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On Rabbits, Foxes, Clouds and Rain

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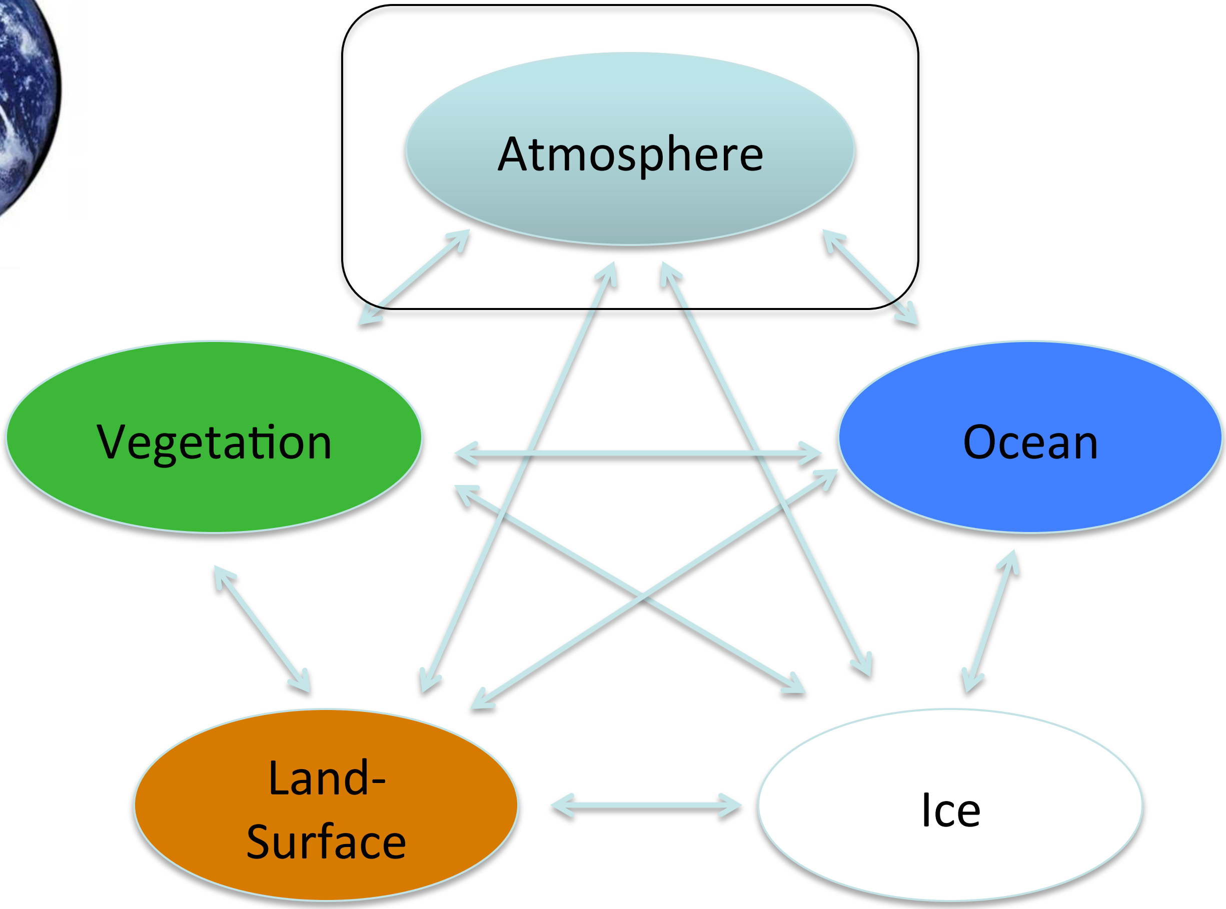
March 1, 2012

The Climate System



Atmosphere

Vegetation

Ocean

Land-Surface

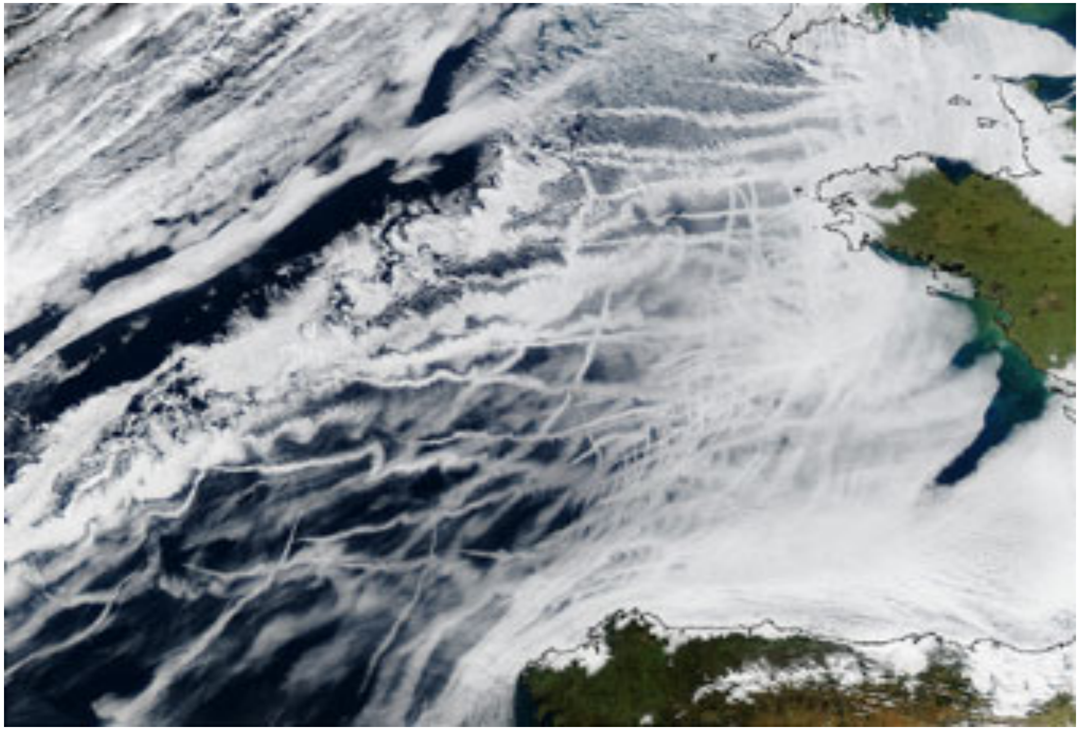
Ice

A tightly coupled system with a number of important components

The Climate System

Role of Clouds in Changing Planetary Albedo

Aerosol Enhances Cloud Brightness

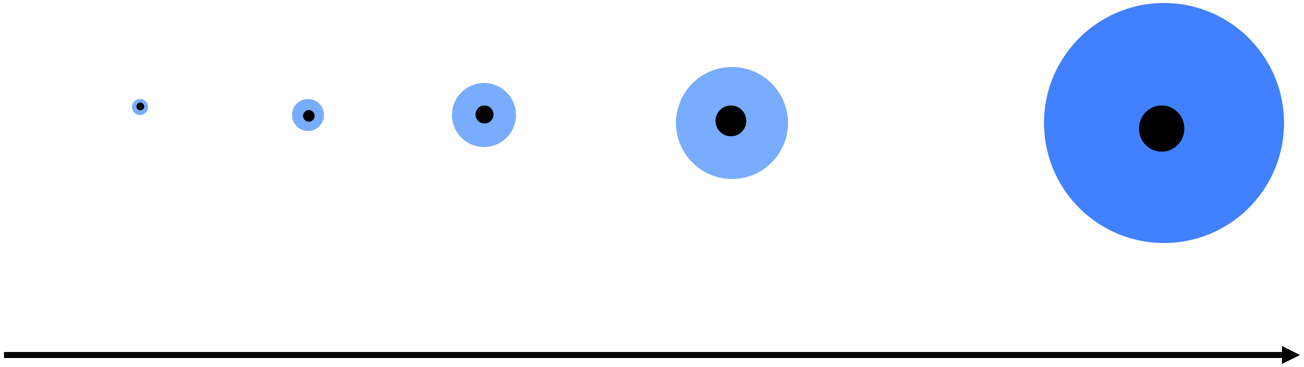


Ship track Images, Aqua, MODIS

Aerosol: A suspension of particles in a medium (air)

A Very Short Course in Cloud Physics

Drops form on tiny suspended particles



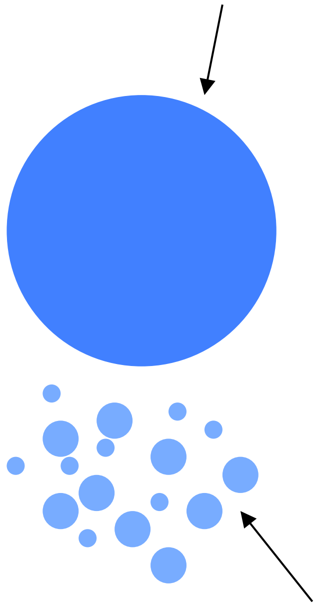
Larger drops form on larger aerosol particles
Drops grow by vapour diffusion

More aerosol → more, smaller drops (all else equal)

Cloud Drops: μm to mm in size

Aerosol particles (sulfate, sea salt, etc.): < 1 μm in size

Drop Coalescence generates Rain



Collect<u>or</u> drop (larger fall velocity V_x)

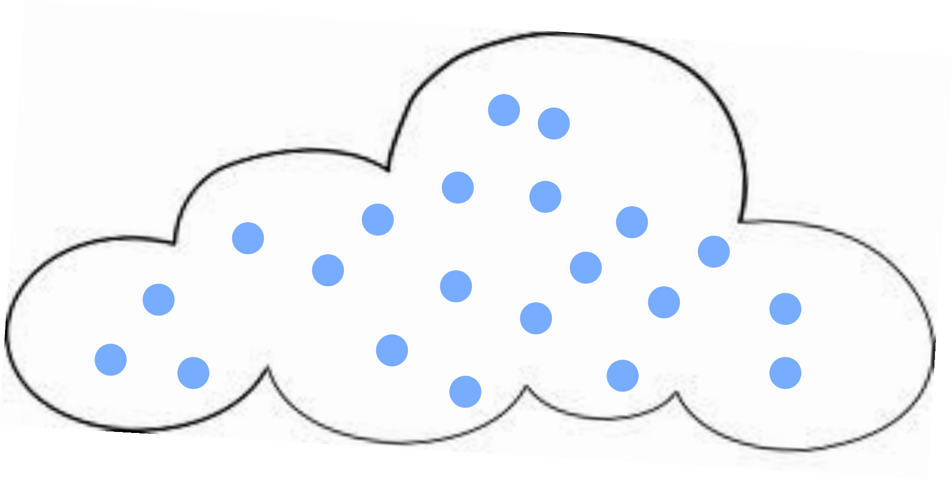
Collect<u>ed</u> droplets
(small fall velocity V_y)

Coalescence efficiency is a strong function of drop size

Aerosol particles affect Precipitation

Few particles/large drops
Precipitation

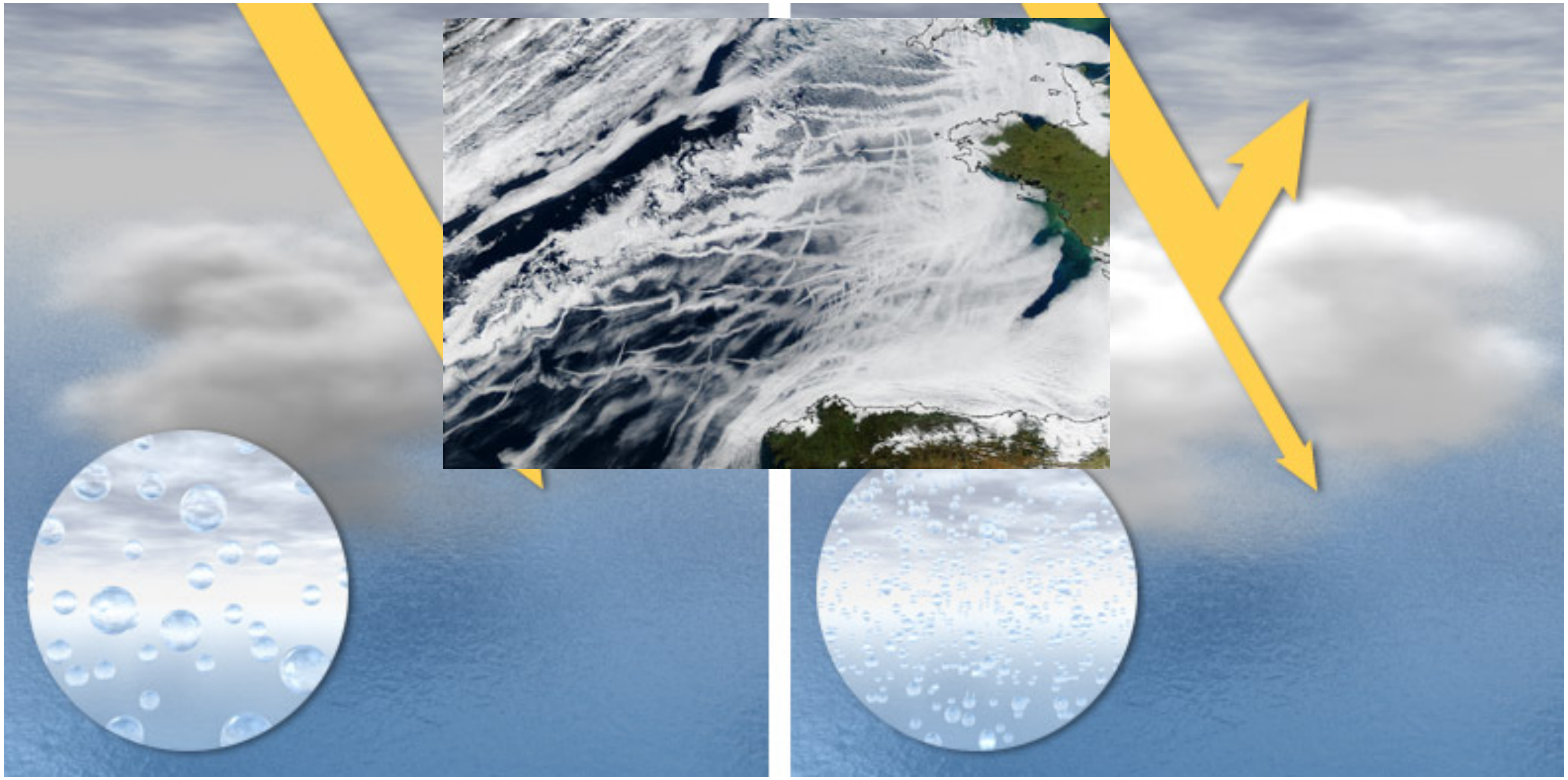
More particles/small drops
No precipitation



Aerosol particles enhance cloud brightness

Less reflective clouds (large drops)

