Aerosol Effects on Marine Boundary Layer Cloud Systems: From Microphysics to Emergence

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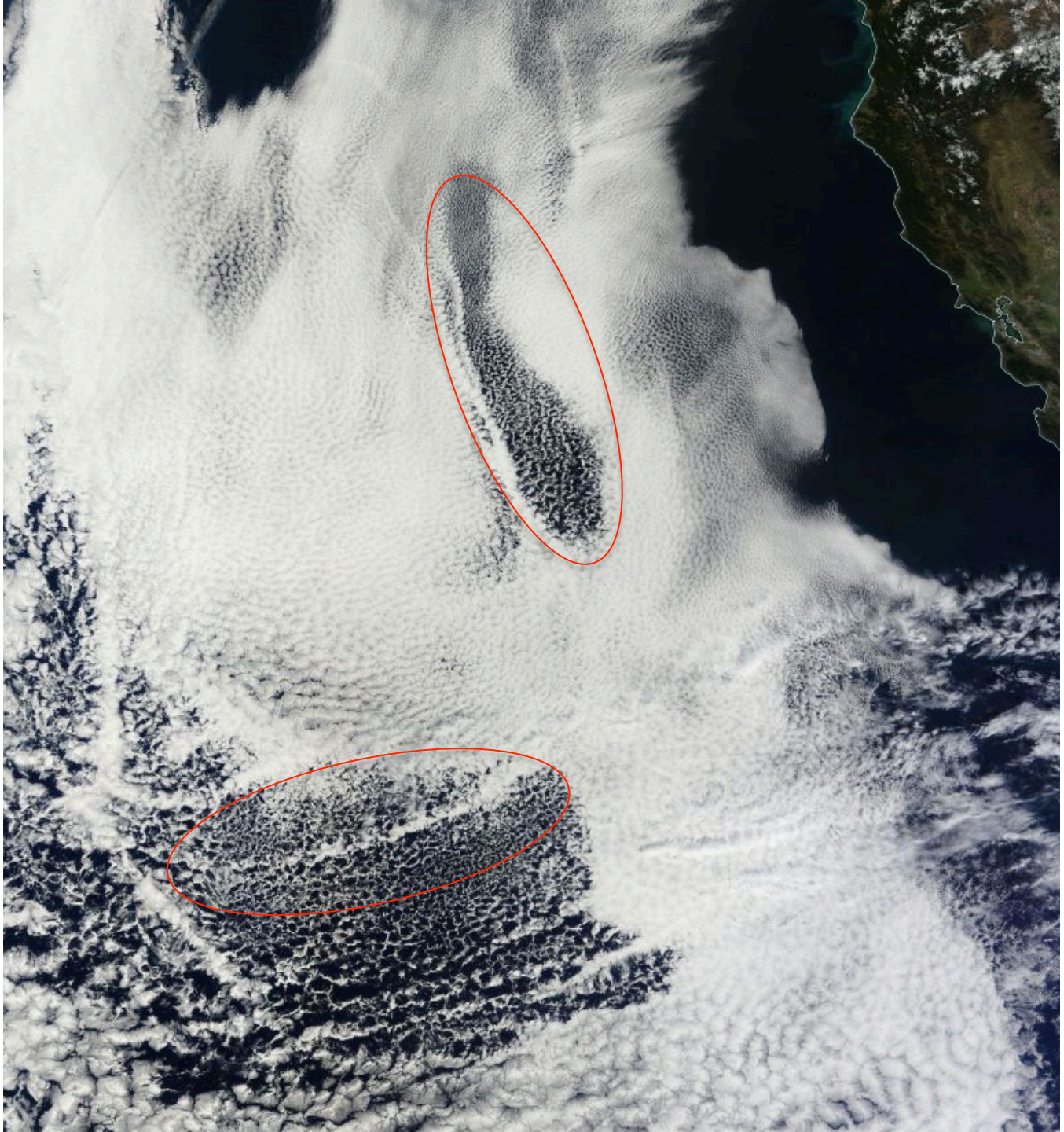
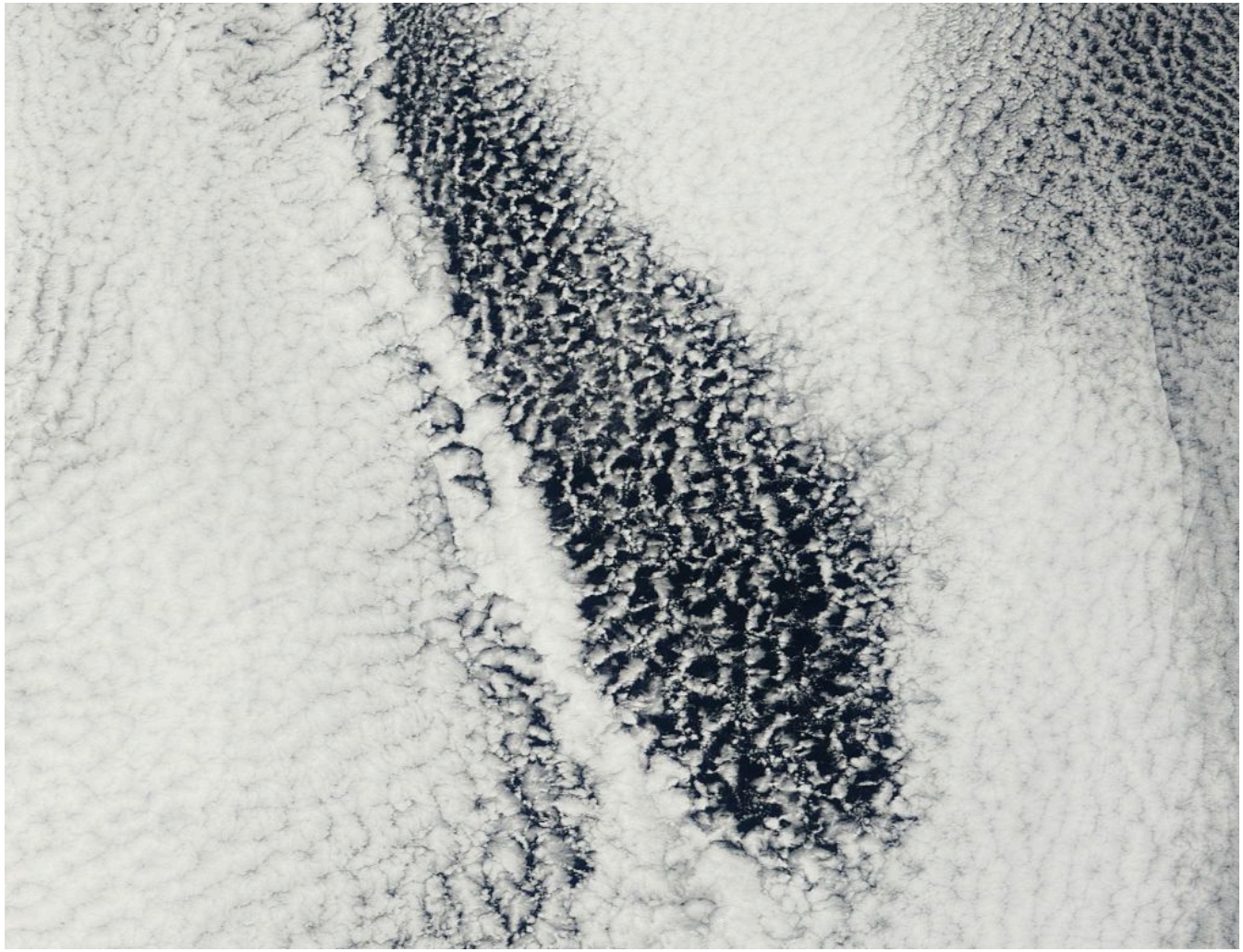
Yoram Kaufman Memorial Symposium June 2016



MODIS
(Feb 15 2013)

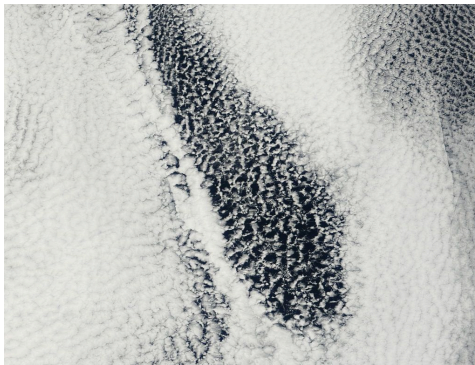
Pocket of open cells



MODIS (Feb 15 2013)

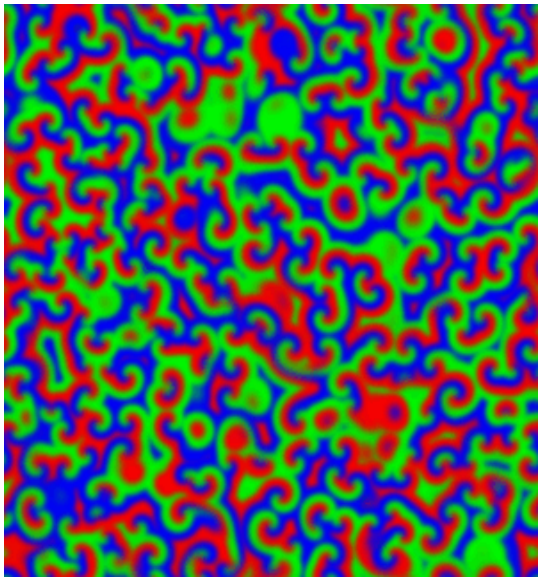
What we have learned about Closed and Open Cells

- Closed cells: (mostly) non-precipitating; high cloud fraction, f_c
- Open cells: precipitation and low f_c
- Pockets of open cells form in a closed cell environment
  - Initial thermodynamic state is ~ the same
- Transition from closed to open cell occurs rapidly (hours)
- Ship tracks appear to 'fill-in' open cells (timescales less clear)

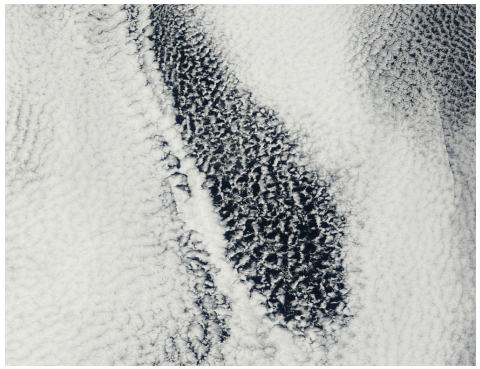


From Microphysics to Emergence

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



Belousov-Zhabotinsky chemical oscillator
(non equilibrium thermodynamics)



