Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 1: Supercell Tornadic Storms

Warning Decision Training Branch

The title for this instructional component (IC) is **Conceptual Models for Origins and Evolutions of Convective Storms** . This is the first IC in the AWOC Severe Track. Lesson 1 will introduce the IC and then describe conceptual models for supercell tornadic storms.

AWOC Severe Track Training Components

IC 1 – Conceptual Models

IC 2 – Threat Assessment

IC 3 – Storm Interrogation Strategies

IC 4 – Application and Review

The entire Severe Track is divided up into 4 ICs. IC 1 is on conceptual models of storms. This instruction forms the foundation for how we visualize and come to understand important processes in convective storms.

IC1 Performance Objective

- The trainee will identify aspects of recent (1994-present) research on conceptual models that describe convective storm structure and evolution.

The performance objective for this entire IC is that the trainee will identify aspects of recent (1994-present) research on conceptual models that help describe important processes in convective storms or storm systems.

There will be a test (25 questions) on the objectives for this module.

IC1 Lesson Plan

Lesson 1: Supercell tornadic storms
Lesson 2: Squall line tornadic storms
Lesson 3: Hail storms
Lesson 4: Organized multicell storms
Lesson 5: Flash flooding
Lesson 6: Summary

The instruction for IC1 is broken up into 6 lessons, with the following topics in each lesson:

1. Tornadic supercell storms
2. Squall line tornadoes
3. Hail storms
4. Organized multicell storms
5. Flash flooding (meteorological and hydrological effects)
6. Summary of learning objectives

Individual learning objectives are designed into each Lesson and the IC test is on the objectives.

IC1 Learning Objectives

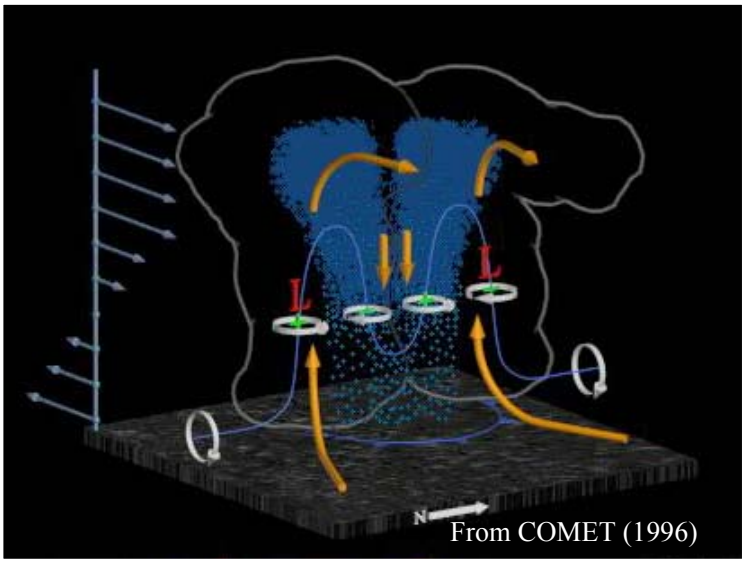
Lesson 1 : Supercell tornadic storms

1. Identify the role of shear on supercell structure and evolution.
2. Determine supercell motion using the ID method.
3. Explain the role of baroclinic generation of vorticity.
4. Identify some characteristics of favorable boundaries for supercell tornado development.
5. Describe the role of the rear-flank downdraft for tornado development.
6. Explain the primary buoyancy effects in supercell storm development.
7. Identify the fundamental conceptual model of a supercell.
8. Identify some considerations regarding cyclic tornado evolution.

These are the learning objectives for lesson 1.

Role of Deep Shear

(non-linear dynamic forces)

