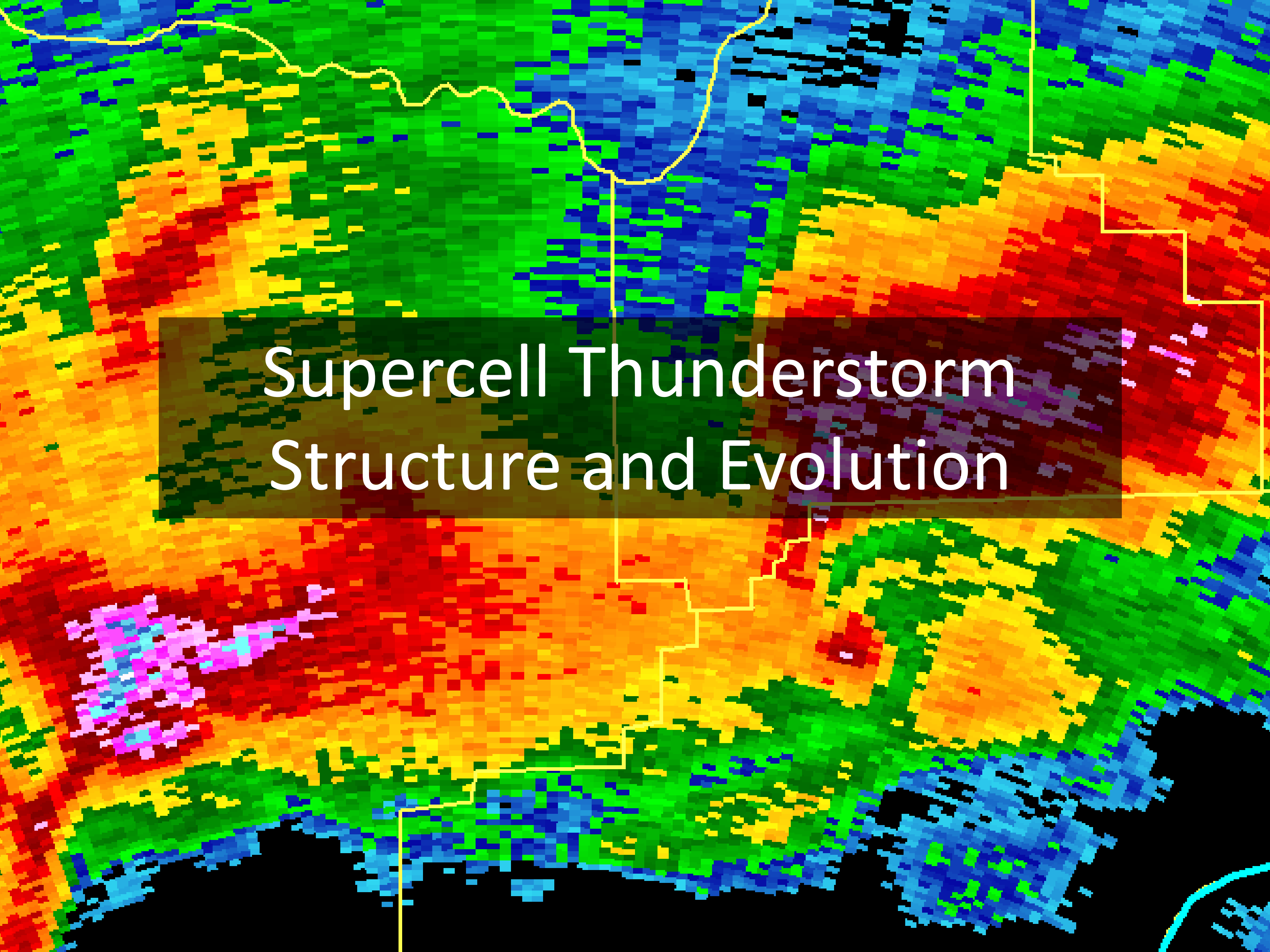
Supercell Thunderstorm Structure and Evolution



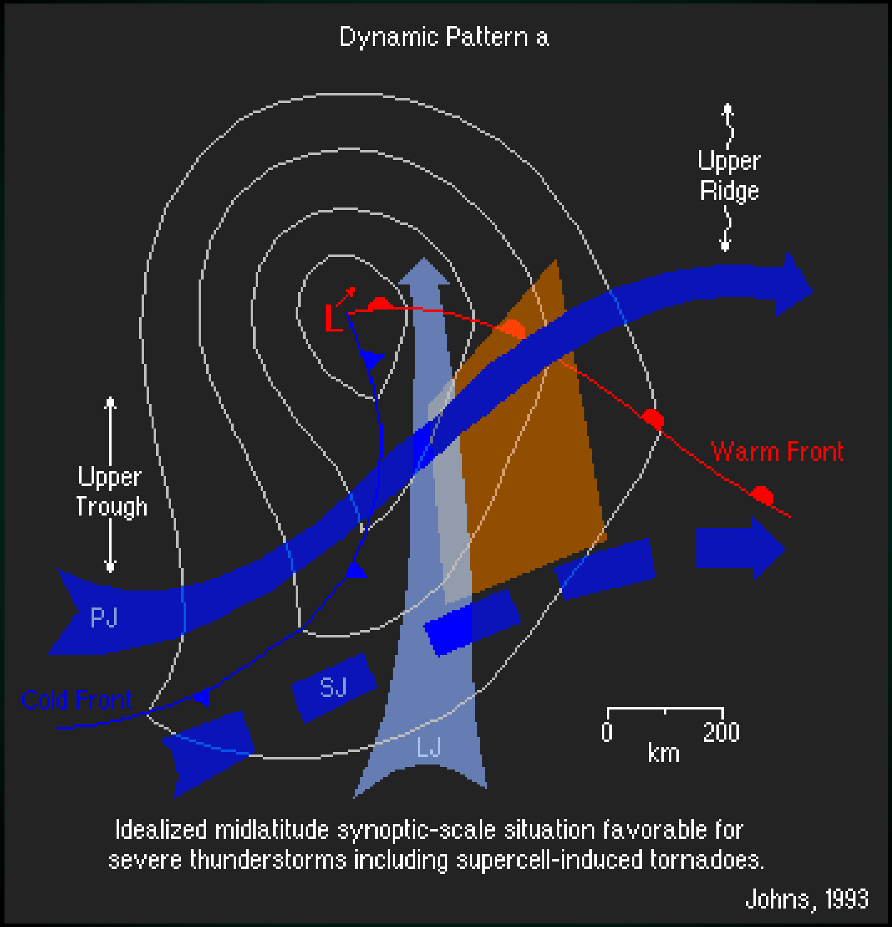
Supercellular Convection

- Most uncommon, but most dangerous storm type
- Produces almost all instances of very large hail and violent (EF4-EF5) tornadoes
- Highly organized due to strong environmental vertical wind shear and dynamic process in storm
- Buoyancy important, but less so than pulse/MCS storms since supercells dynamically controlled
- Long lifecycle; 1-4 hours is quite common; “super” cell was coined based on duration
- Contains a sustained rotating updraft (mesocyclone)

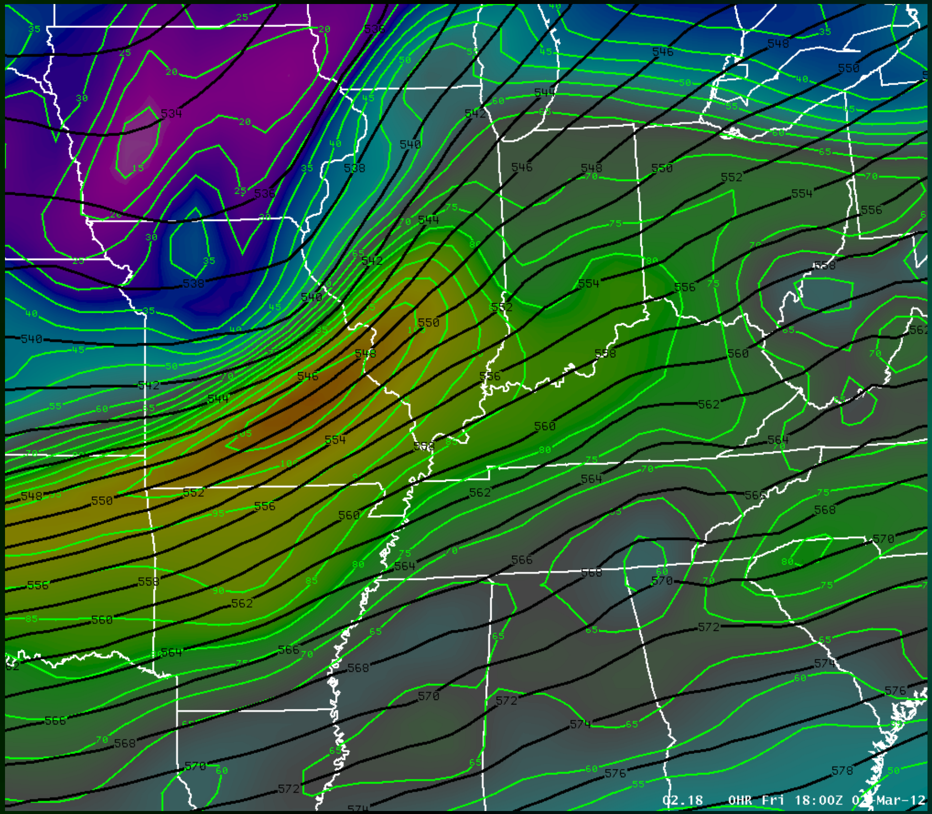
Important Concepts of a Supercell

- Mesocyclone
- Hook Echo
- Weak Echo Region (WER)
- Bounded Weak Echo Region (BWER)
- Creation of rotation in updraft
- Dynamic process
- Front Flank Downdraft (FFD)
- Rear Flank Downdraft (RFD)
- Splitting storm; right and left movers
- Wall cloud; tail cloud; mammatus cloud
- V-Notch

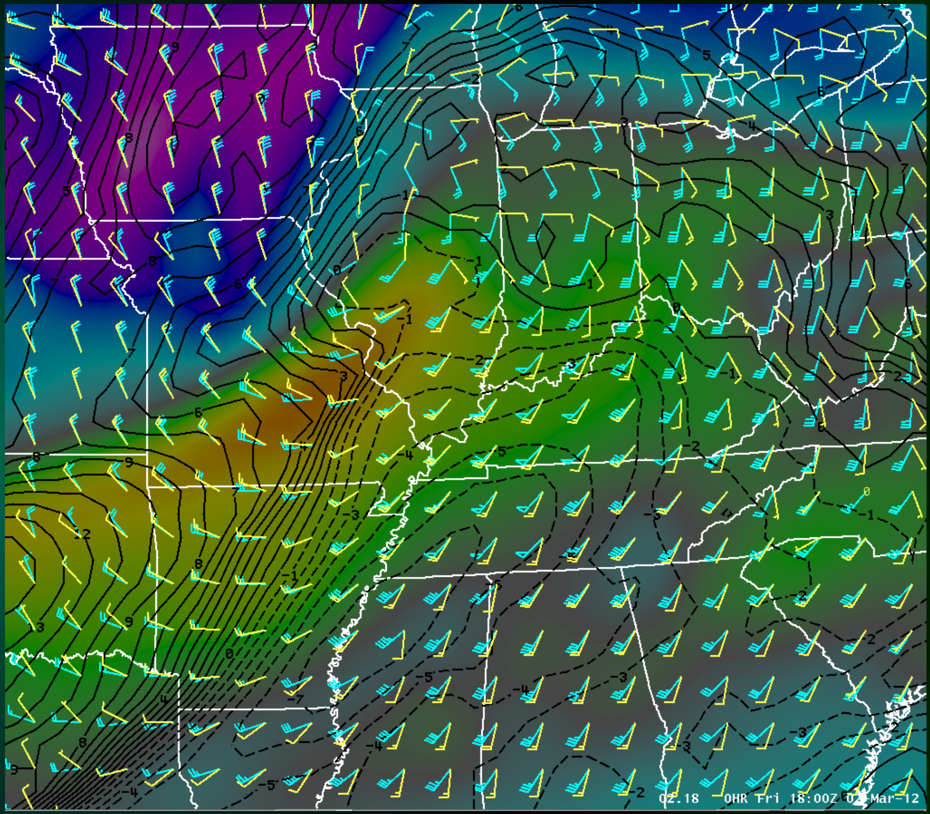
Supercell Environment



Supercell Environment



500 mb heights (black) and isotachs (green; image)

