# On the Stability of the Aerosol-Cloud-Precipitation System

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CMMAP
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# Current paradigms for aerosol-cloud interactions in GCMs

- Parameterization of aerosol indirect effects
  - Series of effects: $1^{st}$, $2^{nd}$.. $n^{th}$
  - lack nuance of real world processes
  - sometimes put into climate models without regard to scale, model *infrastructure*
- Resolution of aerosol-cloud interactions
  - Superparameterization
  - PDF approaches

# This Talk

- Explore a *dynamical systems* view of aerosol-cloud interactions

- Detailed modeling of the system with LES and low-dimensional model analogues

- Can low dimensional models play a role in parameterization of aerosol-cloud interactions?

# Outline

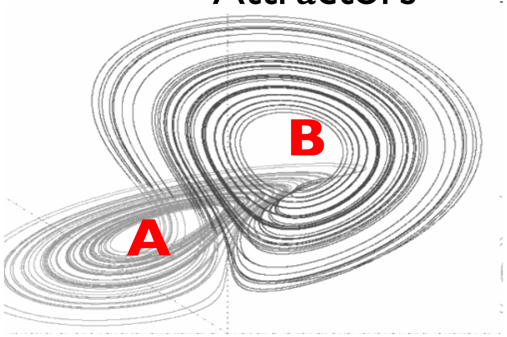
- The macroscopic view of a system
- Order
- Preferred Modes
- Resilience of Modes
- Transitions between Modes
- Simplified Equation Sets

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

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

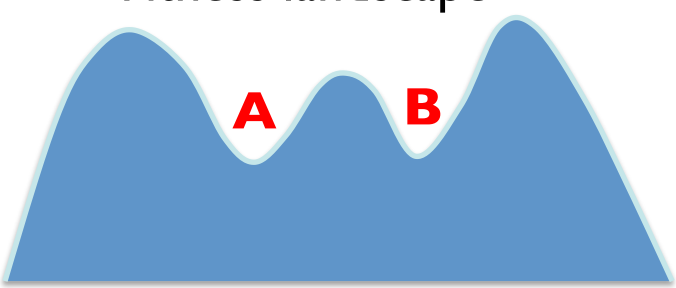
$$\frac{dz}{dt} = xy - \beta z$$

Attractors



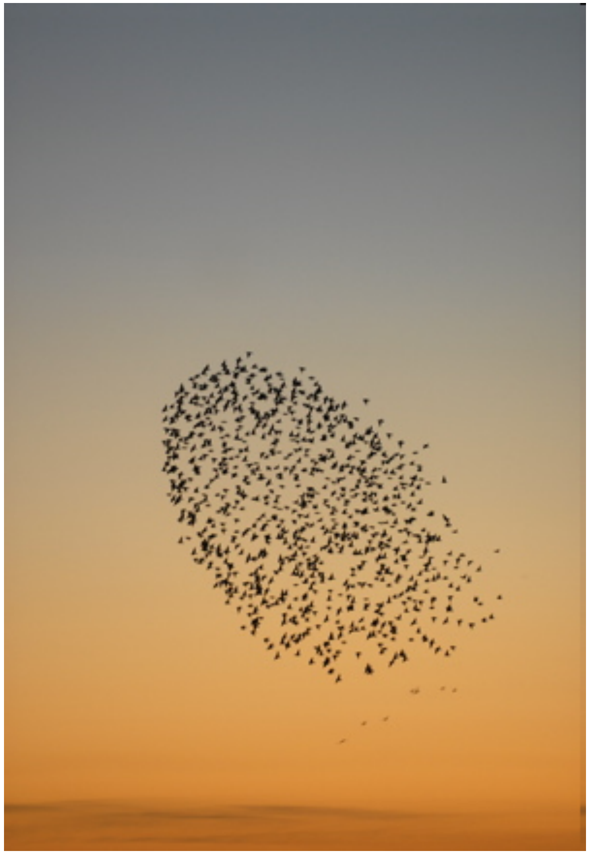

Lorenz, 1963

Fitness landscape




Depth of valley = strength of attractor

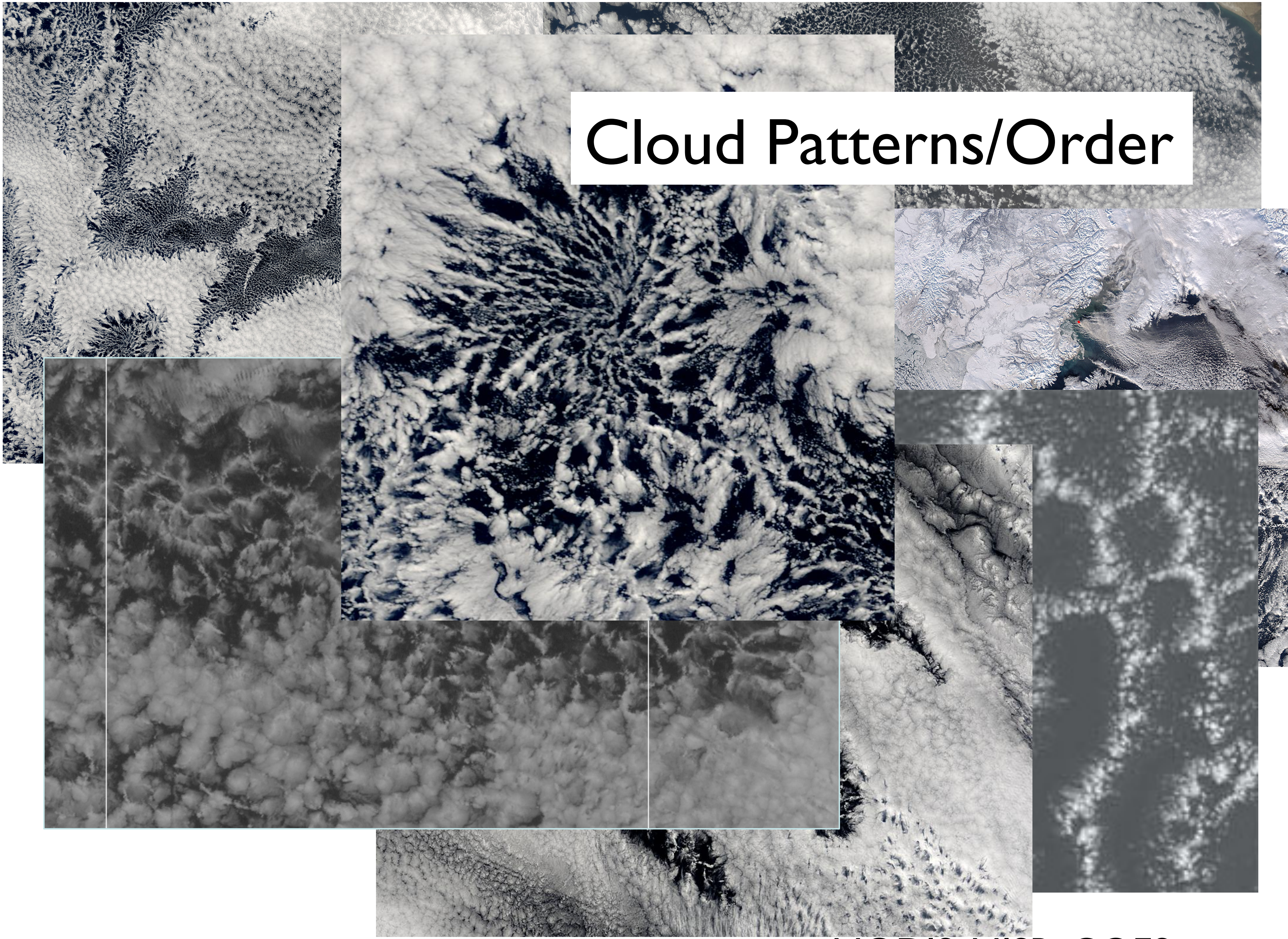
# Macroscopic Order



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

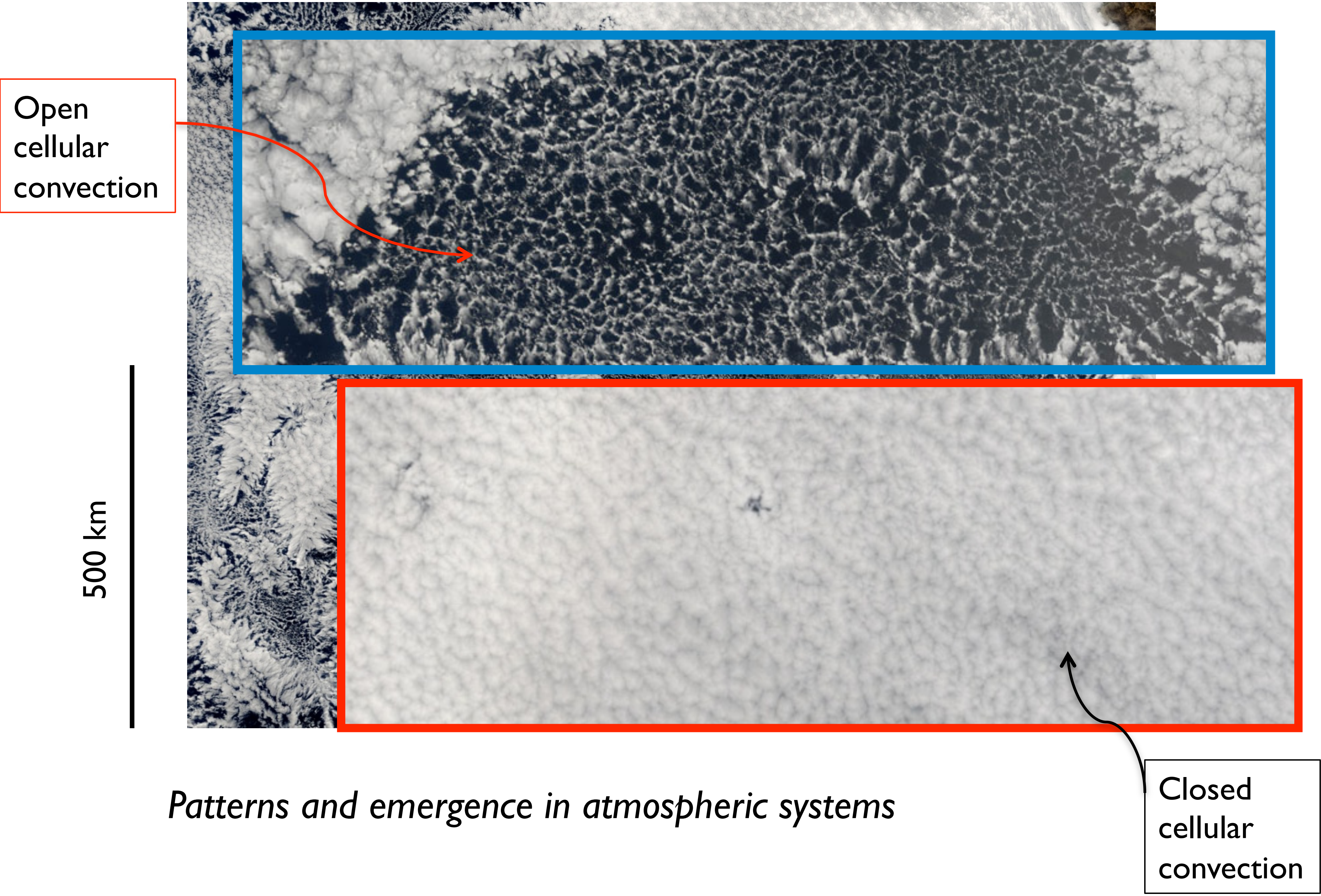
*Don't need to model every bird or every grain of sand to obtain the emergent properties of the system*

# Cloud Patterns/Order



MODIS, MISR, GOES images

# Patterns: Mesoscale Cellular Convection in Stratocumulus




*Patterns and emergence in atmospheric systems*

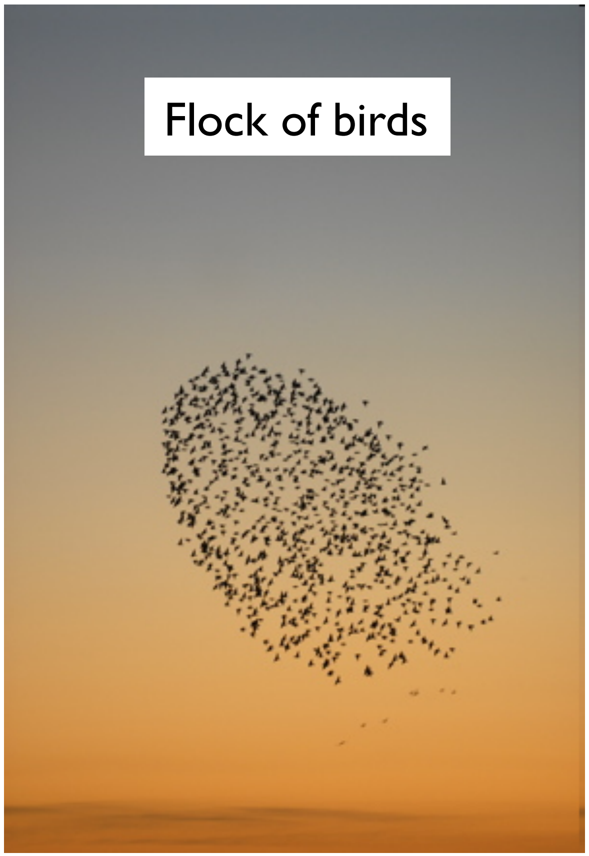
*"Emergence"*

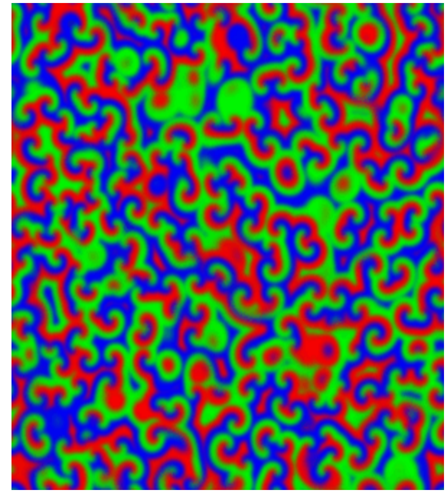
*System-wide patterns emerge from local interactions between elements that make up the system*

