Mesoscale Meteorology

4.3 Multicell Storms

Unlike air-mass storms, which have a lifespan of less than an hour, many thunderstorms can persist for longer periods of time. These storms are generally made up of many cells. Each individual cell goes through a life cycle but the group persists.

These storms are called *multicellular* thunderstorms, or simply *multicells*. Multicellular storms consist of a series of evolving cells with each one, in turn, becoming the dominant cell in the group. Cold outflow from each cell combines to form a much larger and stronger gust front. Convergence along the gust front tends to trigger new updraft development. This is the strongest in the direction of storm motion. New cell growth often appears disorganized to the naked eye.

4.3.1 General Characteristics

Types

- Multicell cluster storm
  - A group of cells moving as a single unit, often with each cell in a different stage of the thunderstorm life cycle.
  - Multicell cluster 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.

Associated weather

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

Organized multicell storms have higher severe weather potential, although unorganized multicells can produce pulse storm-like bursts of severe events.

Multicell storms as seen by radar

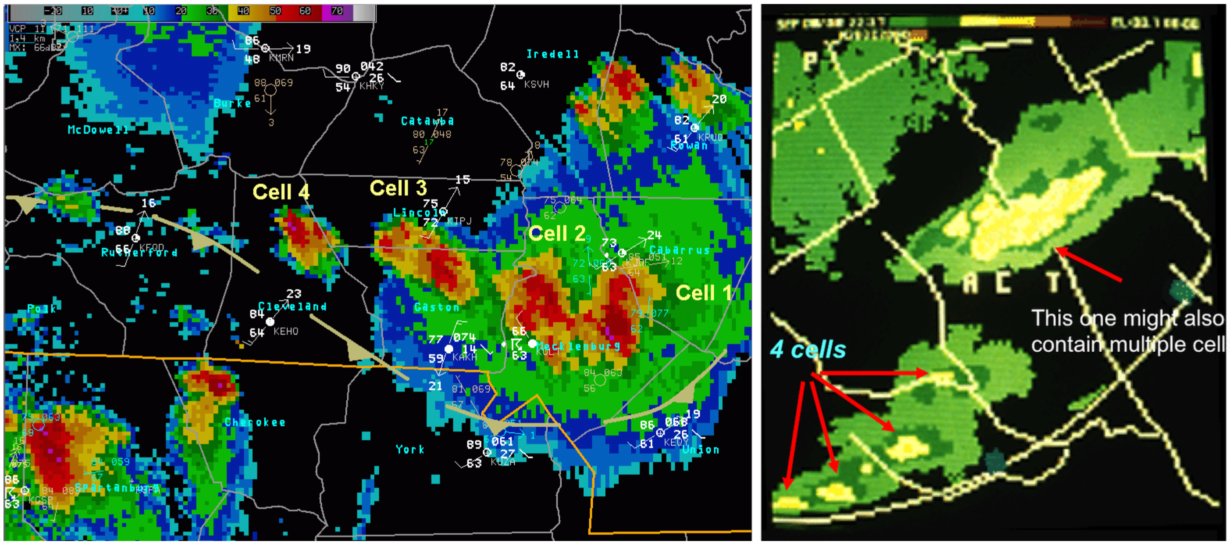


Figure 1: Radar depiction of multicellular storms.

Radar often reflects the multicell nature of these storms, as shown above. 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 portion

4.3.2 Formation

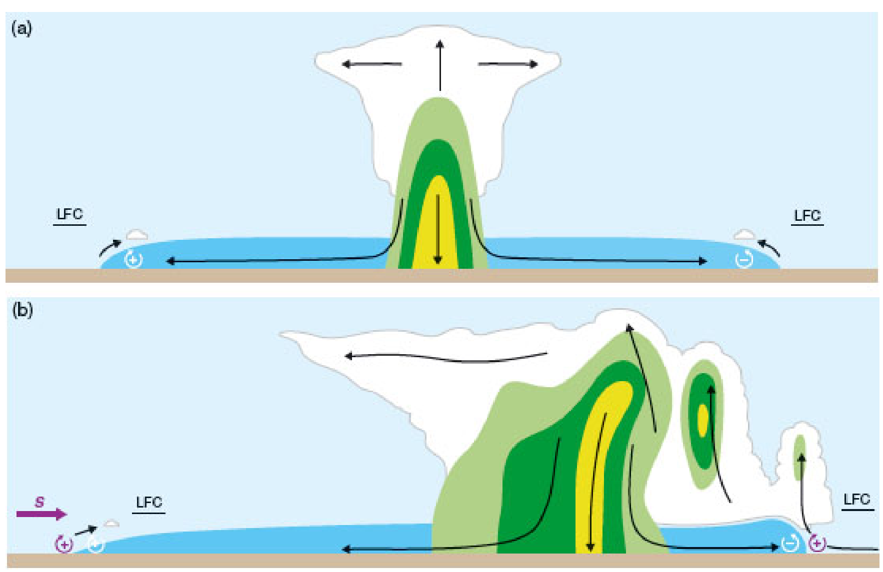


Figure 2: Comparison of lifting by the gust front in (a) a no-shear, single-cell environment and (b) a moderate-shear, multicell environment (the shear is westerly). [From: Markowski and Richardson]

Conditions for development

- Moderate to strong conditional instability. Once clouds form, there is a significant amount of buoyant energy to allow for rapid cloud growth.
- Low to moderate vertical wind shear, generally with little clockwise turning

Importance of vertical wind shear

Single-cell storms are associated with very weak shear, resulting in a vertically-stacked structure. The outflow boundary is often too weak to trigger additional convection. Often the outflow boundary "outruns" the motion of the storm cell. As a result, even if new convection develops, it is generally too far away to interact with the parent cell. Conversely, weak to moderate shear keeps the gust front near the storm updraft. This triggers new convection adjacent to older cells and connects with the parent cell.