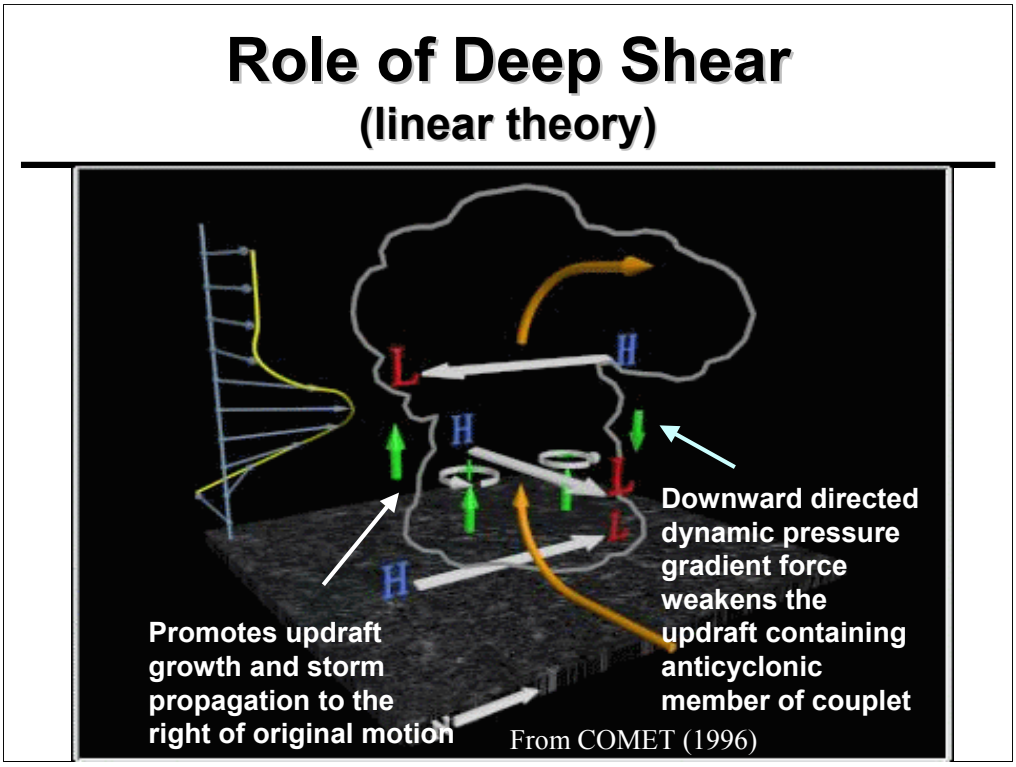


The interaction of the updraft with an environment characterized by strong vertical shear of the horizontal wind permits some storms to develop nonhydrostatic vertical pressure gradients that can be as influential in developing updrafts as the buoyancy effects (Weisman and Klemp 1984).

The midlevel rotation arises from a couple of dynamical forces at play. The end result is the tilting of horizontal vorticity into the updraft. The mid-level low pressure centers on the updrafts result from the PGF arising to help counter-balance the centrifugal force. Where updraft is strongest (at midlevels) the vertical vortices are most intense. With the dynamic pressure at its lowest aloft, an enhanced vertical pressure gradient force promotes the development of new updrafts within the centers of rotation. Greatest tilting of horizontal vorticity occurs to the right and left of the shear vector. Development of rotation in mid levels and the updraft also occurs **right and left of shear vector**. Precipitation develops in the middle of widening updraft which acts to split the updraft into two parts. Similar upward dynamic forcing leads to equally strong splitting supercells.

Once the supercell is deviating off the hodograph, it experiences streamwise vorticity and storm-relative helicity in its inflow layer. Tilting of the updraft into the updraft immediately produces vertical vorticity well correlated with the the updraft.

RKW theory also explains another internal dynamic force which affects supercell morphology.

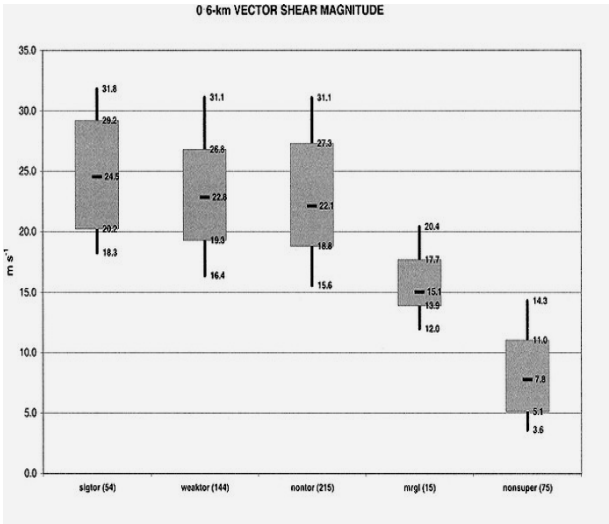


These are also linear forces arising from an updraft interacting with the sheared flow. Note the high-to-low pressure gradient developing across the updraft in the direction of the local shear vector at each levels. The shear vectors are veering with height thus high pressure is produced on upshear side (west), low pressure on downshear side (east) . This reinforces the storm inflow . With a clockwise curved-hodograph, there is an upward directed pressure gradient force that causes new updraft development and therefore, storm propagation to the right of its original motion. Meanwhile, the left side of the updraft would experience a downward directed PGF which would tend to weaken or even destroy the anticyclonic member of the rotation couplet.

In summary, shear affects supercell propagation, which is a result of : a)linear shear processes-dynamic low forming on the right (left) sides of an updraft relative to the shear vector promoting right (left) propagation vector, and 2) curved shear processes-dynamic (high) low pressure forms on the up (down) shear sides of an updraft. The changing shear vector creates upward pressure gradient force and new updraft right of the original updraft with respect to the mean shear vector.

Role of Deep Shear

- **Lower-bound thresholds of 0-6 km bulk shear of 15-20 m/s can be used as a first approximation for potential supercell environments**



Thompson et al. (2003)

The complete reference is R.L. Thompson, R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, (2003): Close proximity soundings obtained from the Rapid Update Cycle. Deep shear produces rotation that is in the updrafts of supercells. When there is 15 m/s or greater shear from 0 to 6 km, you get rotation that arises from dynamic pressure forces in storms.

This study indicates bulk shear (surface to 6 km AGL) has limited utility in distinguishing between supercells that produce significant tornadoes and those that do not (also see Rasmussen and Blanchard, 1998).

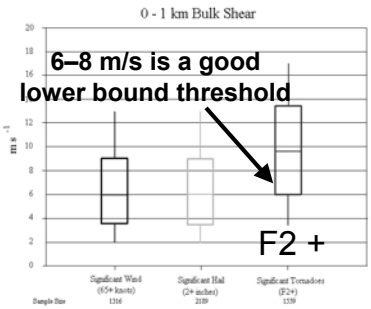
Operationally, lower-bound thresholds of bulk shear (0 to 6 km) of **15-20 m/s** and mean shear values around **.001 s^{-1}** can be used as a first approximation to help determine potential supercell environments. Note: additional factors (e.g., buoyancy distributions, mesoscale variations, etc.), should be considered as well because they can significantly modulate the character of severe storm environments.

