Old and New Paradigms for Aerosol-Cloud-Precipitation studies

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DOE/ASR Science Team Meeting

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A brief history of the world…

current

Mixed-messages

1800s: Coulier, Aitken, Wilson: Aerosol is necessary for droplet formation

1920s, 30s: Aitken; Kohler (CCN)

1938: importance of giant CCN for drizzle (Houghton)

1960s: Aerosol suppresses rain (Squires, Warner)

1970s: Aerosol brightens clouds (Twomey)

1989: Aerosol increases lifetime (Albrecht)

1997: semidirect effect (Hansen)

2005: “invigoration” (Koren et al.)

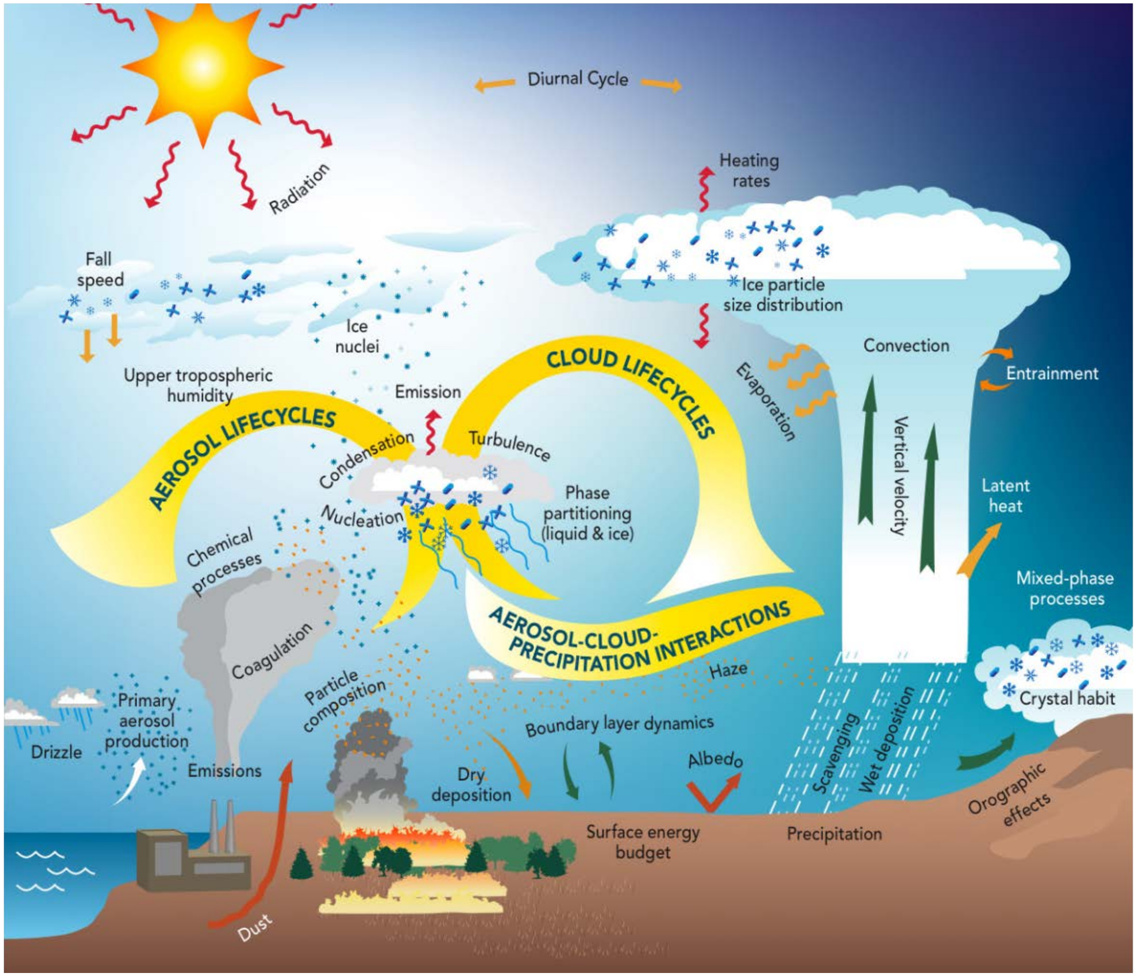
The outcome

- A series of aerosol indirect effects
  - 1^{st}, 2^{nd}.. n^{th}
  - often poorly defined
  - misinterpreted
  - shoe-horned into climate models, often without regard to scale, aggregation

This Talk

- The Mesoscopic view
- Order
- Preferred Modes
- Robustness of Modes
- Transitions between Modes
- Simplified Equation Sets

Strongly coupled system: Aerosol-Cloud-Dynamics-Radiation-Land Surface



From DOE/ASR Science and Program Plan

- Complexity at a huge range of spatiotemporal scales
- Number of degrees of freedom of this system is staggering
- Important implications for climate

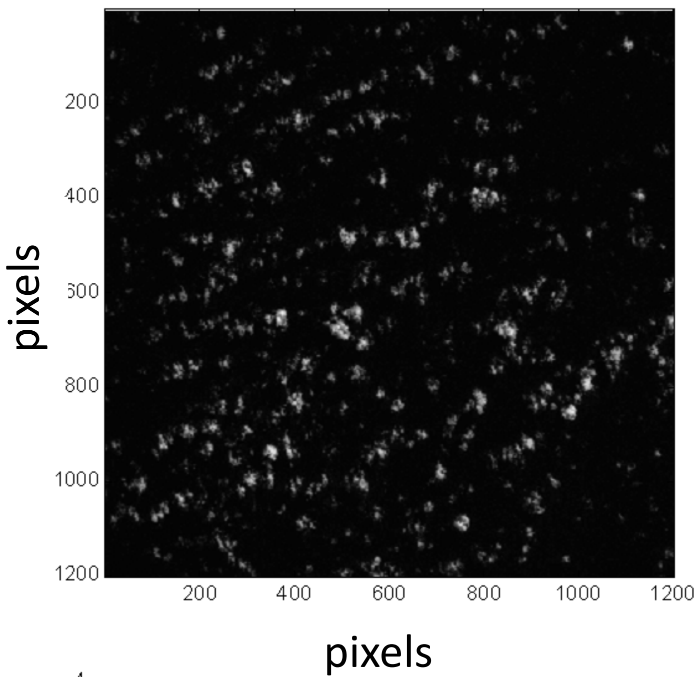
Mesoscopic Order

Microscopic = individual birds or grains of sand
Mesoscopic = bird flock or sand dune

Don't need to model every bird or every grain of sand to obtain the emergent properties of the system

Order

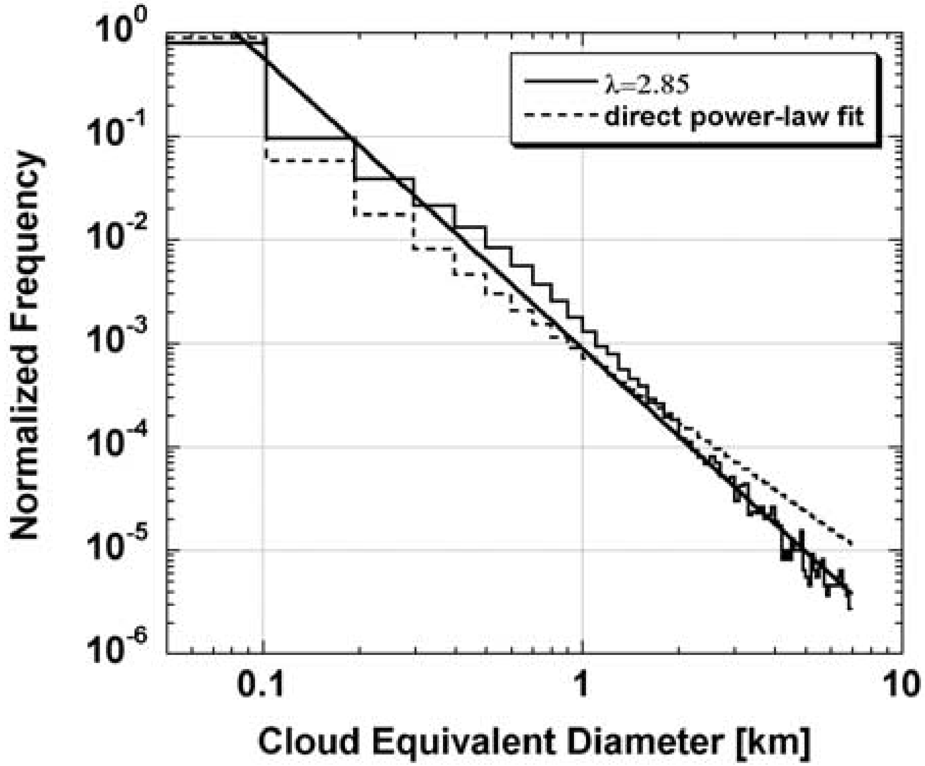
- Cloud Size distributions follow power laws

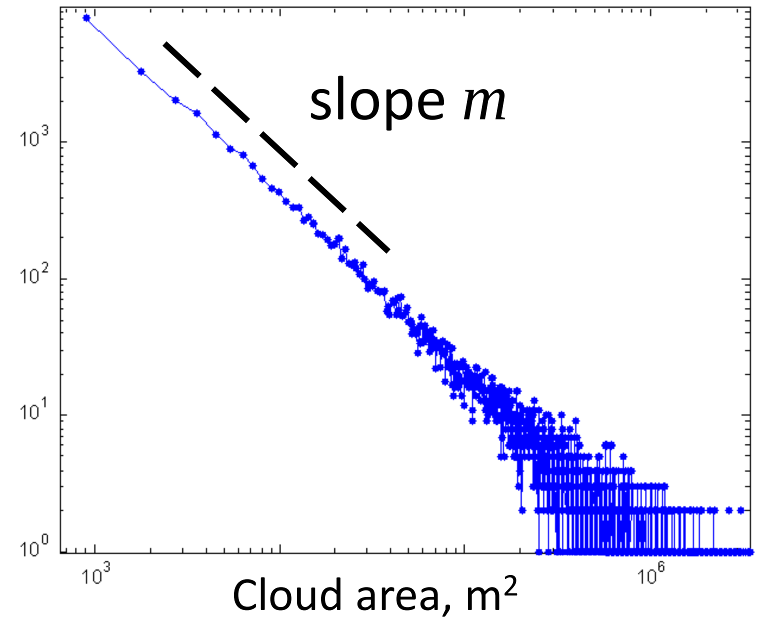


Landsat 30 m imagery

Photo: Barbados (CIRPAS Twin Otter)

