Chapter 3
Convective Dynamics
3.3. Multicell Storms – Part II

Cell Regeneration in 2D multicell storms

• Representative modeling studies


Model simulated 2D-multicell storm

(Lin and Joyce 2001, JAS)

Summary of life cycle

Based on Lin et al 1998.

Formation and maintenance of the gust front updraft (GFU)

Rearward advection of the growing GFU

Cutting off of the growing cell (c1) from the GFU by the upstream compensating downdraft

Cell generation and coexistence of the growing (c2 and c3) and propagating (c1) cells

Based on Lin et al 1998.

In Lin et al (1998), the following processes are believed to repeat for cell regeneration (see previous illustration).

• (i) Near the edge of the gust front, the gust front updraft is formed by the low-level convergence ahead of the gust front near the surface.

• (ii) The upper portion of the gust front updraft grows by feeding on the midlevel inflow since the gust front propagates faster than the basic wind, creating mid-level as well as low-level convergence.

• (iii) The growing cell \((C_1)\) produces strong compensating downdrafts on both sides. The downdraft on the upstream (right) side cuts off this growing cell from the gust front updraft.

• (iv) The period of cell regeneration is inversely proportional to the midlevel, storm-relative wind speed.

Numerical Experiments in support of Lin et al’s conceptual model
(a) Skew-$T$ plot of the temperature and dewpoint profiles used in the simulations. This is a smoothed version of the 1430 HNT 22 May 1976 sounding presented in Ogura and Liou (1980). (b) Wind profiles used to initialize the simulations (from Lin et al 1998).

Life Cycle of simulation 2D-multicell storm

Vertical cross sections of vertical velocity (thin contours in intervals of 1 m s$^{-1}$) for the $U = 10$ m s$^{-1}$ case.

The cold pool / density current may be roughly represented by the 1 K potential temperature perturbation contour (bold dashed) near the surface.

The rainwater is shaded (>0.0005 g kg$^{-1}$) and the cloud boundary is bold contoured (>0 g kg$^{-1}$). The corresponding integration time is shown at the top of each panel (from Lin 1998).
Time-space plot of $w$ at $z=2.5$ km for various wind profiles

All of the storms simulated produce cells in a periodic fashion.

The regeneration periods are 9.0, 9.6, 10.1, 11.3, and 12.1 min for cases $U = 7.5, 10, 12.5, 15, \text{ and } 20 \text{ m s}^{-1}$, respectively.

The larger-shear cases have weaker front-relative inflow at the lower-mid level, i.e., the rearward advection is weaker, leading to slower separation of the cells from GFU, therefore longer periods.

Fig. 3. Time-space plot of vertical velocity at $z=2.5$ km for the various cases. The base state wind-speed at $z=2.5$ km is given in the upper right-hand corner of each plot. Contour interval is 4 m s$^{-1}$. Positive (negative) values are solid (dashed). Panel (a)-(e) show cases with $\Delta U = 7.5, 10, 12.5, 15, \text{ and } 20 \text{ m s}^{-1}$, respectively.

(a) Cell regeneration period (y axis) vs the far upstream storm relative midlevel inflow (SRMLI) speeds for the profile shown in Fig. 3 (curve a). The $U$ (in m s$^{-1}$) is shown beside its corresponding point. (b) Same as (a) except 2.5–5.5-km layer averaged near-storm SRMLI (curve b).

Therefore, the cell regeneration period decreases almost linearly as the midlevel inflow speed increases.