4.3.3 Life Cycle

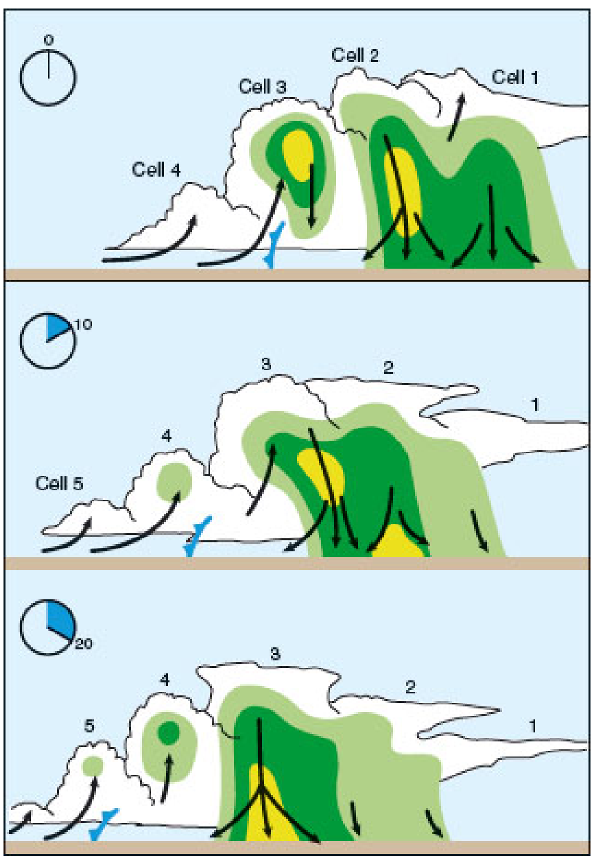


Figure 3: Schematic of the evolution of multicellular convection. [From: Markowski/Richardson]

- $t = 0$
  - Cell 1 is entering its dissipative stage.
  - Cell 2 is in its mature stage.
  - Cell 3 begins to form precipitation.
  - Cell 4 begins to ascend toward the EL.
- $t \sim 10$ min
  - Cell 2 precip weakens its updraft.
  - Cell 1 has almost completely dissipated.
  - Cell 3 top has passed through its EL, decelerating, then spreads horizontally into an anvil.
  - Cell 4 continues to develop, Cell 5 has been initiated.
- $t \sim 20$ min
  - Cell 1 and Cell 2 have nearly dissipated.
  - Cell 3 is dominated by downdrafts, weakens.
  - Cell 4 approaches the EL, nears maturity.
  - Cell 5 continues to grow.
- This cycle repeats - Cell 3 replaces Cell 2, Cell 4 replaces Cell 3, Cell 5 replaces Cell 4, and so on.

4.3.4 Cell Motion versus Storm Motion

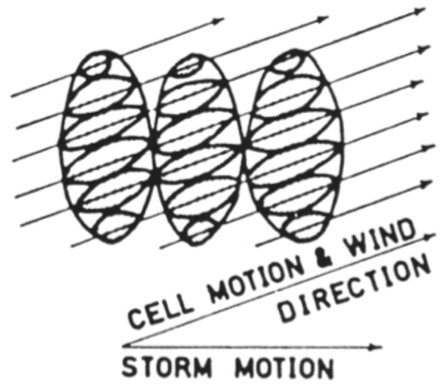


Figure 4: Schematic depicting cell motion versus storm motion. [From: Marwitz 1972]

Cells inside a storm (system) do not necessarily move at the same speed and/or direction as the overall storm system. Why?

New cells tend to form on the side of the storm where the warm, moist air at the surface is located. This is called the preferred flank, and in the central Plains this is often on the south or southeast side. Individual cells tend to move with the velocity of the mean wind averaged over their depth. This movement combined with the repeated development of new cells on the preferred flank leads to discrete propagation of the storm system. This propagation may be slower or faster than the mean wind, and it is often in a different direction than the mean wind.

4.3.5 Structure

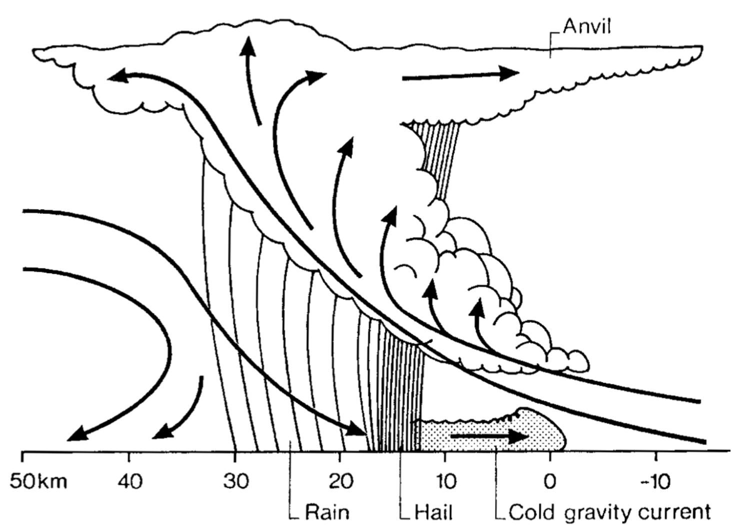


Figure 5: A schematic model of a thunderstorm and its density current outflow. [From: Simpson 1997]

4.3.6 Thunderstorm Outflow as a Density Current

The gust front associated with thunderstorm outflow propagates along the surface in the form of a density or gravity currents.

