Chapter 3
Convective Dynamics
(Part II)

3.3. Multicell Storms
Multicell Storm

- Multicell cluster storm - A group of cells moving as a single unit, with each cell in a different stage of the thunderstorm life cycle. Multicell storms can produce moderate size hail, flash floods and weak tornadoes.

- Multicell Line (squall line) Storms - consist of a line of storms with a continuous, well developed gust front at the leading edge of the line. Also known as squall lines, these storms can produce small to moderate size hail, occasional flash floods and weak tornadoes.

Multicell Storm Weather

Multicell severe weather can be of any variety, and generally these storms are more potent than single cell storms, but considerably less so than supercells, because closely spaced updrafts compete for low-level moisture.

Organized multicell storms have the higher severe weather potential, although unorganized multicells, which are simply conglomerates of single cells, can produce pulse storm-like bursts of severe events.

**MULTICELL CLUSTER STORM**

- Severe weather occurs as downbursts...moderate-size hail....flash floods....and weak tornadoes
- Severe events more frequently occur near the updraft/downdraft interface which, in order of occurrence, is on the rear (southwest) and front (east) storm quadrants
- Moderate degree of predictability of severe events
- Moderate danger to public; Moderate to high danger to aviation
Multiple Cells Seen by Radar

- Radar often reflects the multicell nature of these storms, as seen with the central echo mass and its three yellowish cores in the lower portion of this photo.

- Occasionally, a multicell storm will appear unicellular in a low-level radar scan, but will display several distinct tops when a tilt sequence is used to view the storm in its upper extremities.

Life Cycle of Multicell Storms

Figure 10.2. Vertical section of an ordinary multicell hailstorm, along the storm's direction of travel through a series of evolving cells \( (n-2, n-1, n, n+1) \). The solid lines are streamlines of flow relative to the moving system; on the left their broken ends represent flow into and out of the plane, and on the right they represent flow remaining within a plane a few kilometers closer to the reader. Light shading represents the extent of the cloud, and the three darker shades represent radar reflectivities of 35, 45, and 50 dBZ. (From Browning et al., 1978.)
Life cycle - evolution of cells in a multicell cluster

This illustration portrays a portion of the life cycle of a multicell storm.

As cell 1 dissipates at time = 0, cell 2 matures and becomes briefly dominant. Cell 2 drops its heaviest precipitation about 10 minutes later as cell 3 strengthens, and so on.

• A closer view at T = 20 minutes (from in the earlier slide) shows that cell 3 still has the highest top, but precipitation is undercutting the updraft in the lower levels. New echo development is occurring aloft in cells 4 and 5 in the flanking line, with only light rain falling from the dissipating cells 1 and 2 on the northeast side of the storm cluster.

• The inset shows what the low-level PPI radar presentation might look like. This storm appears to be unicellular but the several distinct echo tops tell us otherwise.
Here is a real storm, with radar superimposed. Observe the physical similarities to the second slide. This Texas Panhandle storm was non-severe. Looking north-northeast from about 20 miles. Note that the updraft numbering is reversed.

Cell Motion versus Storm Motion

- Cells inside a storm (system) do not necessarily move at the same speed and/or direction as the overall storm system.
- The storm system can move as a result of the successive growth and decay of cells.
- It can also move because the cell motion.
- Environmental winds can have significant influence on the cell and/or storm movement, but they do not necessarily follow the wind.

Figure 16.3. Schematic diagrams of the (a) Wingham, (b) Albemarle, and (c) Rimley storms, demonstrating the concept of cell motion as opposed to storm motion in an organized multicell storm system. (From Mewhirz, 1972.)
The growth of a multicell storm

Time (0-21min)

Height (3-12km)

Figure 3.1: Illustration of the growth of a multicell thunderstorm. (a) Vertical cross section from the northeast-southwest of a typical eastward-moving multicell hailstorm in South Dakota showing “daughter” clouds on the storm’s right flank. New cells form to the southwest, develop radar-detectable precipitation aloft, and then a deep radar echo; figure is in a sense a look at different stages in the life of a thunderstorm cell. Cloud (stippled area); radar reflectivity in dBZ (solid lines). (After Dennis et al., 1970; from Browning, 1977). (b) Schematic horizontal (above) and vertical (below) radar reflectivity contours in dBZ (solid lines) for an ordinary multicell storm at various stages during its evolution. Cell motion (arrow); cell 3 is shaded to emphasize the history of an individual cell (from Chisholm and Kenick, 1972; Browning, 1977). (Courtesy of the American Meteorological Society)

Cell Regeneration in Multicell storms

- Before we discuss the cell regeneration in multicell storms, we will first look the gust front dynamics, which plays an important role in long-lasting convective systems.
A Schematic Model of a Thunderstorm and Its Density Current Outflow