Rasmussen and Blanchard (1998)found that mean shear in the lowest 4 km AGL was able to distinguish (to a degree) between supercells that produced significant tornadoes and those that only produced large hail. Recent and ongoing research has focused on mean shear in the lowest kilometer above the ground and have found even more distinguishing signals

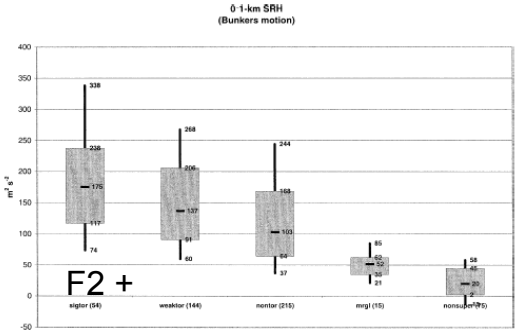
Other research such as Craven et al. (2002) and Markowski et al. (2002) using proximity soundings have found that the 0-1 km layer shear is the primary distinguishing kinematic parameter that separates supercells that produce significant tornadoes from those that do not . Also, see Markowski et al. (2002) study of RUC model proximity soundings which showed a statistically significant difference in the lowest 1 km layer. Observations of mature derecho environments (Evans and Doswell, 2001) suggested that bulk shear in the lowest 2 km was predominately greater than 15 m/s when combined with high CAPE.

Role of Low Level Shear

- **Vertical shear magnitude and storm-relative helicity (SRH) in the lowest 1 km above the ground are larger for significant tornadic storms than for nontornadic supercells**



From Craven et al. (2002)



From Thompson et al. (2003)

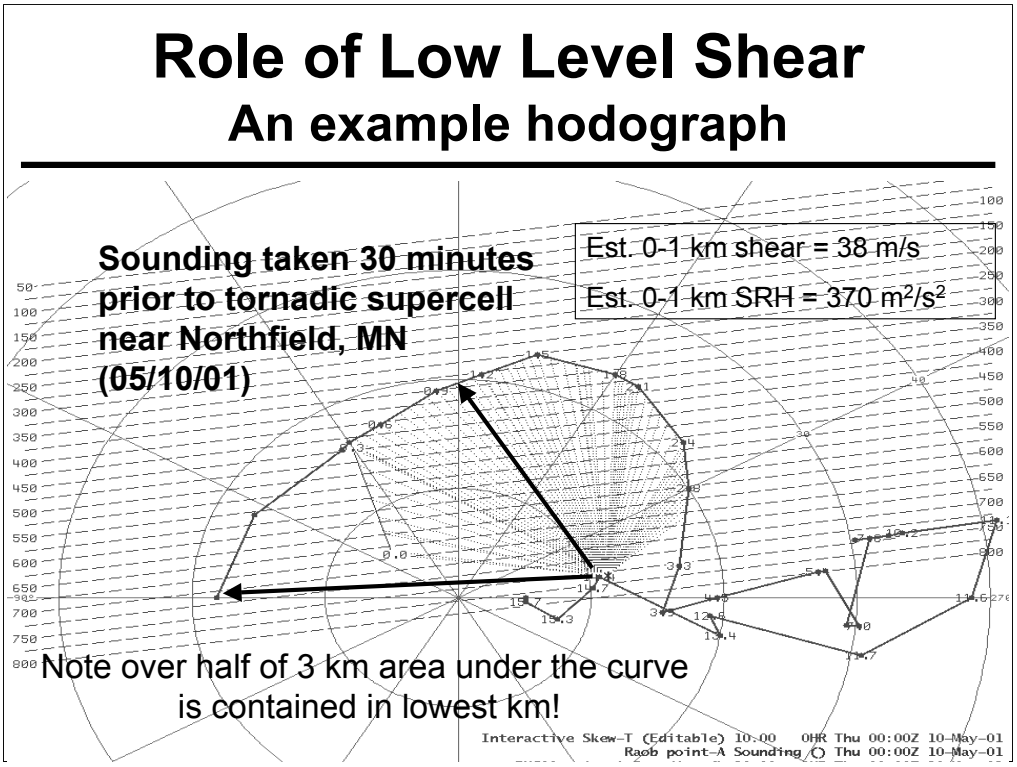
Stronger low level shear appears to be associated with a higher frequency of significant (F2 rating or higher) tornado events. The most important results from Craven et al. (2002) were in discriminating between significant hail/wind events and significant tornadoes. The low level shear parameter, 0-1 km AGL bulk shear, indicated more than a quartile offset between significant tornadoes (F2 or larger) and significant (2" Hail or larger). Most F2 and larger tornadoes occur with bulk shear above 10 m/s. Lower threshold is likely a bit lower than 10 m/s, say 6-8 m/s.

Much like the lower threshold that has been established for deep layer shear and supercell development (i.e. 20 m s-1 ; Weisman and Klemp 1982; Davies and Johns 1993; Rasmussen and Blanchard 1998; Bunkers et al. 2000; Craven

2000), it appears that **6-8 m/s (12-16 kts)** may be used as a lower threshold for significant tornado events.

These results are consistent with Edwards and Thompson (2000), who found a substantial difference between the mean 0-1 km SRH for supercells with significant tornadoes versus supercells with either weak or no tornadoes observed. A limitation of these results is that supercells may exert an influence on low-level shear and buoyancy profiles up to 30 km away from the storm, effectively altering what had been the pre-storm environment. Apparent storm impacts on local environments have been documented during formal field experiments (e.g., Markowski et al. 1998), and have been observed by storm chasers across the Great Plains of the United States since the 1970s.