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.

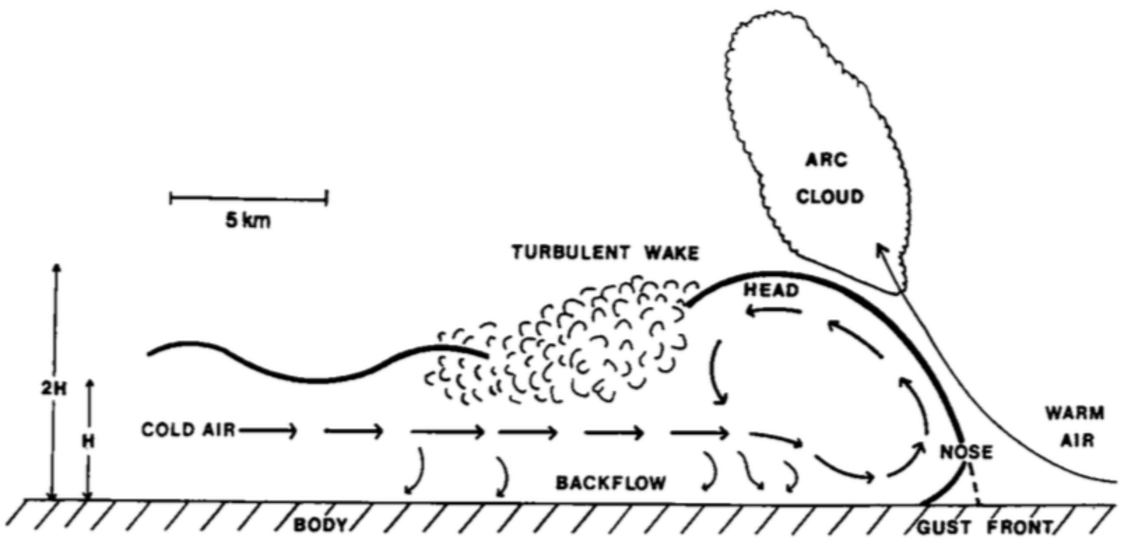


Figure 6: Schematic of thunderstorm outflow. [From: Lin 2007]

Propagation of a gust front

The low-level-inflow-relative speed of a gust front often determines the propagation of the storm system. This is almost certainly true for two-dimensional squall lines. Therefore, the determination of gust front speed is important.

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

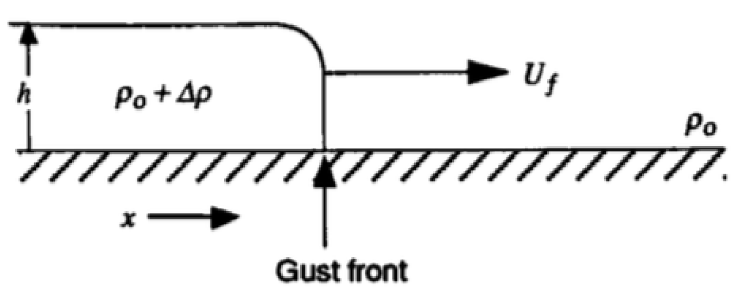


Figure 7: Schematic of gust front propagation.

For an idealized density current, like that shown in Fig. 7, we apply a simple equation

$$\frac{du}{dt} = -\frac{1}{\rho_0}\frac{\partial p^{'}}{\partial x}. \tag{1}$$

What have we neglected? Friction, Coriolis, and 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 ($\partial/\partial t = 0$) in this coordinate system. This is a reasonably valid assumption when turbulent eddies are not considered. Therefore, $du/dt = u\ du/dx$, and Eq. (1) becomes

$$\frac{\partial(u^2/2)}{\partial x} = -\frac{1}{\rho_0}\frac{\partial p^{'}}{\partial x} \tag{2}$$

Next, we integrate Eq. (2) along a streamline that follows the lower boundary from far upstream (where $u = U$ and $p^{'} = 0$) to a point right behind the gust front (where $u = 0$ and $p^{'} = dp$).

$$\int_{x_{\mathrm{gf}}}^{x_{\mathrm{up}}} \frac{\partial(u^2/2)}{\partial x}\,dx = \int_{x_{\mathrm{gf}}}^{x_{\mathrm{up}}} -\frac{1}{\rho_0}\frac{\partial p^{'}}{\partial x}\,dx \quad \rightarrow \quad \frac{U^2}{2} = \frac{\Delta p}{\rho_0} \quad \rightarrow \quad U = \sqrt{\frac{2\Delta p}{\rho_0}} \tag{3}$$

Equation (3) is the propagation speed of the gust front as related to the surface pressure perturbation (dp) associated with the cold pool/density current. This solution is very general. The contributions to the surface pressure perturbation from the cold pool, upper-level heating, non-hydrostatic effects (vertical acceleration), and dynamic pressure perturbations can all be included.

Assuming that dp is purely due to the hydrostatic effect of heavier air/fluid inside the cold pool of depth h, the above formula can be rewritten as (assuming the pressure perturbation above the cold pool is zero)

$$U = \sqrt{2gh\frac{\Delta\rho}{\rho_0}} \tag{4}$$

because

$$\int_0^h \frac{\partial p^{'}}{\partial z}\,dz = -\int_0^h g\Delta\rho\,dz \quad \rightarrow \quad \Delta p = gh\Delta\rho$$

In Eq. (4), we have made use of the vertical equation of motion (with $dw/dt = 0$) and integrated from the surface to the top of the density current at height 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, which is not a surprising result. When other effects are included, the speed may be somewhat different. However, it is generally correct to say that a deeper and/or heavier (colder) density current/cold pool propagates faster.