Cloud Size Distributions





$$n(a) = ba^{-m}$$

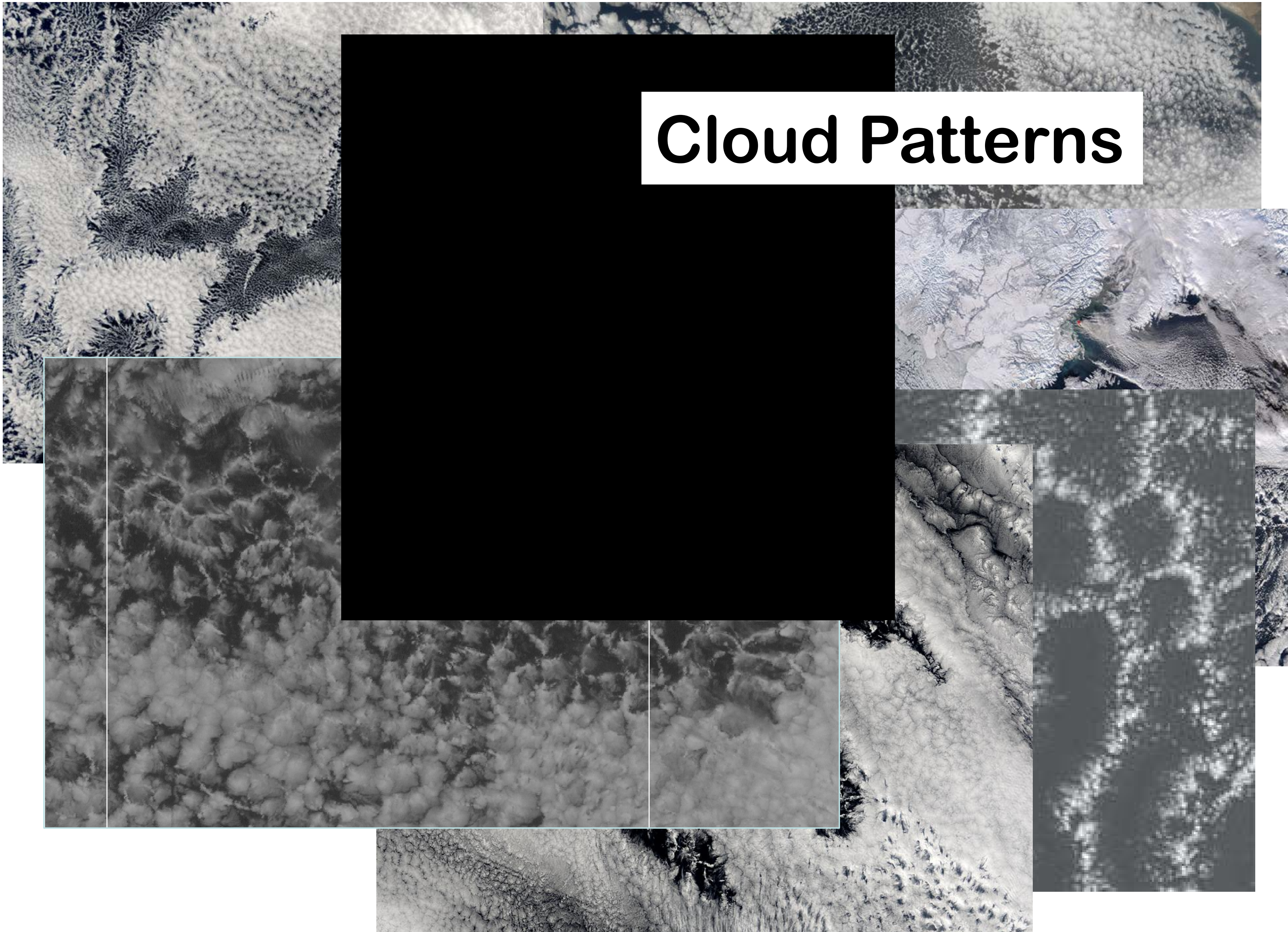
a = area of individual cloud

Zhao and DiGirolamo 2007
ASTER 15 m imagery

Koren, et al., 2008
Landsat 30 m

See also Benner and Curry, 1998

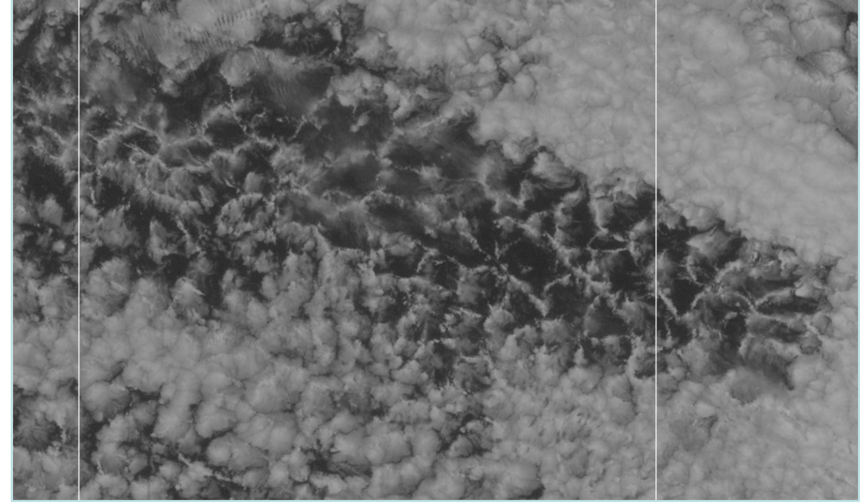
Cloud Patterns

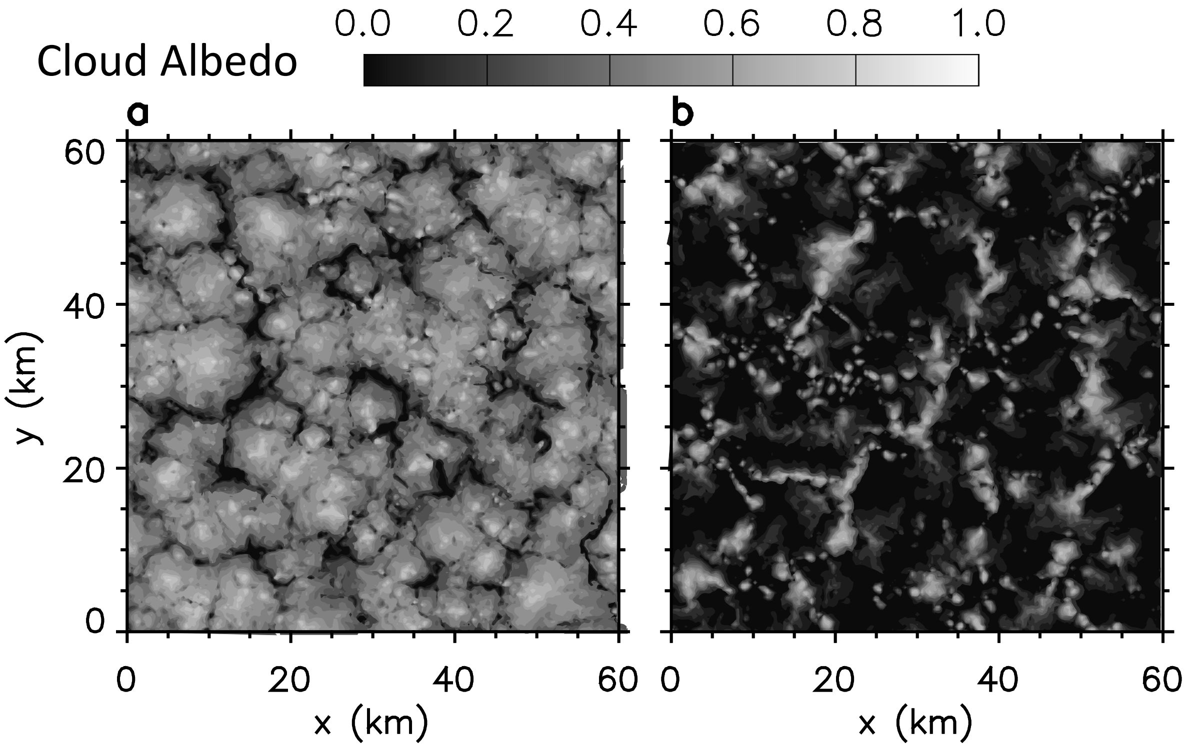


MODIS, MISR, GOES images

Preferred Modes

Open and closed-cells

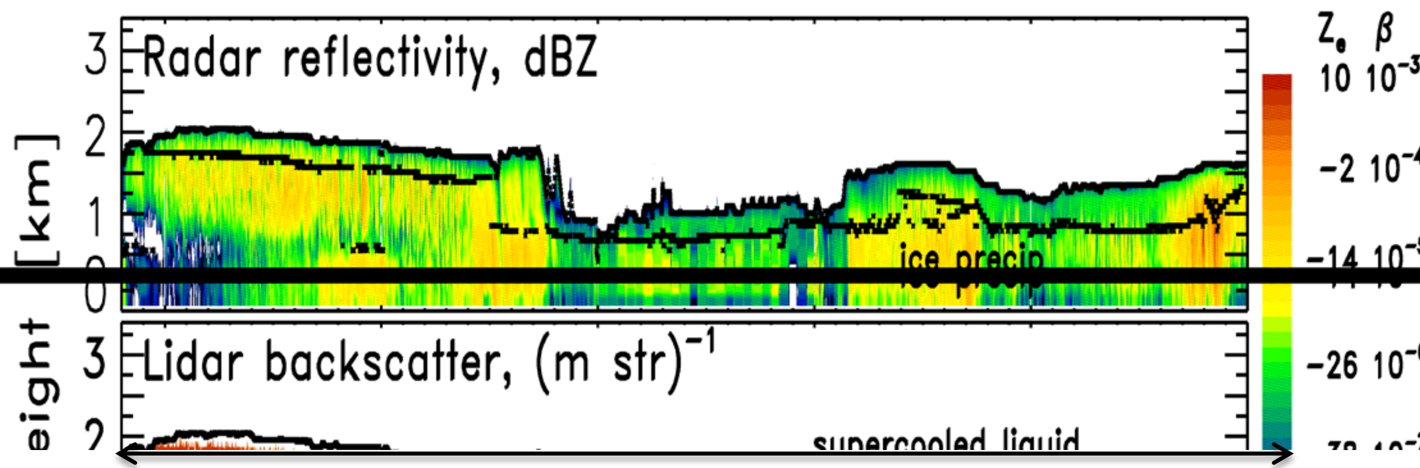




Feingold, Koren, Wang, Xue, Brewer (2010)

See also Bretherton et al. 2004; Stevens et al. 2005; Savic-Jovcic and Stevens 2008; Xue et al. 2008; Wang and Feingold 2009

Resilient Mixed Phase Arctic Stratus

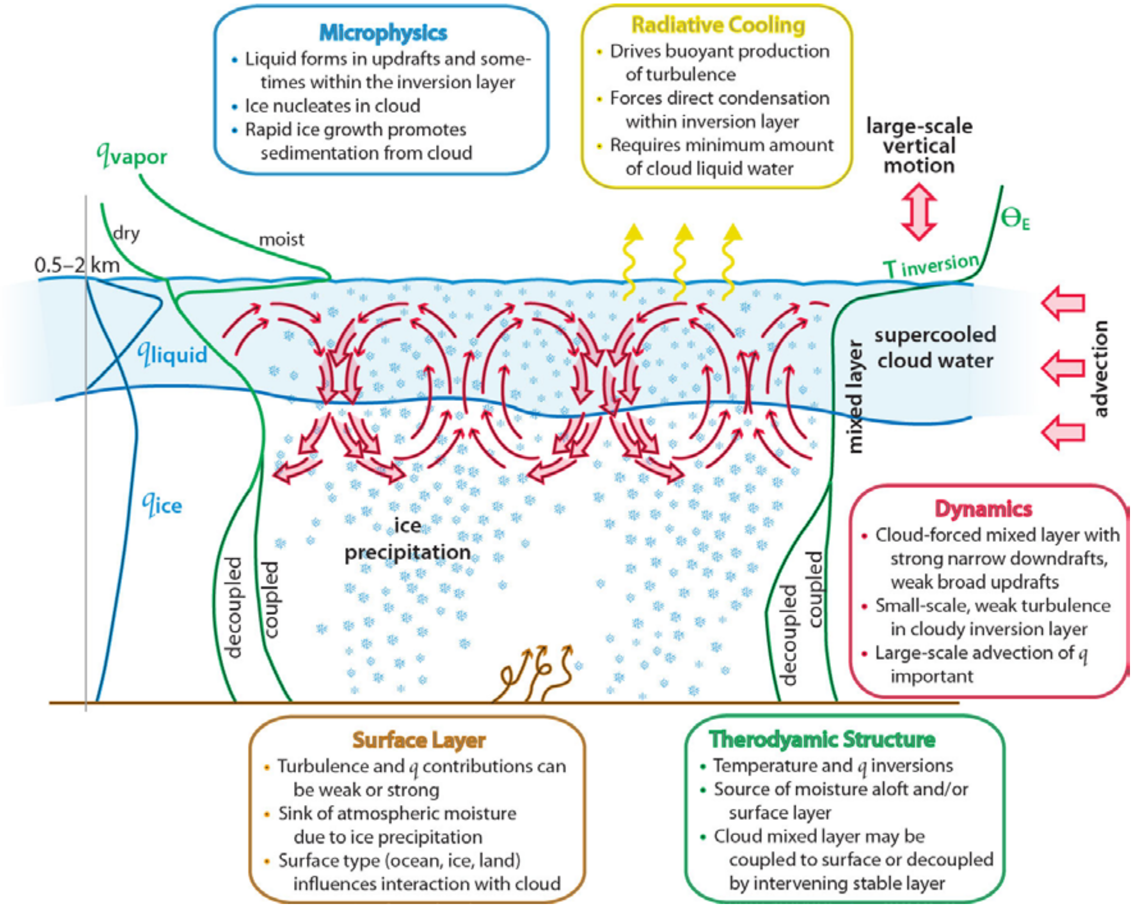


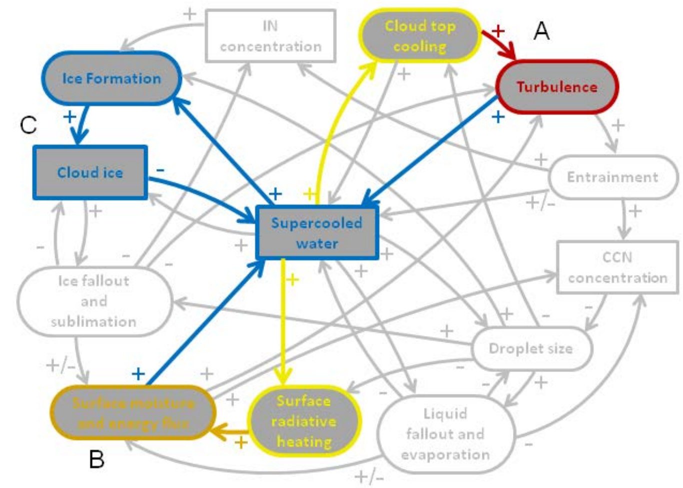
Clouds persist for days on end

Why is this cloud system stable when ice is present??

Morrison, DeBoer, Feingold, Harrington, Shupe, Sulia, Nature Geo. 2011

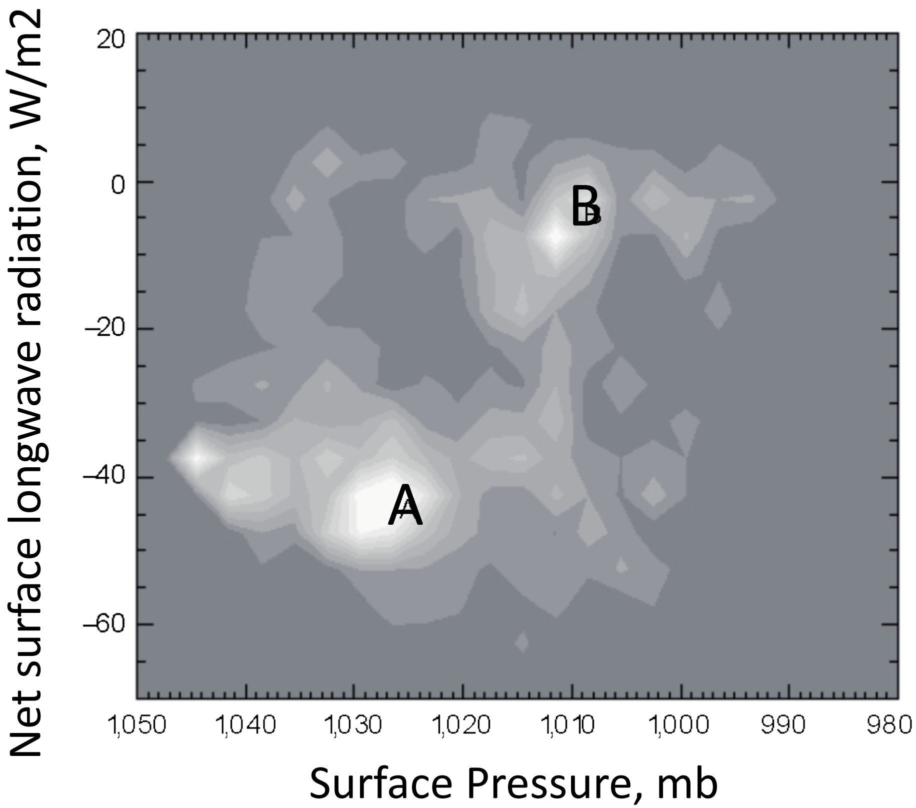
Many complex interactions → system wide order





Morrison, DeBoer, Feingold, Harrington, Shupe, Sulia, Nature Geo. 2011

Preferred States



A and B are resilient stable states

A = Radiatively clear
B = Cloudy

See also Stramler et al. 2010

Morrison, DeBoer, Feingold, Harrington, Shupe, Sulia, Nature Geo. 2011

Transition between States

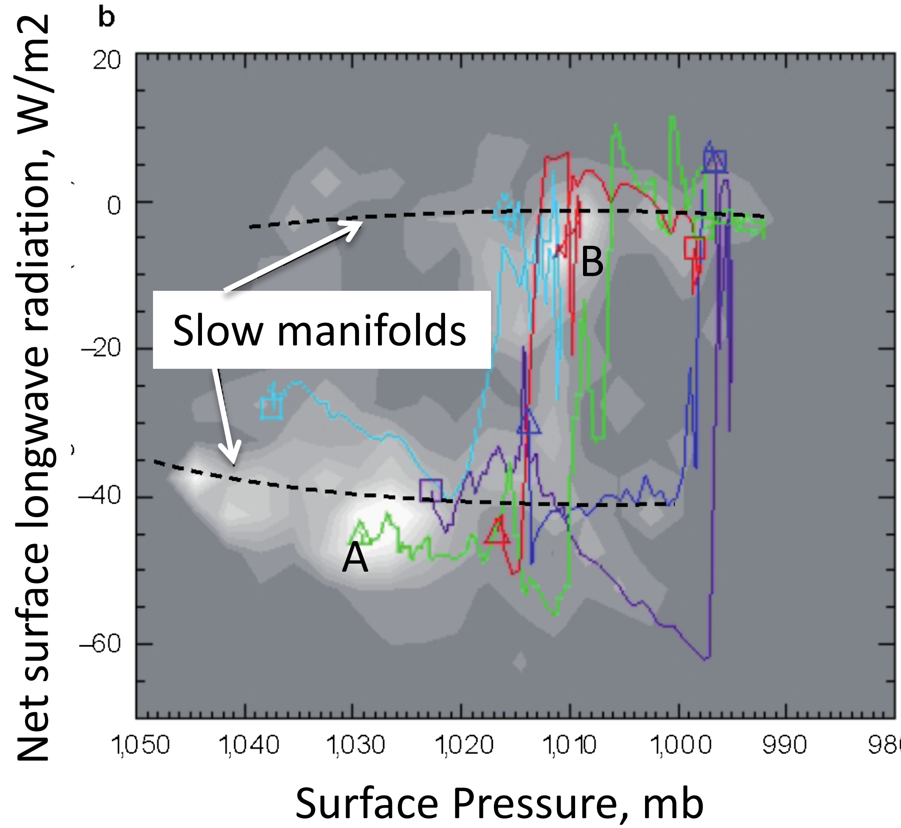
Fast processes: local interactions

Slow processes: broad meteorological environment

Fast processes "slave" system to the slow manifold

Transitions occur when changes to the largescale environment are significant

Support from LES (e.g., Solomon 2011)

