Convective Dynamics

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Overview

Multicellular 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.

Multicellular Storms

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.

Types

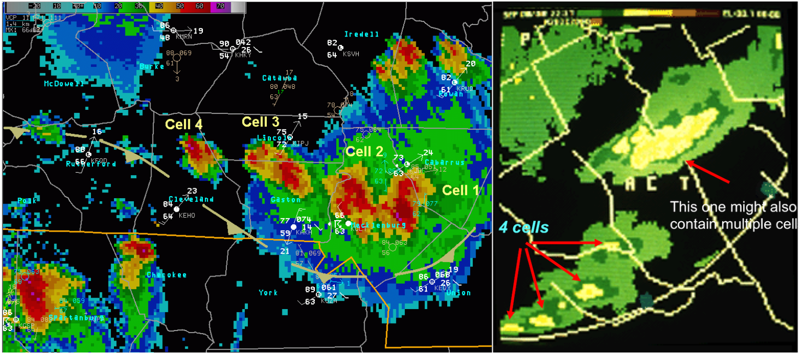
- Multicell cluster storm
  - A group of cells moving as a single unit, often with each cell in a different stage of the thunderstorm life cycle.
  - Multicell cluster storms can produce moderate size hail, flash floods and weak tornadoes.

- 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

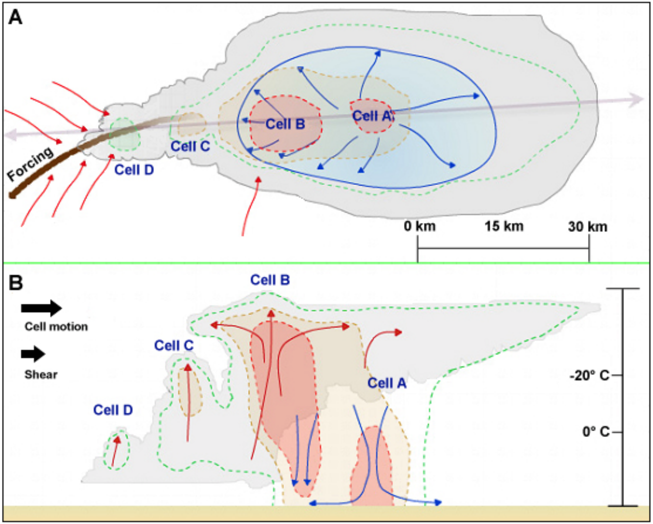
Multicell severe weather can be of any variety, and generally these storms are more potent than single cell storms. They are, however, considerably less potent than supercells because closely spaced updrafts compete for low-level moisture.

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



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

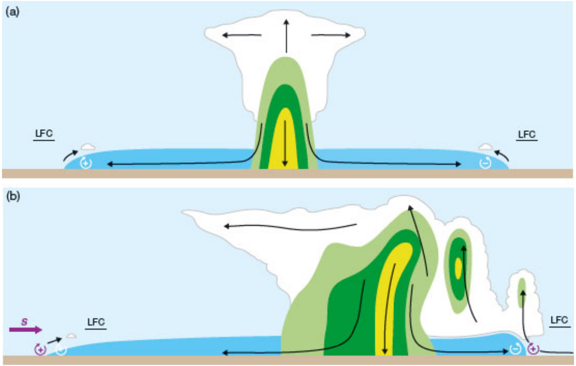
Multicell storms as seen by radar



Conditions for development

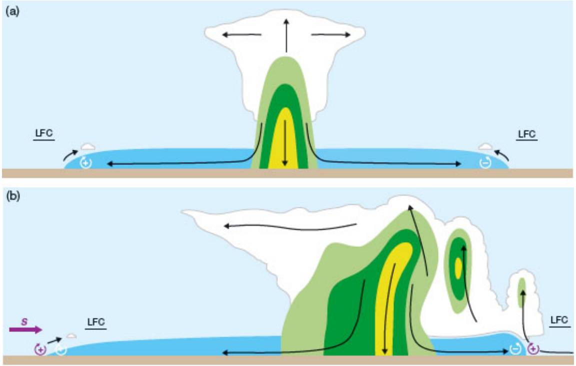
- Moderate to strong conditional instability. Once clouds form, there is a significant amount of buoyant energy to allow for rapid cloud growth.
- Low to moderate vertical wind shear, generally with little clockwise turning