MODIS

CO Geological Survey: Sand Dunes

John Holmes (Wikipedia)

From Microphysics to Emergence

Microphysical Rules:

Rules of interaction between drops and their environment

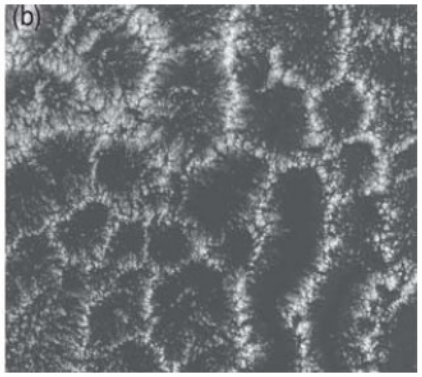
Condensation on nuclei

Drop collision-coalescence

+ continuity of fluid motion

Sedimentation and evaporation

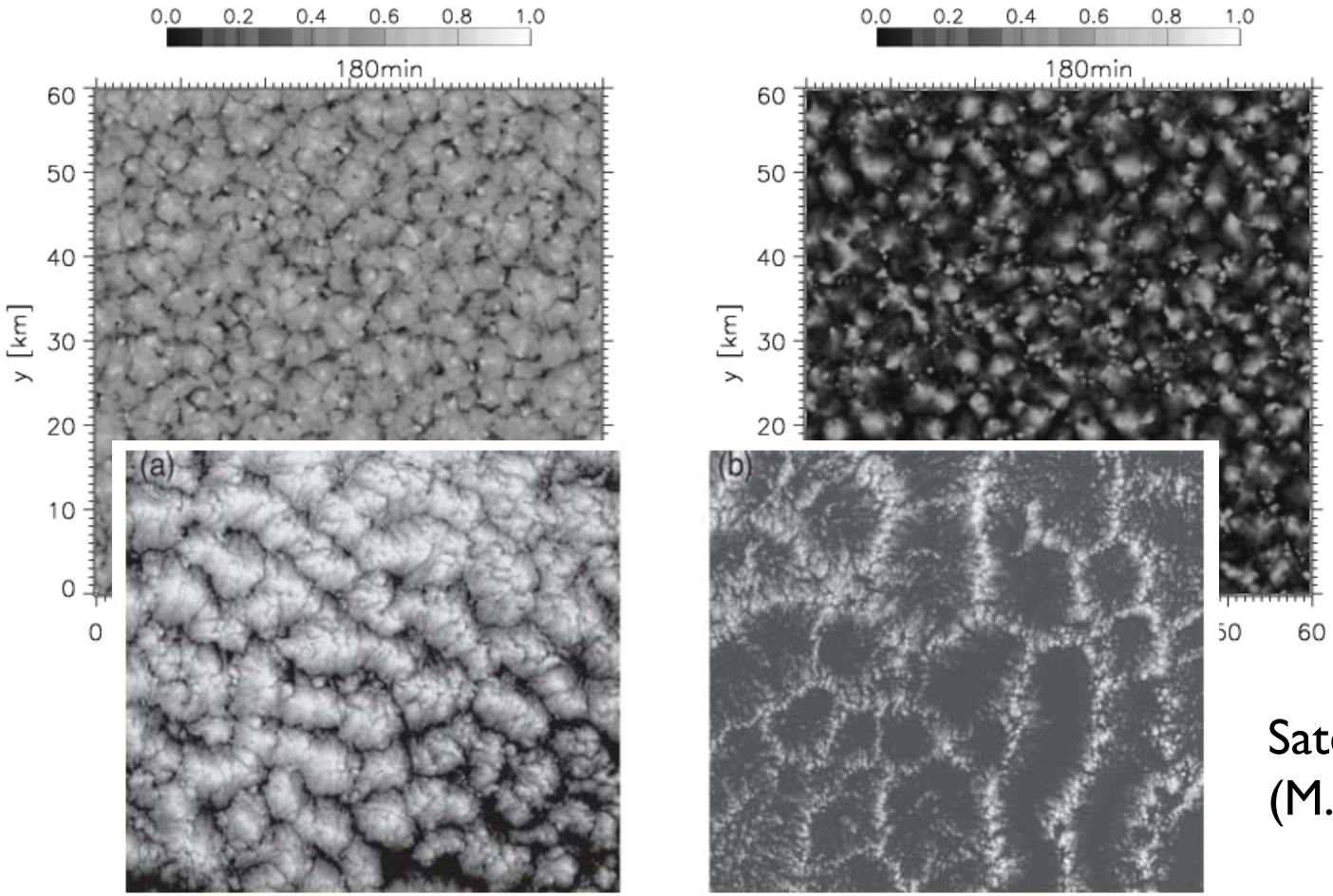
Emergence: system-wide patterns emerge from local interactions between elements that make up the system



M. Garay

Self-Organizing Cloud States

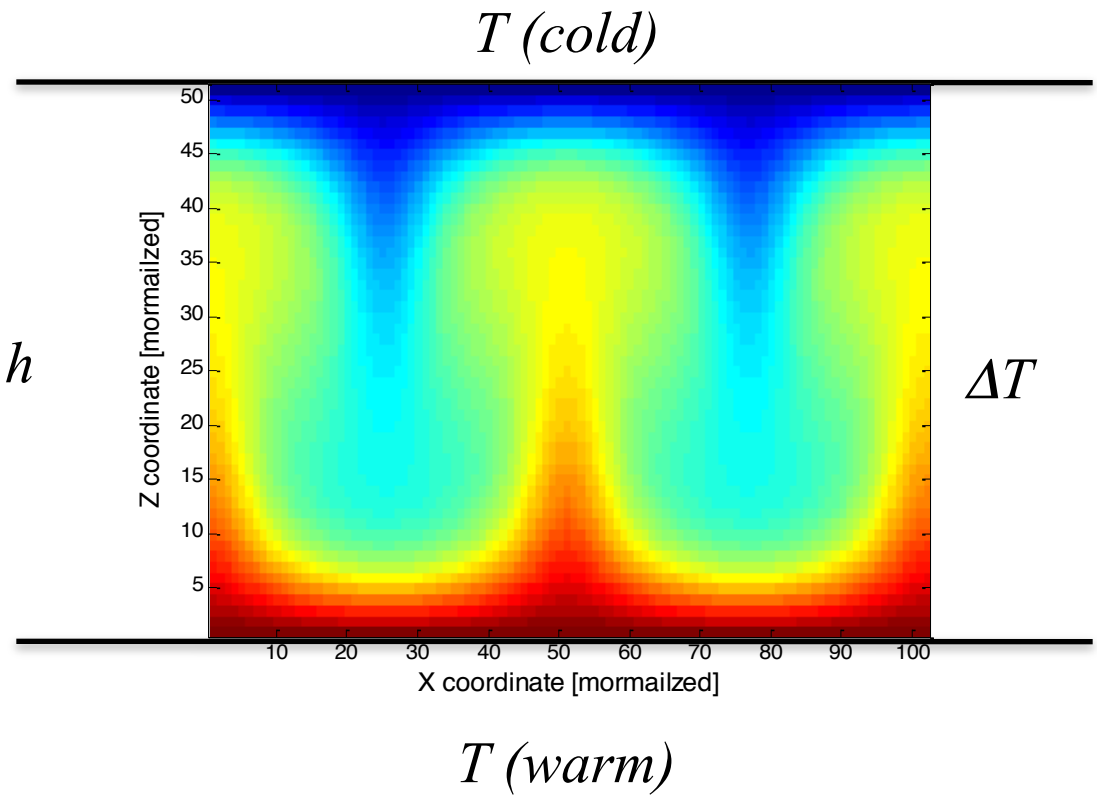
Identical initial conditions except for aerosol



Satellite images
(M. Garay)

Wang and Feingold (2009)