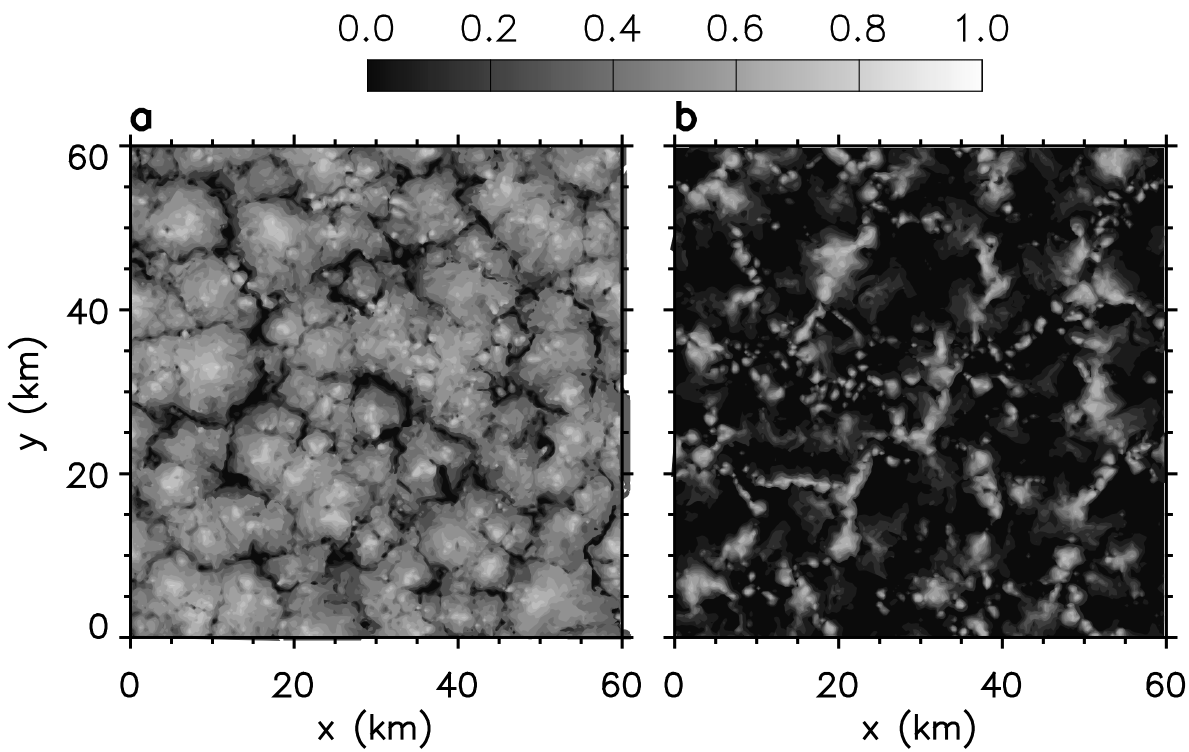


Colored trajectories: transition between states
Triangle = start; square = end

A = Radiatively clear
B = Cloudy

Aerosol Influences

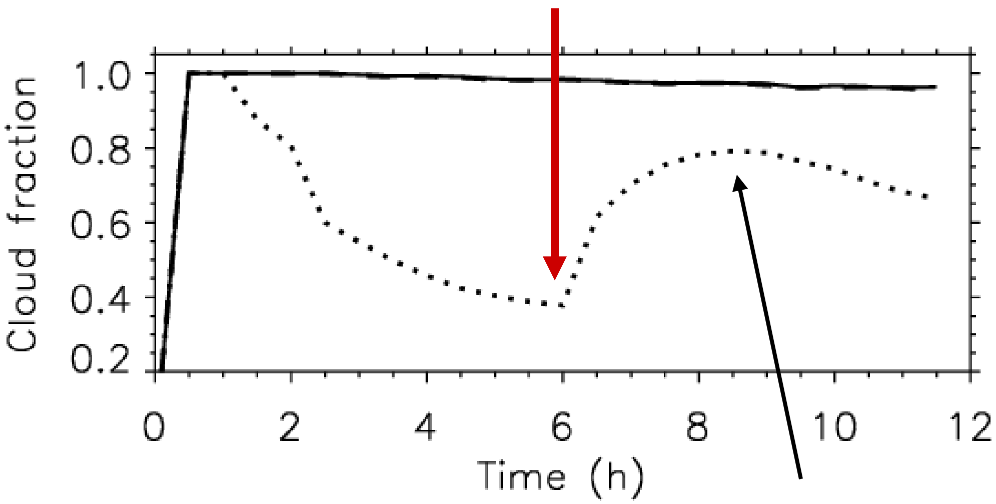
How resilient are the open and closed-cell states?



Resilience

Self-organising systems are resilient to change

Massive aerosol perturbation



Closed-cell case

Open-cell with massive aerosol perturbation (65 → 300 cm^{-3}) at 6h

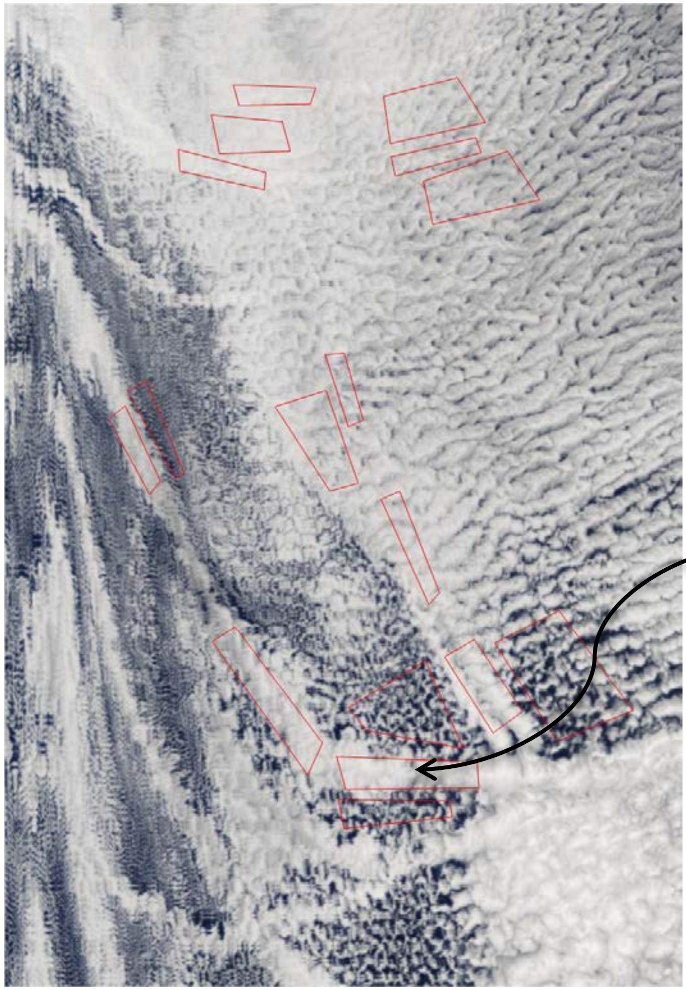
-Thin “anvil cloud” lacks dynamical support

- Cells remain open

- *a certain amount of random perturbation may facilitate rather than hinder self-organization*
- *possible implications for geoengineering (Wang et al. 2011)*

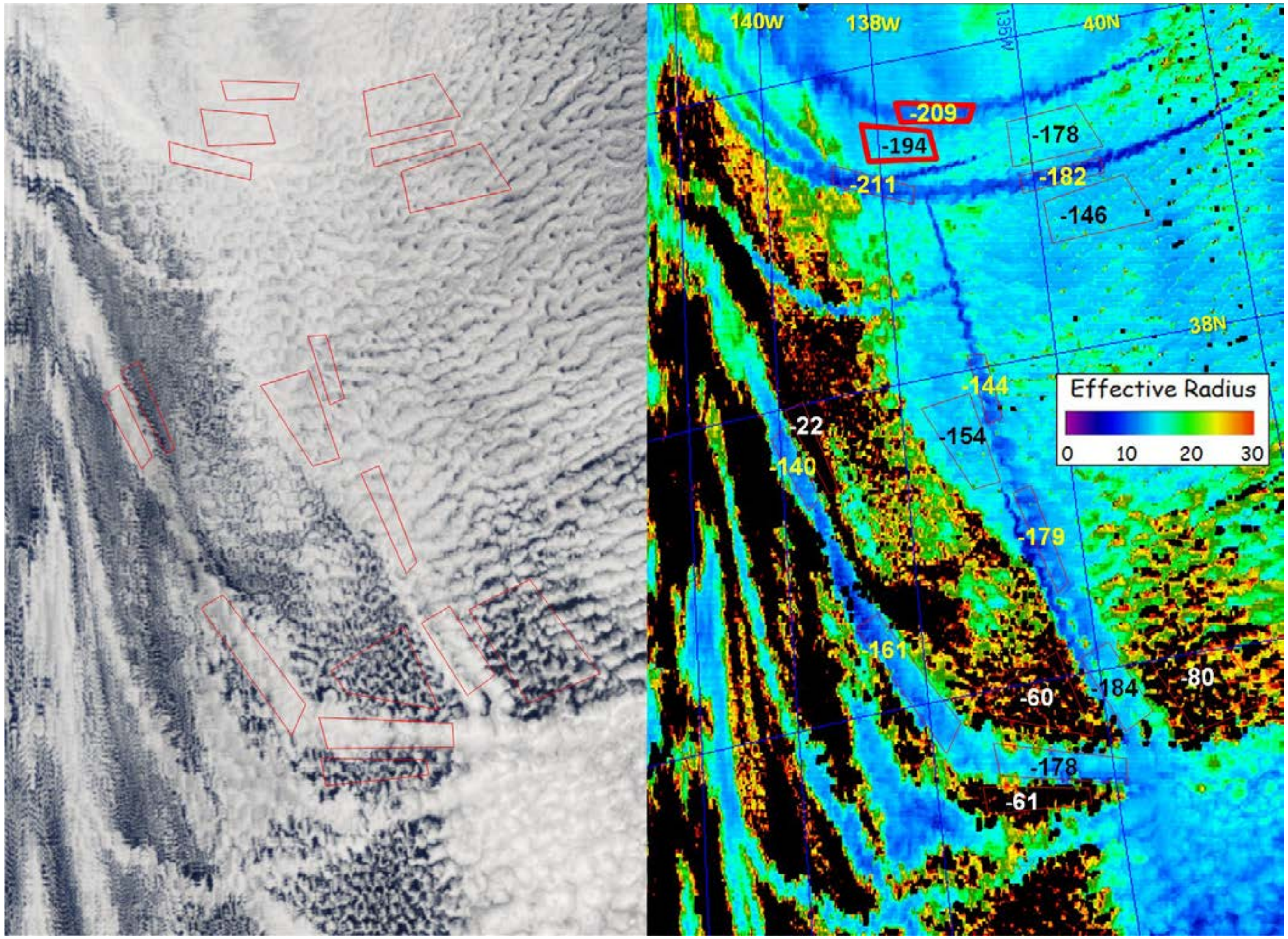
Wang and Feingold, 2009b

The counter example!



Distinct closing of open cells by ship tracks

Goren and Rosenfeld, 2012



Goren and Rosenfeld, 2012

Aerosol influences in trade cumulus

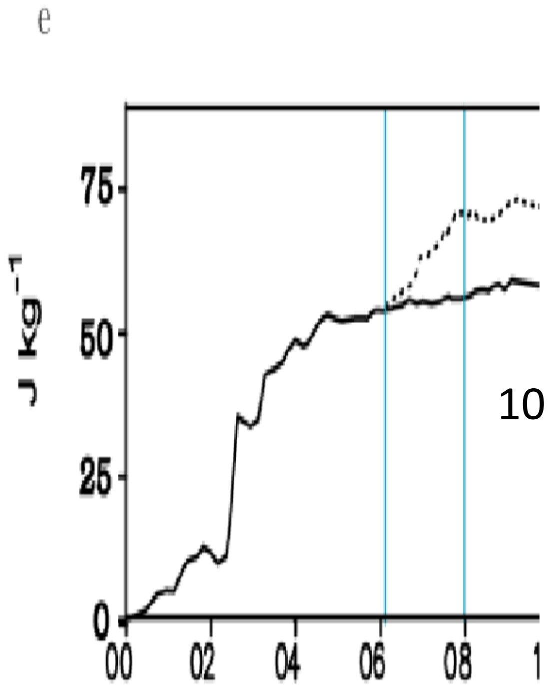
Photo Jen Small
RICO clouds

Robust features vs. Transients

RICO

LWP

w'w'



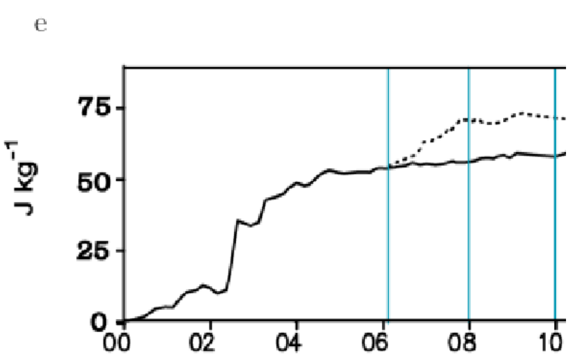
10 h

τ for inversion adjustment: days

τ for thermodynamic adjustment ~ 0.5 days

10 h

CAPE



Clean (50 cm^{-3})

Polluted (250 cm^{-3})

Lee, Feingold, Chuang, 2012

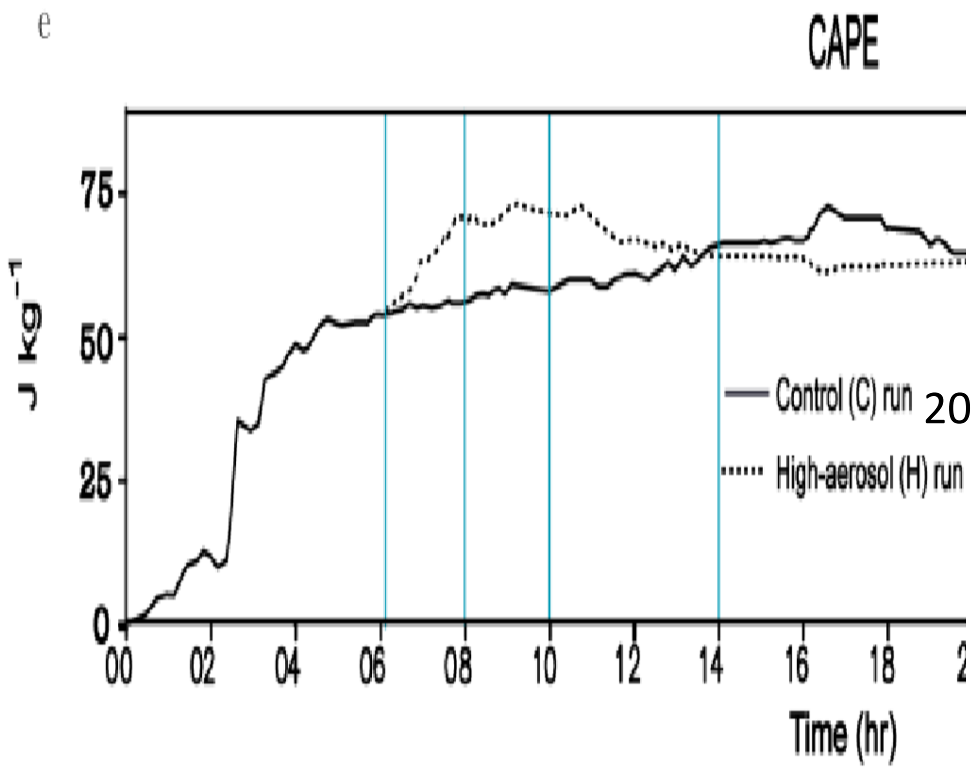
10 h

Robust features vs. Transients

RICO

LWP

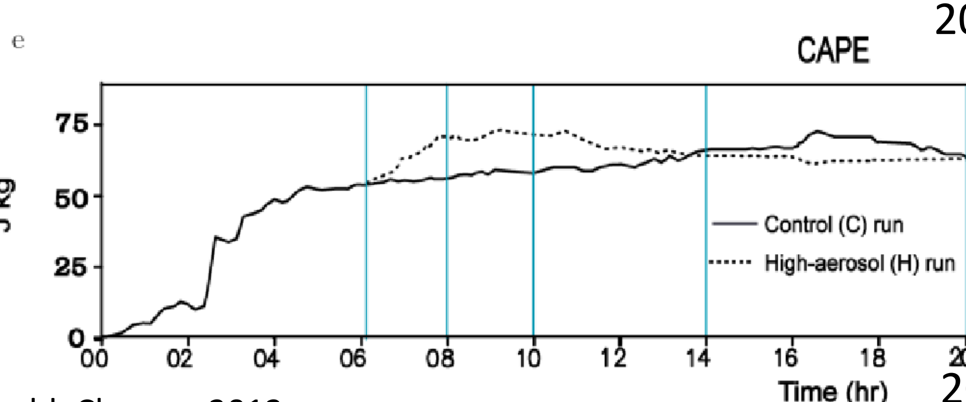
w'w'