Note that in interpreting and applying these results, an observed value does not always result in the preferred frequency category. In other words, a weaker than F2 tornado could result even if you see values of shear or SRH in the "significant" TOR category.



This is a example proximity hodograph from the 10 May 2001 Northfield, MN F2 tornadic storm. Likely the sounding exhibits influences directly from the storm, since it was taken less than an hour from touchdown time and less than 30 miles from the tornado itself.

Role of Low Level Shear

- Updrafts in strong low-level shear can persist at levels where there is no parcel buoyancy.
- Low-level inflow brings low-level SRH into the updraft.

Low-level shear is related to updraft persistence and the likelihood of tornado formation. What sort of updraft are we talking about? In order for the tornadogenesis process to occur, the updraft must process near-ground, SRH-rich air. This happens when the updraft extends below the region of buoyant ascent toward the ground, a result of vertical pressure gradient forces related to the interaction of the updraft with lower-tropospheric shear. Further, because tornadoes form beneath the updraft, the low-level ascent should not be shallowly sloped as it often is when the storm is associated with a vigorous gust front.

Sheared updrafts can persist at levels where there is no parcel buoyancy, and it is the low-level processing of inflow that brings low-level SRH into the updraft. Supercell storms are more likely than other storm types to produce tornadoes largely because they have relatively long updraft persistence. Updraft persistence is related most strongly to shear through the lowest one-half of the troposphere (because this forces low-level lifting as just mentioned), as well as a combination of precipitation distribution and low-level humidity. The latter two factors are important in controlling the nature and vigor of the pool of evaporatively cooled air that may or may not form beneath the storm. Vigorous low-level cold pools beneath the updraft are detrimental to tornado formation. If the near-ground air is relatively dry, lesser precipitation falling around the updraft could produce a vigorous cold pool. On the other hand, if the near-ground air is nearly saturated, cooling will be weak even if there is a lot of precipitation around the updraft (Rasmussen, 2002).

Role of Shear

Key points

- Sufficient vertical shear (through a deep layer) produces mid level rotation in storms.
- Interaction of updraft with vertically sheared environment permits some storms to develop nonhydrostatic vertical pressure gradients and enhanced vertical motions.
- Low level shear (e.g., 0-1 km AGL) is the primary distinguishing kinematic parameter that separates supercells that produce significant tornadoes from those that do not.

The other parameter that distinguishes significant tornadoes from non-significant ones is low level humidity (LCL heights).

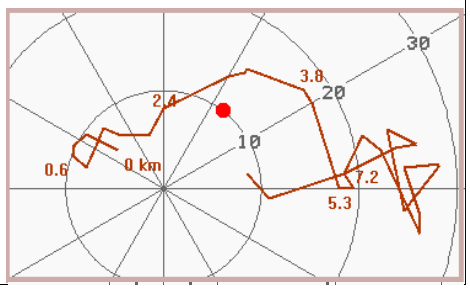
Forecasting Supercell Motion

- The Internal Dynamics (ID) method (Bunkers et al., 2000) incorporates the process by which the updraft interacts with vertical shear to cause deviant motion in supercells.
- Can be used to calculate storm motion for cyclonic and anticyclonic rotating storms resulting from a storm split

The Bunkers ID method is vastly superior to old supercell storm motion methods such as 30R75. That method didn't work for storms moving in all quadrants. You can plot supercell storm motion using ID method in AWIPS Volume Browser.

Estimating Supercell Motion

- The Internal Dynamics (ID) method
  - Plot the 0-6 km mean wind
  - Draw the 0-6 km shear vector
  - Draw a line orthogonal to the shear vector through the mean wind
  - Plot the left (right) moving storm 7.5 m/s to the left (right) of the mean wind along the orthogonal line.



Just follow the directions, or use BUFKIT. Note, there have been several observations where actual supercell motion was much different than what the ID method suggested. Interaction with other storms, boundaries, topographic effects, etc. All of these may affect the motion.

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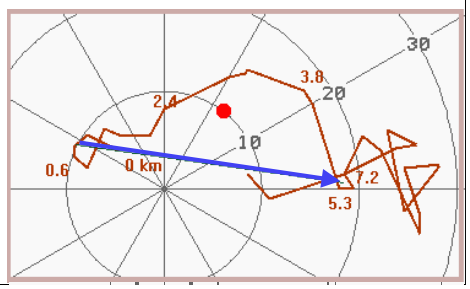

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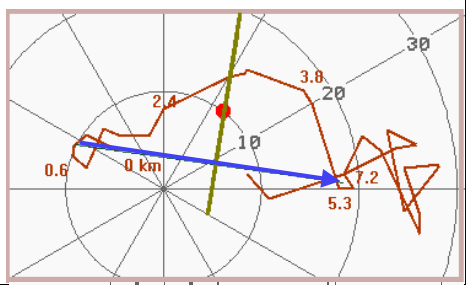

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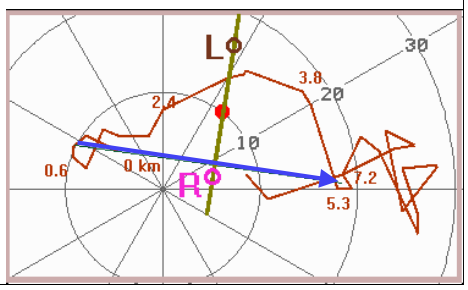
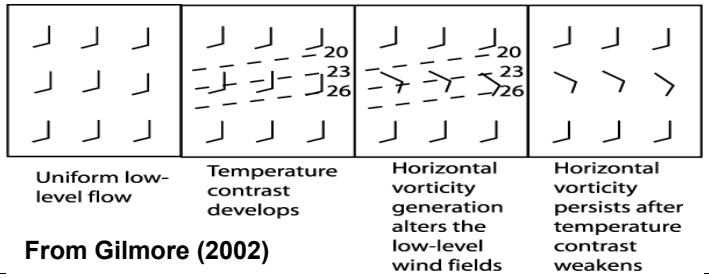