Downdraft Circulation - Density Current in a Broader Sense

(Simpson 1997)

Role of cold pool in a convective storms

At the surface, the cold pool propagates in the form of density or gravity current
In the Atmosphere - Thunderstorm Outflow

The Gust front propagates along the surface in the form of density or gravity current

A density current, or gravity current, is a region of dense fluid propagating into an environment of less dense fluid because of the horizontal pressure gradient across the frontal surface.

\[ c = k \left( \frac{\Delta p}{\rho} \right)^{1/2} \]
In the Laboratory

In Nature
(Lava flow on Surtsey, Iceland 1963)
Schematic of a Thunderstorm Outflow
(Goff 1976, based on tower measurements)

Gust Front / Density Current Dynamics

• Book section to read: Houze, Pages 313-319.

We will look at the following aspects of density current at this time:

• Propagation speed of gust/density current front
• Pressure perturbation underneath the cold pool/density current
• Pressure perturbation ahead of gust front
• Pressure perturbation associated with vertical (rotor) circulations
The propagation of gust front

- The low-level-inflow-relative speed of gust front often to a large extend determines the propagation of the storm system. This is almost certainly true for 2-D squall lines. Therefore the determination of gust front speed is important.

- Gust/density current propagates due to horizontal pressure gradient across the front – created mainly by the density difference across the front.

Gust Front Propagation Speed – How to determine it?

- For an idealized density current shown above, we apply simple equation
  \[ \frac{du}{dt} = \frac{1}{\rho_0} \frac{\partial \rho'}{\partial x} \]

- What have we neglected? Friction, Coriolis effect, effect of vertical motion

- Now, to simplify the problem, let’s look at the problem in a coordinate system moving with the gust front. In this coordinate system, the density current/gust front is stationary, and the front-relative inflow speed is equal to the speed of the gust front propagating into a calm environment.

- We further assume that the flow is steady in this coordinate system, a reasonably valid assumption when turbulent eddies are not considered. Therefore
  \[ \frac{\partial}{\partial t} = 0 \Rightarrow \frac{\partial}{\partial x} \left( \frac{du}{\rho} \right) = \frac{1}{\rho_0} \frac{\partial \rho'}{\partial x} \]
Gust Front Propagation Speed

- Integrate the above equation along a streamline along the lower boundary from far upstream where \( u = U \) and \( p' = 0 \) to a point right behind the gust front where \( u = 0 \) and \( p' = \Delta p \):

\[
\frac{U^2}{2} = \frac{\Delta p}{\rho_o} \Rightarrow \ U = \sqrt{\frac{2\Delta p}{\rho_o}}
\]

- The above is the propagation speed of the gust front as related to the surface pressure perturbation (\( \Delta p \)) associated with the cold pool/density current.

- The above formula is most general. The contributions to the surface pressure perturbation from cold pool, upper-level heating, nonhydrostatic effect (vertical acceleration) and dynamic pressure perturbation can all be included.

Gust Front Propagation Speed

- If we assume that the \( \Delta p \) is purely due to the hydrostatic effect of heavier air/fluid (\( \rho = \rho_o + \Delta \rho \)) inside the cold pool of depth \( h \) (other effects as listed in previous slide are neglected), the above formula can be rewritten as (assuming pressure perturbation above the cold pool is zero):

\[
U = \sqrt{\frac{2g\Delta \rho}{\rho_o} h}
\]

because \( \int_{h}^{\infty} \frac{dp'}{\rho_o} dz = \int_{h}^{\infty} g\frac{\Delta \rho}{\rho_o} dz = 0 - \Delta p = -g\frac{\Delta \rho}{\rho_o} h \)

- In this case, the speed of density current is mainly dependent on the depth of density current and the density difference across the front, not a surprising result.

- When other effects are included, the speed can be somewhat different. But it is generally correct to say that deeper and/or heavier (colder) current/cold pool propagates faster.
Pressure perturbations ahead of the gust front

- In the previous idealized model in the front-following coordinate, the inflow speed decreases to zero as the air parcel approaches the front from far upstream. There must be horizontal pressure gradient ahead of the gust front to de-accelerated the flow. There must by positive pressure perturbation ahead of the gust front and this positive pressure perturbation has to be equal to that produced by cold pool.

- We can rewrite the earlier equation as

\[
\frac{\partial u^2}{\partial x} - \frac{1}{\rho_0} \frac{\partial p'}{\partial x} = \frac{1}{\rho_0} \left[ \frac{u^2}{2} + \frac{p'}{\rho_0} \right] = 0 \Rightarrow \frac{u^2}{2} + \frac{p'}{\rho_0} = C
\]

\[
\frac{u^2}{2} \frac{p'}{\rho_0} \text{ is constant along the streamline following the lower boundary.}
\]

Pressure Perturbations according to the Bernoulli Principle

- The Bernoulli energy conservation or the Bernoulli principle says that along a streamline, pressure is lower when speed is higher. This principle has many applications.