4.3.7 Pressure Perturbations Ahead of the Gust Front

In the previous idealized model in the front-following coordinate system, the inflow speed decreases to zero as an air parcel approaches the front from far upstream. Thus, there must be a horizontal pressure gradient ahead of the gust front that decelerates the flow. That means there must be a positive pressure perturbation ahead of the gust front and it has to be equal to that produced by cold pool.

We can rewrite Eq. (2) as

$$\frac{\partial(u^2/2)}{\partial x} = -\frac{1}{\rho_0}\frac{\partial p'}{\partial x} \quad \rightarrow \quad \frac{\partial}{\partial x}\left[\frac{u^2}{2} + \frac{p'}{\rho_0}\right] = 0 \quad \rightarrow \quad \frac{u^2}{2} + \frac{p'}{\rho_0} = C. \tag{5}$$

Thus, $u^2/2 + p'/\rho_0$ is constant along the streamline following the lower boundary. This represents a special form of the Bernoulli function (with the effect of vertical displacement excluded).

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 due to the special shape of the airfoil/wings. Air above the wings has a higher speed and, therefore, a lower dynamic perturbation pressure. Conversely, the pressure below the wing is higher. The resulting pressure difference creates the lift needed to keep the airplane airborne. The pressure difference is proportional to the difference of velocity squared:

$$\Delta p = \rho(u_1^2 - u_2^2) = \rho(u_1 + u_2)(u_1 - u_2). \tag{6}$$

Therefore, the lift is larger as the speed and the speed difference become larger. When there is a strong tail wind due to *e.g.*, microburst, an aircraft can lose lift (because the reduction in aircraft relative headwind) and crash! Therefore the hazard of a microburst can be due to the horizontal wind as much as due to the downdraft.

Apply the values at the far upstream ($u = U$ and $p' = 0$) and right ahead of the gust front ($u = 0$) to Eq.(5). The pressure perturbation just ahead of the gust front (the so-called stagnation point), p'_{stag}, is then given by

$$p'_{\text{stag}} = \frac{\rho_o U^2}{2}. \tag{7}$$

Since the density perturbation outside of the cold pool (ahead of the gust front) is zero, there is no hydrostatic contribution to the pressure. Thus, the pressure perturbation is purely *dynamic*. Clearly p'_{stag} is positive, so we expect to see a positive (dynamic) pressure perturbation ahead of the gust front and a pressure gradient force that points away from the front. In fact it is this pressure gradient force that causes the inflow deceleration, therefore horizontal convergence, which allows for vertical (dynamic) lifting near and ahead of the gust front.

4.3.8 Pressure Perturbations Associated with Rotors / Eddies

Above the density current head there usually exists 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. The pressure gradient is needed to balance the centrifugal force. The equation, called *cyclostrophic* balance and often applied to tornadoes, is

$$\frac{1}{\rho}\frac{\partial p}{\partial n} = \frac{V_s^2}{R_s},$$

where n is the coordinate directed inward toward the center of the vortex, R_s is the radius of curvature of the flow, and V_s is the wind speed at a distance R_s from the center of the circulation. To overcome centrifugal force, pressure at the center of a circulation is always lower. The faster the eddy rotates and the smaller the eddy is, the lower the central pressure.

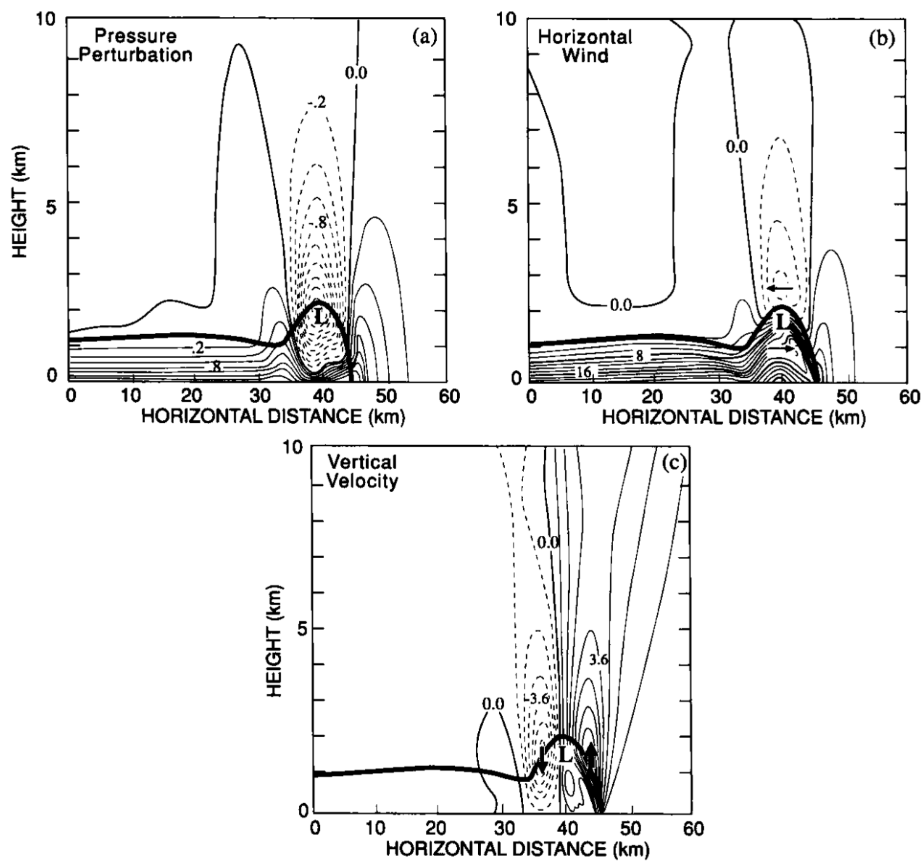


Figure 8: Numerical simulation of a thunderstorm outflow structure illustrating the pressure perturbation minimum and associated airflow in the head of the gust-front outflow. [From: Droegemeier and Wilhelmson 1987]

4.3.9 Cell Regeneration in 2D Multicell Storms

We will examine two representative modeling studies that address the theory of cell regeneration.