Stronger SRMLI allows faster separation of cells from GFU, therefore shortens the cell regeneration period

Fig. 6. (a) Cell regeneration period (y axis) vs the far upstream storm relative midlevel inflow (SRMLI) speeds for the profiles shown in Fig. 3 (curve a). The $\Delta U$ (in m s$^{-1}$) is shown beside its corresponding point. (b) Same as (a) except 2.5–5.5-km layer averaged near-storm SRMLI (curve b).
Life Cycle of Simulated Storm according to Lin et al 1998

- The life cycle of an individual cell for the above case:
- First, the GFU begins to expand vertically (e.g., at $t = 252$ min), signaling the release of a new convective cell, which occurs at an interval of 9.6 min in this particular case.
- As the new cell moves rearward relative to the gust front, compensating downdrafts begin to form on either side. This aids its separation from the gust-front updraft (GFU), after which the cell strengthens and begins to precipitate as it moves into the modified air at the rear of the system.
- The cell begins to split at low levels, which appears to be the results of rainwater loading.
- Subsequently, another cell develops at the GFU. Due to its supply of less buoyant low-level air being cut off by this new cell, the mature updraft weakens, releases all of the rain that has been collecting in it at midlevels, and continues to dissipate as it enters the trailing stratiform region.
- The process then repeats itself, leading to a series of cell growth and decay, characteristic of the strong evolution model, that is, classic multicell storm.

Summary of Lin and Joyce (2001) paper

- The paper further investigated the mechanisms of cell regeneration, development, and propagation within a two-dimensional multicell storm proposed by Lin et al (1998).
- Their advection mechanism was reexamined by performing simulations utilizing a plateau with five additional wind profiles having a wider range of shear. All five cases gave results that show that the cell regeneration period decreases with the storm-relative midlevel inflow, similar to that proposed by Lin et al (1998).
- Numerical experiments in this paper that used a different thermodynamic sounding were found to also support the advection mechanism.
- It was found that without precipitation loading, an individual cell is still able to split. In this case, the compensating downdraft produced by vertical differential advection is responsible for cell splitting and merging.
Cell Regeneration theory of Fovell et al

- Fovell and Tan (1998, MWR) also examined the cell regeneration problem using a numerical model.

- They noted that the unsteadiness of the forcing at the gust front is one reason why the storm is “multicellular”. The cells themselves “feed back” to the overall circulation.

- The multicellular storm establishes new cells on its forward (upstream) side, in the vicinity of the forced updraft formed at the cold pool boundary, that first intensify and then decay as they travel rearward within the storm’s upward sloping front-to-rear airflow.

- The cells were shown to be convectively active entities that induce local circulations that alternately enhance and suppress the forced updraft, modulating the influx of the potentially warm inflow.

- An explanation of the timing of cell regeneration was given that involves two separate and successive phases, each with their own timescales.

Introduction of Fovell and Tan (1998)

1. Introduction

The mature squall line often appears as a narrow, quasi-linear band of intense convection trailed by a wider zone of light precipitation. Prominent in its circulation is an ascending “front-to-rear” (FTR) jet (Houze 1993, 348), largely consisting of air drawn from the low-level environmental inflow, that resides above a subcloud cold-air pool maintained by the evaporation of hydrometeors falling from the jet. The cold pool spreads along the surface, and convergence at its leading edge, or gust front, creates the forced updraft that provides the initial lift required by the potentially warm inflowing air parcels to reach their level of free convection (LFC).

The overall quasi-steady dynamics of the squall-line storm are now fairly well understood (see survey by Houze (1993)). The FTR airflow itself, however, is rarely steady. Instead, convective “cells,” short-lived discrete elements representing locally concentrated convective activity, are often found embedded within. New cells typically form on the storm’s forward side, in or near the forced updraft, and subsequently travel rearward within the FTR jet, ultimately to be replaced by another cell. The cell life cycle, comprising initiation, maturation, and decay, typically spans an hour or less (Browning et al. 1976). A cross section normal to the squall line reveals a “multicellular” family of cells, each representing a different stage in the life cycle. As the longevity of the multicellular storm seems largely due to its ability to generate new, replacement cells, the cell life cycle and generation mechanisms involved in new cell establishment are important topics for study.