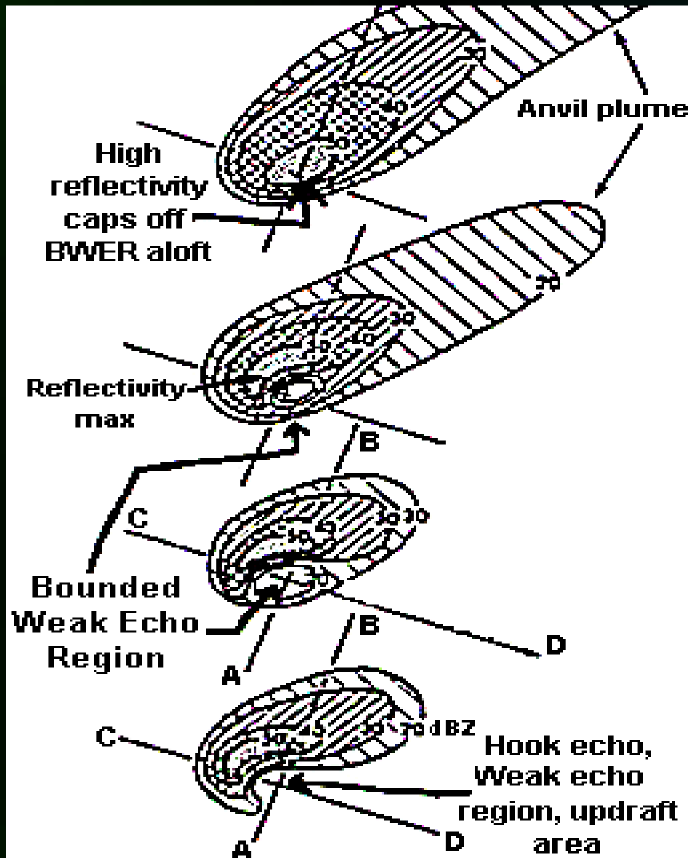


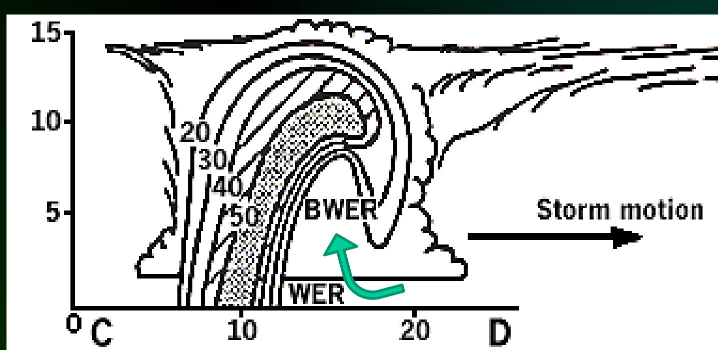
Sfc/850 mb winds; sfc LIs (black); 500 mb isotachs (image)

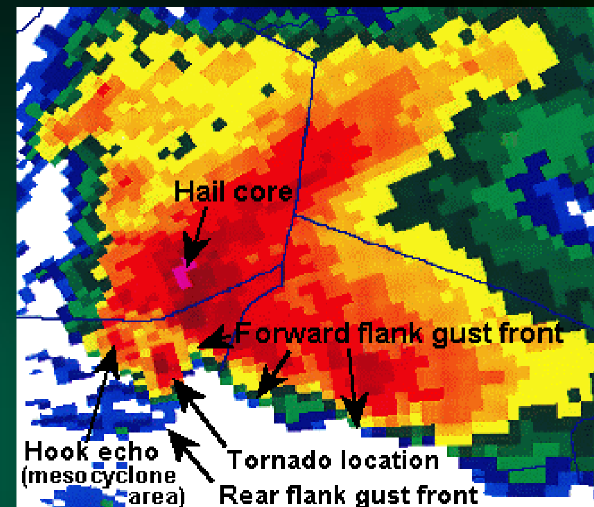
Typical supercell pattern:

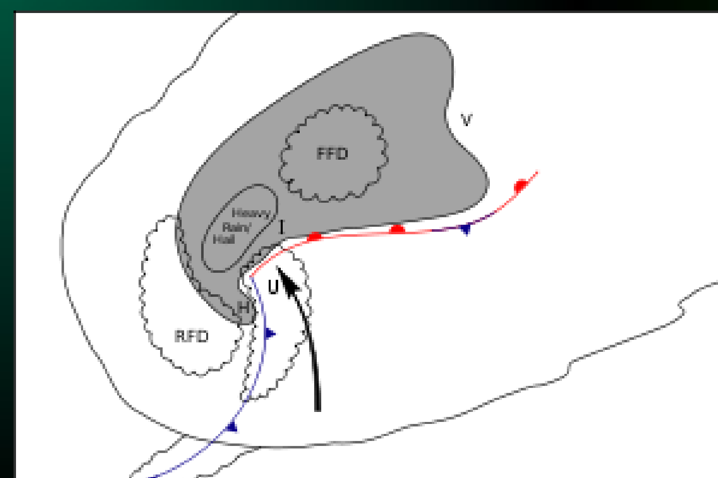
Upper trough/low to NW with jet exit region (even right exit region) over area. LLJ increases in response pulling axis of instability and strong shear northward. Storms often form in gradient zone of instability

Classic Supercell Structure



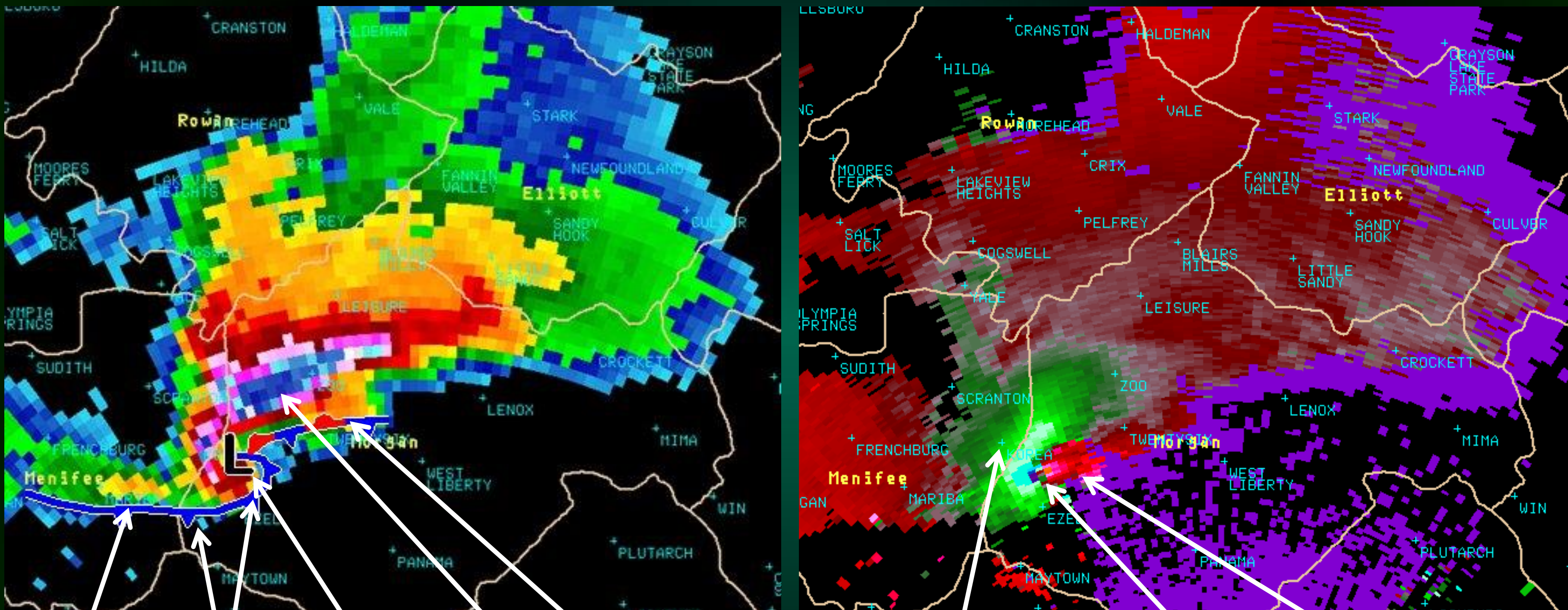






Classic Supercell Structure

West Liberty, KY Supercell March 2, 2012



Flanking line

Leading edge of RFD

Tornado location (debris ball)

Very large hail

Leading edge of FFD

RFD wrapping around mesocyclone and back side of storm

Low-level mesocyclone/ tornado location

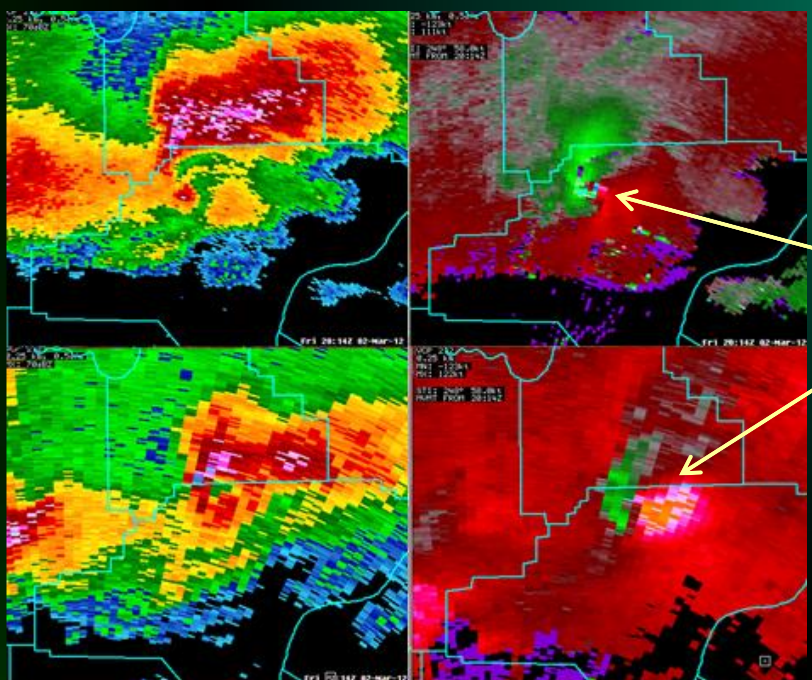
Storm-relative inflow into updraft

Convective-scale low and frontal structure

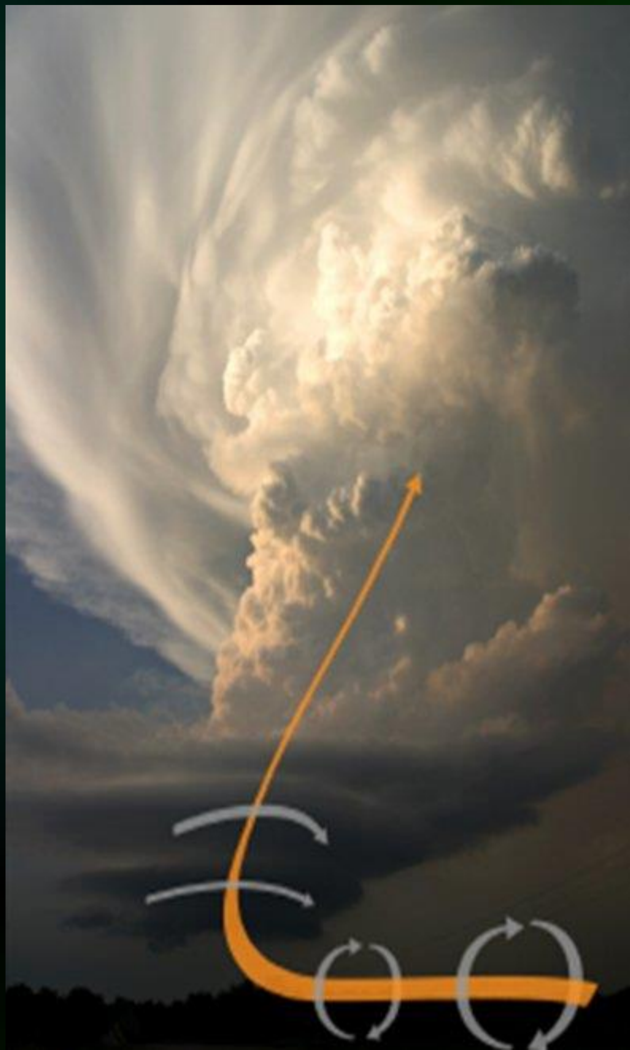
Retrieved Velocity: 118 kts inb, 76 kts outb (194 kt ΔV)

Supercell Characteristics: <u>**_Mesocyclone_**</u>

- Rotating updraft in a supercell; strongest in mid-levels
- Rotation develops as environmental horizontal vorticity tilts and accelerates into vertical. Storm dynamic process important
- Parent circulation that can lead to a tornado (necessary but not sufficient for a tornado; must have strong low-level rotation too)
- Can last for hours. Associated with EF0-EF5 tornadoes (almost all violent tornadoes associated with mesocyclones)