- Lin *et al.*
  - Lin, Y.-L., R. L. Deal, and M. S. Kulie, 1998: Mechanisms of cell regeneration, development, and propagation within a two-dimensional multicell storm. *J. Atmos. Sci.*, **55**, 1867-1886.
  - Lin, Y.-L., and L. Joyce, 2001: A further study of mechanisms of cell regeneration, propagation and development within two-dimensional multicell storms. *J. Atmos. Sci.*, **58**, 2957–2988.
- Fovell *et al.*
  - Fovell, R. G., and P. S. Dailey, 1995: The temporal behavior of numerically simulated multicell-type storms, Part I: Modes of behavior. *J. Atmos. Sci.*, **52**, 2073-2095.
  - Fovell, R. G., and P.-H. Tan, 1998: The Temporal Behavior of Numerically Simulated Multicell-Type Storms. Part II: The Convective Cell Life Cycle and Cell Regeneration. *Mon. Wea. Rev.*, **126**, 551-577.

Lin *et al.*

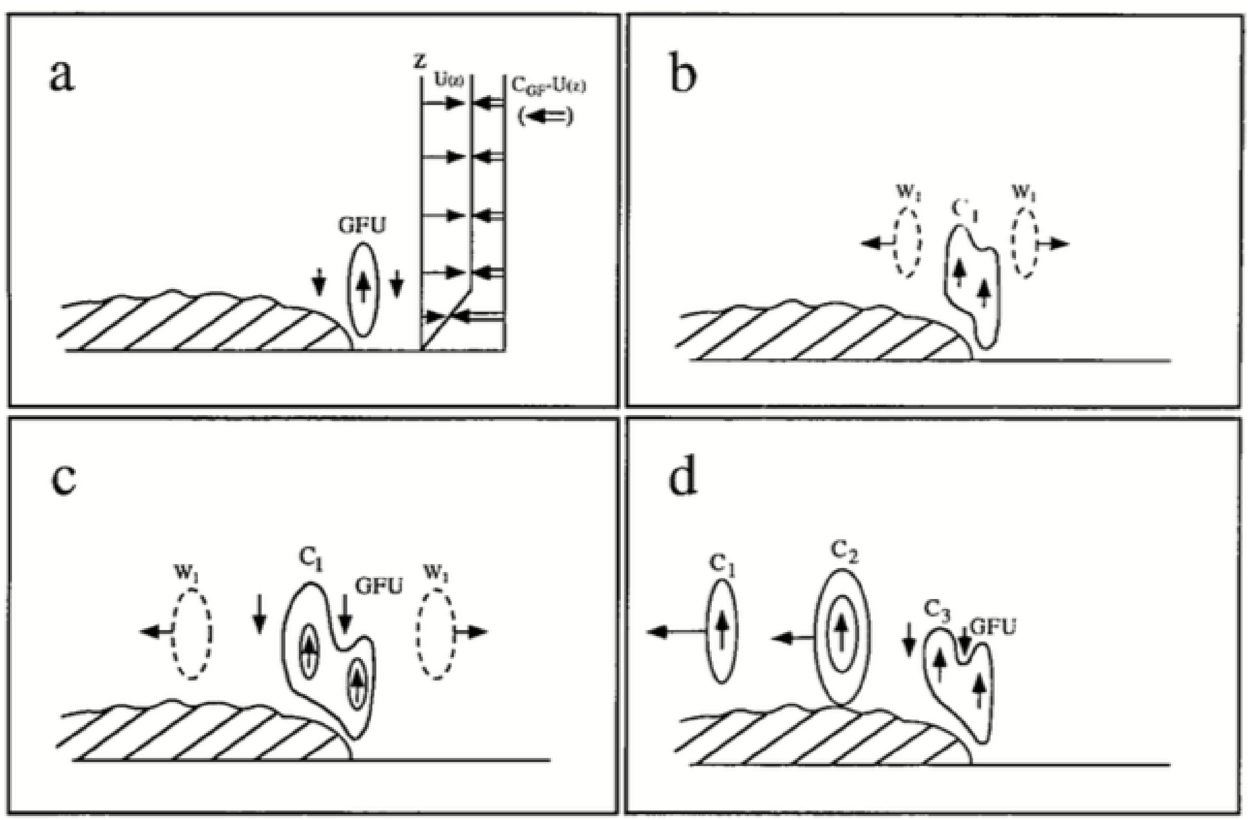


Figure 9: Lin et al. conceptual model.

Conceptual model of Lin et al. (see Fig. 9)

1. 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.

2. 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.

3. The growing cell (C1) produces strong compensating downdrafts on both sides. The downdraft on the upstream (right) side cuts off this growing cell from the gust front updraft.

4. 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.

