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

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Pocket of open cells
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)
Emergence: system-wide patterns emerge from local interactions between elements that make up the system.
From Microphysics to Emergence

**Microphysical Rules:**

Rules of interaction between drops and their environment

- Condensation on nuclei
- Drop collision-coalescence
- Sedimentation and evaporation

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

+ continuity of fluid motion

M. Garay
Self-Organizing Cloud States

Identical initial conditions except for aerosol

Satellite images (M. Garay)

Wang and Feingold (2009)
Rayleigh-Bénard Convection

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

- \( \Delta T \) = temperature difference between surfaces
- \( \alpha \) = thermal expansion coefficient
- \( g \) = gravitational acceleration
- \( h \) = separation between the surfaces
- \( \nu \) = kinematic viscosity
- \( \chi \) = thermal diffusivity
“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

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

Precipitation is initiated

Downdrafts, opening of cell

Surface divergence

Feingold, Koren, Wang, Xue, Brewer (2010)
Rearrangement of Open Cells

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

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
Predator-Prey Model

Lotka-Volterra Equations
(circa 1926)

\[ \frac{dx}{dt} = x(\alpha - \beta y) \]
\[ \frac{dy}{dt} = -y(\gamma - \delta x) \]

\( x = \text{prey} \)
\( y = \text{predator} \)

4 parameters:
\( \alpha, \beta, \gamma, \delta \)
System of coupled oscillators

\[
\begin{align*}
\frac{dH_{i-1}}{dt} &< 0 \\
\frac{dH_i}{dt} &> 0 \\
\frac{dH_{i+1}}{dt} &< 0
\end{align*}
\]

Convergence

\[
\begin{align*}
\frac{dH_{i-1}}{dt} &> 0 \\
\frac{dH_i}{dt} &< 0 \\
\frac{dH_{i+1}}{dt} &> 0
\end{align*}
\]

Divergence

\(\eta = \text{coupling strength}\)

Feingold and Koren, NPG 2013
System of coupled cloud 'metronomes'

\[
\frac{dH_{i,j}}{dt} = \frac{H_{0,i,j} - H_{i,j}}{\tau_1} - \frac{\alpha H_{i,j}^2}{c_1 N_{i,j}} + \sum_{m \neq i} \sum_{n \neq j} \eta_{m,n} \dot{H}_{m,n}(t - \tau_{c,m,n})
\]

\[
\frac{dN_{i,j}}{dt} = \frac{N_{0,i,j} - N_{i,j}}{\tau_2} - c_2 N_{i,j} R_{i,j}
\]

and

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

\[\eta_{m,n} = \text{coupling strength}\]

Coupling term (delay due to distance between clouds)

Microphysical delay

Feingold and Koren, NPG 2013
Open cells

Time: 840 min

Time: 880 min

Closed cells

Time: 200 min

Time: 250 min

Feingold and Koren, NPG 2013
What about Open $\rightarrow$ 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
- Prescribed variation in the drop concentration

![Diagram showing open and closed cells with a rapid transition]

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

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<th>$N_d, \text{ mg}^{-1}$</th>
<th>time, h</th>
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</table>
Some Time Series

domain average fields

- 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