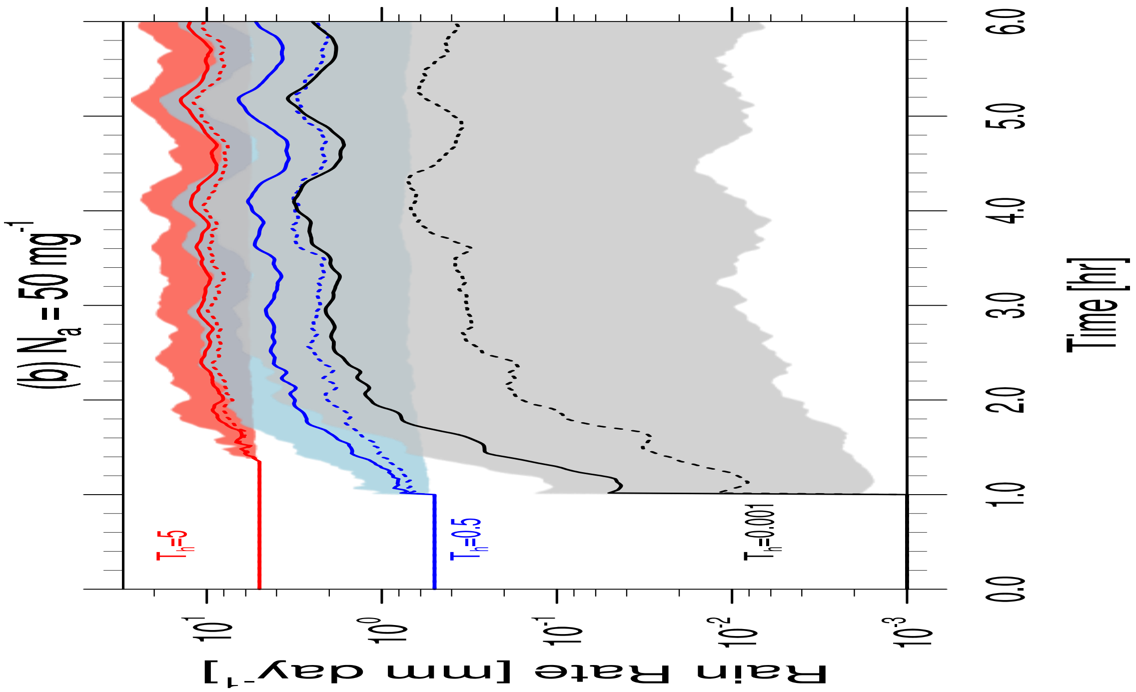
POP = Probability of Precipitation

Constraining dL/dN

Can S_o or S_{pop} be used to constrain d*L*/dN?

Large Eddy Simulation (Stratocumulus)

WRF, 2-moment microphysics; N_a = 25, 50, 75, 100 mg^{-1} + perturbed physics
DYCOMS-II RF02



Three R thresholds:
T_h = 0.001, 0.5, 5 mm day-1

Solid: mean
Dashed: median
Shaded: 10th – 90th percentiles

Lebo and Feingold ACP 2014

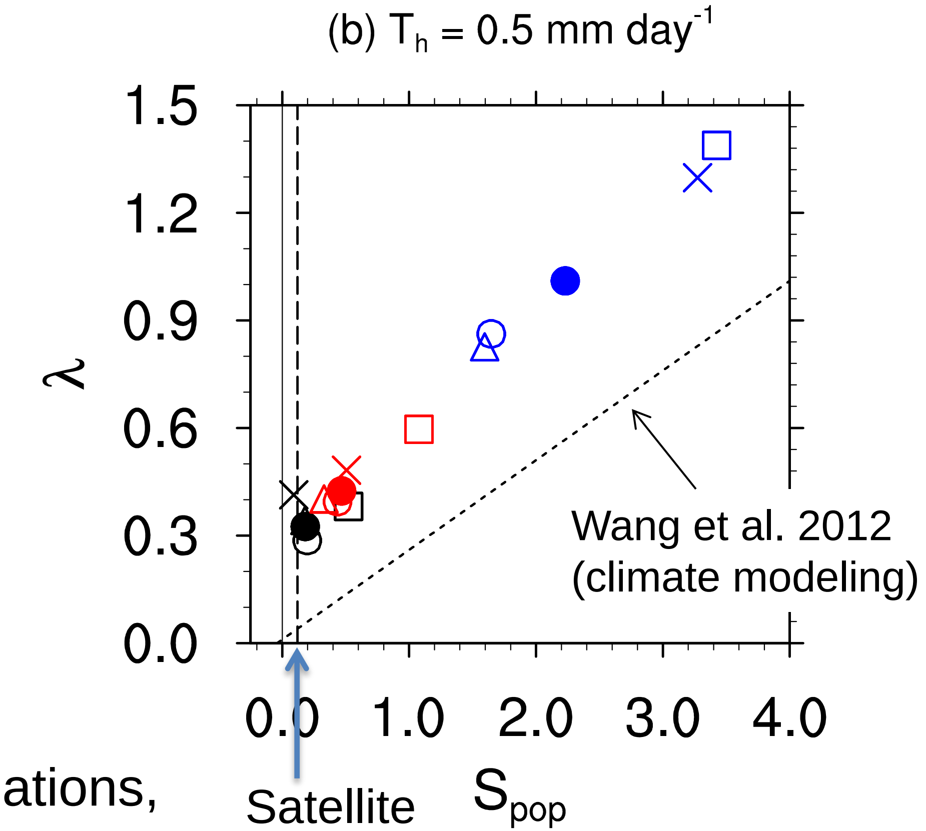
Constraining dL/dN

Can S_o or S_{pop} be used to constrain d*L*/dN?

Large Eddy Simulation (Stratocumulus)

Quantitative differences from GCM-based relationship

$$\lambda = \frac{dlnL}{dlnN}$$


(b) T_h = 0.5 mm day^{-1}

Wang et al. 2012 (climate modeling)

Satellite observations

Symbols: Different aerosol perturbations, Different model physics

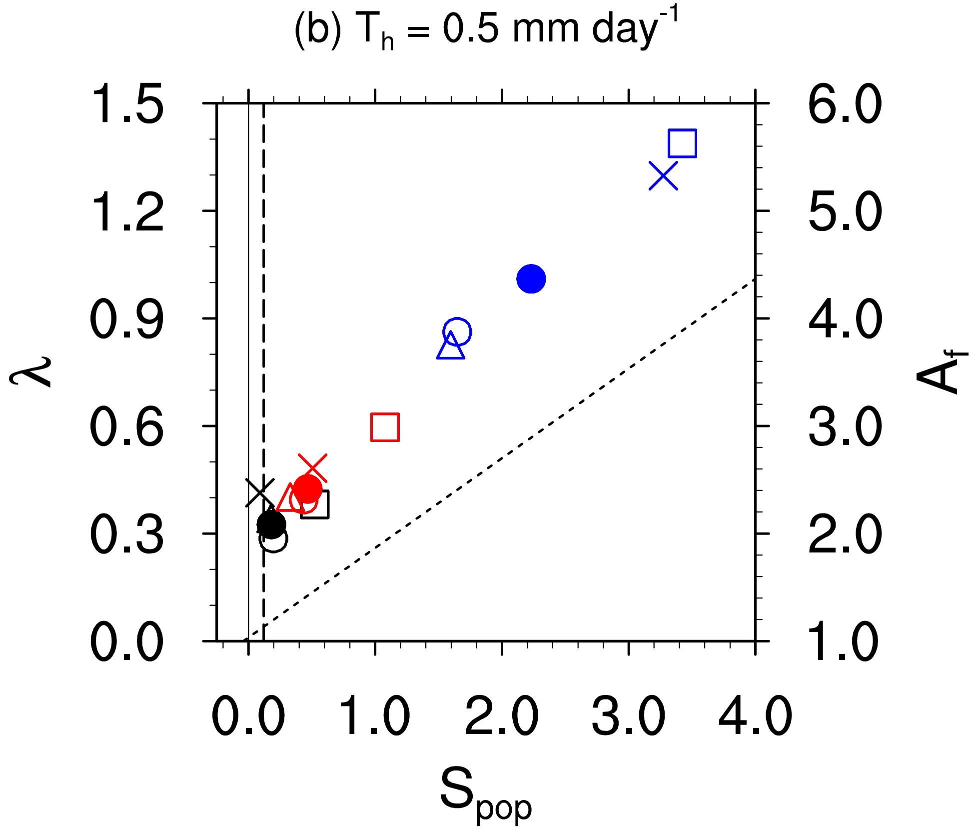
Constraining dL/dN

Right axis:

$$A'_\circ = A_\circ \left[1 + \frac{5}{2}\frac{d\ln L}{d\ln N} + \ldots\right]$$

$$A_f = \frac{A'_\circ}{A_\circ} = \left[1 + \frac{10}{3}\lambda + \ldots\right]$$

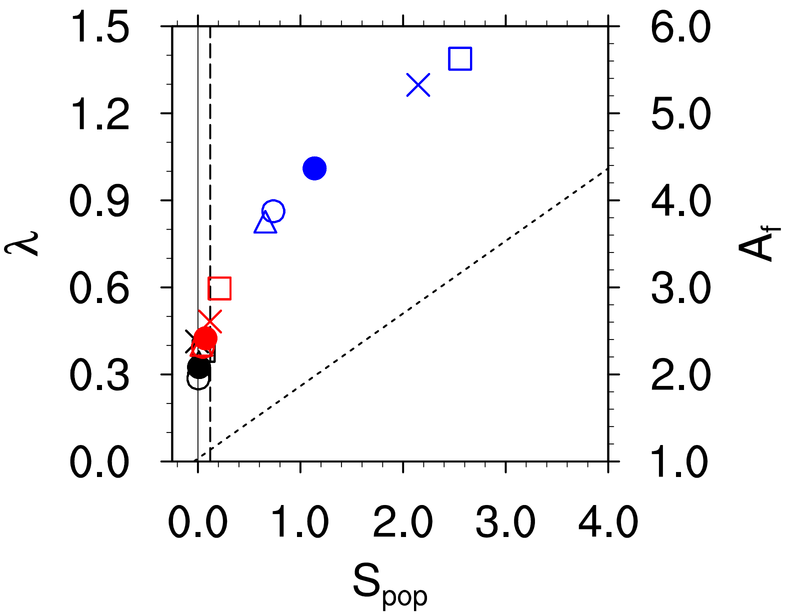
A_f = Albedo susceptibility enhancement factor due to λ (enhancement over Twomey albedo susceptibility)