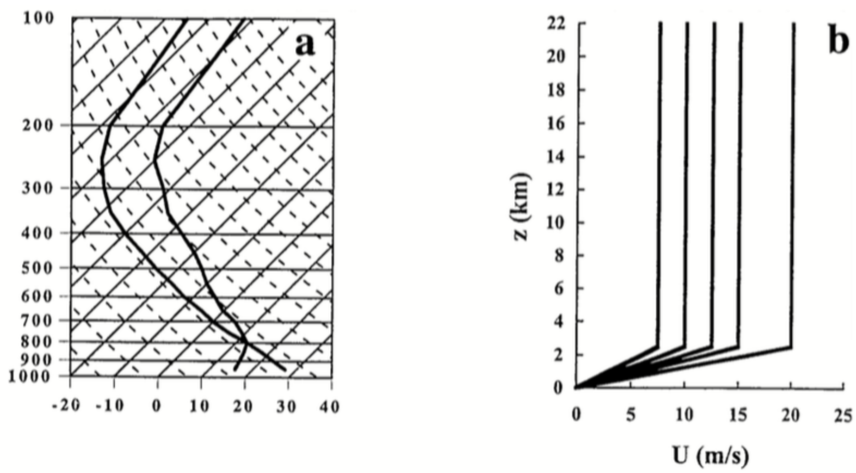


Figure 10: (a) Skew-T plot of the temperature and dewpoint profiles used in the simulations, (b) wind profiles used to initialize the simulations (from Lin et al 1998).

Lifecycle of a simulated two-dimensional multicell storm (see Fig. 11)

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

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

- The rainwater is shaded ($> 0.0005\ \mathrm{g\ k^{-1}g}$) and the cloud boundary is bold contoured ($> 0\ \mathrm{g\ k^{-1}g}$). The corresponding integration time is shown at the top of each panel.

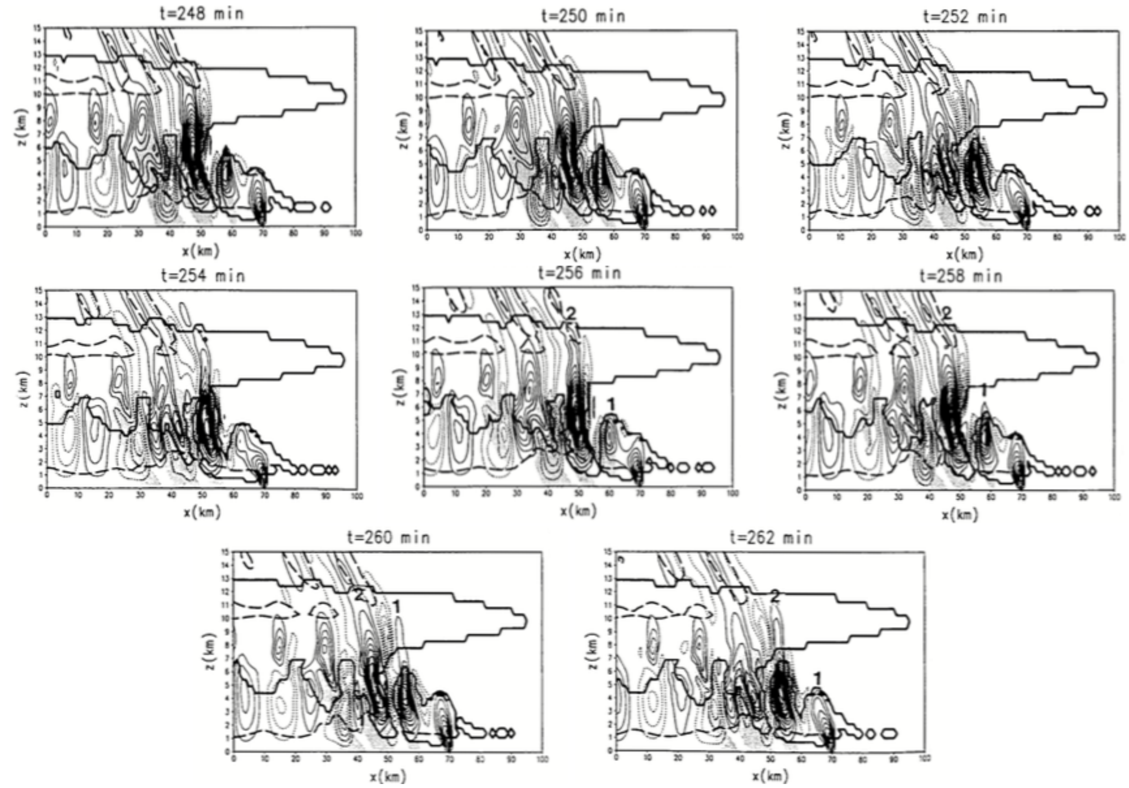
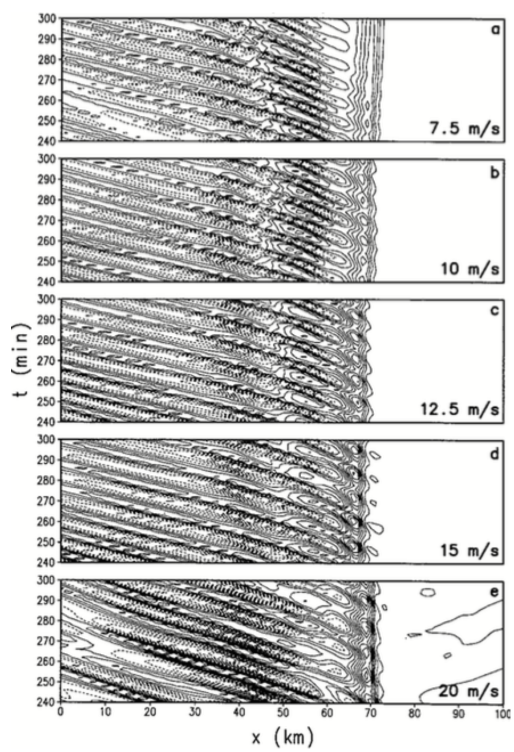
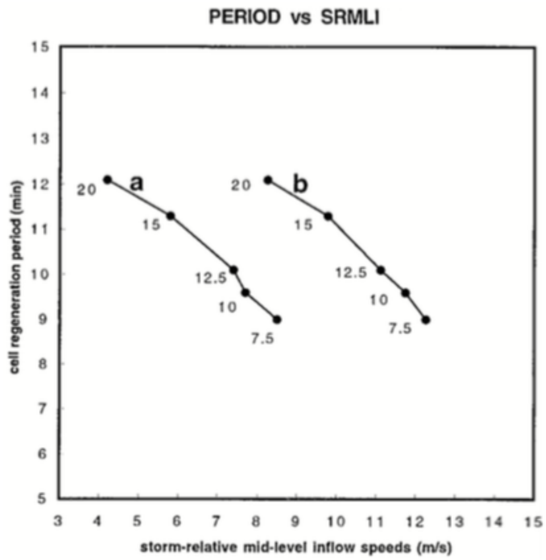