The cell life cycle has been shown to be sensitive to a wide variety of factors, including (but not limited to) the amount and distribution of vertical wind shear (Thorpe et al. 1982; Dudhia et al. 1987; Fovell and Ogura 1989; and Fovell and Dailey 1995) and model microphysics (Fovell and Ogura 1988). It has often been noted that new cells tend to form in or near the gust front’s forced updraft, but not until previously established cells have moved rearward within the FTR airflow. This has sometimes been interpreted as a horizontal advective timescale (Miller 1978; Thorpe et al. 1982; Wilhelmson and Chen 1982; Fovell and Ogura 1989), though this raises the questions of how and why cells become discrete (or “cut off”) from the forced lifting as well as how and when new cells will form. Hane et al. (1987), for example, hypothesized that periodic convergence enhancement at the gust front, caused by the spreading of the previous cell’s downdraft along the surface, could represent one controlling factor influencing the timing of new cell generation. Wilhelmson and Chen (1982), on the other hand, discounted this relationship.
Recently, Yang and Houze (1995, hereafter YH) interpreted the convective cells as being manifestations of vertically trapped, rearward propagating gravity waves. In their view, the cutoff process is a transient gravity wave response to the forced updraft’s nearly steady forcing, and rearward cell propagation can be described in terms of gravity wave phase speeds. This interpretation was based on their observation that convective cell updrafts come to acquire the typical signatures of rearward propagating gravity waves, which include a “quadrature” phase relationship between local warming (positive potential temperature perturbation) and upward motion, with the former leading (i.e., rearward of) the latter by one-quarter wavelength in the direction of the wave’s motion.

This study examines the convective cell life cycle and the cutoff process, including factors influencing subsequent new cell generation. In the simulations presented herein, the convective cells themselves do not behave as gravity waves until they (or remnants thereof) have become convectively inactive. That occurs late in the life cycle when the cells have passed into the storm’s trailing region, far from the leading edge of the storm. By that time, new cell development has usually already occurred at the storm’s leading edge. Instead, the cutoff process will be shown to result from the cell’s own induced local circulation that also causes the episodic mixing of stable air into its inflow. This mixing erodes the cell’s convective instability, and thus the cell effectively sows the seeds of its own demise. As they mature, the cells do eventually manifest quadrature phasing between local warming and upward motion, but this is due to the detrainment of the cell’s original, least diluted, and thus most positively buoyant air. The cell’s own induced circulation not only undermines the cell itself, but also appears to help hasten the next convective development.

Simulation using the same thermodynamic sounding as the study of Lin et al (Fovell and Tan 1998)

Vertical velocity $w$ (2 m/s contours) and potential temperature perturbation (shaded) fields for a 50 km × 10 km subdomain at four times during one cell generation cycle for the 2D simulation.

Negative contours are dashed and the zero contour is omitted. For $\theta$, contours (interval 2 K) are included for negative values less than or equal to 2 K only (Fig.1 of Fovell and Tan 1998).

During this mature phase, the storm’s ground relative motion was eastward at 15.3 m s$^{-1}$ and it generated new cells at approximately 11-min intervals in a simple periodic fashion.
Time series illustrating the forced updraft’s temporal variation for the 2D simulation spanning a period incorporating the four times (labeled A–D) depicted in the previous figure.

The forced updraft strength was persistent yet unsteady, fluctuating by several meters per second during the cell cycle.

Variation of the forced updraft as a manifestation of a convective feedback process

- Pressure field induced by perturbation buoyancy (derived from u and w momentum equations):
  \[ \nabla^2 p^* = \frac{\partial (\gamma B^* \partial)}{\partial z} \]

- Equation of the horizontal component of vorticity (in the x-z plane), neglecting friction,
  \[ \eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} = \text{horizontal vorticity in y direction} \]
  \[ \frac{d\eta}{dt} = -\frac{\partial B^*}{\partial x} \]

- We call generation of horizontal vorticity by horizontal gradient of buoyancy the baroclinic generation of vorticity
Schematic illustrating the effect of an individual convective cell on the storm’s low-level circulation

- Panel (a) shows the BPGA (buoyancy pressure gradient acceleration) vector field associated with a finite, positively buoyant parcel.