20 h

20 h

CAPE



20 h

Clean (50 cm^{-3})

Polluted (250 cm^{-3})

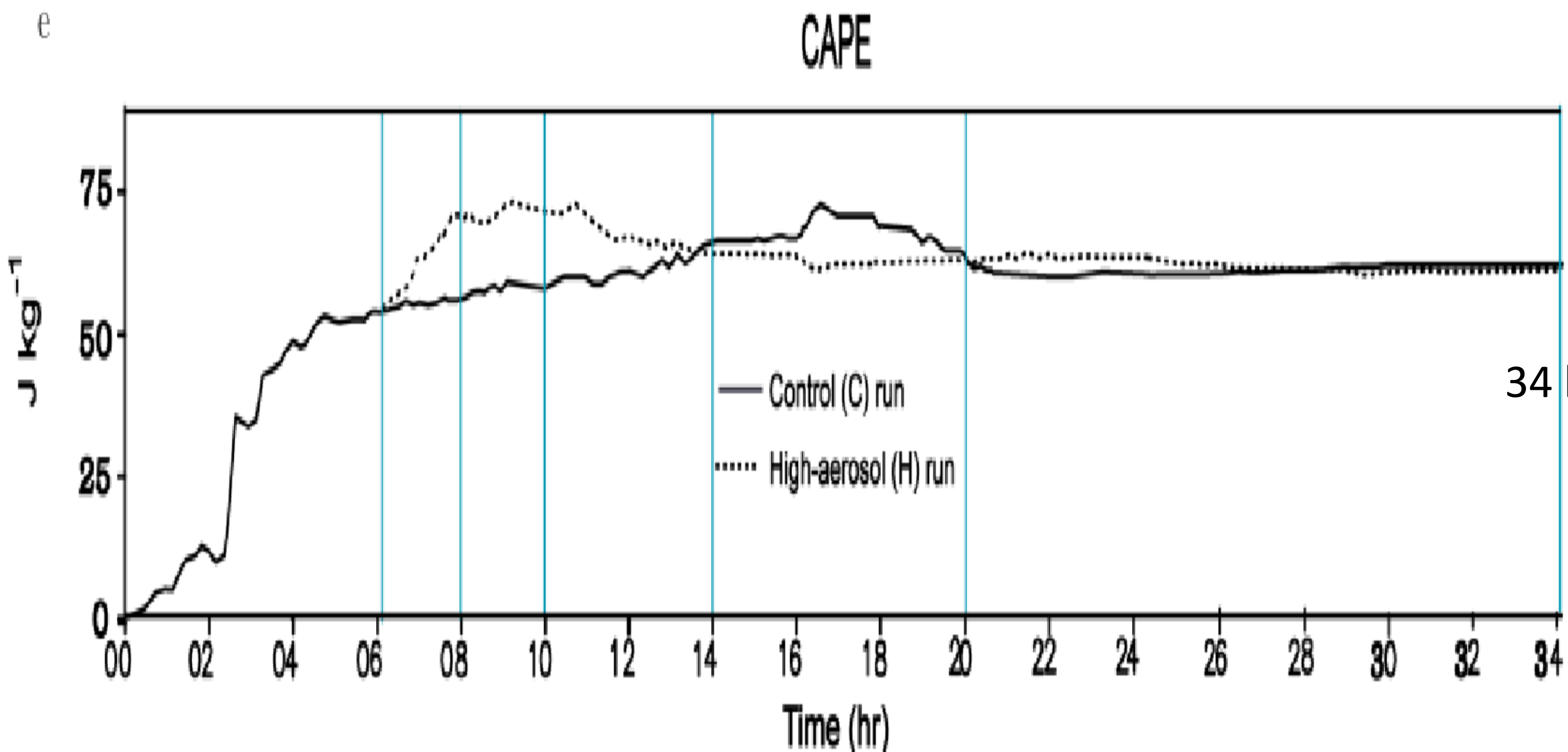
Lee, Feingold, Chuang, 2012

Robust features vs. Transients

RICO

LWP

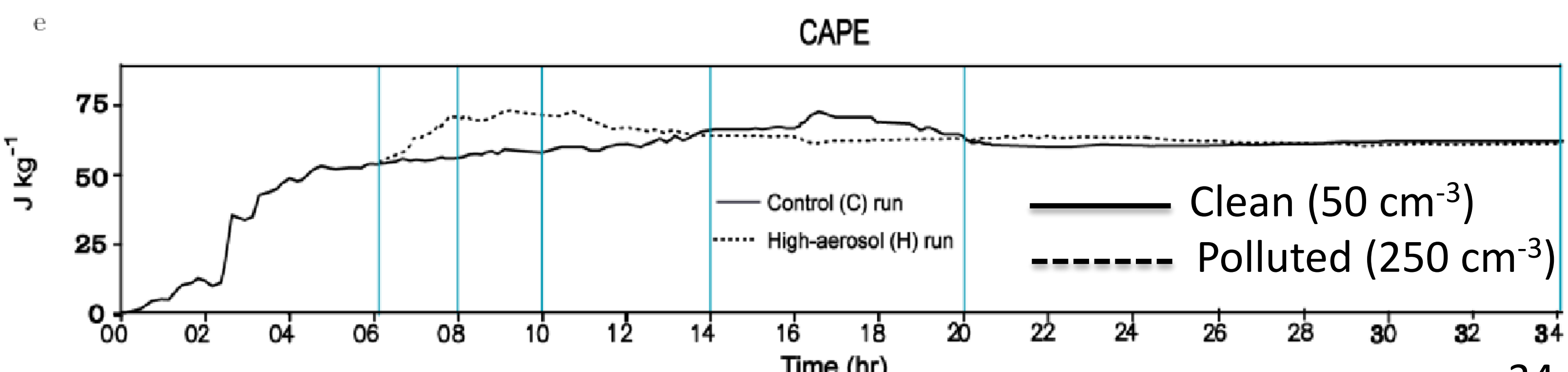
w'w'



34 h

34 h

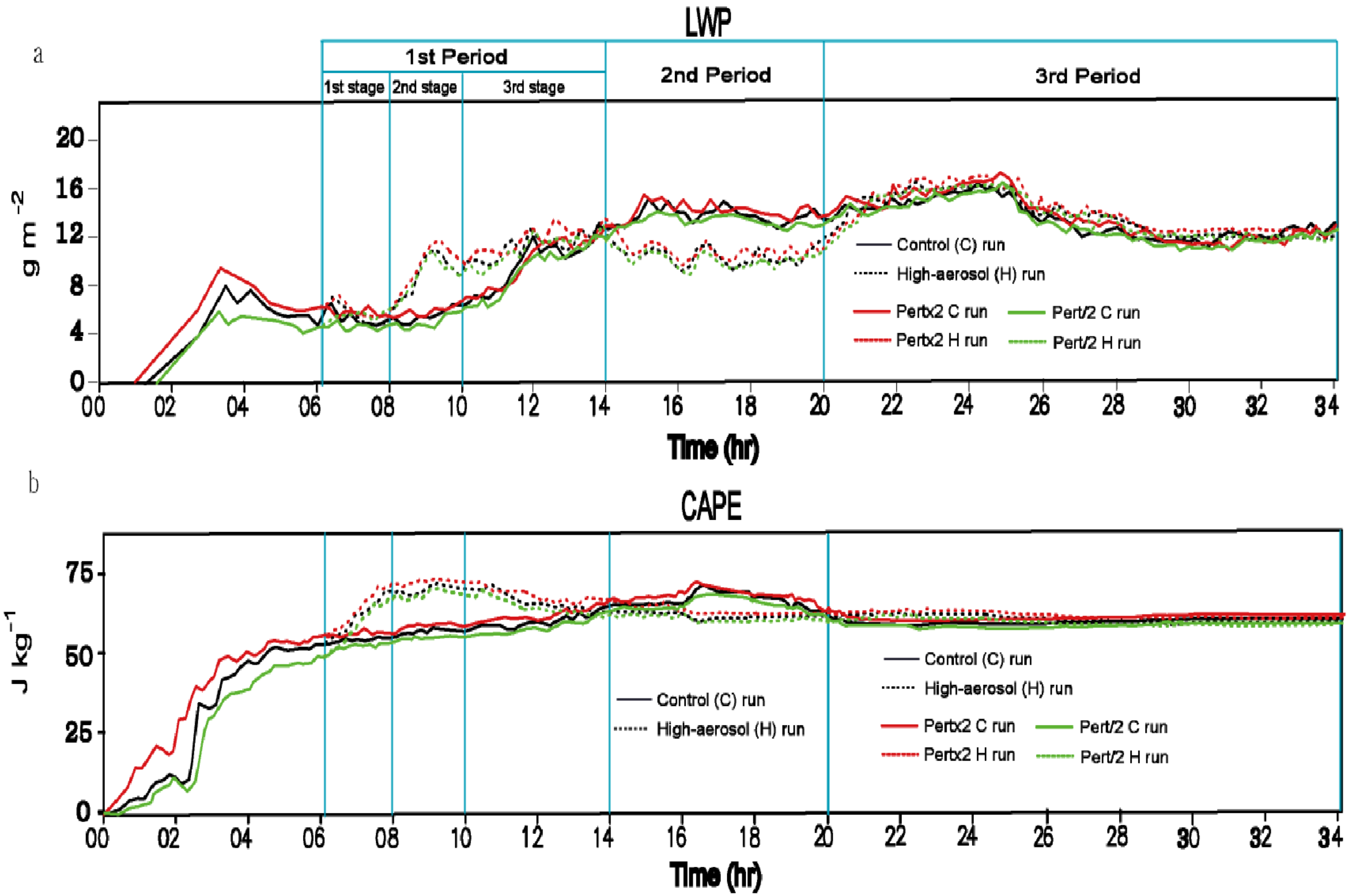
CAPE



Lee, Feingold, Chuang, 2012

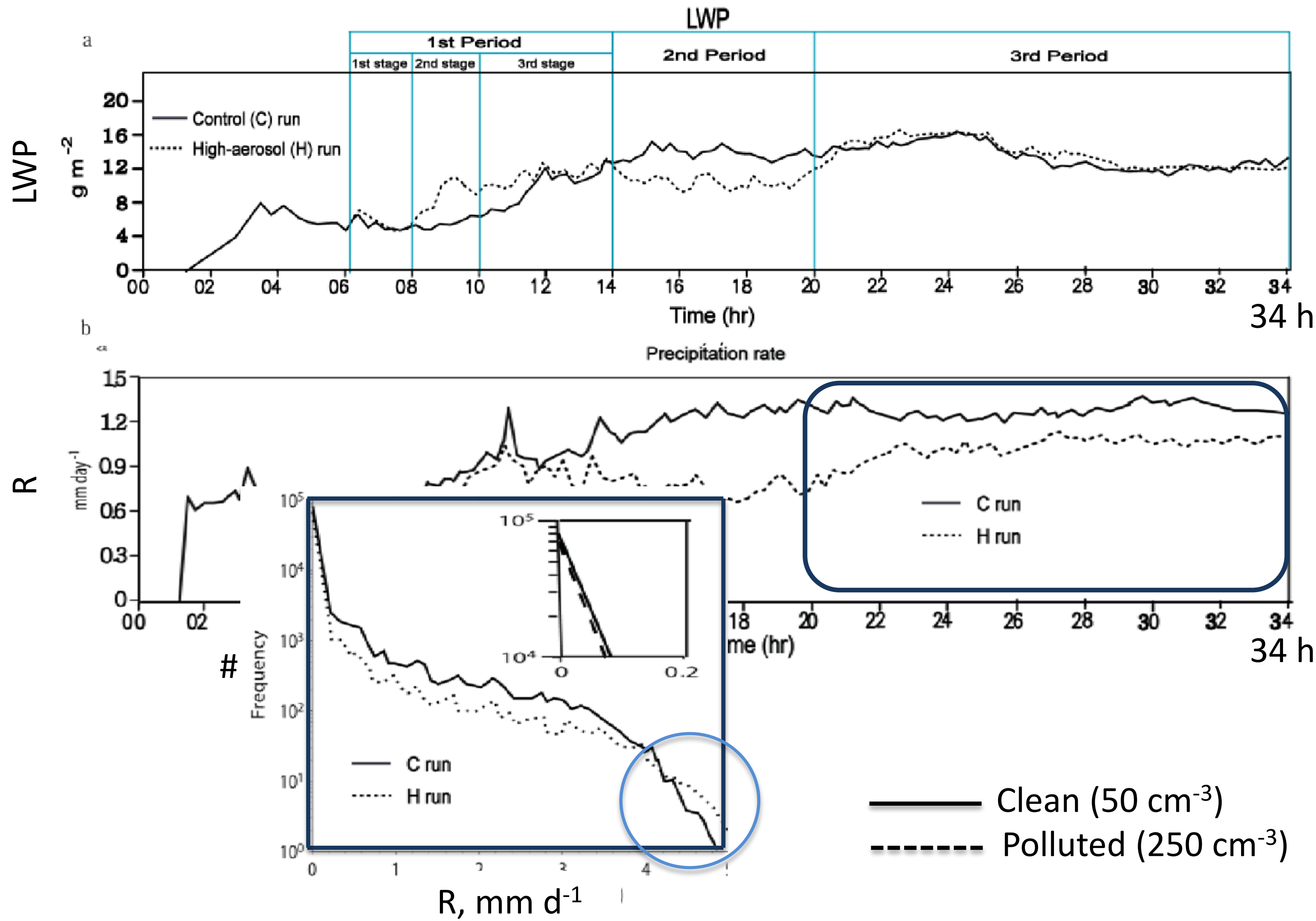
34 h

“RICO Ensemble”