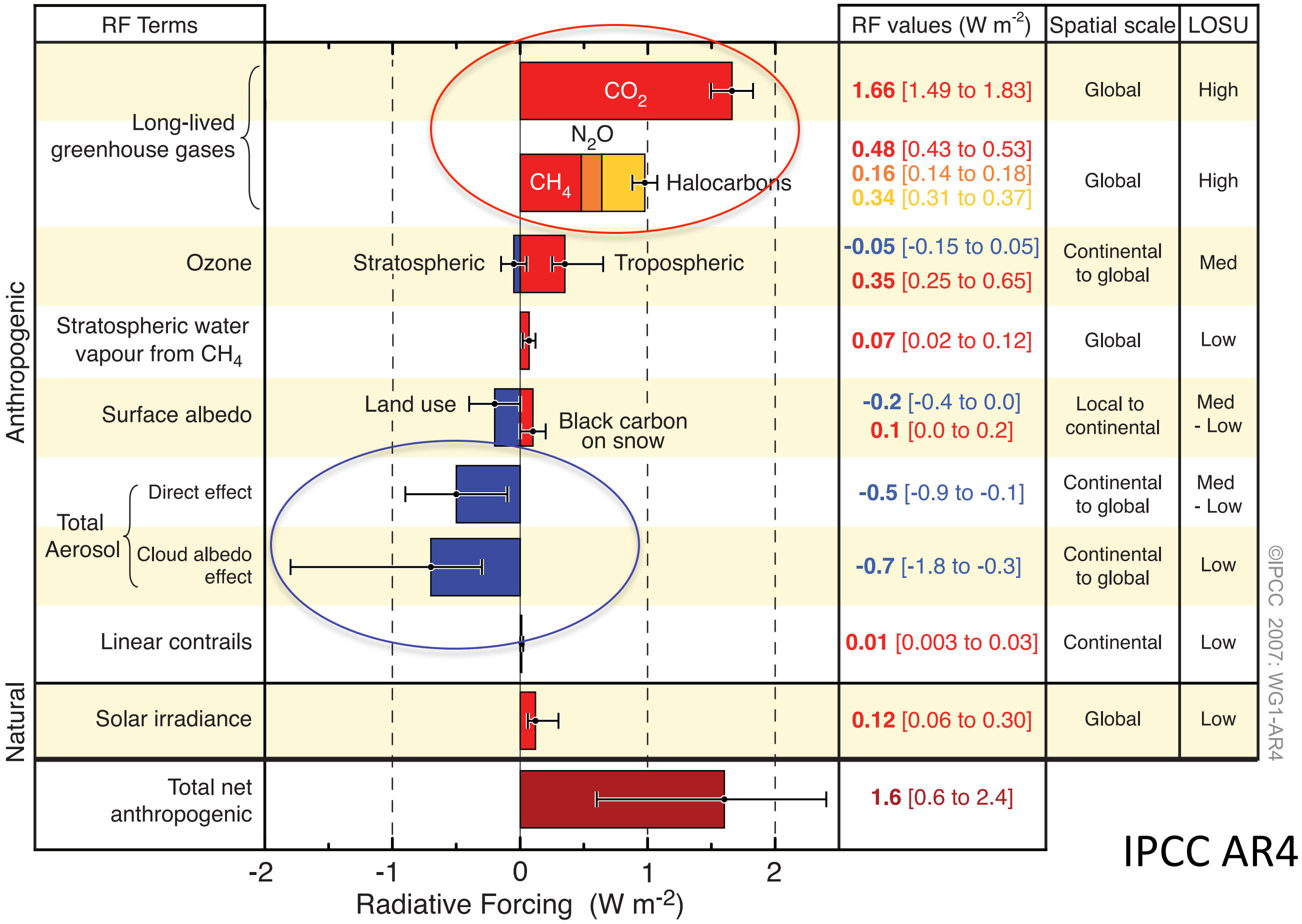
Reflective clouds (small drops)



Robert Simmon

The Climate System

Radiative Forcing Components



	RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
Anthropogenic	Long-lived greenhouse gases	**1.66** [1.49 to 1.83]	Global	High
		0.48 [0.43 to 0.53] **0.16** [0.14 to 0.18] **0.34** [0.31 to 0.37]	Global	High
	Ozone	**-0.05** [-0.15 to 0.05] **0.35** [0.25 to 0.65]	Continental to global	Med
	Stratospheric water vapour from CH_4	**0.07** [0.02 to 0.12]	Global	Low
	Surface albedo	**-0.2** [-0.4 to 0.0] **0.1** [0.0 to 0.2]	Local to continental	Med - Low
	Total Aerosol Direct effect	**-0.5** [-0.9 to -0.1]	Continental to global	Med - Low
	Total Aerosol Cloud albedo effect	**-0.7** [-1.8 to -0.3]	Continental to global	Low
	Linear contrails	**0.01** [0.003 to 0.03]	Continental	Low
Natural	Solar irradiance	**0.12** [0.06 to 0.30]	Global	Low
	Total net anthropogenic	**1.6** [0.6 to 2.4]		

IPCC AR4

Role of Aerosol & Clouds in Changing Planetary Albedo

The Scale Problem

Aerosol-Cloud-Precipitation interactions and feedbacks must be represented at a range of spatiotemporal scales:

μm to 1000s km

seconds to days

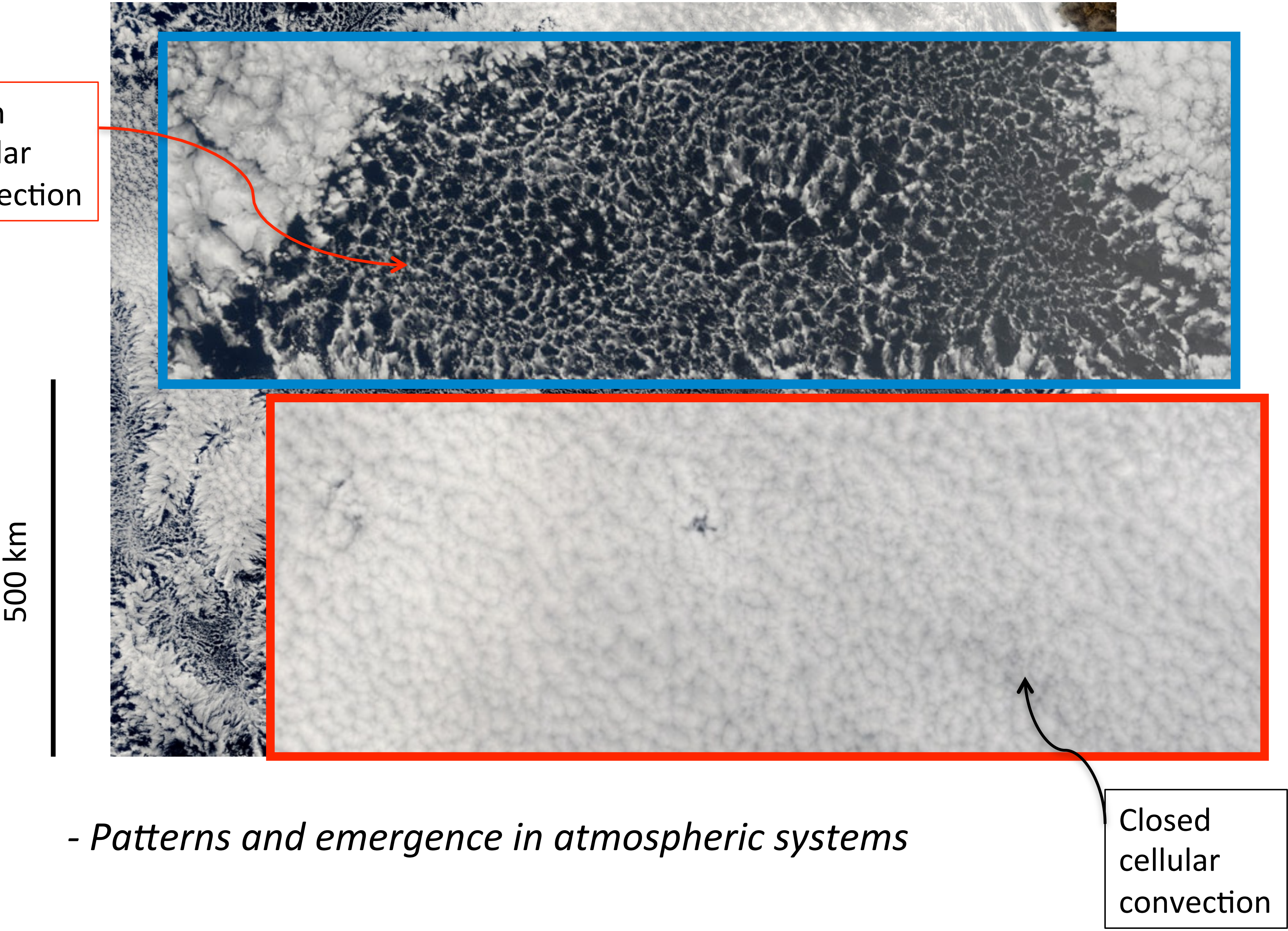
The number of degrees of freedom of the system is staggering!

A System Characterized by Complexity

- Dynamics
- Microphysics
- Radiation
- Aerosol

A host of feedbacks between the components

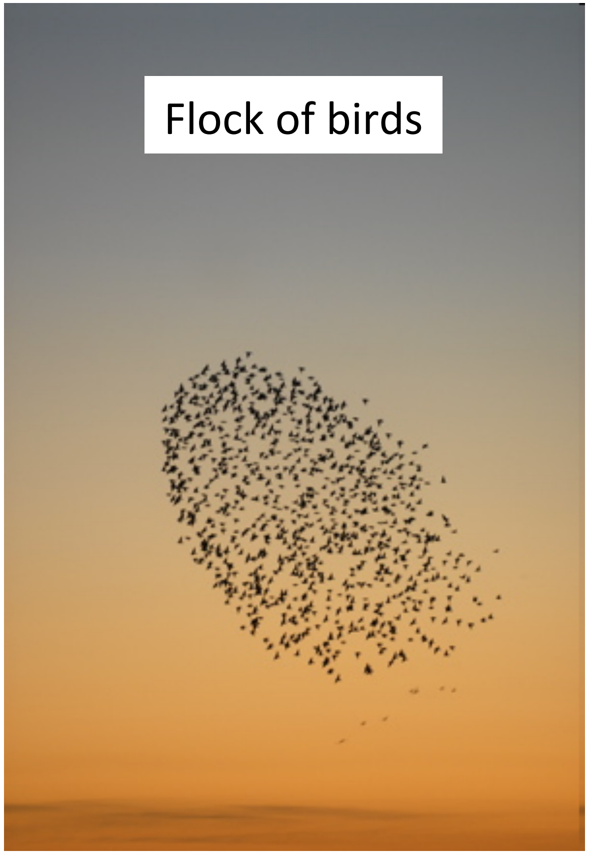
Patterns: Mesoscale Cellular Convection in Stratocumulus

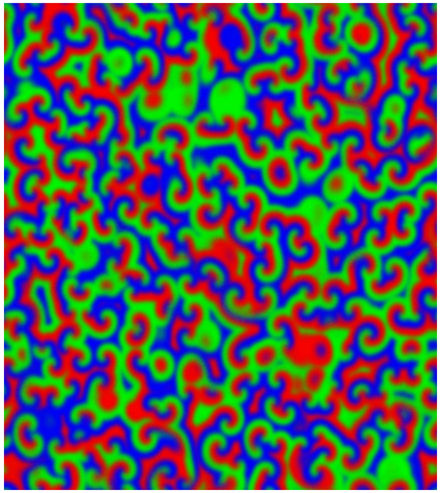


- Patterns and emergence in atmospheric systems

Other examples

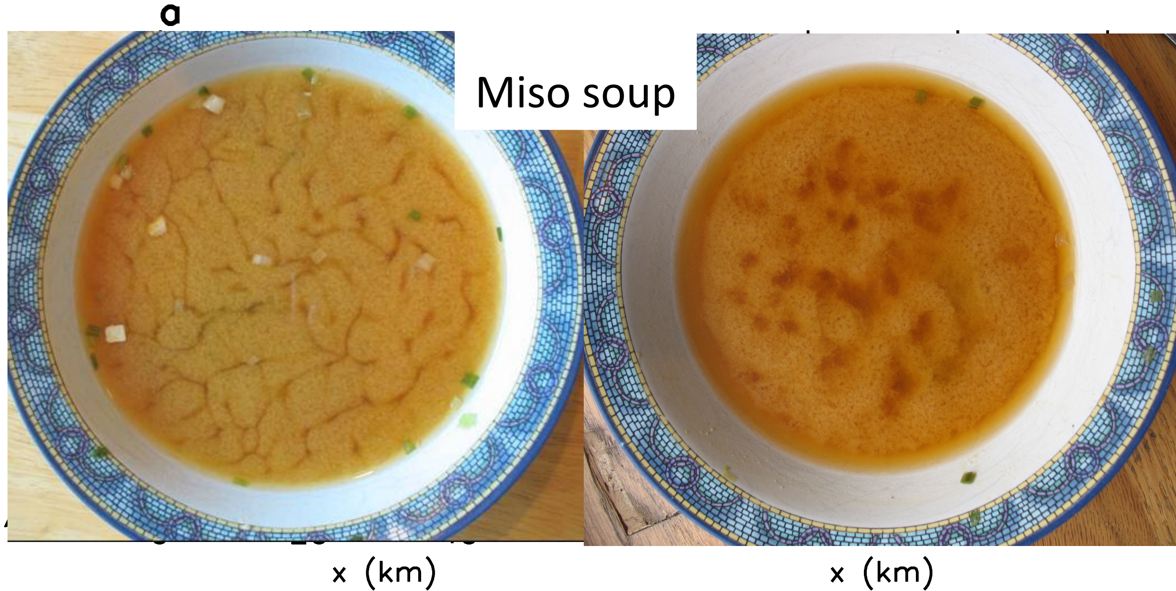
Flock behaviour





Computer simulation of BZ reaction

Oscillatory behaviour in Belousov-Zhabotinskii chemical reactions



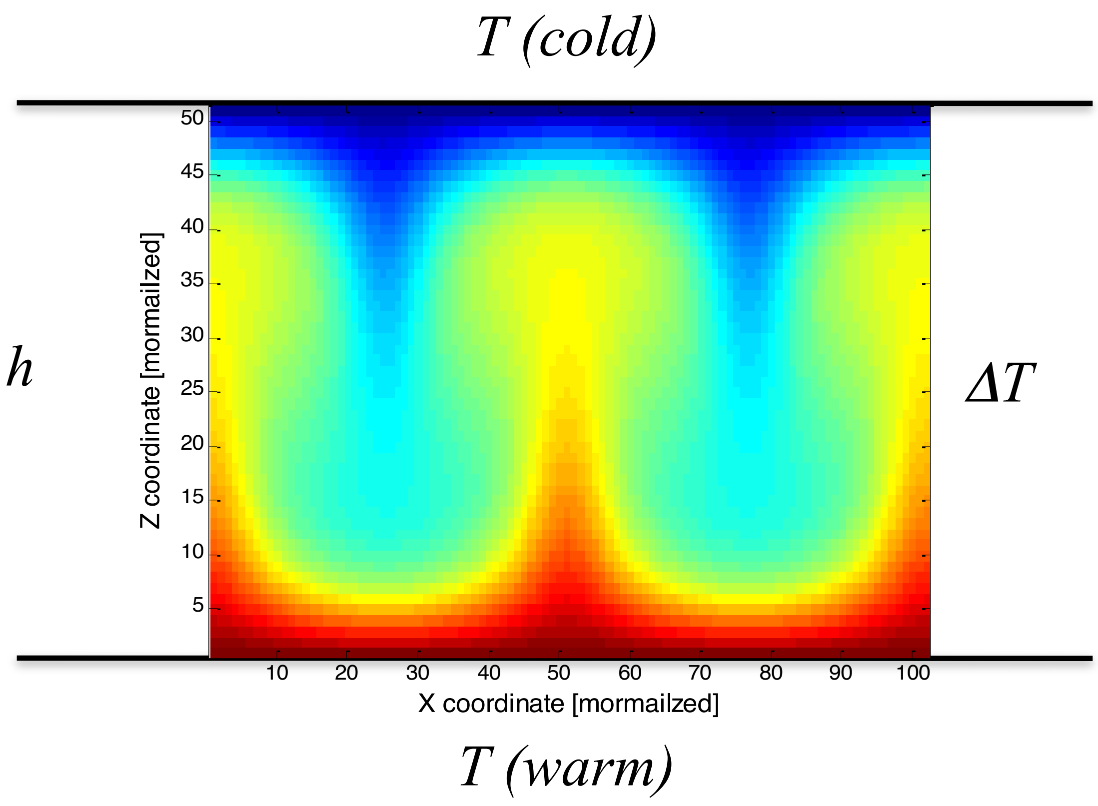
Numerical simulation of “Rayleigh-Bénard Convection