Importance of vertical wind shear



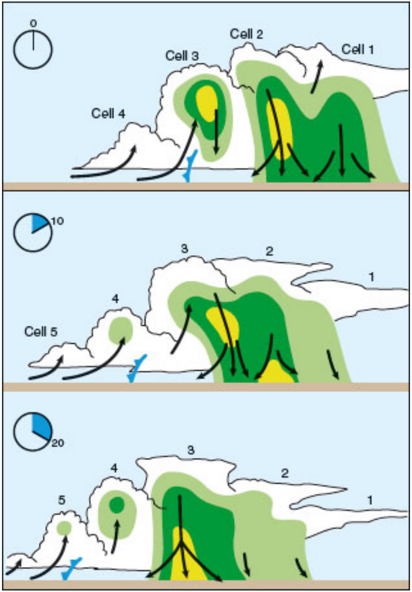
Single-cell storms are associated with very weak shear, resulting in a vertically-stacked structure. The outflow boundary is often too weak to trigger additional convection. Often the outflow boundary "outruns" the motion of the storm cell. As a result, even if new convection develops, it is generally too far away to interact with the parent cell.

Importance of vertical wind shear



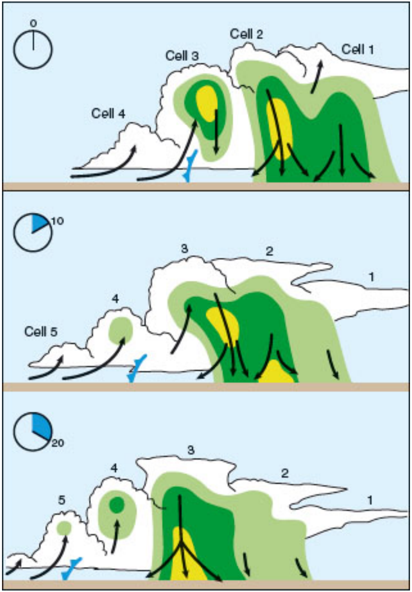
Conversely, weak to moderate shear keeps the gust front near the storm updraft. This triggers new convection adjacent to older cells and connects with the parent cell.

Lifecycle



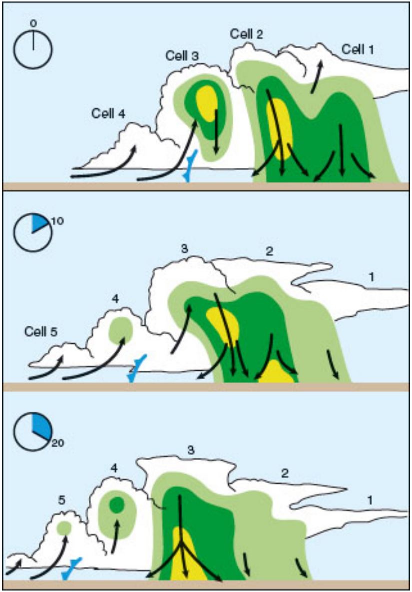
- $t = 0$ min
  - Cell 1 is entering its dissipative stage.
  - Cell 2 is in its mature stage.
  - Cell 3 begins to form precipitation.
  - Cell 4 begins to ascend toward the EL.