For more information see http://meted.ucar.edu/convectn/ic411/

Role of Baroclinic Generation of Vorticity

- The buoyancy gradient enhances streamwise vorticity and SRH.
  - Note 1: Augmented horizontal vorticity from the forward flank region is usually not enough to produce tornadoes.
  - Note 2: Augmented horizontal vorticity remains long after thermal gradient weakens.

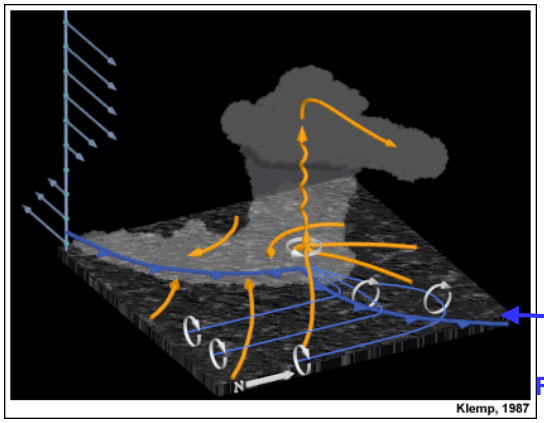


From Gilmore (2002)

These findings are from VORTEX results and illustrate how difficult it is to analyze horizontal vorticity fields on the mesoscale. They could be all over the place when there are multiple boundaries such as outflow boundaries.

Effects of Low Level Shear

(vorticity stretched into updraft)



This augmented horizontal vorticity from FFD is usually insufficient for tornadogenesis (from VORTEX results)

Forward Flank Downdraft (FFD)

From COMET (1996)

From COMET's (Convective Storm Matrix, 1996), the generation of low-level rotation is a result of the processes described so far. This 3-D figure depicts a classic supercell in its mature phase. The near-surface vortex lines (in blue) represent the environmental vorticity bending toward the storm's updraft in the baroclinic zone of the forward flank downdraft. This diagram , based on simulations in the mid to late 80s, indicates the baroclinic generation of horizontal vorticity in the FFD region. Once vorticity enters the updraft, it is stretched vertically to create much stronger low-level rotation. This process can be an important contributor to low-level storm rotation, which previously was thought led directly to tornadogenesis. However, VORTEX results in the mid-90s and more recent storm scale numerical simulations suggested that augmented horizontal vorticity from the FFD is usually insufficient for tornadogenesis. In moist low-level conditions, there might not be a discernable FFD (thus no baroclinicity). The tornadic scale stretching is thought to come from the RFD (more later).

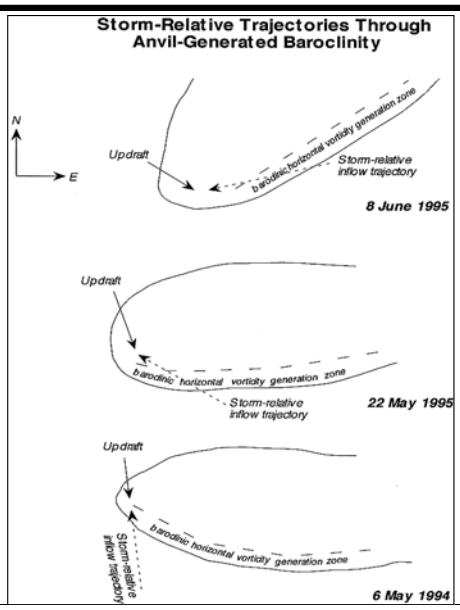
Horizontal vorticity enhancements are necessary for low-level mesocyclogenesis, which appears to precede tornadogenesis if additional key supercell structures develop (e.g., the RFD).

Only in cases where large-scale low-level horizontal vorticity is already very high (e.g., 0–3-km mean horizontal vorticity of $1 \times 10^{2}\ s^{1}$ or greater or storm-relative helicity of $500\ m^{2}\ s^{2}$ or greater) or deep-layer shear is very strong (e.g., $50\ m\ s^{1}$ in the lowest 10 km AGL), can forward flank baroclinity alone provide sufficient augmentation of the horizontal vorticity associated with the large-scale mean shear for tornadogenesis to occur. Other sources for streamwise vorticity that may become stretched into the updraft originate from behind the cold front boundary (aka RFD). More on this next.