- It is why airplanes can fly because the special shape of the airfoil / wings – air above the wings has a higher speed therefore lower dynamic, perturbation pressure, and the pressure below higher. The pressure difference creates the lift needed to keep the airplane float.

- The pressure difference is proportional to the difference of velocity squared:

\[
\Delta p = \rho (u_1^2 - u_2^2) = \rho (u_1 + u_2)(u_1 - u_2)
\]

- Therefore larger the speed is and the large the speed difference is, the larger is the lift.

- When there is a strong tail wind due to e.g., microburst, an aircraft can lose the lift and crash! Therefore the hazard of microburst can be due to the horizontal wind as much as due to the downdraft.
Pressure perturbations ahead of the gust front

- At the far upstream, \( u = U, p' = 0 \), right ahead of the gust front, the speed is reduced to zero (\( u=0 \)) – this is the so-called stagnation point. The pressure at this point, \( p_{\text{stagnation}} \), is given by, according to previous equation:

\[
p_{\text{stagnation}} = \frac{\rho_0 U^2}{2}
\]

- Since density perturbation outside the cold pool / ahead of the gust front is zero therefore there is no hydrostatic contribution to the pressure. The pressure perturbation is purely dynamic.

- Clearly \( p_{\text{stagnation}} \) is positive so expect to see positive (dynamic) pressure perturbation ahead of the gust front and PGF pointing away from the front.

- In fact it is this PGF that causes the inflow deacceleration therefore horizontal convergence hence vertical (dynamic) lifting near and ahead of the gust front.

Numerical simulation of density currents showing the pressure perturbations associated with density current

![Numerical simulation of density currents](image)

*Figure 8.41* Numerical-model simulation of a thunderstorm outflow structure illustrating the nature of the surface pressure perturbation maxima associated with the outflows. (a) Potential temperature perturbation (K, thin contours, negative values dashed) and pressure perturbation (mb, heavy contours) show a maximum of pressure perturbation at the left-hand side of the domain which is hydrostatic. (b) Horizontal divergence (units of \( 10^{-4} \) s\(^{-1} \), negative values dashed). (From Droegemeier and Wilhelmson, 1987. Reprinted with permission from the American Meteorological Society.)
Pressure perturbations associated with rotors / rotating (Kelvin-Halmholtz) eddies

• Above the density current head there usually exist vorticity-containing rotating eddies. Most of the vorticity is generated by the horizontal density/buoyancy gradient across the frontal interface.

• Associated with these eddies are pressure perturbations due to another dynamic effect – pressure gradient is need to balance the centrifugal force. The equation is

\[
\frac{1}{\rho} \frac{\partial p}{\partial n} = -\frac{V^2}{R_s}
\]

• To overcome centrifugal force, pressure at the center of a circulation is always lower. The fast the eddy rotates and the smaller the eddy is, the lower is the central pressure.
Pressure perturbations in the head region and associated (rotor) circulation

Figure 8.42 Numerical model simulation of a thundery outflow structure illustrating the pressure perturbation, minimum and associated inflow in the head of the outflow. (a) Pressure perturbation (vectors in mb, negative values dotted), (b) Extracts of horizontal velocity (m s⁻¹), (c) isotherms of vertical air motion (m s⁻¹). The bold solid contour denotes the surface boundary (~0.1C potential temperature perturbation). (From Droegemeier and Wilhelmson, 1986. Reprinted with permission from the American Meteorological Society.)

Density Current Studies by Xue et al


• Links to density current animations etc.
Cell Regeneration in 2D multicell storms

- Representative modeling studies (both used ARPS):

Important references on cell regeneration in two-dimensional multicell storms


Advection Mechanisms of Cell Regeneration
(Lin et al 1998, 2001, JAS)

- The cell regeneration is explained by the advection mechanism.

- The following processes occur periodically during cell regeneration:
  - (i) Near the edge of the gust front, the gust front updraft is formed by low-level convergence ahead of the gust front near the surface.
  - (ii) The upper portion of the gust front updraft grows by midlevel inflow since the gust front propagates faster than the basic wind.
  - (iii) The growing cell tends to produce and is flanked by strong compensating downdrafts. The upstream downdraft tends to cut off the growing cell from the gust front updraft.

- It is found that the period of cell regeneration is inversely proportional to the midlevel, cold-pool wind speed, i.e., the period of regeneration is governed by the strength of cold-pool relative mid-level advection.

- This is the so-called advection mechanism.
(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).

Time-space plot of $w$ at $z=2.5$ km for various wind profiles

All of the storms simulated—whether strongly or weakly evolving—produce cells in a periodic fashion. The regeneration periods are 9.0, 9.6, 10.1, 11.3, and 12.1 min for cases $U = 7.5, 10, 12.5, 15,$ and 20 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, as found in the earlier cases with gust front forcing.