Lifecycle



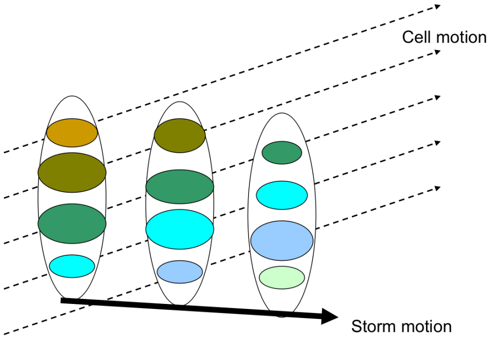
- $t = 10$ min
  - Cell 2 precip weakens its updraft.
  - Cell 1 has almost completely dissipated.
  - Cell 3 top has passed through its EL, decelerating, then spreads horizontally into an anvil.
  - Cell 4 continues to develop, Cell 5 has been initiated.

Lifecycle



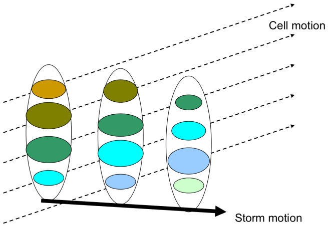
- $t = 20$ min
  - Cell 1 and Cell 2 have nearly dissipated.
  - Cell 3 is dominated by downdrafts, weakens.
  - Cell 4 approaches the EL, nears maturity.
  - Cell 5 continues to grow.
- This cycle repeats - Cell 3 replaces Cell 2, Cell 4 replaces Cell 3, Cell 5 replaces Cell 4, and so on.

Cell Motion versus Storm Motion



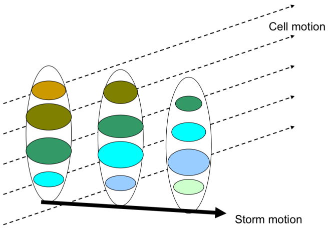
Cells inside a storm (system) do not necessarily move at the same speed and/or direction as the overall storm system. Why?

Cell Motion versus Storm Motion



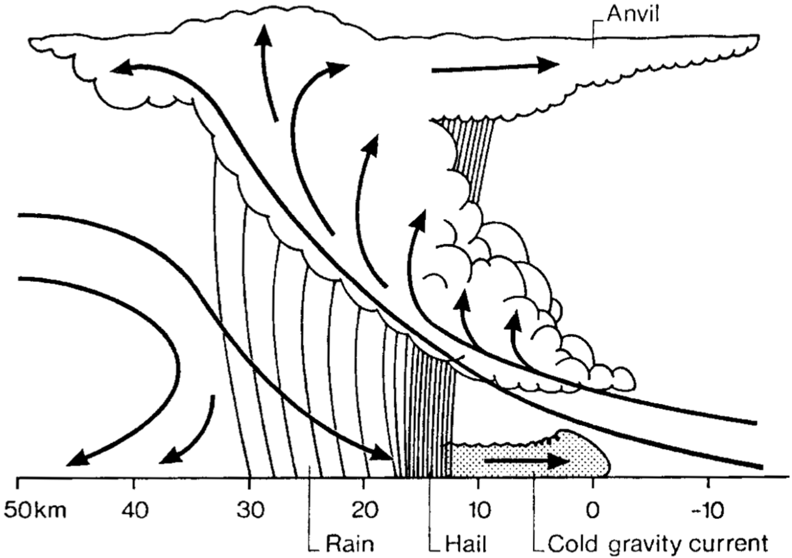
New cells tend to form on the side of the storm where the warm, moist air at the surface is located. This is called the preferred flank, and in the central Plains this is often on the south or southeast side. Individual cells tend to move with the velocity of the mean wind averaged over their depth.