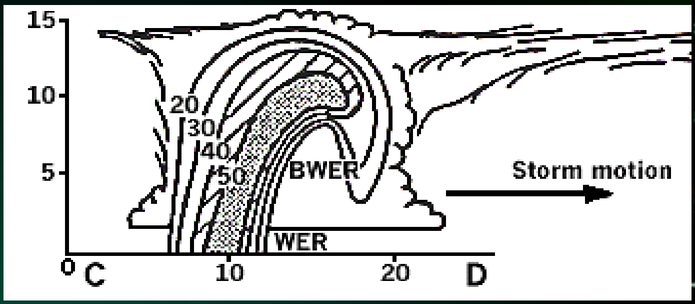


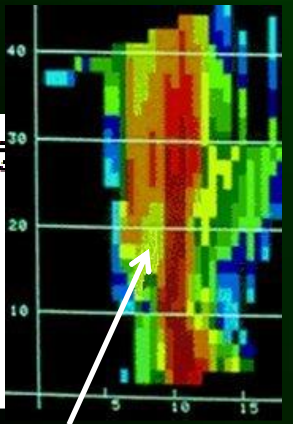
Low-level (top) and mid-level (bottom) cyclonically-rotating updraft (radar to south)



Supercell Characteristics: ***<u>WER/BWER</u>***

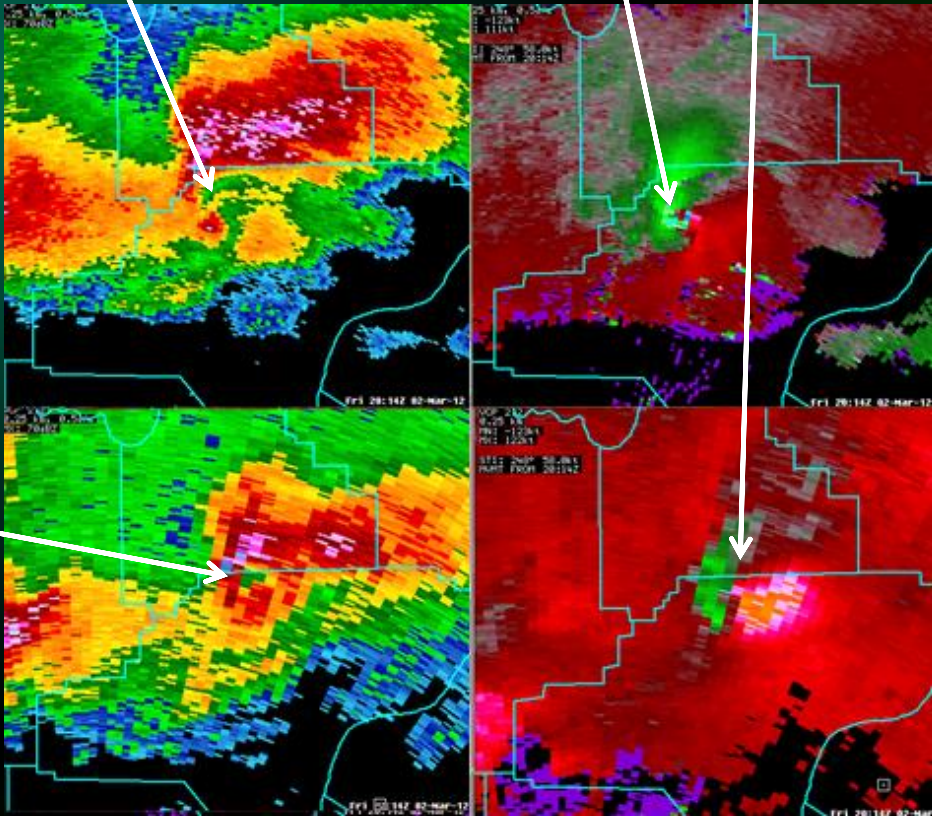
- *<u>Weak echo region (WER)</u>* is a low-level area of weak/low reflectivity on radar as strong updraft suspends and prevents precipitation from falling in this area
- Coincident/near inflow and updraft zone in and near hook echo
- *<u>Bounded weak echo region (BWER)</u>* is a mid-level weak/low reflectivity (cavity) aloft as intense updraft suspends and prevents precipitation from forming and falling in this area. Sometimes called an *echo free vault*
- Area of low reflectivity is "bounded" on all sides by higher reflectivity and signifies significant overhang/tilt of reflectivity
- BWER location is coincident with core of meso-cyclone (rotating updraft)

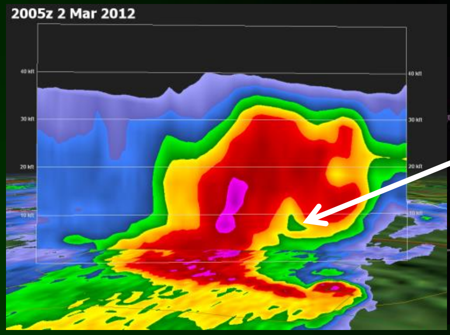




WER and BWER coincident with mesocyclone

Low-level WER

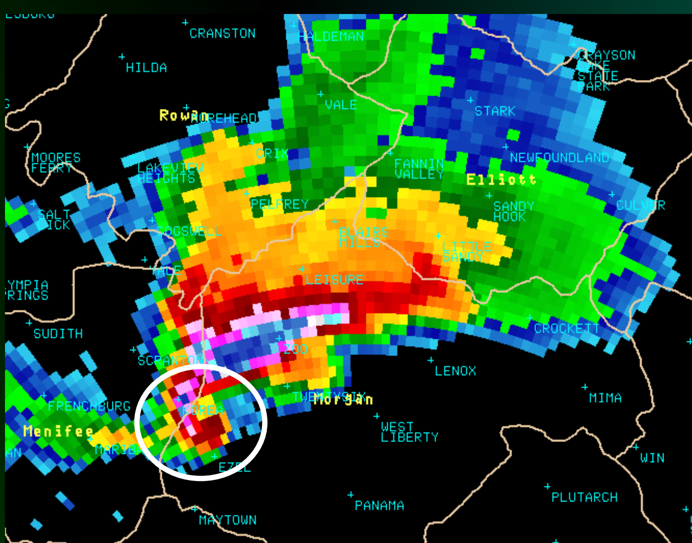




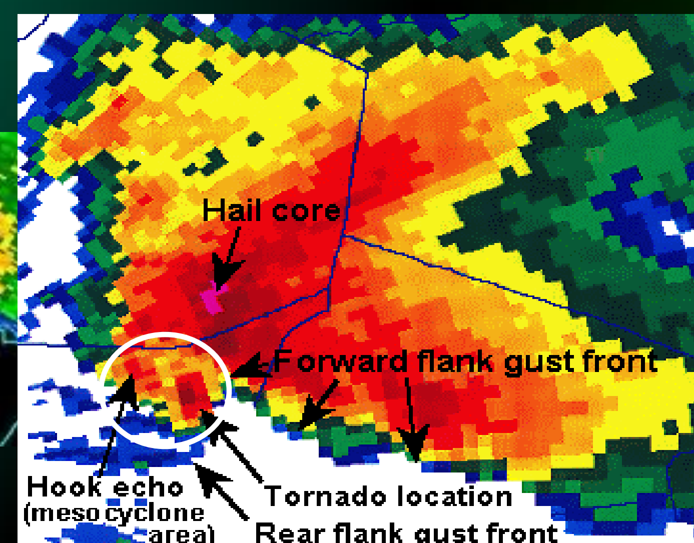
Mid-level BWER

Supercell Characteristics: **Hook Echo**

- In intense supercells, mid-level mesocyclone becomes strong enough to wrap precipitation around to backside of updraft, creating a characteristic pendant or hook echo. Low-level mesocyclone (from which a tornado can form) is located within notch of hook
- Represents a band of precipitation (or hail stones) located near boundary between updraft and downdraft, surrounded by WER. Significant temperature gradients can occur across it
- Presence of hook echo does not mean a tornado is occurring or will develop, but signifies processes important to tornadogenesis. Supercell tornadoes occur in hook area



Debris ball:
Tornado on ground

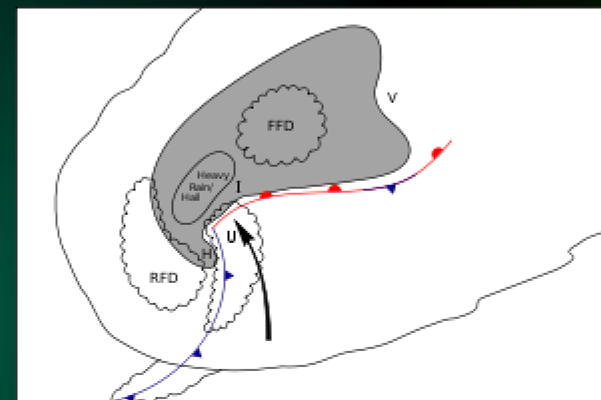


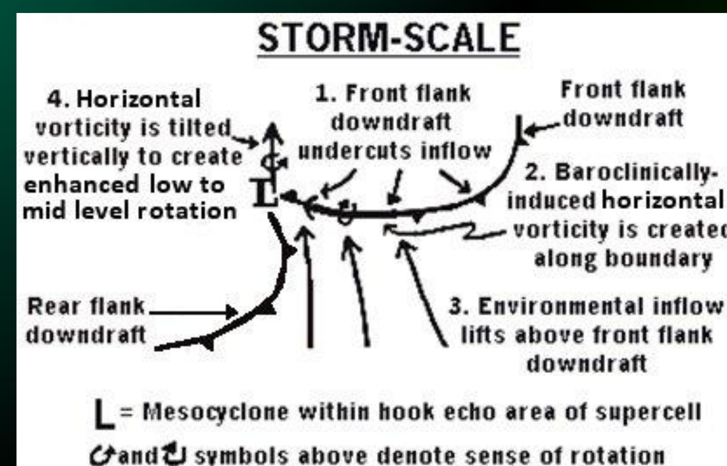
Supercell Characteristics:
Front Flank Downdraft

- Forms from water loading (dragging cool air downward), melting, and evaporation which creates a cold pool and outflow boundary northeast of hook echo and tornado location

- Outflow boundary is on leading and southern side of FFD. Storm-relative inflow advances into boundary from the south or east as boundary becomes quasi-stationary

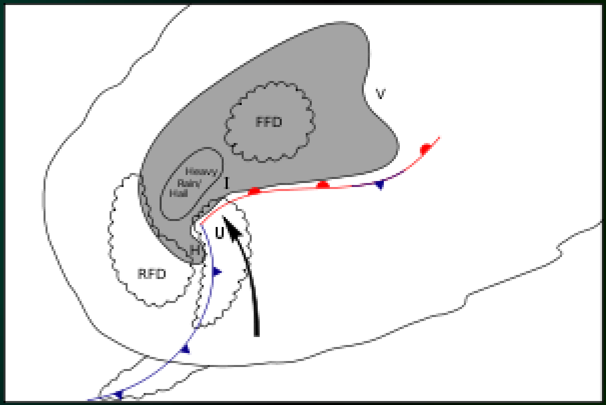
- Horizontal vorticity occurs along boundary as inflow air rides over top of outflow from north. Vorticity can be pulled west along boundary, converge into hook area, and be tilted into updraft (U) to augment low- and mid-level mesocyclone. However, RFD seems to be most associated with tornadogenesis