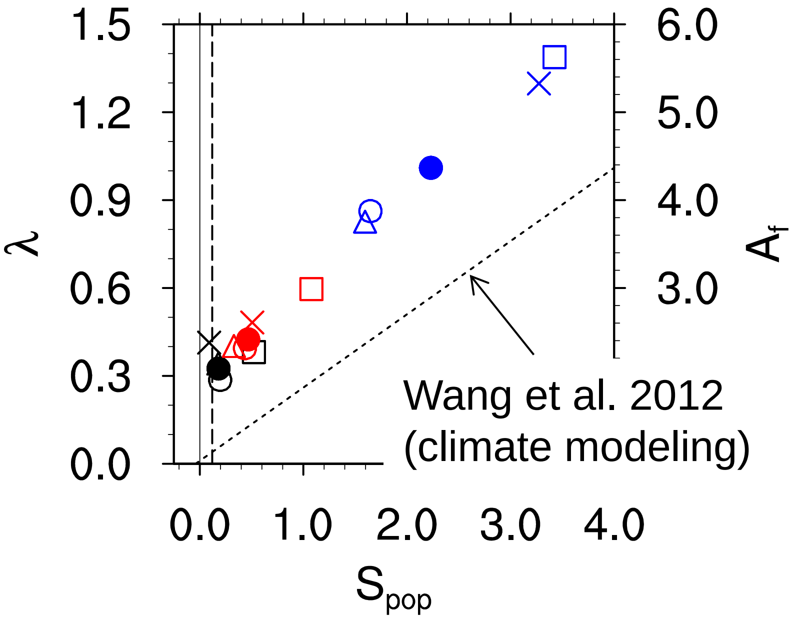
Lebo and Feingold ACP 2014

Influence of R threshold

(a) $T_h = 0.001$ mm day^{-1}

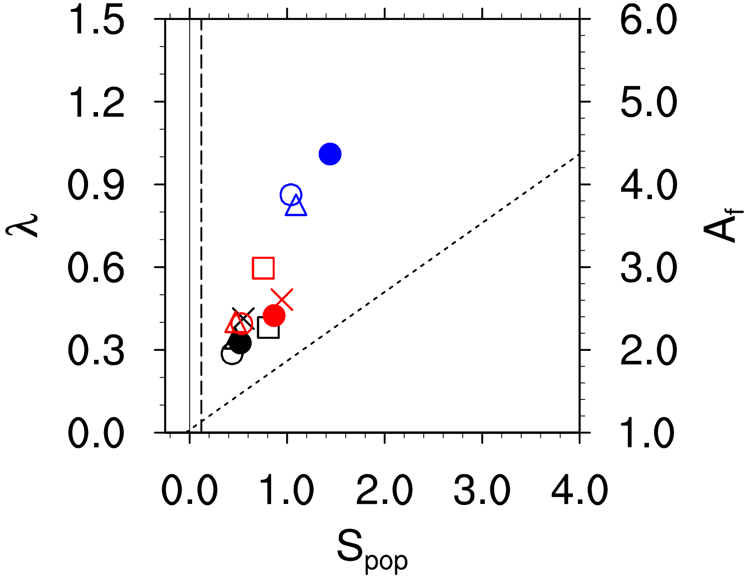


(b) $T_h = 0.5$ mm day^{-1}



Wang et al. 2012
(climate modeling)

(c) $T_h = 5$ mm day^{-1}



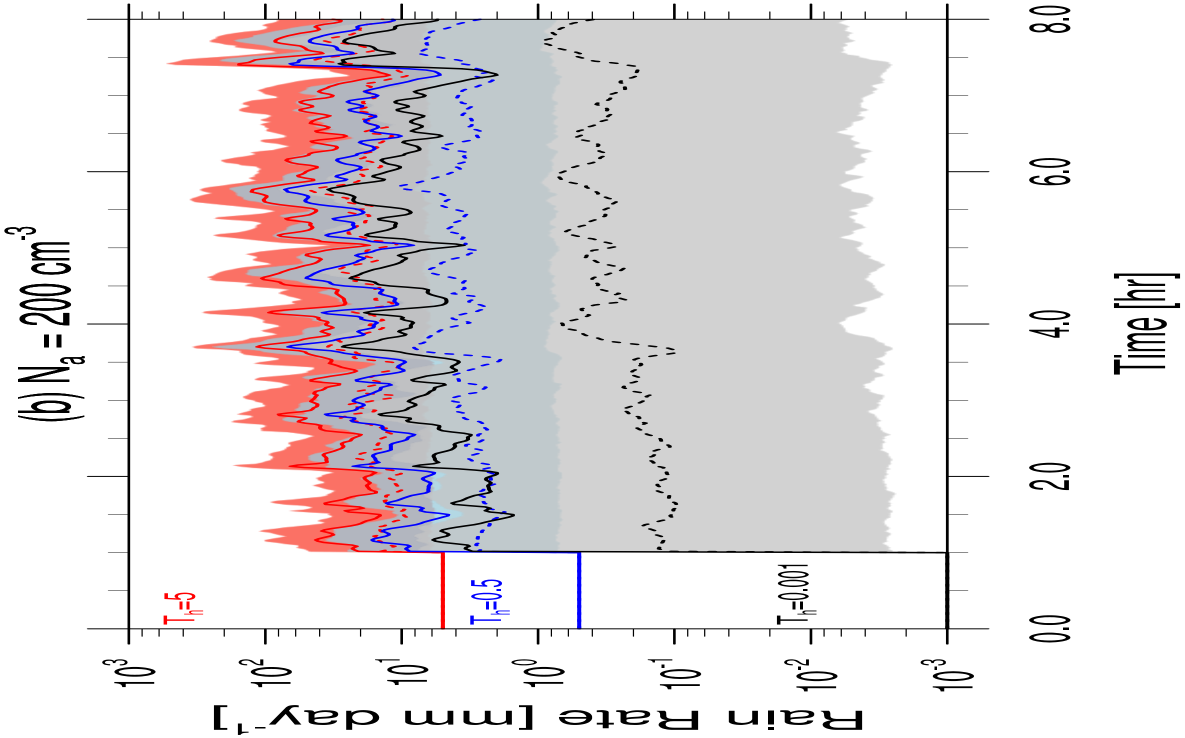
Large Eddy Simulation (Stratocumulus)

Lebo and Feingold
ACP 2014

Constraining dL/dN

Large Eddy Simulation (Trade-wind Cumulus)

RAMS (TAU bin microphysics); N_a = 100, 200, 300, 400, 500 cm^{-3}
RICO (modified to increase rain)



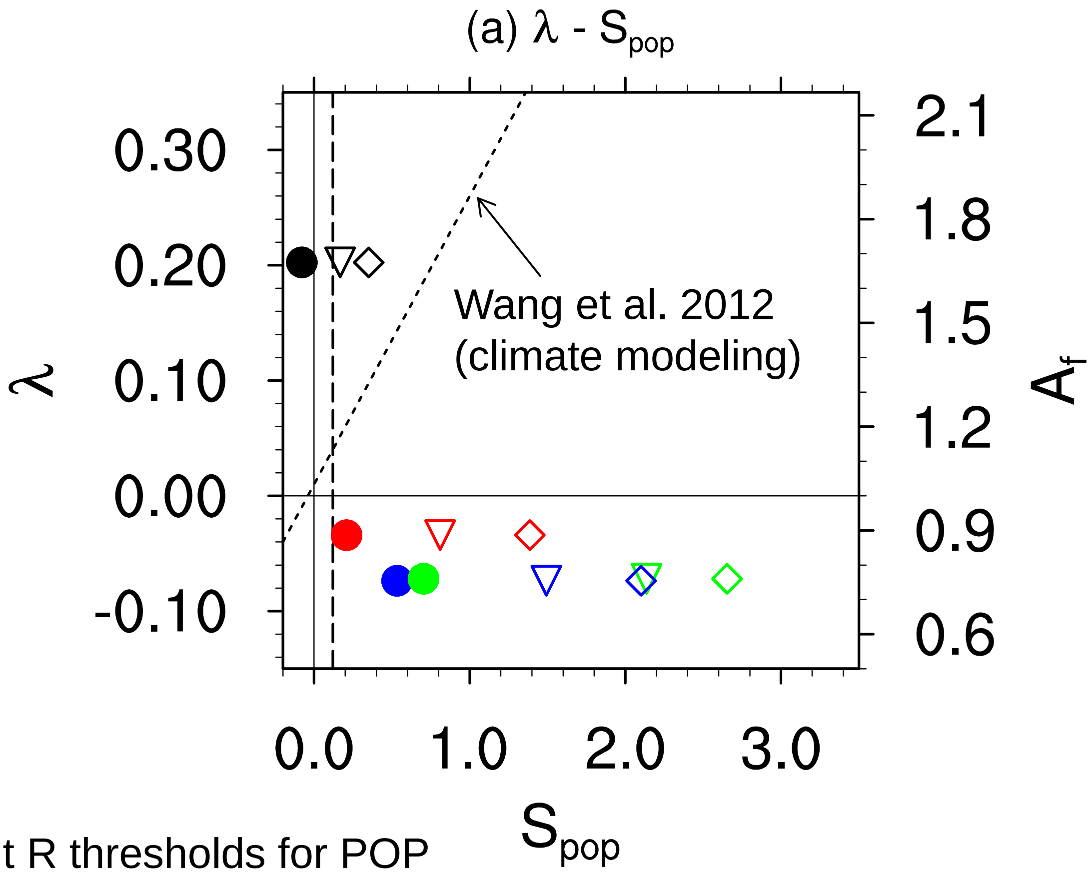
Solid: mean
Dashed: median
Shaded: 10th – 90th percentile

Lebo and Feingold ACP 2014

Constraining dL/dN

Large Eddy Simulation (Cumulus)

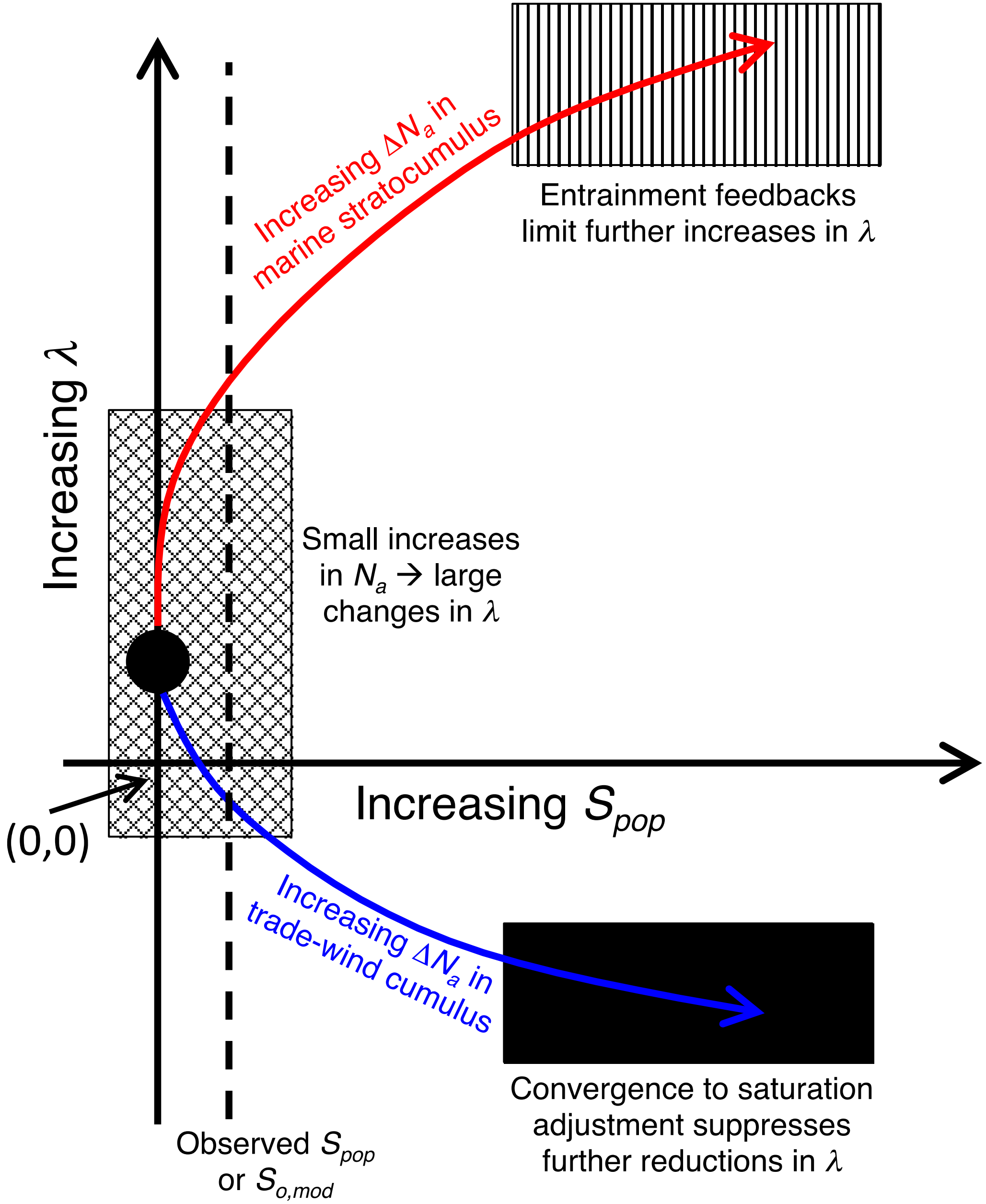
λ becomes negative for large enough aerosol perturbations
Evaporation-entrainment feedback reduces L



