The aerosol-cloud-precipitation system: In search of simplicity

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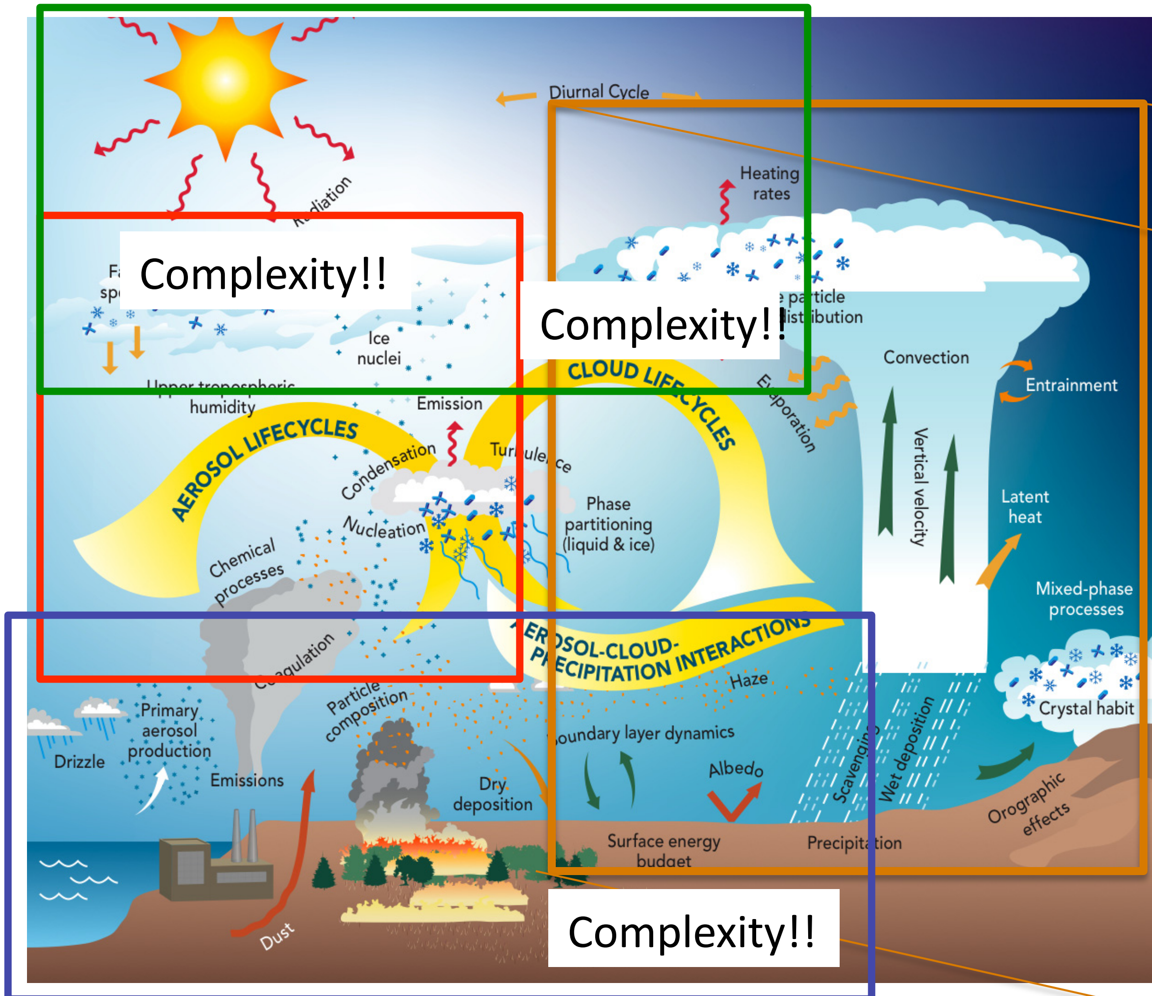
Acknowledgements: Hailong Wang, Huiwen Xue, Alan Brewer