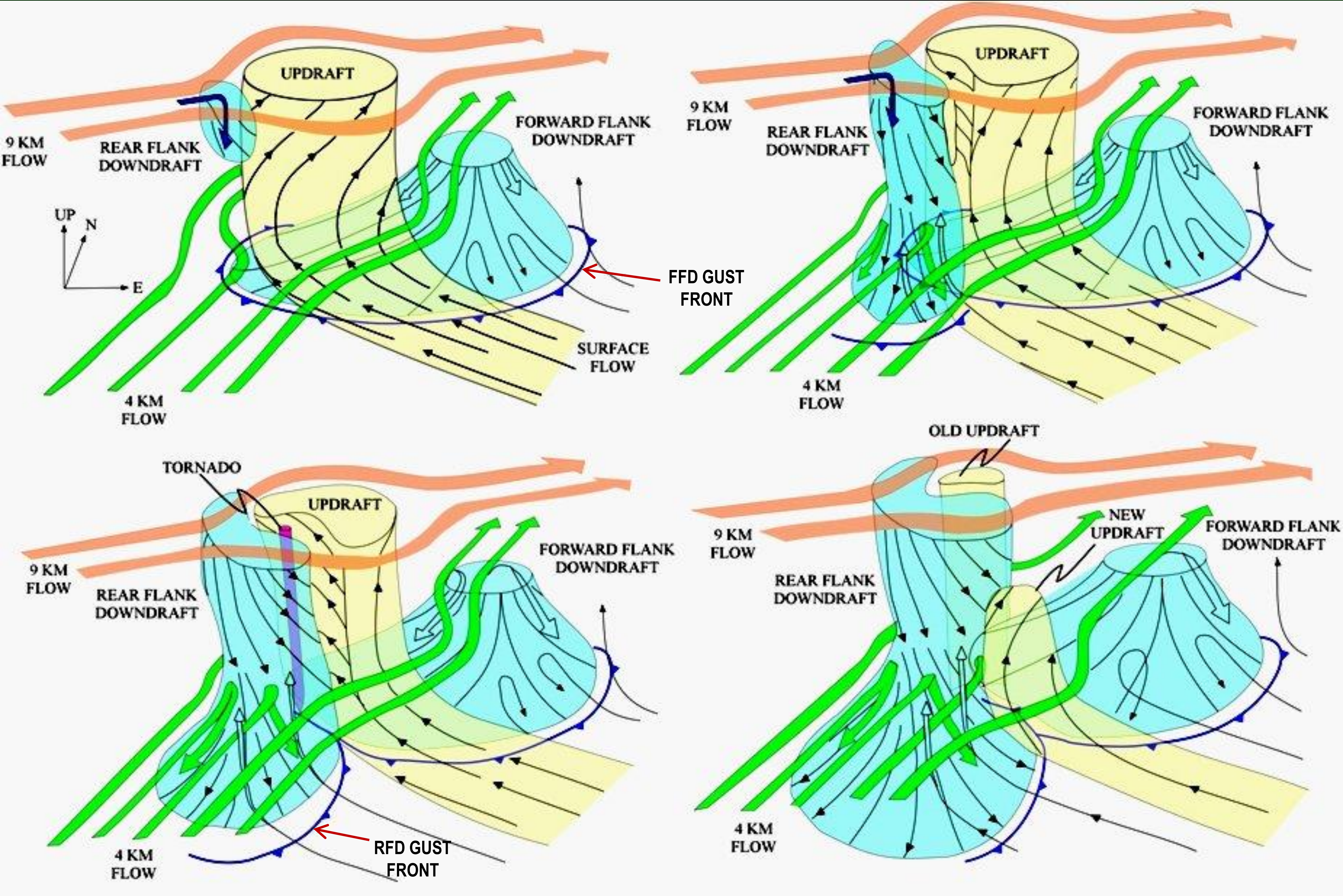


Supercell Characteristics: **Rear Flank Downdraft**

- Complex thermodynamically and dynamically induced region of subsiding air that develops on rear side of main updraft of supercell
- Formation can occur due to thermodynamics – evaporative cooling and increase in negative buoyancy, or dynamics – blocking flow and vertical pressure gradient forces that lead to descent
- Rotating updraft acts as an obstruction (barrier) to mid-upper level flow. As high pressure builds on upwind end of storm, air begins to sink forming RFD on back side of supercell. Drier air entrained from behind storm can increase negative buoyancy. When RFD hits ground, it spreads out along RFD gust front and can cause significant straight-line wind damage
- RFD can arrive at surface warmer than surroundings due to adiabatic warming in absence of precipitation and evaporative cooling, or arrive cooler due to evaporative cooling. Properties of RFD have an impact on whether a tornado will form or not
- RFD gust front is leading edge of downdraft and arcs back into updraft/hook area where it can enhance low-level convergence and low-level spin up of vorticity to enhance tornadogenesis
- Just south of tornado location, significant straight-line wind damage can occur along RFD gust front



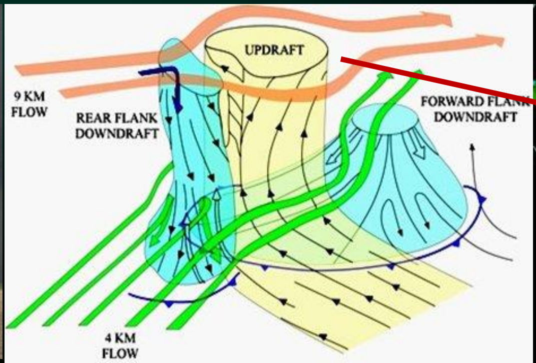
Supercell Characteristics: <u>Rear Flank Downdraft</u>

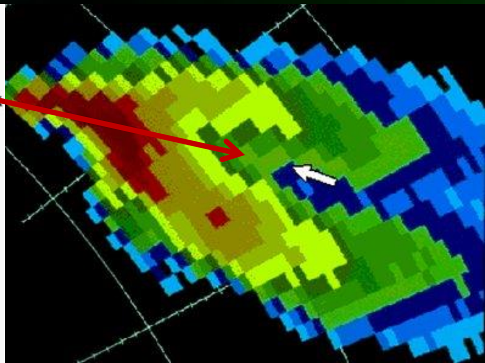


Supercell Characteristics: **Types of Clouds/V-Notch**

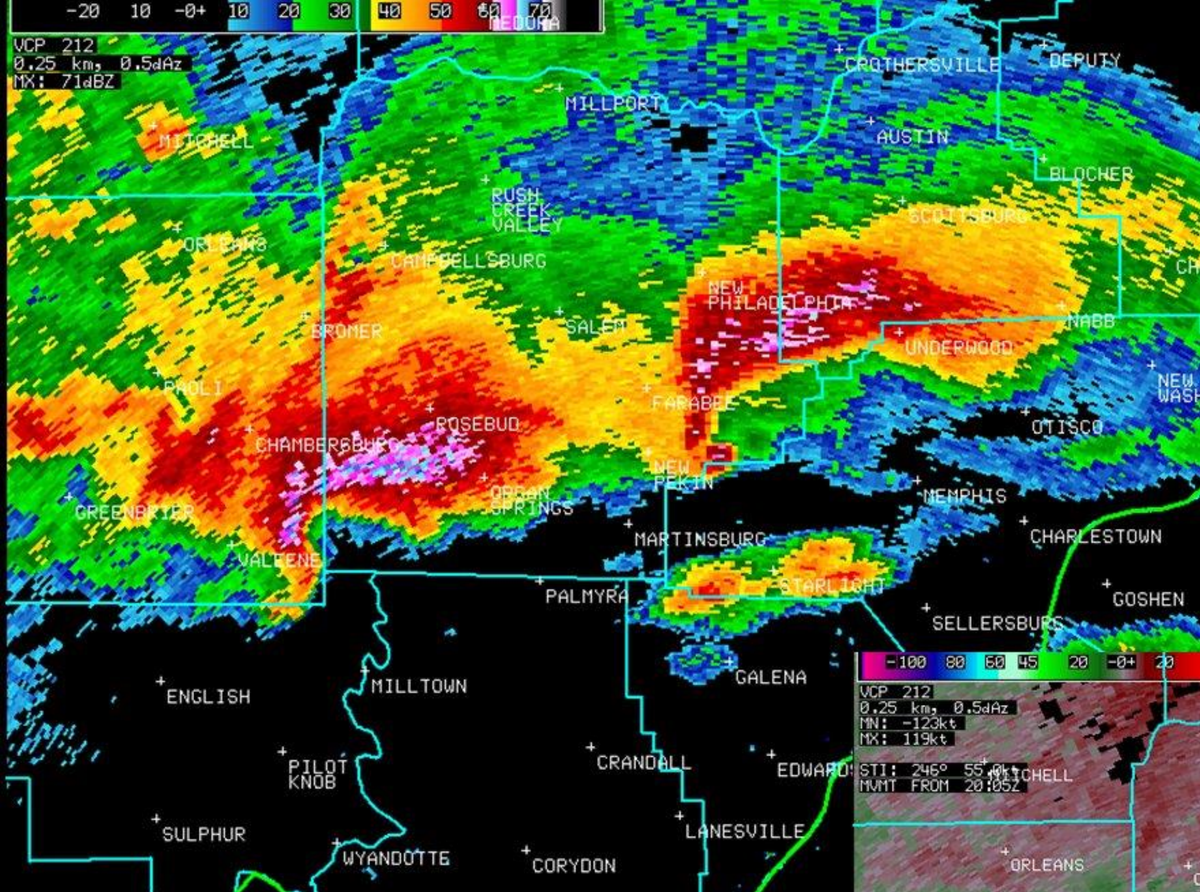
- *Wall cloud*: A lowering, rotating cloud base where humid rain-cooled air from downdraft is drawn into updraft. An indication of low-level mesocyclone from which tornado drops
- *Tail cloud*: Tail of wall cloud that points toward FFD. Feeder air coming into low-level mesocyclone
- *Mammatus cloud*: Forms on underside of anvil. Composed of pockets of cooled air as particles fall and evaporate. Does not produce severe weather, but may be associated with a strong/severe storm
- *V-Notch*: Slot of lower reflectivity values that can appear on downwind edge of reflectivity field surrounded by higher values in strong supercells. Due to blocking flow aloft around updraft core



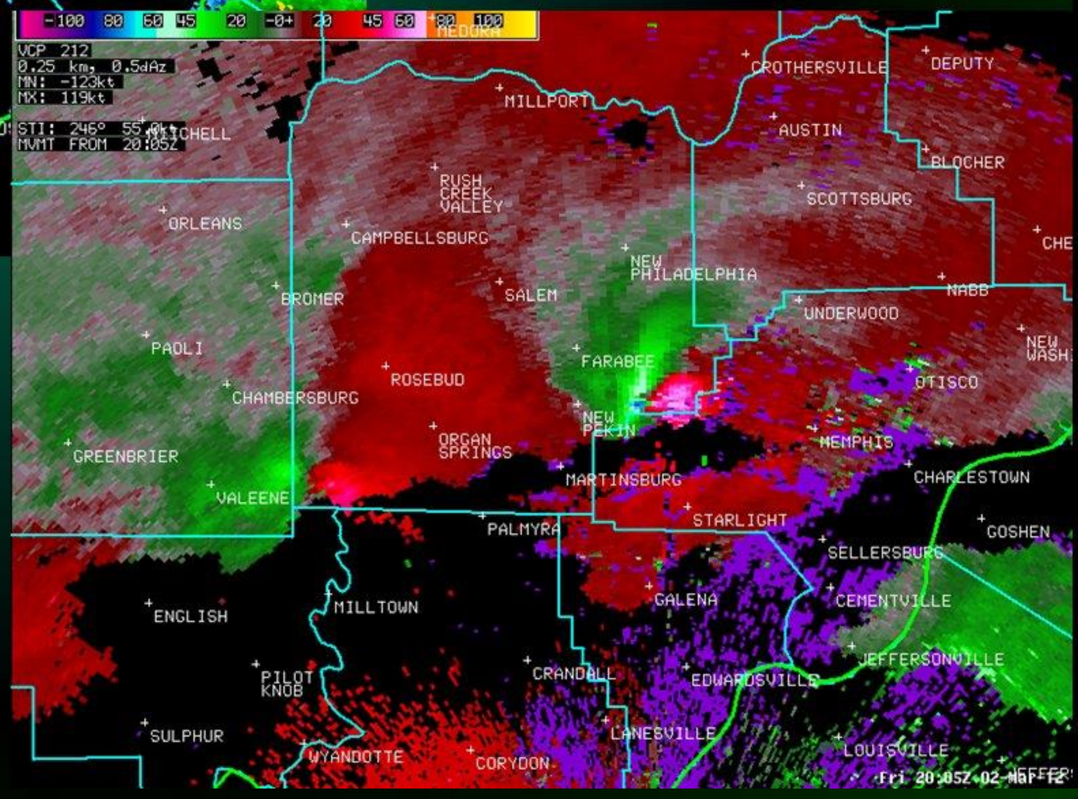




March 2, 2012 Supercells over Southern Indiana

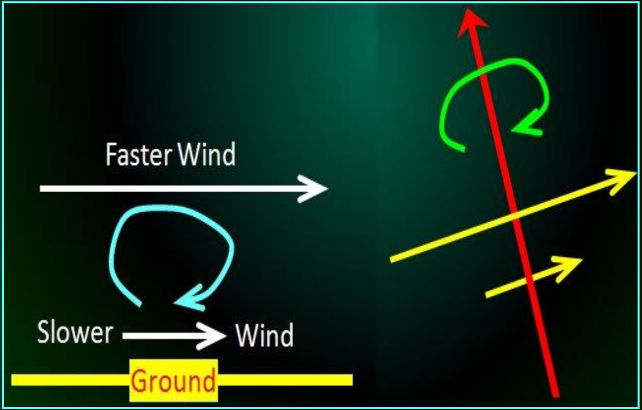


Classic low-level supercell structure is evident in reflectivity and S-R velocity data. A *debris ball* (small area of high reflectivity) is shown in hook, meaning a tornado may be on ground. A cell merger into inflow flank of lead supercell occurred just before tornado intensified. Lead supercell produced a 49-mile track tornado, which peaked at EF4 intensity. A bow echo approached from the west late in loop.