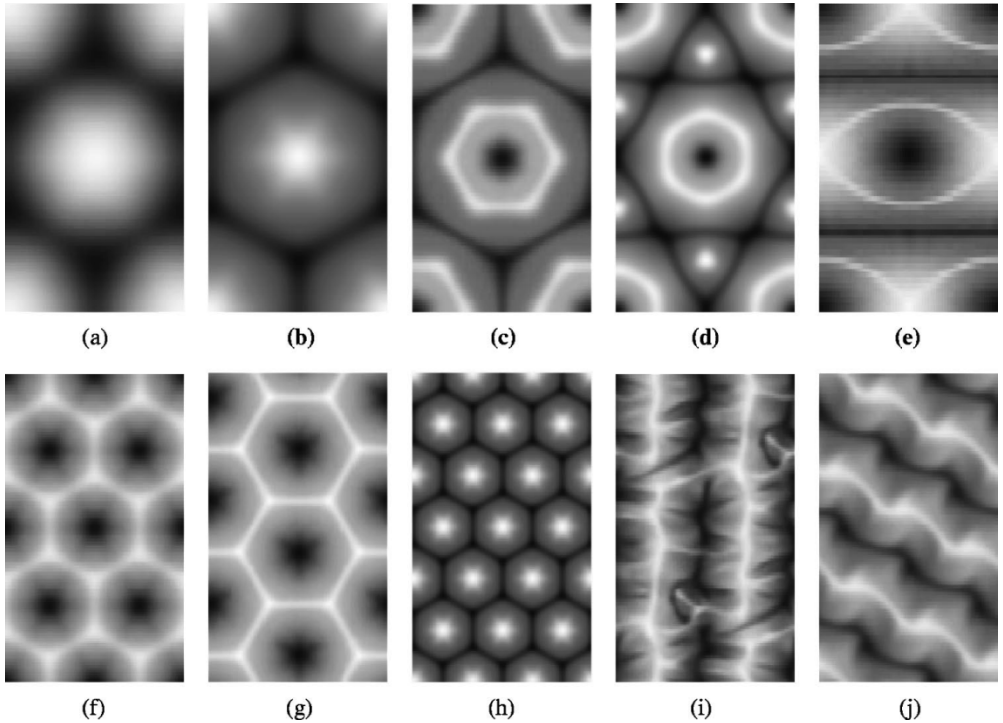
Rayleigh-Bénard Convection



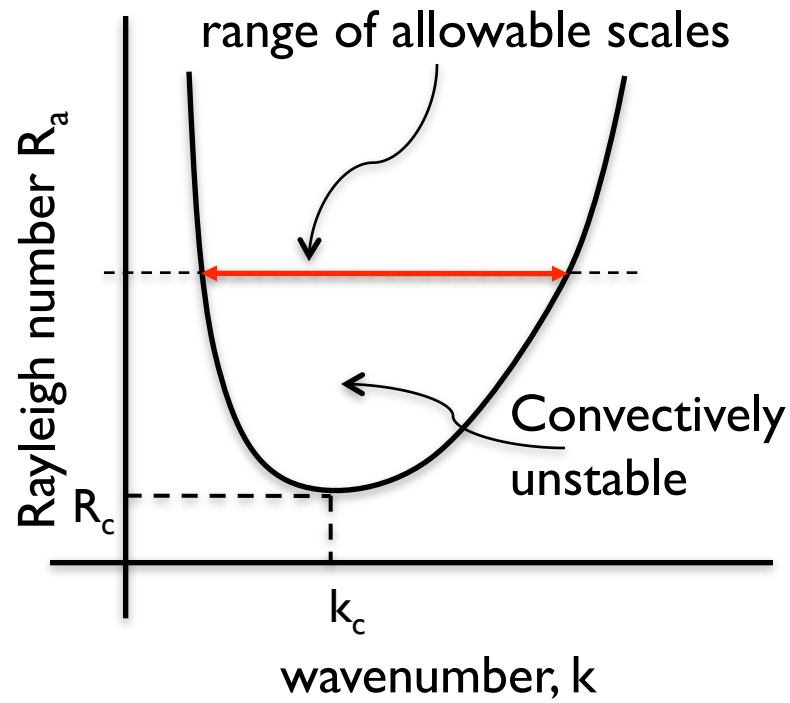
$$R_a = \alpha g \Delta T h^3 / (\nu \chi)$$

ΔT = temperature difference between surfaces
α = thermal expansion coefficient
g = gravitational acceleration
h = separation between the surfaces
ν = kinematic viscosity
χ = thermal diffusivity

Rayleigh-Bénard Convection



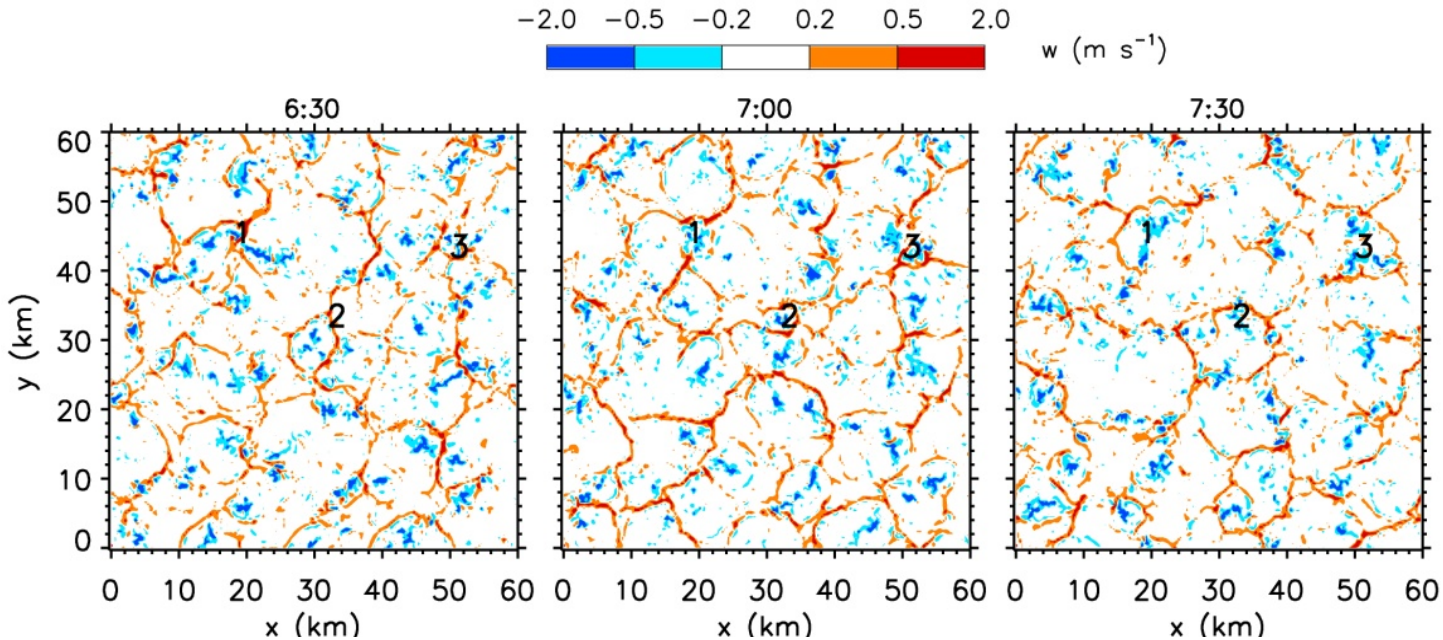
Controlled lab experiments



$R_c \sim 10^3$

"The features of the flow evolution agree with the idea of the flow seeking an optimal scale" Getling and Brausch, Phys. Rev. E 2003