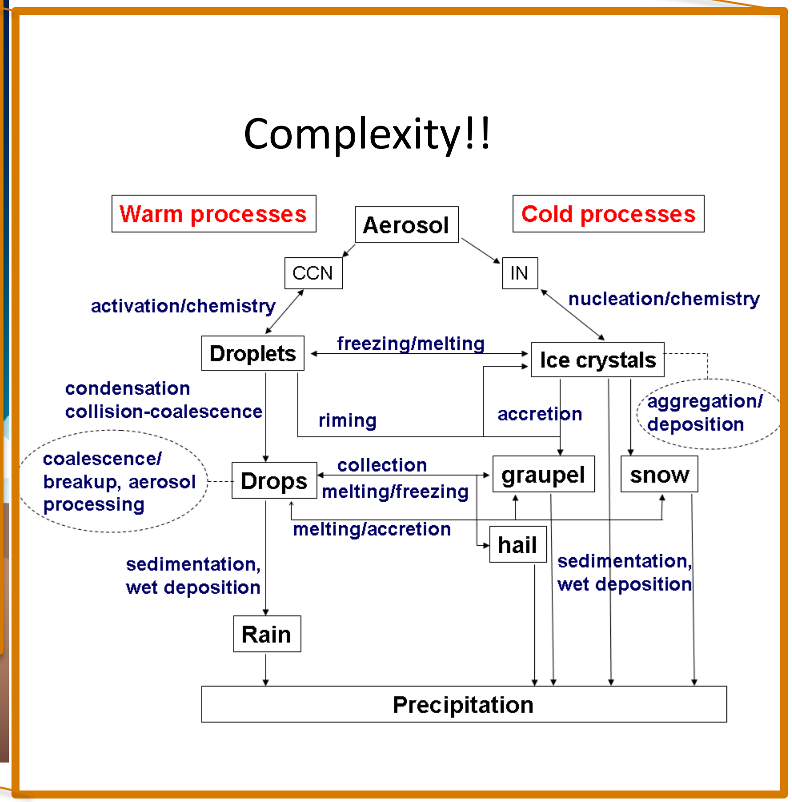
Organizers of WCRP

WCRP October 2011

A complex system: Aerosol-Cloud-Dynamics-Radiation-Land Surface-…

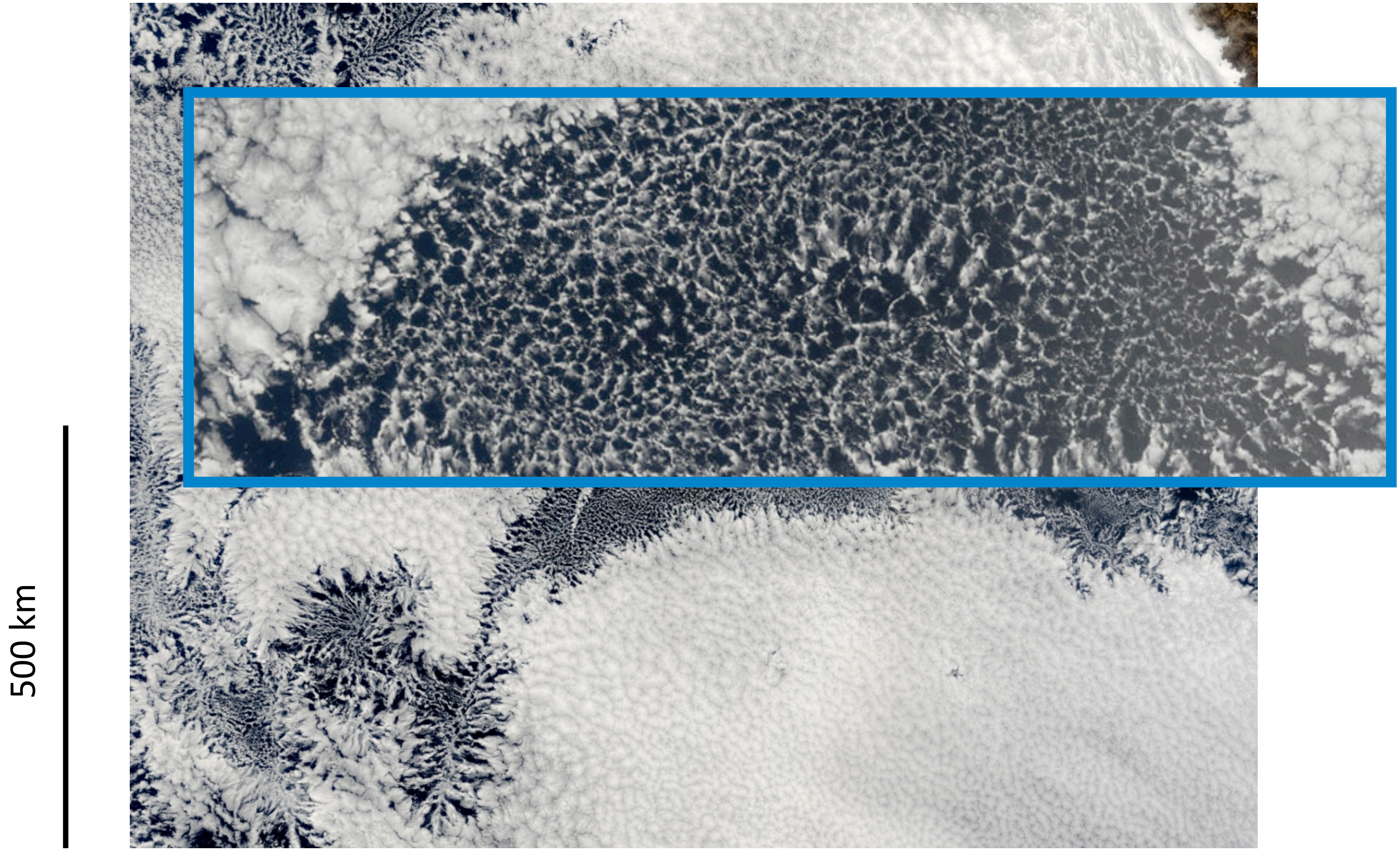


From DOE/ASR Science and Program Plan



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

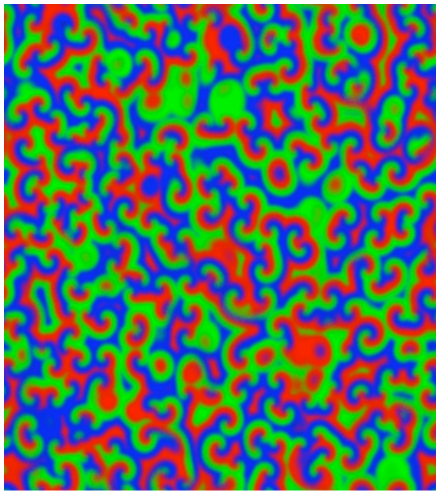
Mesoscale Cellular Convection



MODIS image, South East Pacific

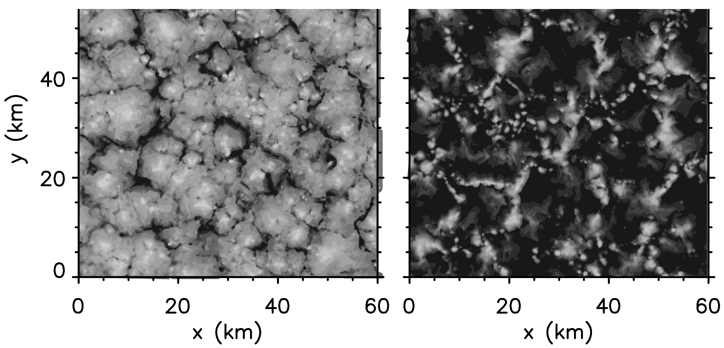
- *Radiative forcing of the ocean-cloud system*
- *Patterns and emergence in atmospheric systems*

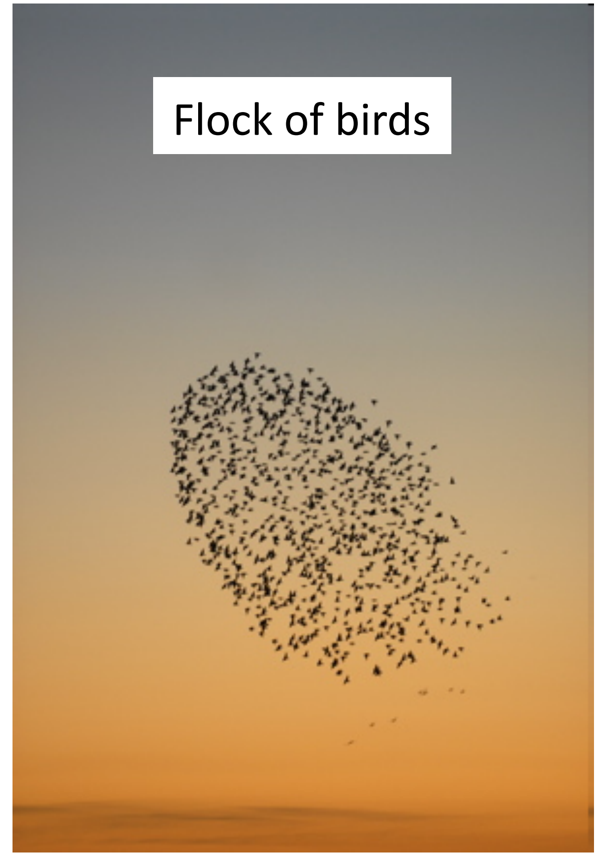
Patterns and Synchronization in Natural Systems



Oscillatory behavior in Belousov-Zhabotinskii chemical reactions

Cloud fields





Flock of birds

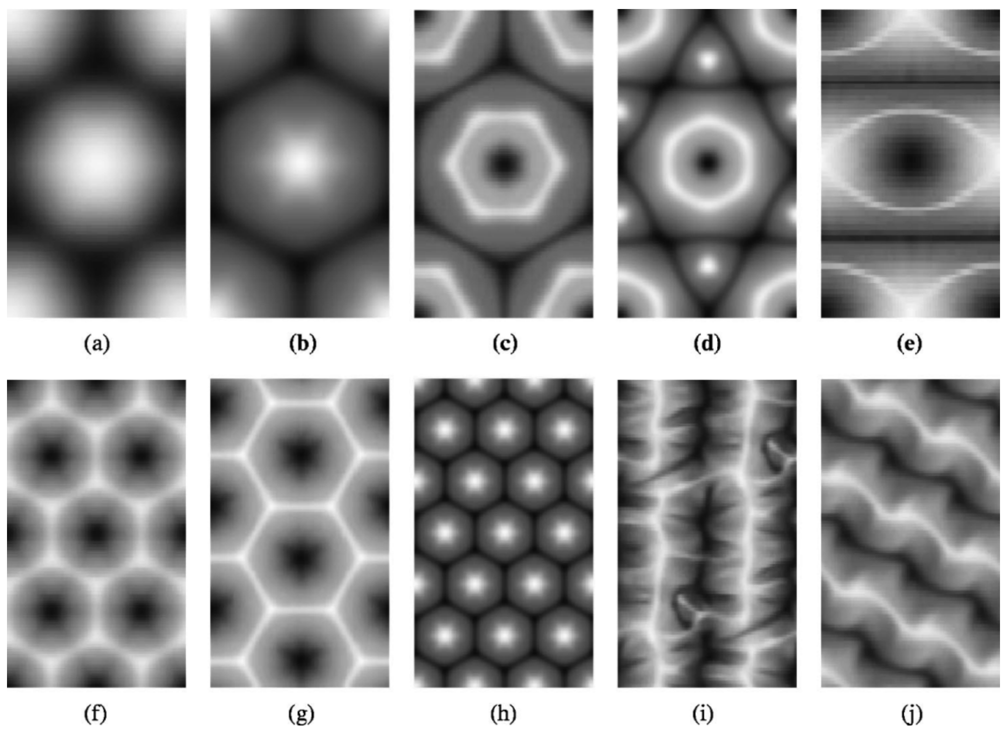
Mud pools

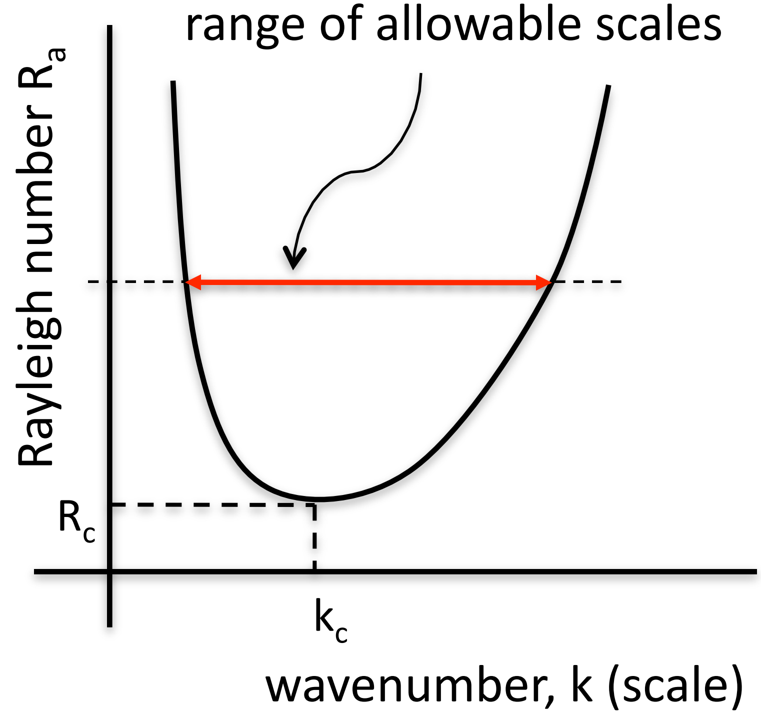
"Emergence"

System-wide patterns emerge from local interactions between elements that make up the system

Implication: Complex problems with huge number of degrees of freedom may be amenable to solution with much more simple set of equations

Rayleigh-Bénard Convection





Controlled lab experiments with different scales:
Patterns and preferred modes

Getling and Brausch, Phys. Rev. E 2003

Aerosol/drizzle selects the state

Albedo

Closed-cell
Albedo ~ 0.6
(non-
precipitating)