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

# *Other examples*

Flock behaviour

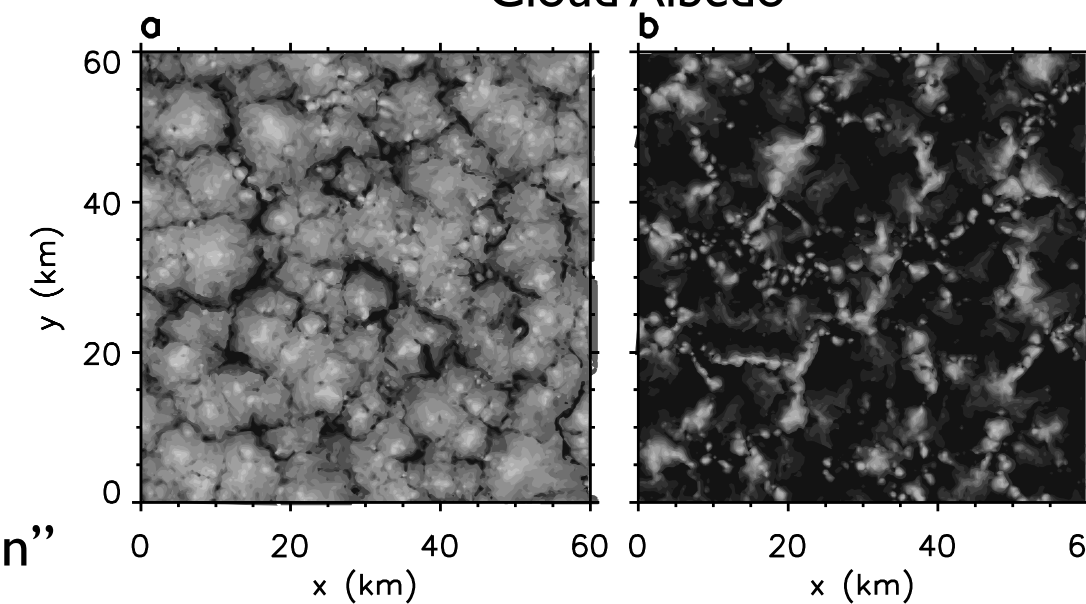


Computer simulation of BZ reaction

Oscillatory behaviour in Belousov-Zhabotinskii chemical reactions

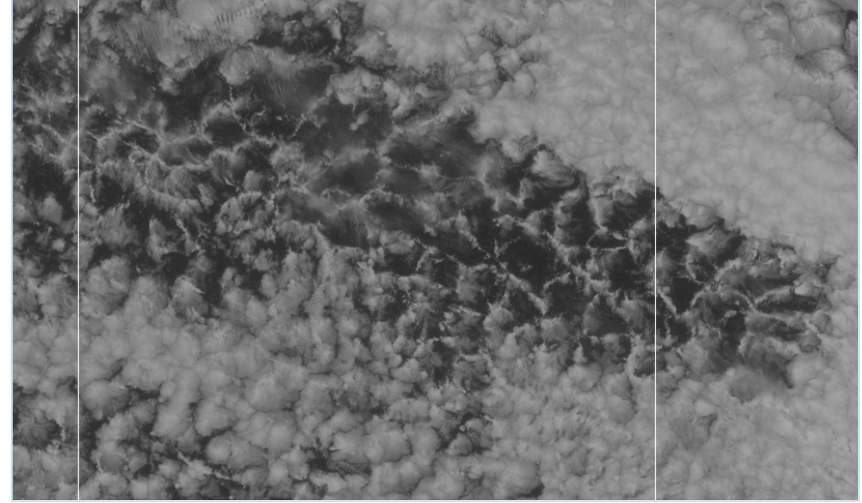
Cloud Albedo

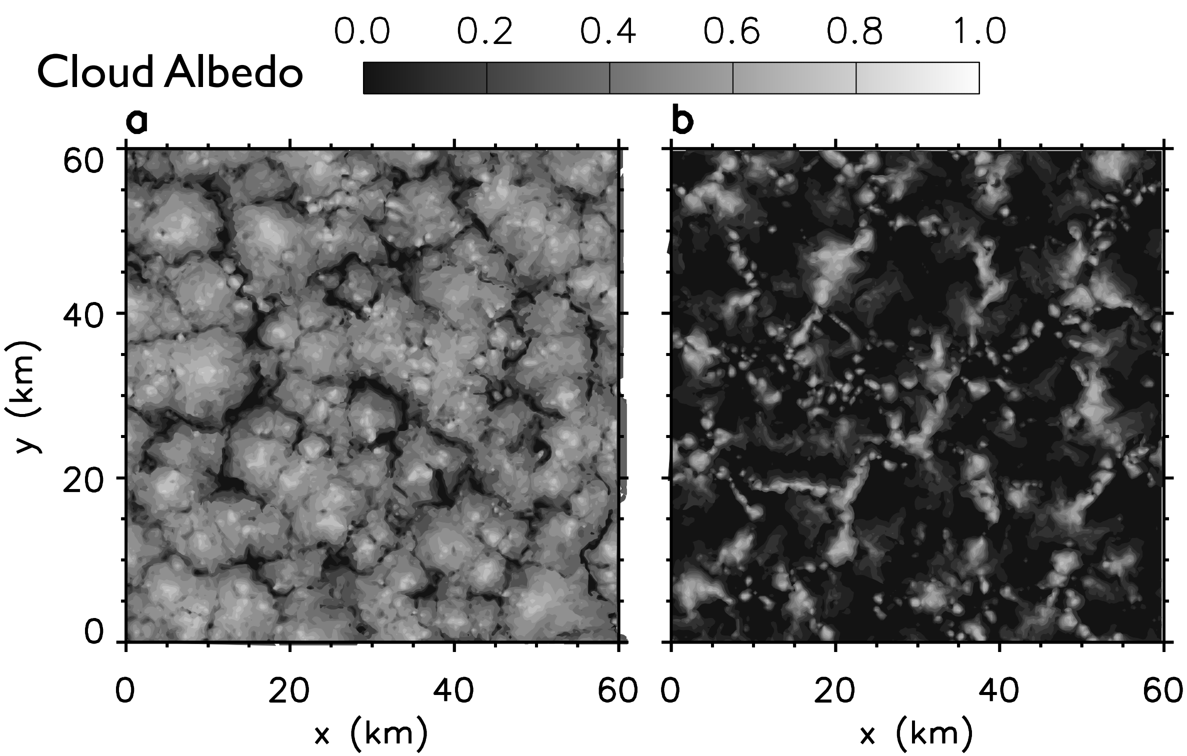



Numerical simulation of "Rayleigh-Bénard Convection"

# Preferred Modes

# Open and closed-cells: Self-organization



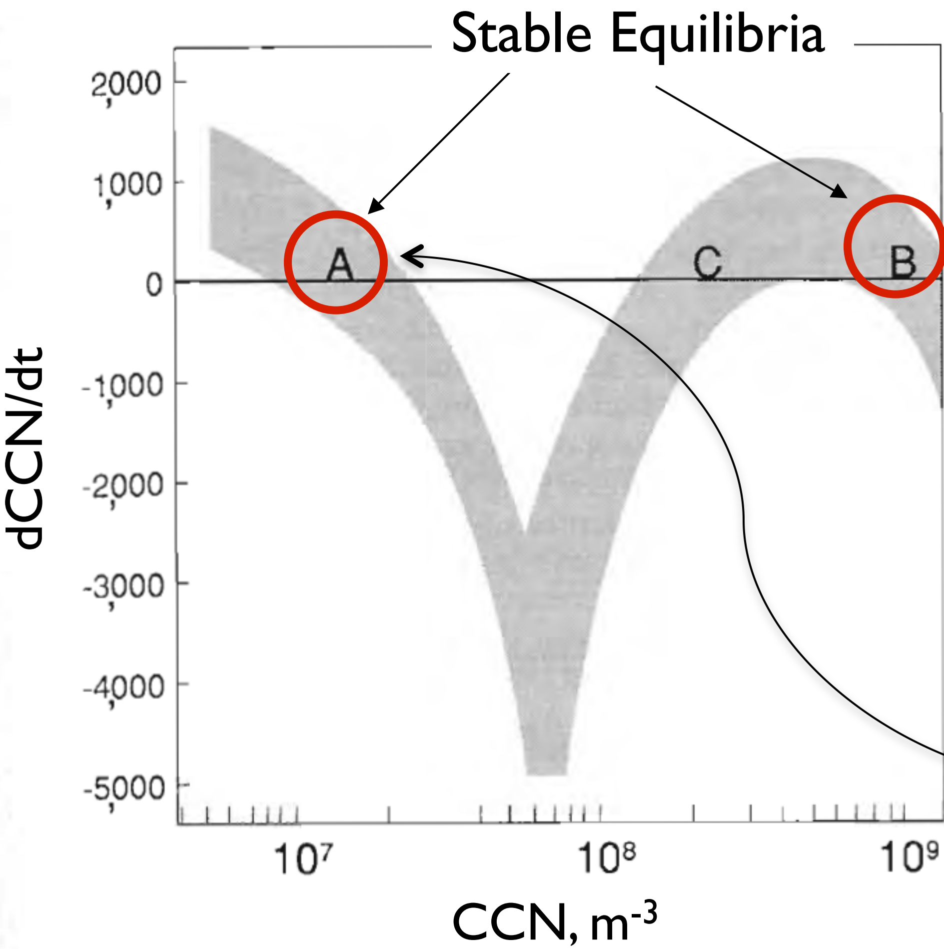



*Feingold, Koren, Wang, Xue, Brewer (2010)*

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

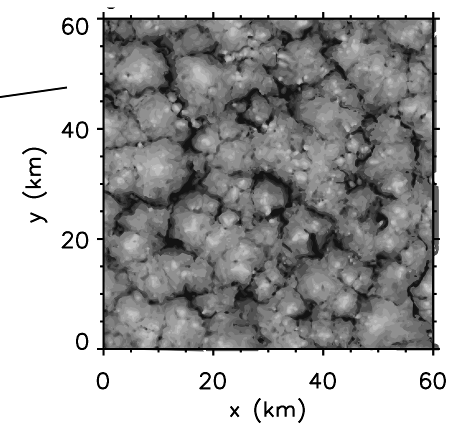
# System Equilibria

Atmospheric systems prefer certain modes



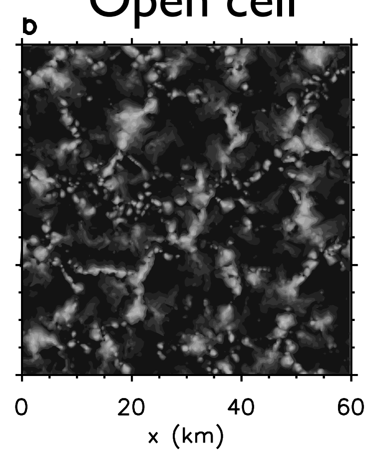

Baker and Charlson, 1990
Mixed-layer model

Closed cell




Non-drizzling, closed-cell mode

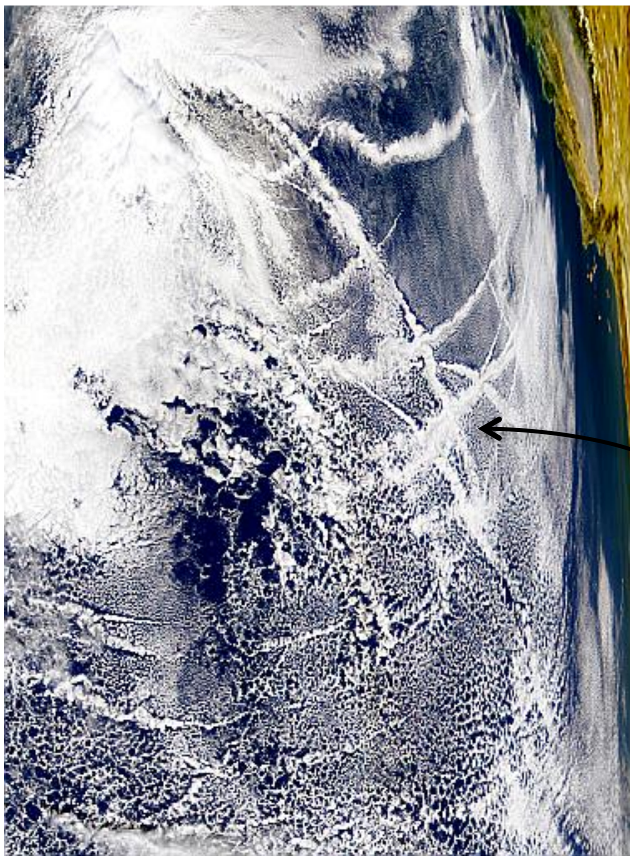
Open cell



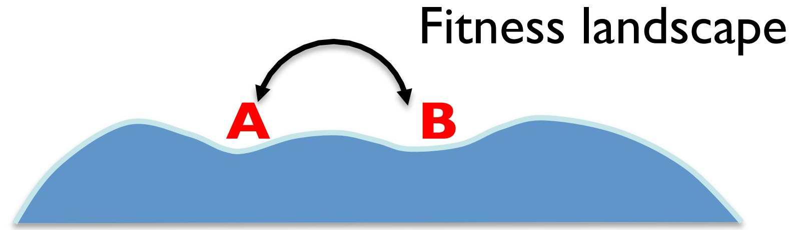

Drizzling, open-cell mode

# Resilience to aerosol perturbations

*Open cells readily revert to closed cells*
*System is <u>not</u> resilient to change*