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

↓

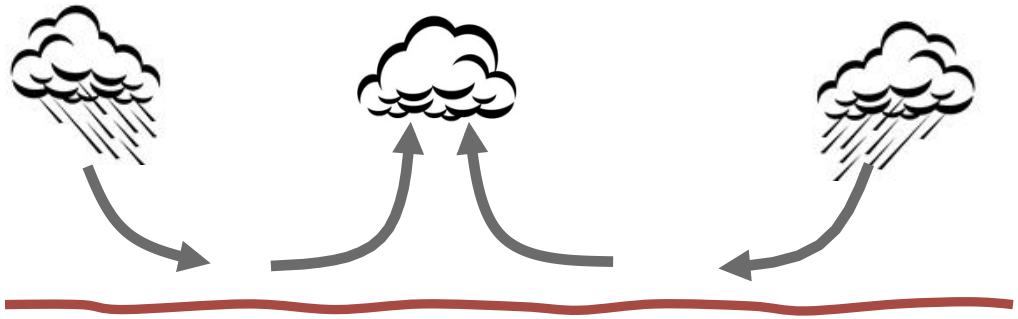
Precipitation is initiated

↓

Downdrafts, opening of cell

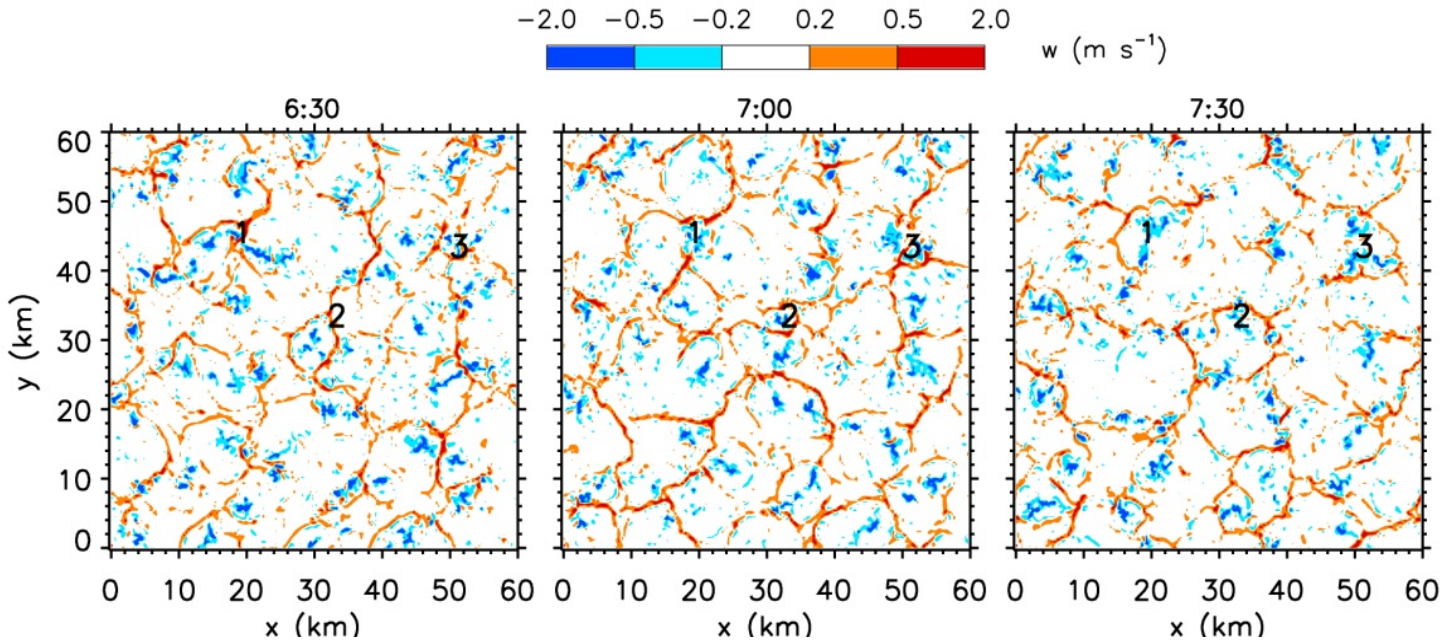
↓

Surface divergence



Y-convergence

Rearrangement of Open Cells



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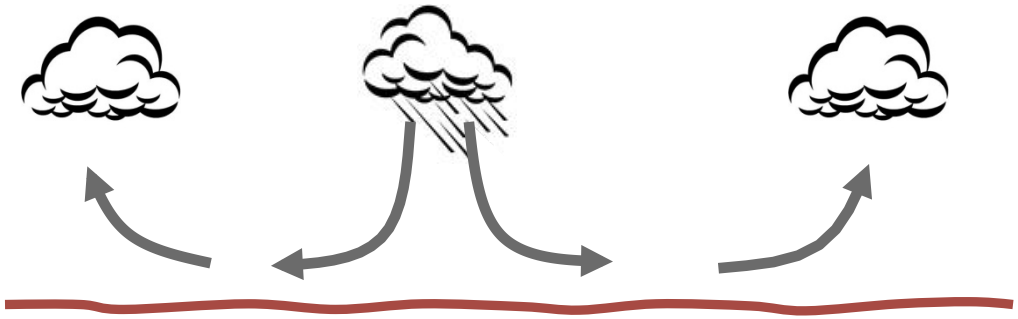
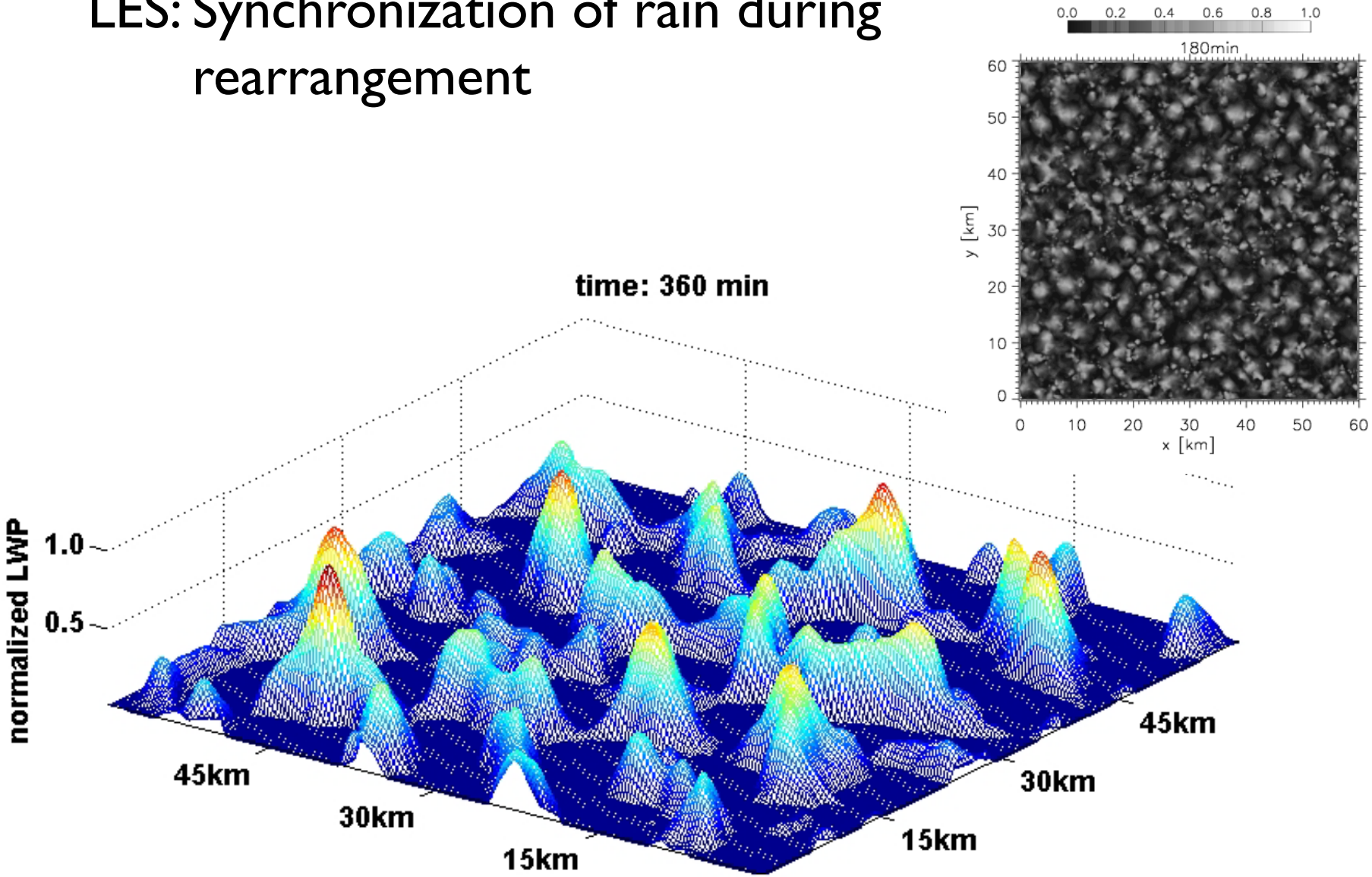


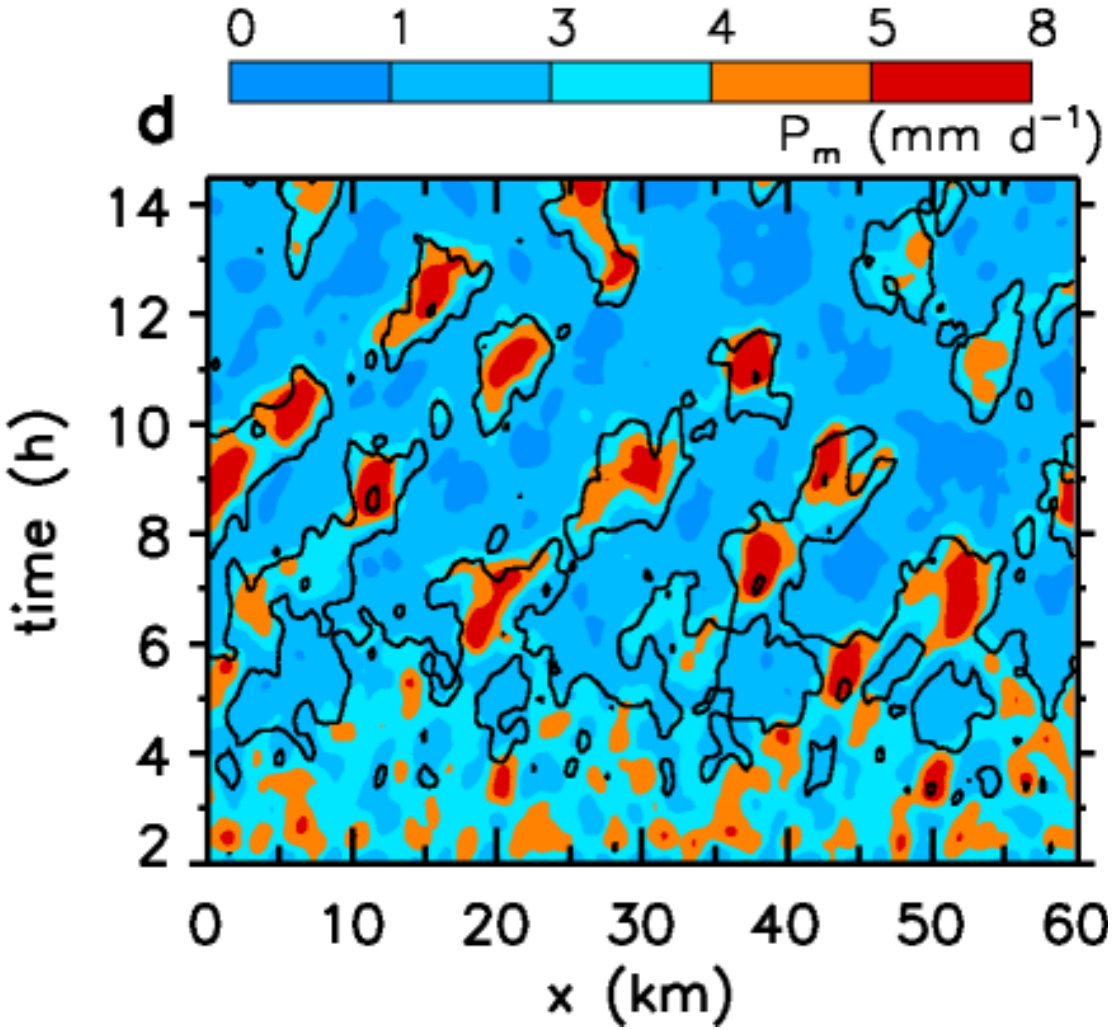
Divergence

LES: Synchronization of rain during rearrangement



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

Synchronization: Oscillations in Precipitation



Hovmöller diagram

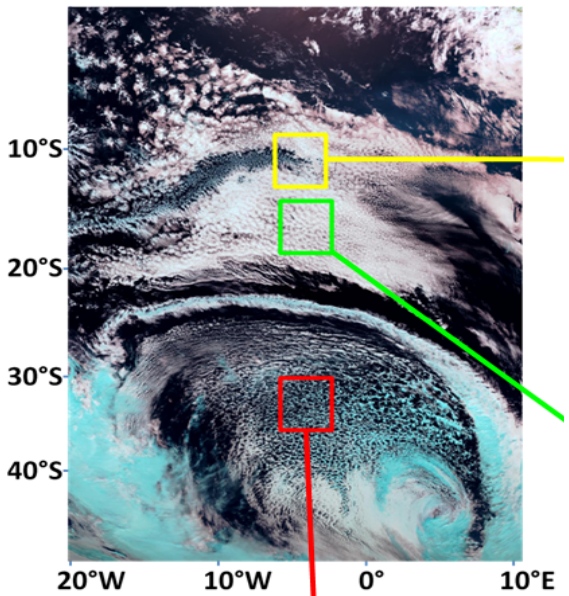
Periodic shift in rain "grid"

Colored contours: rain

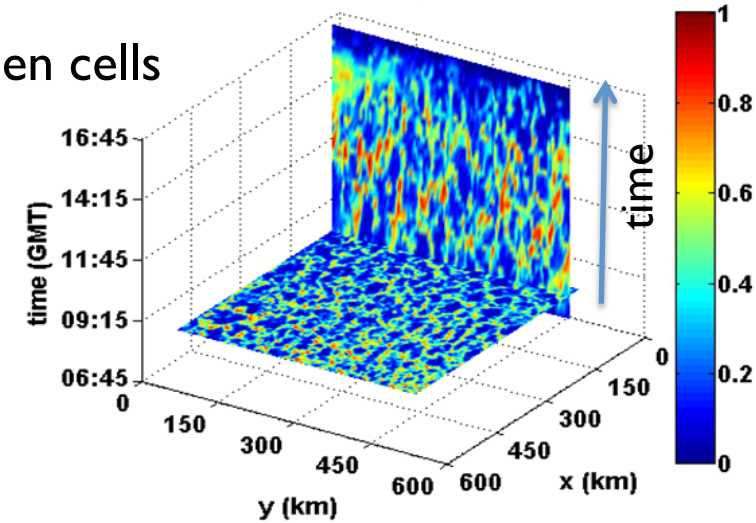
Contours: updraft

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

Open Cell Rearrangement vs. Closed Cell ‘Rigidity’