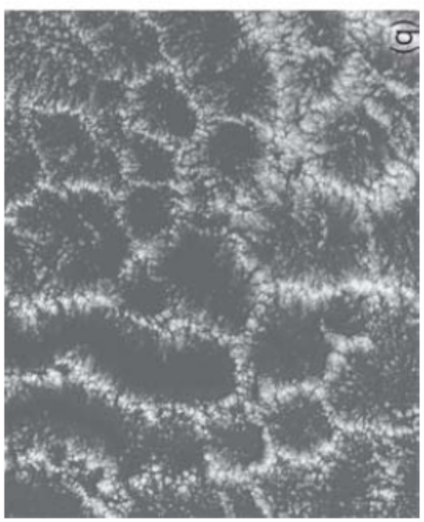
→ **high aerosol**

Onset of
drizzle
results i
transitio
to open-
convecti

WRF Model
+ 2-moment

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

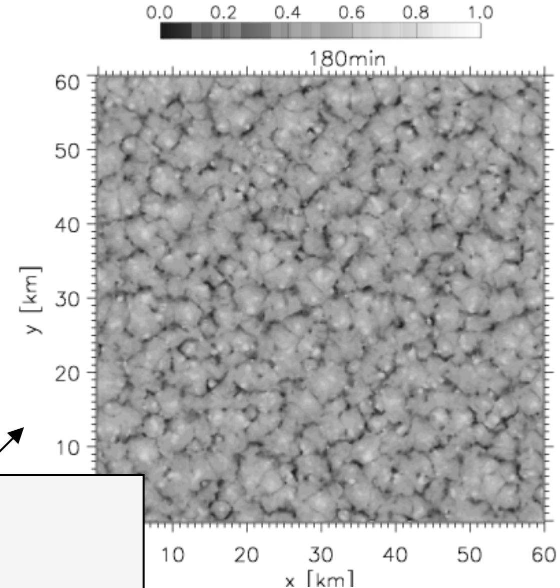
(ii) The open state rearranges

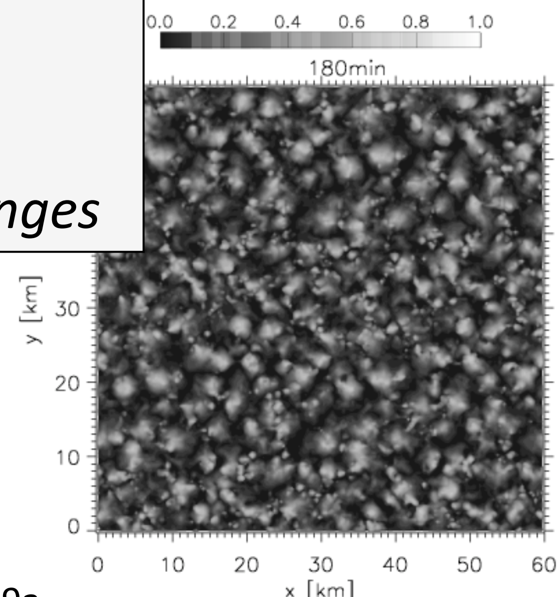


Open-cell
Albedo ~ 0.2
(precipitating)