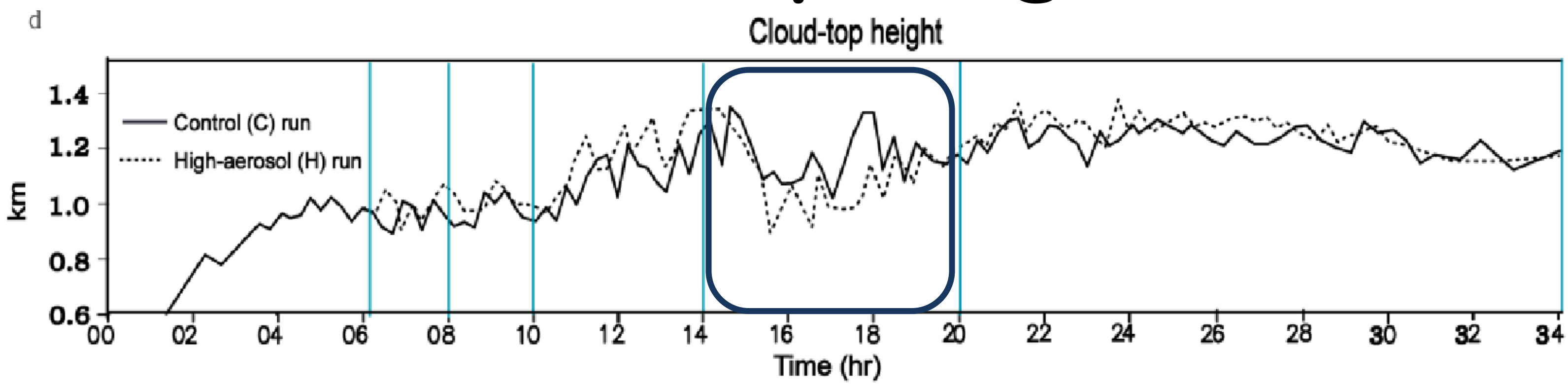
Many fields converge to a steady state

Rainrate

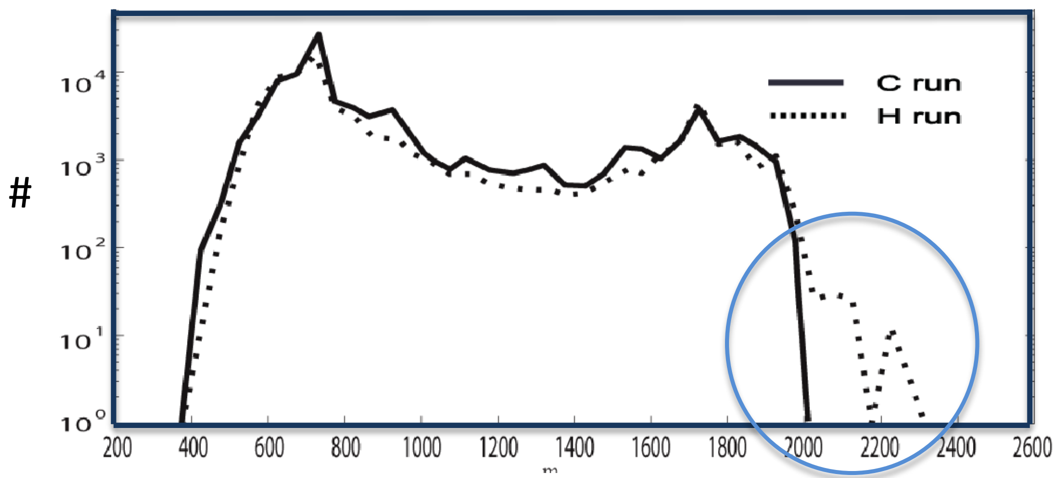


Lee, Feingold, Chuang, 2012

Cloud-top height



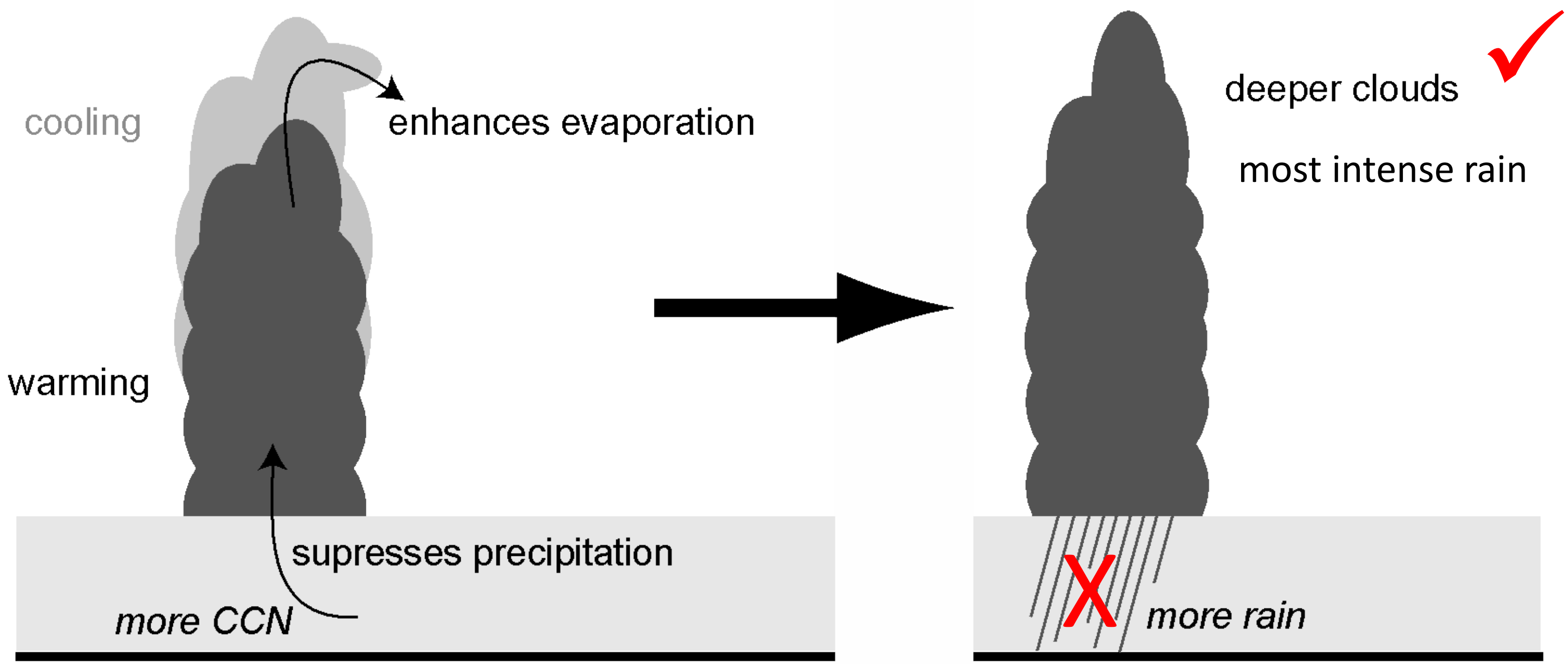
Clean (50 cm^{-3})
Polluted (250 cm^{-3})



Cloud top height, m

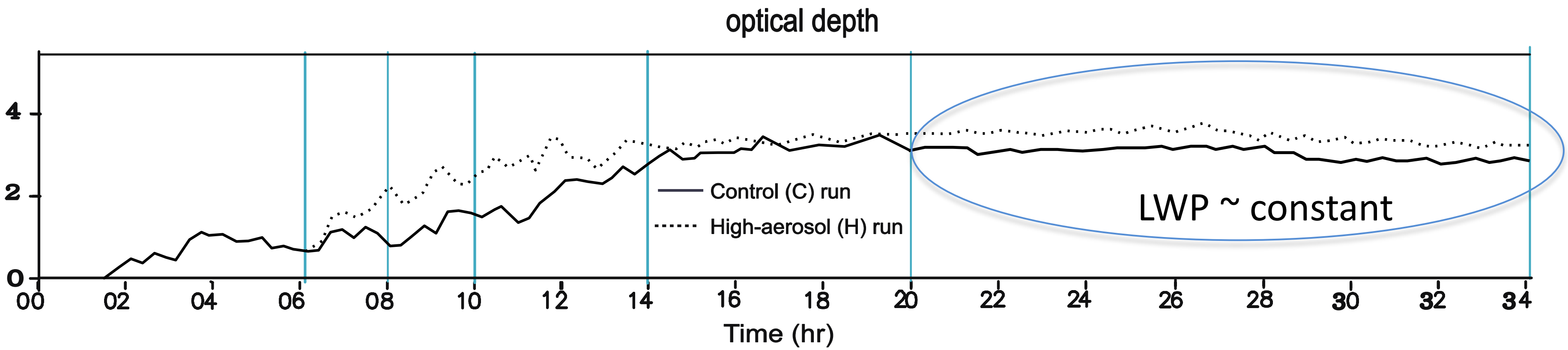
Even when the clean case is more active, the deepest clouds are associated with high aerosol

Lee, Feingold, Chuang, 2012



Stevens and Feingold 2009

Influence on cloud optical depth



Only about half of the Twomey increase in albedo is realised

i.e., 1/2 x (250/50)$^{1/3}$

Clean (50 cm^{-3})

Polluted (250 cm^{-3})

Aerosol influences on deep convective clouds

Preferred modes?

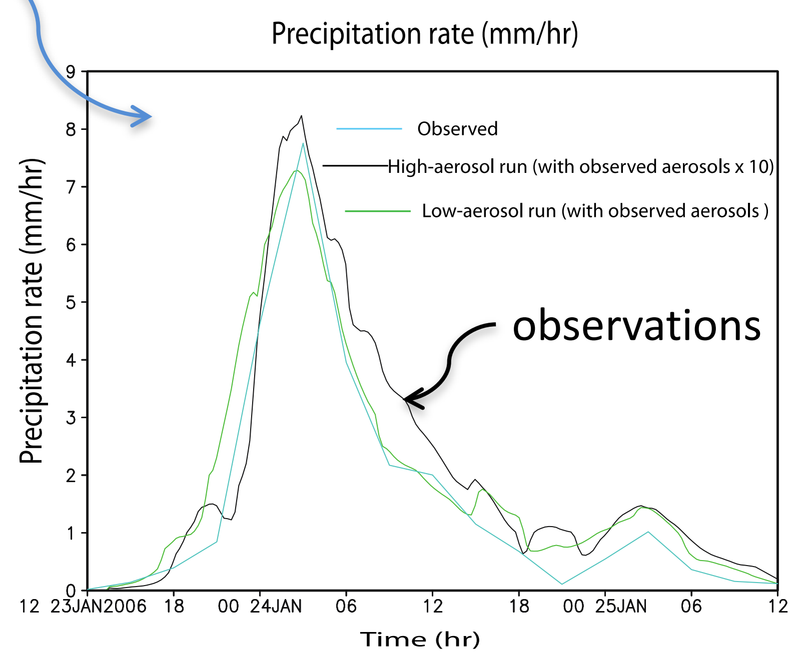
TWP-ICE: Strongly forced: very weak aerosol influence on mean R

Precipitation rate

TWP-ICE

Morrison and Grabowski (2011)
EULAG + M-microphysics

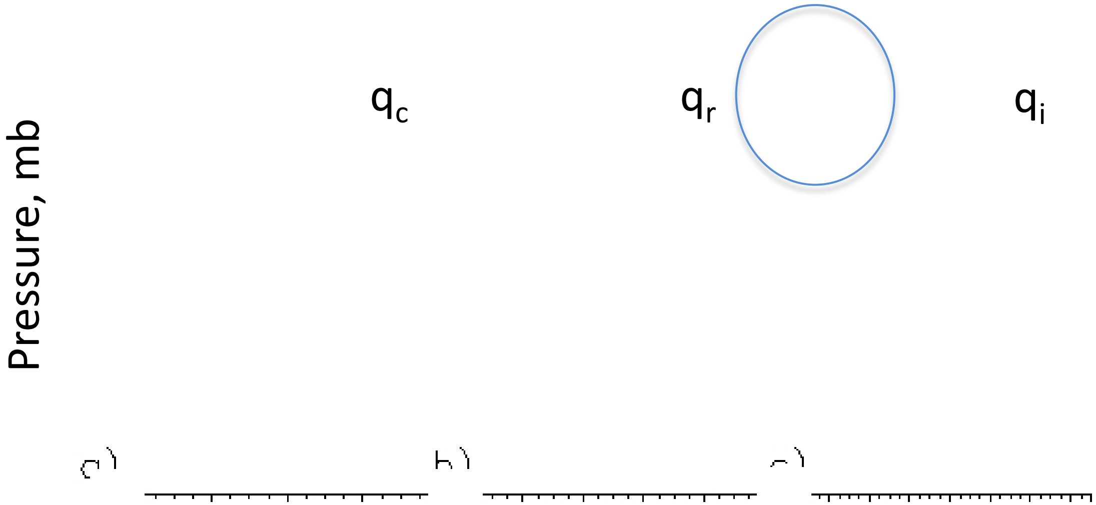
3 ~ superimposed lines for different aerosol



- *Similar mean R*
- *< 10% increase in total precip over 2 day period for 10x increase in aerosol*

Lee and Feingold (2012)
GCE+RAMS microphysics

TWP-ICE: Invigoration?

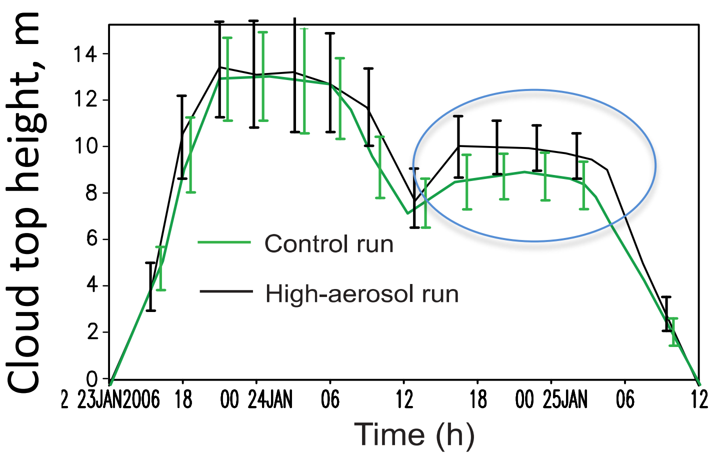


Morrison and Grabowski (2011)
EULAG + M-microphysics

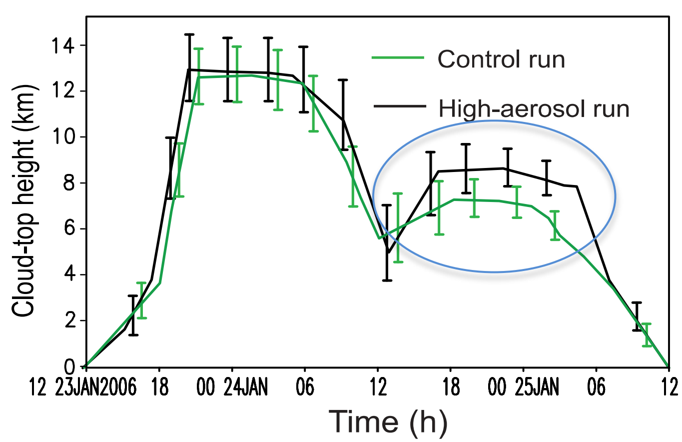
Small increases in cloud top height associated with higher Ni;
Not invigoration

Little to no influence of aerosol on cloud top height

Convective cloud



Stratiform cloud



Lee and Feingold (2012)
GCE+RAMS microphysics

Cloud top height elevation (> 1 km) for higher aerosol in less active period

SGP

Cloud top temperature

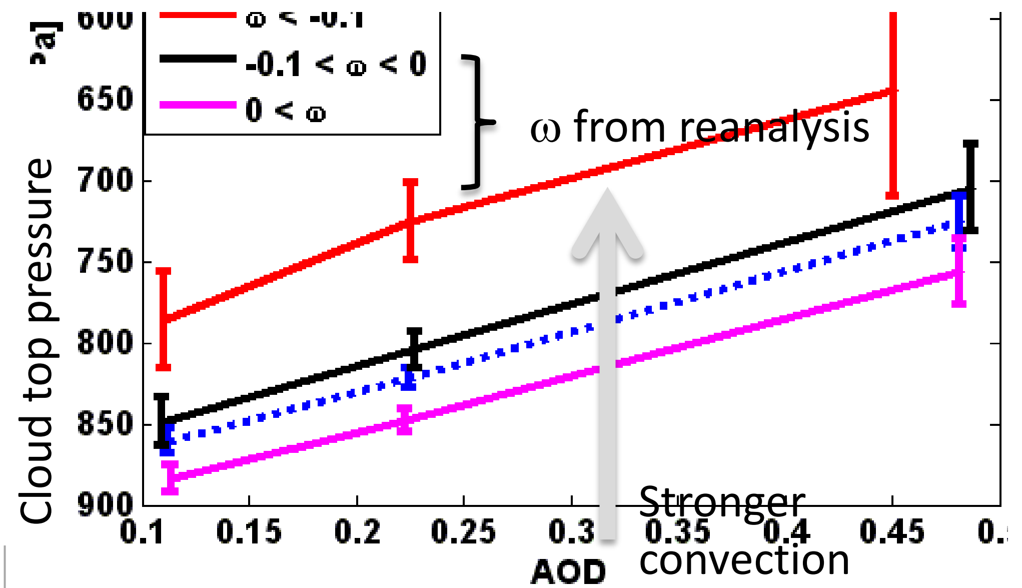
Li et al., 2011 10 yrs ground-based data

For mixed-phase, convective clouds:
- Higher cloud tops correlate with higher surface CN concentrations

Surface CN concentration

Atlantic ocean (tropics)

Koren et al. 2010
- Mixed-phase, convective clouds
- Higher cloud tops correlate with higher AOD
- Vertical velocity dominates AOD effect



AOD

Li et al., 2011 SGP, 10 yrs ground based data

Higher frequency of heavier rain for high aerosol loading

higher aerosol

Lower aerosol

Model results:

Increase in rain amount with increasing aerosol for warm-base summertime Convection (weak shear)

TRMM rainrates:

- Reanalysis provides meteorology (updraft, RH)
- Meteorology dominates R
- R increases with increasing AOD
- Note: heavier TRMM rainrates, not total precip.