“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



ΔT = temperature difference between surfaces

α = thermal expansion coefficient

g = gravitational acceleration

h = separation between the surfaces

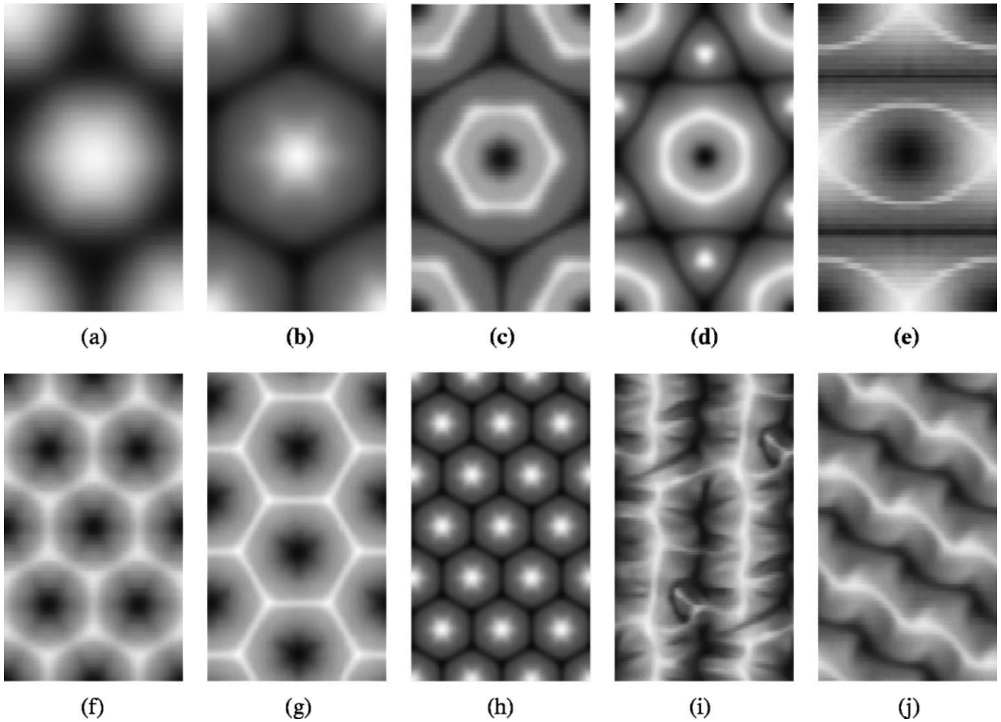
ν = kinematic viscosity

χ = thermal diffusivity

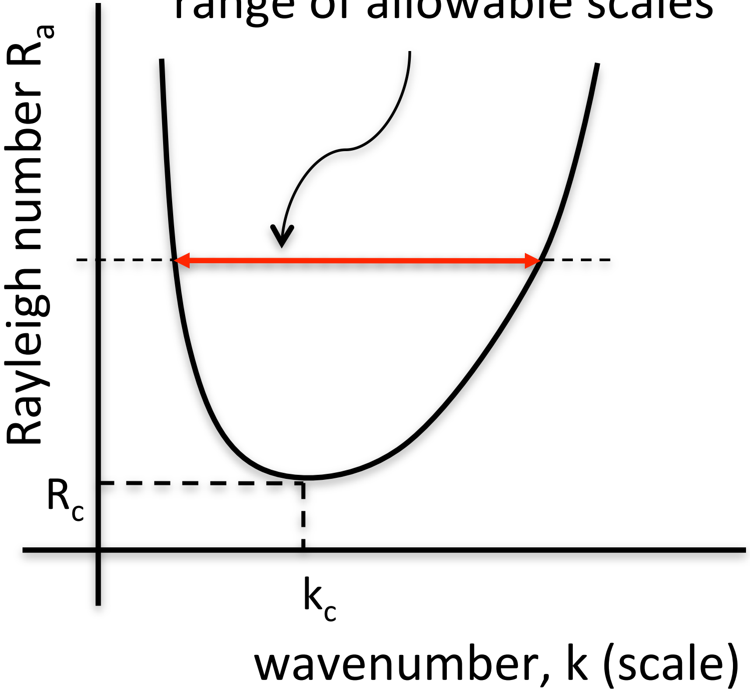
$$R_a = \alpha g \Delta T h^3 / (\nu \chi)$$

Transition from conduction to convection occurs when the Rayleigh number exceeds a critical value R_c

Rayleigh-Bénard Convection



Convective regime: range of allowable scales



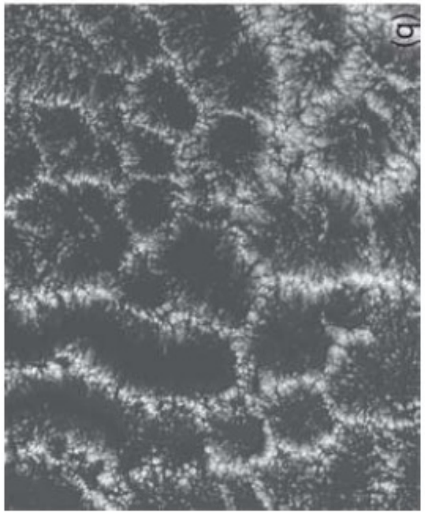
Controlled lab experiments with different scales: Patterns and preferred modes

Getling and Brausch, Phys. Rev. E 2003

Aerosol/drizzle selects the state

Albedo

Satellite images



Closed-cell
Albedo ~ 0.6
(non-precipitating)

→ **high aerosol**

Onset of ***drizzle*** *results i* *transitio* *to open-* *convecti*

WRF Model
+ 2-moment

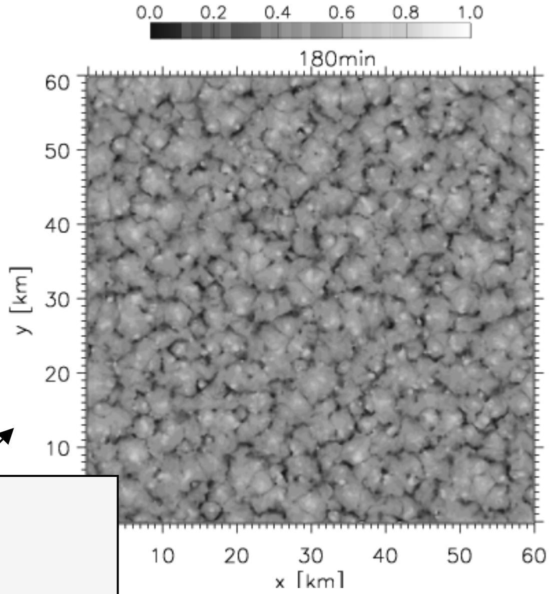
(i) Aerosol "selects" the state of the system (same meteorology)

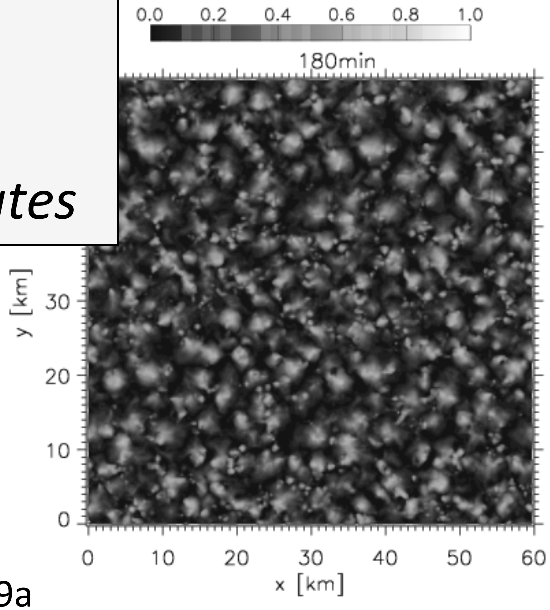
(ii) The stable state oscillates

Open-cell
Albedo ~ 0.2
(precipitating)

→ **low aerosol**

Albedo





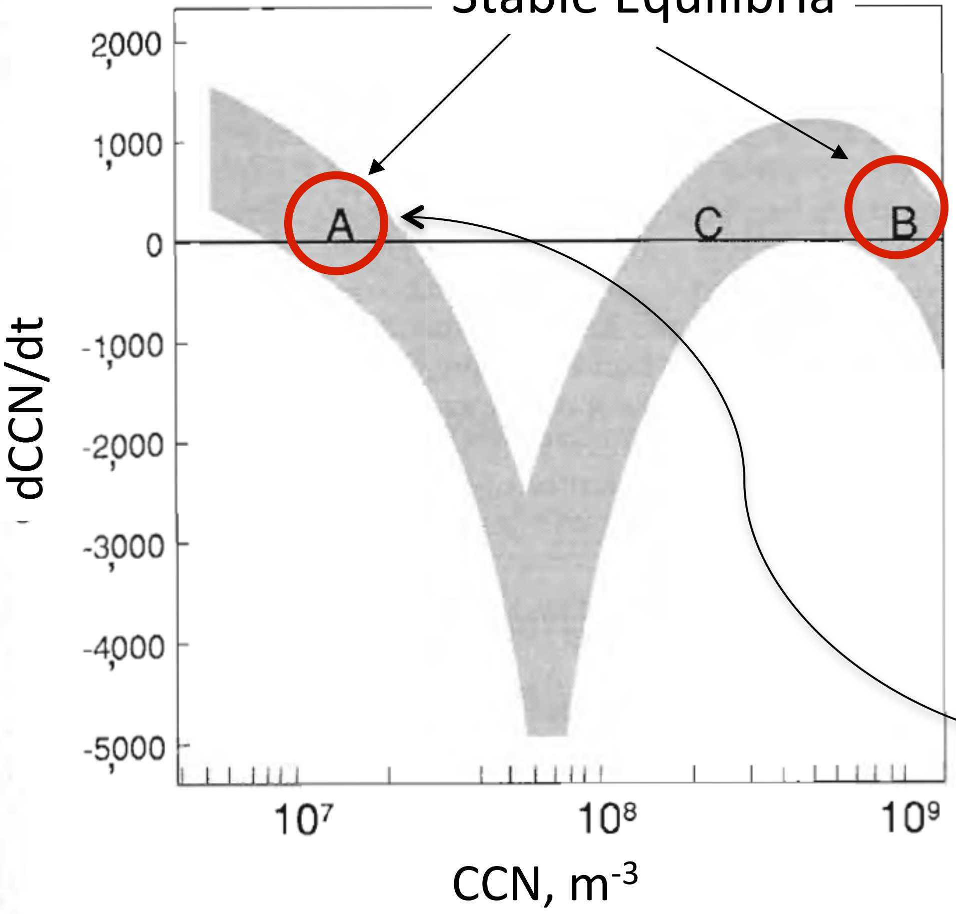
Garay et al. 2004, MISR

Wang and Feingold, 2009a

System Equilibria

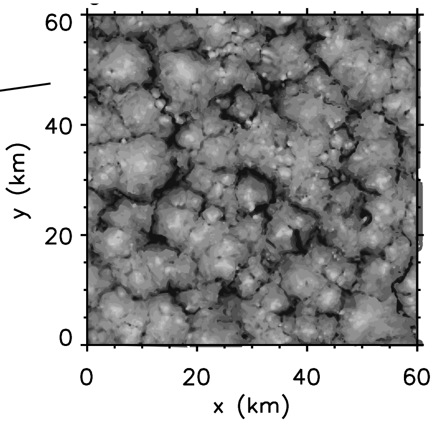
Atmospheric systems prefer certain modes

Stable Equilibria



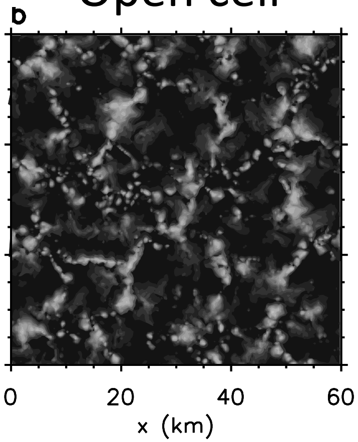
Baker and Charlson, 1990
Mixed-layer model