MODIS image courtesy NASA

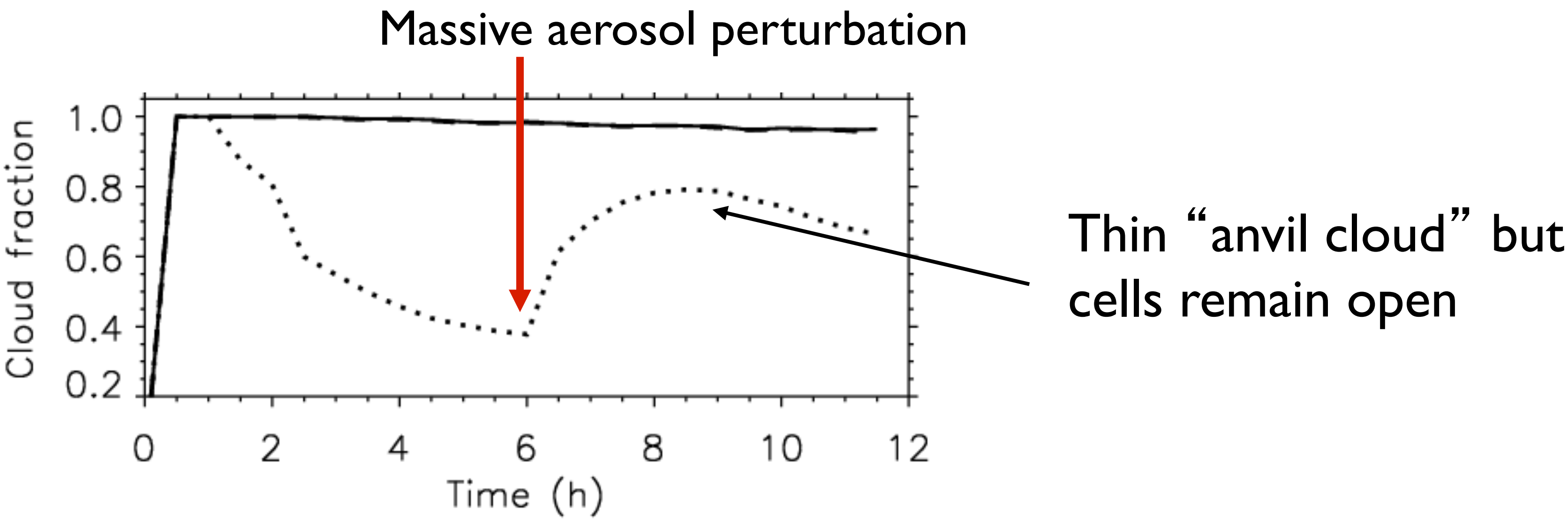



Depth of valley = strength of attractor

*Distinct closing of open cells by ship tracks*

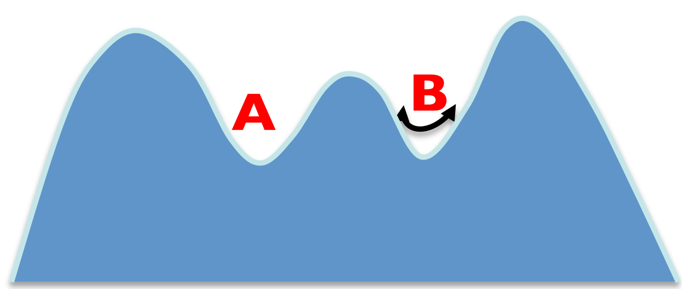
# Resilience to aerosol perturbations

*System* *<u>is</u>* *resilient to change*




| | |
|---|---|
| ——— | Closed-cell case |
| ·············· | Open-cell with massive aerosol perturbation (65 → 300 $cm^{-3}$) at 6h |

Modelled clouds from
Wang and Feingold, 2009



# Aerosol/drizzle selects the state

Closed-cell
Albedo ~ 0.6
(non-
precipitating)

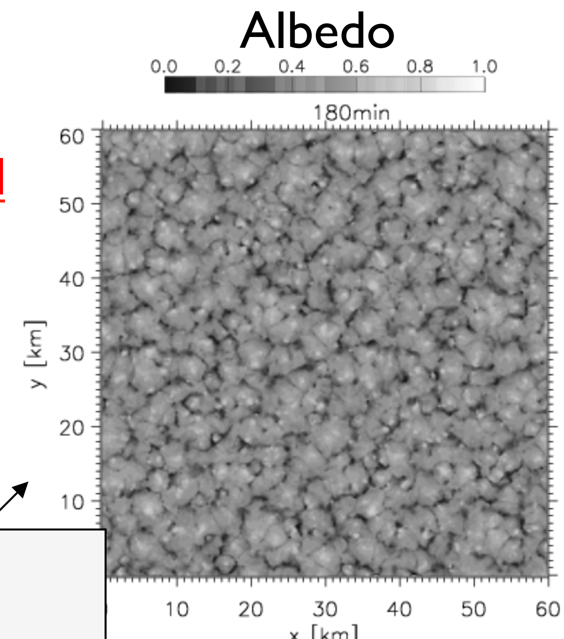
→ **high aerosol**

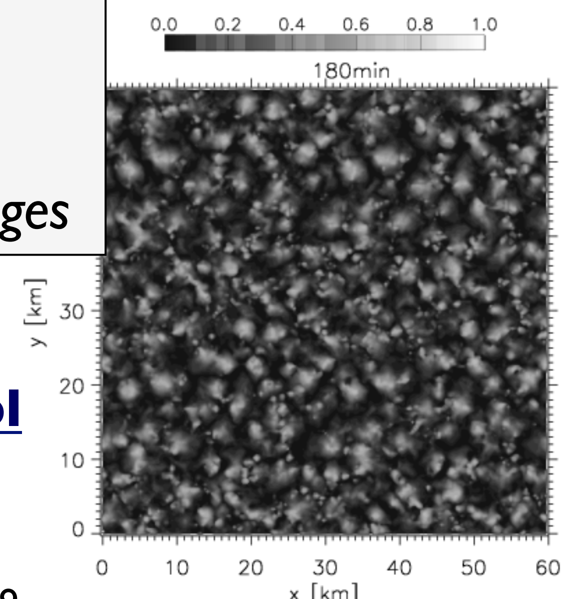
*Onset of*
***drizzle***
*results in*
*transition*
*to open-c*
*convectio*

WRF Model
+ 2-moment

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

*(ii) The stable state rearranges*



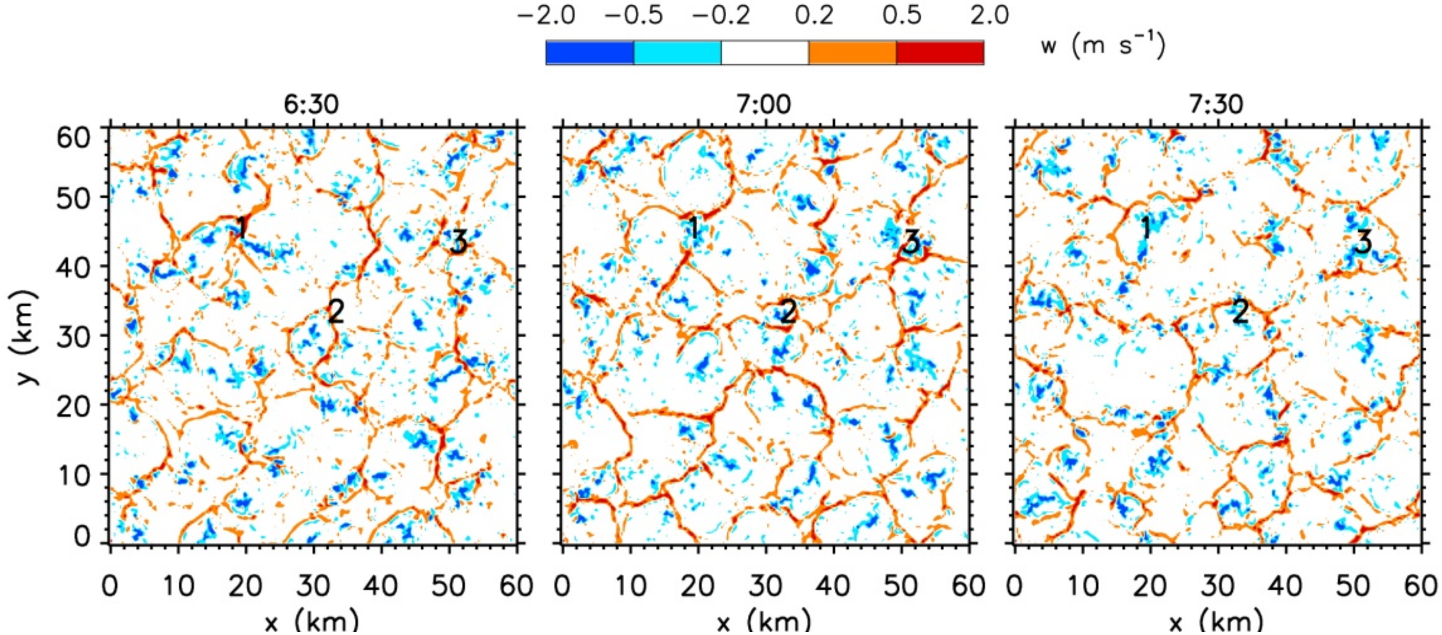




Open-cell
Albedo ~ 0.2
(precipitating)