Rain rate, mm/h

Stronger convection

Koren et al. 2012

Simplified Equation Sets

Predator-Prey Model

Lotka-Volterra Equations
(circa 1926)

[redacted]

x = prey

y = predator

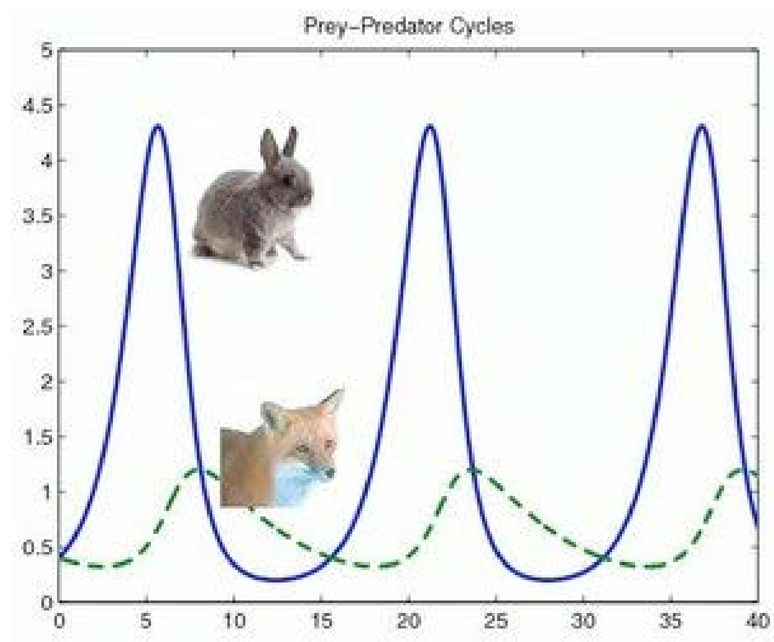


Image courtesy of Wikipedia

4 parameters:
♋📪 ♌📪 ♑📪 ♎

Predator-Prey Model

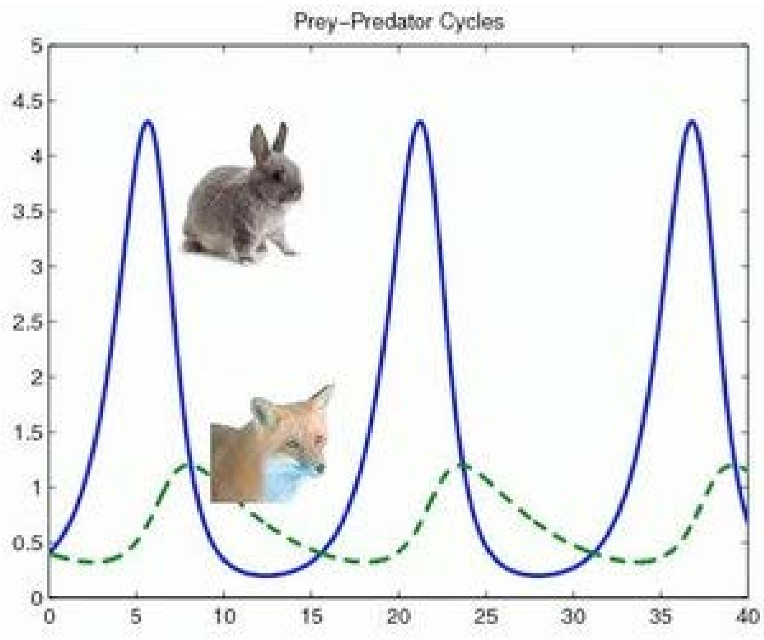


Image courtesy of Wikipedia

Many possible predator-prey pairs:

Rain; Cloud (Koren and Feingold)
Convection; Instability (Nober and Graf)
Droplets; Supersaturation
Ice; Water (Bergeron-Findeisin; U. Wacker)

4 parameters:

♋📭 ♌📭 ♑📭 ♎

Predator-Prey model for Convection

$$\frac{dn_i}{dt} = n_i F_i + \sum_{j=1}^{N} K_{ij} n_i n_j$$

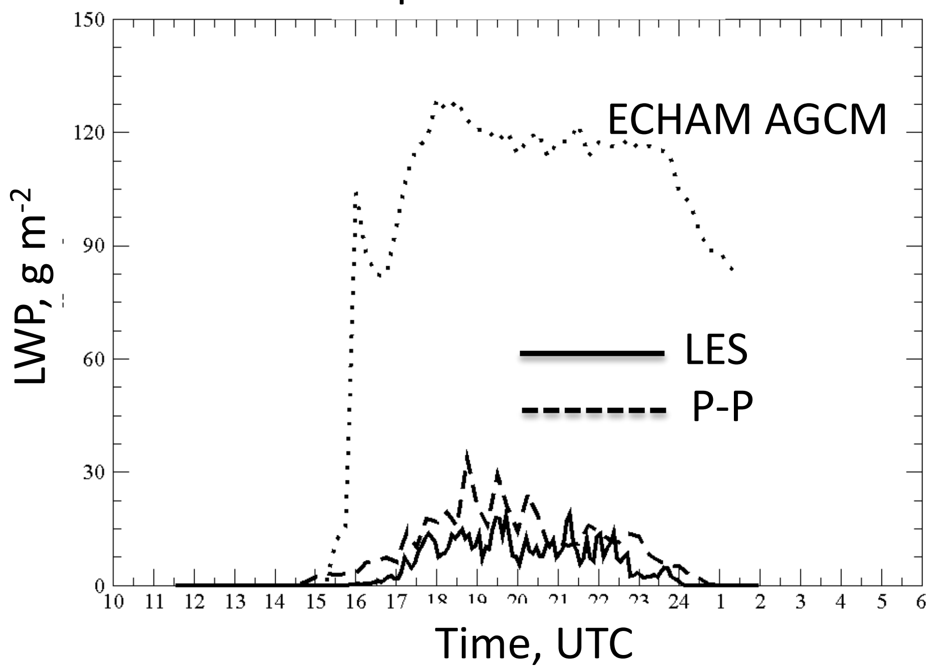
i=1, n

n_i =*number of clouds of type i*

F_i = *"food supply" (instability)*

K_{ij} = *interaction matrix*

Liquid Water Path



Cloud size distribution

% of clouds

Cloud radius, m

Clouds = Predators
Instability = Prey

Nober and Graf 2005

ECHAM Single Column Model

Precipitation rate

SGP IOP 1997

Observations

P-P model

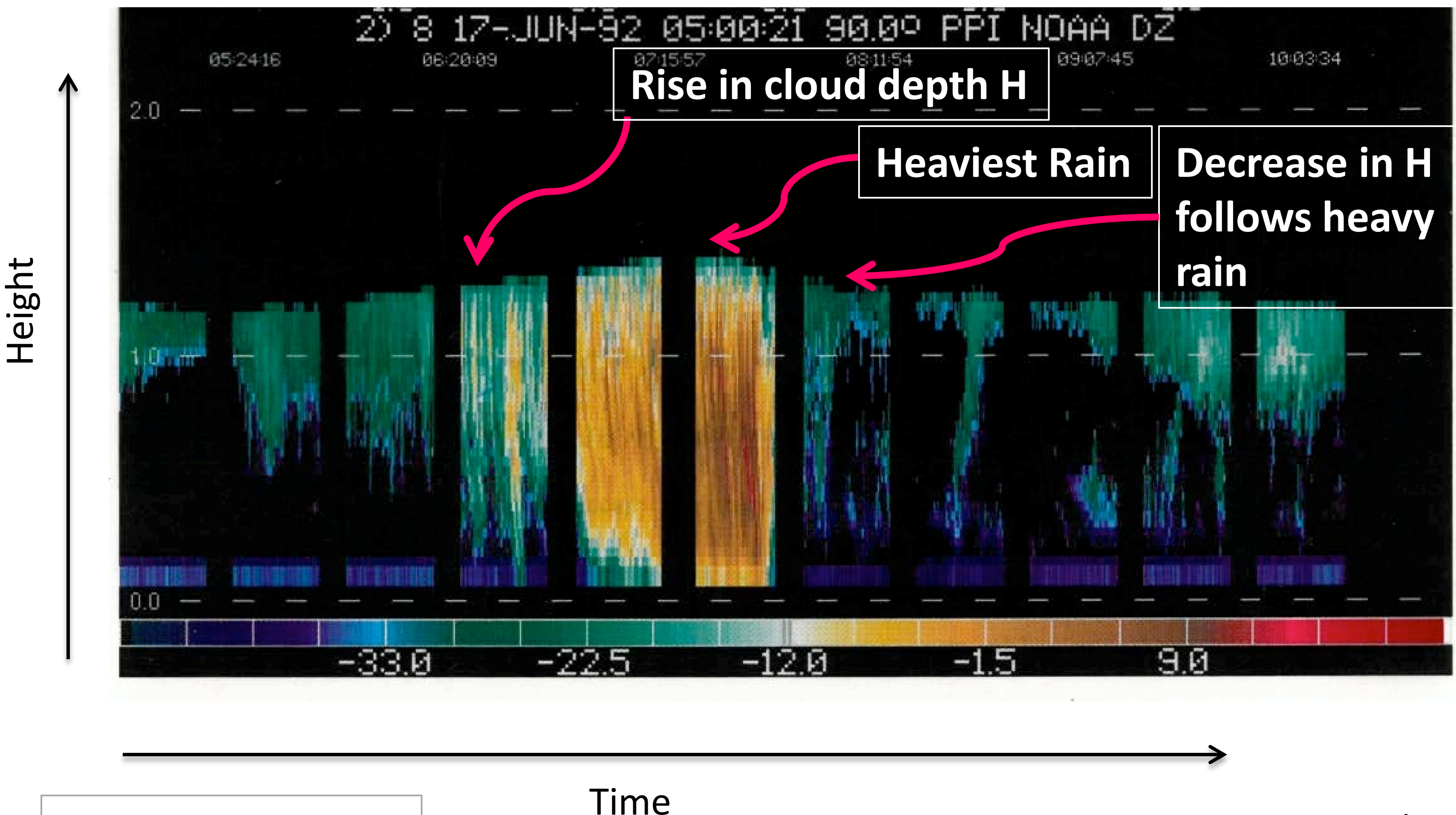
Precipitation rate

Darwin TWP-ICE 2005

Wagner and Graf 2010

Predator-Prey Model for Aerosol-Cloud-Precipitation

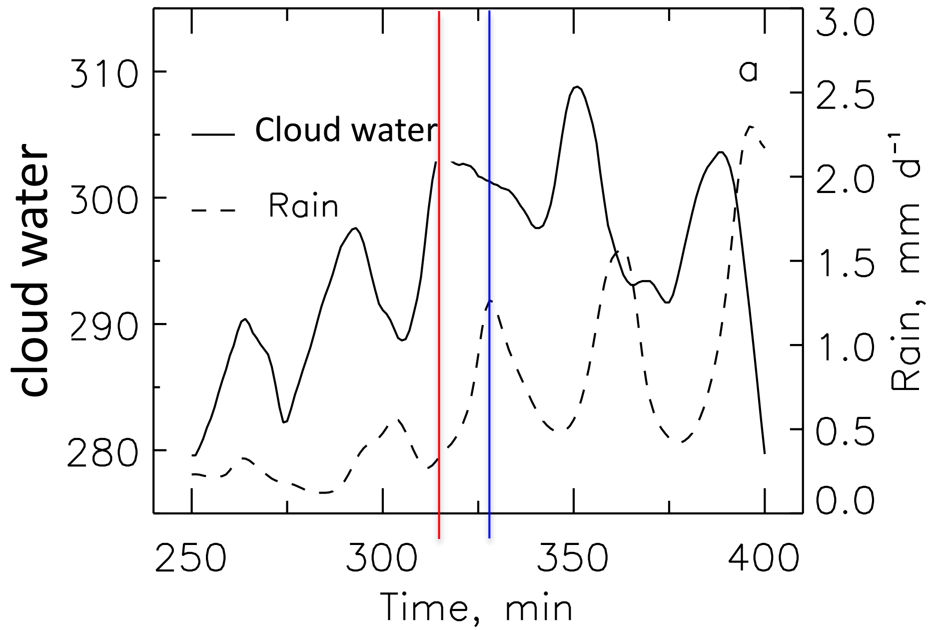
Vertical Profile of Radar reflectivity (a proxy for Rainrate) from N. Atlantic (Azores, Porto Santo, 1992; ASTEX)

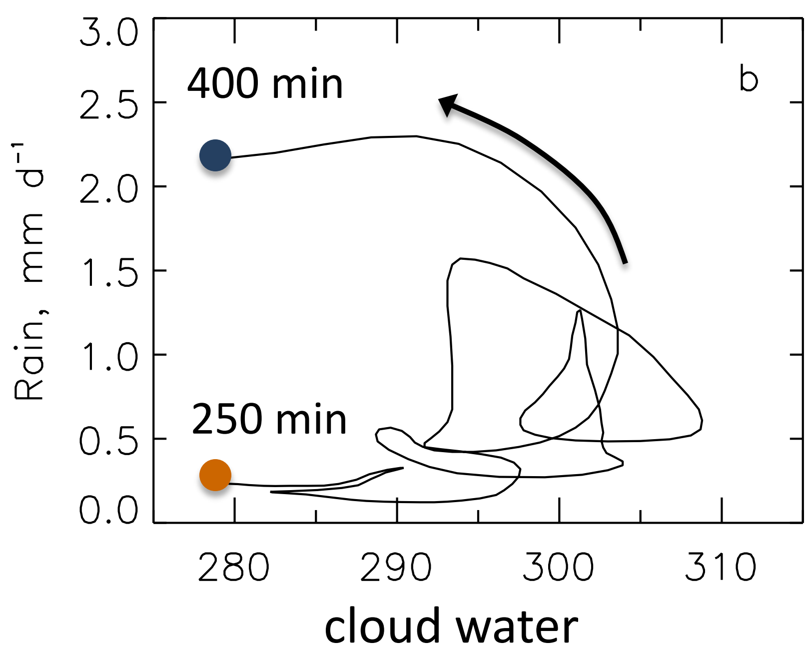


Rain = Predator
Cloud = Prey

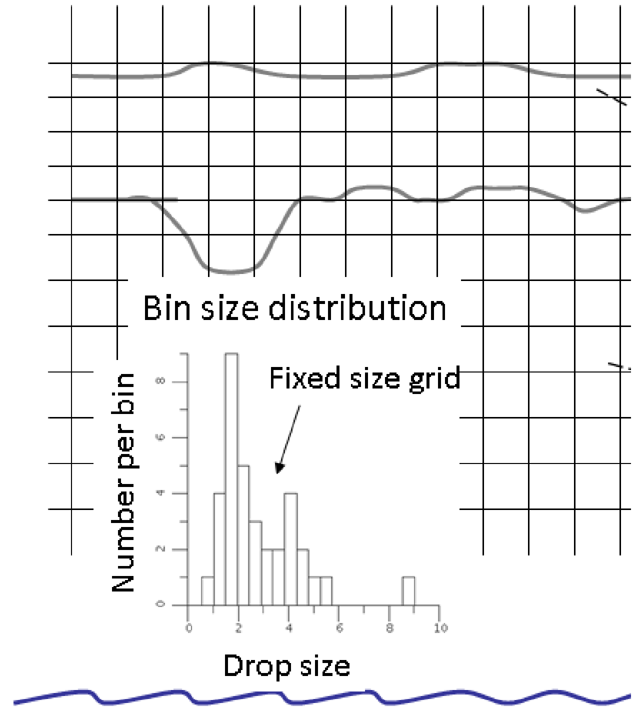
Data courtesy NOAA WPL Radar Group

Large Eddy Simulation of Aerosol-Cloud-Precipitation





Large Eddy Simulation:
Solution to Navier-Stokes Eqns on 3-D grid (~ 200 x 200 x 200)