Open cells



Koren and Feingold 2013

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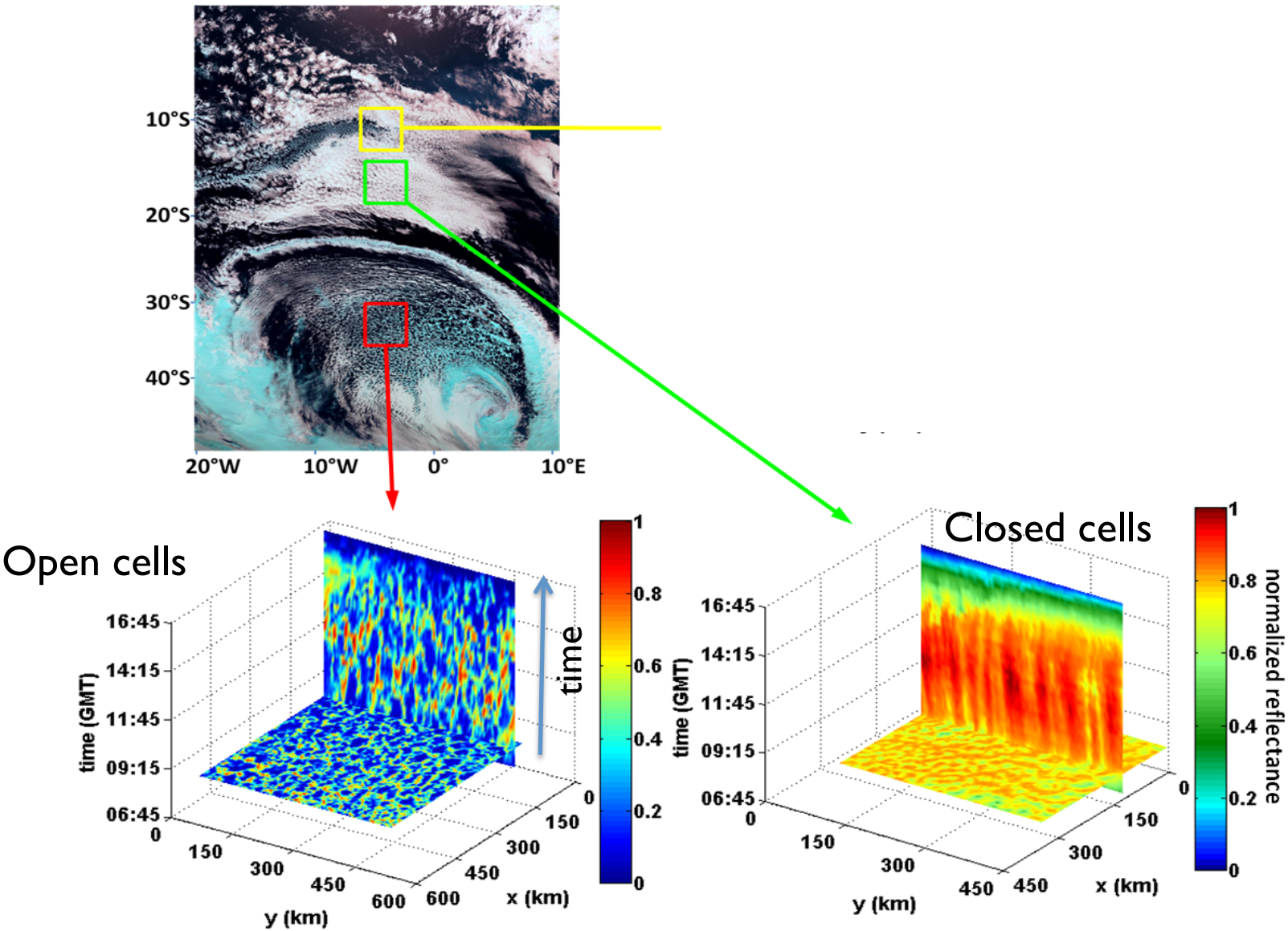
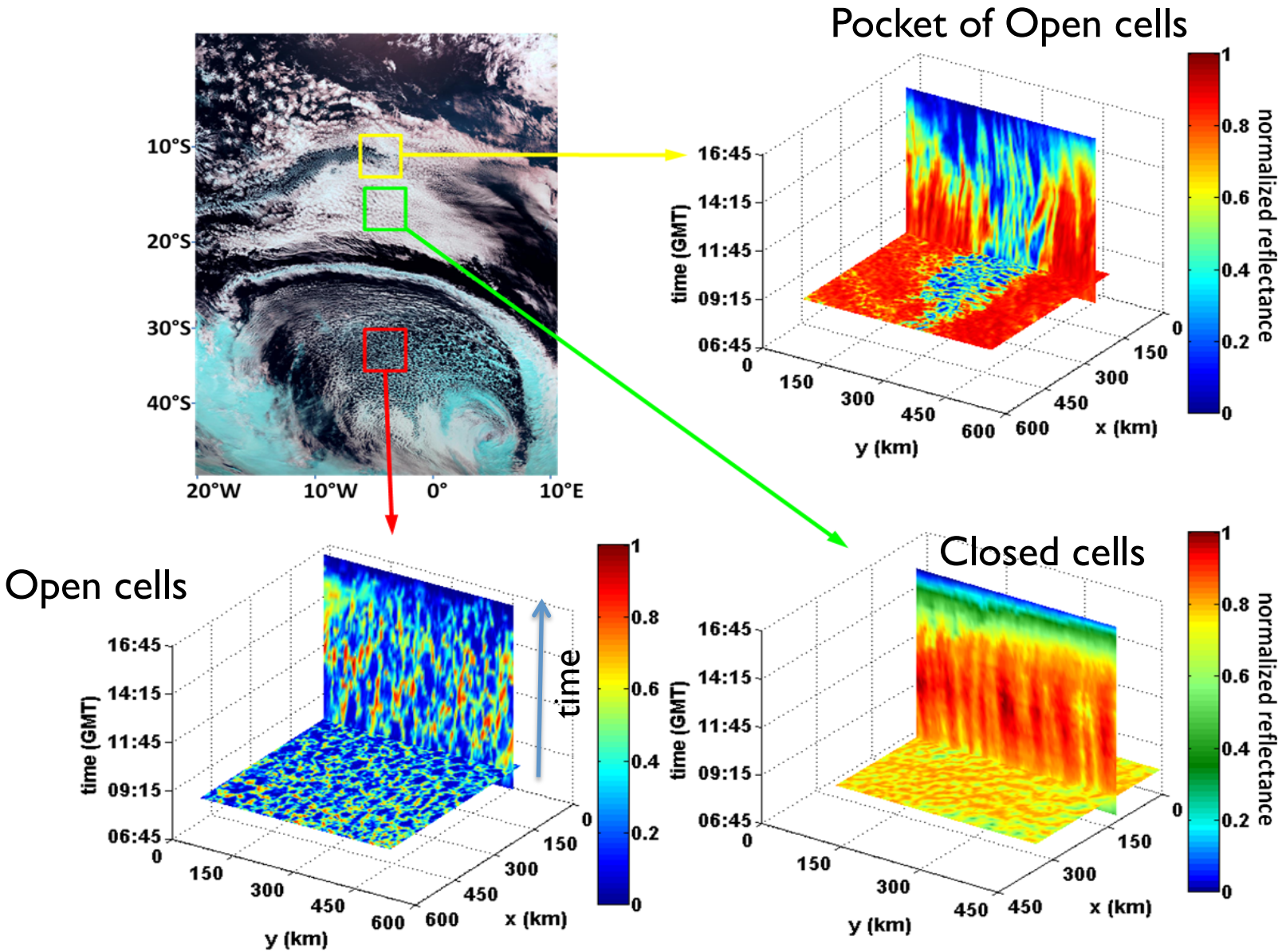


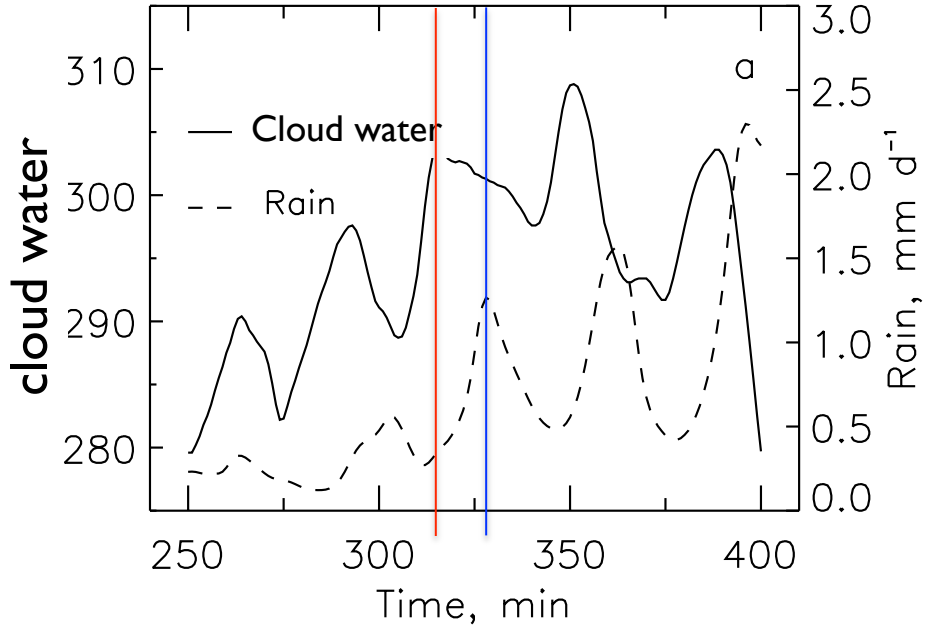
Koren and Feingold 2013

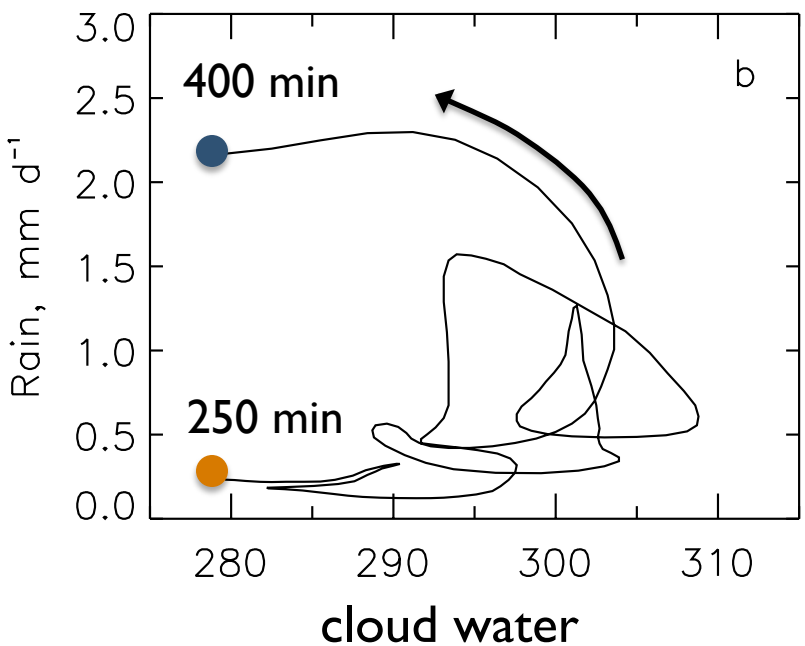
Open Cell Rearrangement vs. Closed Cell 'Rigidity'