Symbol types: Different R thresholds for POP
Colours: increasing aerosol perturbation

Lebo and Feingold ACP 201

Summary Schematic



Conclusions

- Precipitation susceptibility: S_o or S_{pop}, dependence on LWP, *time*
- “Lifetime effect”: $\lambda = \mathrm{dlnLWP/dlnN}$
- Examined use of satellite remote sensing to measure S_{pop} as a way to constrain □lifetime effect□

  - LES produces λ-S_{pop} relationships with non-zero intercept
    - Even if S_{pop} is small, λ may not be

  - λ-S_{pop} relationship is both scale and regime dependent (SCu behaves differently from Cu)

  - Aggregated results based on regime-based large eddy modeling unlikely to equal GCM-based global average

  - Cautionary note regarding use of GCMs to explore underlying scaling

The Non-Linearity of Collision-Coalescence

or

In Praise of Twomey

Cloud Contact time

Simple Models

Box model of collision-coalescence (bin microphysics)

Cloud contact time = simulation time

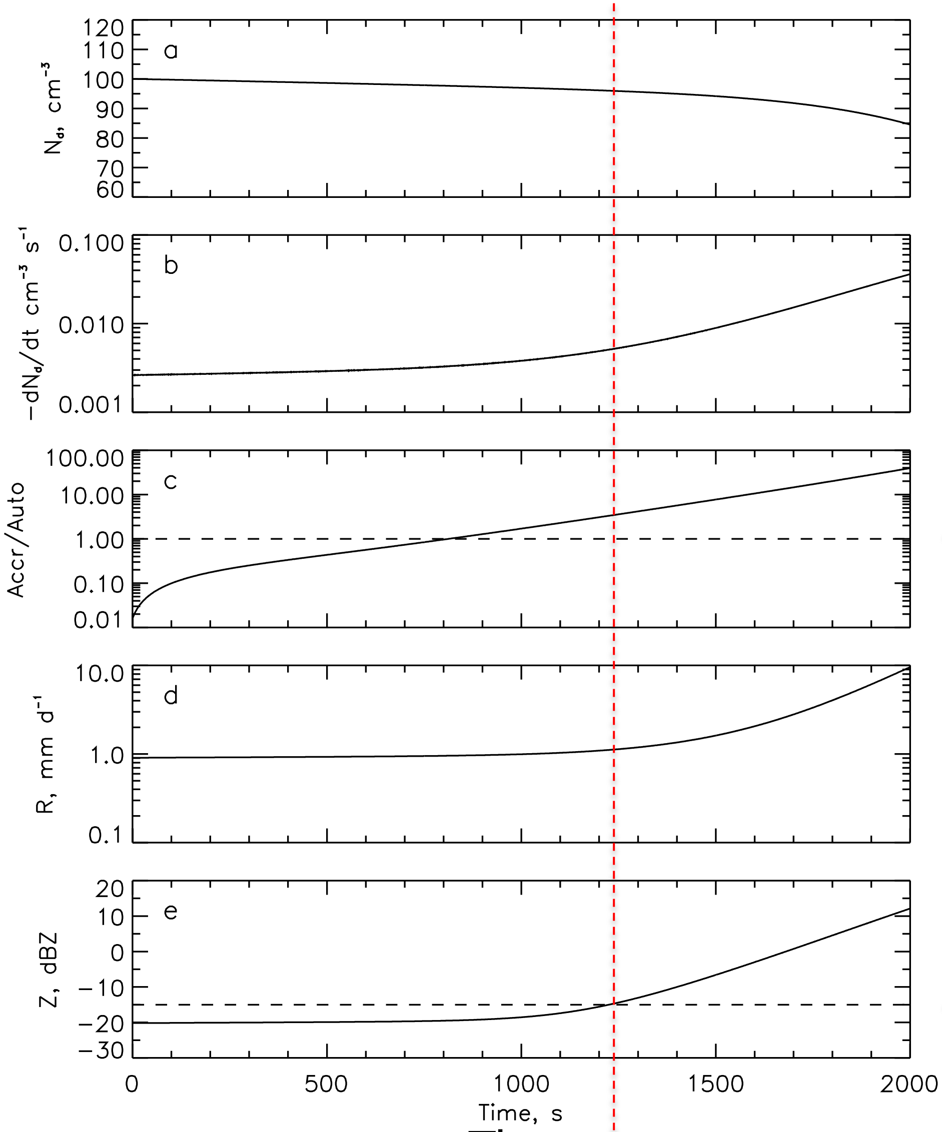
N_d

$-dN_d/dt$

Accr/Auto

R

Z



Accr=Auto

Z=-15dBZ

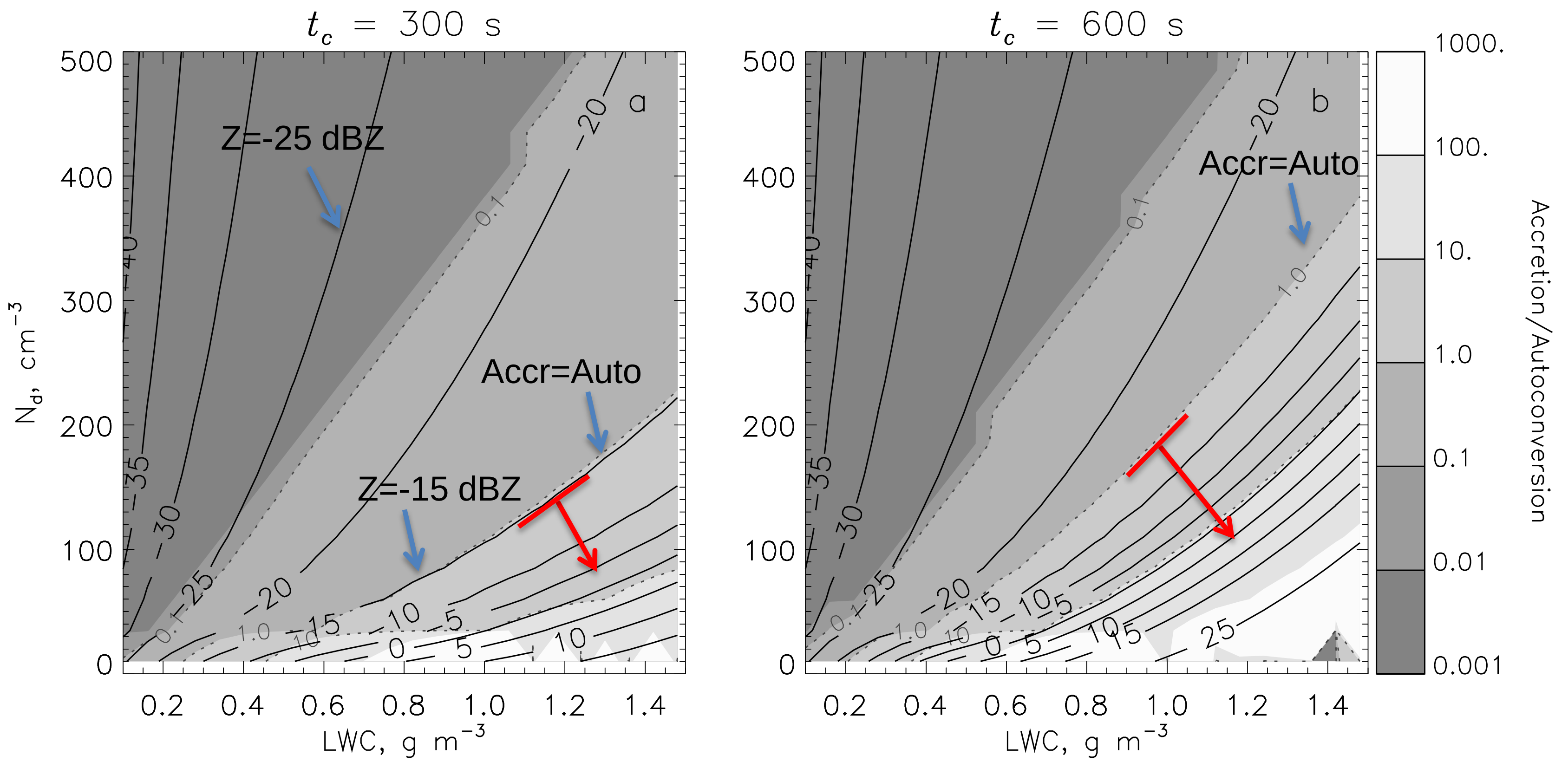
Time, s

Feingold et al. 2013

Simple Models

Box model of collision-coalescence (bin microphysics)

Solid contours: Z (dBZ)



Z=-25 dBZ

Accr=Auto

Z=-15 dBZ

Accr=Auto

- With increasing time, more of the domain is dominated by accretion
- Auto/Accr contours roughly parallel to Z contours

Feingold et al. 2013

Simple Models

Box model of collision-coalescence (bin microphysics)