→ **low aerosol**

Wang and Feingold, 2009

# Rearrangement of Open Cells




**Red:** Updrafts
**Blue:** Downdrafts/precipitation

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

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

↓

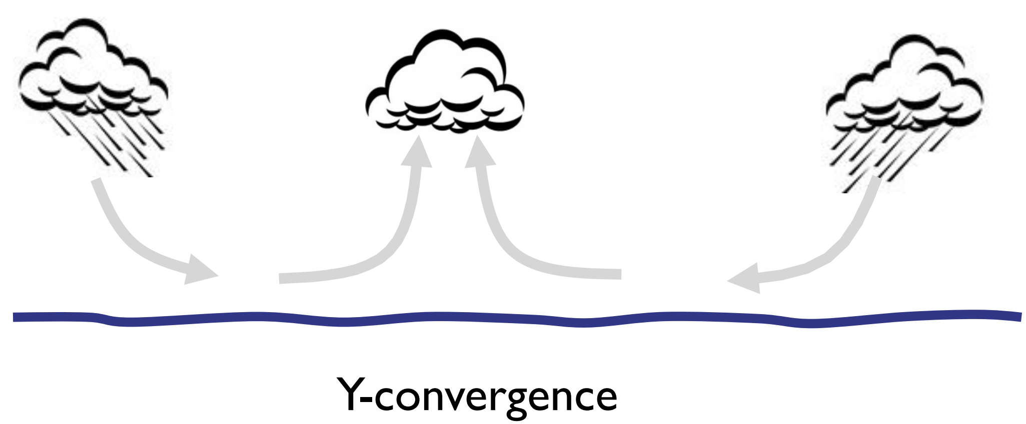
Precipitation is initiated

↓

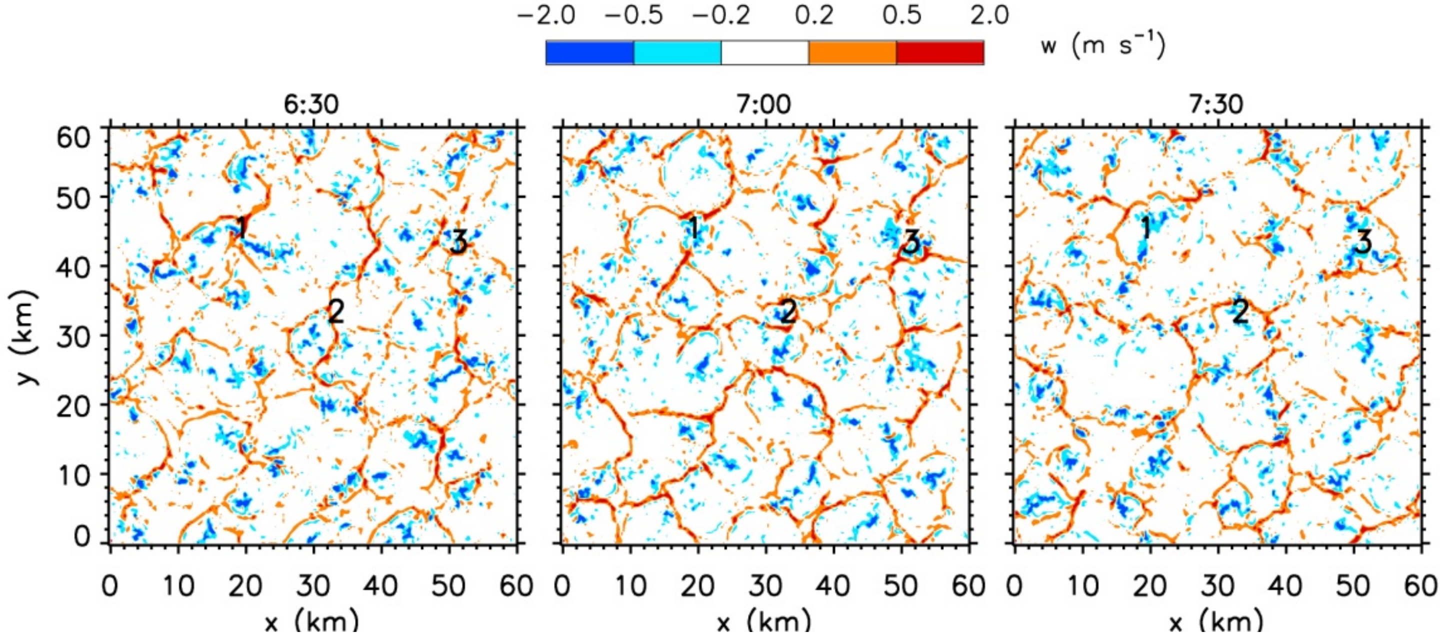
Downdrafts, opening of cell

↓

Surface divergence



# Rearrangement of Open Cells

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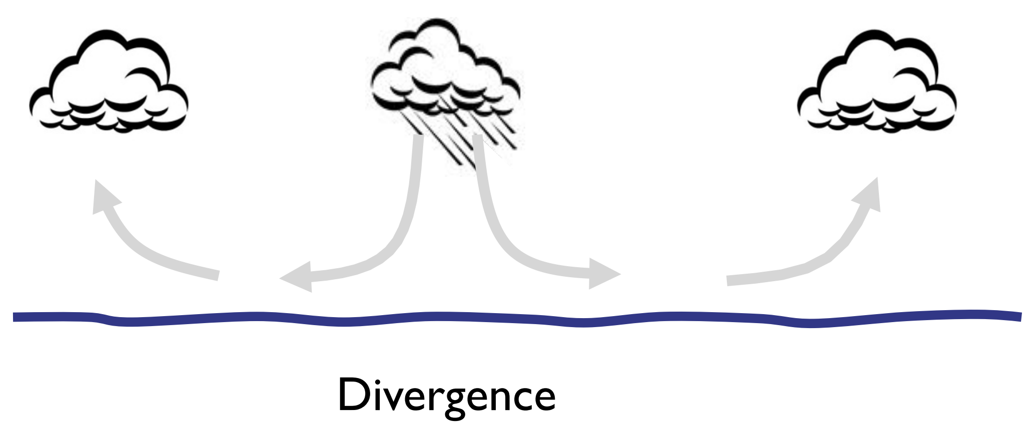
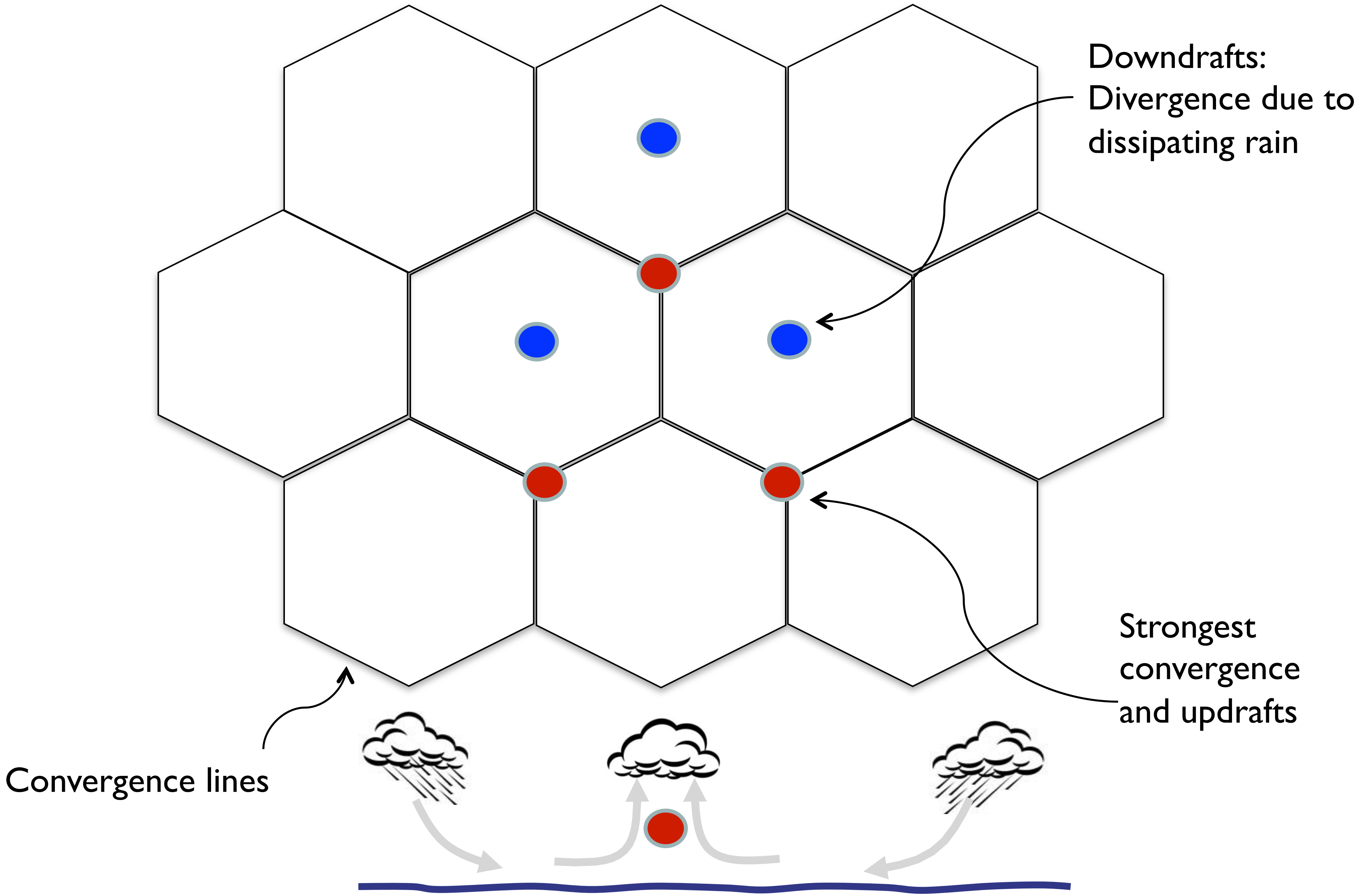
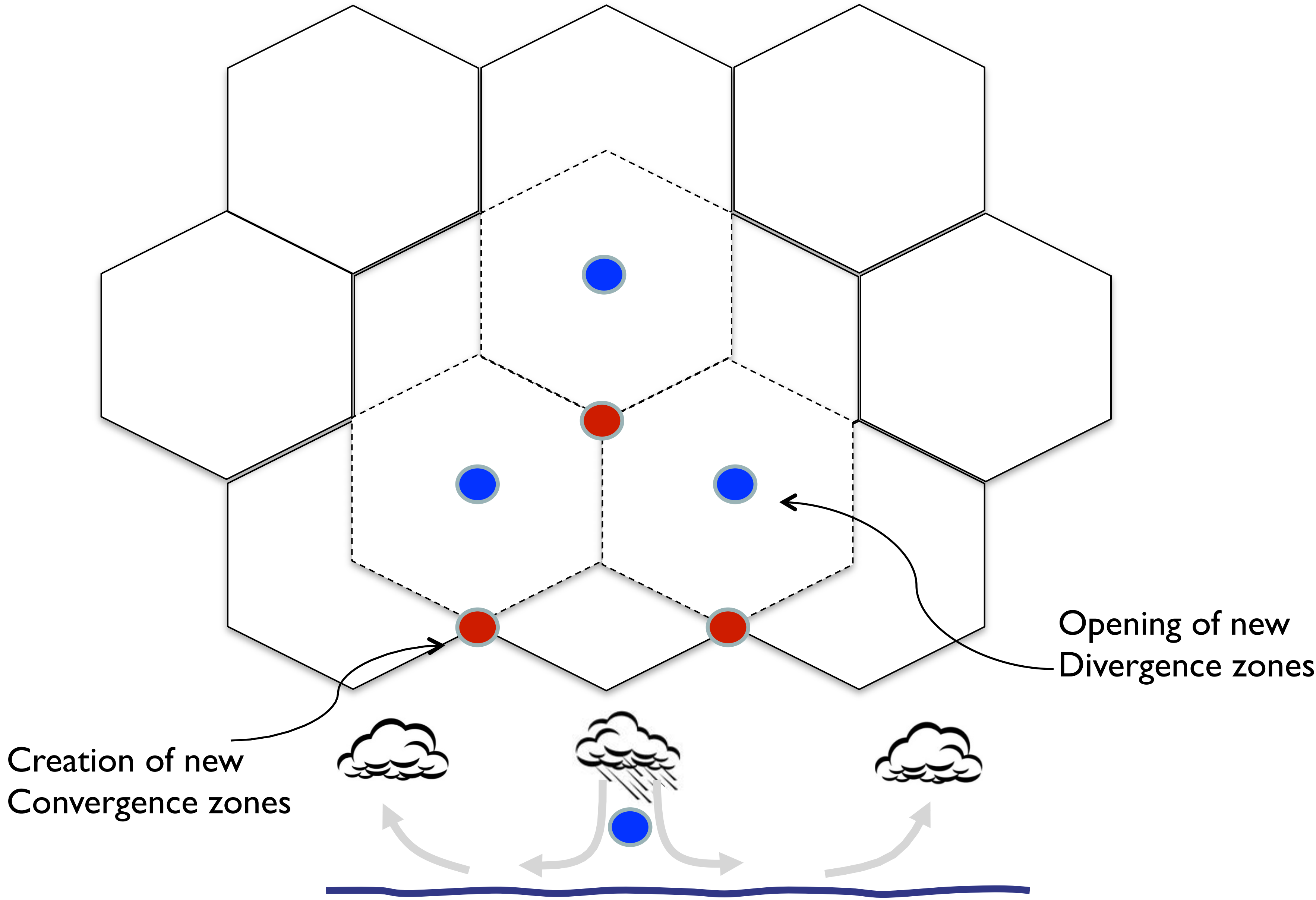