→ **low aerosol**

Albedo

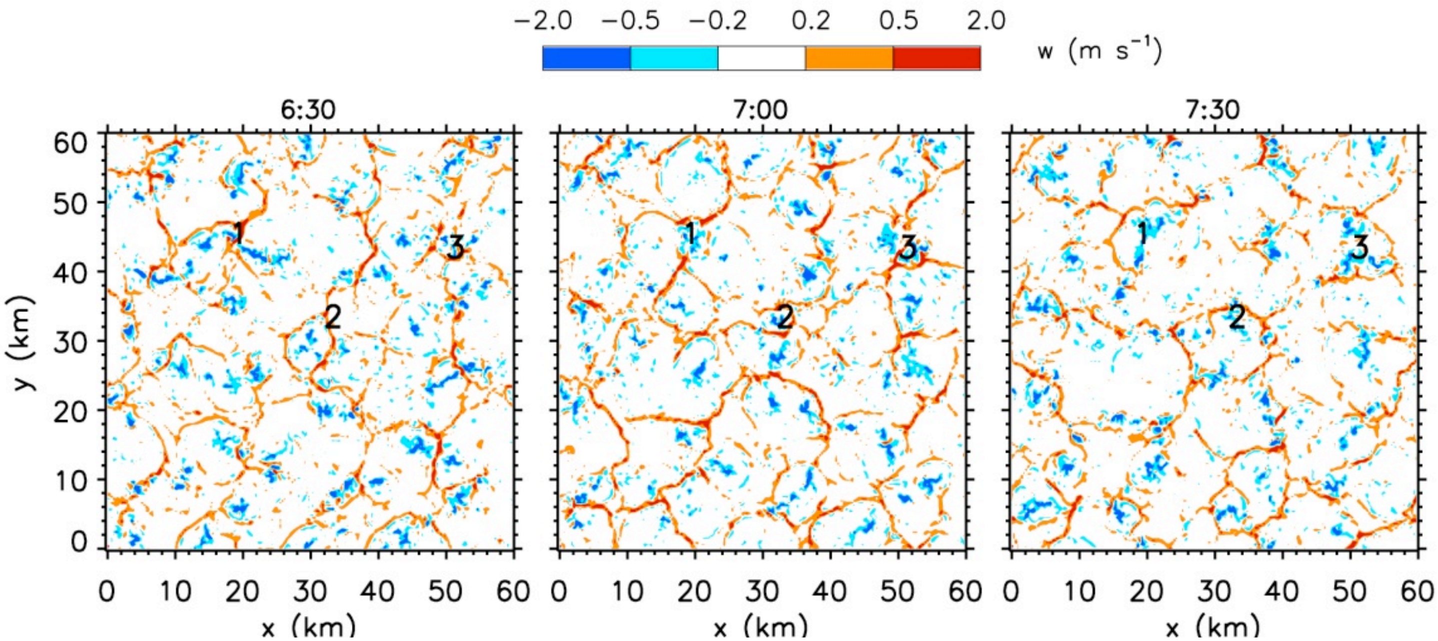




Garay et al. 2004, MISR

Wang and Feingold, 2009a

Rearrangement of Open Cells



No advection

Orange: Updrafts

Blue: Downdrafts/precipitation

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

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

↓

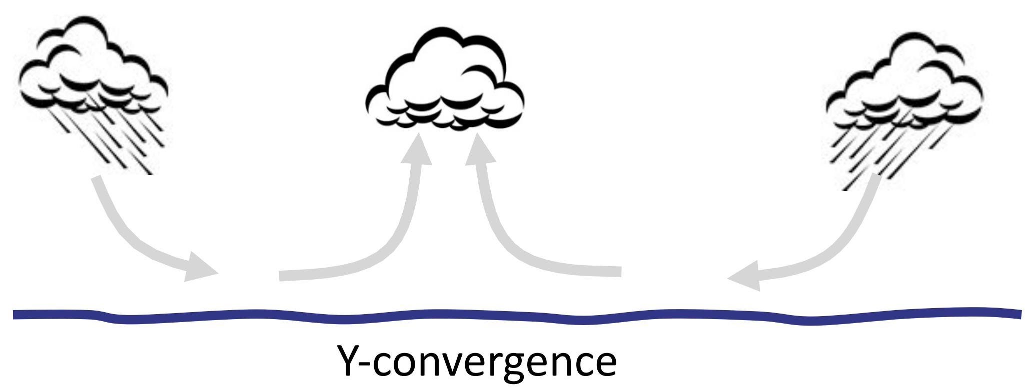
Precipitation is initiated

↓

Downdrafts, opening of cell

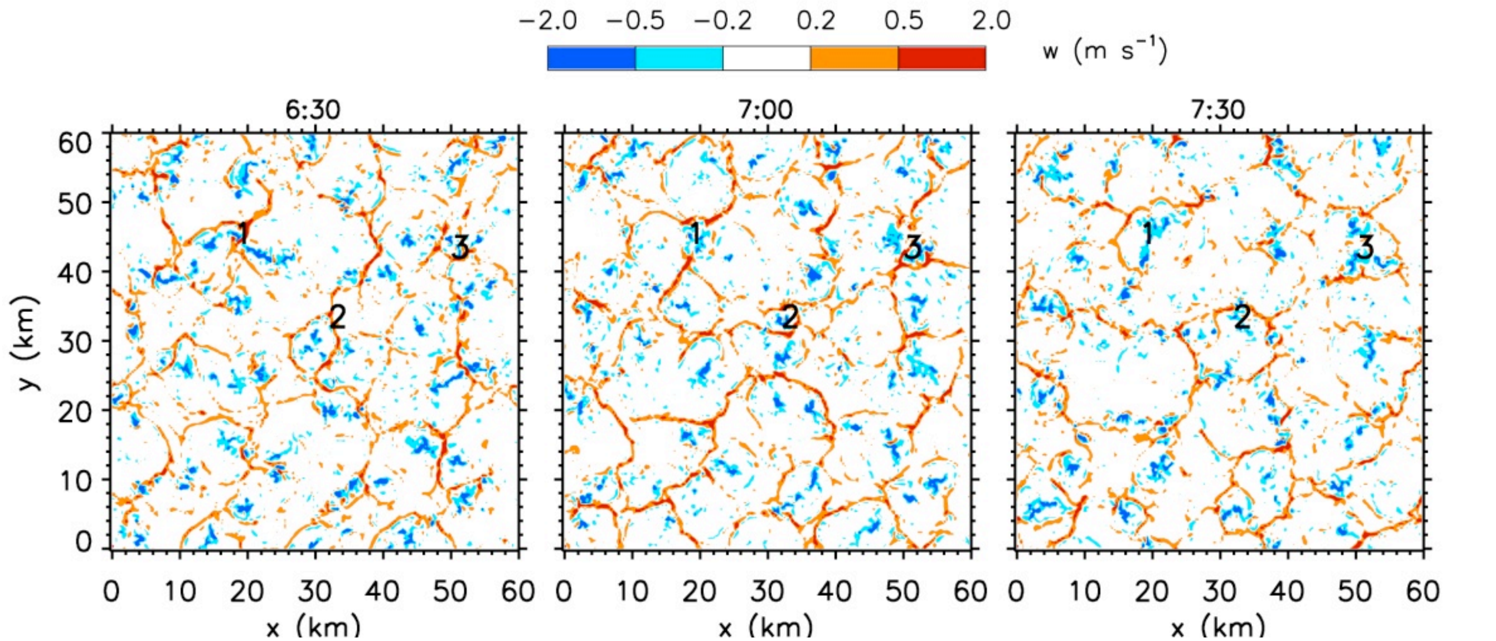
↓

Surface divergence



Buoyancy → cloud → rain → destroys buoyancy

Rearrangement of Open Cells



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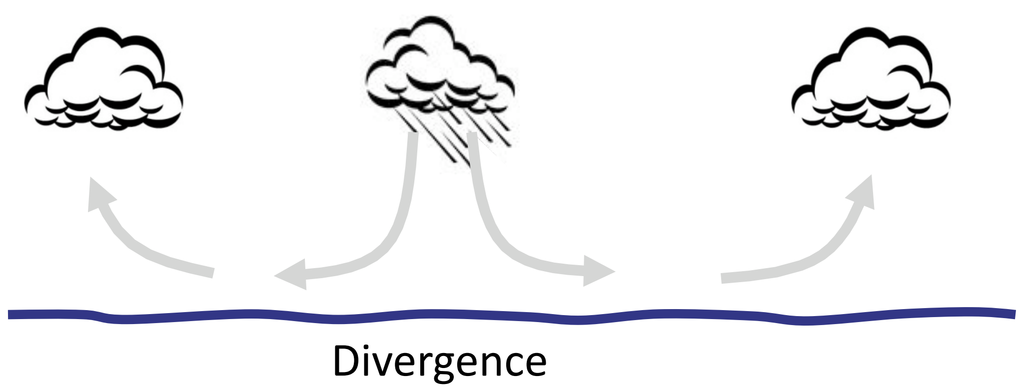
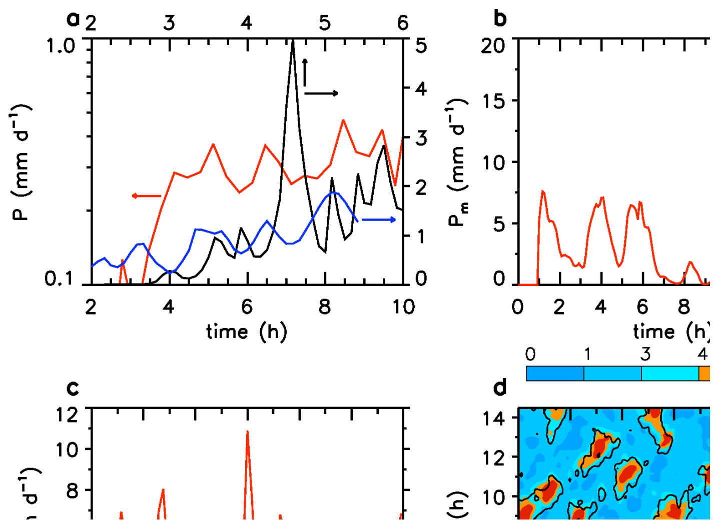


Emergence due to interaction between outflows

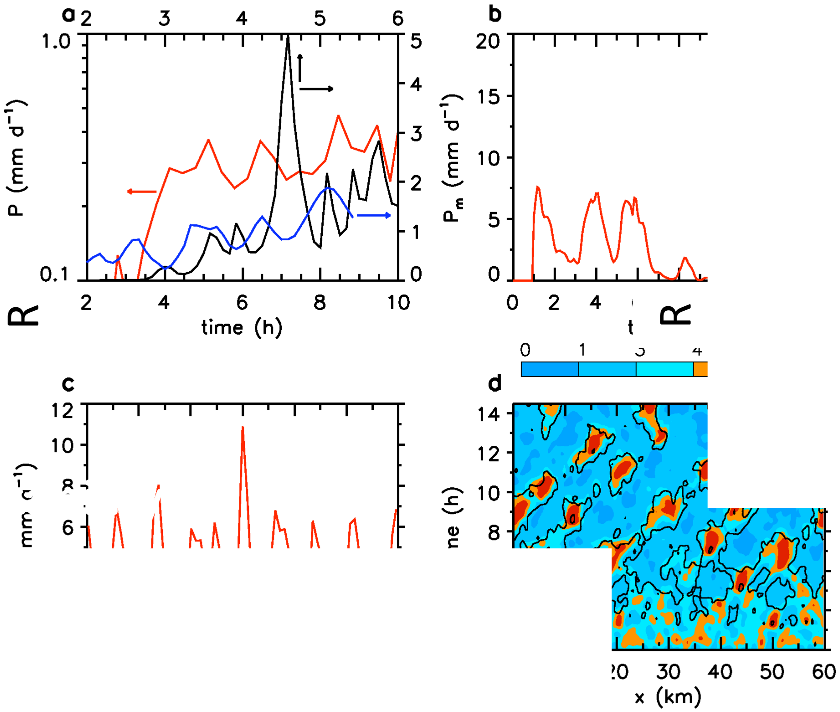
Synchronization: Oscillations in Precipitation



3 LES cases:
DYCOMS
ATEX
VOCALS

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

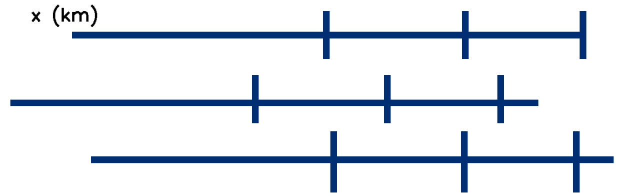
Synchronization: Oscillations in Rainrate



3 LES cases:
DYCOMS
ATEX
VOCALS

Hövmuller diagram

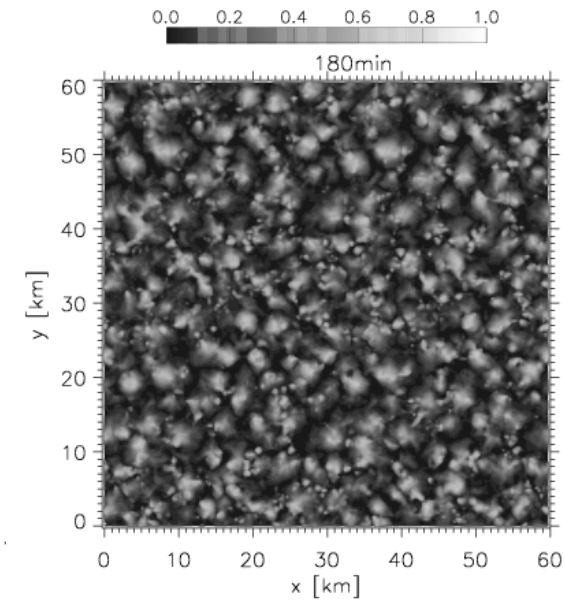
Shift in rain "grid"