Closed cell



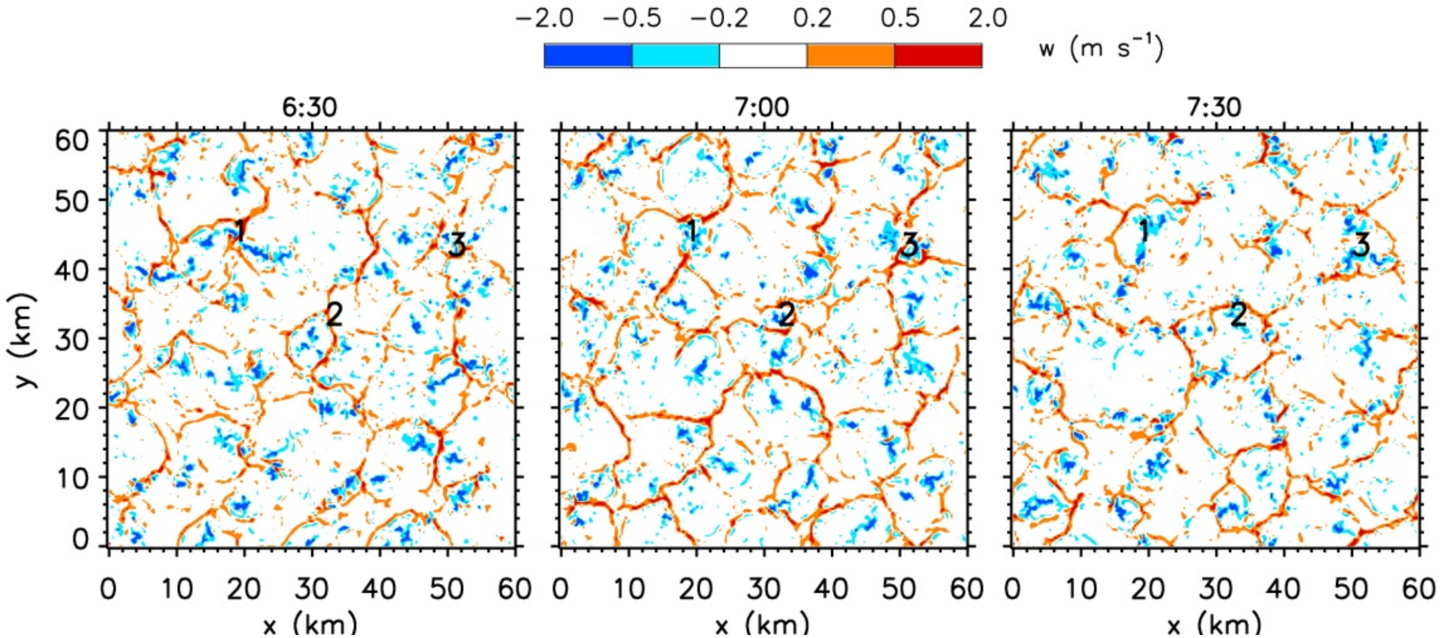
Non-drizzling, closed-cell mode

Open cell



Drizzling, open-cell mode

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

↓

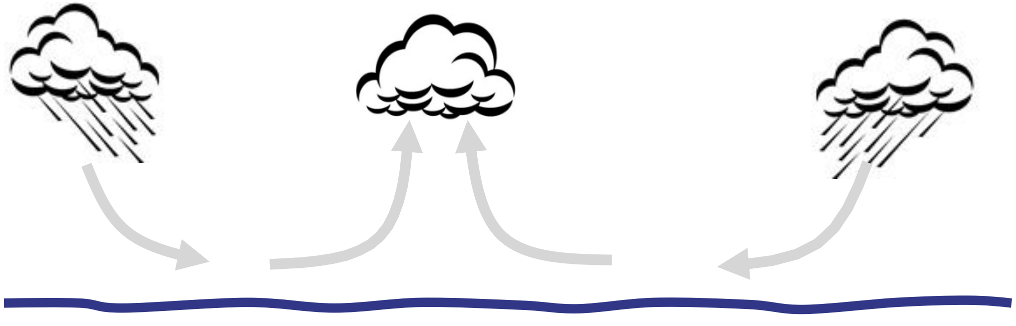
Precipitation is initiated

↓

Downdrafts, opening of cell

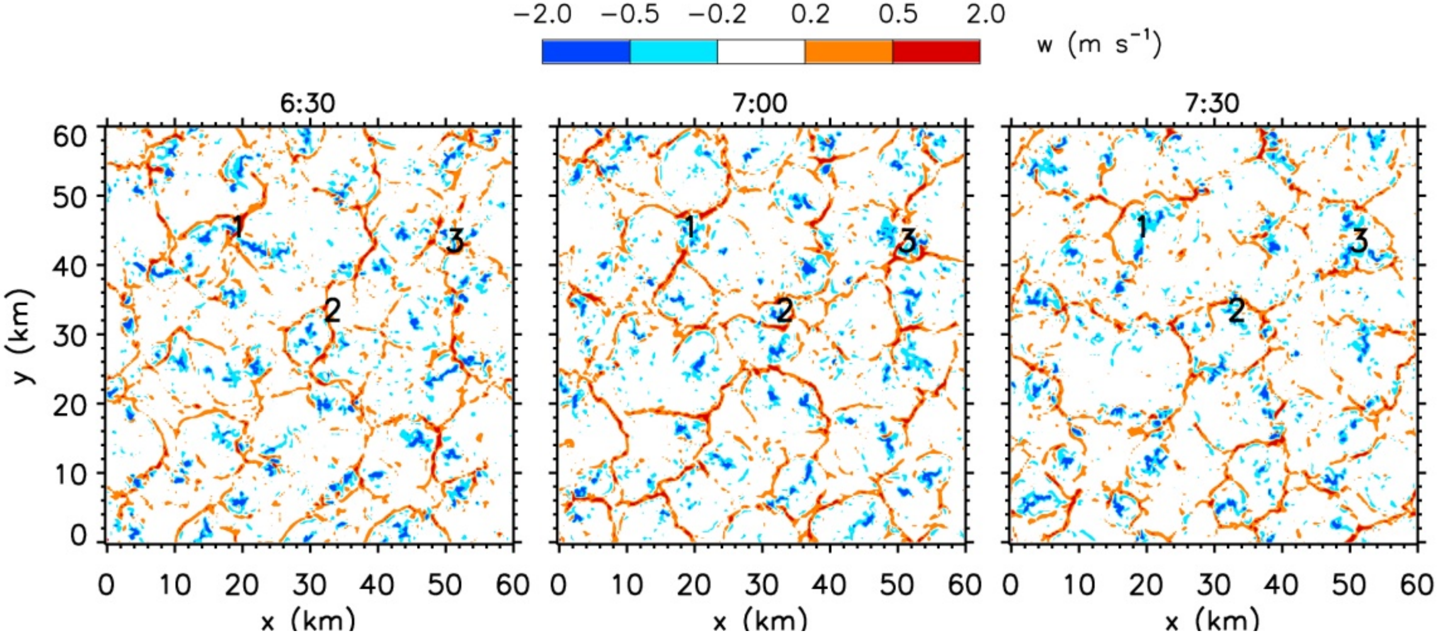
↓

Surface divergence



Y-convergence

Rearrangement of Open Cells



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Downdrafts, opening of cell

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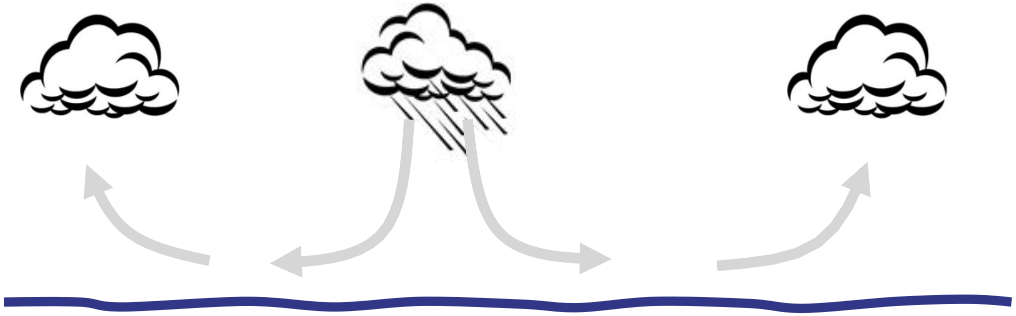
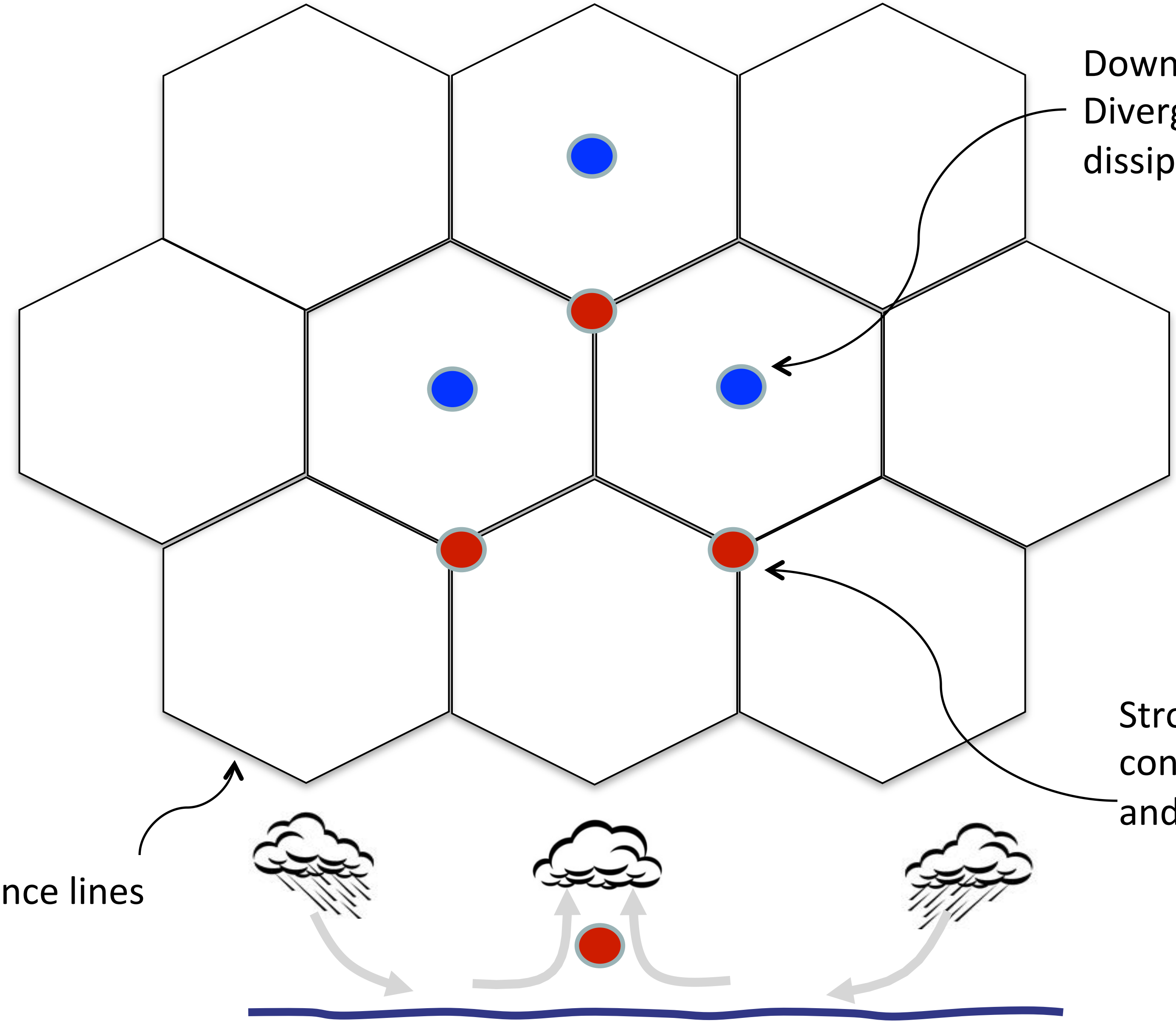
Surface divergence