Cell Motion versus Storm Motion

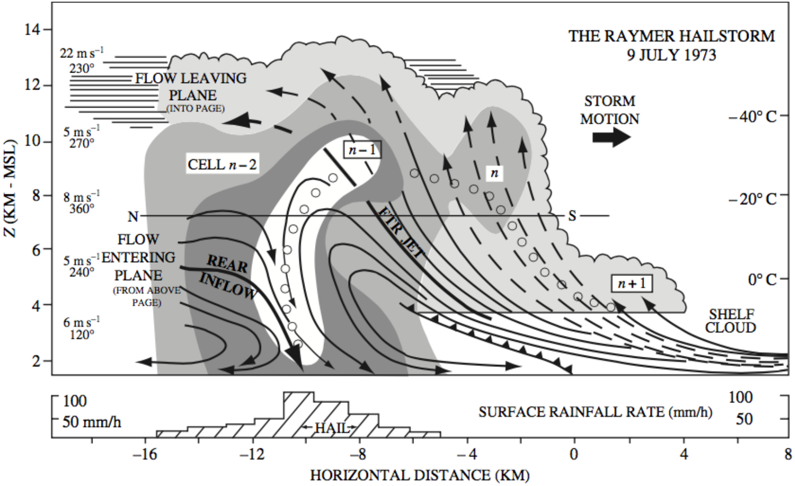


This movement combined with the repeated development of new cells on the preferred flank leads to discrete propagation of the storm system. This propagation may be slower or faster than the mean wind, and it is often in a different direction than the mean wind.

Structure

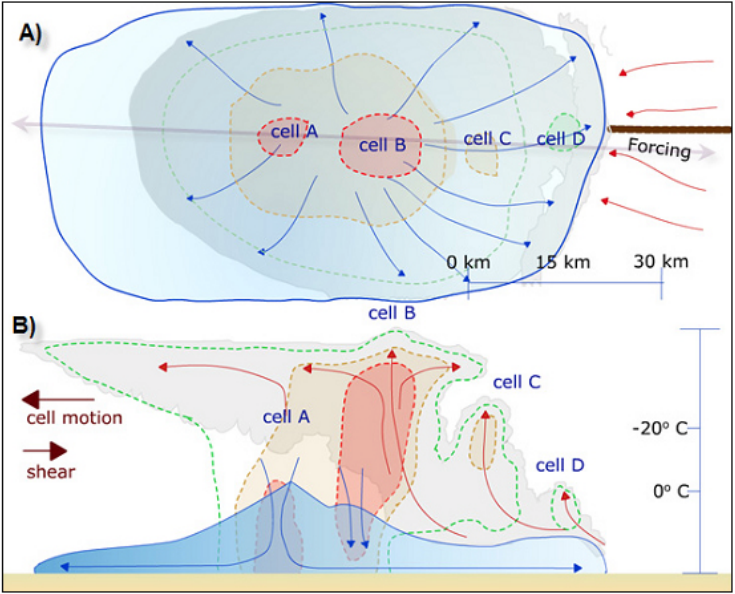


Structure



THE RAYMER HAILSTORM
9 JULY 1973
22 m s⁻¹ 230°
FLOW LEAVING PLANE (INTO PAGE)
5 m s⁻¹ 270°
CELL n – 2
n – 1
n
STORM MOTION
–40° C
–20° C
0° C
8 m s⁻¹ 360°
N
S
FLOW ENTERING PLANE (FROM ABOVE PAGE)
5 m s⁻¹ 240°
REAR INFLOW
FTR JET
n + 1
SHELF CLOUD
6 m s⁻¹ 120°
Z (KM - MSL)
14
12
10
8
6
4
2
100
50 mm/h
HAIL
SURFACE RAINFALL RATE (mm/h)
100
50
–16
–12
–8
–4
0
4
8
HORIZONTAL DISTANCE (KM)