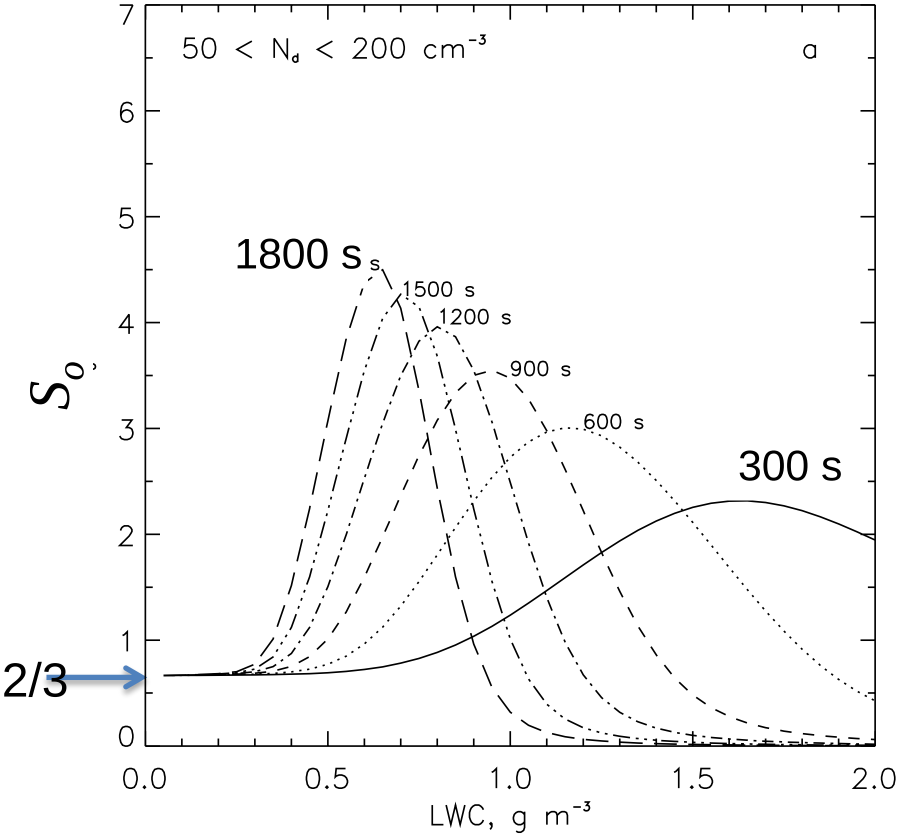
$$R \quad q_l^{\alpha} N_d^{-\beta}$$

$$v(r) \propto r^b$$

$$N r_m^{3+b} \simeq (N r_m^3)^{\alpha} N^{-\beta}$$

$$\alpha = 1 + b/3$$

$$\beta = b/3$$



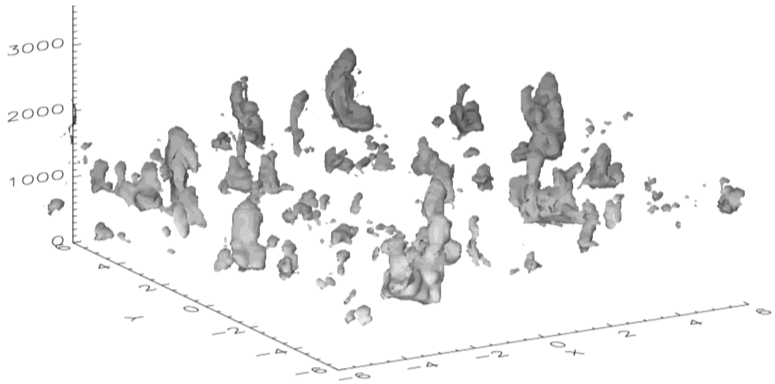
Cleaner aerosol conditions

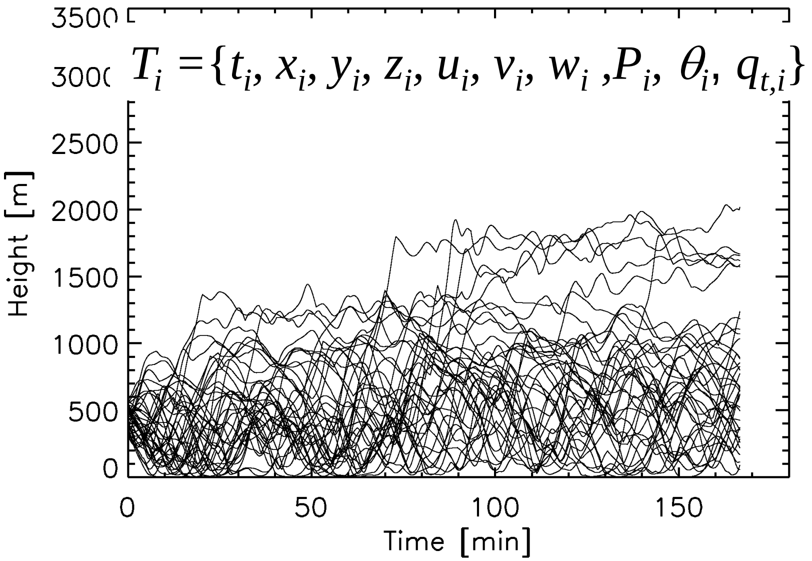
Theoretical S_o=2/3 for Stokes fall velocity regime (*b*=2)

LWC

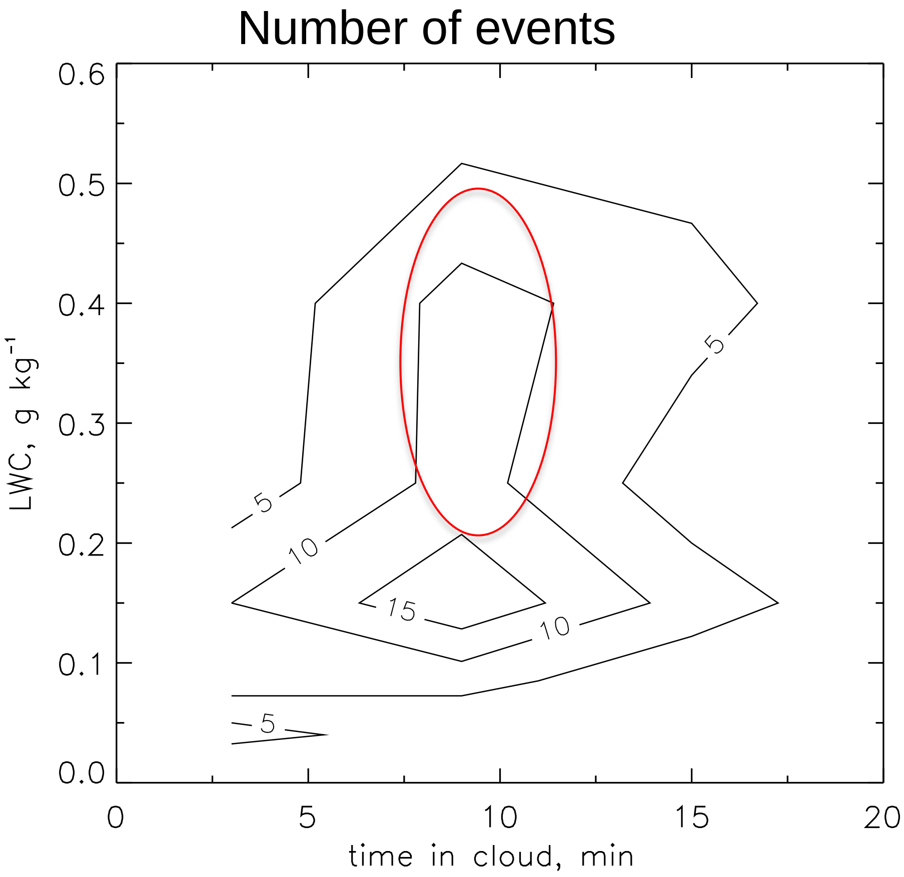
Feingold et al. 2013

Analysis of trajectories from Large Eddy Simulation of Cumulus



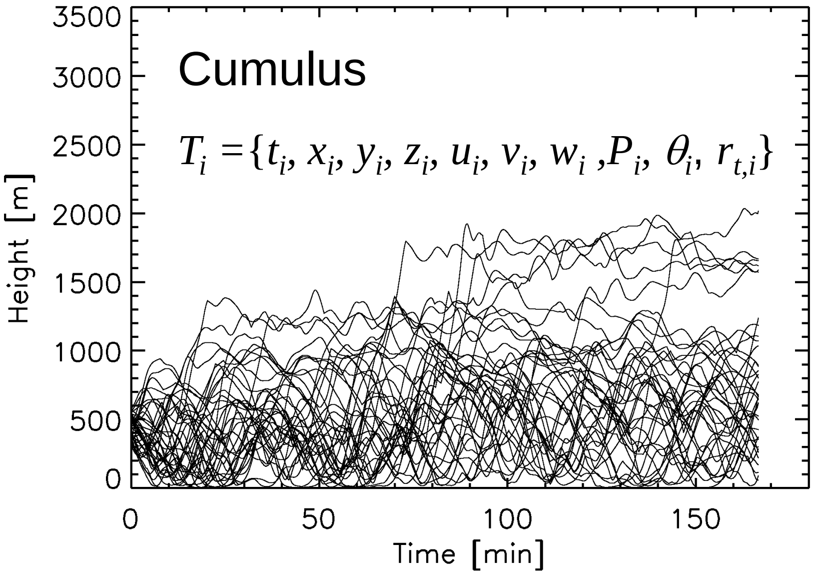


$$T_i = \{t_i,\ x_i,\ y_i,\ z_i,\ u_i,\ v_i,\ w_i\ ,P_i,\ \theta_i,\ q_{t,i}\}$$

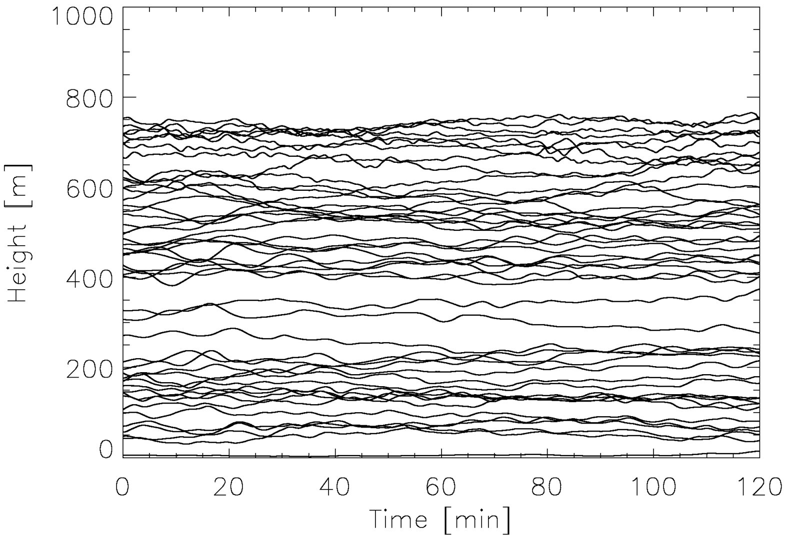


Calculate the cloud contact as a function of LV $\int \mathrm{LWC}(t)dt$

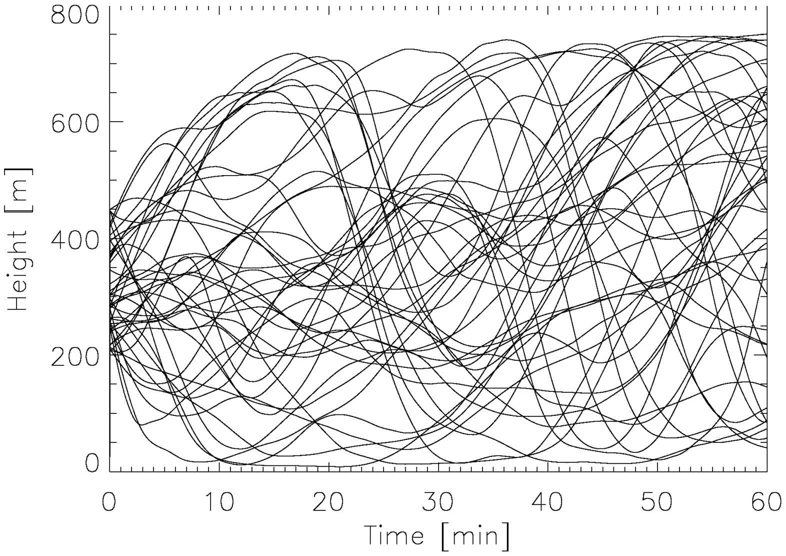
Alternative models: Trajectories from Large Eddy Simulation