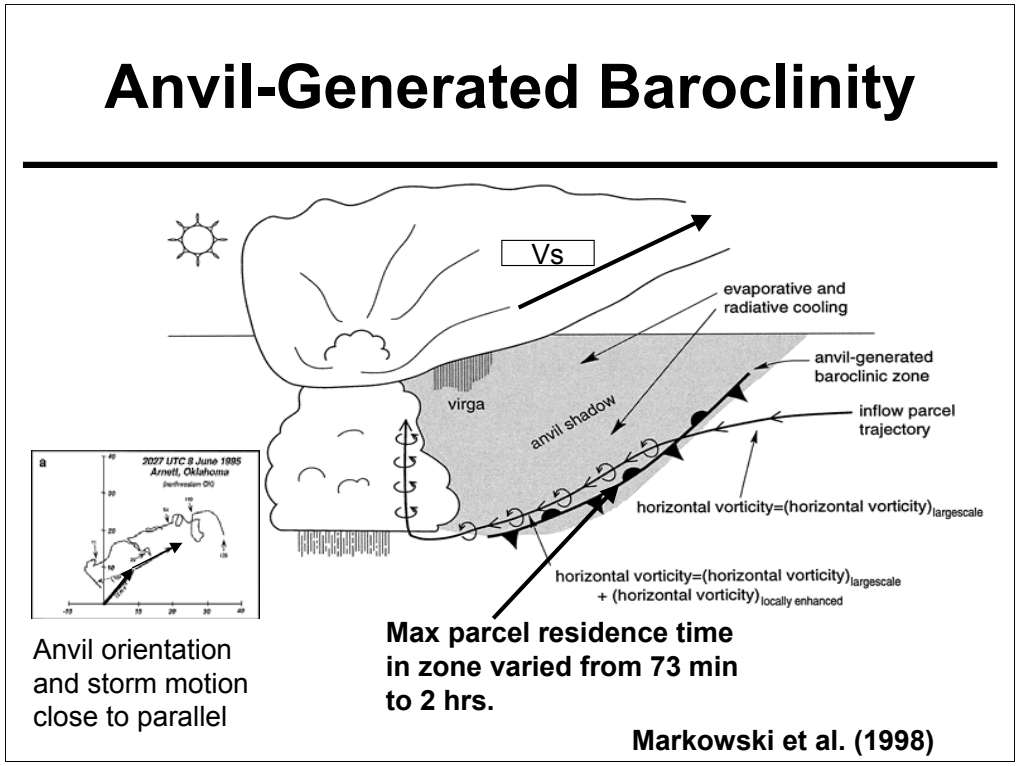
Anvil Shadow Effects

- Storm anvils can promote baroclinic generation of vorticity (mostly streamwise) and longer parcel times in the zone.

From Markowski et al. (1998)



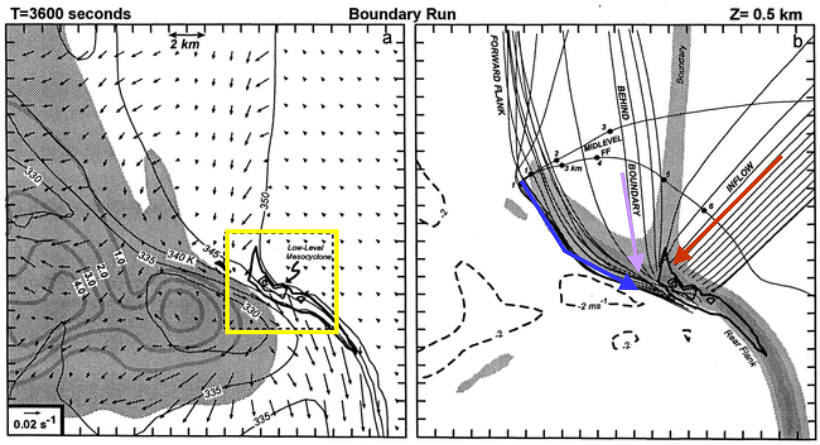
Due to low-level temperature gradients along the edges of anvil shadows, a baroclinic zone develops. Residence time in the baroclinic zone, estimated by analyzing storm-relative winds from proximity sounding hodos were shown to produce horizontal vorticity (~ 10 –2 s –1) that can be acquired by updraft inflow parcels. Schematic representation of the storm-relative trajectories through the anvil-generated baroclinic zones on 8 June 1995, 22 May 1995, and 6 May 1994. (from Rasmussen et al., 1998) In the first two cases, not only does the vorticity generated contain a greater streamwise component, but the parcel residence times in the baroclinity are longer.



This is a conceptual model by Markowski et al. (1998) showing enhancement of low-level horizontal vorticity by an anvil-generated baroclinic zone. The amount of horizontal vorticity generated is a function of baroclinity and parcel residence time in the baroclinic zone. Residence time is a function of both storm-relative inflow speed and crossing angle with respect to the baroclinity. Horizontal vorticity will be mostly streamwise if the crossing angle of the storm relative near-surface inflow with respect to the anvil zone is very small (~ 0) . The estimated max. parcel residence time was 73 min to ~ 2 hrs for the 3 cases examined. Their research of proximity hodographs in baroclinic regions revealed that: to maximize horizontal vorticity generation in the near-ground inflow, the head of the storm motion vector should lie close to the line drawn from the heads of the 0–500-m mean wind vector and the wind vector near the equilibrium level. This assumes that the baroclinic zone is aligned closely with the anvil edge.

Horizontal vorticity generated with a streamwise component can serve to enhance the storm-relative helicity already present in the environment due to the low-level vertical shear. SRH has been shown to be the source for net updraft rotation in supercells. Thus, the observations of anvil-generated baroclinity may have implications for the origin or enhancement of updraft rotation in thunderstorms.