Structure

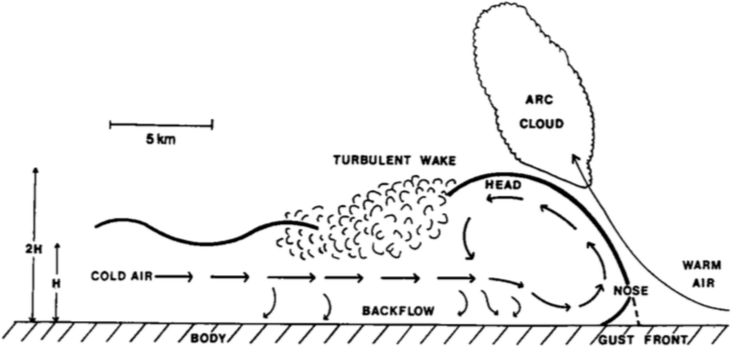

A)
cell A
cell B
cell C
cell D
Forcing
0 km
15 km
30 km
B)
cell B
cell C
cell A
cell D
cell motion
shear
-20º C
0º C

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.

Thunderstorm Outflow as a Density Current

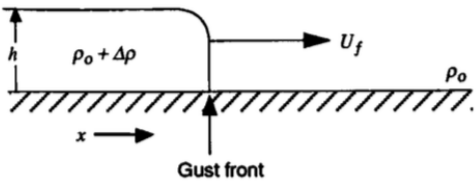


Gust Front Propagation

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.

Gust Front Propagation



Gust Front Propagation

For an idealized density current, 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.

Gust Front Propagation

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.

Gust Front Propagation

Therefore, $du/dt = u\ du/dx$, and Eq. (1) becomes

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

Gust Front Propagation

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 $p^{'} = \Delta p$).

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

$$\rightarrow \quad U = \sqrt{\frac{2\Delta p}{\rho_0}} \qquad (3)$$

Gust Front Propagation

$$U = \sqrt{\frac{2\Delta p}{\rho_0}}$$

Equation (3) is the propagation speed of the gust front as related to the surface pressure perturbation (Δp) 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.

Gust Front Propagation

Assuming that Δp 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

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

Gust Front Propagation

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

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.

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.

Pressure Perturbations Ahead of the Gust Front

We can rewrite Eq. (2) as

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

$$\rightarrow \quad \frac{u^2}{2} + \frac{p^{'}}{\rho_0} = C. \tag{5}$$

Pressure Perturbations Ahead of the Gust Front

$$\frac{u^2}{2} + \frac{p'}{\rho_0} = C.$$

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).

An aside on the Bernoulli principle

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.

An aside on the Bernoulli principle

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.

Pressure Perturbations Ahead of the Gust Front

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), $p^{'}_{\text{stag}}$, is then given by

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

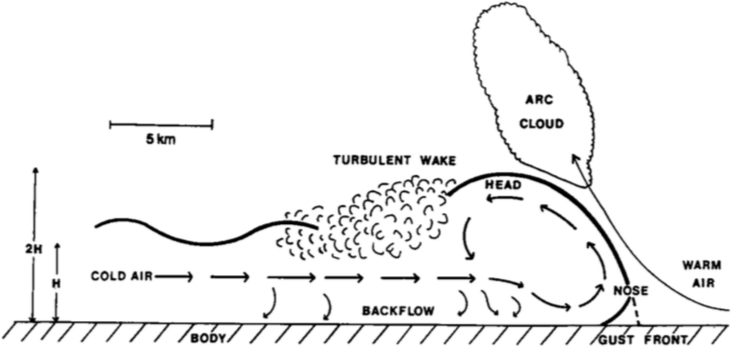
Pressure Perturbations Ahead of the Gust Front

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.

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.