Stratus, decoupled boundary layer



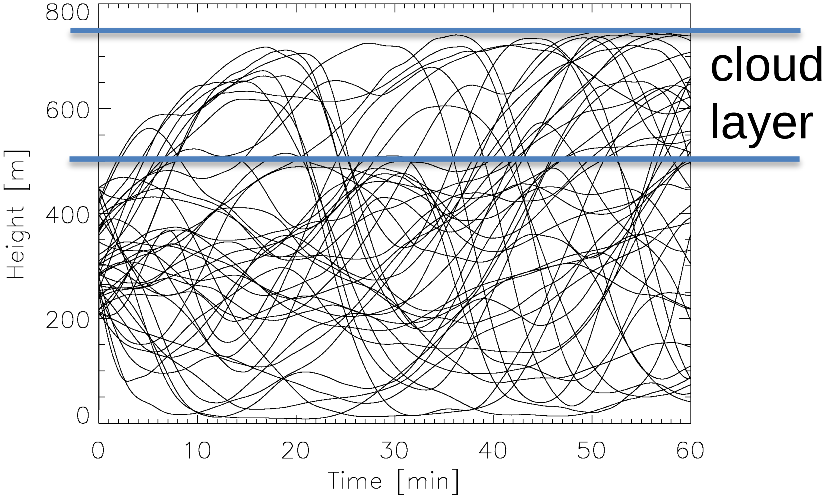
SCu, well-mixed boundary layer



- Trajectories carry history that includes effects of
  - entrainment-mixing
  - cloud contact
  - extent of coupling with surface
- Different regimes have distinctly different trajectories

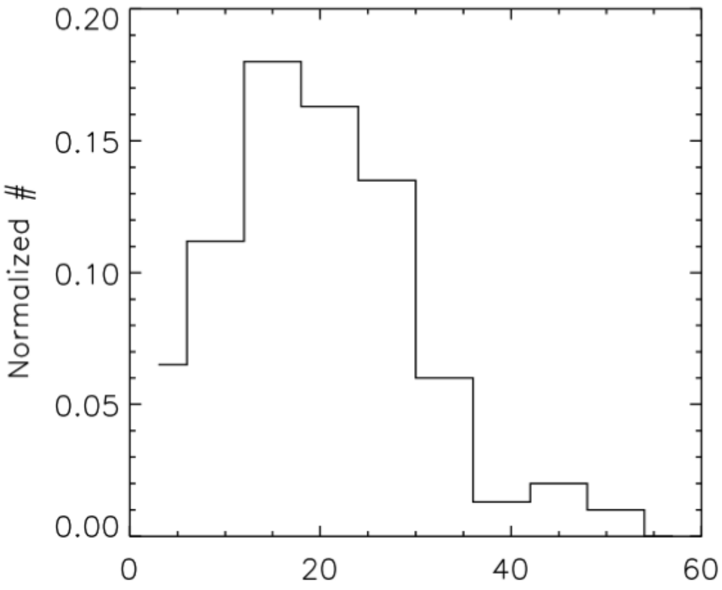
Feingold et al. 1998

Trajectory properties



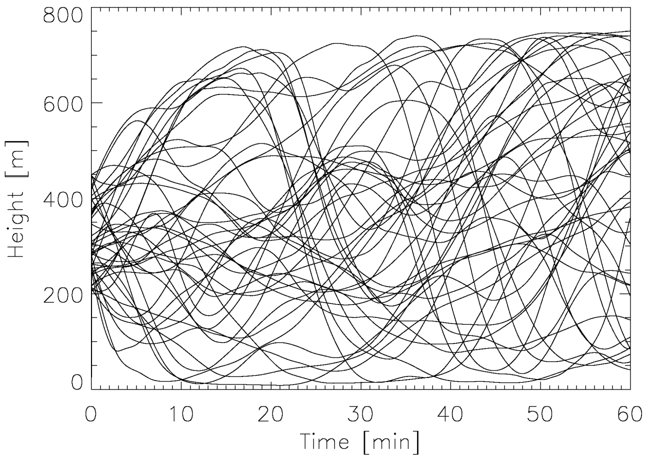
cloud
layer

PDF of in-cloud
residence time



time in cloud, min

Method



- Run microphysical model along set of 500 trajectories
- Parcels represent effects of
  - entrainment
  - activation
  - time varying updraft
  - collision-coalescence
- Each set of simulations is done for a range of aerosol conditions ($25 < N_a < 1000$ cm^{-3})
- Calculate $S_o = -dlnR_i/dlnN_{d,i}$
- Re $\int \mathrm{LWC}(t)dt$ ud residence time, LWC, and (Lagrangian liquid water “path”)

$$\int \mathrm{LWC}(t)dt$$

- Bin by

- *Range of parcel conditions are captured*

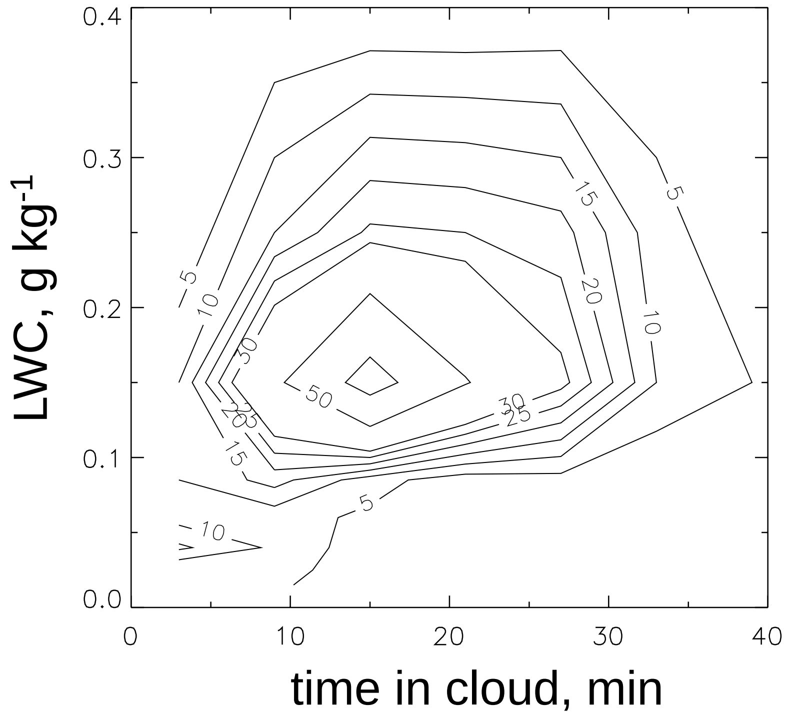
- **Limitations:**
  - No mixing between parcels

LES

$$(R_i, N_{d,i}) = f(T_i, N_a)$$

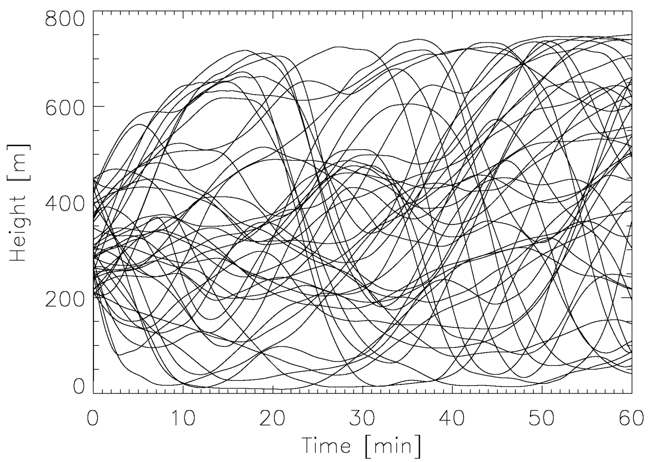
T_i = trajectory properties

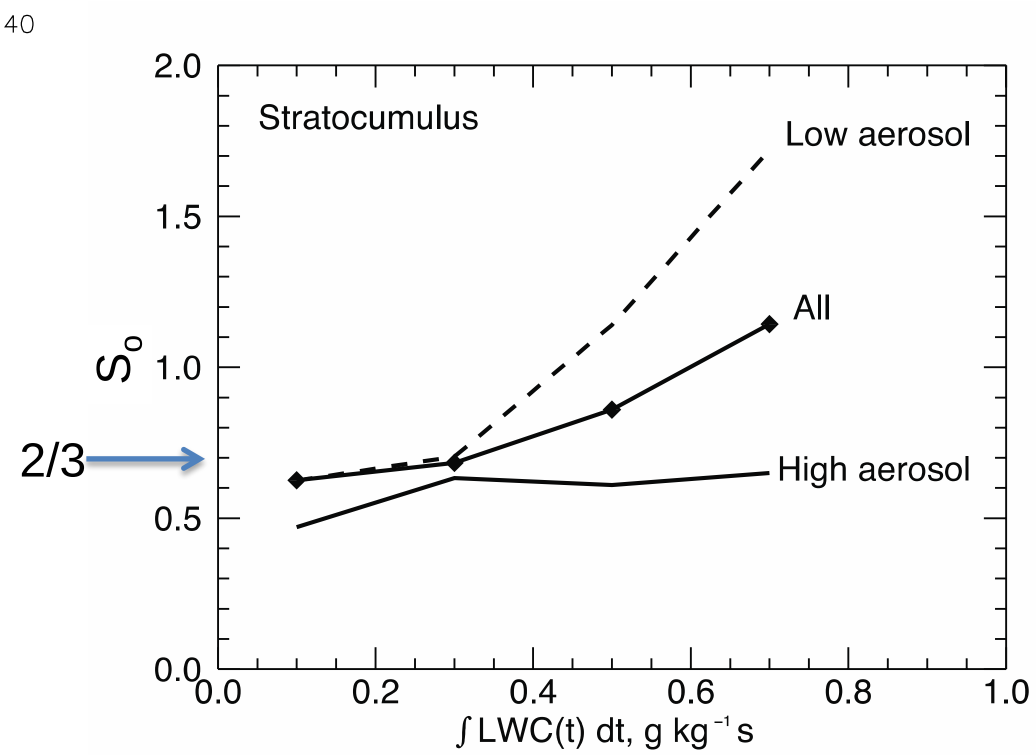
$$T_i = \{t_i, x_i, y_i, z_i, u_i, v_i, w_i, P_i, \theta_i, r_{t,i}\}$$