Sources of Streamwise Vorticity



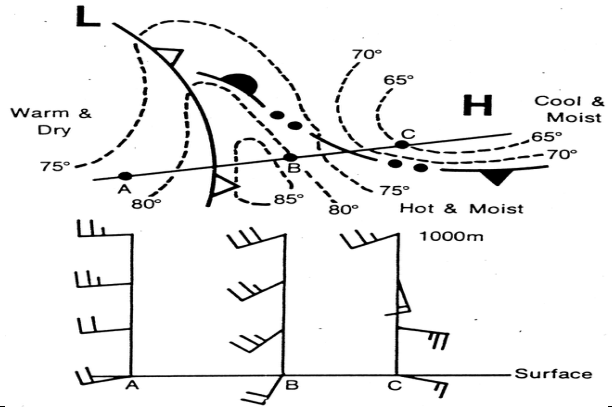
Parcels from behind the boundary and in the forward flank regions acquire streamwise horizontal vorticity; which, after tilting and stretching by storm's updraft can aid low-level mesocyclogenesis (Atkins et al., 1999)

From Atkins et al. (1999), the low-level storm structure (0.5 km AGL) at 3600s for the boundary simulation. (a) Rainwater mixing ratio greater than 0.1 g kg^{-1} is shaded gray. The gray contours are rainwater mixing ratio starting at 1.0 g kg^{-1}. Thin black lines are θ_e (K). Thick black lines are vertical vorticity with contours starting at 0.01 s^{-1} and a contour interval of 0.01 s^{-1}. The vector field is horizontal vorticity. (b) Positive and negative vertical velocities are gray shades and thick dashed lines, respectively. The contour and shade interval is 2 m s^{-1} and the 0 m s^{-1} contour is not plotted. Thin solid lines are the projection of the 3D trajectory locations. Numbers at the black dots on the midlevel trajectories are the height of the parcel (AGL). Thick solid lines are vertical vorticity, contoured as in (a).

Parcels from behind the boundary and forward-flank regions had acquired streamwise horizontal vorticity, which was then tilted and stretched by the storm's updraft. The preexisting boundary provides an important additional source region of parcels at low levels that have acquired solenoidally generated streamwise vorticity. These results support the hypothesis put forth by Wicker (1996), that low-level streamwise vorticity enhances low-level mesocyclogenesis and confirm the discussion by Markowski et al. (1998), and Rasmussen (2000) that horizontal vorticity generated at low levels along boundaries is an important vorticity source for low-level mesocyclones. Vertical vorticity along the preexisting boundary augments low-level mesocyclogenesis.

Characteristics of Boundaries that Enhance Supercell Tornadoes

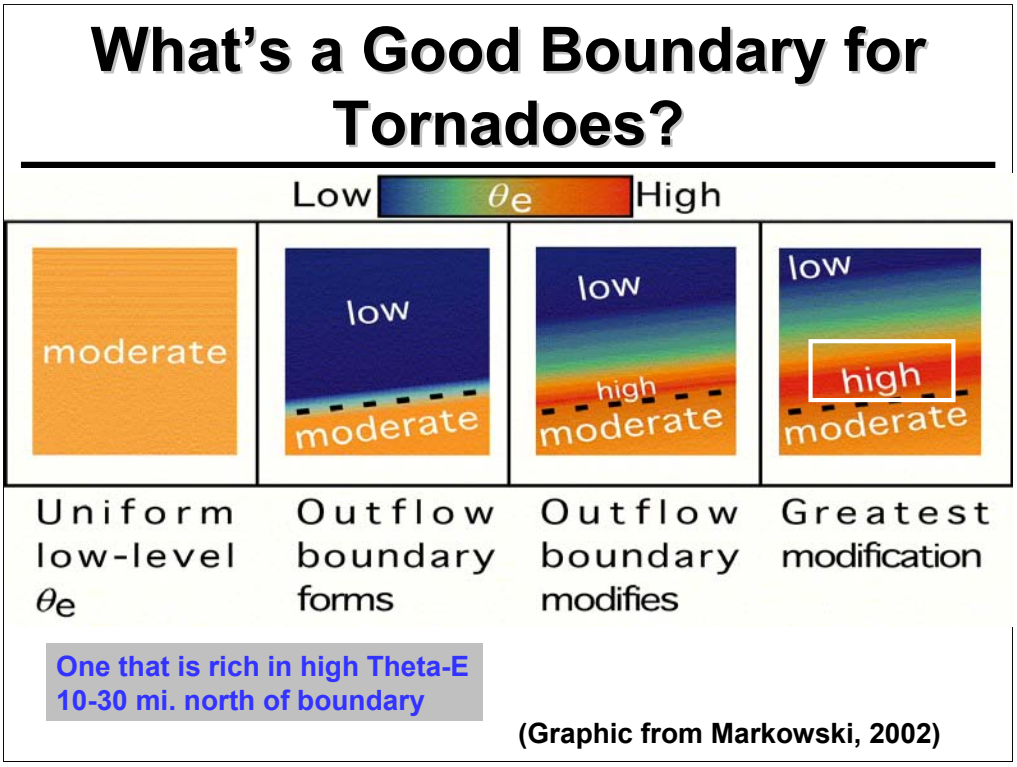
- Boundaries can promote enhanced horizontal vorticity and storm relative helicity on the immediate cool side.
- Thus, boundaries are an important source for vertical vorticity.



Maddox et al. (1980)

Boundaries can promote enhanced horizontal vorticity and storm relative helicity on the immediate cool side. Through tilting and stretching processes, **boundaries help produce enhanced vertical vorticity** - important vorticity source for low-level mesocyclogenesis. This graphic shows the important mesoscale modifications to thermodynamic and kinematic fields (esp. in low levels) in the vicinity of boundaries (from Maddox et al., 1980).

Net result from this backing flow is that intense horizontal stretching can occur in the storm's inflow, as parcels accelerate toward the updraft. We'll look at some important findings from VORTEX as the importance of boundaries in our conceptual models of supercell storms.