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

**Life Cycle of simulation 2D-multicell storm**

Vertical cross sections of vertical velocity (thin contours in intervals of 1 m s$^{-1}$) for a portion of the computational domain in the moving frame of reference with the gust front for the $U = 10$ m s$^{-1}$ case. Positive (negative) values are solid (dashed). The density current may be roughly represented by the 1 K potential temperature perturbation contour (bold dashed) near the surface. The rainfall 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).
Summary of Life Cycle of Simulated Storm in Previous Slide (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 then 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.

**Fig. 13.** A schematic model for the cell regeneration and propagation within a two-dimensional multicell thunderstorm. Four stages are found: (a) formation and maintenance of the gust front updraft (GFU), (b) rearward advection of the growing gust front updraft, (c) cutting off of the growing cell \( (c_1) \) from the gust front updraft by the upstream compensating downdraft, and (d) cell regeneration and coexistence of the growing \( (c_2, c_3) \) and propagating \( (c_4) \) modes. From Lin et al 1998.
Conceputal Model for Cell Regeneration as Illustrated in the Previous Slide

In Lin et al (1998), cell regeneration is explained by an advection mechanism. The following processes are repeated for cell regeneration (see schematics).

- (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 the midlevel inflow since the gust front propagates faster than the basic wind. Relatively stronger gravity waves are produced by this growing cell ($C_1$), which is still attached to the gust front updraft.

- (iii) The growing cell ($C_1$) tends to produce strong compensating downdrafts on both sides. The upstream (right) downdraft tends to cut off the growing cell from the gust front updraft. During this stage, maxima perturbation potential temperature are collocated with the updrafts in the middle and lower layers. The convective cell-induced gravity waves propagate both upstream and downstream without amplification. It is found that the period of cell regeneration is inversely proportional to the midlevel, storm-relative wind speed.

Cell Regeneration theory of Fovell et al

- Fovell and Tan (1998, MWR) looked deeper into the cell regeneration problem using a numerical model (ARPS) and notes that the unsteadiness of the forcing at the gust front is one reason why the storm in "multicellular". The cells themselves "feed back" to the overall circulation.

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

- In Fovell and Tan (1998), the cell life cycle is examined in several complementary fashions. The cells are 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. This transient circulation also drives the episodic mixing of stable air into the inflow that results in the cell’s ultimate dissipation. The timing of cell regeneration is also examined; an explanation involving two separate and successive phases, each with their own timescales, is proposed. The second of these phases can be shortened if a “convective trigger,” another by-product of the cell’s circulation, is present in the storm’s inflow environment.
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), 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.

Introduction of Fovell and Tan (1998) - continued

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 previous study (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 (labeled A–D) during one cell generation cycle for the 2D simulation. Abscissa coordinates are subdomain relative. Negative contours are dashed and the zero contour is omitted. For $w$ 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 simply periodic fashion.

Simulation using the same thermodynamic sounding as the previous study (Fovell and Tan 1998)

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):
  \[ \psi^2 p' = \frac{\partial (\bar{B}' + \bar{B})}{\partial z} \]

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

- We call generation of horizontal vorticity by horizontal gradient of buoyancy the baroclinic generation.

Explanation of interaction of cold-pool generated circulation and that induced by the inflow shear by Rotunno, Klemp and Weisman (1988, RKW)
Explanation of interaction of cold-pool generated circulation and that induced by the inflow shear by Rotunno, Klemp and Weisman (1988, RKW)

- Now we consider the low-level circulation at the boundary of the negatively buoyant cold pool. Rotunno et al. (1988) used the vorticity framework to discuss its steady-state aspects.

- There are two opposing circulations, one baroclinically generated at the pool boundary (here, producing negative vorticity and a counterclockwise circulatory tendency), the other associated with the vertical wind shear (here, having positive horizontal vorticity and a clockwise circulation), that combine to establish the forced updraft (Fig. 10c).

- RKW argued that the relative strengths of these two circulations determine the path taken by parcels rising within the forced updraft.

- If equally matched, the parcels should continue rising vertically. When the cold pool’s circulation is stronger, however, parcels will be impelled rearward as they rise. This “suboptimal” situation results in the characteristic FTR airflow of mature squall line circulations.

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 RKW’s 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.

- The dominance of the cold pool circulation ensures that the new cell and its positive buoyancy will soon 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.
Cell Regeneration in 2D multicell storms

- Fig. 16. 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 not so much different, both points to the importance of rearward movement of older cells and the separation of the cell from the new cells

- The rate of separation depends on the mid-level advective flow speeds

- The difference is in the details on how the new cell is influenced by the older cell.