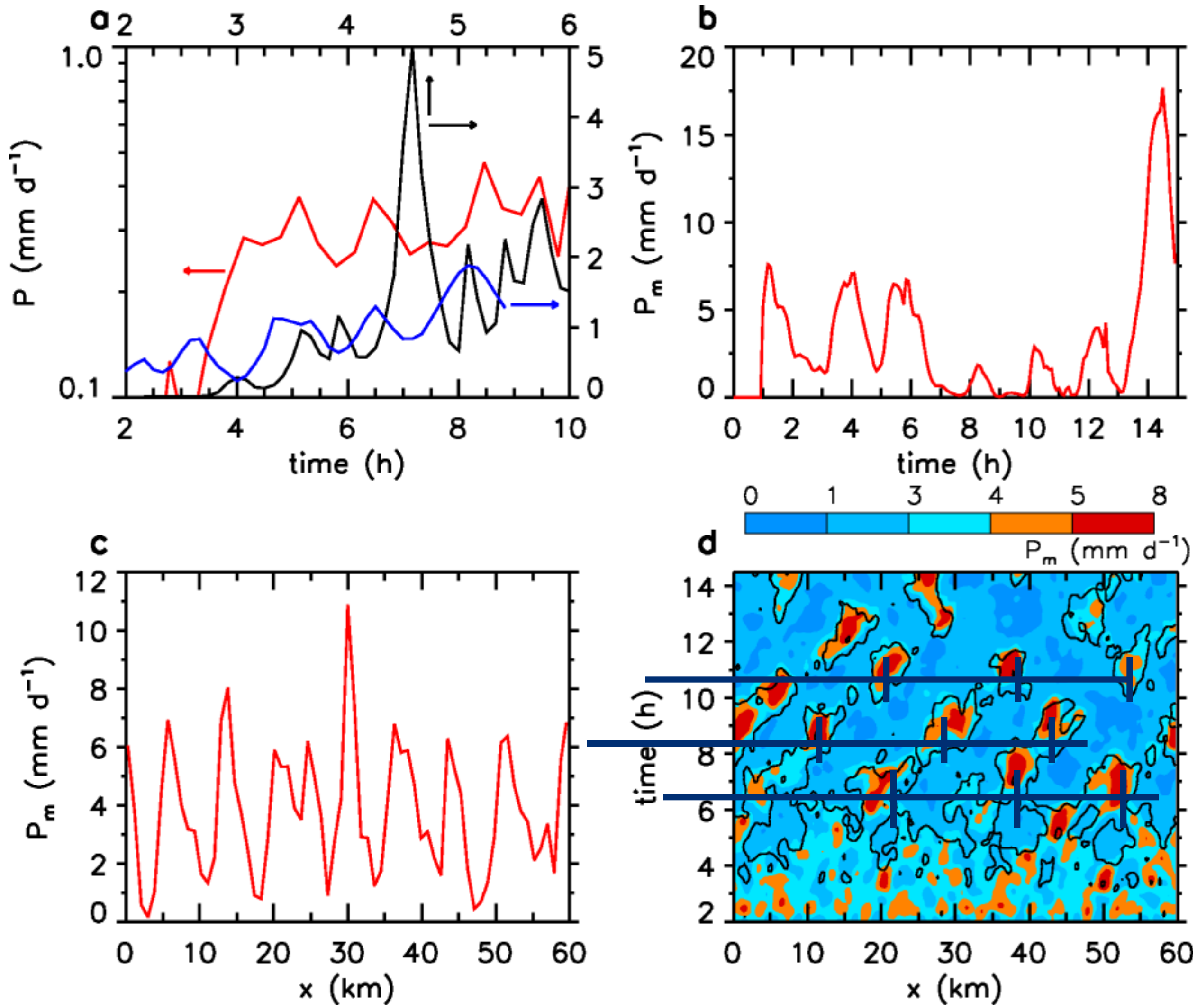
# Surface Convergence Patterns



# Shifting of the Patterns



# Synchronization: Oscillations in Precipitation




**3 LES cases:**
**DYCOMS**
**ATEX**
**VOCALS**

Hovmoller diagram

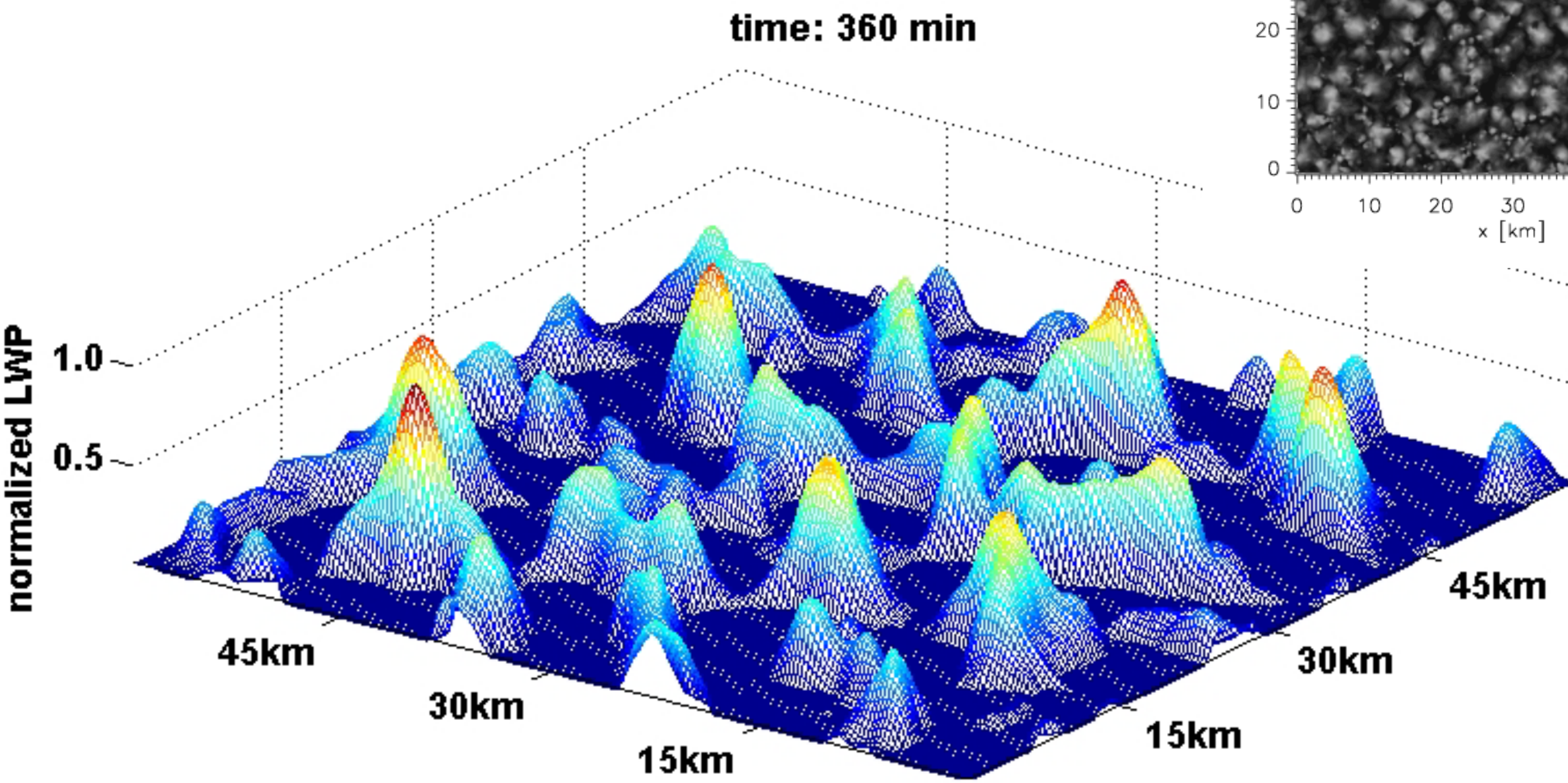
*Shift in rain "grid"*

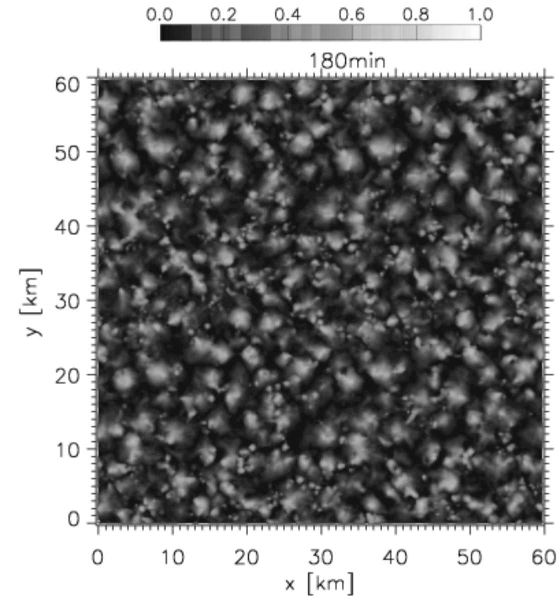
Colored contours: rain

Contours: updraft

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

# Synchronization of Coupled Oscillators




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

# Resilience through interaction of outflows

Stability attained by cloud elements communicating with one another

Low aerosol conc. or cloud thickening

→ Drizzle

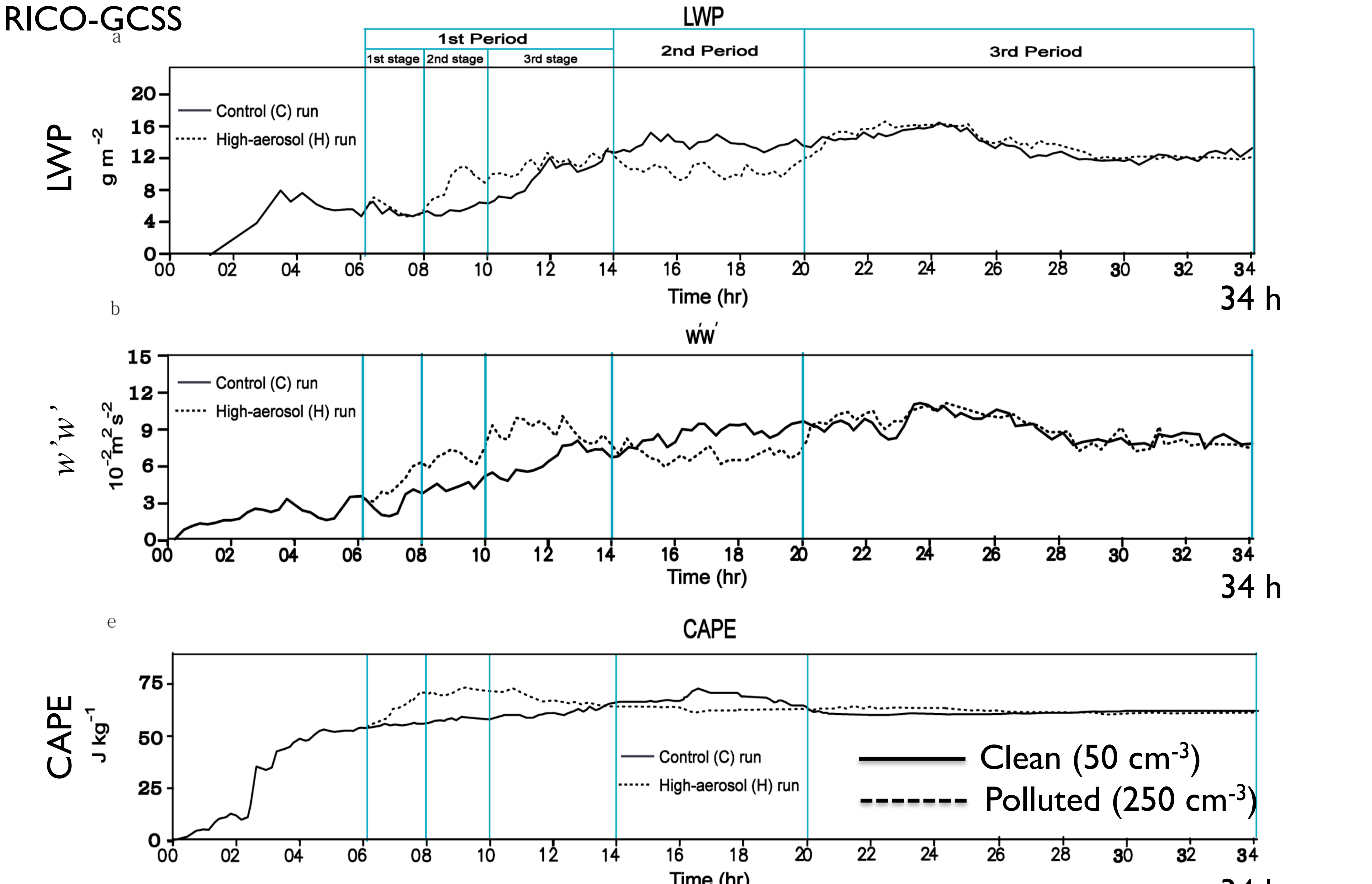
→ Interaction between cloud elements via colliding outflows

→ Stabilization of system

# Aerosol influences in Trade Cumulus

Photo Jen Small
RICO clouds

# Resilience in a non-precipitating Cu system




Lee, Feingold, Chuang, 2012

# Resilience through communication with the environment

Stability is attained by cloud elements communicating with their environment

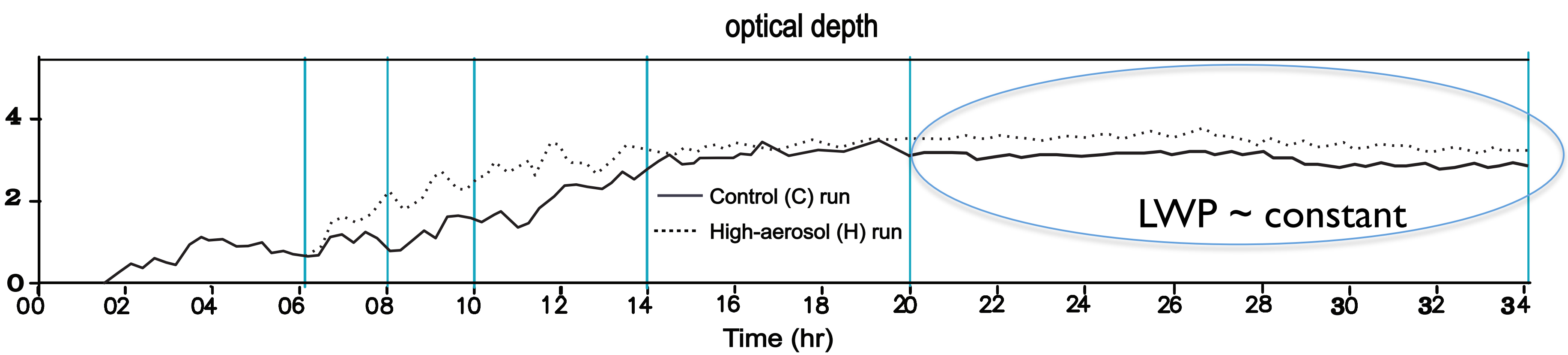
Aerosol perturbations to cloud microphysics

→ changes in BL thermodynamics

→ changes in cloud field properties

→ homogenization

# Influence on cloud optical depth




*Only about 75% of the Twomey increase in albedo is realized because of horizontal and vertical spatial variability in microphysical properties*

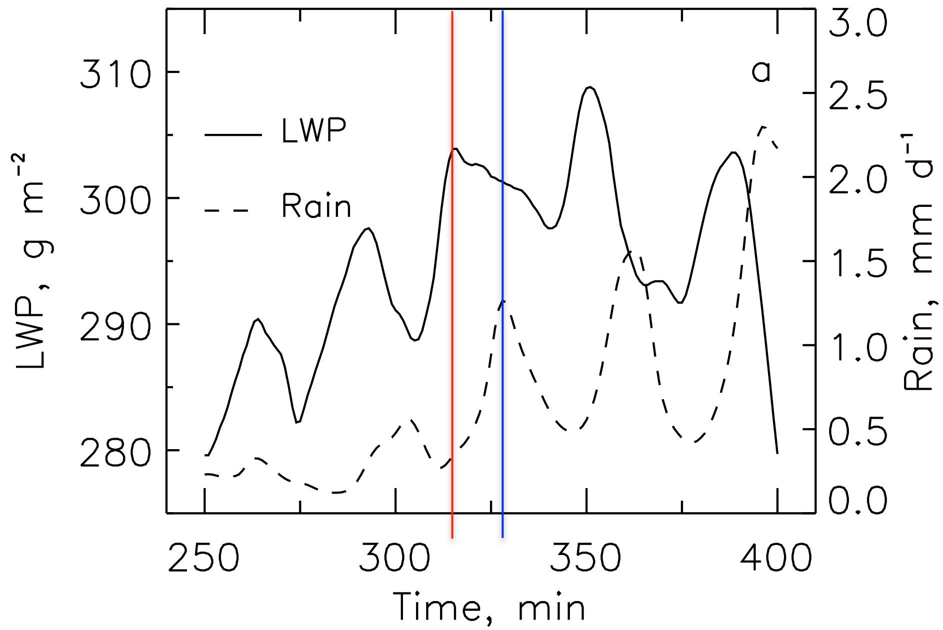
Clean (50 cm$^{-3}$)