Figure 11: Vertical profiles of vertical velocity (thin contours in intervals of $1\ \mathrm{ms}^{-1}$) for a portion of the domain in the moving frame of reference of the gust front for the $10\ \mathrm{ms}^{-1}$ case.

- 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 storm cell 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 $20\ \mathrm{ms}^{-1}$, 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.





- Cell regeneration period (y axis) vs the far upstream storm relative midlevel inflow (SRMLI) speeds (curve a) for the profiles in Fig. 10. The $U(\mathrm{ms}^{-1})$ is shown beside its corresponding point. (b) Same as (a) except 2.5-5.5-km layer averaged near-storm SRMLI.
- 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

- First, the GFU begins to expand vertically (*e.g.*, at $t = 252\ \mathrm{min}$), signaling the release of a new convective cell, which occurs at an interval of $9.6\ \mathrm{min}$ 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)

- 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 that used a different thermodynamic sounding were found to also support the advection mechanism.
- Without precipitation loading, an individual cell was still able to split. In this case, the compensating downdraft produced by vertical differential advection is responsible for cell splitting and merging.

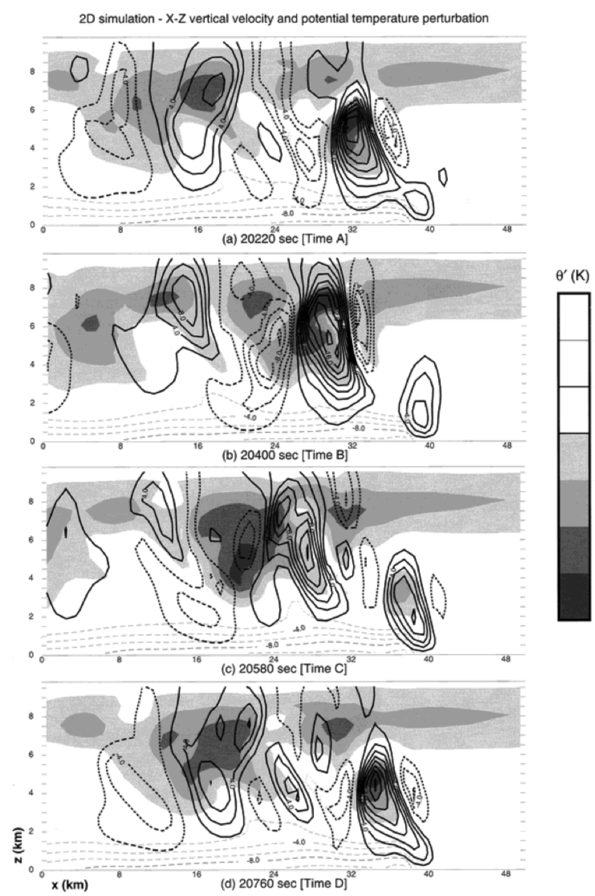
Fovell *et al.*

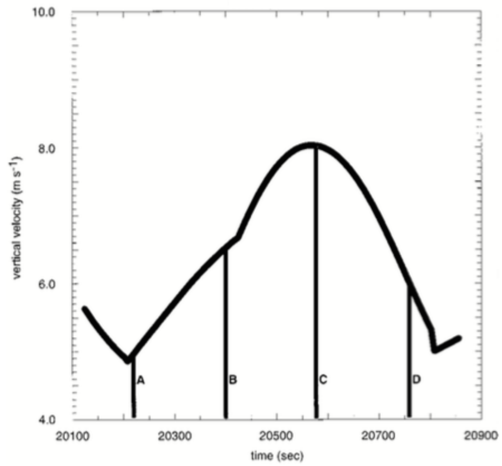
Conceptual model of Fovell et al.

- 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.

Numerical experiments in support of Fovell et al.'s conceptual model.