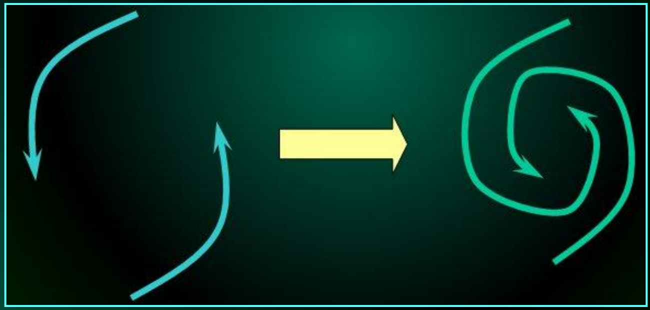
Development and Enhancement of Updraft Rotation

- In order for supercells to rotate (i.e., to create a rotating updraft/mesocyclone), there must be some type of rotation available in environment
- Important processes in creating and enhancing rotation about a vertical axis (vertical vorticity): *environmental wind shear, convergence, low-level boundary, tilting, vertical stretching*
- ***Environmental wind shear***: Primary way to create updraft rotation is from environmental vertical wind shear, which creates horizontal rotation (vorticity) in environment
- Ground-relative and storm-relative westerly winds increase with height, creating rotation about a horizontal axis (rolls)
- The stronger the vertical shear, the stronger the horizontal vorticity. Strong environmental shear is crucial to updraft rotation development and strength

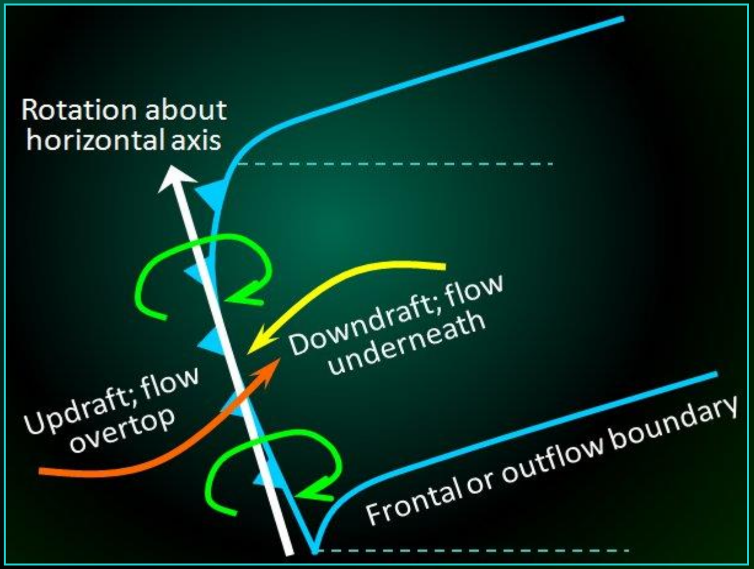


Development and Enhancement of Updraft Rotation

- ***Convergence***: Consider a sink. Initially there is some weak rotation, but as water converges toward drain, speed of rotation increases. This is conservation of angular momentum – radius of rotation decreases so rotational velocity must increase. Convergence into updraft can result in rotation development or increase in existing rotation (ice skater effect)



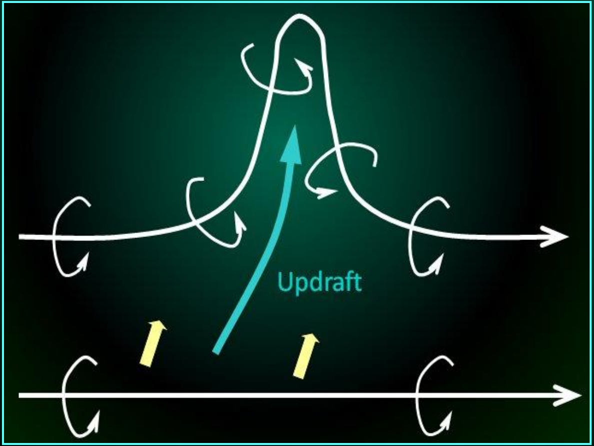
- ***Low-level boundary***: Air travelling along a frontal zone or outflow boundary will develop rotation about a horizontal axis (horizontal vorticity) as warm air rides over top and cool air flows underneath horizontal boundary

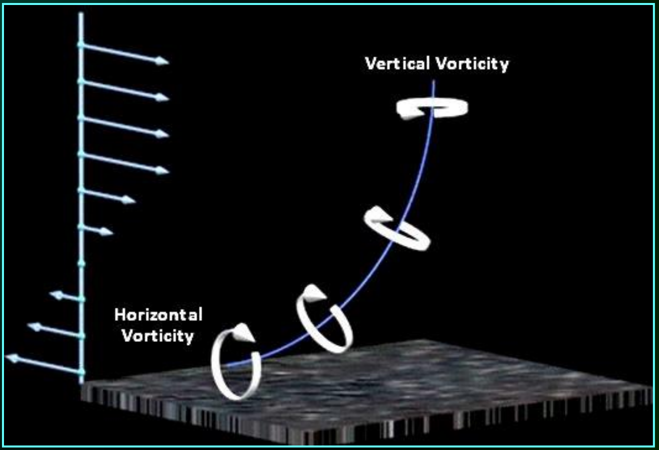


- Convergence and low-level boundary are smaller-scale sources of horizontal vorticity than that created by environmental wind shear. These smaller sources augment the necessary larger scale shear in enhancing and focusing horizontal vorticity generation

Development and Enhancement of Updraft Rotation

- ***Tilting***: In order to create vertical rotation (vorticity) from horizontal rotation (vorticity), must tilt horizontal rotation into vertical. In thunderstorms, this tilting is achieved by the updraft



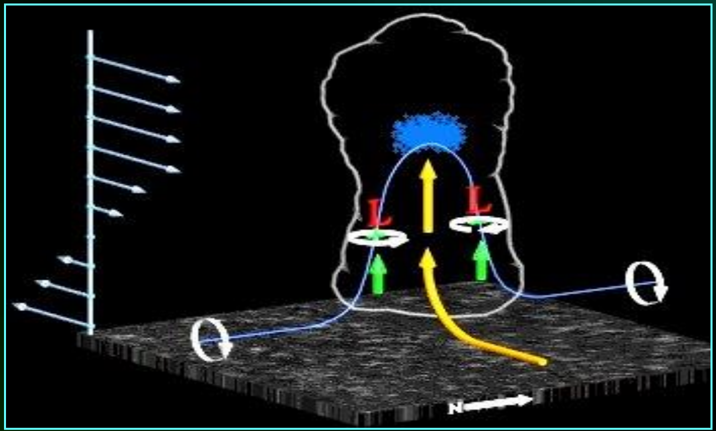


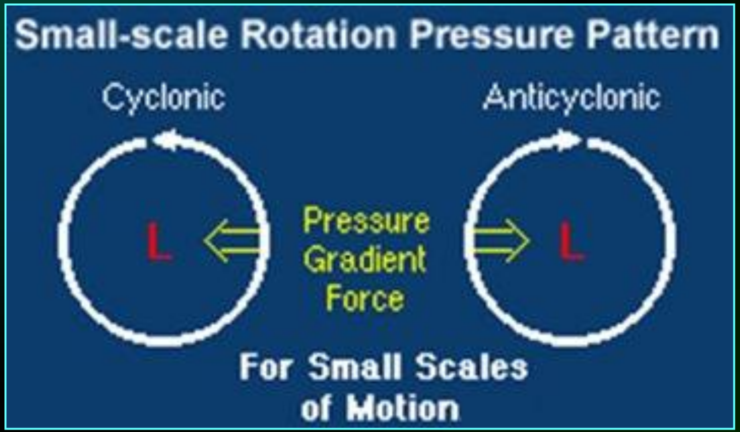
Development and Enhancement of Updraft Rotation

- ***Vertical stretching***: Updraft accelerates as it rises and is usually strongest in mid levels
- Increasing speed with height causes vertical stretching, i.e., vertical divergence which is compensated for by horizontal convergence (column narrows in width)
- Angular momentum (AM) must be conserved
- AM = (Mass) x (Rotational Velocity) x (Radius to Axis of Rotation). Since radius to axis of rotation decreases, rotational velocity must increase, i.e., vertical stretching increases updraft speed
- Vertical stretching due to vertical acceleration is a crucial process to strong mid-level mesocyclone development

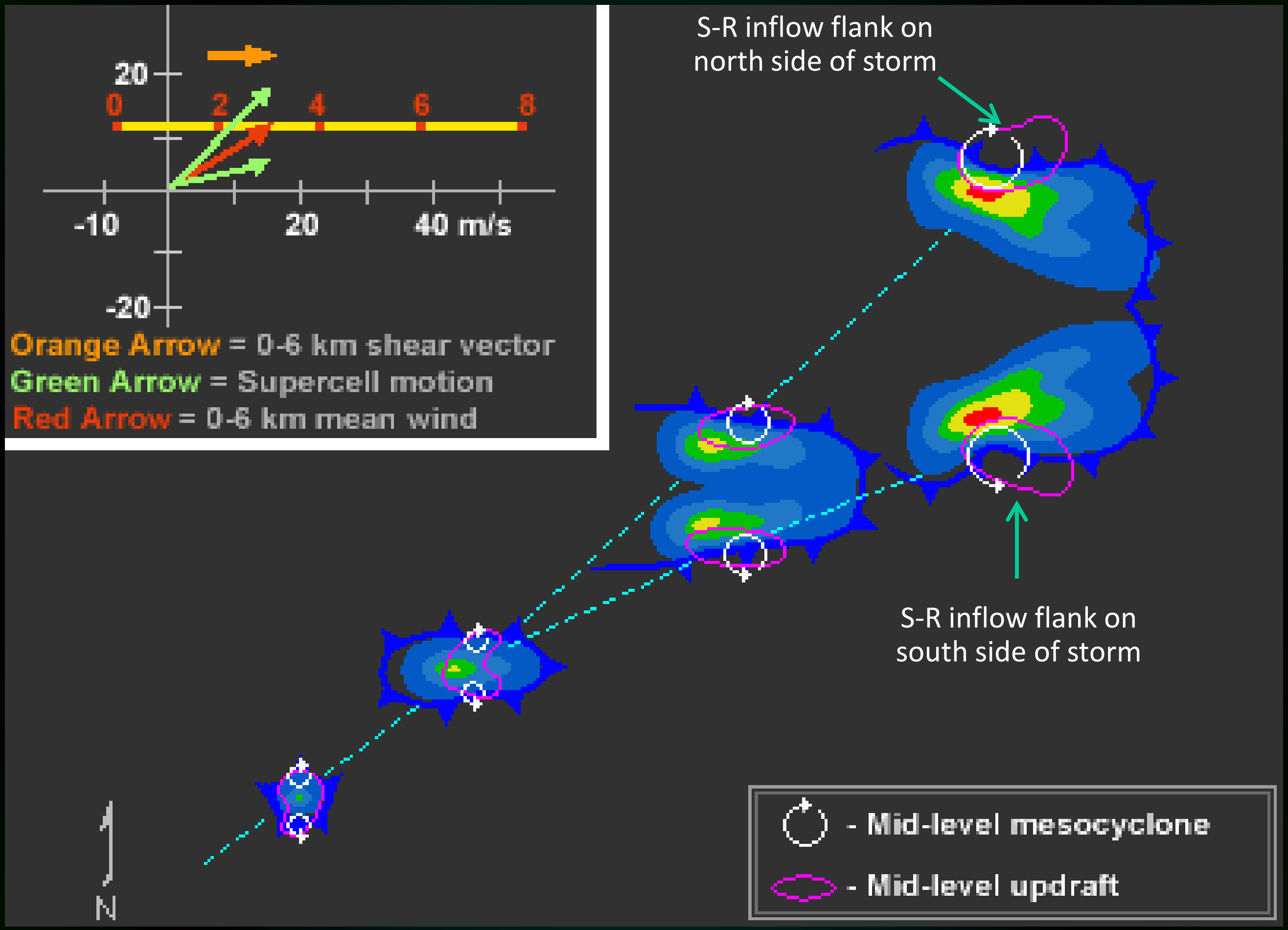
Dynamical Process in Supercells

- Environmental shear leads to a rotating updraft as horizontal vorticity is titled and stretched into updraft. This causes development of a *dynamic process* in storm which affects evolution, strength, longevity, and motion of supercell
- Rotation about a vertical axis must be balanced by a pressure gradient force pointed toward center of rotation, i.e., low pressure is dynamically produced at center of rotation with PGF directed toward it. Low is strongest in mid-levels of storm where rotation/updraft is strongest
- Low pressure leads to an even stronger updraft in mid-levels as supercell can actually “suck up” air into low. This in turn causes even more rotation (due to vertical stretching) as updraft speed increases with height, which in turn can feed back and cause an even stronger mid-level low. Results in enhanced steady-state updraft. Deeper shear usually means more efficient dynamic process
- Dynamic forces are as or more important than buoyancy forces in supporting updraft strength and rotation. Dynamic process can cause splitting supercells and a right movement of storm compared to mean wind. Process is also important to tornado development