Anticlockwise loops in R; Cloud phase space

Rain = Predator
Cloud = Prey

Koren and Feingold 2011, PNAS

Balance Equations: average system state

Cloud Depth H

$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t - T)$$

Loss term due to rain

Rainrate R

$$R = \alpha H^3 N_d^{-1}$$

Empirically and theoretically based

$$R(t) = \frac{\alpha H^3(t - T)}{N_d(t - T)}$$

Delay function (time for rain to develop)

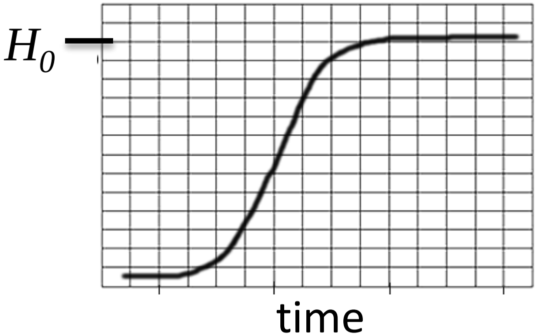
Drop concentration N_d

$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t - T)$$

Loss term due to rain

Notes:

Source terms represent a range of forcings that result in exponential rise to H_0 or N_0 within a few τ



N_d (or aerosol) modulates H-R interaction

Balance Equations

Cloud Depth H

$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t-T)$$

Rainrate R

$$R(t) = \frac{\alpha H^3(t-T)}{N_d(t-T)}$$

Drop concentration N_d

$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t-T)$$

Notes:

Five parameters:

Carrying Capacity: H_0 , N_0

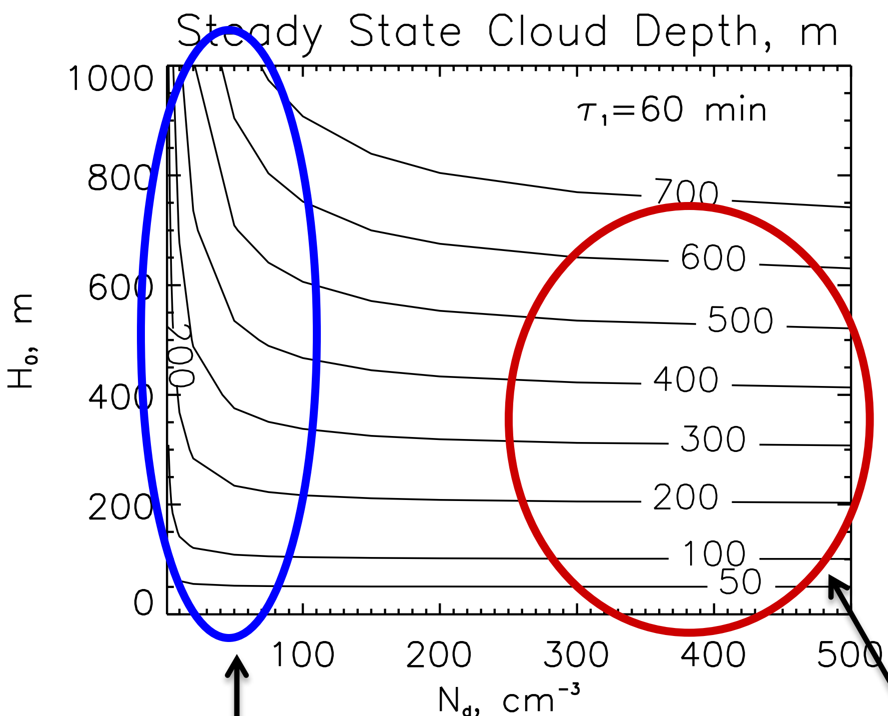
Time constants: τ_1, τ_2

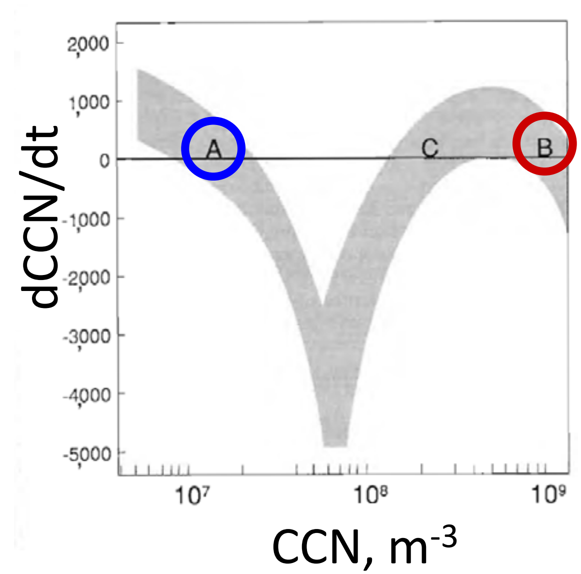
Delay time: T

Aerosol protects cloud from rain

Steady State Solution to Cloud Depth H

$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t - T) = 0 \qquad H = \frac{(N_d^2 + 4\gamma\tau_1 N_d H_0)^{\frac{1}{2}} - N_d}{2\gamma\tau_1}$$



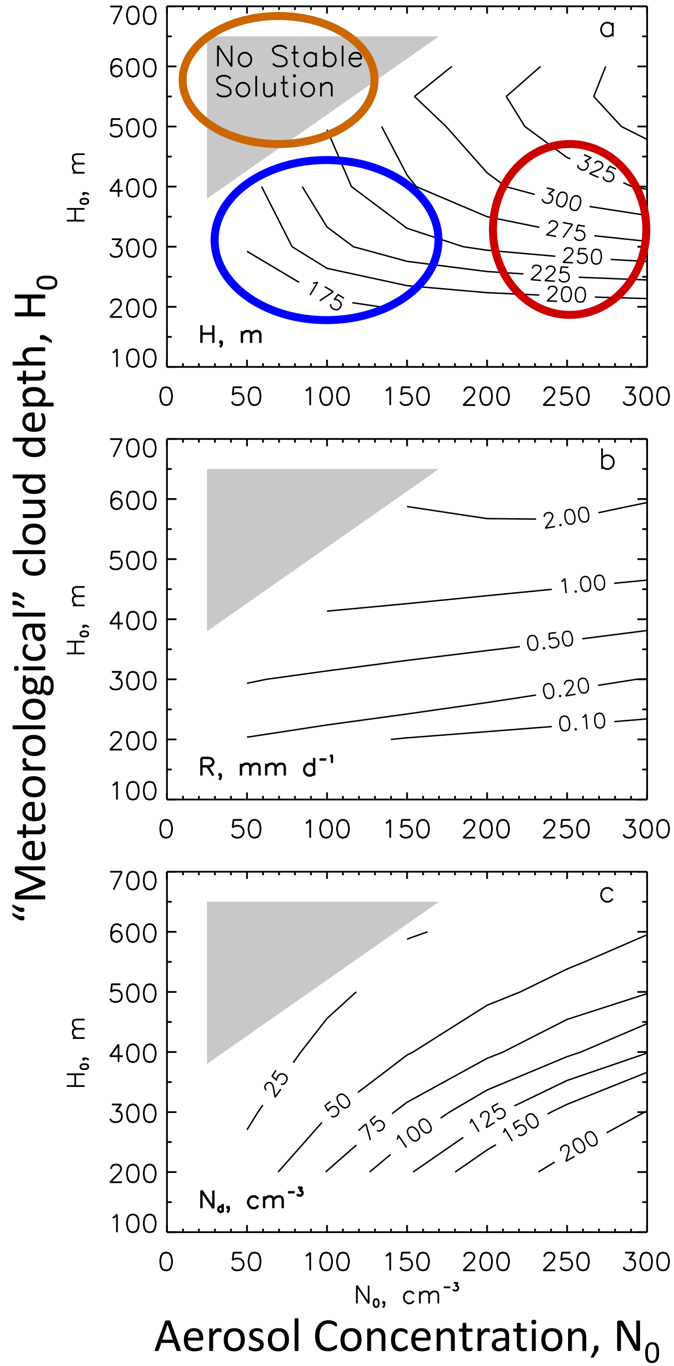


Baker and Charlson, 1990

Cloud Depth determined by drop concentration N_d

Cloud Depth determined by H_0

Koren and Feingold 2011, PNAS



Time-Dependent Steady State Solutions

$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t-T)$$

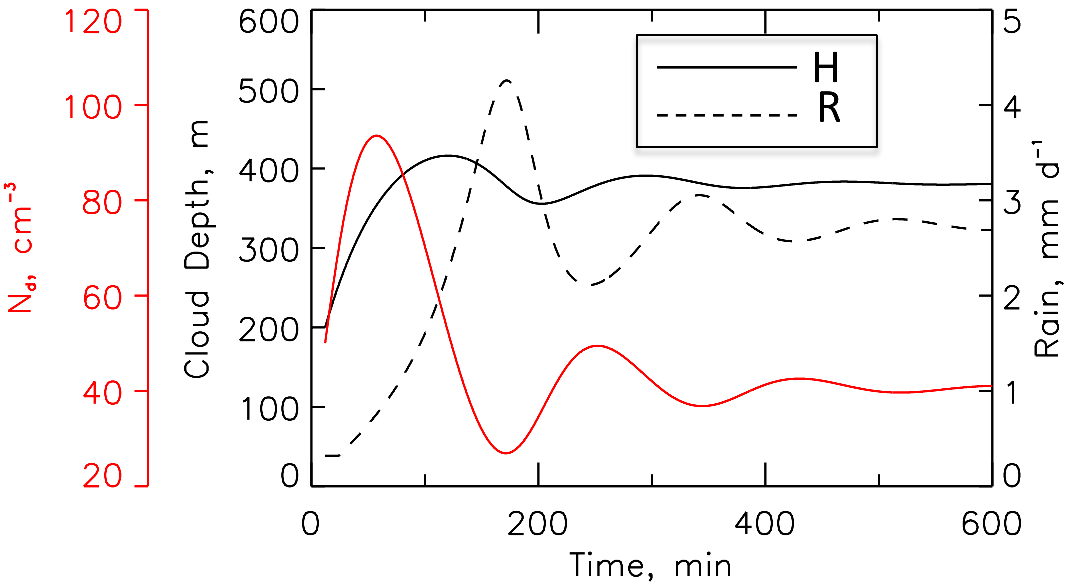
$$R(t) = \frac{\alpha H^3(t-T)}{N_d(t-T)}$$

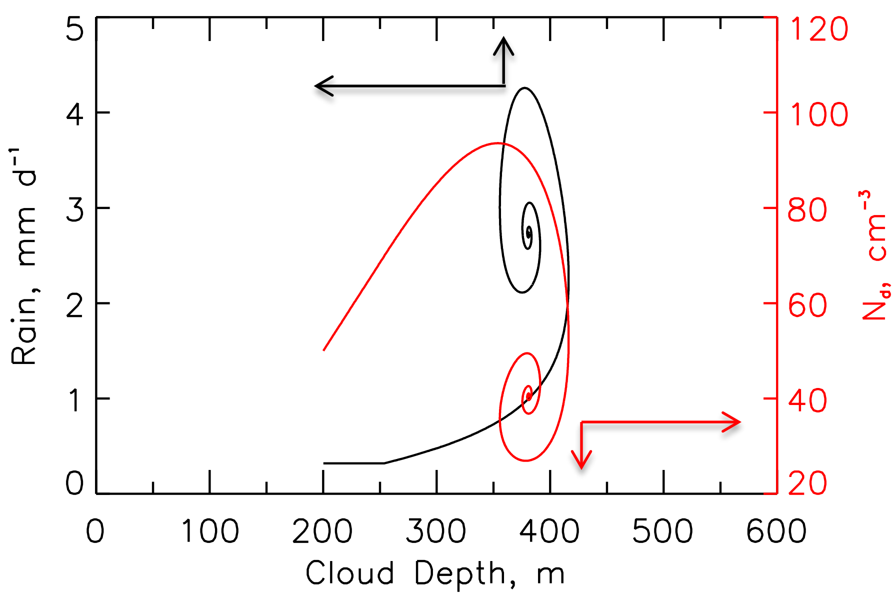
$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t-T)$$

Collapsed boundary layer

Koren and Feingold 2011, PNAS

Oscillating Solutions: Steady State





At steady state:
Aerosol sources are sufficient to maintain balance between sources and rainfall removal

H_0 = 530 m
N_0 = 180 cm^{-3}

$\tau_1 = \tau_2 = 60$ min

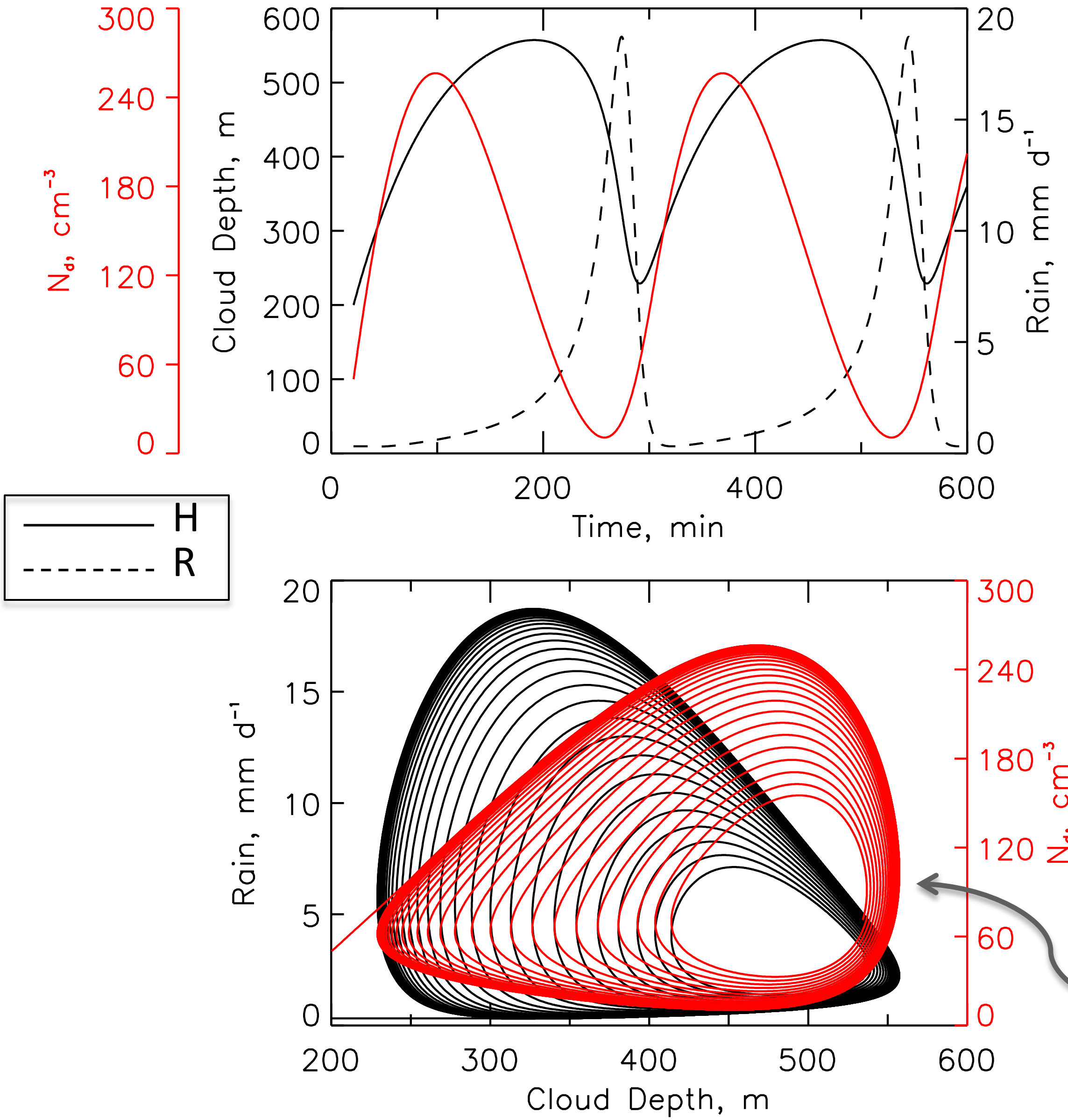
T = 10 min

H; N
H; R

7 day simulation

Koren and Feingold 2011, PNAS

Oscillating Solutions: No Steady State



$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t - T)$$

$$R(t) = \frac{\alpha H^3(t - T)}{N_d(t - T)}$$

$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t - T)$$

H_0 = 670 m
N_0 = 515 cm^{-3}
$\tau_1 = \tau_2 = 84$ min
T = 21.5 min

H; N
H; R

Oscillation around a steady state

7 day simulation

Koren and Feingold 2011, PNAS

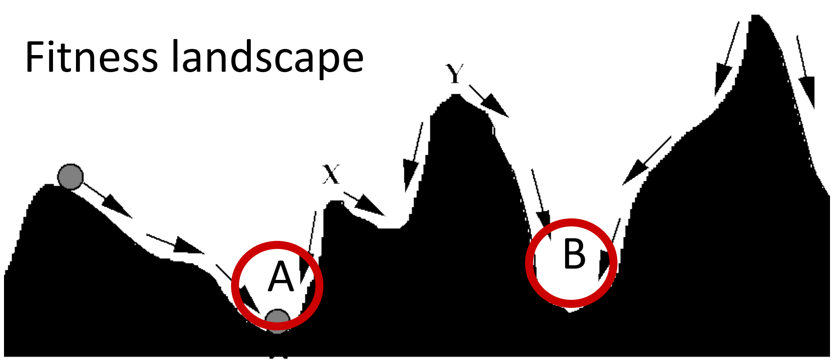
Stability

How stable are the stable states?
How readily does the system transition from one state to another?