- Panel (b) shows the full $F_b$ field and the circulatory tendency associated with baroclinic vorticity generation.

- Panel (c) presents an analysis of the circulation tendency at the subcloud cold pool (stippled region) boundary.

- Panel (d) adds a positively buoyant region with its attendant circulatory tendency, illustrating the initial formation of a convective cell.

- Panel (e) shows the cell’s effect at a subsequent time (Fig. 10 of Fovell and Tan 1998).

The influence of transient cell’s circulation on new cell generation

- At first, the positively buoyant air created by latent heating within the incipient cell is located above the forced updraft, as depicted in Fig. 10d.

- The new cell’s circulation enhances the upward acceleration of parcels rising within the forced updraft while partially counteracting the rearward push due to the cold pool’s circulation.

- As a result, the forced lifting is stronger and parcels follow a more vertically oriented path than they would have been able to without the condensationally generated heating.
The influence of transient cell’s circulation on new cell generation

- The influence of the transient cell’s circulation depends on its phasing relative to the forced updraft.

- When the cold pool circulation dominates, the new cell and its positive buoyancy will be advected rearward.

- As it moves away from the forced updraft, the intensifying cell soon begins to exert a deleterious effect on the low-level lifting, as depicted in Fig. 10e.

- Instead of reinforcing upward accelerations in the forced lifting, the new cell is assisting the cold pool circulation in driving the rising parcels rearward. Thus, at this time, the forced lifting is weaker than it would have been in the absence of convection.

- As the cell continues moving rearward, its influence wanes, permitting the forced updraft to reintensify as the suppression disappears.

Three stages in life cycle of a convective cell

Stage 1 (initiation of cell)
Buoyancy-induced circulation helps new cell rise, strengthen. Potentially warm air ingested from below.
Rise of cell establishes ribbon of potentially warm air in FTP airflow emanating from low-level storm inflow.

Stage 2 (maturation of cell)
Growing cell’s buoyancy-induced circulation acts to weaken forced lifting, reduce potentially warm inflow.
Stable, potentially cold air mixes into cell’s inflow from wake beneath, eroding its convective instability.
Cell’s original, least diluted air concentrated near top of updraft. In 3D simulation, cell dynamically splits.

Stage 3 (dissipation of cell)
Cell’s buoyancy-induced circulation on front-facing flank weakens as mixing erodes instability. Cell "splinters" and disorganizes.
During disorganization, original, least diluted air effectively "detained" from splintered updraft, spreading about (above and to sides) of updraft shown. In consequence, on rear-facing side, buoyancy-induced circulation acts to dissipate rear-facing flank of updraft, slowing cell’s rearward propagation.

Cell Regeneration in 2D multicell storms

- The three stages of a convective cell.

- Equivalent potential temperature (shaded) and vertical velocity (contoured) fields were taken from Fig. 3. Note the reference, frame shown is not fixed in space, but rather tracks the cell’s principal updraft.

- For more details, read Fovell and Tan (1998). Link to the PDF format paper is found at the course web site.
Summary on Cell Regeneration Theories

- Looked harder, the two theories are more complementary than contradictory. Both examine the rearward movement of older cells and the separation of the cell from the new cells.

- Lin et al focus on the environmental condition that affects the rearward cell movement then on the associated cell regeneration.

- Fovell’s work emphasizes cell and cold pool interaction and the associated gust-front forcing/lifting. The change in the gust-front lifting is considered to play an important role in modulating the intensity and generation of new cells at the gust front.

- Hence, Lin et al’s work looks to the external factor while Fovell et al’s work looks to the internal dynamics for an explanation of the multi-cellular behavior—in my opinion—each is looking at a different but complementary aspect of the problem.