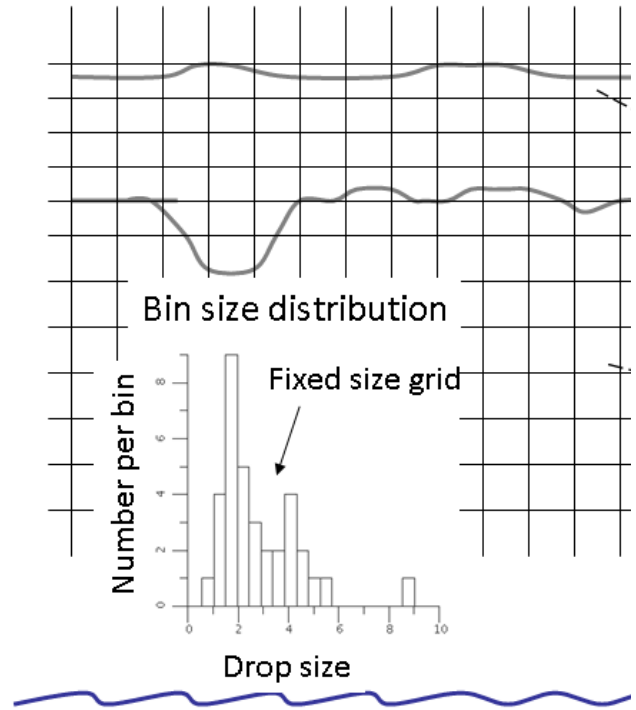


Koren and Feingold 2013

Oscillations in Large Eddy Simulation of Aerosol-Cloud-Precipitation







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

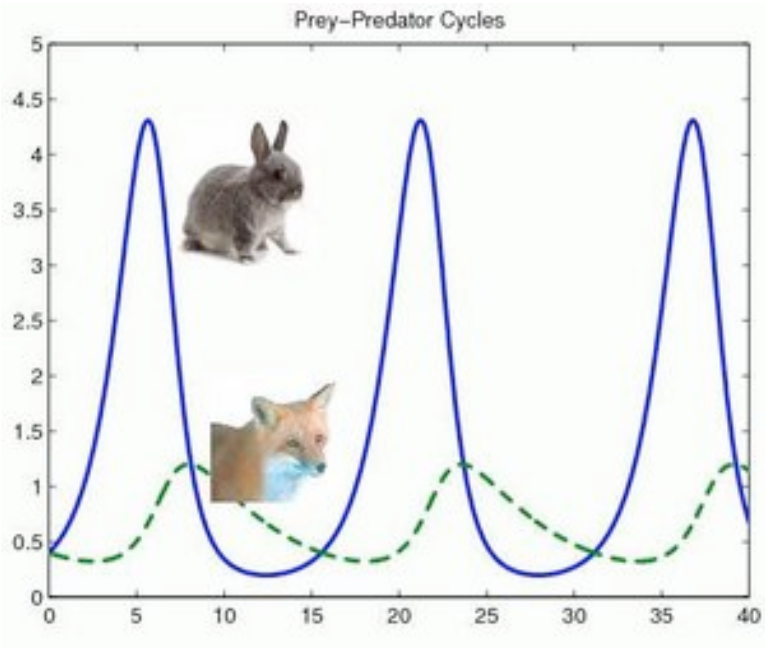
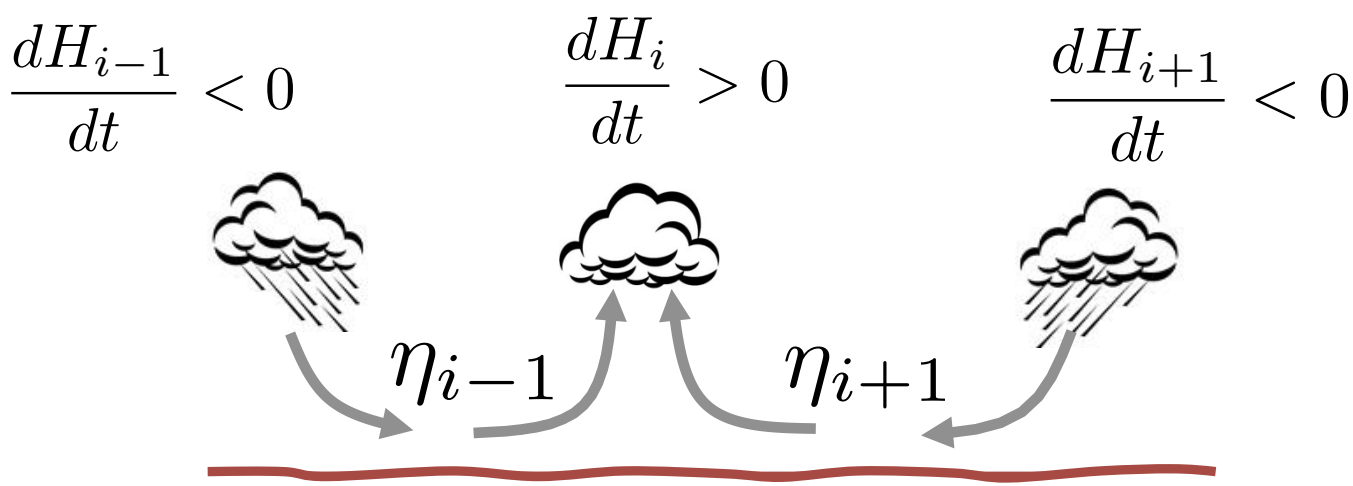


Image courtesy of Wikipedia

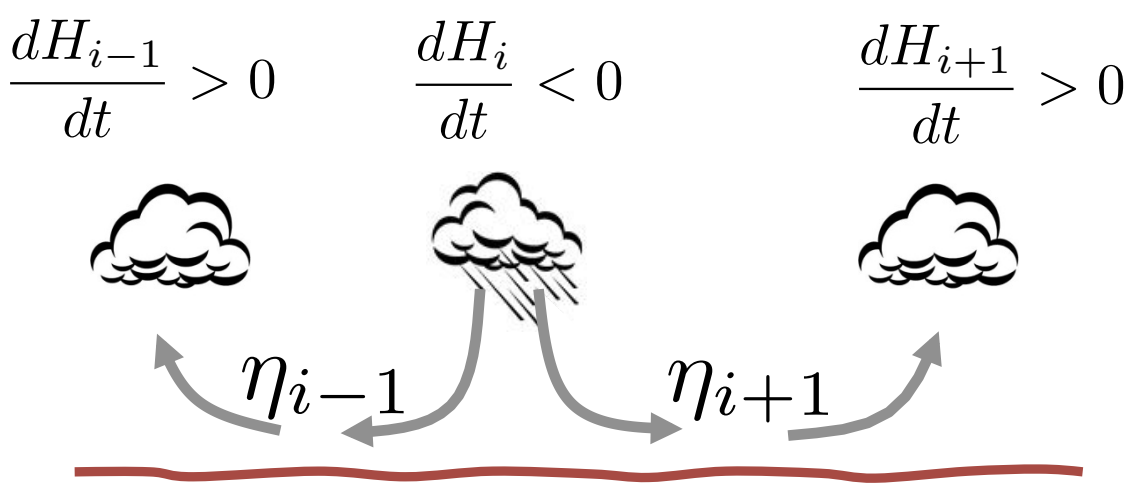
4 parameters:
$\alpha, \beta, \gamma, \delta$

System of coupled oscillators



η = coupling strength

Convergence



Divergence

Feingold and Koren, NPG 2013

System of coupled cloud 'metronomes'

$$\frac{\mathrm{d}H_{i,j}}{\mathrm{d}t} = \frac{H_{0,i,j} - H_{i,j}}{\tau_1} - \frac{\alpha H_{i,j}^2}{c_1 N_{i,j}}$$

$$+ \sum_{m \neq i}^{I} \sum_{n \neq j}^{I} \eta_{m,n} \dot{H}_{m,n}(t - \tau_{\mathrm{c},m,n})$$