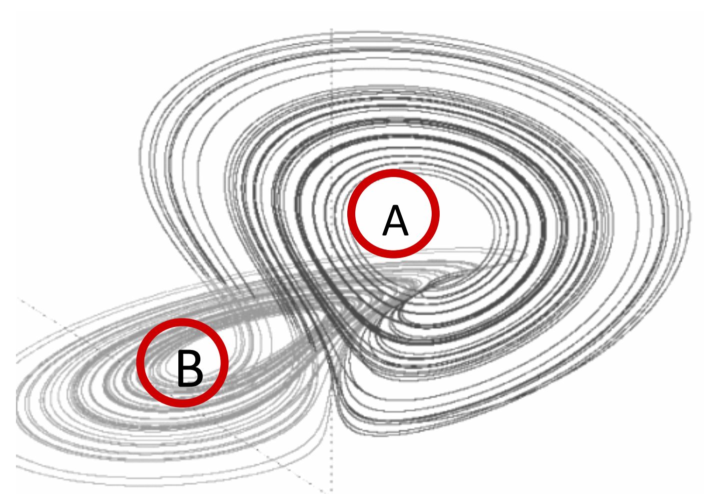
States A and B are stable
and self-sustaining

Small perturbations strengthen
the resilience of the state

Fitness landscape



Attractors



Lorenz, 1963

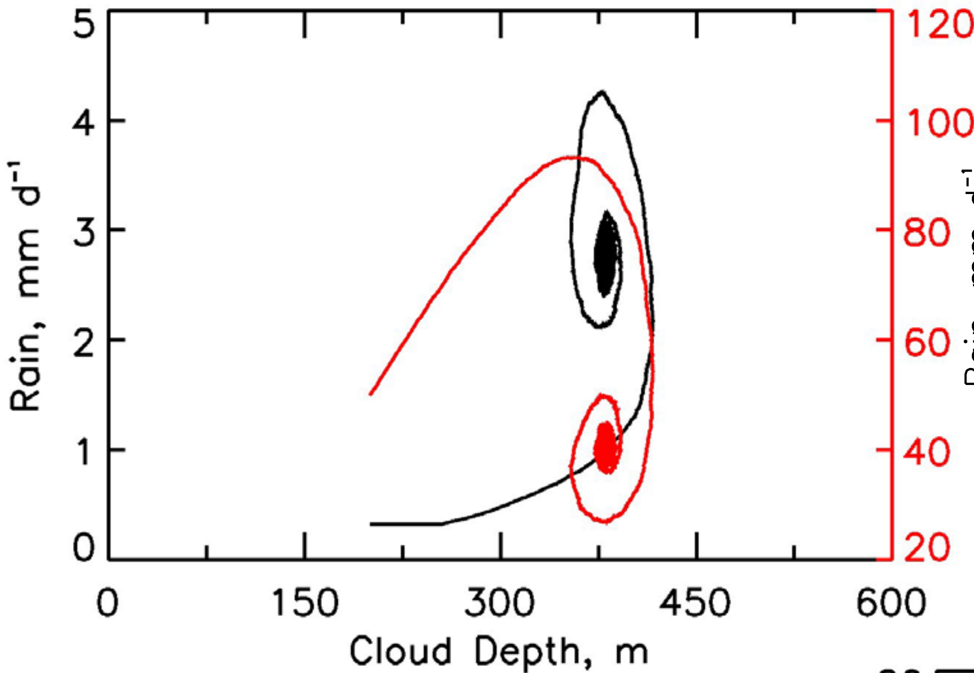
$$\frac{dx}{dt} = \sigma(y - x)$$

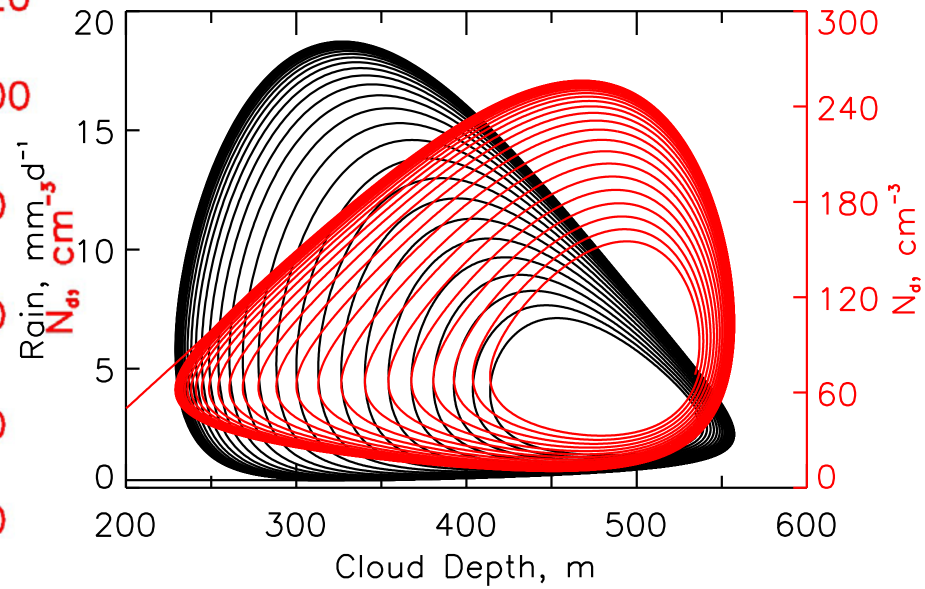
$$\frac{dy}{dt} = x(\rho - z) - y$$

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

A, B: Attractors (low potential, high fitness)

Heylighen

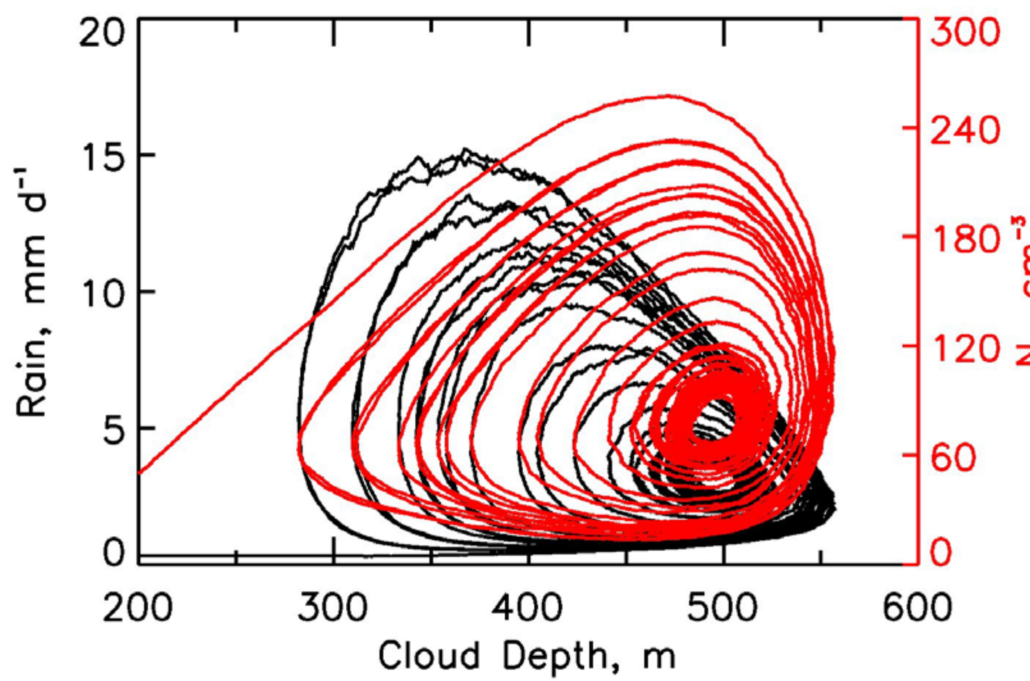




± 50% perturbations to H_0 and N_0 every second: Solutions are robust

Small perturbations strengthen the resilience of the state;

Large enough perturbations will lead to collapse



Koren and Feingold 2011, PNAS

The Parameterization Paradigm

- Empiricism used to represent physics

  Examples:
  - Autoconversion ~ $LWC^a N^b$
  - $d\ln r_e / d\ln N = -\alpha$

- Scale issues, averaging/aggregation issues
  - "scale-aware parameterizations"
  - E.g. Bennartz et al. (2011) for autoconversion/accretion

Self-organizing systems approach

- Coupled *simple* prognostic equations representing emergent properties of the system
  - E.g., cloud-precip cycles, bistability, robustness
  - Small number of free parameters, tuned to mimic system-wide behaviour in different conditions/regimes

- Slow manifolds (Bretherton et al. 2010)

$$dz_i/dt = w_e(z_i) - Dz_i$$

Balance equation for BL depth z_i

$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \dot{H}_r(t-T)$$

$$R(t) = \frac{\alpha H^3(t-T)}{N_d(t-T)}$$

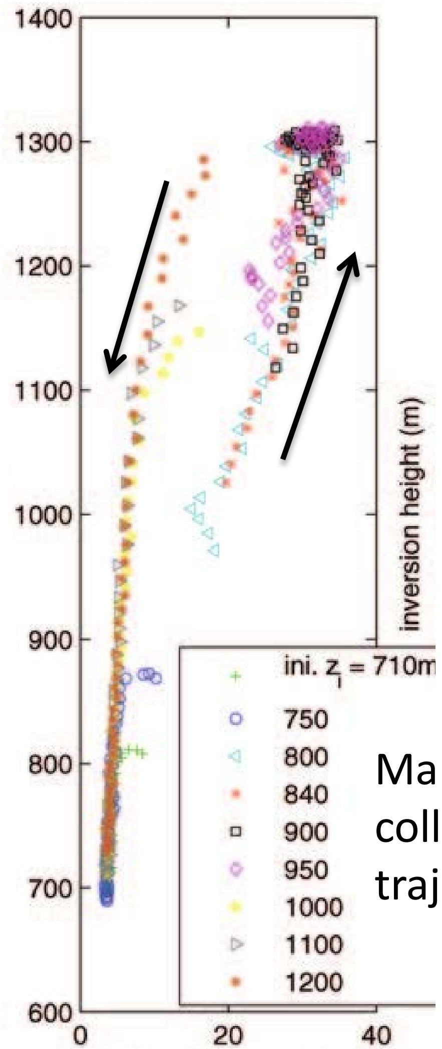
$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t-T)$$

Prognostic predator-prey equations for cloud water (H), rainwater (R) and drop concentration (N)

- Convective parameterizations
- “Org” parameter (Mapes)
- Lorenz (1960s)

Slow manifolds

LES of Stratocumulus



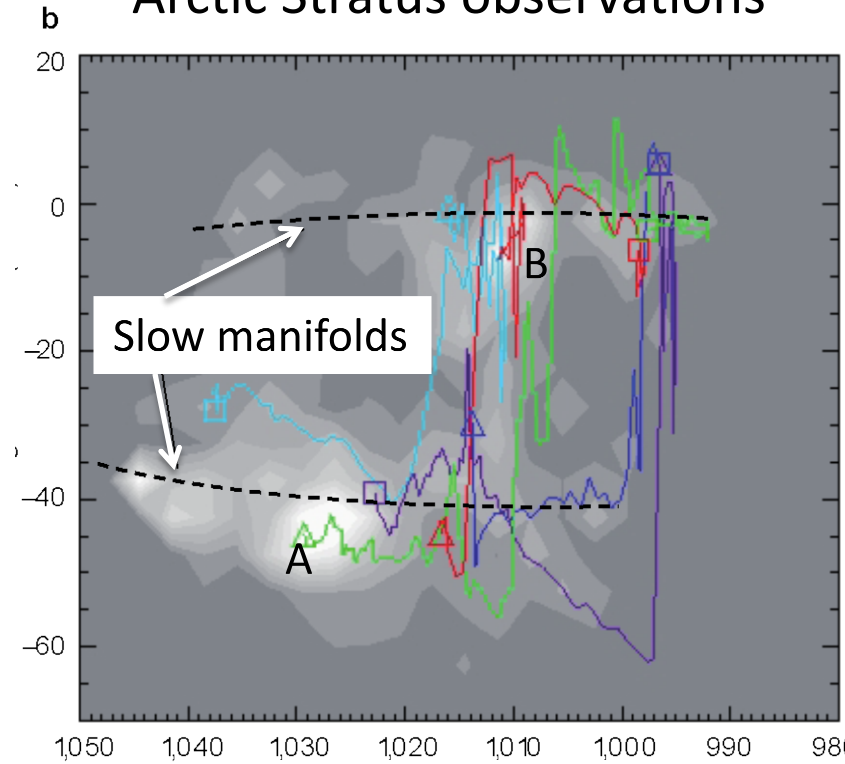
Inversion height, m

Liquid Water Path

Many simulations collapse onto two trajectories

Arctic Stratus observations

Net surface longwave radiation, W/m2



Surface pressure, mb

Colored trajectories: transition between states

Triangle = start; square = end

A = Radiatively clear

B = Cloudy

Bretherton et al. 2010

Morrison et al., 2011

Final Thoughts

- Maintain the effort on the process level understanding
  - These are the local interactions that generate emergent behaviour
- Retain/refine the fundamental physics of the 1^{st}, 2^{nd}…. n^{th} indirect effects (e.g. aerosol effects on N_d, collision-coalescence, etc..)
  - Discard these simple constructs when attempting to include these processes in large scale models
  - E.g., hardwiring of cloud lifetime to autoconversion parameterizations
- Develop the mesoscopic, systems view
  - Example: Predator-Prey model for convection or aerosol-cloud-precipitation, slow manifolds, etc..