Stratocumulus

Well-mixed boundary layer:
Broad distribution of cloud contact time

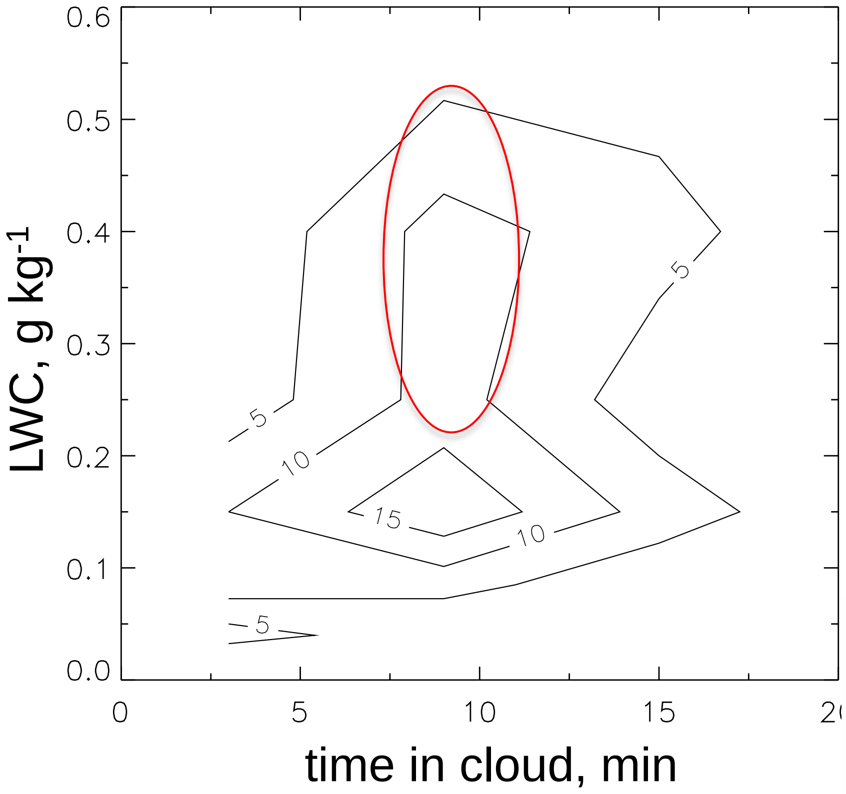


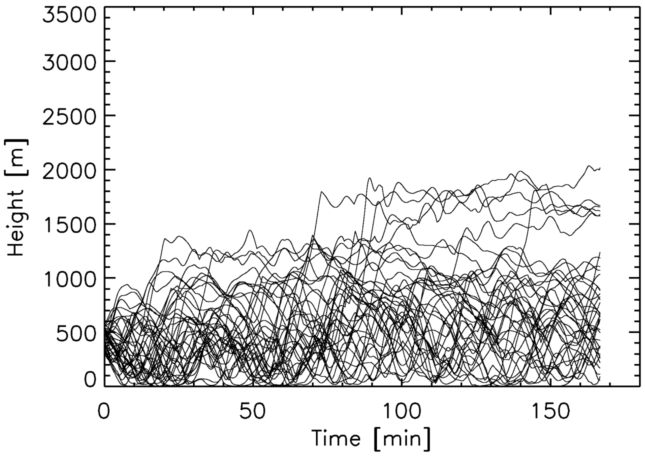


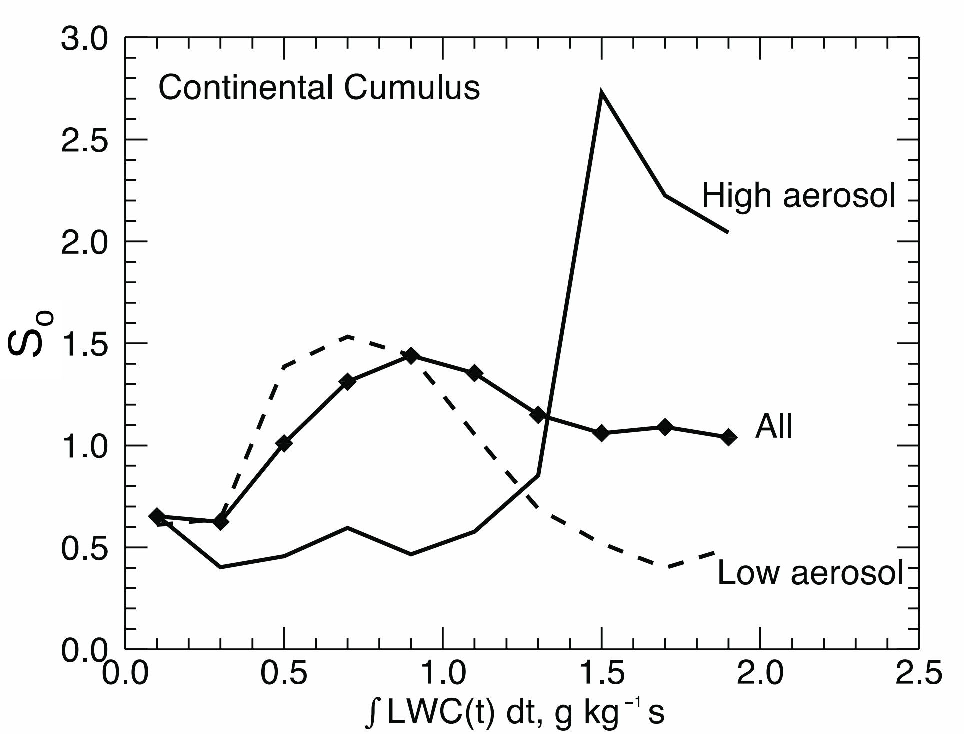
Feingold et al. 2013

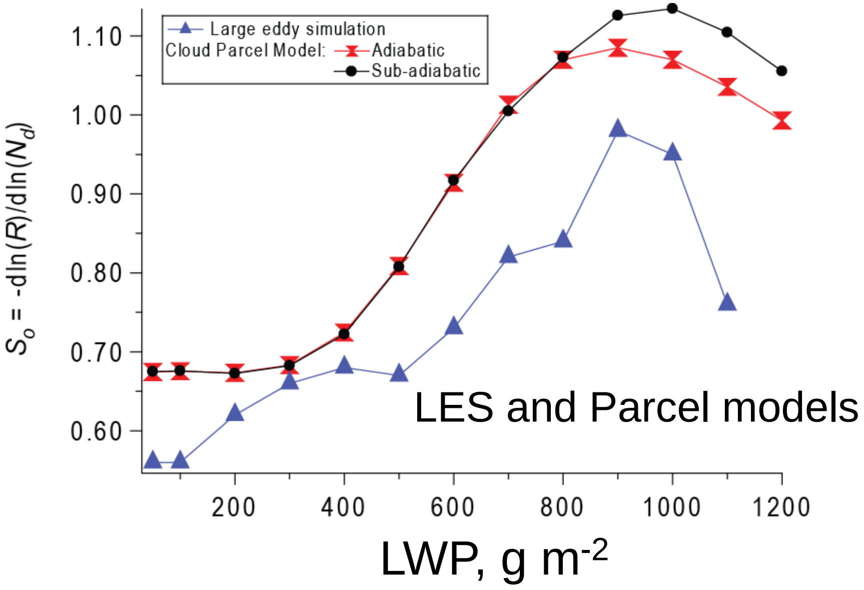
Continental Cumulus

Convective boundary layer: Infrequent contact time but often at high LWC

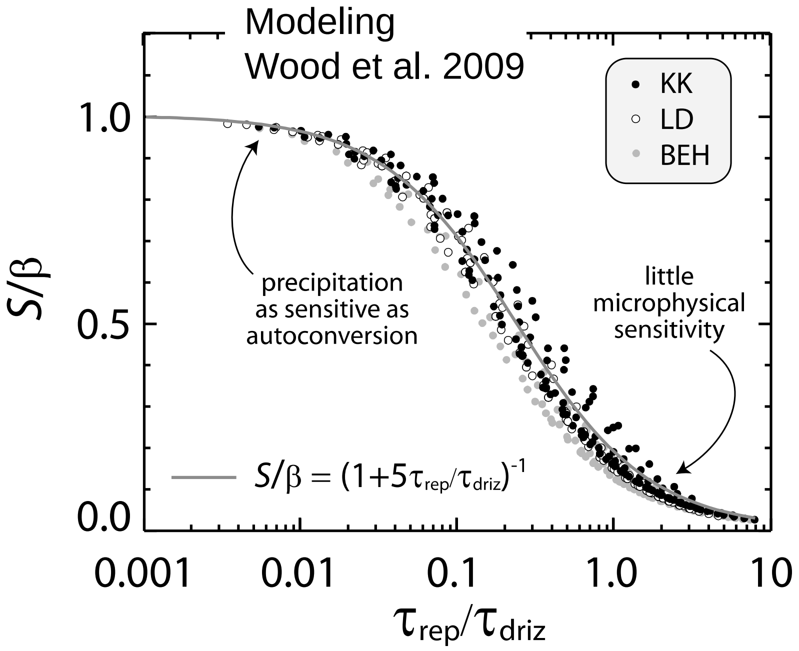








LES and Parcel models



Modeling
Wood et al. 2009

precipitation as sensitive as autoconversion

little microphysical sensitivity

Time-limited

Steady-state
(unlimited time)

Qualitative behaviour is different because of contact time!

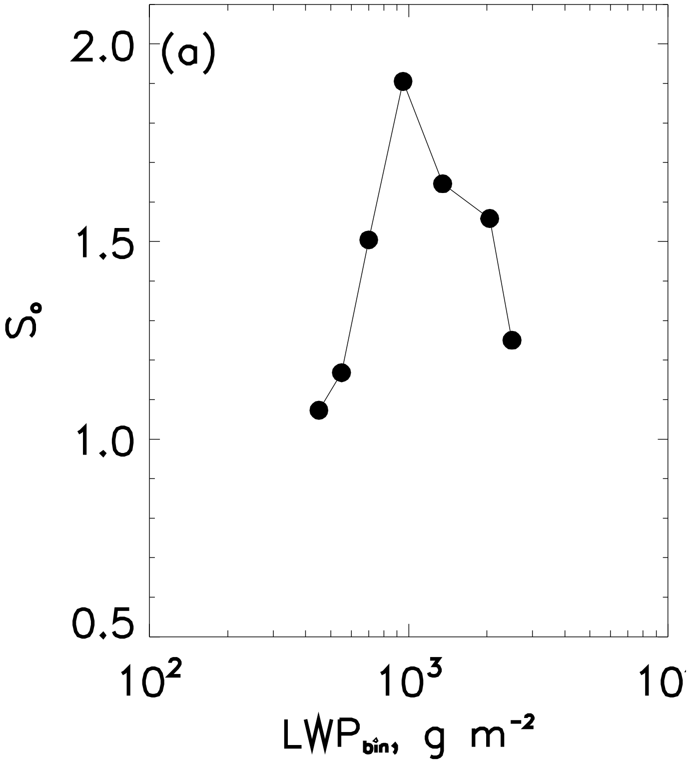
Conclusions Part I

- The increase in precipitation susceptibility S_o with LWP appears to be a result of *limited time* available for collision-coalescence
    - Susceptibility changes as a function of lifecycle of cloud
    - Trajectories tend to have limited in-cloud residence time in well-mixed Scu or in trade cumulus: autoconversion is important
    - Eventually S_o will decrease with LWP (accretion dominates autoconversion and/or in-cloud residence time is long enough)
- Challenge for GCMs:
    - don’t resolve small-scale convection
    - many don’t retain any memory of the precipitation process from one time step to the next