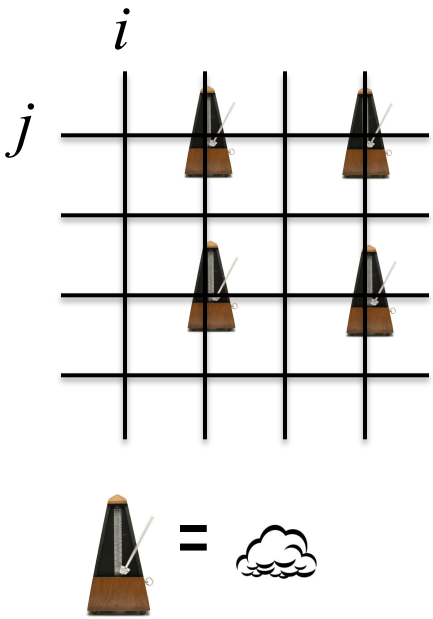
Coupling term (**delay** due to distance between clouds)

$$\frac{\mathrm{d}N_{i,j}}{\mathrm{d}t} = \frac{N_{0,i,j} - N_{i,j}}{\tau_2} - c_2 N_{i,j} R_{i,j}$$

and

$$R_{i,j}(t) = \frac{\alpha H_{i,j}^3 (t - T)}{N_{i,j}(t - T)},$$

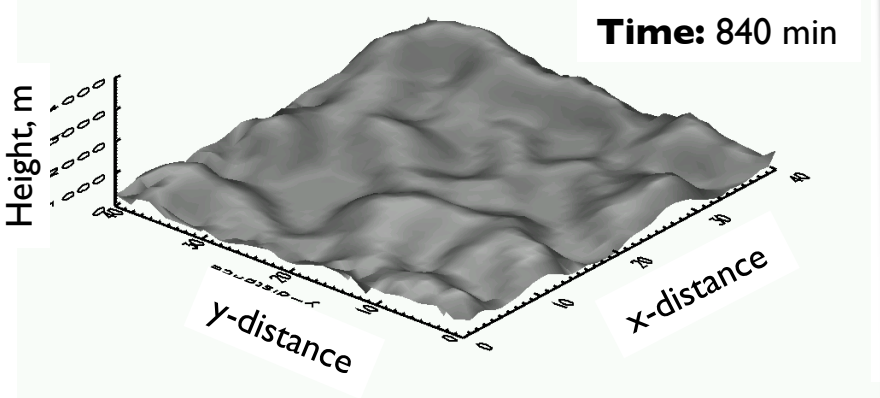
Microphysical **delay**

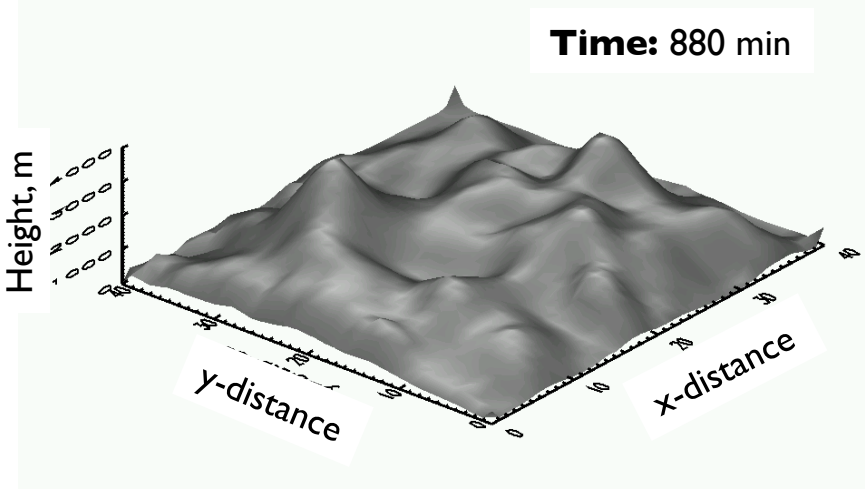


$\eta_{m,n}$ = coupling strength

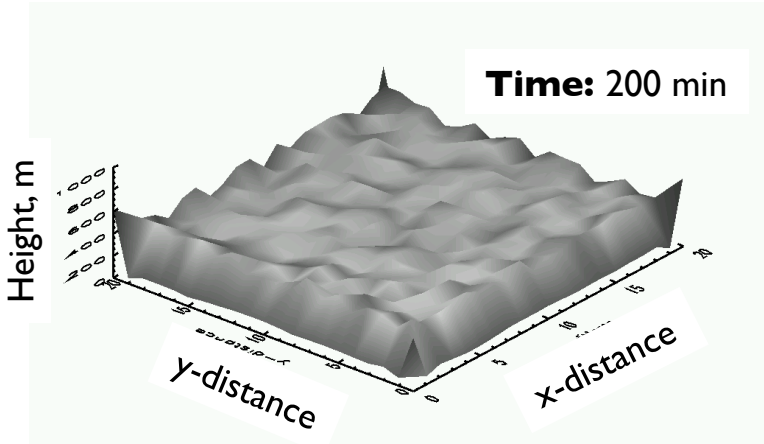
Feingold and Koren, NPG 2013

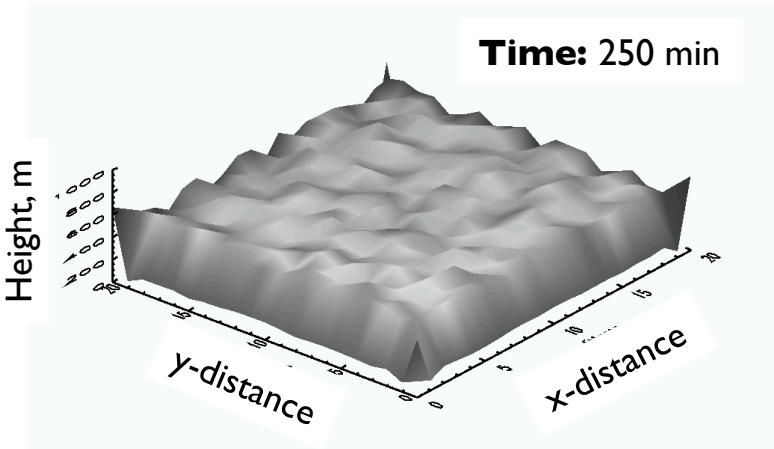
Open cells





Closed cells

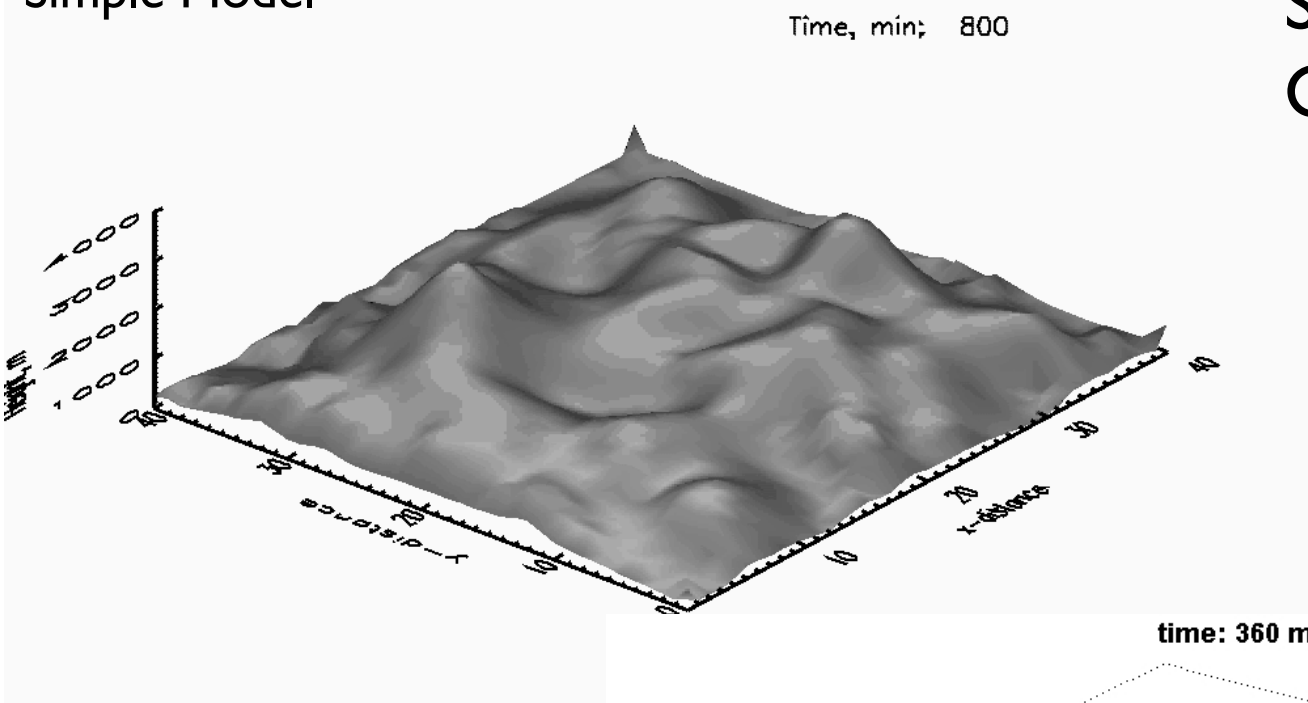




Feingold and Koren, NPG 2013

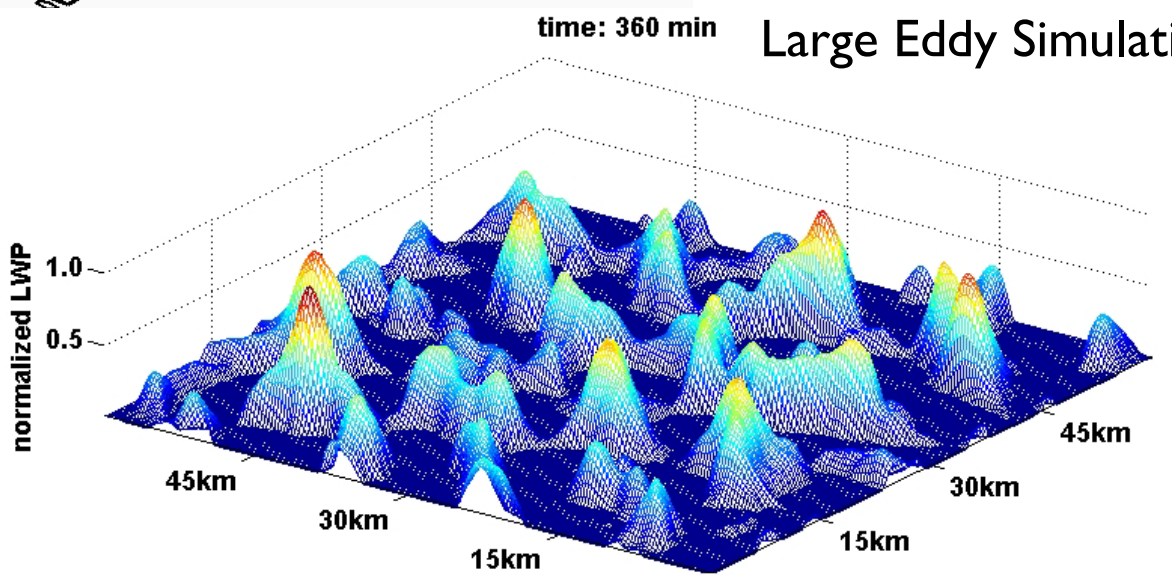
Synchronization of Coupled Oscillators

Simple Model



Feingold and Koren, NPG 2013

Large Eddy Simulation

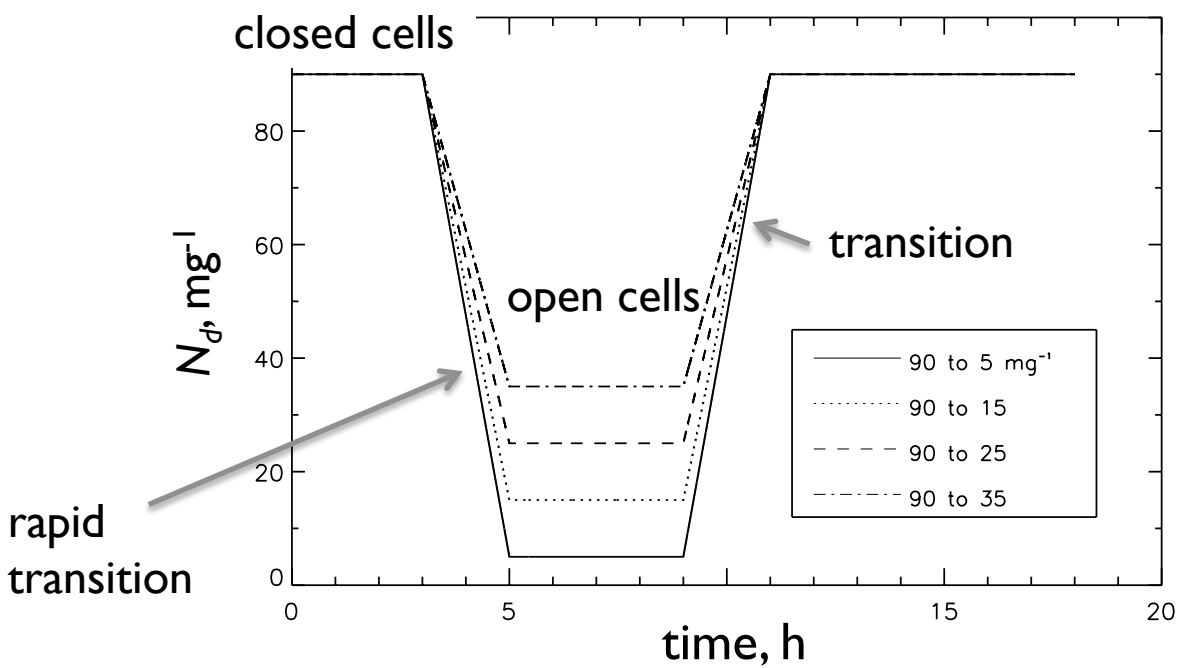


Feingold, Koren, Wang, Xue, Brewer (2010)

What about Open → Closed Transitions?

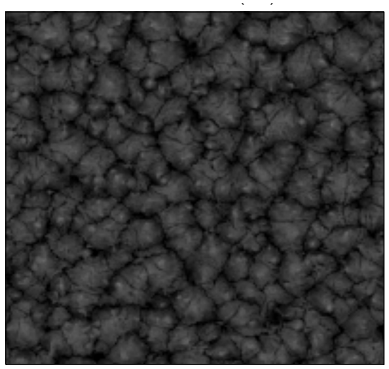
Cloud Resolving Modeling

- System for Atmospheric Modeling (SAM)
- DYCOMS-II RF02 (Drizzling case)
- Warm phase, two-moment bulk
- Mesoscale structures in large domains (40 km x 40 km)
- Grid size: $\Delta x = \Delta y = 200$ m; $\Delta z = 10$ m; $\Delta t = 1$ sec; T = 18 h