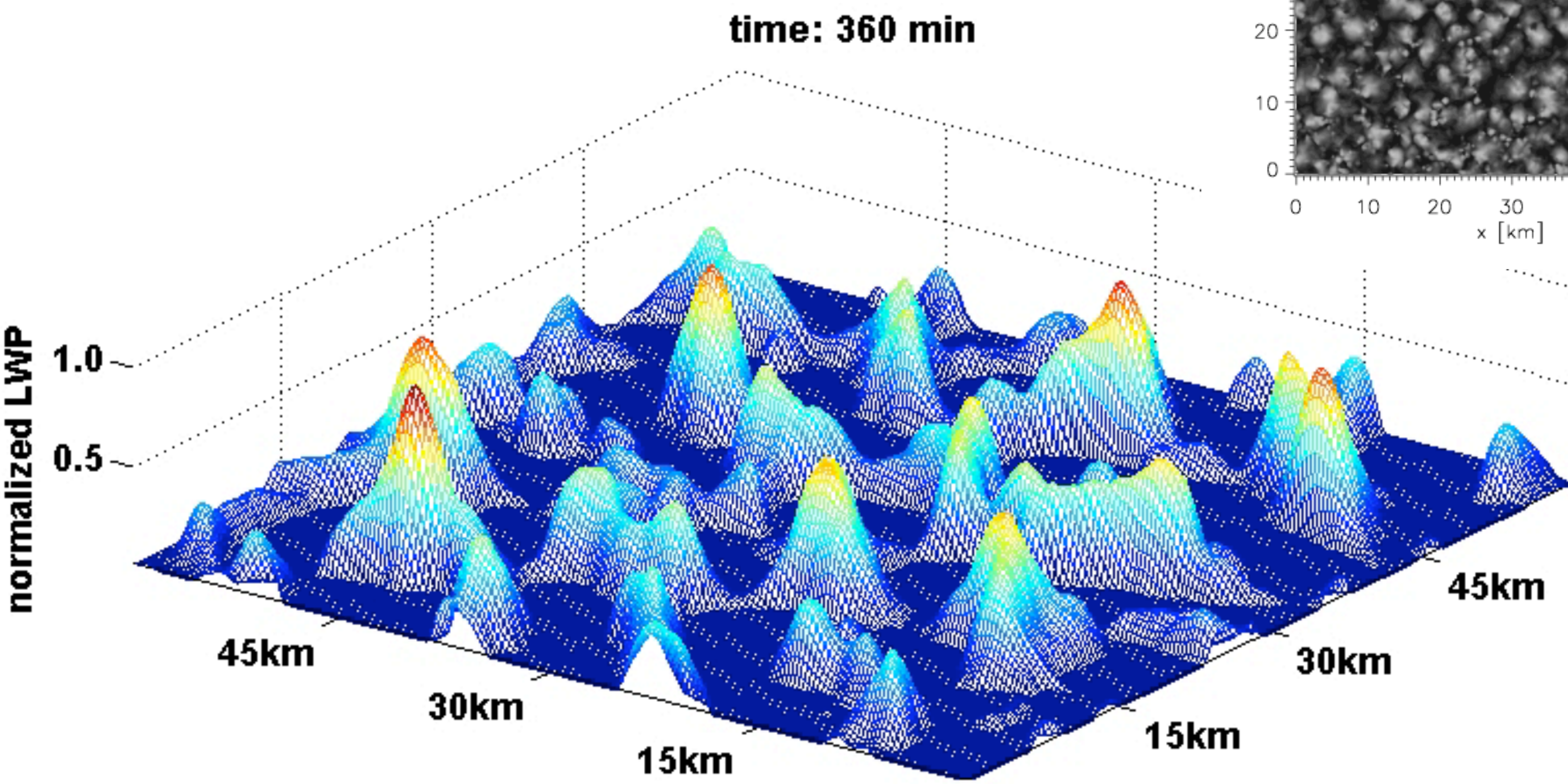


Colored contours: rain
Contours: updraft

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

Synchronization of Coupled Oscillators

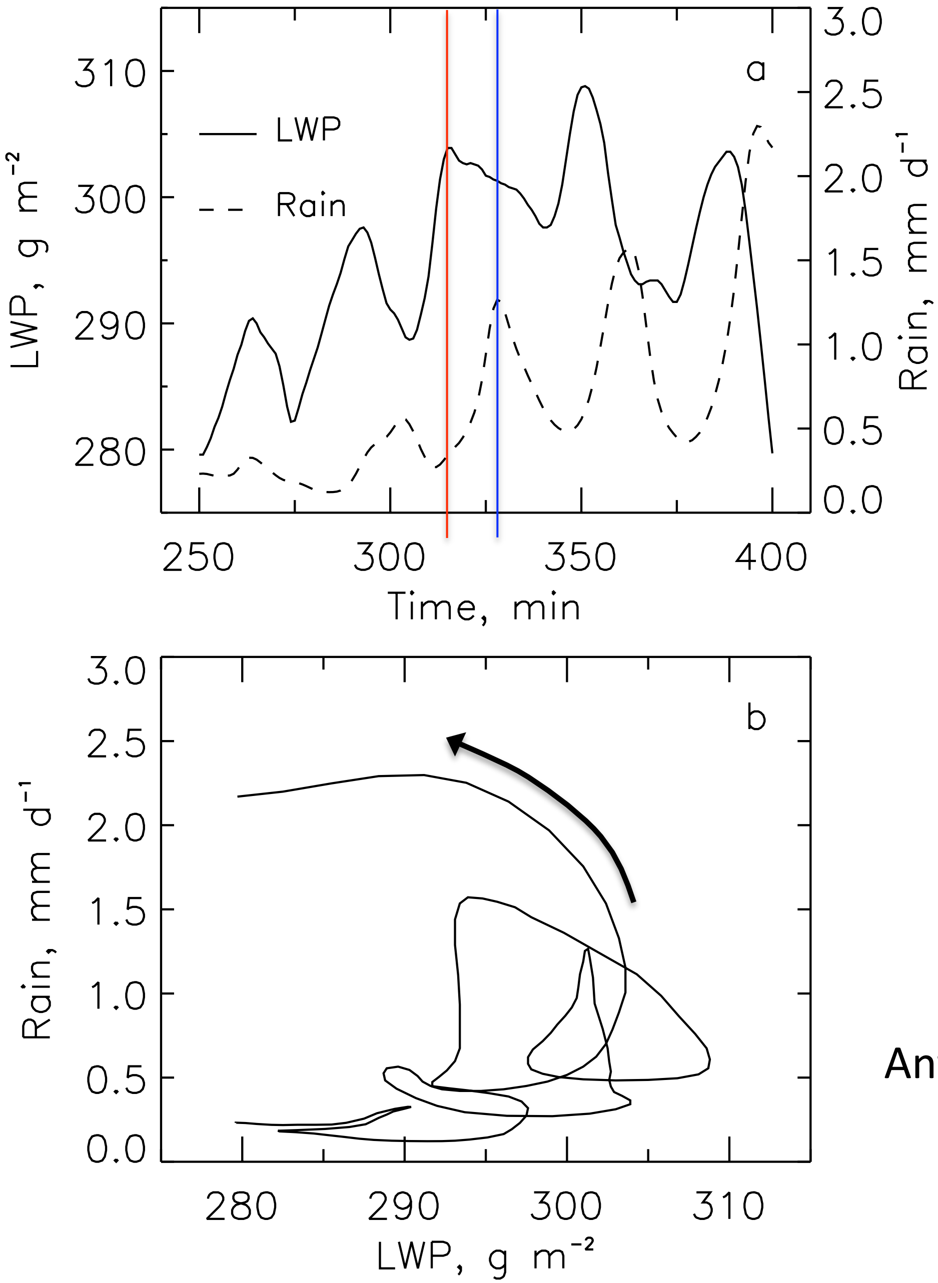




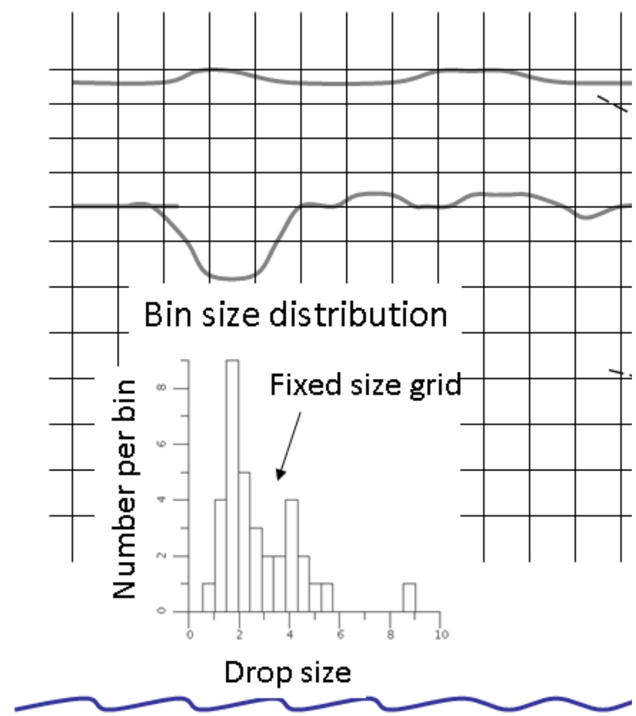
Feingold, Koren, Wang, Xue, Brewer (2010)

Are Oscillating Patterns Common?

Large Eddy Simulation of Aerosol-Cloud-Precipitation



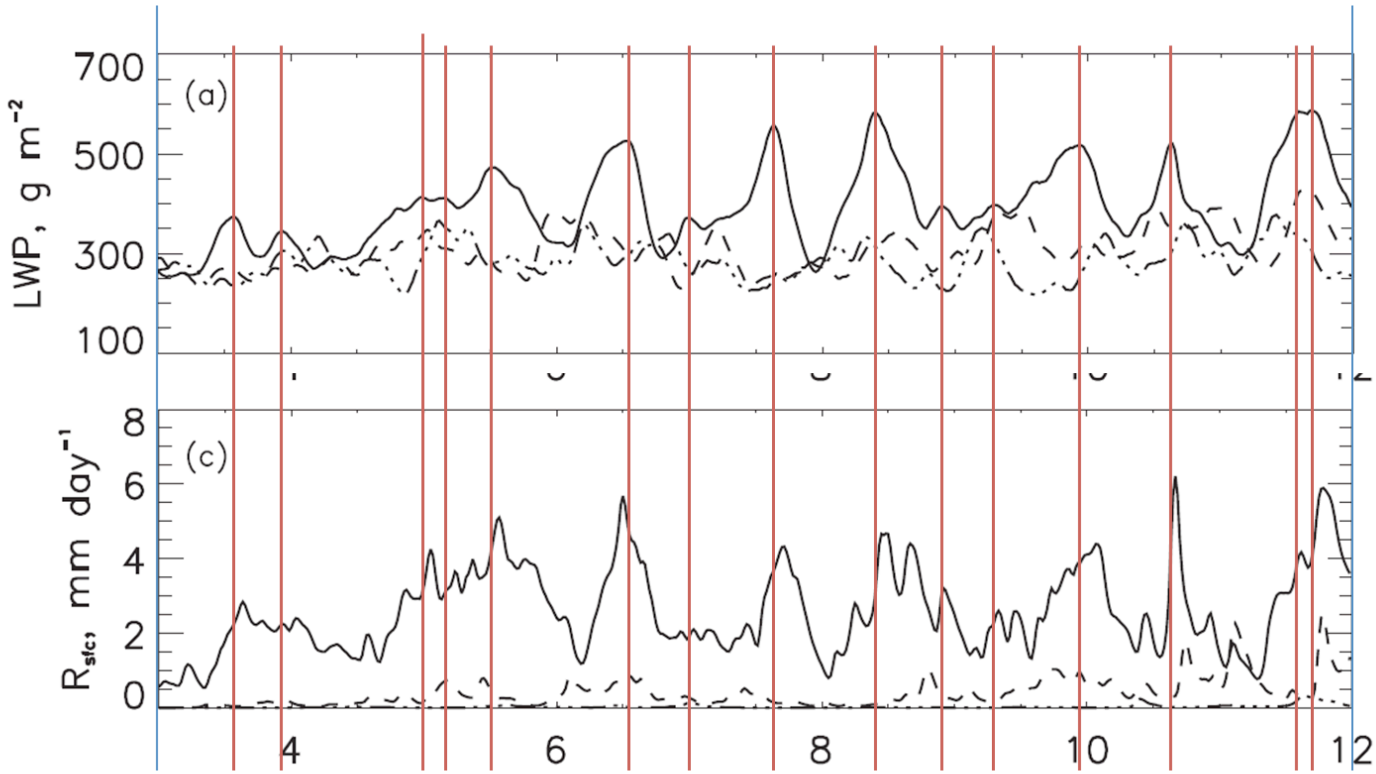
3-D grid (~ 100 x 100 x 100)