Divergence

Surface Convergence Patterns

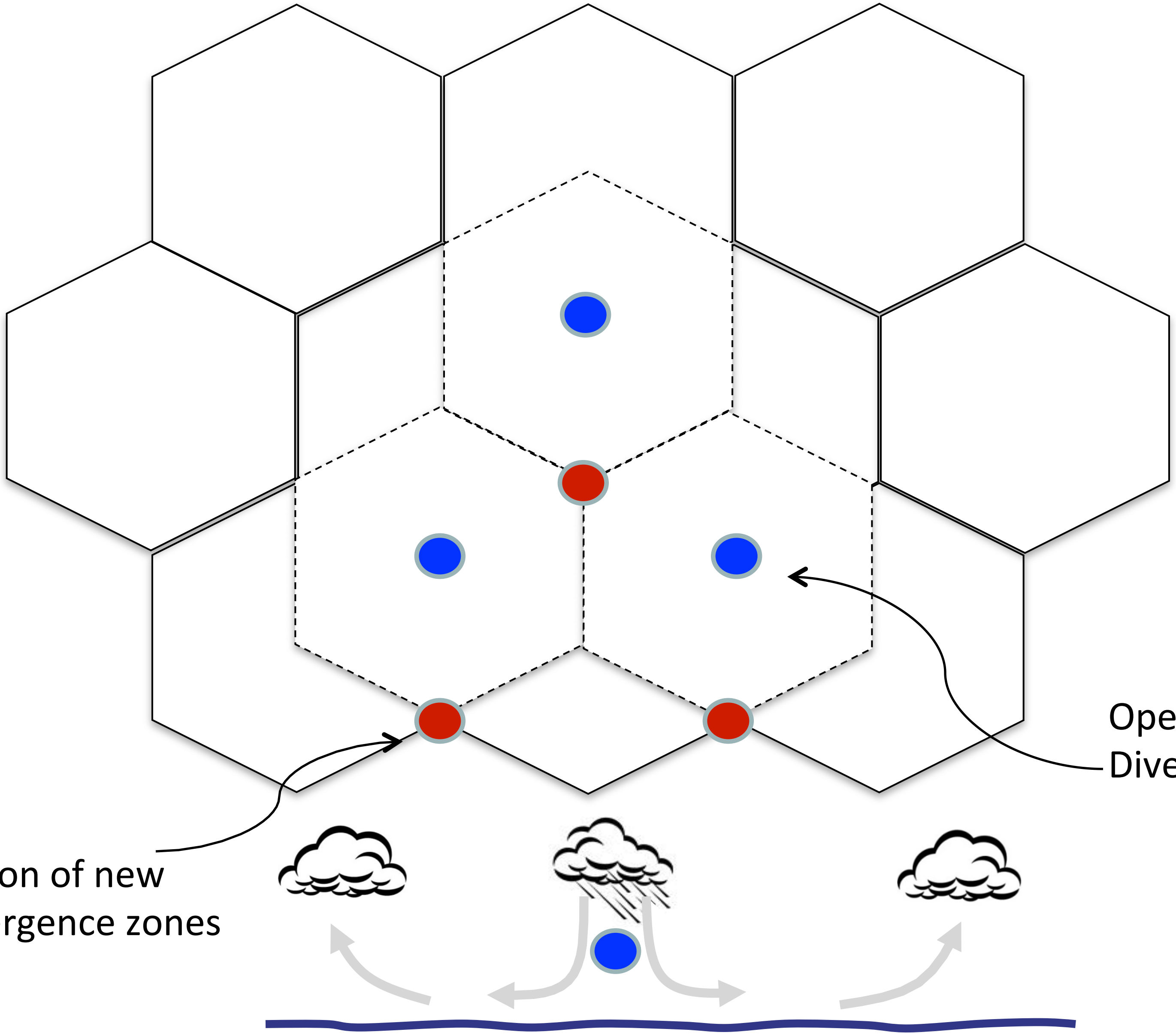


Downdrafts: Divergence due to dissipating rain

Strongest convergence and updrafts

Convergence lines

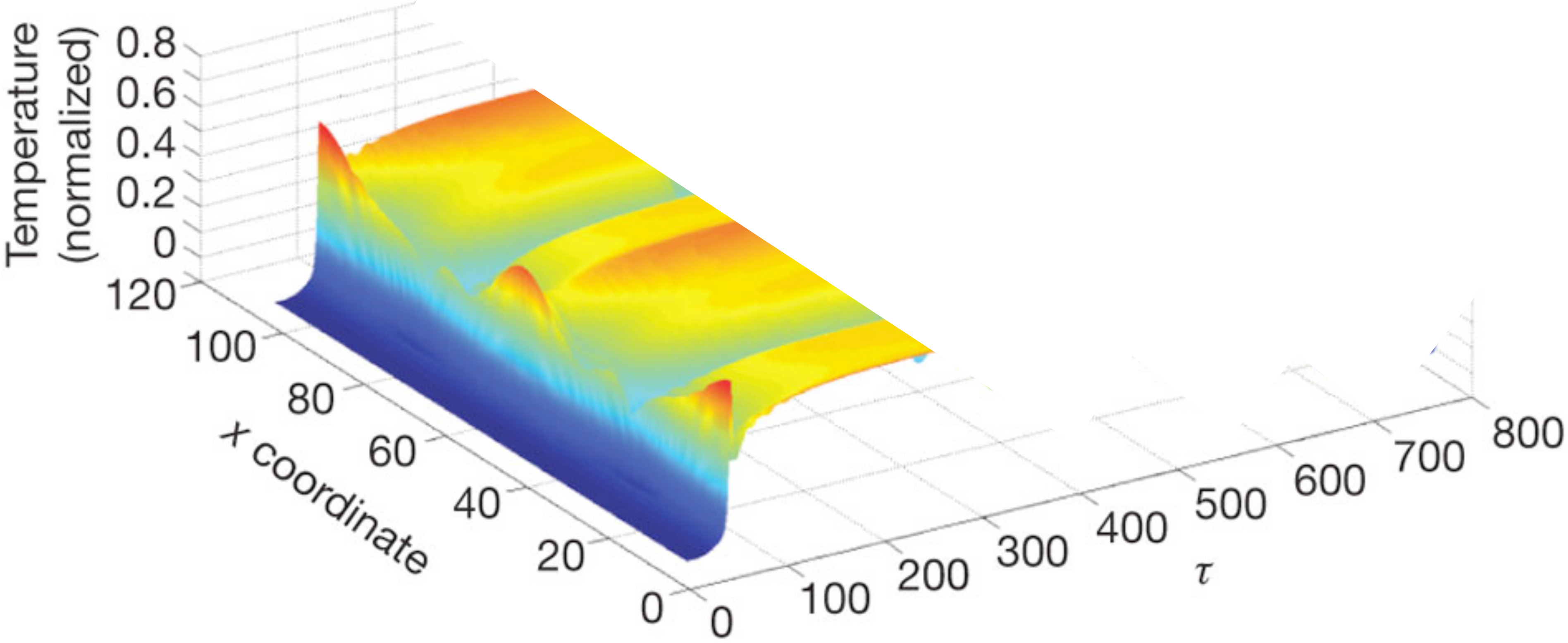
Shifting of the Patterns



Opening of new
Divergence zones

Creation of new
Convergence zones

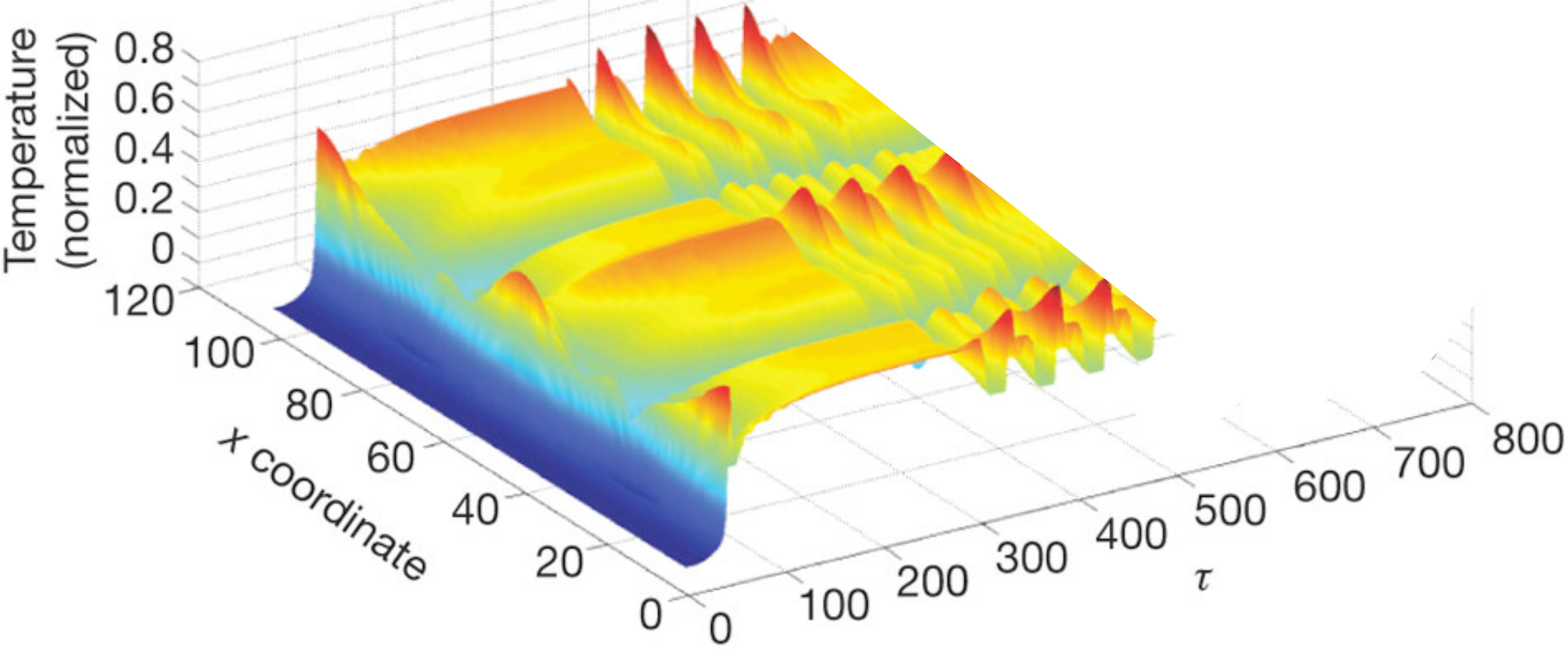
Steady-state convection



2-D code courtesy www.LBMethod.org (Lattice-Boltzmann Method)

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

Weak perturbations:
Rain→negative buoyancy



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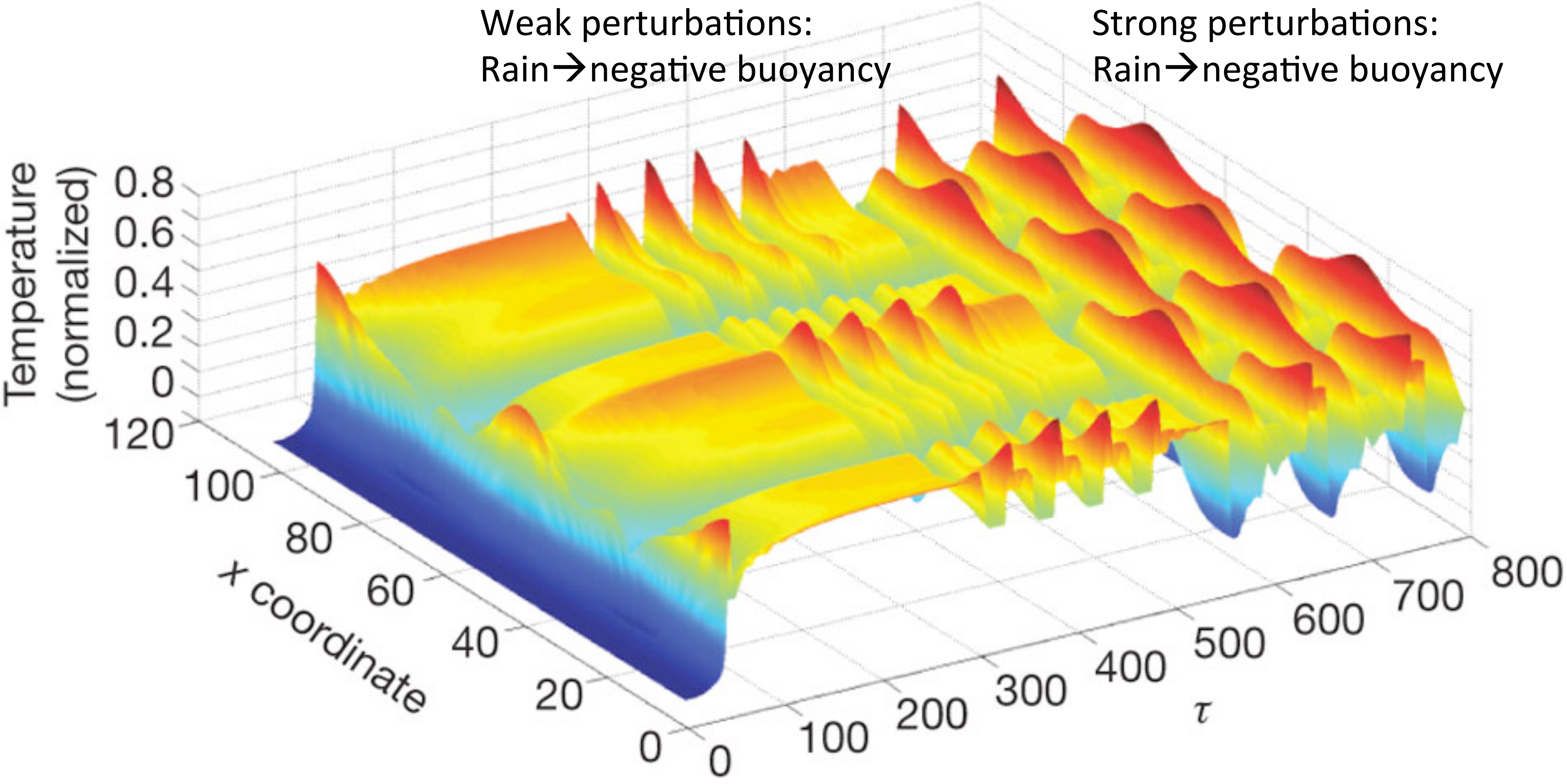

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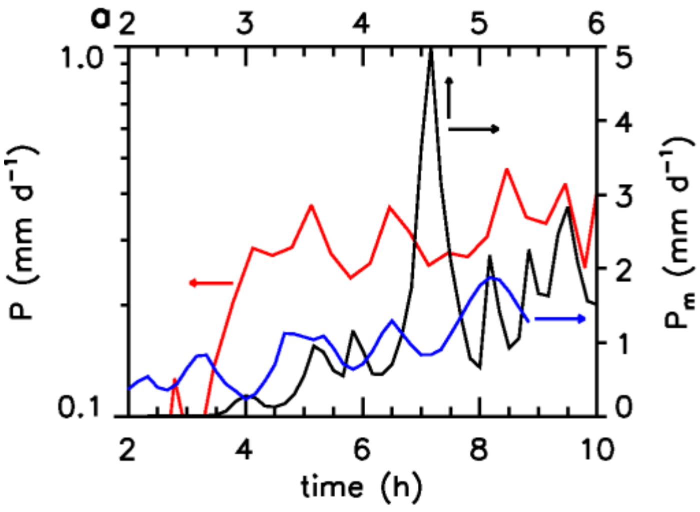
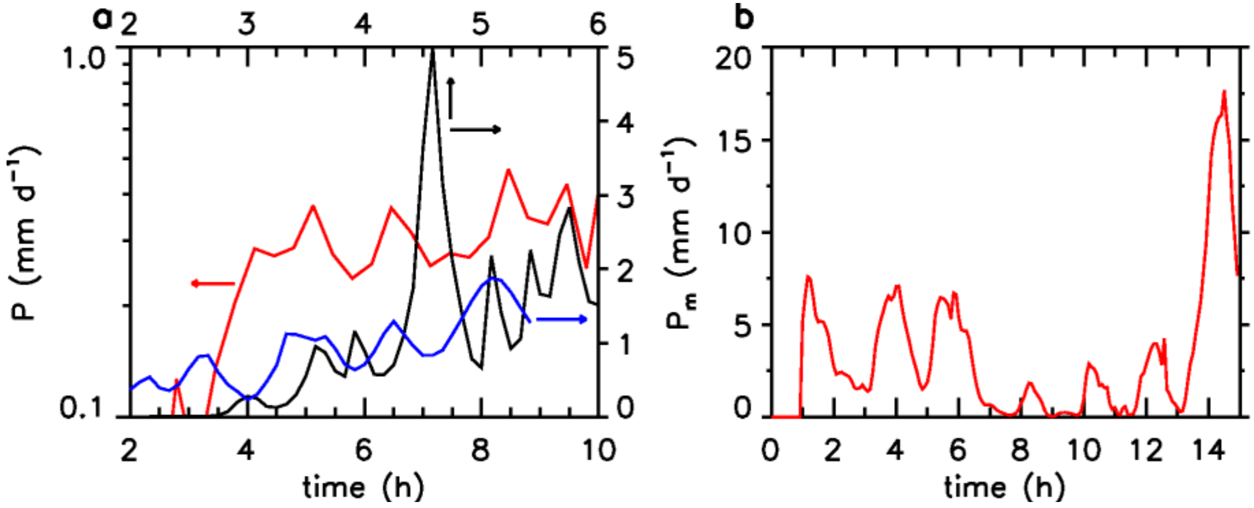
Synchronization: Oscillations in Precipitation



3 LES cases:
DYCOMS
ATEX
VOCALS

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

Synchronization: Oscillations in Precipitation



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DYCOMS

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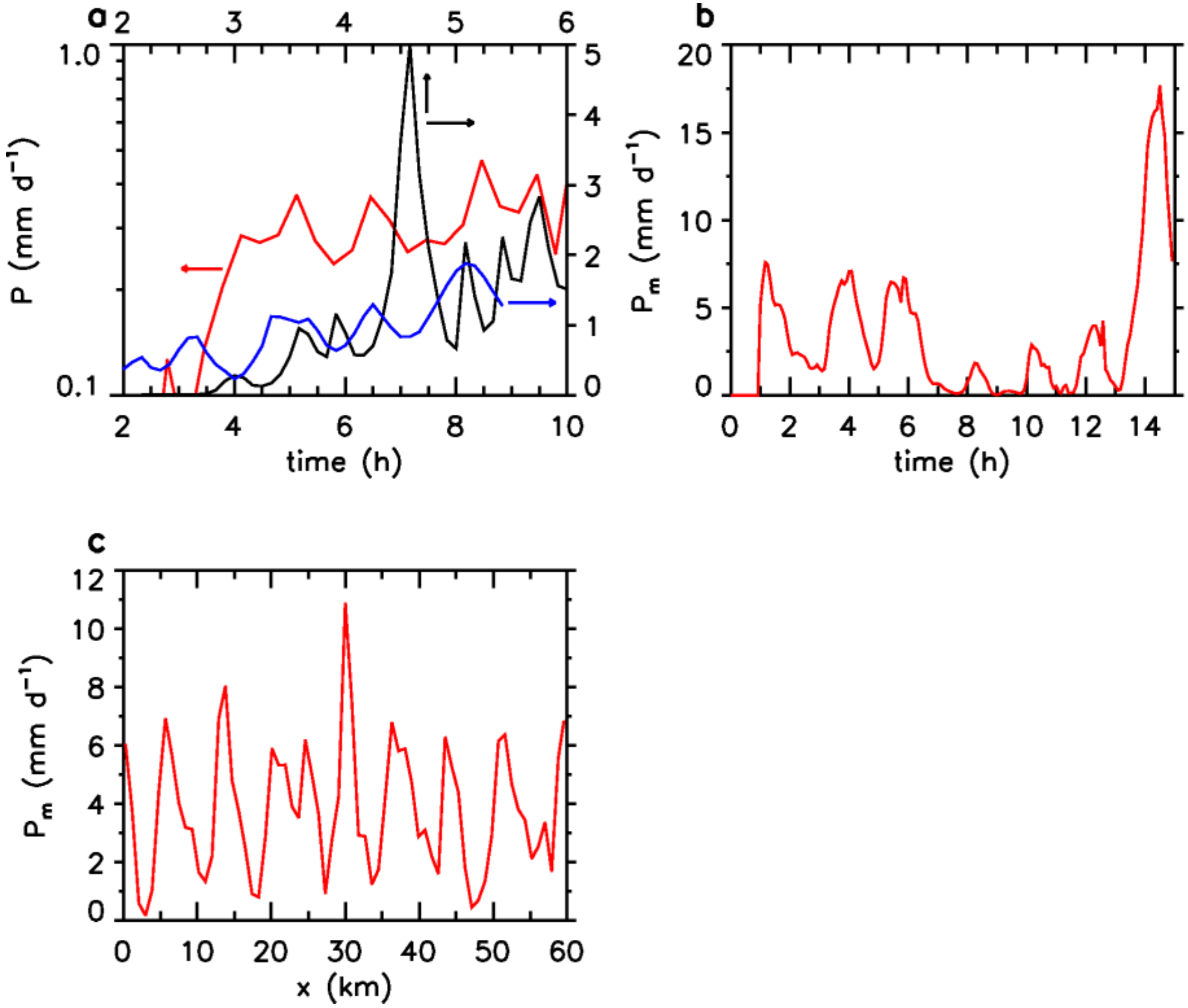