LES of Trade Cumulus (tracking individual clouds)

$$I = \int R(t)\,dt = C\,LWP^{\alpha} N_d^{-\beta} t_c^{\gamma}$$

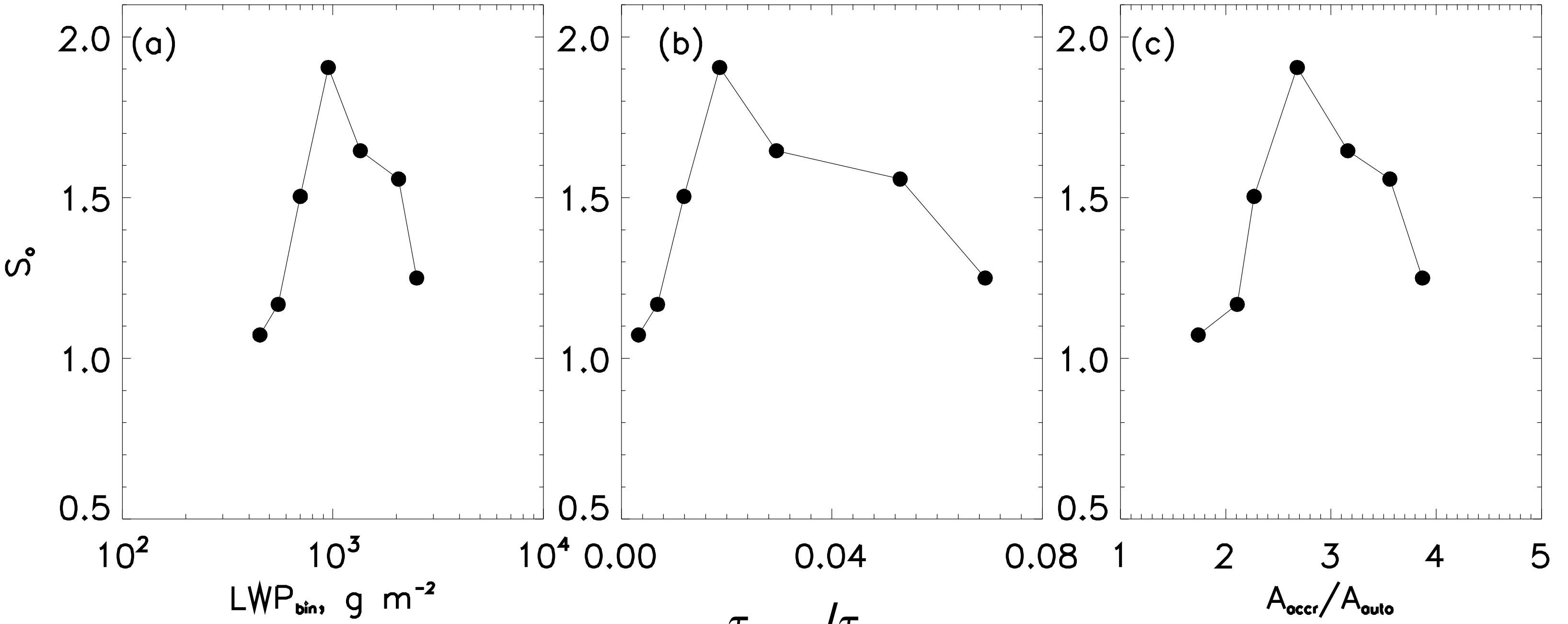
For cumulus:
α = 1.9
β = 0.9
γ = 1.2



Modified RICO sounding to produce more rain

Jiang et al. 2010 (JGR

LES of Trade Cumulus (tracking individual clouds)

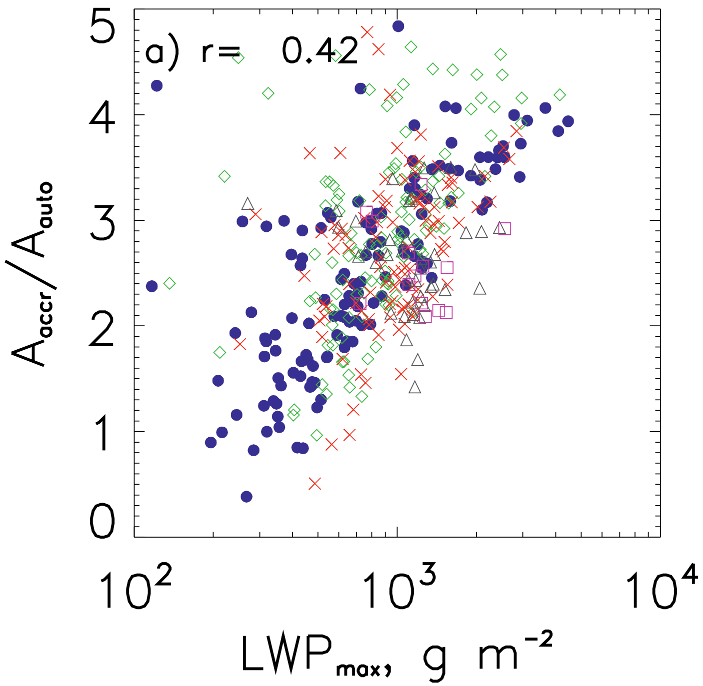


τ_{cond}/τ_{driz}

A_{accr}/A_{auto}

Jiang et al. 2010 (JGR

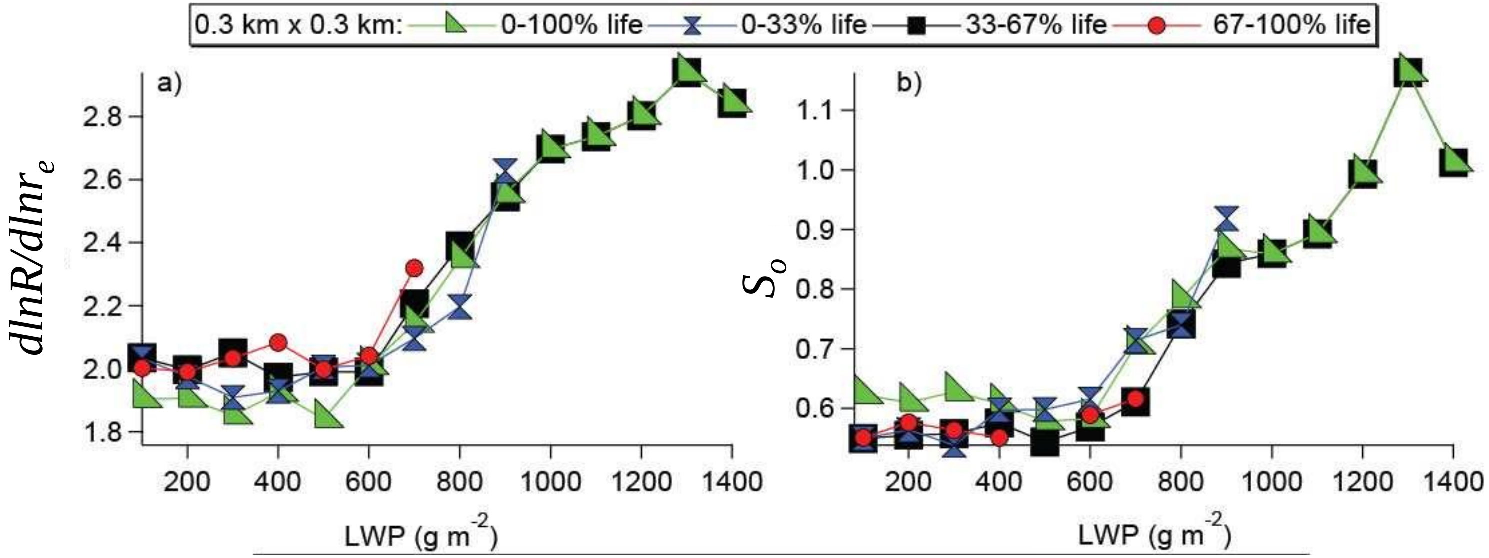
LES of Trade Cumulus (tracking individual clouds)



Jiang et al. 2010 (JGR

Analysis of individual trade cumuli generated by LES

0-100% 0-33% 33-67% 67-100%



Influence of lifecycle of cloud

- S_o changes as cloud lifecycle progresses
- R response to r_e captures the essence of S_o (both in terms of qualitative shape and lifecycle dependence)

Duong, Sorooshian, Feingold 2011

Analysis of individual trade cumuli generated by LES

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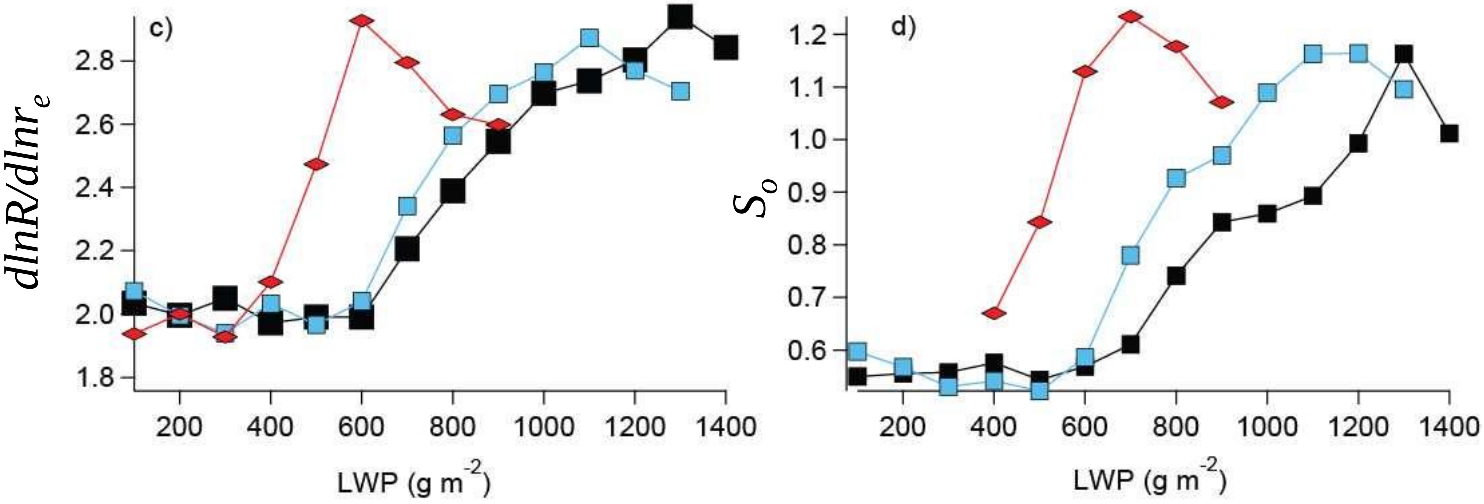
- Quantifying S_o is difficult
  - Scale, aggregation