Anticlockwise loops in R; LWP phase space

Koren and Feingold 2011, PNAS

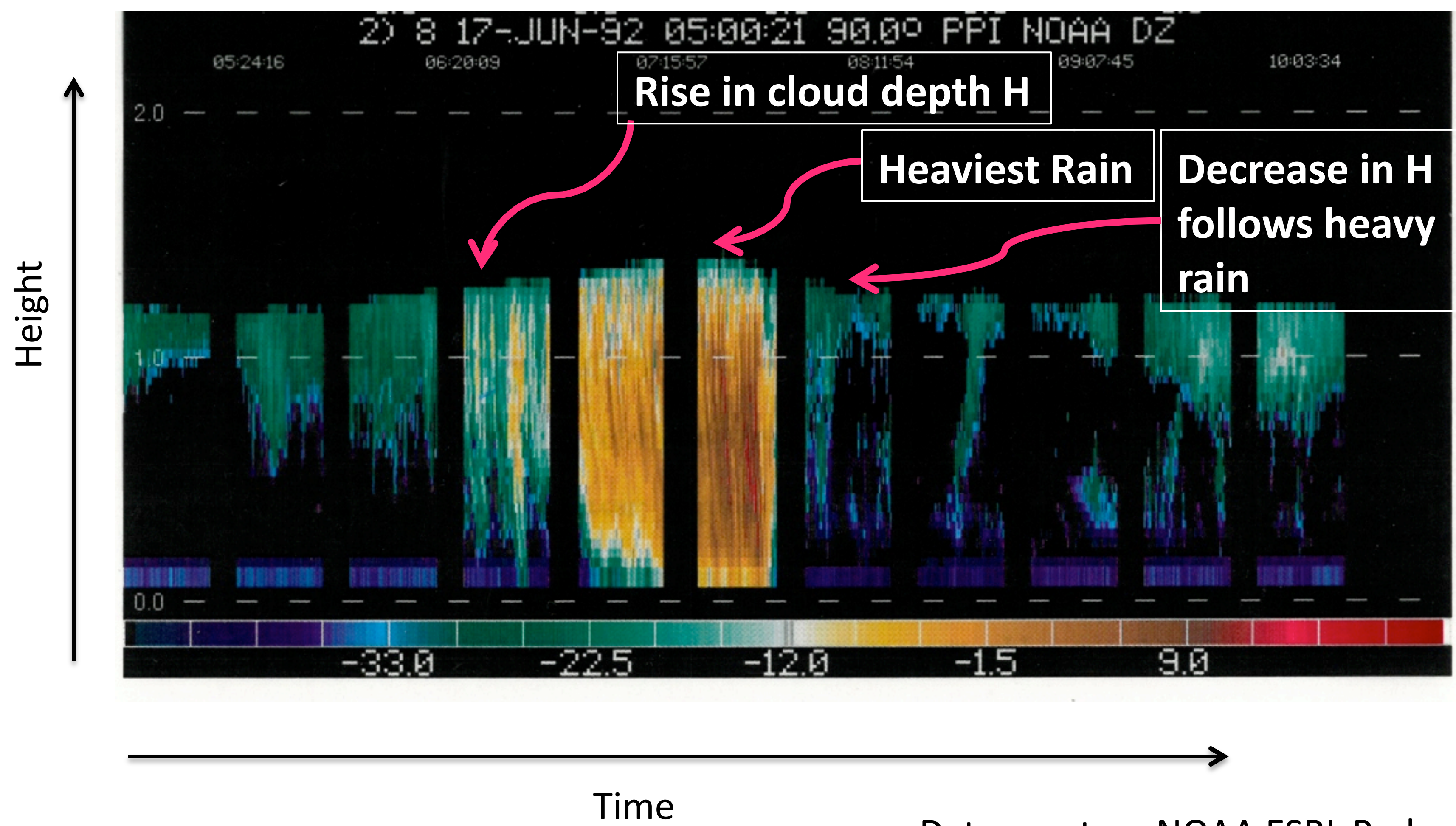
Similar patterns in trade cumulus simulations (RICO)



Time, h

Jiang et al. 2010

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



Data courtesy NOAA ESRL Radar Group

Predator-Prey Model

Lotka-Volterra Equations
(circa 1926)

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

$$\frac{dy}{dt} = -y(\gamma - \delta x)$$

$x =$ prey

$y =$ predator

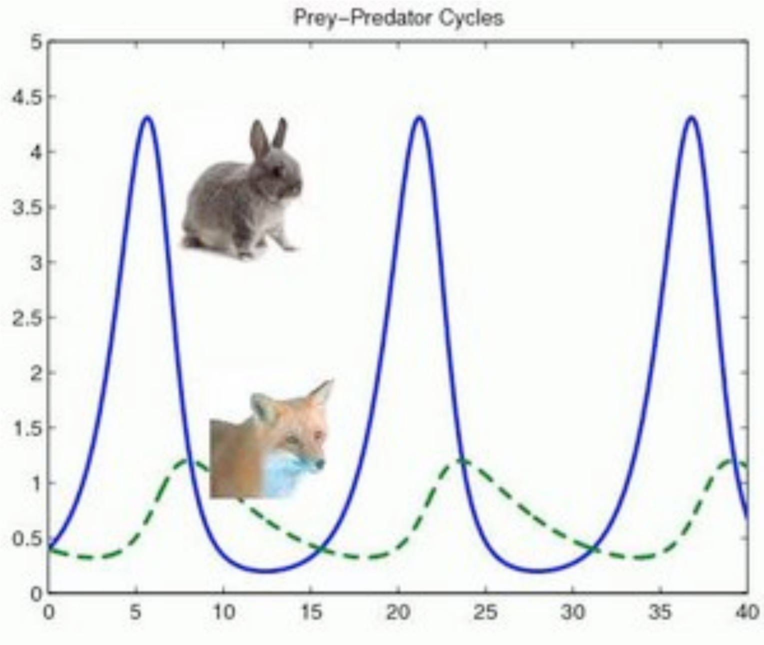
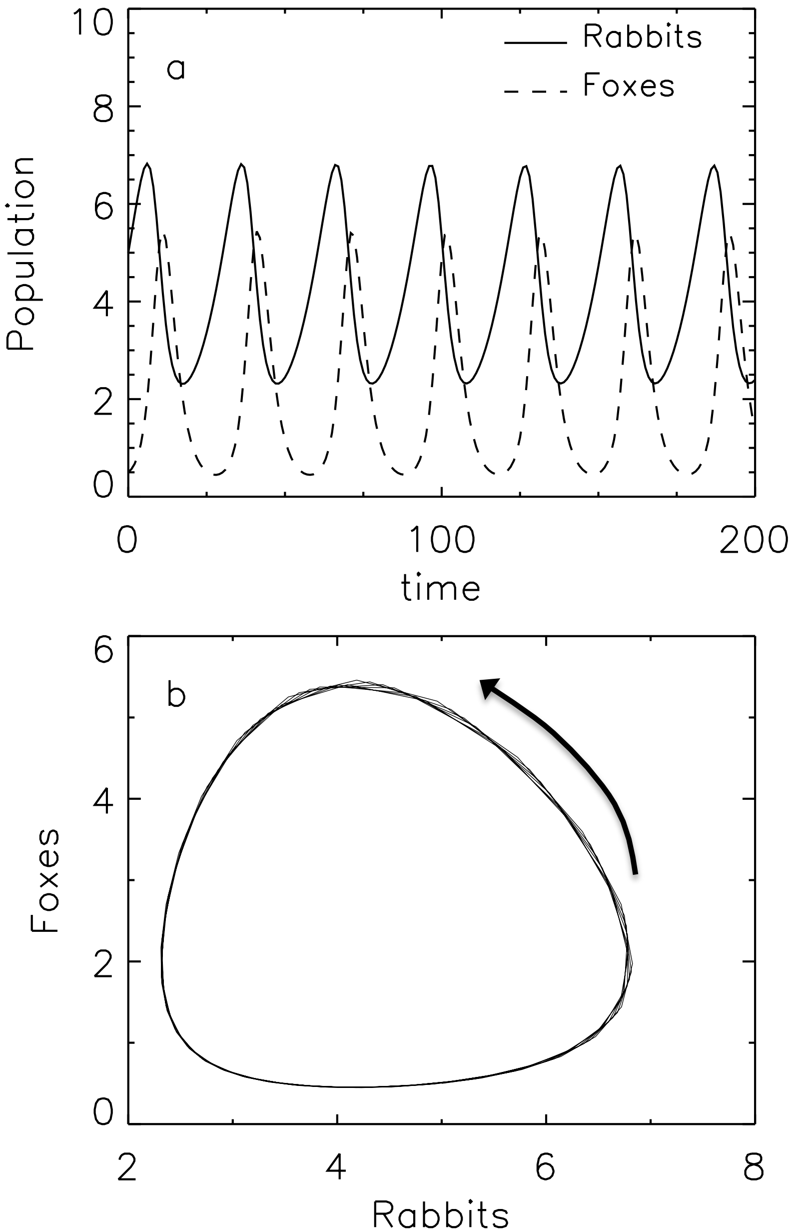


Image courtesy of Wikipedia

4 parameters:
a, b, g, d

Predator-Prey Model



Clouds=Rabbits; Rain=Foxes

- Cloud builds up
- Rain follows some time behind
- Rain destroys cloud
- Cloud regenerates
  (met forcing, colliding outflows, etc)

and so on…

Many possible predator-prey pairs:

Rain; Aerosol
Convection; Instability (Nober and Graf)
Droplets; Supersaturation
Ice; Water (Bergeron-Findeisin)

Koren and Feingold 2011, PNAS

3 simple coupled Balance Equations:

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

Cloud depth

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

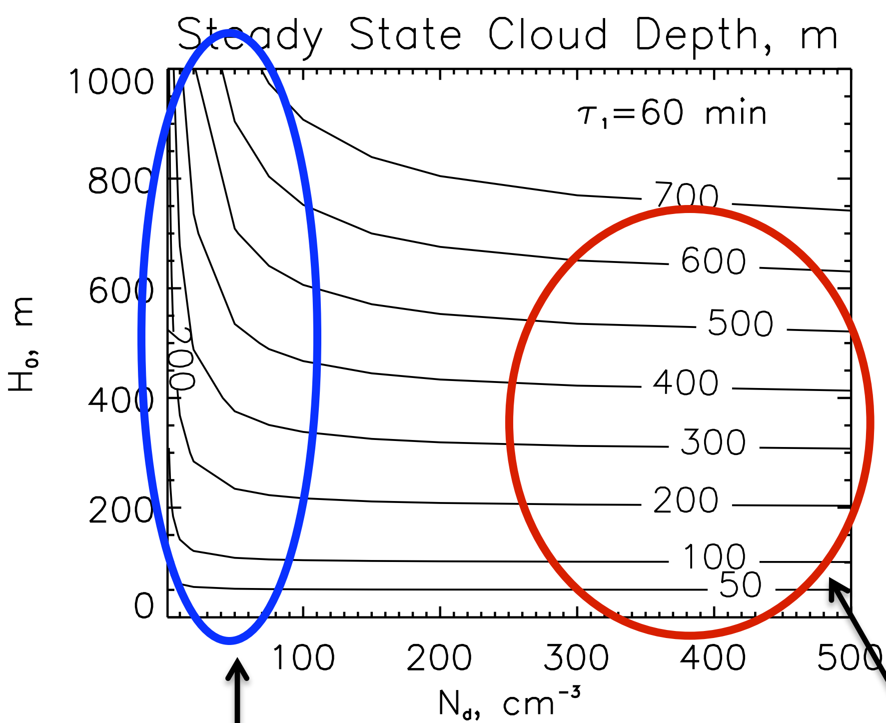
Rainrate

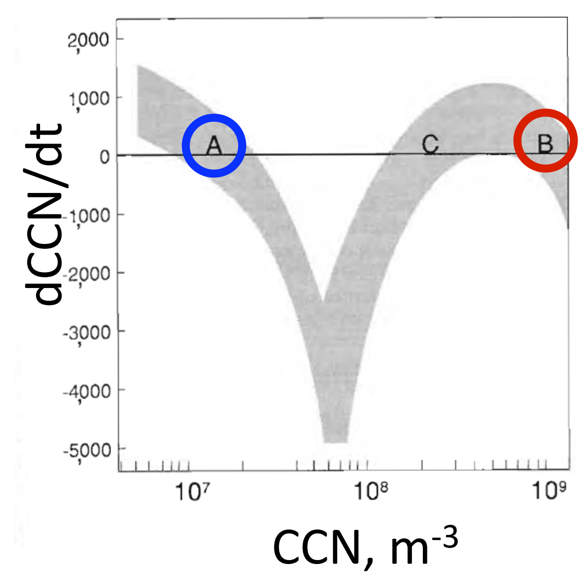
$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t - T)$$

Drop conc.

Steady State Solution to Cloud Depth H

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



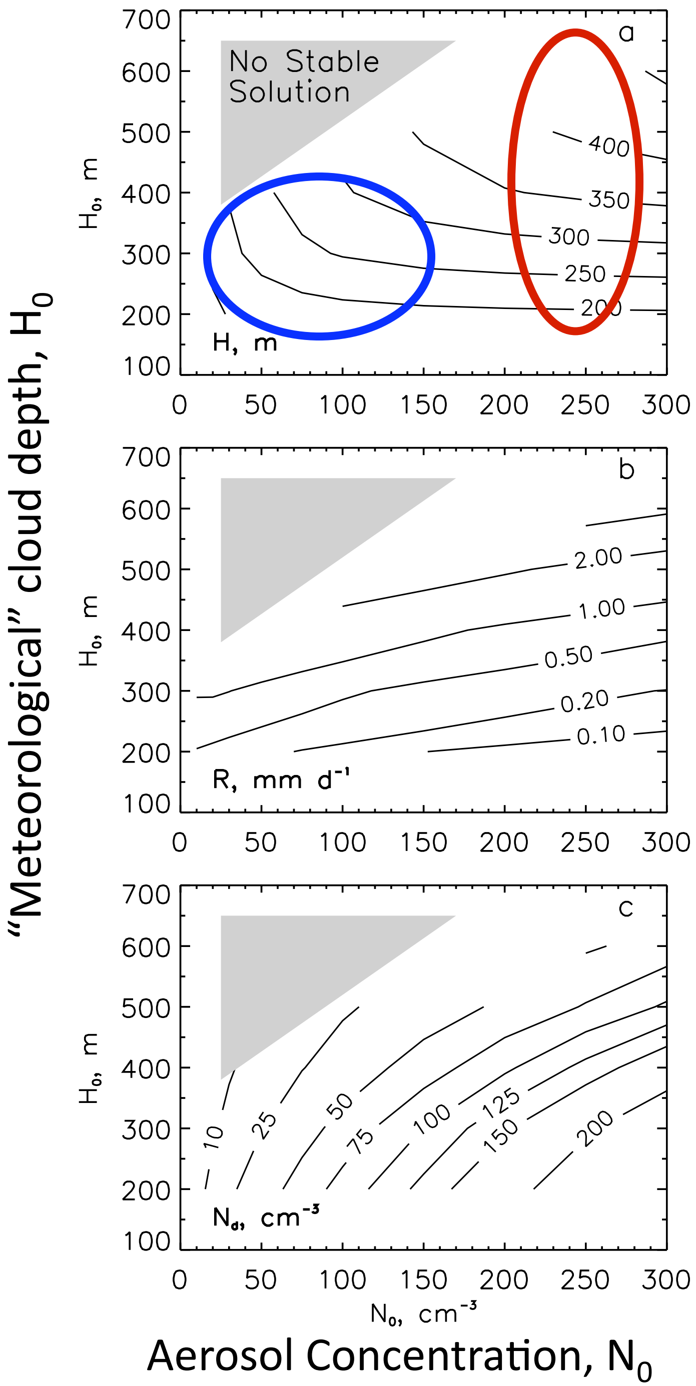


Baker and Charlson, 1990

Cloud Depth determined by drop concentration N_d

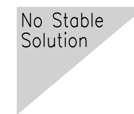
Cloud Depth determined by H_0

Koren and Feingold 2011, PNAS



Time-Dependent Steady State Solutions

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



Strongly precipitating conditions; Aerosol is depleted

$$R(t) = \frac{\alpha H^3(t - T')}{N_d(t - T')}$$

Strong dependence of R on H_o

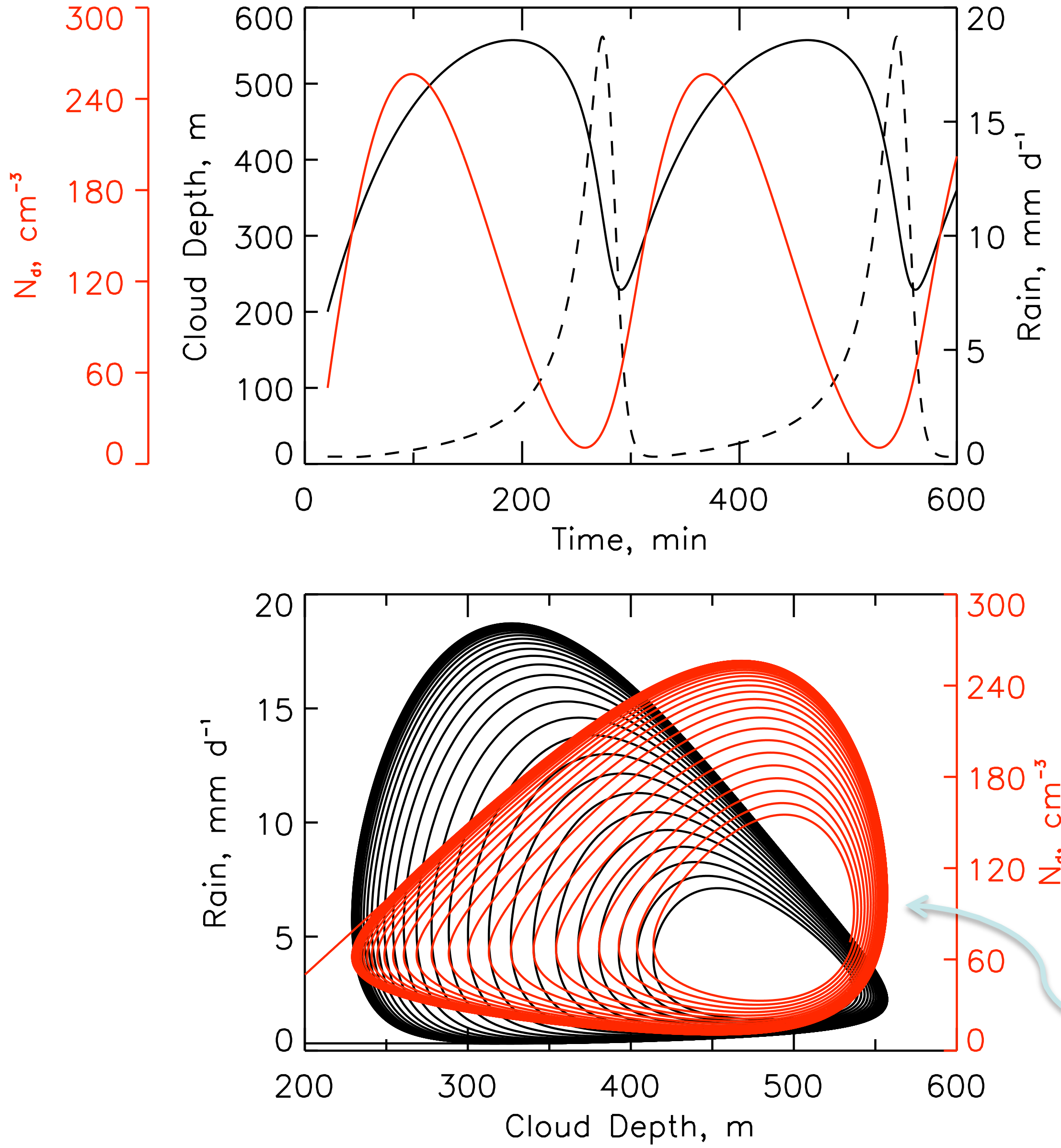
$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t - T)$$