- <u>Prescribed variation in the drop concentration</u>

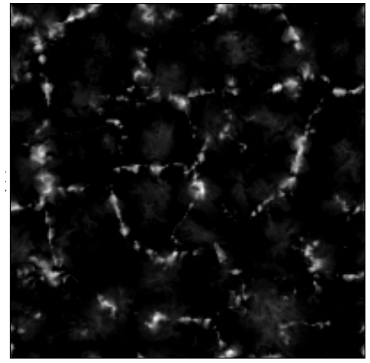


Feingold, Koren et al. 2015

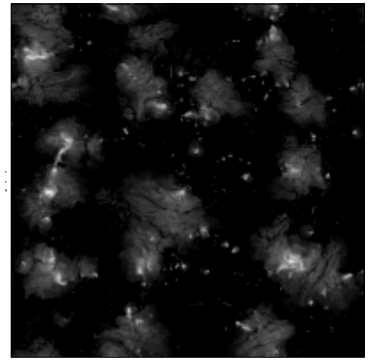
Results



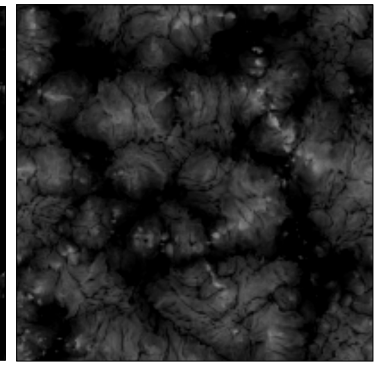
Closed cells soon after initiation



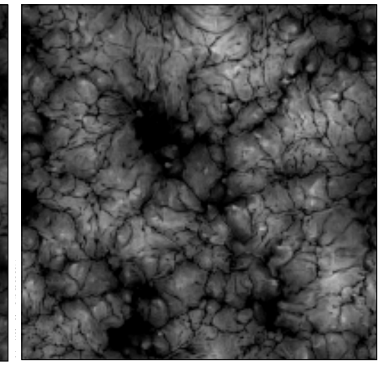
Open cells: raining period



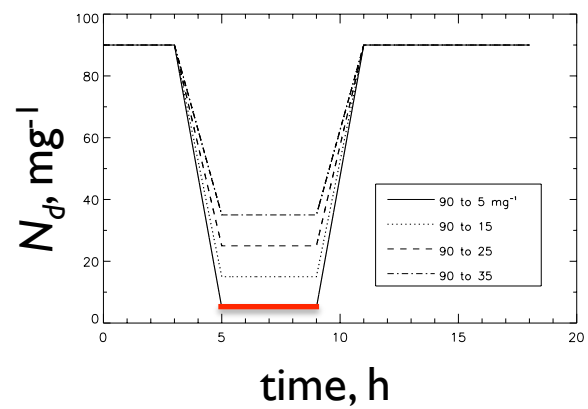
Beginning of recovery period: formation of "anvils"



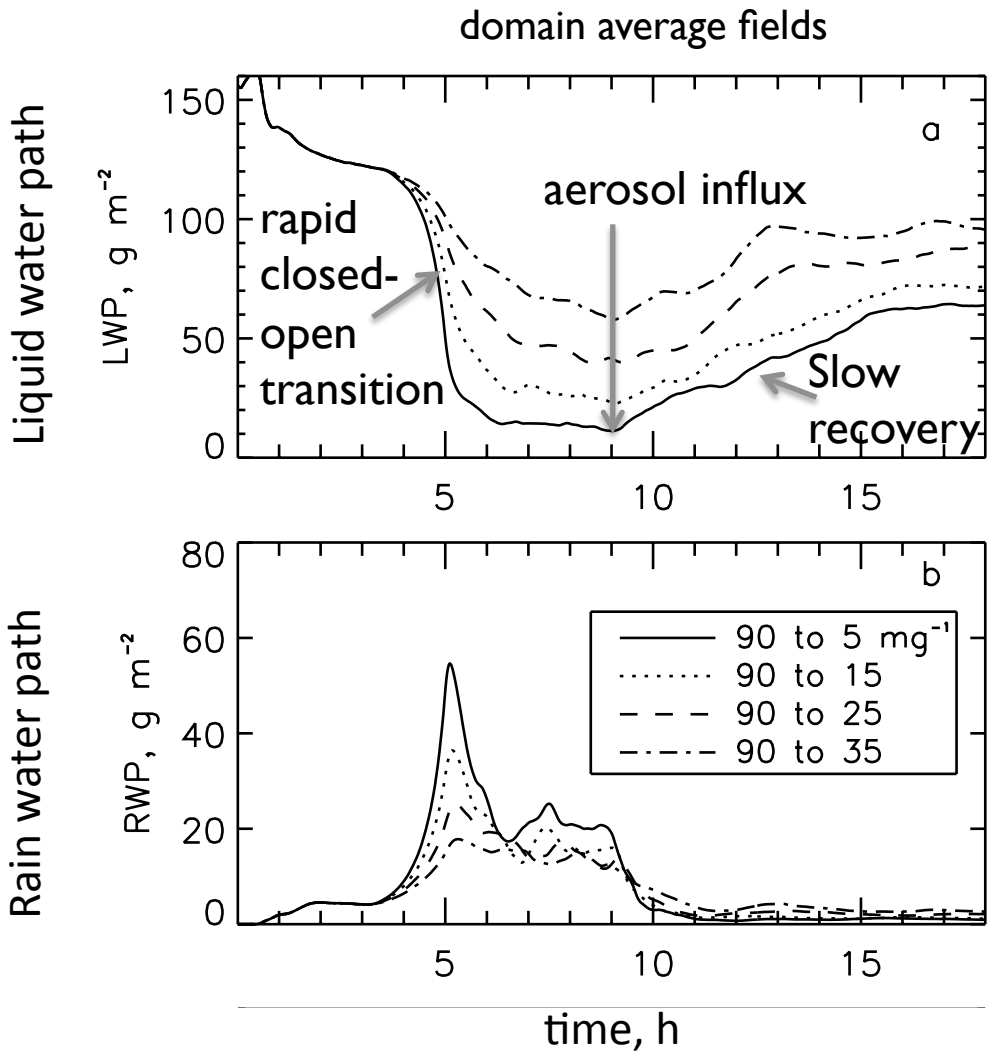
Further recovery



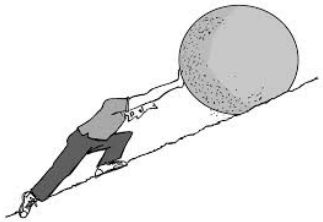
t=18 h



Some Time Series



- Rapid transition from closed to open
- Slower recovery
- Asymmetry in recovery is more pronounced for stronger rain
- Strong rain event associated with loss of LWP
- Rain persists even after N has fully recovered



Summary

- Cloud Systems often choose one of two states: closed and open cells
  - The aerosol can determine the state (via precipitation)

- Cloud system described as a predator-prey system
  - Closed cells are in approximate steady state
  - Open cells rearrange periodically

- A system of coupled oscillators demonstrates key characteristics produced by LES

- The asymmetry in the closed-open-closed transition is related to the stabilization caused by the rain