0.3 x 0.3 km 0.5 x 0.5 km 0.7 x 0.7 km

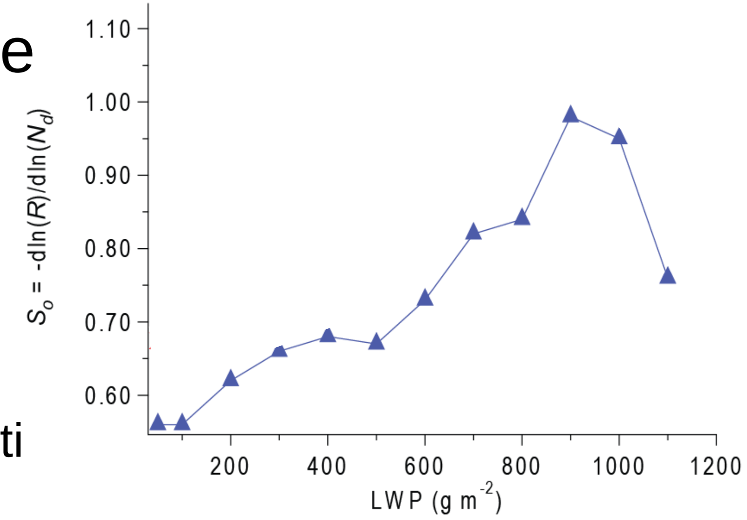


Influence of averaging

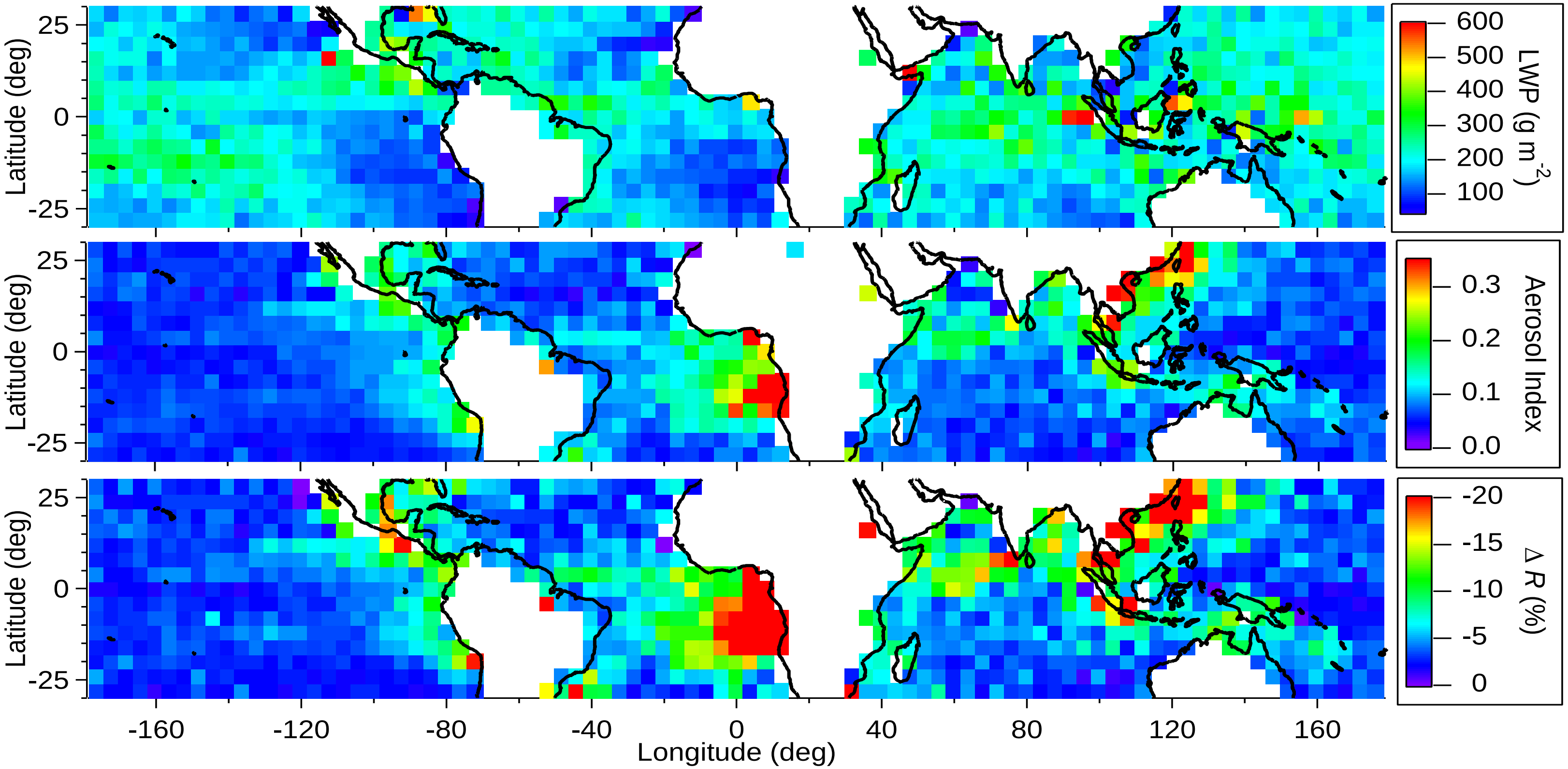
Duong, Sorooshian, Feingold 2011

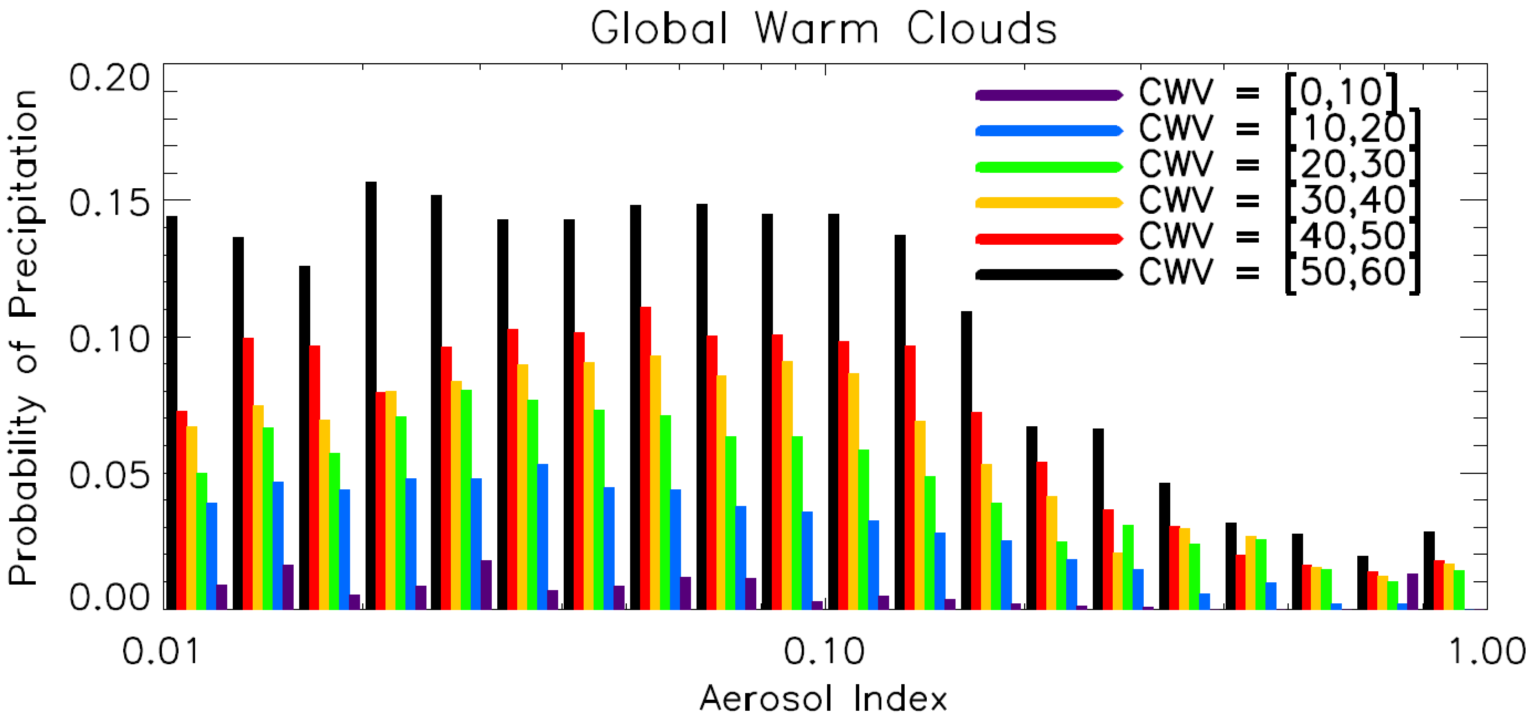
S_o represents a potential for influence

How might this map out globally?



Convolving S_o with LWP and aerosol perturbati



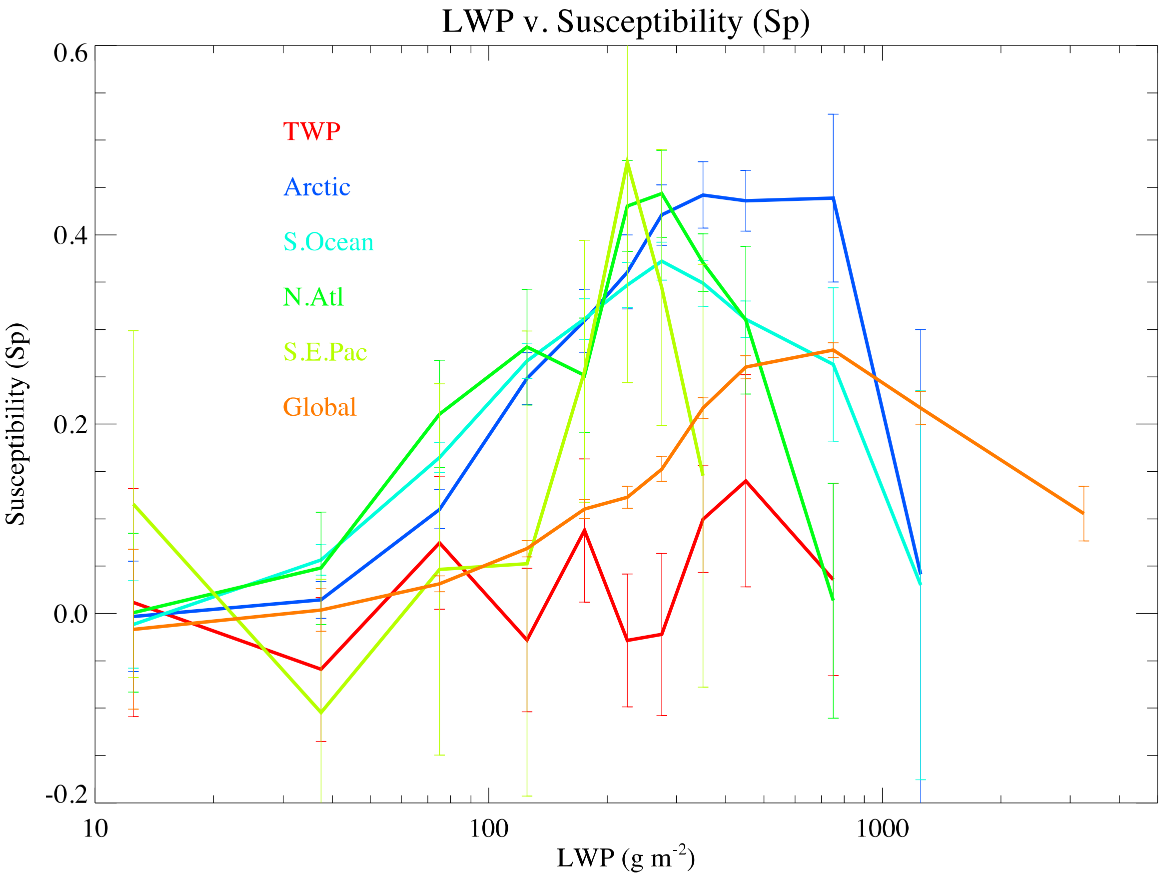


POP decreases with increasing aerosol - more so at higher water va

Lebsock, Stephens, Kummerow: CloudSat and MODIS data

Susceptibility in Climate Models

Used to diagnose balance of Autoconversion and Accretion



Gettelman et al. 201