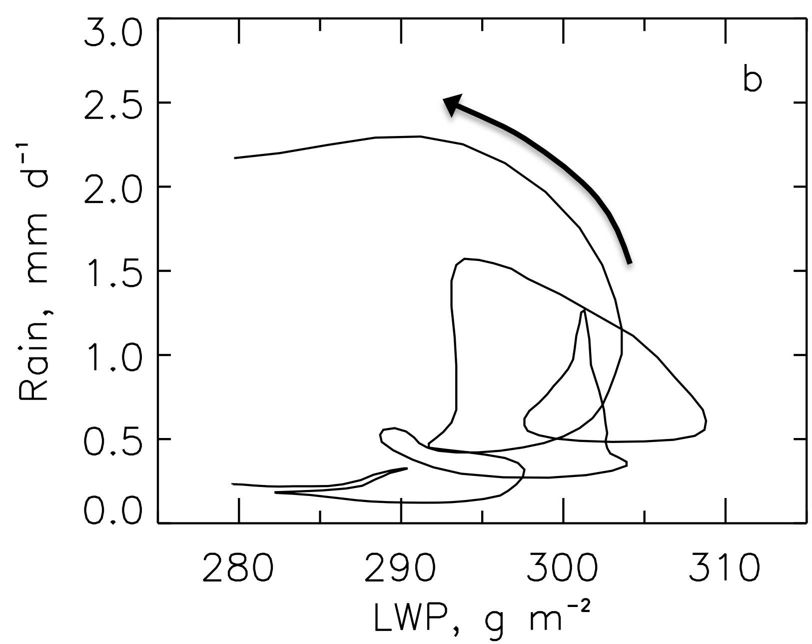
Polluted (250 cm$^{-3}$)

*i.e.,* $3/4 \times (N_{d,H}/N_{d,C})^{1/3}$

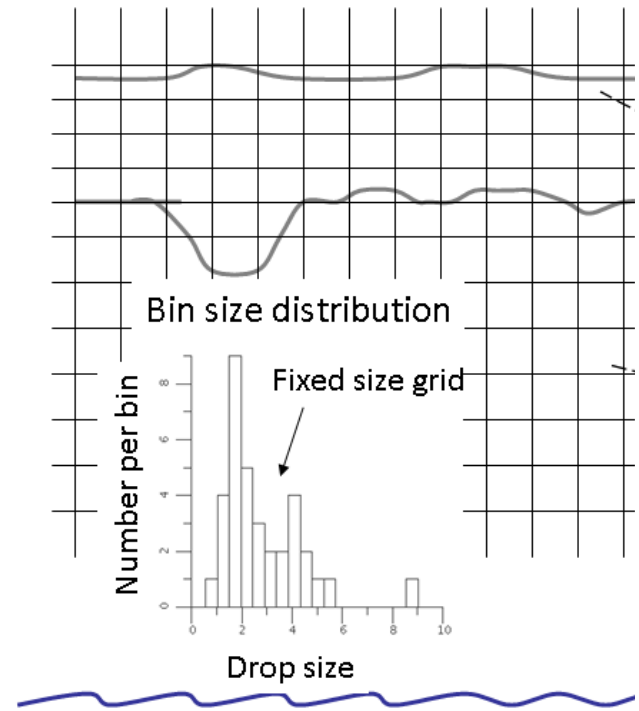
# Simplified Equation Sets
# (low dimensional models)

# 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

# Predator-Prey Model

# Predator-Prey Model

Lotka-Volterra Equation for Population Dynamics (circa 1926)

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

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

$x =$ prey

$y =$ predator

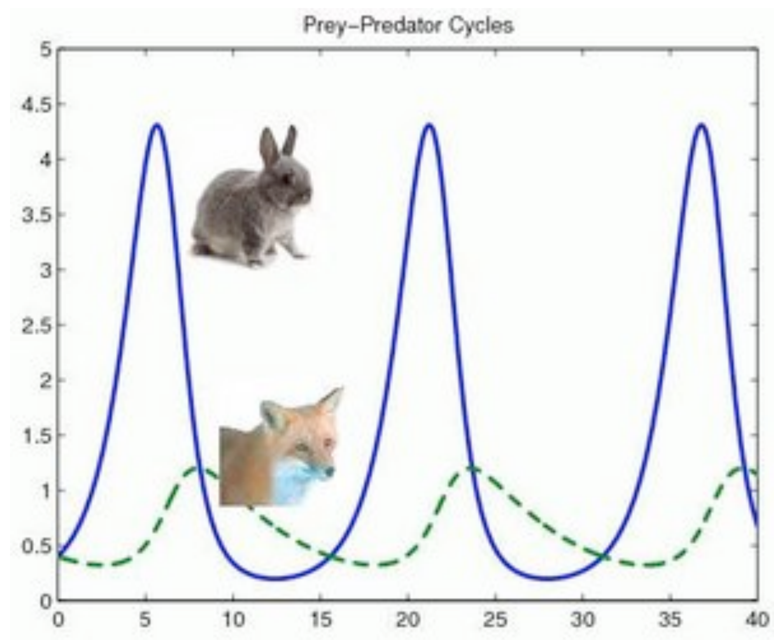
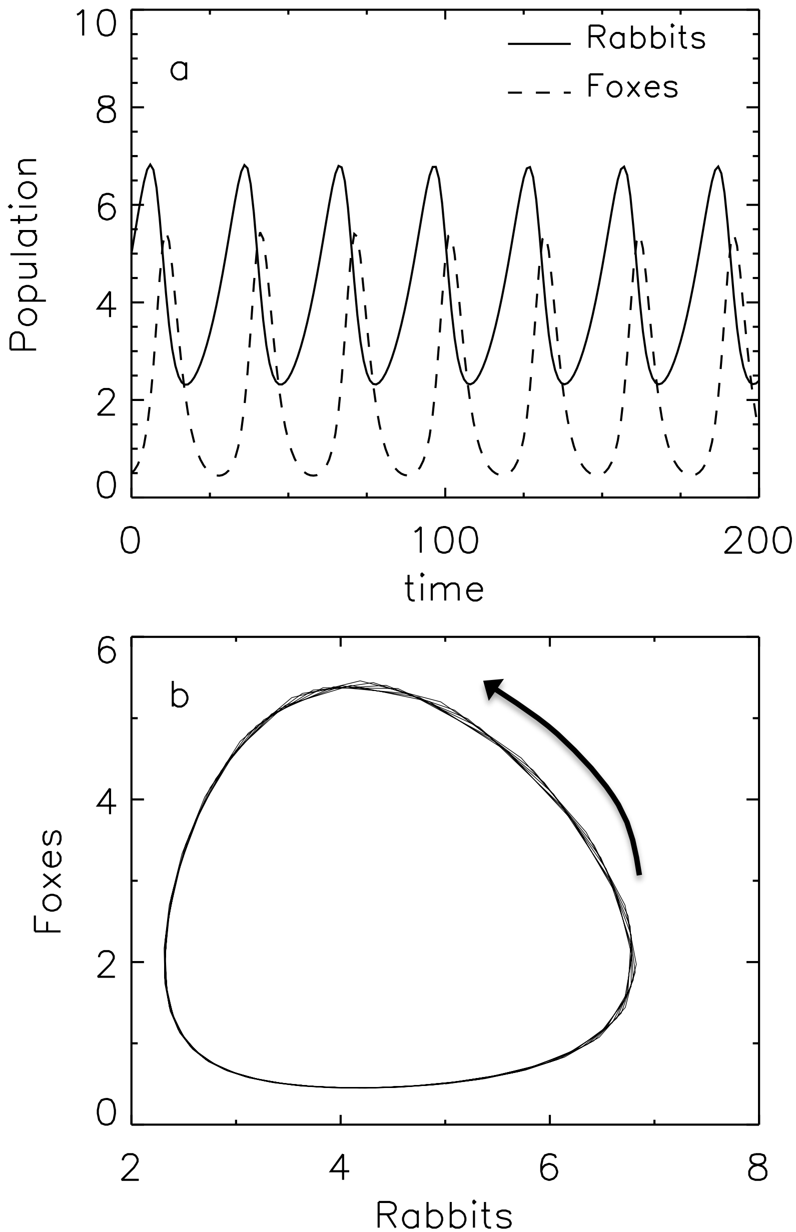