- Simulation using the same thermodynamic sounding as the study of Lin *et al*.
- Vertical velocity w (2 ms^{-1} contours) and potential temperature perturbation (shaded) fields for a $50\, kilo\mathrm{m} \times 10\ \mathrm{km}$ subdomain at four times during one cell generation cycle for the 2D simulation.
- Negative contours are dashed and the zero contour is omitted. For θ, contours (interval 2 K) are included for negative values less than or equal to 2 K only.
- During this mature phase, the storm's ground relative motion was eastward at $15.3\ \mathrm{ms}^{-1}$ 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):

$$\nabla^2 p_h' = \frac{\partial(\rho_0 B')}{\partial z}.$$

- Equation of the horizontal component of vorticity (in the x-z plane), neglecting friction, is given by

$$\frac{\partial \eta}{\partial t} = -\frac{B'}{\partial x} \quad \text{where} \quad \eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$

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

The effect of an individual convective cell on the storm's low-level circulation (see Fig. 12)

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

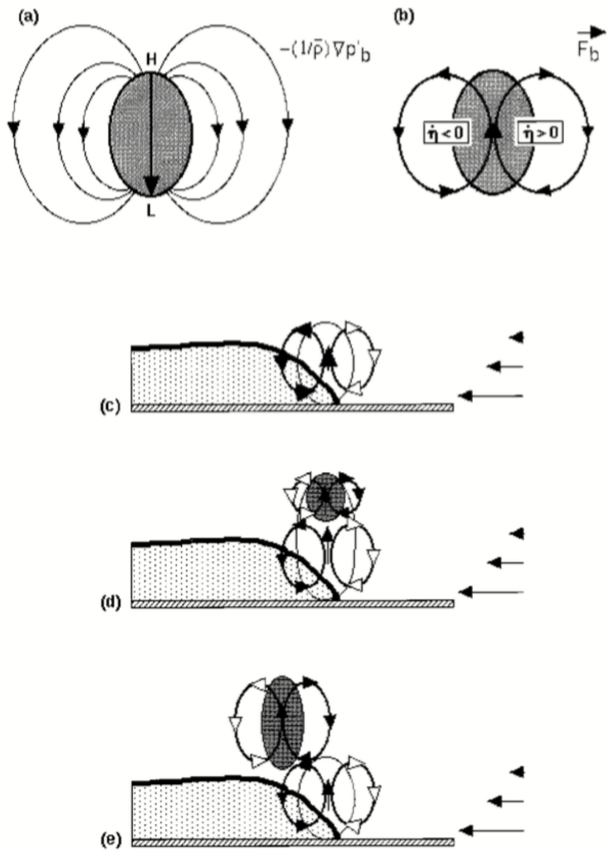


Figure 12: Schematic illustrating the effect of an individual convective cell on a storm's low-level circulation

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.
- 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 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 is 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.
- 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.

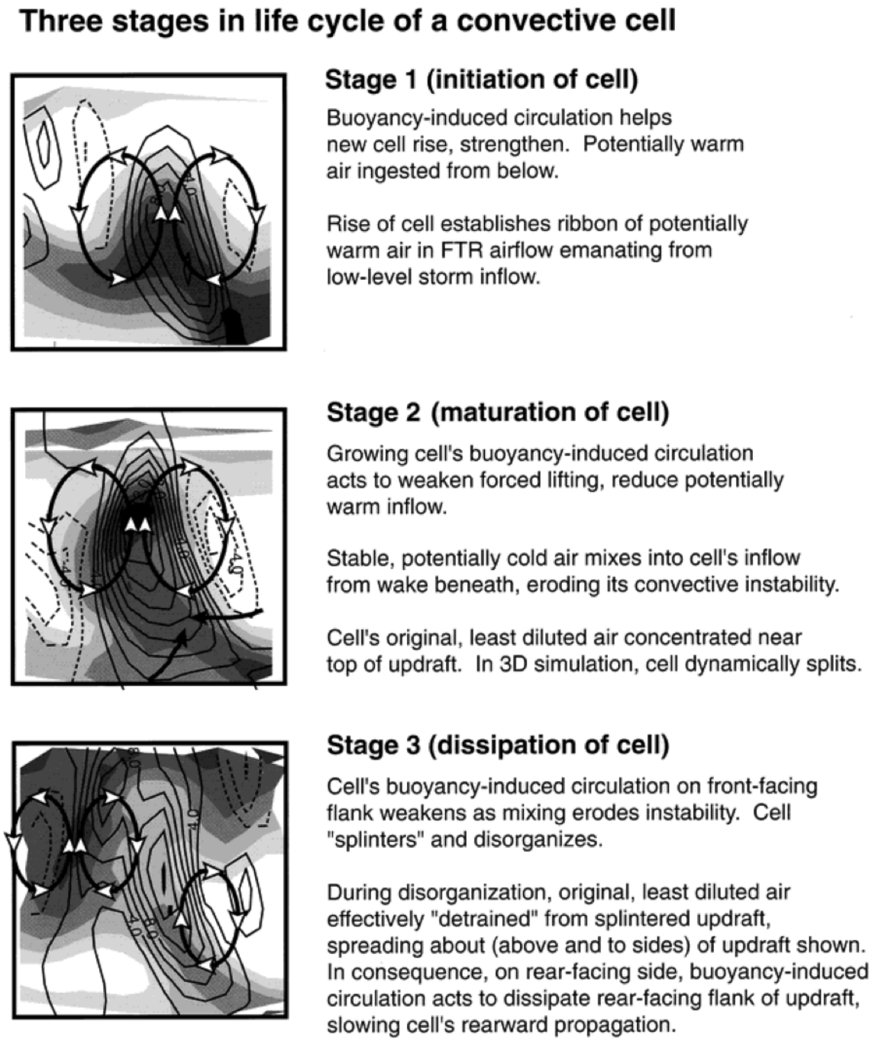


Figure 13: The three stages of a convective cell, with equivalent potential temperature (shaded) and vertical velocity (contoured) fields. Note the reference, frame shown is not fixed in space, but rather tracks the cell's principal updraft.

Summary on Cell Regeneration Theories

- 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* focused on the environmental conditions that affect the rearward cell movement than 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.