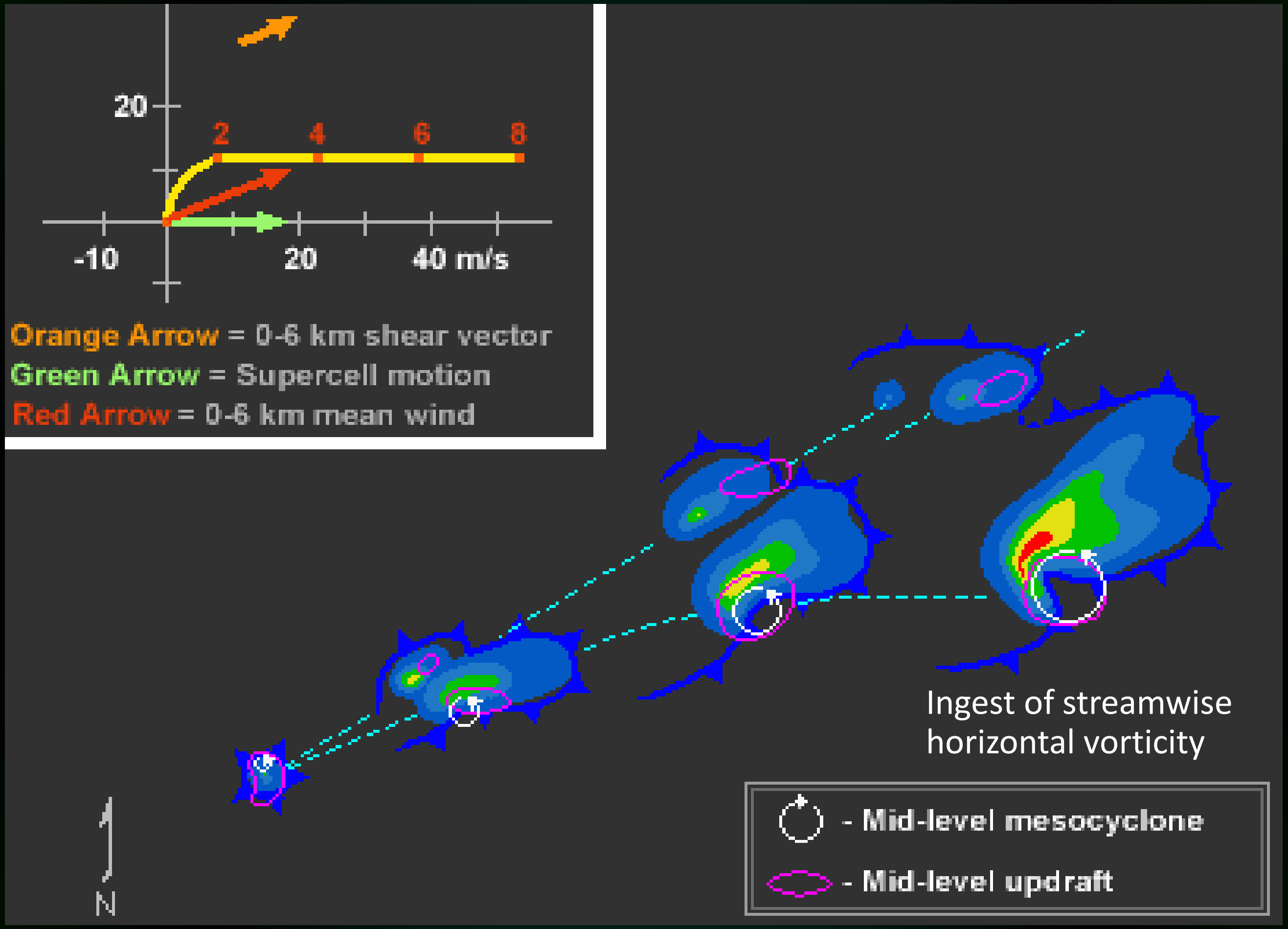


Hodograph Type Vs. Supercell Characteristics



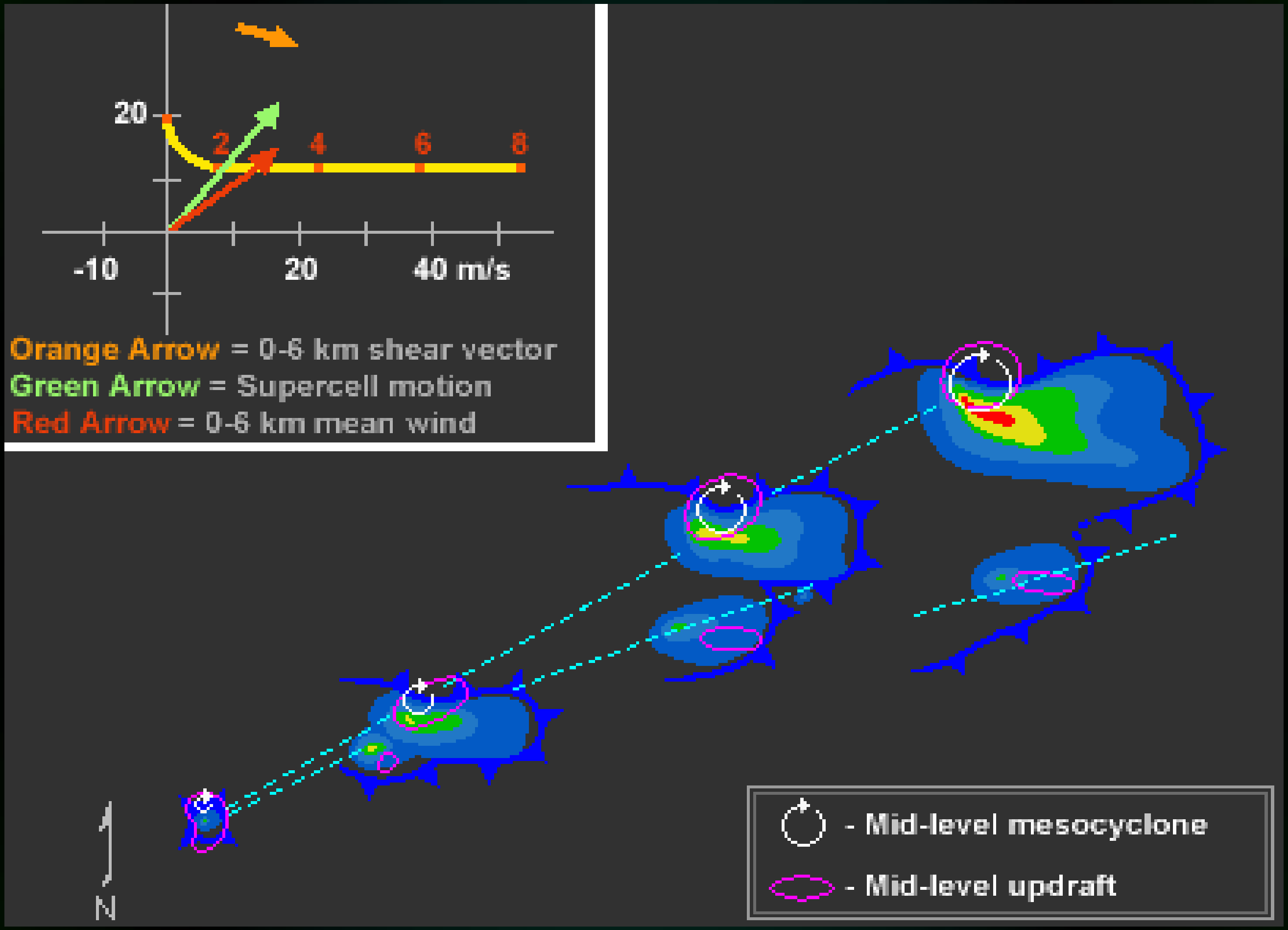
Straight hodograph favors storm split with equally strong left and right movers. Right (left) mover has an cyclonically (anticylonically) rotating updraft. The right (left) mover moves to right (left) of the mean wind at a speed slower (faster) than the mean wind.

Hodograph Type Vs. Supercell Characteristics

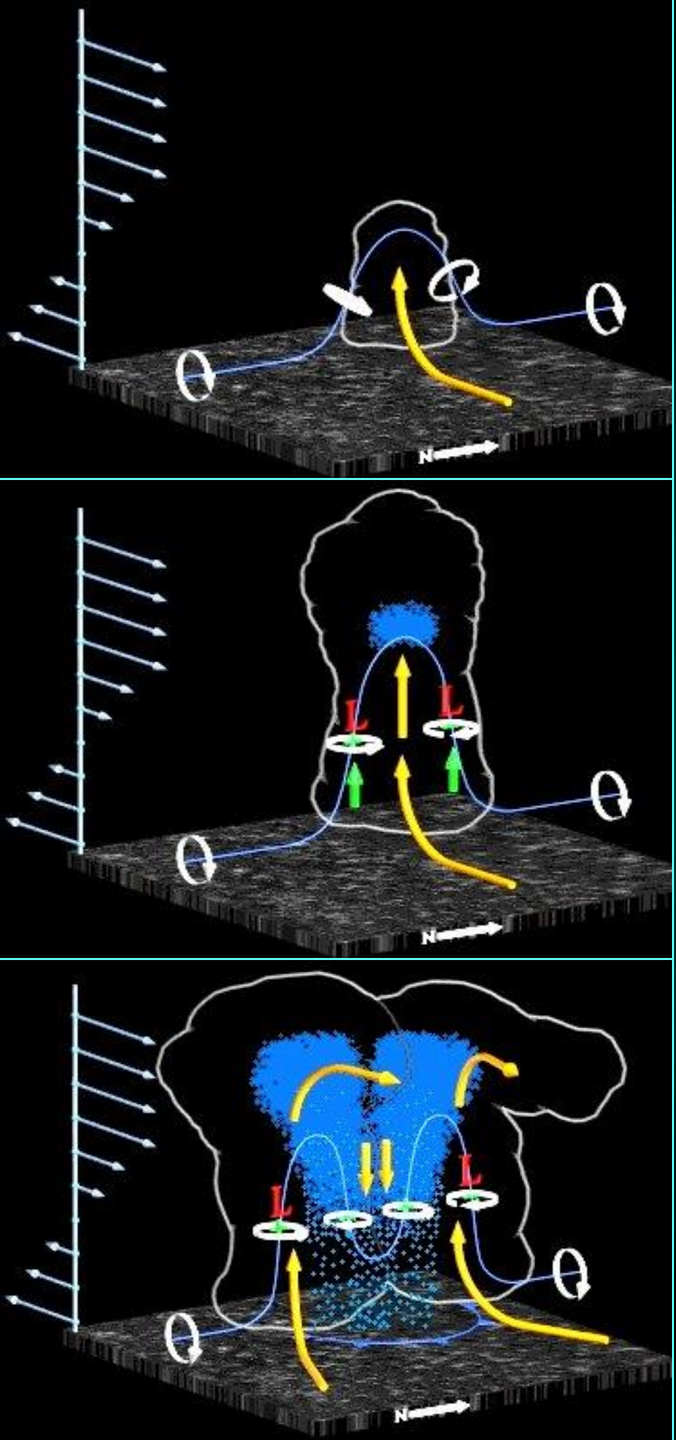


Curved hodograph favors storm split with dominant right mover and weakening left mover. Intense cyclonically rotating updraft develops in right mover on southern inflow flank of storm, as streamwise vorticity is tilted into updraft. S-R inflow is enhanced into right mover due to presence of low-level jet. Left mover experiences little S-R inflow as it is moving away from the low-level jet.

Hodograph Type Vs. Supercell Characteristics



Curved hodograph (opposite curvature) favors storm split with dominant left mover and weakening right mover. Often, hodograph would be below x-axis implying northerly ground-relative and storm-relative winds providing inflow into left mover from the north. This type of scenario is not common.