Image courtesy of Wikipedia

4 parameters:
$\alpha, \beta, \gamma, \delta$

# 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)

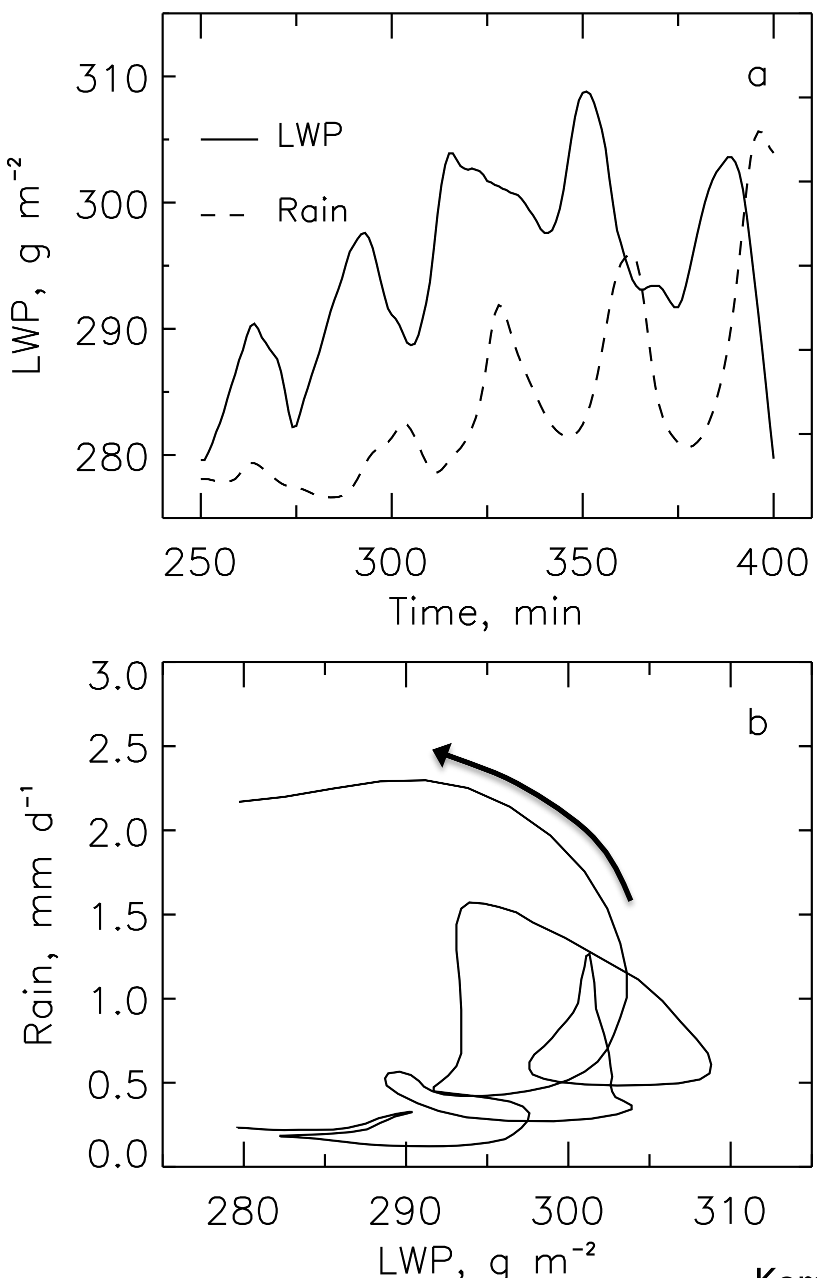
and so on…

*Many possible predator-prey pairs:*

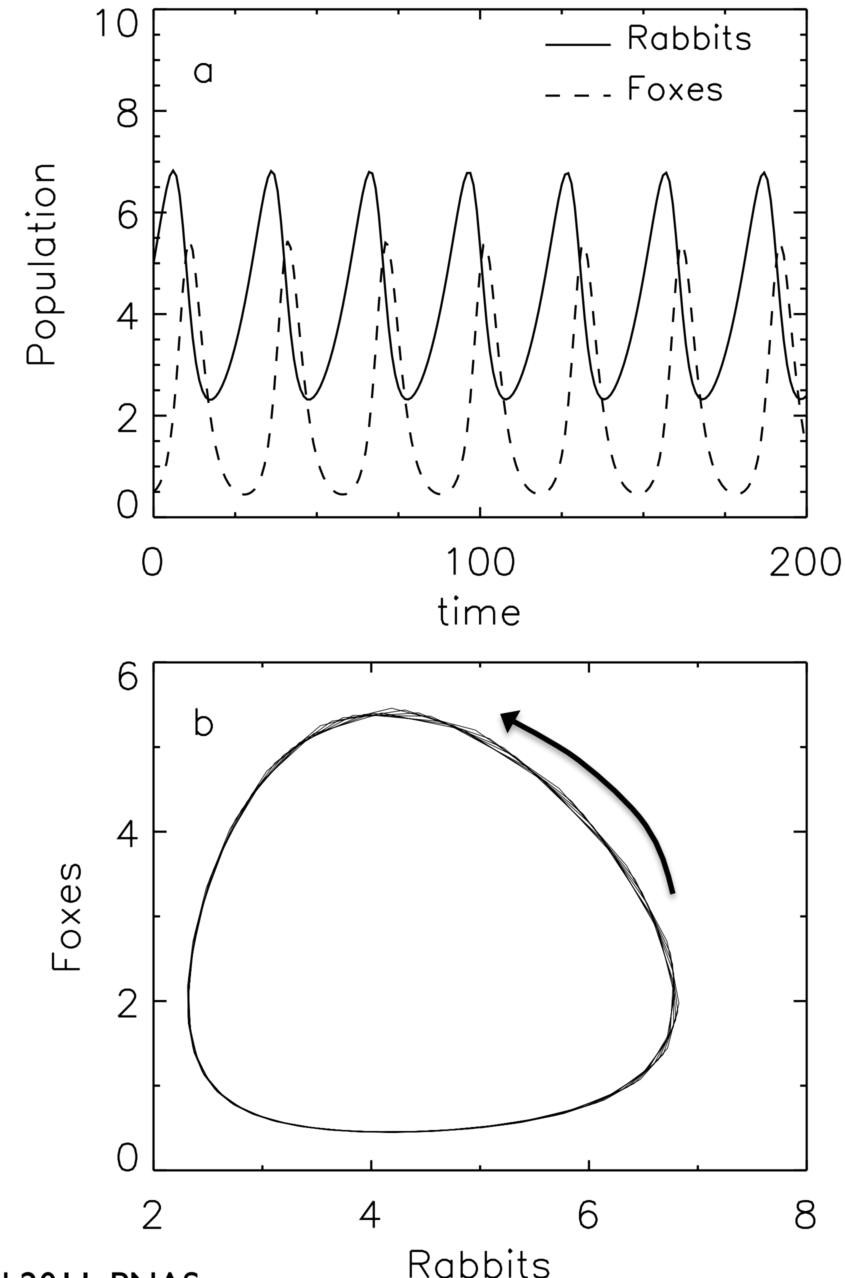
Rain; Aerosol
Convection; Instability (Nober and Graf)
Droplets; Supersaturation
Ice; Water (Bergeron-Findeisen)

Koren and Feingold 2011, PNAS

# Large Eddy Simulation of Aerosol-Cloud-Precipitation




# The Predator-Prey Problem




Koren and Feingold 2011, PNAS

# (Adapted) Predator-Prey Model

# Balance Equations

## 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)

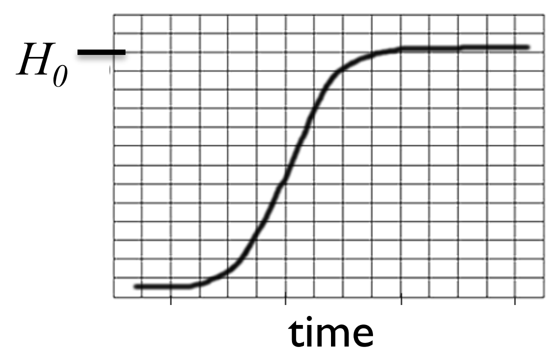
## Drop concentration $N_d$

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

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 $\tau$




$N_d$ (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: $\tau_1$, $\tau_2$

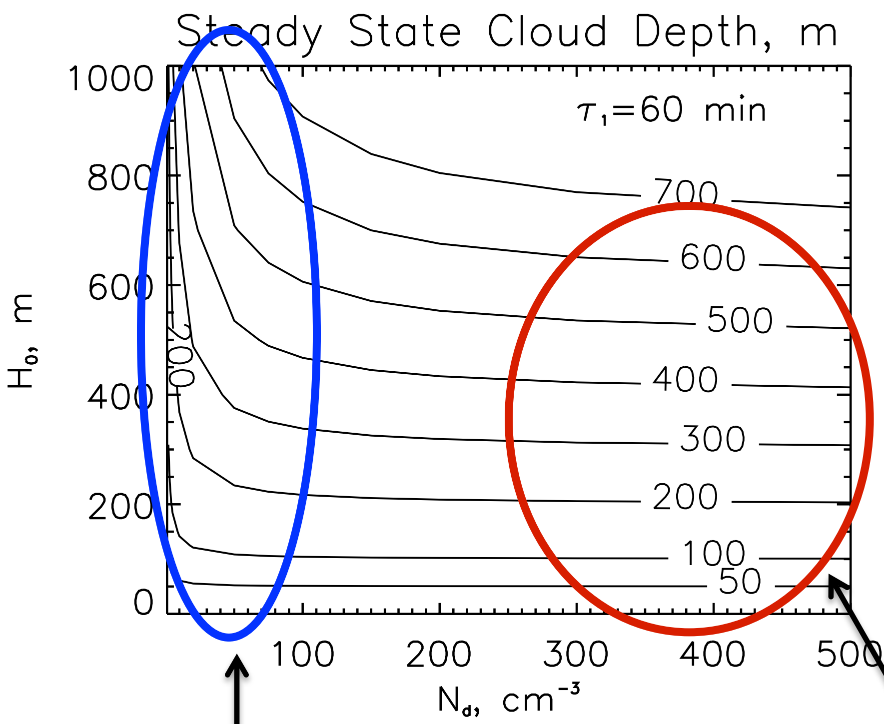
Delay time: $T$

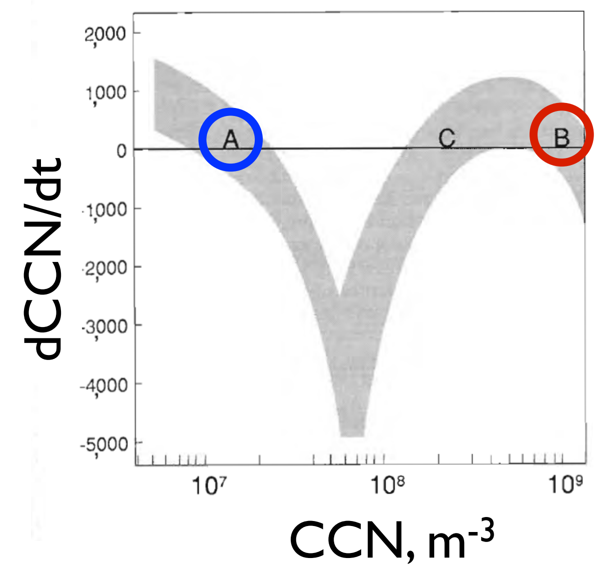
$$R = \alpha H^3 N_d^{-1}$$

Pawlowska and Brenguier 2003
vanZanten et al. 2005
Kostinski 2008

# Steady State Solution to Cloud Depth H

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



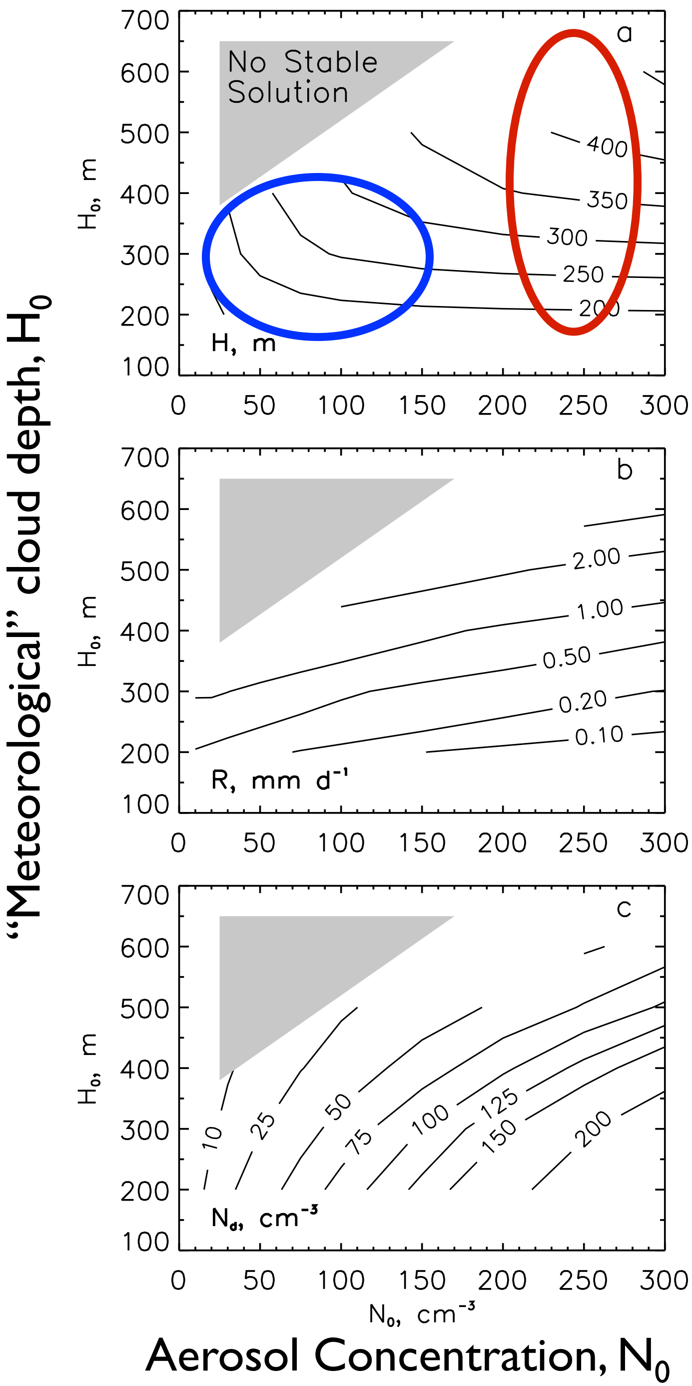




Baker and Charlson, 1990

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 $H_o$

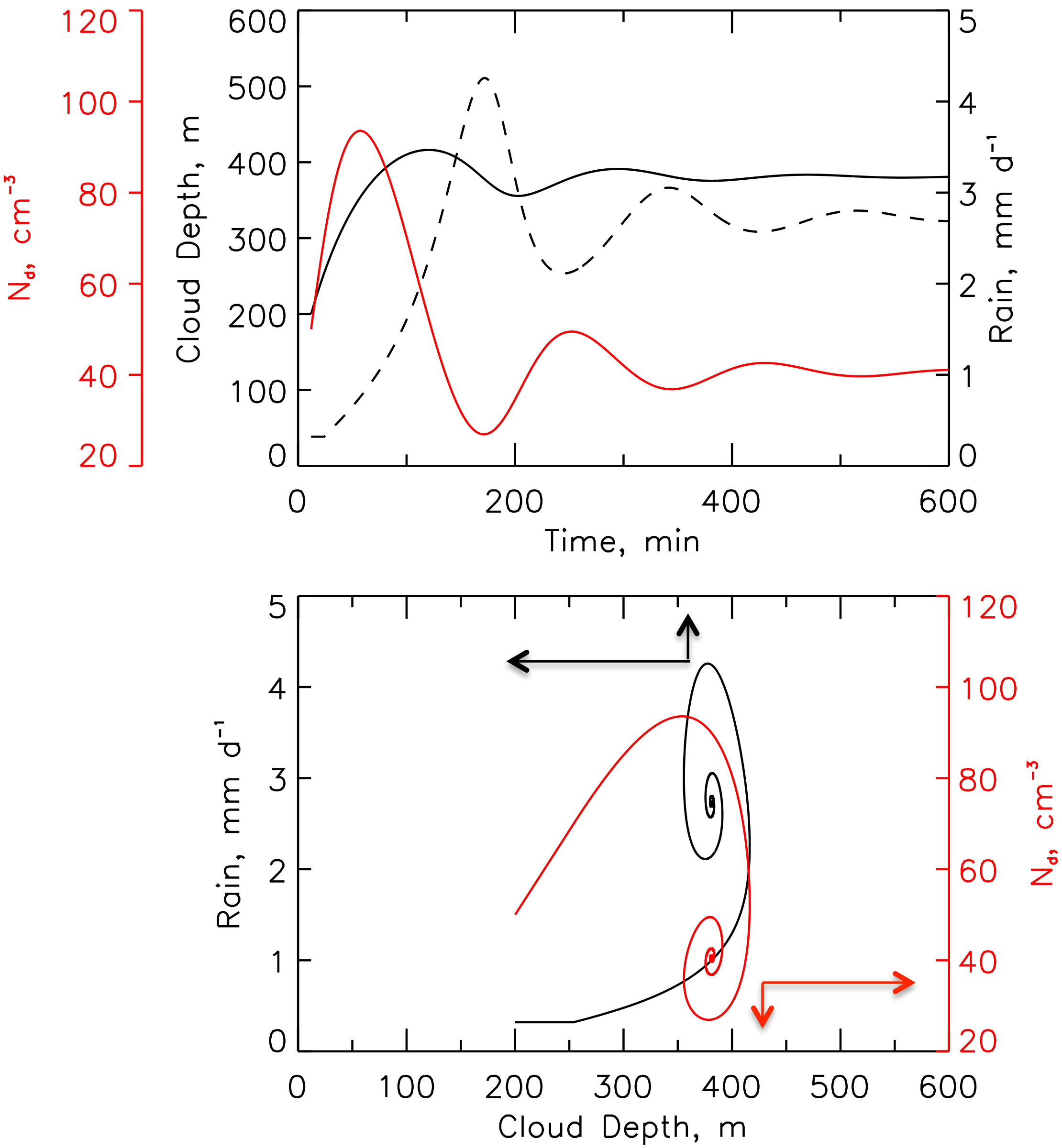
$$\frac{dN_d}{dt} = \frac{N_0 - N_d}{\tau_2} + \dot{N}_d(t - T)$$