Pressure Perturbations Associated with Rotors / Eddies

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

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

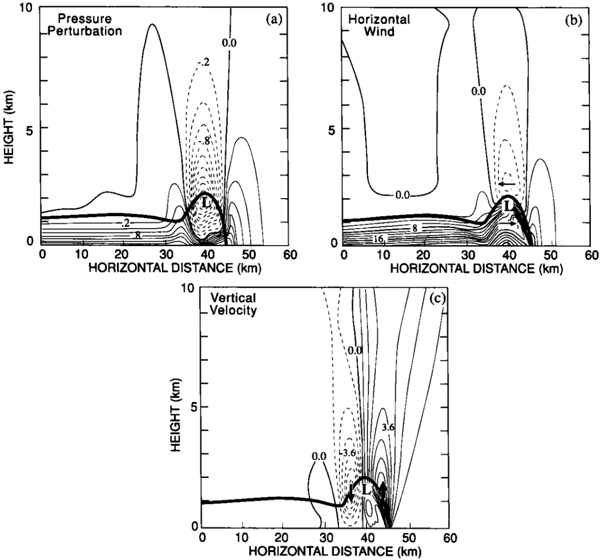
Pressure Perturbations Associated with Rotors / Eddies

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

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.

Pressure Perturbations Associated with Rotors / Eddies



Cell Regeneration in 2D Multicell Storms

Next, we will examine two representative modeling studies that address the theory of cell regeneration in multicell storms.

- Lin *et al.*
- Fovell *et al.*

Lin *et al.*

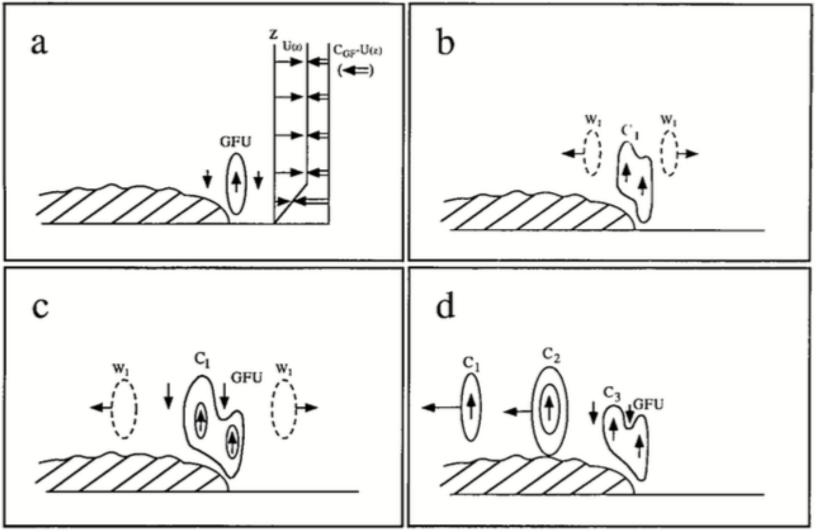
- Lin, Y.-L., R. L. Deal, and M. S. Kulie, 1998: Mechanisms of cell regeneration, development, and propagation within a two-dimensional multicell storm. *J. Atmos. Sci.*, **55**, 1867-1886.
- Lin, Y.-L., and L. Joyce, 2001: A further study of mechanisms of cell regeneration, propagation and development within two-dimensional multicell storms. *J. Atmos. Sci.*, **58**, 2957–2988.

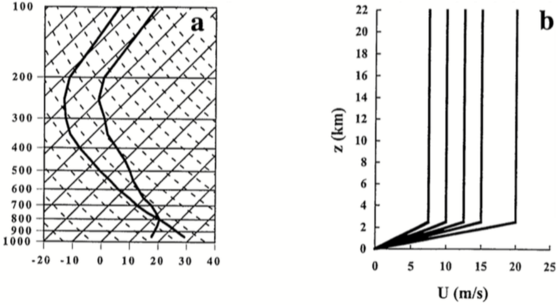
Cell Regeneration in 2D Multicell Storms