Higher N_o supports deeper clouds

Koren and Feingold 2011, PNAS

$\tau_1 = \tau_2$ = 60 min
T = 10 min

Oscillating Solutions: No Steady State



H_0 = 670 m
N_0 = 515 cm^{-3}

τ_1 = 80 min
τ_2 = 84 min

T = 12.5 min

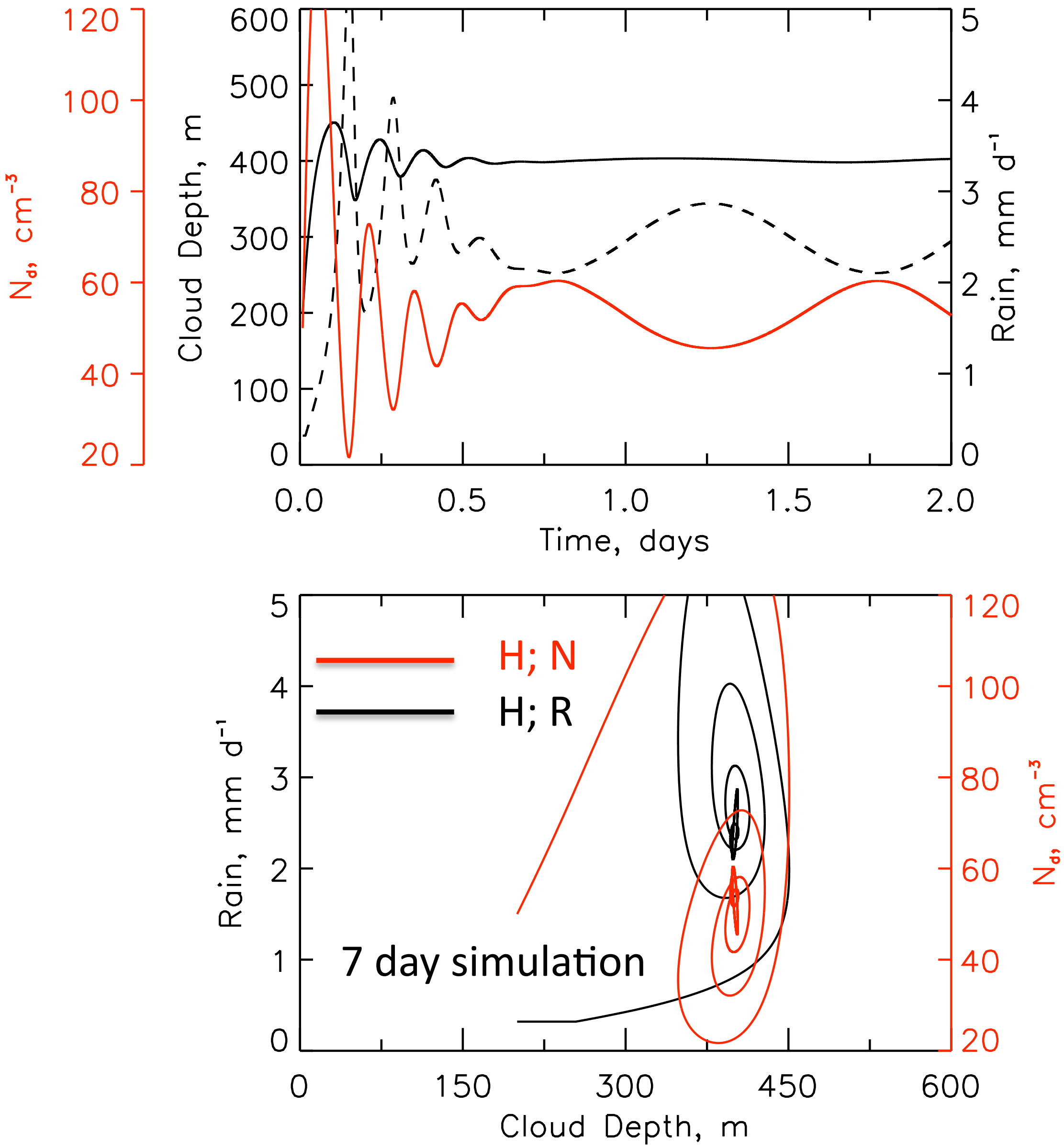
7 day simulation

H; N
H; R

Oscillation around
a steady state

Koren and Feingold 2011, PNAS

Forcing at multiple timescales



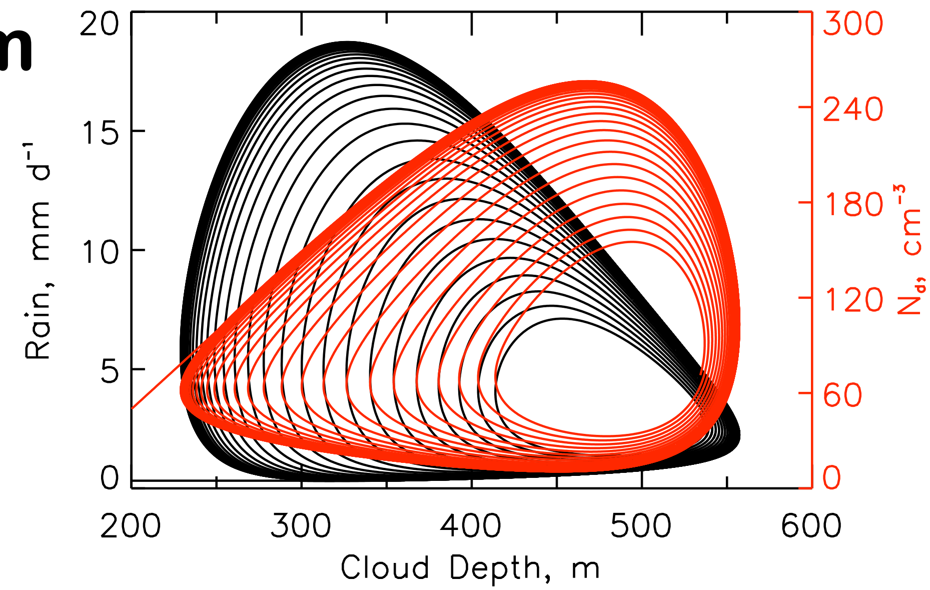
$$\frac{dH}{dt} = \frac{H_0 - H}{\tau_1} + \frac{\Delta H}{\tau_2} + \dot{H}_i(t - T)$$

τ_1 = 1 h (microphysics)

τ_2 = 24 h (largescale forcing)

Robustness of the System

How stable are the stable states?

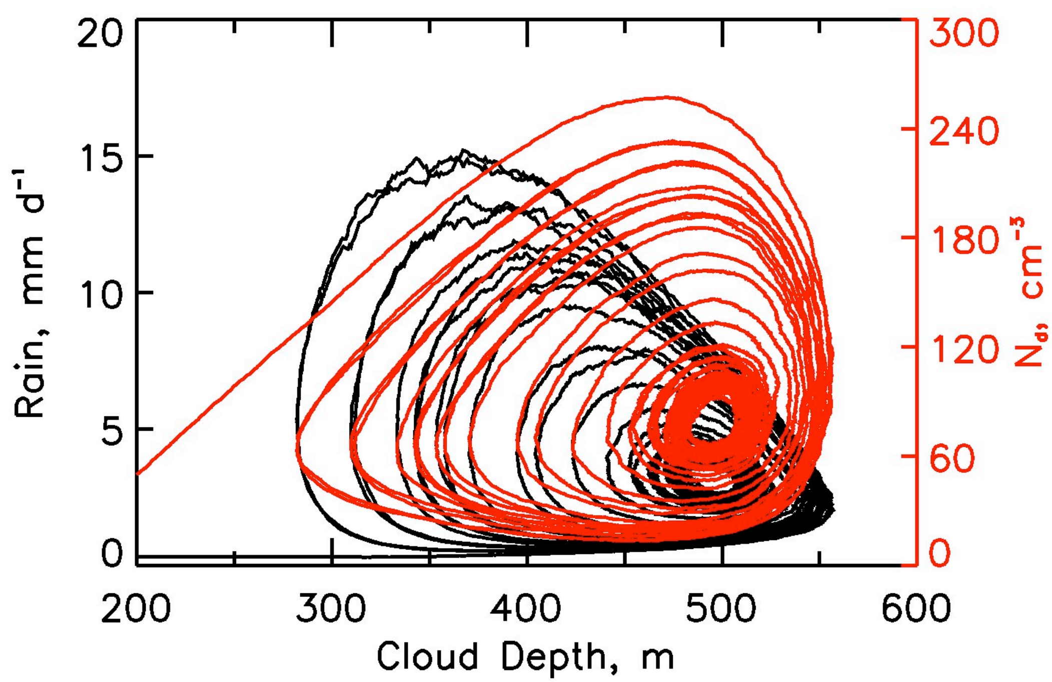


Small perturbations strengthen the resilience of the state

± 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

Summary

- *Emergence*
  - *Local interactions result in system-wide order*
  - *convergence of precipitating outflows*

- *Self-organization*
  - *Aerosol/drizzle can select open/closed cellular state*

- *Synchronization*
  - *Local interactions: synchronized rain, oscillations in open-cell state*

- *The predator-prey problem*
  - *Coupled oscillations in Cloud-Rain "Populations"*
  - *Bifurcation*
  - *Interactions at multiple timescales*

- *Can we exploit emergence to represent complex systems?*
  - *(E.g. Mapes 2011; Bretherton et al. 2010)*