Higher $N_o$ supports deeper clouds

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

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

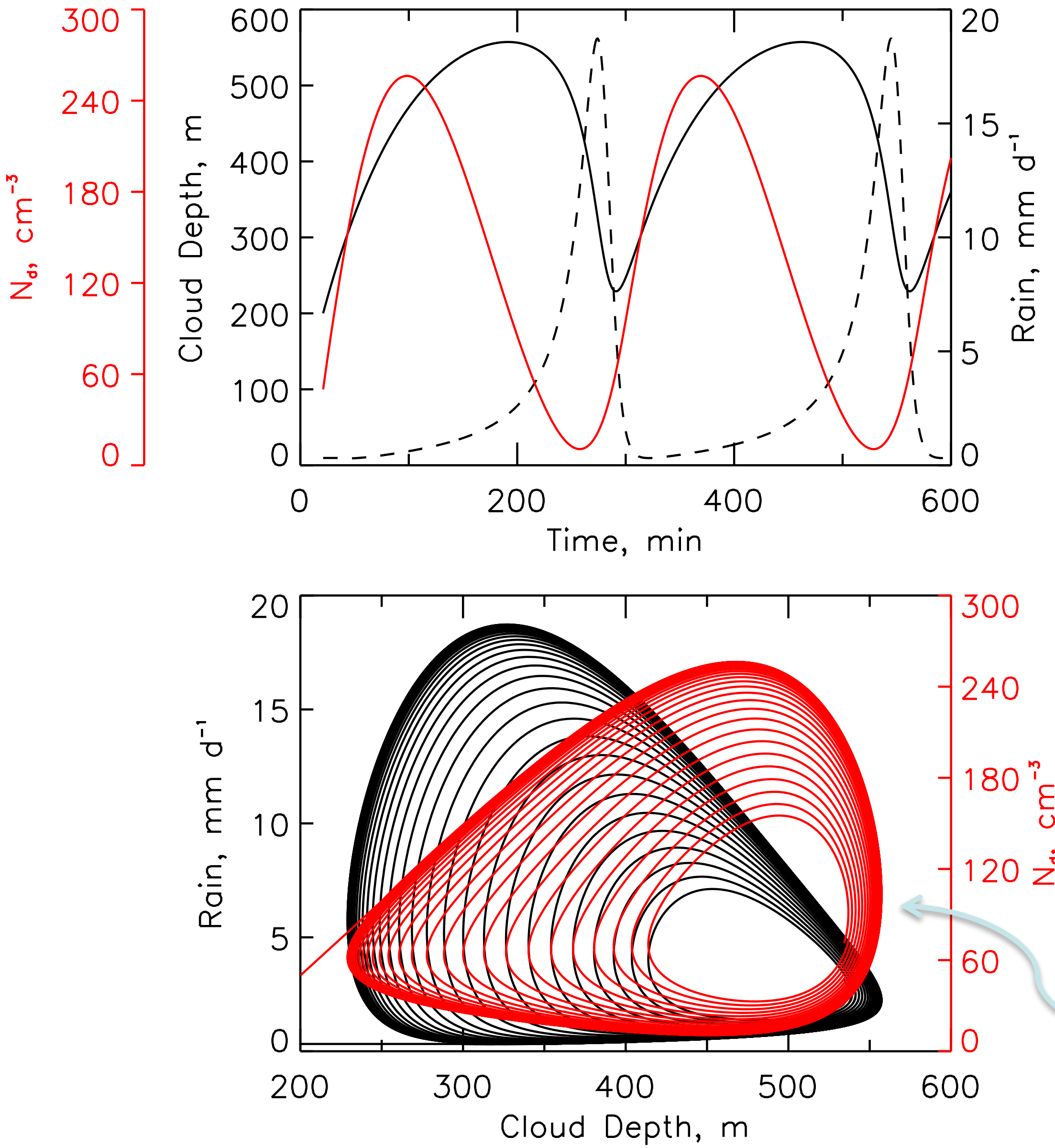
$T$ = 10 min

H; N
H; R

7 day simulation

Koren and Feingold 2011, PNAS

# Oscillating Solutions: No Steady State




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

$\tau_1$ = 80 min
$\tau_2$ = 84 min

$T$ = 12.5 min

7 day simulation

H; N
H; R

Oscillation around a steady state

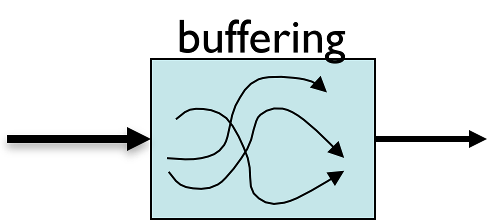
Koren and Feingold 2011, PNAS

# Stability

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

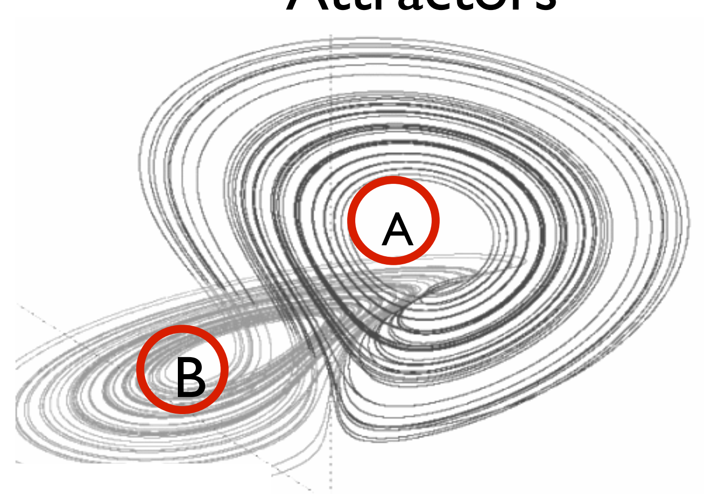
*Stable states A and B are stable and self-sustaining*

*Small perturbations strengthen the resilience of the state*




*Stevens and Feingold, 2009*

Attractors




Lorenz, 1963

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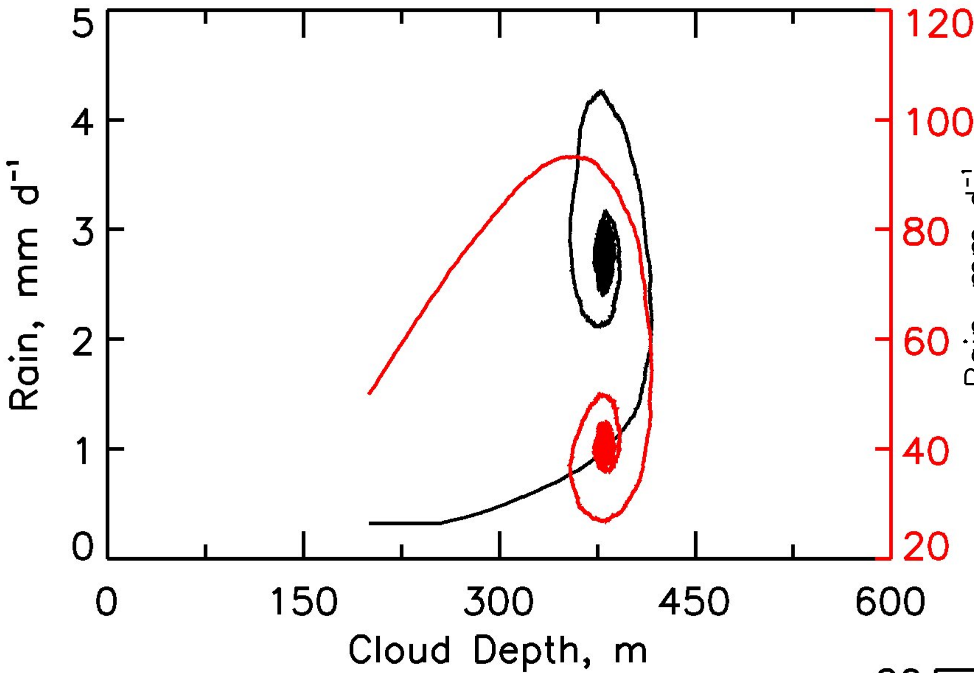
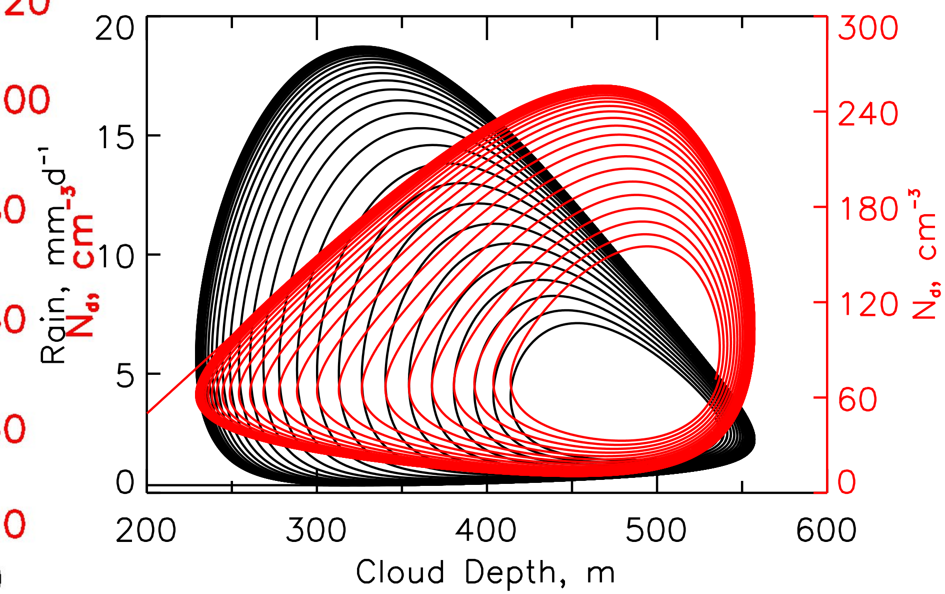
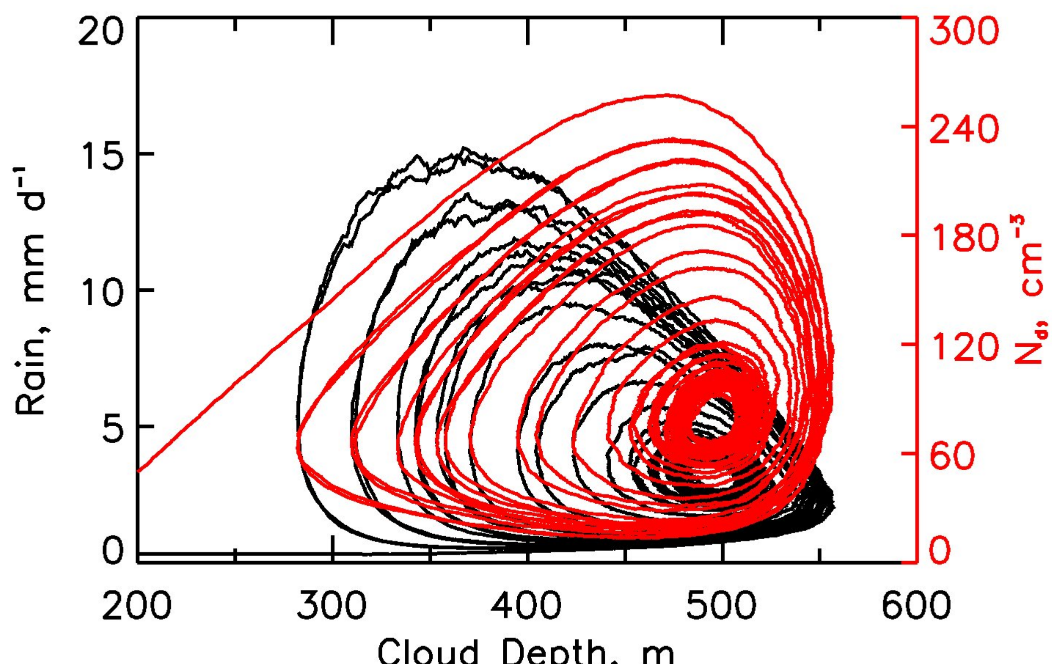



± 50% perturbations to $H_0$ and $N_0$ every second: Solutions are robust

Small perturbations strengthen the resilience of the state;

Large enough perturbations will lead to collapse




Koren and Feingold 2011, PNAS

# System of coupled oscillators

# Summary

- The cloud-precipitation system is often stable to aerosol perturbations

- The dynamical systems approach may be useful to explore stability regimes

- Emergence:  coherent patterns emerge from local interactions
  - Open/Closed cells
  - Flock behaviour
  - Oscillating chemical reactions

- Emergence suggests that low dimensional models might be useful as parameterizations in large scale models
  - (E.g. Shutts 2005; Mapes 2011)