Fovell *et al.*

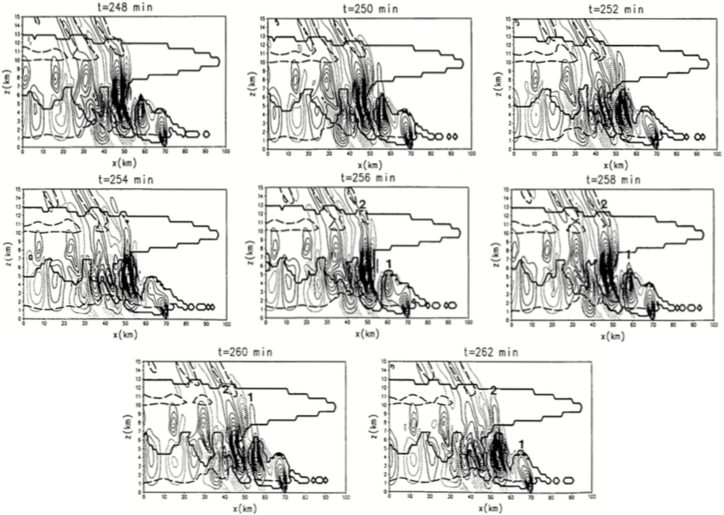
- Fovell, R. G., and P. S. Dailey, 1995: The temporal behavior of numerically simulated multicell-type storms, Part I: Modes of behavior. *J. Atmos. Sci.*, **52**, 2073-2095.
- Fovell, R. G., and P.-H. Tan, 1998: The Temporal Behavior of Numerically Simulated Multicell-Type Storms. Part II: The Convective Cell Life Cycle and Cell Regeneration. *Mon. Wea. Rev.*, **126**, 551-577.

Lin: Conceptual Model

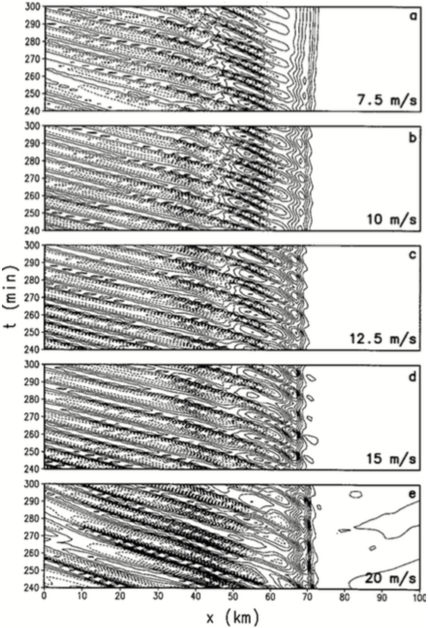



a
100
200
300
400
500
600
700
800
900
1000
-20
-10
0
10
20
30
40
b
z (km)
22
20
18
16
14
12
10
8
6
4
2
0
0
5
10
15
20
25
U (m/s)

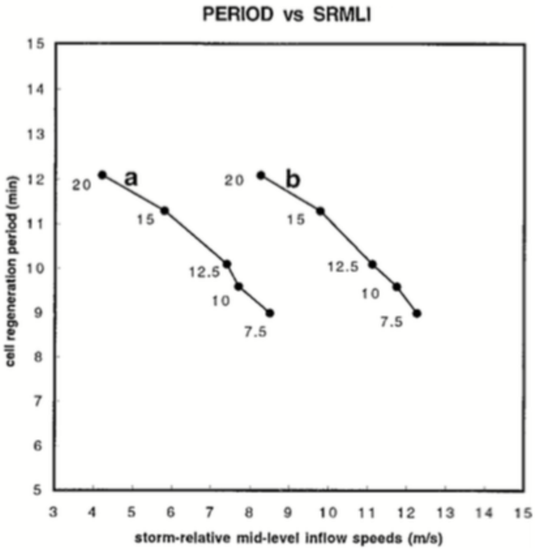
Lin: Lifecycle of Simulated 2D Storm



Lin: Lifecycle of Simulated 2D Storm



Lin: Lifecycle of Simulated 2D Storm



Lin: Lifecycle of Simulated 2D Storm

- 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.

Lin: Lifecycle of Simulated 2D Storm

- 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).

Summary of Lin and Joyce (2001)

- 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.