3 LES cases:

DYCOMS

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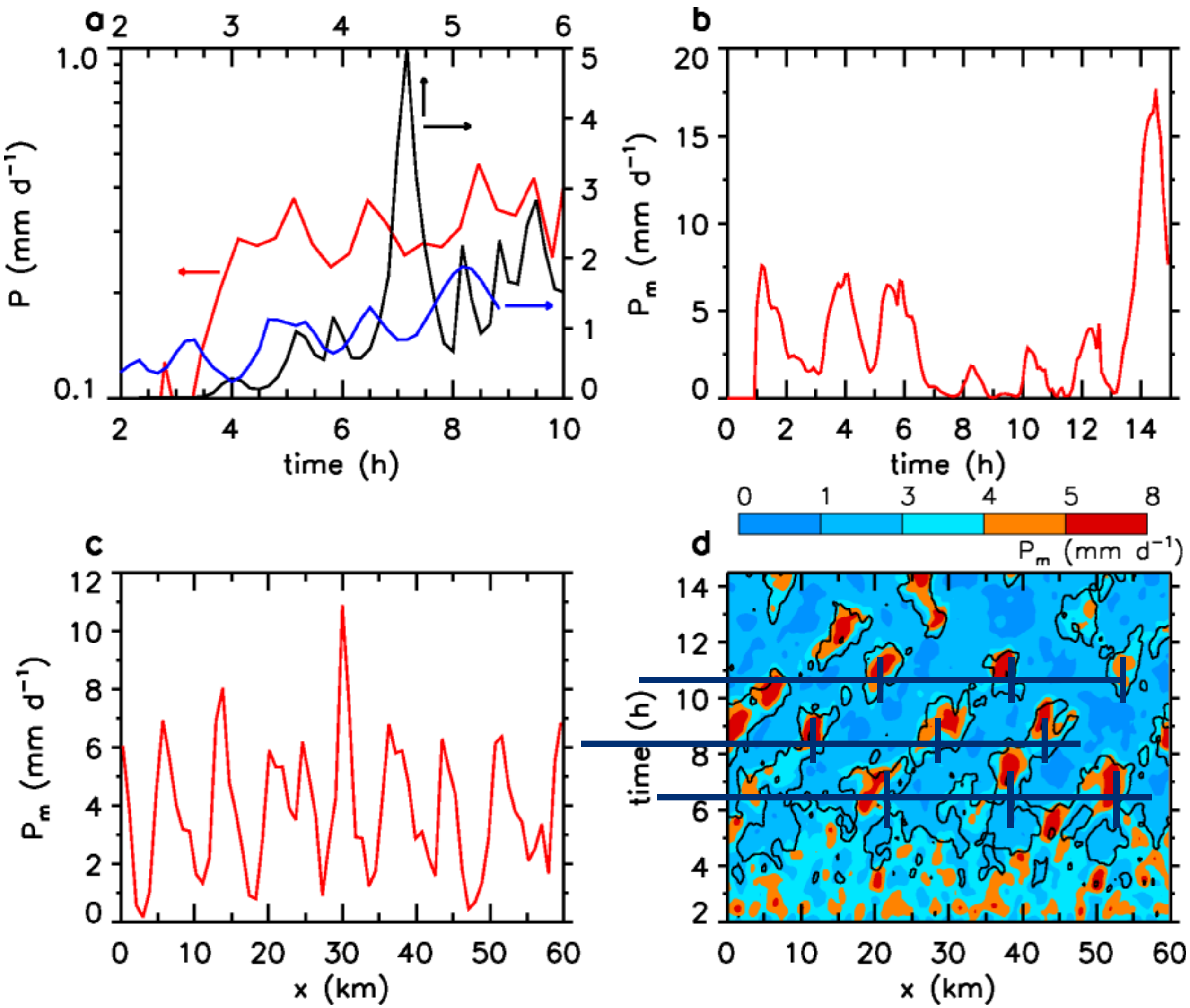


3 LES cases:

DYCOMS

ATEX

VOCALS

Hovmuller diagram

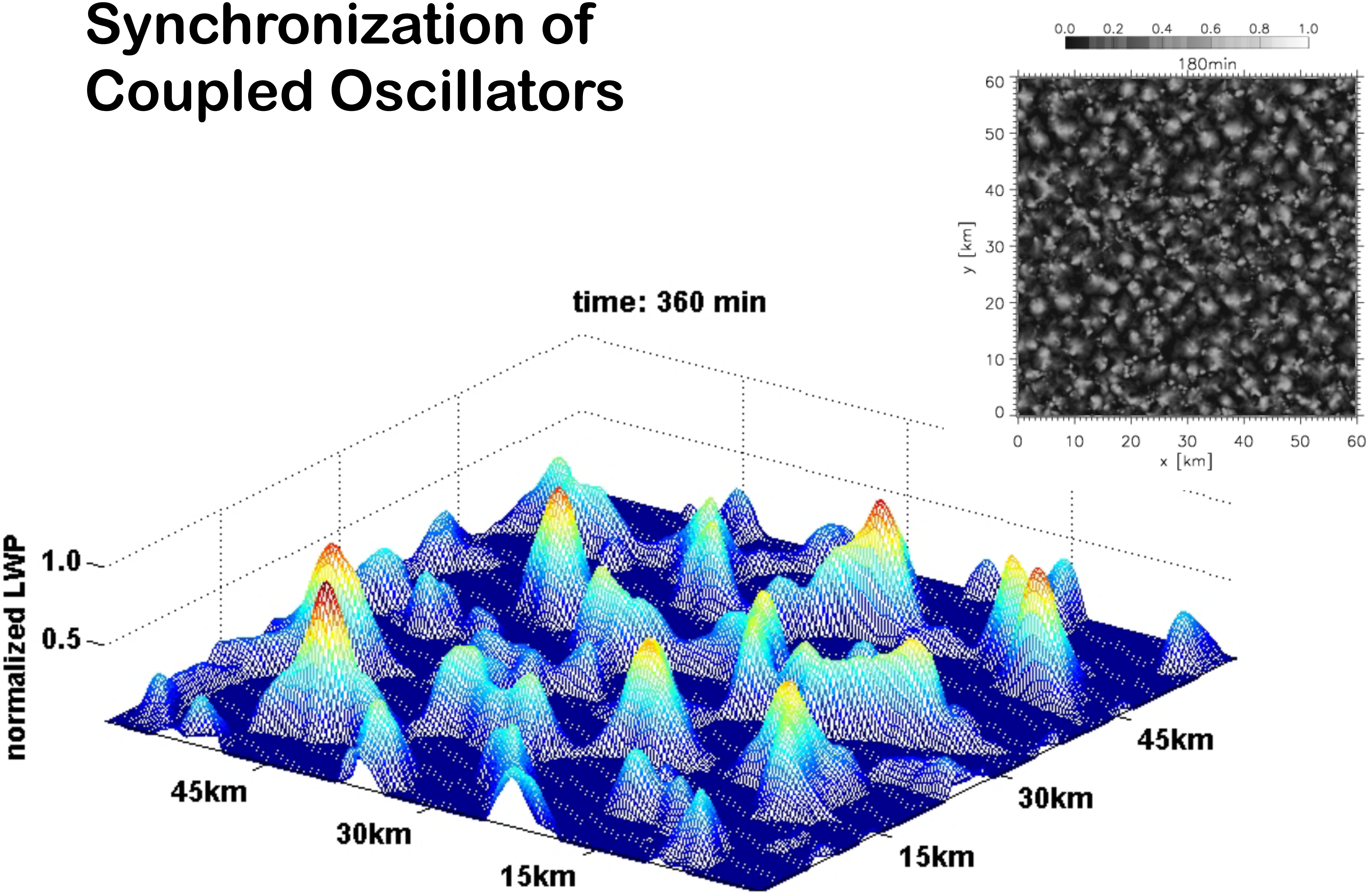
Shift in rain "grid"

Colored contours: rain

Contours: updraft

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

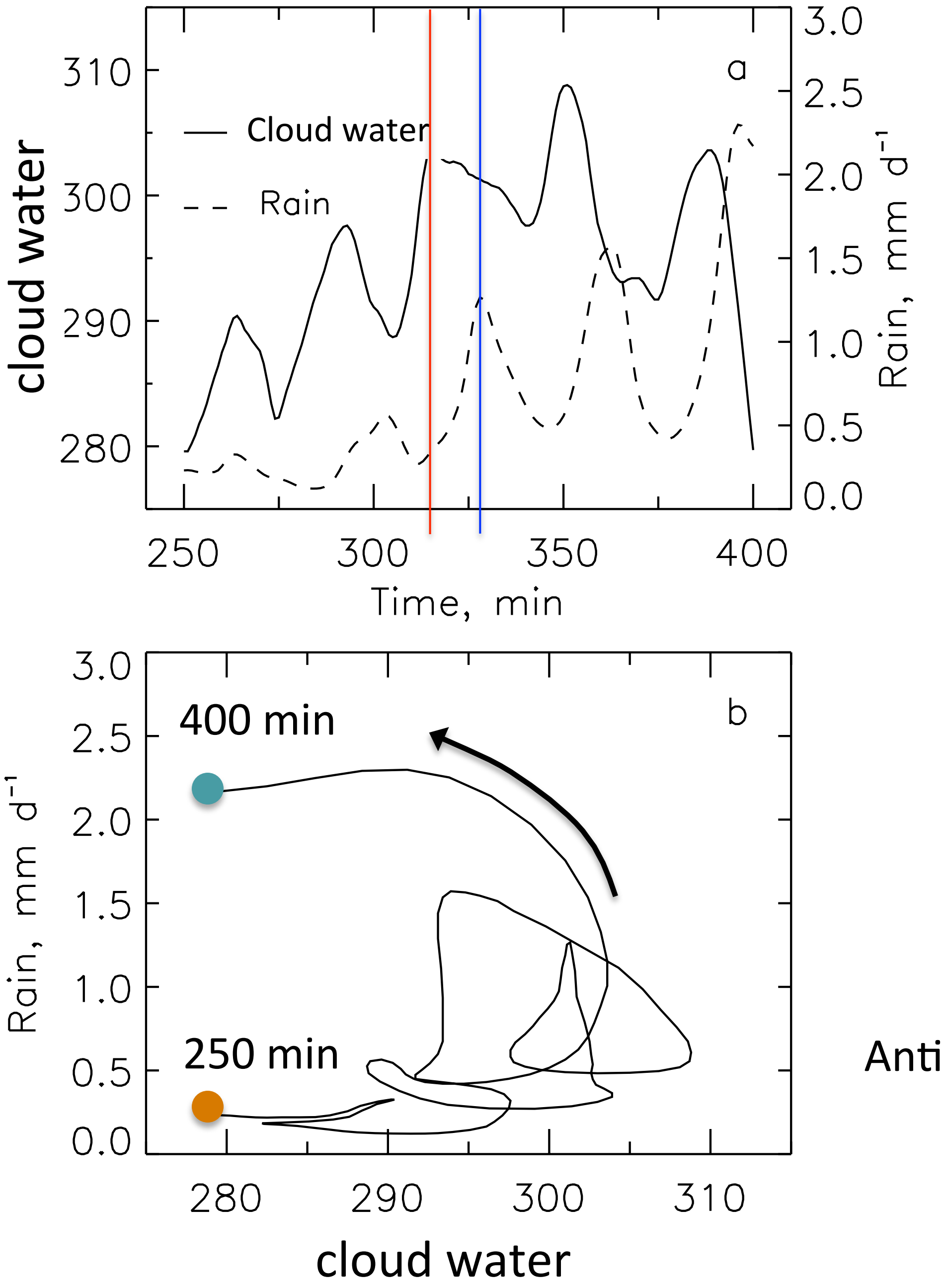
Synchronization of Coupled Oscillators



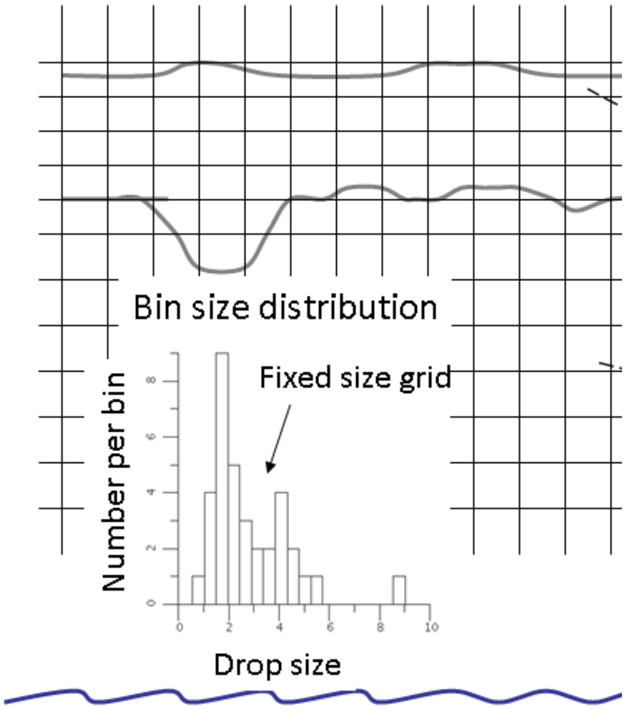
Feingold, Koren, Wang, Xue, Brewer (2010)

Are Oscillating Patterns Common?

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

Koren and Feingold 2011, PNAS

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

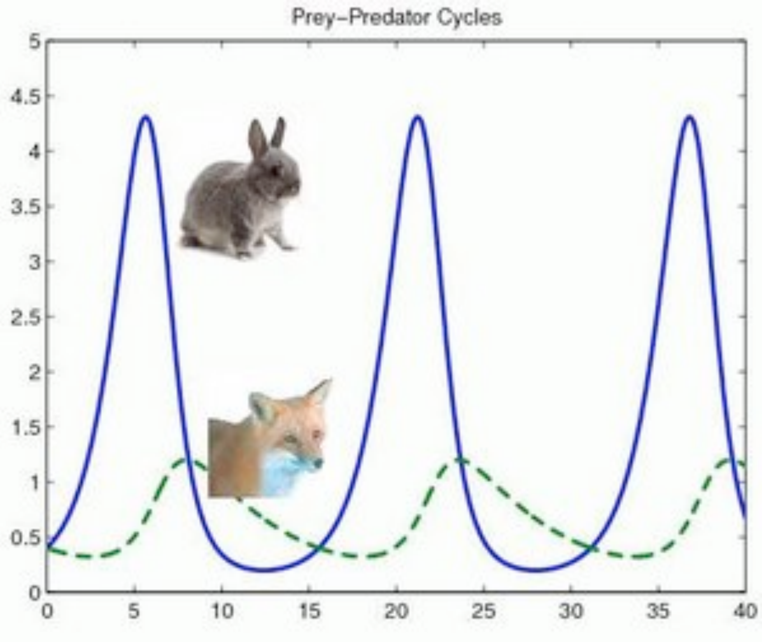
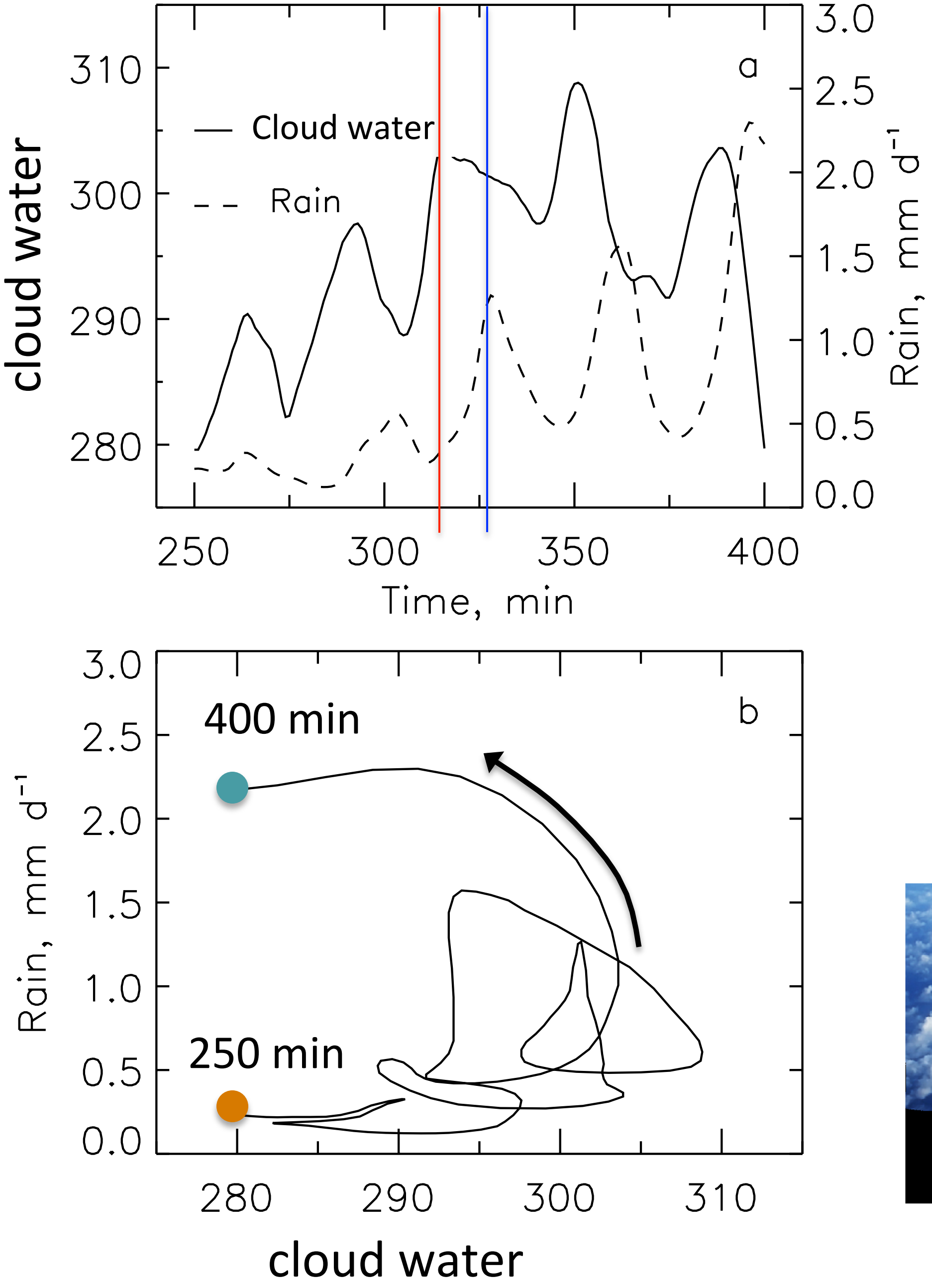