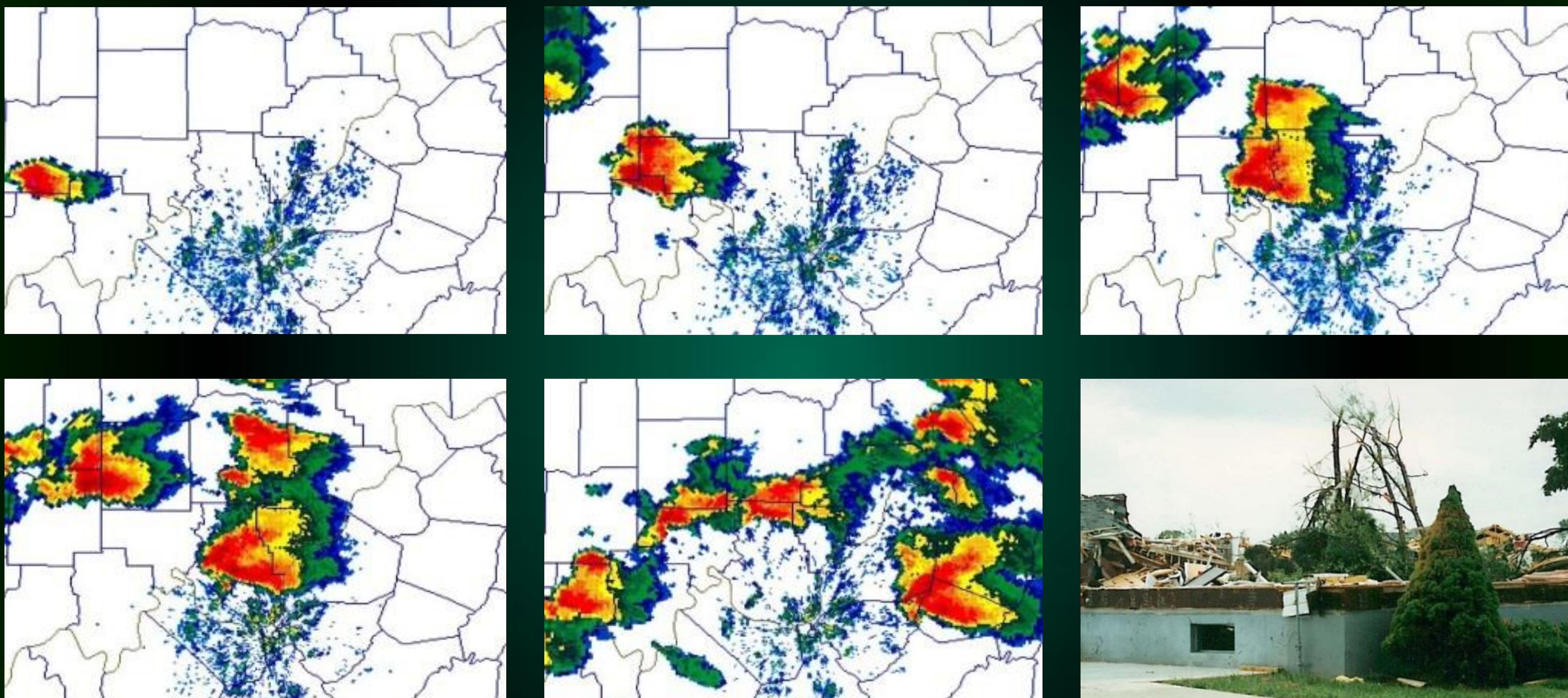


Splitting Supercell

Supercell moving roughly with mean wind – straight hodograph

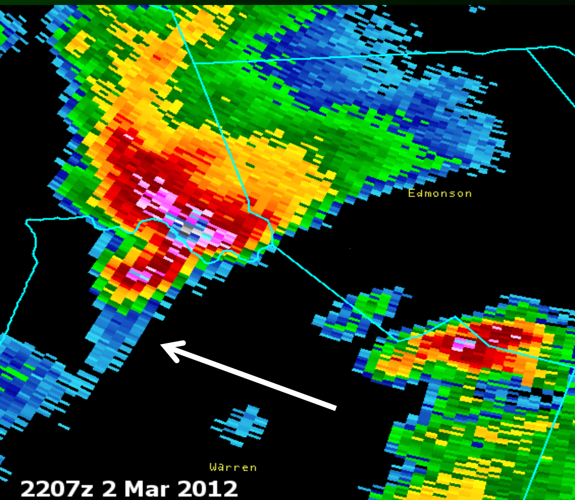
Horizontal vorticity is tilted into updraft creating cyclonic (+) and anticyclonic (-) vertical vorticity on south and north side of storm. Dynamic low pressure in response to rotation enhances updraft. Rain causes downdraft in middle which splits storm in 2. For a right (left) moving storm, cyclonic rotation is in updraft (downdraft) and anticyclonic rotation is in downdraft (updraft) with tight reflectivity gradient (inflow flank) on south/east (north) side of storm.

Splitting Supercell: May 28, 1996

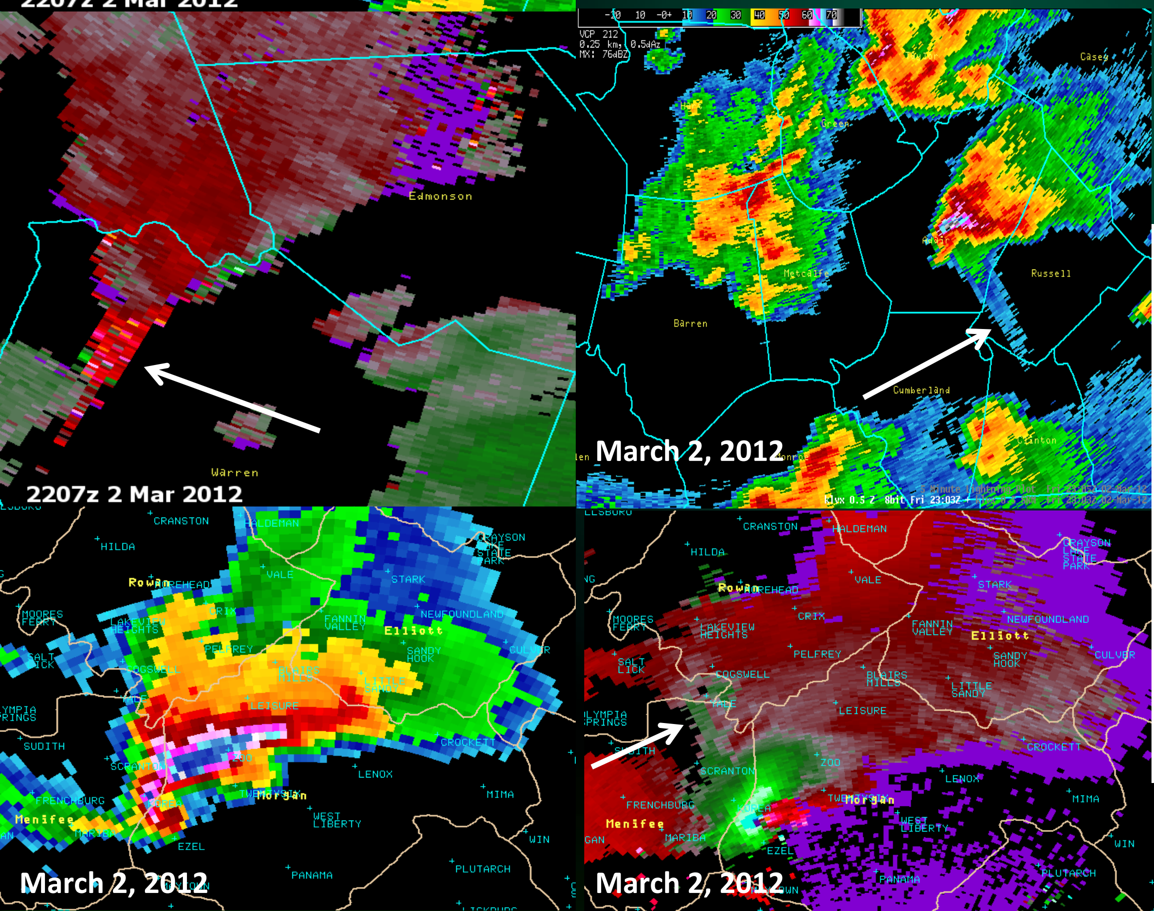


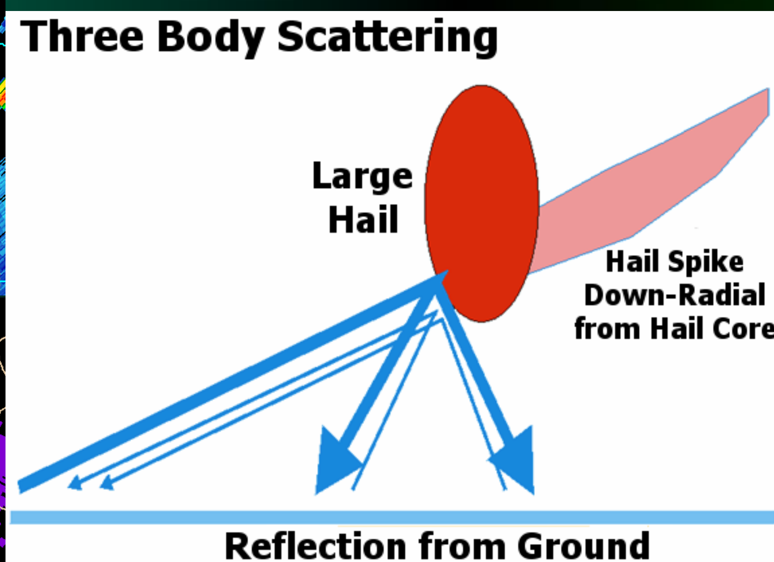
Classic supercell storm split with dominant right mover. Storm started out moving northeast over southern IN, then split with right mover turning to southeast, where it experienced much greater storm-relative inflow and streamwise horizontal vorticity which enhanced storm severity and mesocyclone intensity. The storm produced an F3-F4 tornado just south and east of Louisville.

Three-Body Scatter Spike

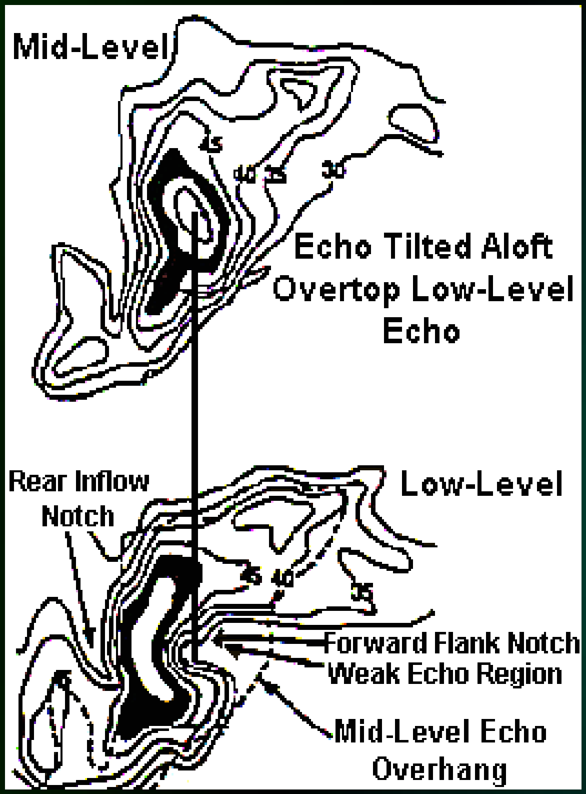


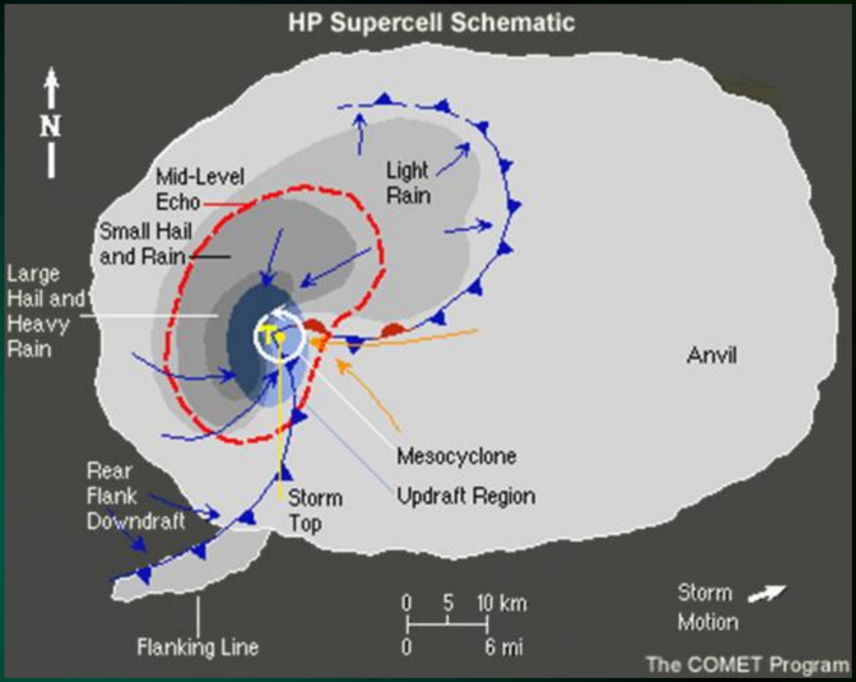
Three-body scatter (hail) spike indicates large hail in storm (area of high reflectivity). Surface hail size is a function of initial diameter, thermal profile to ground, and location of hail vs. heavy rain shaft. The spike, seen in reflectivity and velocity, is strictly an artifact of radar beam being subject to “Mie scattering” instead of “Rayleigh scattering.” Spike always appears down-radial of hail core (i.e., behind core along same radial).