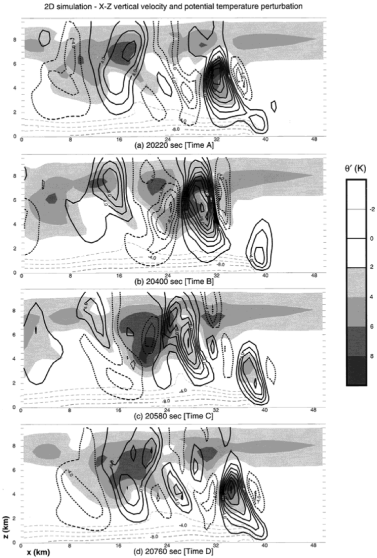
Fovell: Conceptual Model

- 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.

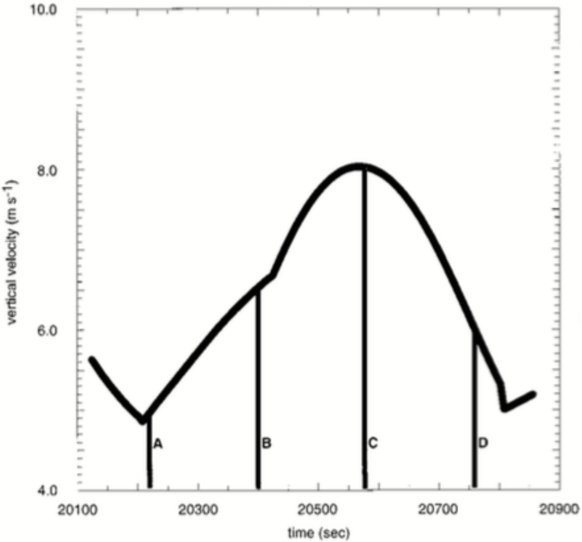
Fovell: Conceptual Model

- 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.

Fovell: Numerical Experiments



Fovell: Numerical Experiments



Fovell: Variation of the Forced Updraft

- Pressure field induced by perturbation buoyancy (derived from u and w momentum equations):

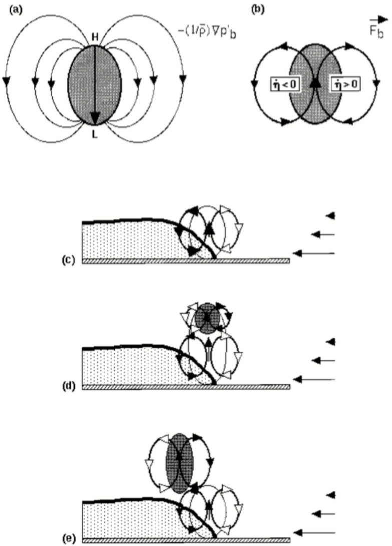
$$\nabla^2 p_h^{'} = \frac{\partial(\rho_0 B^{'})}{\partial z}.$$

- 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*.

Fovell: Effect of an Individual Convective Cell



Fovell: Influence of Transient Cell's Circulation

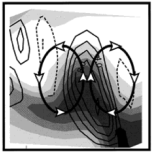
- At first, the positively buoyant air created by latent heating within the incipient cell is located above the forced updraft.
- The new cell's circulation enhances the upward acceleration of parcels rising within the forced updraft while partially counteracting the rearward push due to the cold pool's 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.

Fovell: Influence of Transient Cell's Circulation

- 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.

Fovell: 3 Stages in Life Cycle

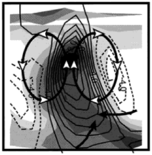
Three stages in life cycle of a convective cell



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 FTR airflow emanating from low-level storm inflow.

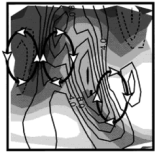


Stage 2 (maturation of cell)

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 "detrained" 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.

Summary of 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.

Summary of Cell Regeneration Theories

- 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.

The End