Image courtesy of Wikipedia

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

Predator-Prey Model



Clouds=Rabbits; Rain=Foxes

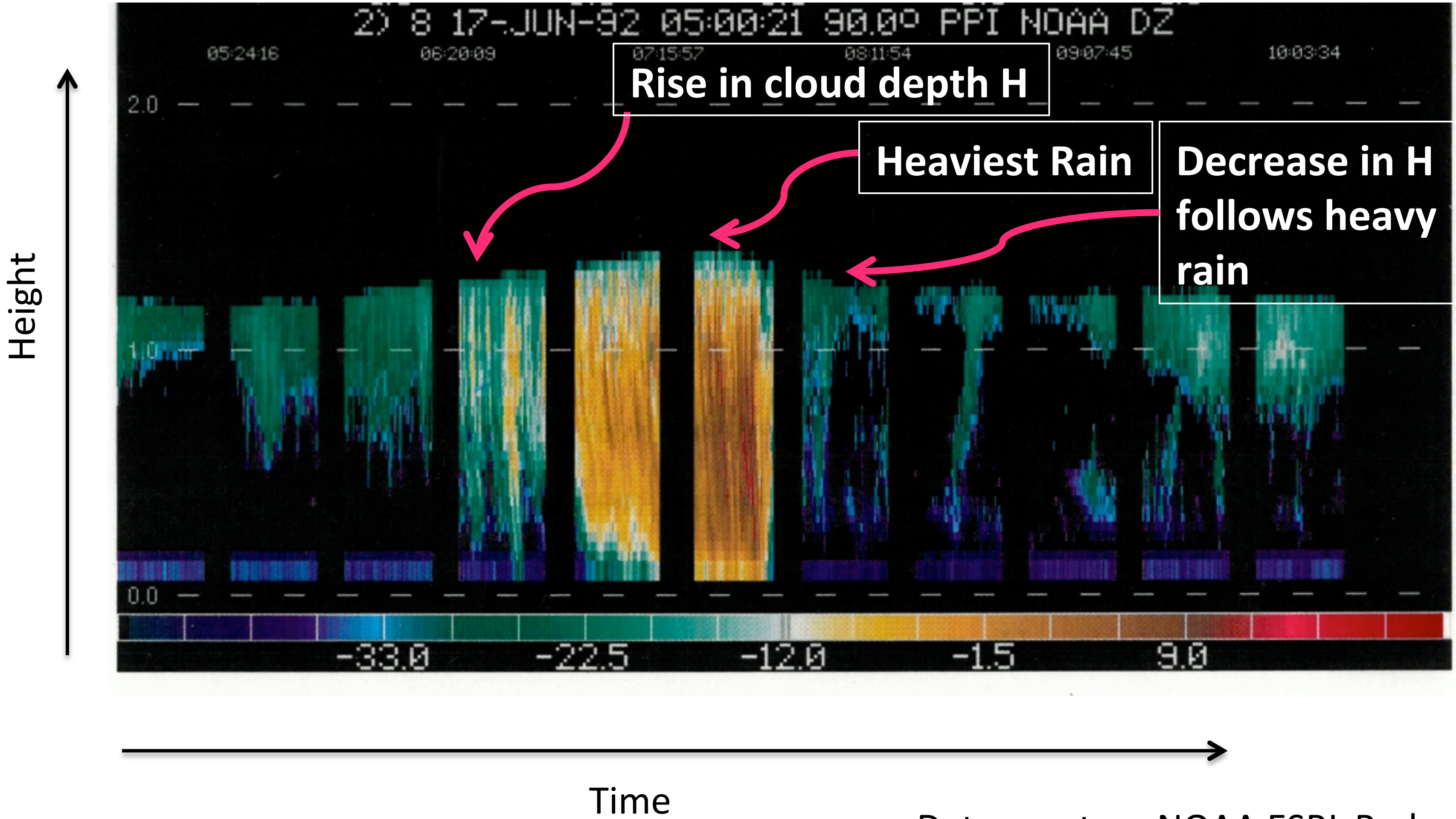
- Cloud builds up
- Rain follows some time behind
- Rain destroys cloud
- Cloud regenerates (meteorological forcing, colliding outflows, etc)

and so on…

Rain preys on clouds

Koren and Feingold 2011, PNAS

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



Rise in cloud depth H

Heaviest Rain

Decrease in H follows heavy rain

Data courtesy NOAA ESRL Radar Group

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)

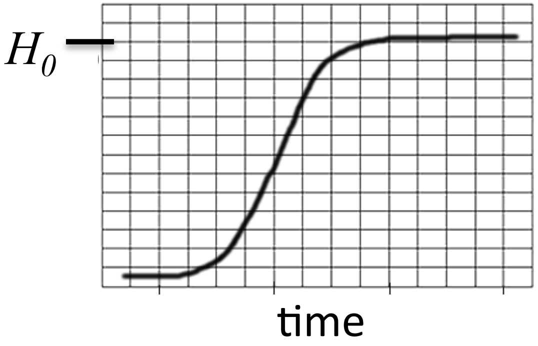
Drop concentration N_d

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

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

Loss terms

Cloud Depth H loss term

$$\dot{H}_r = \frac{dH}{dt} = \frac{dH}{d\mathrm{LWP}}\frac{d\mathrm{LWP}}{dt} \quad ; \qquad \frac{d\mathrm{LWP}}{dt} = -R$$

$$\dot{H}_r = -\frac{1}{c_1 H}R = -\frac{\alpha H^2}{c_1 N_d}$$

Drop concentration N_d loss term (collision-coalescence)

$$\dot{N}_d = -c_2 N_d R$$

Wood 2006

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:

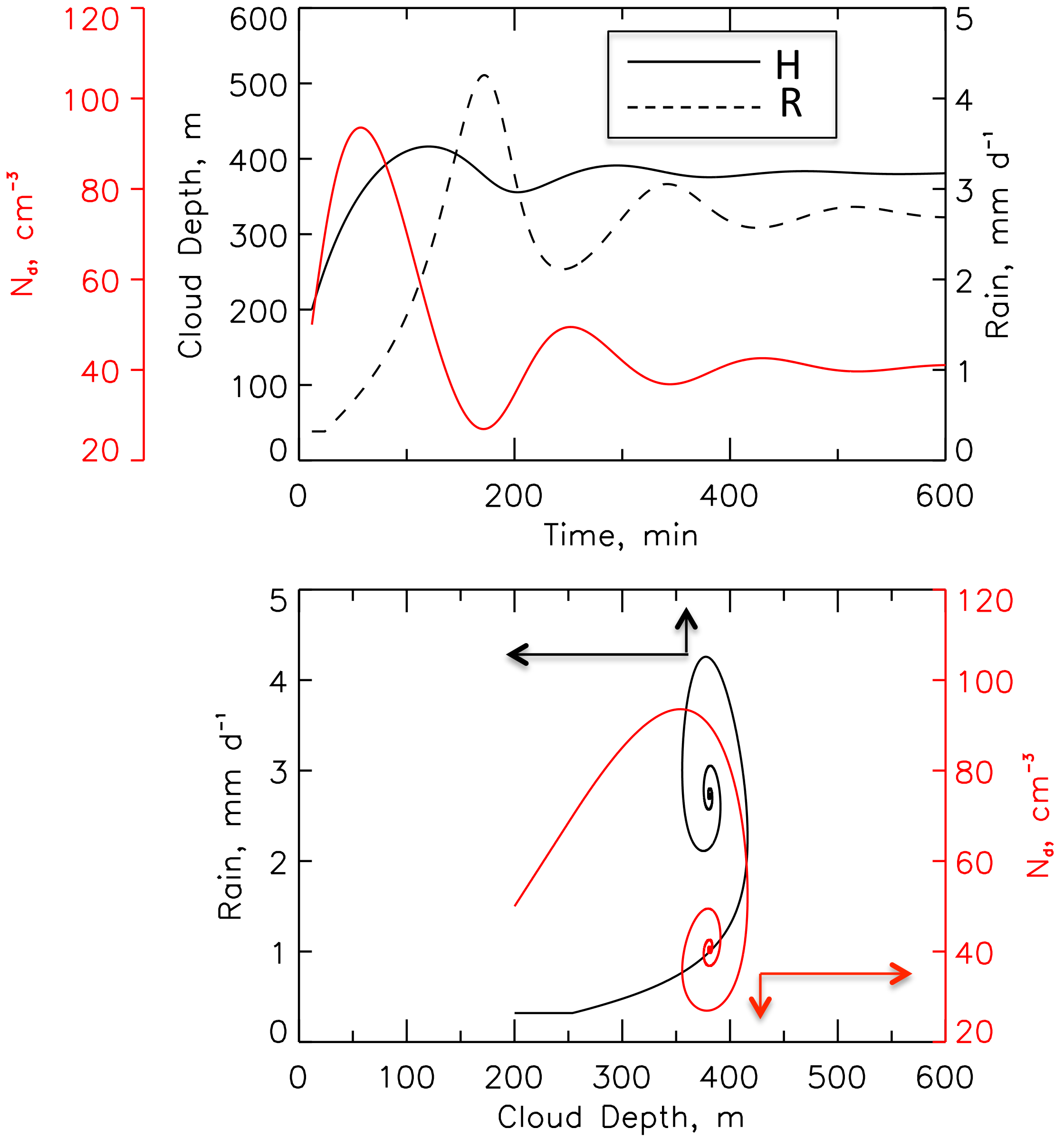
Five parameters:

Carrying Capacity: H_0 , N_0

Time constants: τ_1, τ_2

Delay time: T

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

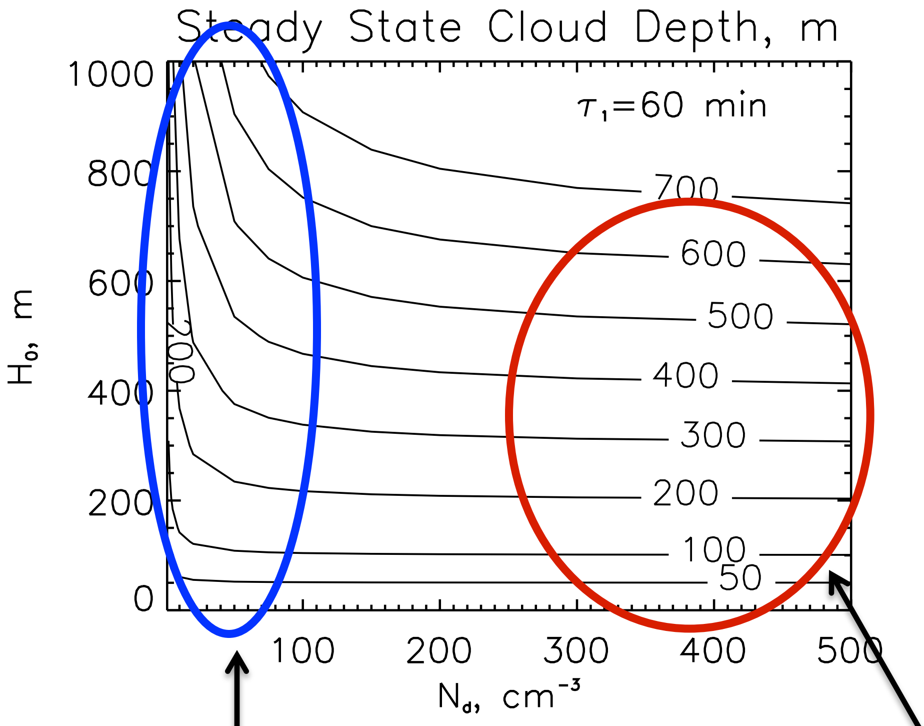
H; N
H; R

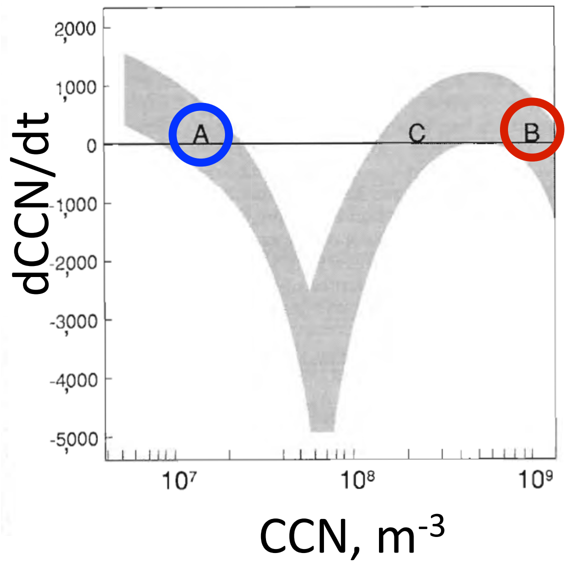
7 day simulation

Koren and Feingold 2011, PNAS

Steady State Solution to Cloud Depth H

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





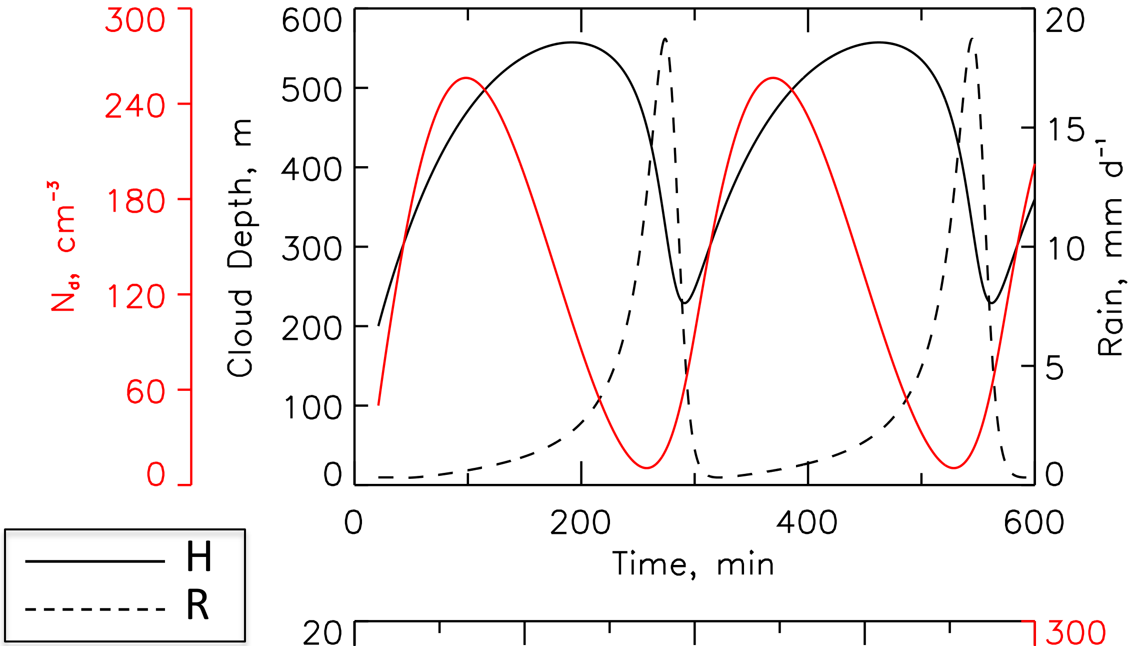
Baker and Charlson, 1990

Cloud Depth determined by drop concentration N_d

Cloud Depth determined by H_0

Koren and Feingold 2011, PNAS

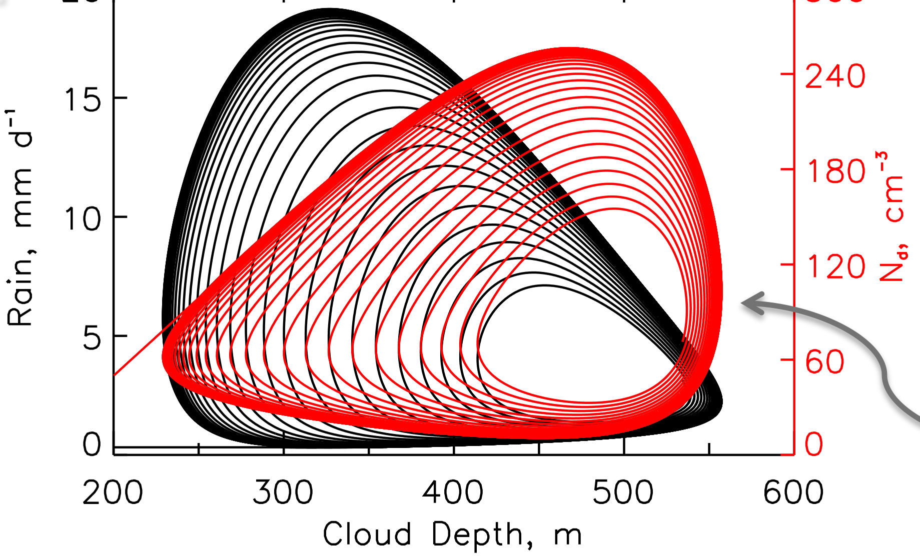
Oscillating Solutions: No Steady State



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

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

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



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

Oscillation around a steady state

7 day simulation

Koren and Feingold 2011, PNAS

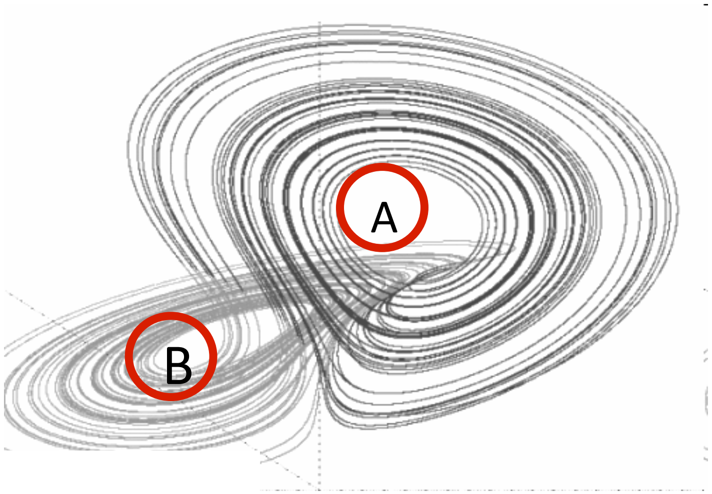
Stability

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

Attractors

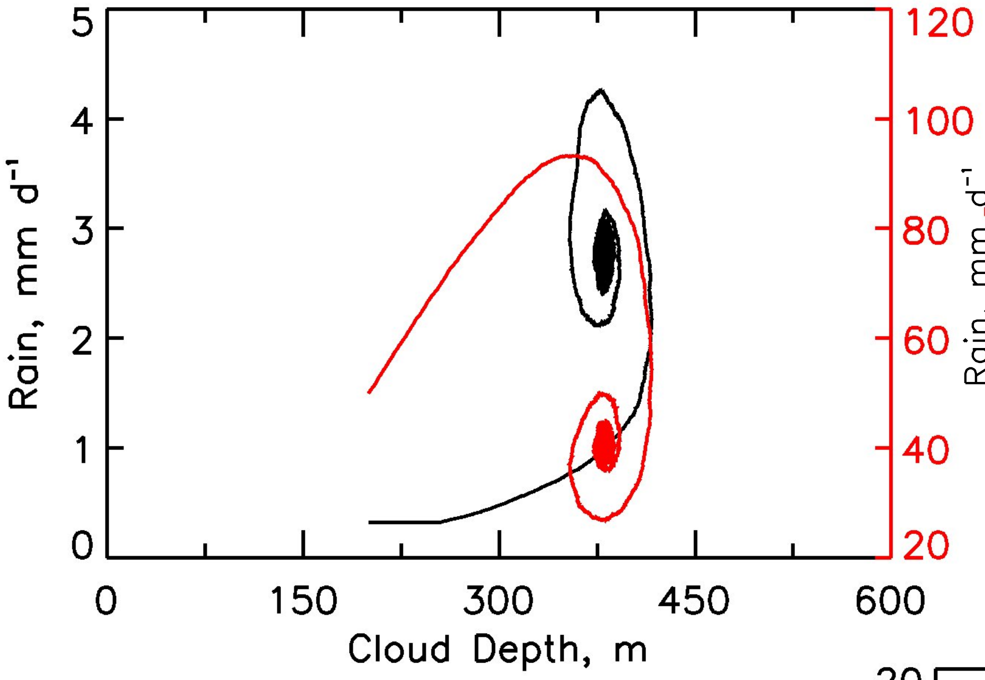


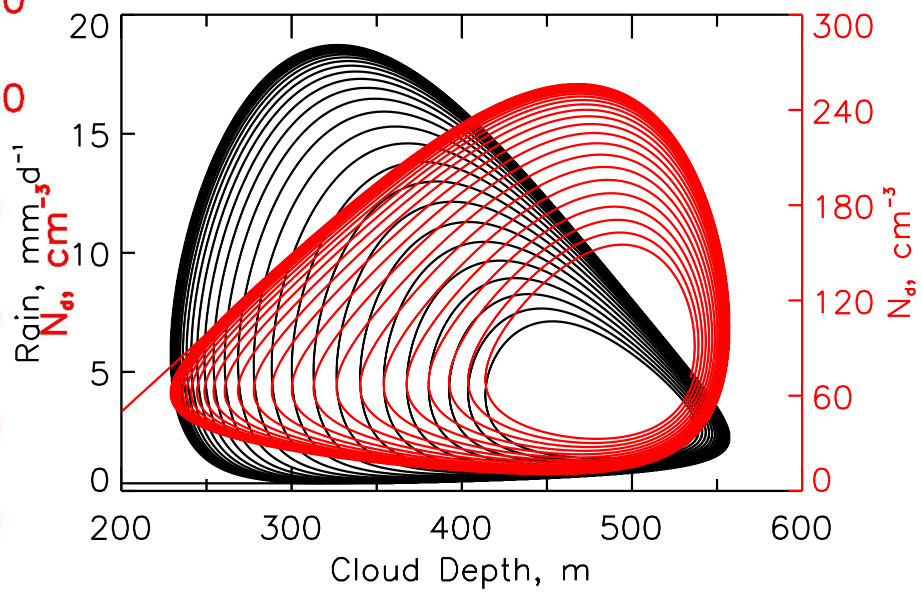
Lorenz, 1954

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

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

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

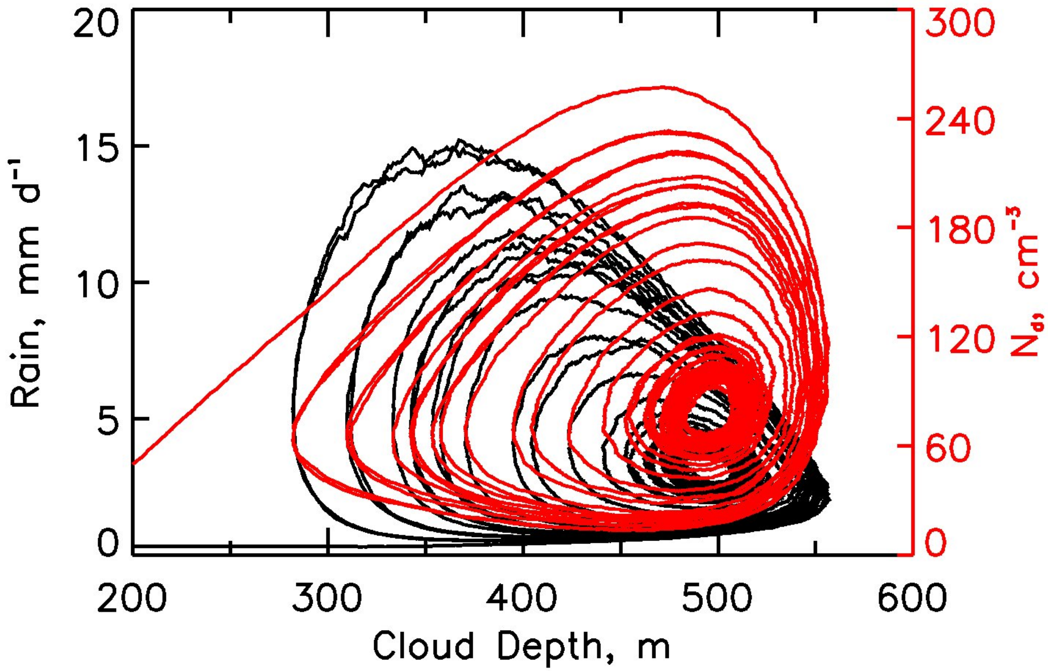




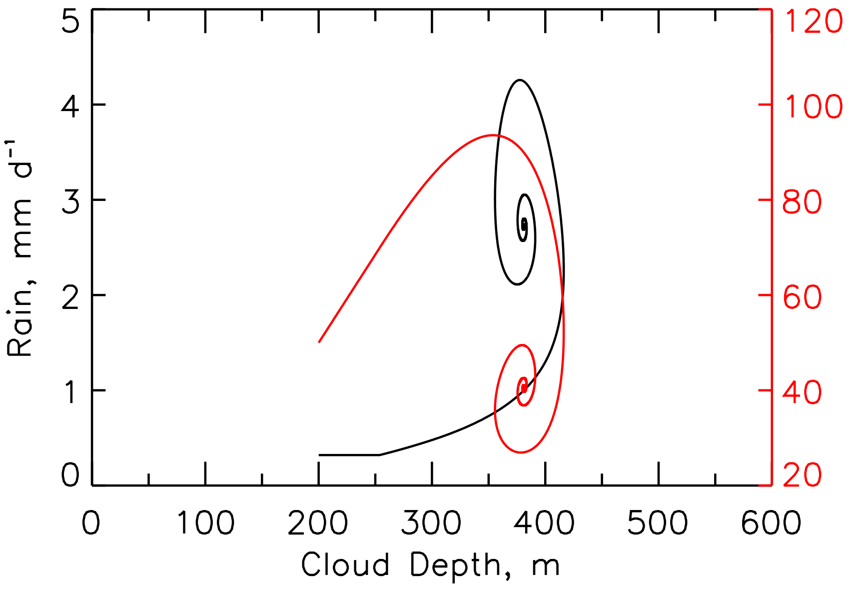
± 50% perturbations to H_0 and N_0 every second: Solutions are robust

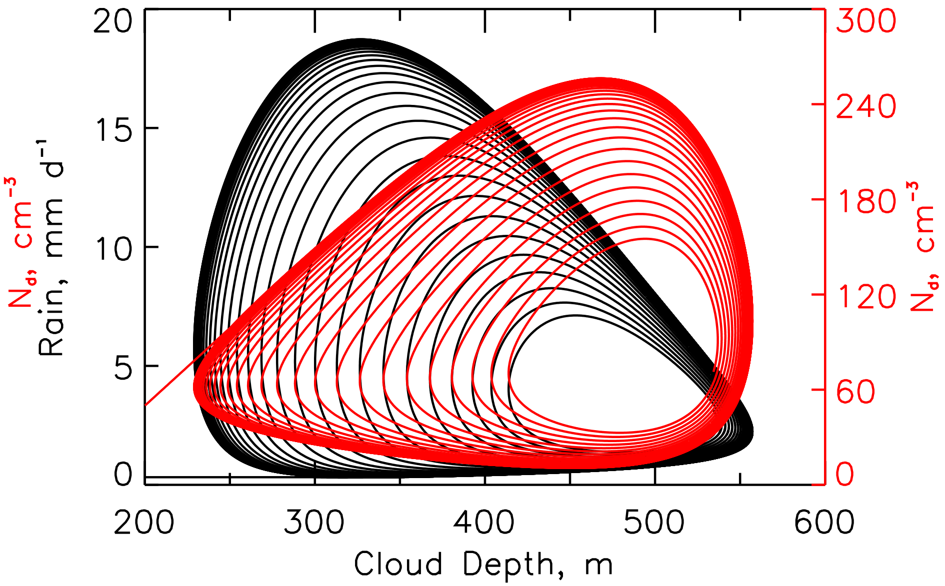
Small perturbations strengthen the resilience of the state;

Large enough perturbations will lead to collapse



Koren and Feingold 2011, PNAS





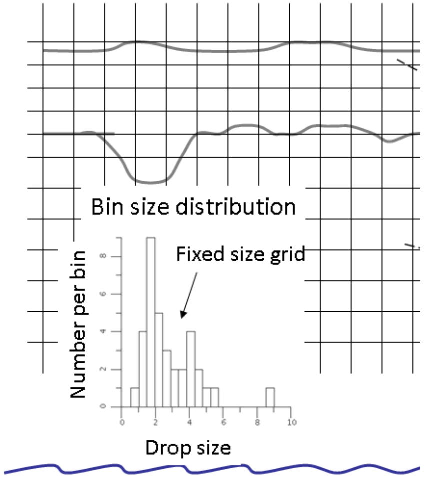
H_0 = 530 m
N_0 = 180 cm^{-3}
$\tau_1 = \tau_2$ = 60 min
T = 10 min

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

Rosenzweig Paradox (1971): the more "food" (larger H_0) you give a predator-prey system, the more unstable it will be

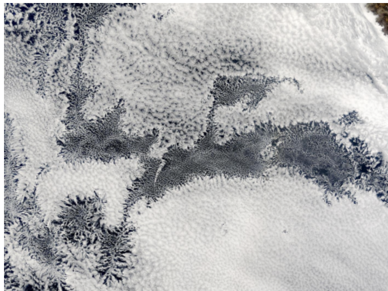
The Way Forward?

1) *<u>Process level</u>* understanding
   “Reductionist” or *“Newtonian”*



2) *<u>Systems</u> approach*
   “Darwinian”

*Synthesis of “Newtonian” and “Darwinian” **



* John Harte, Physics Today October 2002

Summary

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

- *Can we exploit emergence to represent complex systems?*
- *Open cellular state: Coupled system that constantly rearranges itself*
  - *Local interactions: convergence of precipitating outflows*
  - *synchronized rain, oscillations in open-cell state*
- *Aerosol-cloud-precipitation system contains elements of the predator-prey problem*
  - *Coupled oscillations in Cloud-Rain "Populations"*
  - *Bifurcation*

References

- Feingold, Koren, Wang, Xue, Brewer, 2010: Precipitation generated oscillations in open-cellular cloud fields*, Nature August 2010*

- Koren and Feingold, 2011: Aerosol-cloud-precipitation system as a predator-prey problem, *PNAS, July 2011*.