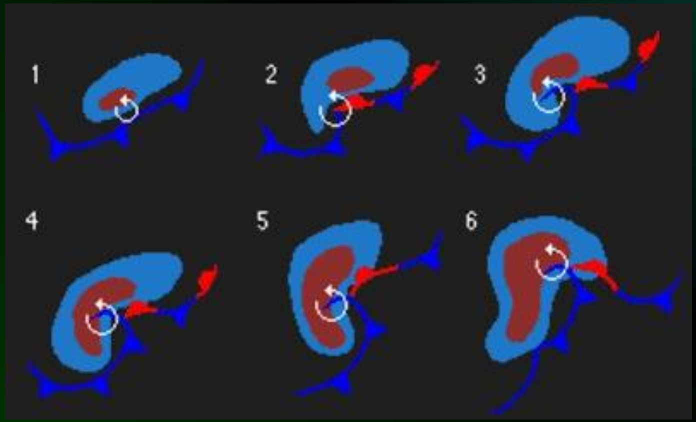




High Precipitation (HP) Supercells

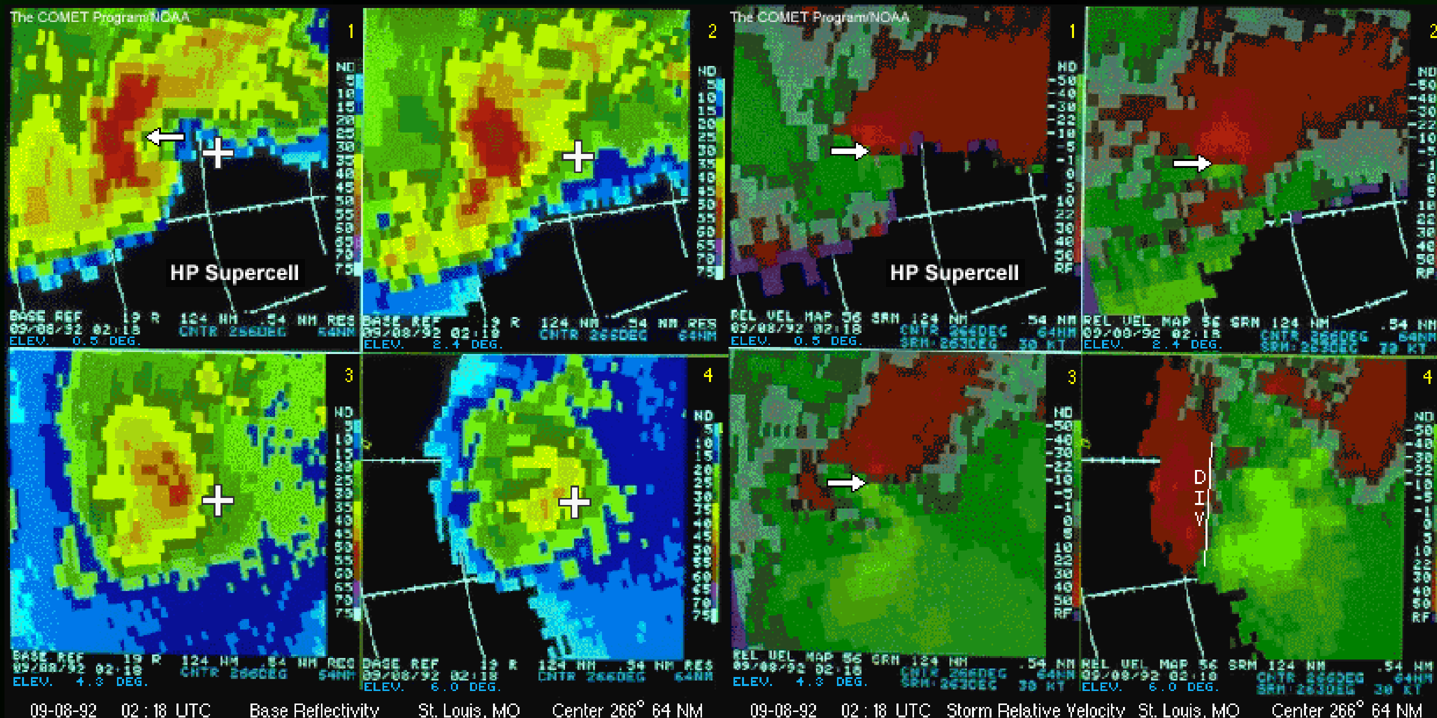


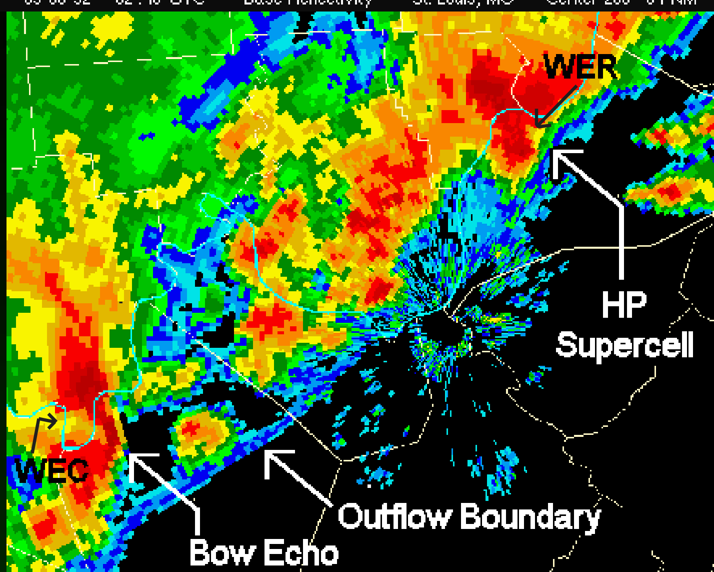




- Low-level notch (kidney bean shape) on leading edge (location of rotating updraft)
- Often embedded within squall lines; travel along boundaries
- Occur in environments with rich low-level moisture and moderate-to-strong wind shear
- Can produce very heavy rain and flash floods, as well as tornadoes, large hail, and damaging winds
- Most common east of the Plains states

High Precipitation (HP) Supercells

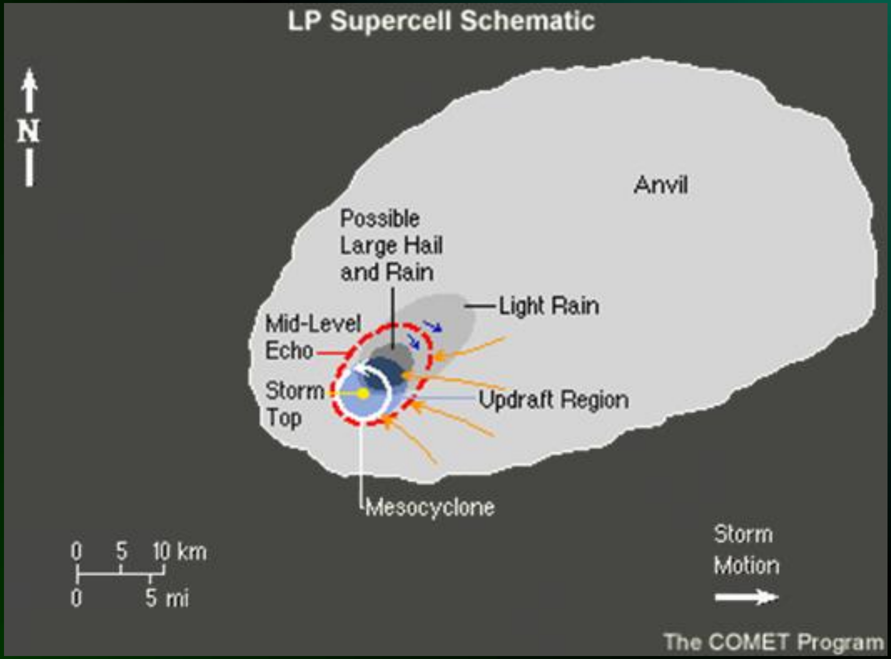


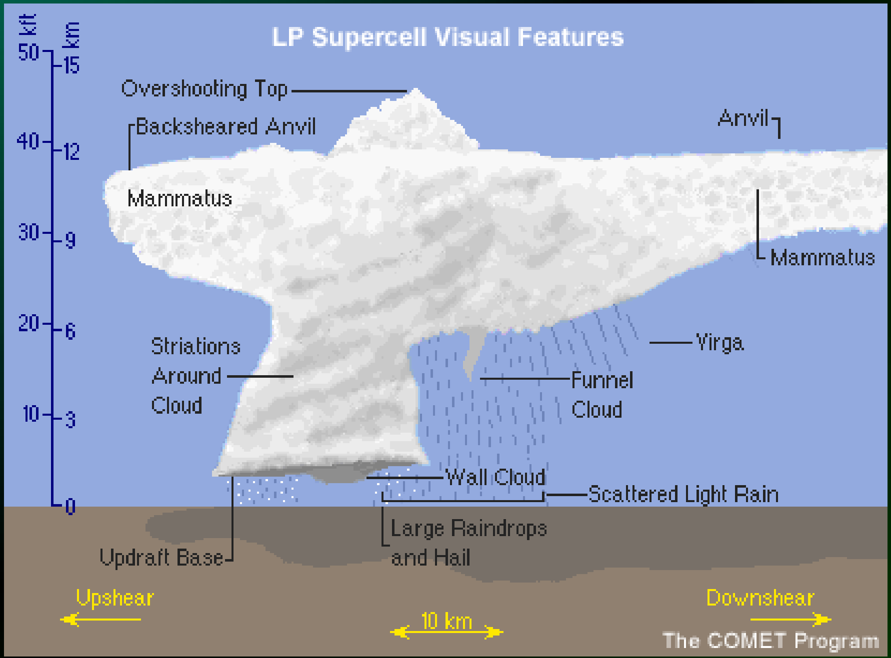


Extensive precipitation wraps around the mesocyclone giving them a kidney bean shape rather than classic hook echo appearance

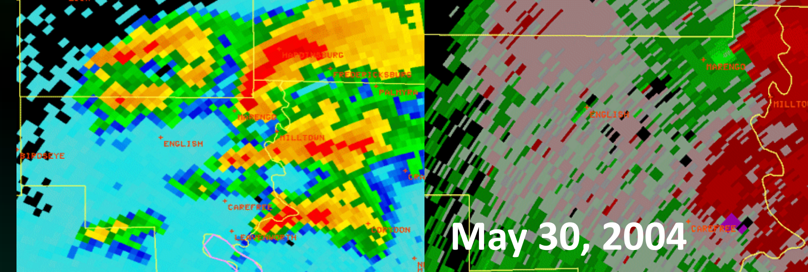
Low Precipitation (LP) Supercells

- Most common along the dryline of west Texas and High Plains, and possibly over parts of western U.S. where less low-level moisture exists
- Drier low-levels. Can be associated with an inverted-V type sounding. Can produce damaging microbursts as evaporation occurs in sub-cloud layer
- Have smaller diameters on radar than other supercell types since there is less precipitation accompanying them
- Generally, LPs are higher-base storms (higher LCL), which tends to preclude tornado formation
- Cloud-to-ground lightening can start fires





Mini/Low-Top Supercells



- Smaller in horizontal and vertical extent than classic storms. Echo tops ~24,000-32,000 ft as low equilibrium level or low tropopause caps off (prevents) deeper/taller convection
- Weaker instability (CAPE 300-1500 J/kg), but can be misleading since CAPE contained in smaller distance between LFC and EL. Consider vertical distribution of buoyancy, not just CAPE values alone
- Contain same attributes as taller, classic storms. Attributes are often just smaller/more subtle
- Maximum reflectivity values may be no more than 50-55 dBZ. Mesocyclones often have lower rotational strength, smaller diameter, and shallower depth than classic storms
- Can produce weak to strong tornadoes, similar to their taller counterparts