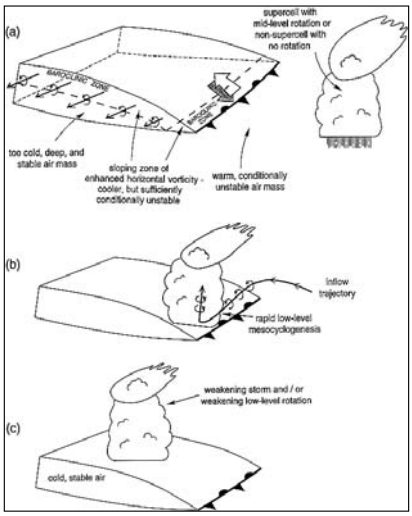
The answer is one that is rich in high equivalent potential temperature, just north of a boundary. In this location is enhanced SRH, which can remain long after the temperature gradient weakens. Through surface data, esp. mesonet, you can observe gradients of Theta-E in the vicinity of boundaries.

Boundaries that have shallow cold air, there is sufficient MLCAPE on the cold side, and the vertical pressure gradient generated by an updraft in low-level shear remains strong, would be a "good" boundary. The more shallow the boundary, the further into the cold air the tornado potential would exist. Based on the VORTEX findings (and the types of boundaries they researched), the greatest tornado potential probably was located from around 10 km on the warm side to roughly 30 km into the cold air.

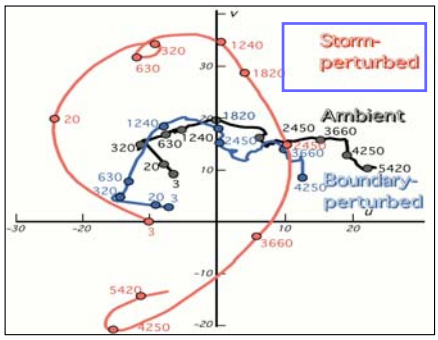
Boundary layer moisture , as measured on the mesoscale, also has direct correlation to tornado development WRT considerations of the Rear Flank Downdraft (RFD) and associated buoyancy characteristics of the storm scale . Note that a main point here is that the enhanced SRH can be around long after the temperature gradient weakens.

Also, note that actual forecasts of SRH increases would be quite difficult. This is because the parcel residence time is most important.

Low Level Tilting & Stretching Process



From Markowski (2002)



Sounding	Time	0-1 km SRH
Ambient	2315	205 $m^2 s^{-2}$
Boundary	2248	405 $m^2 s^{-2}$
Storm	**0100**	**>1000 $m^2 s^{-2}$**

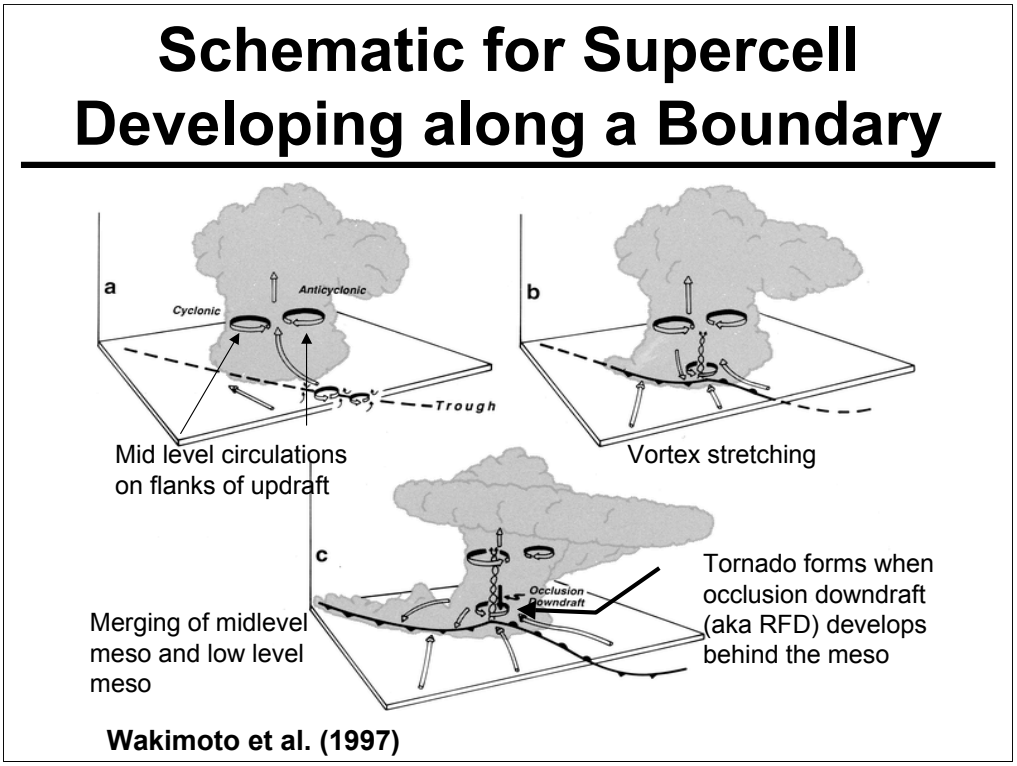
Horizontal vorticity is readily stretched horizontally by storm-induced accelerations to the flow, and then tilted into, and stretched by the storm updraft. **SRH in inflow region of storm is not likely the same as in pre-storm environment, due to low-level inflow acceleration.** Vorticity that is initially mainly horizontal can contribute to quasi-vertical vortices such as supercell mesocyclones through reorientation and stretching. Horizontal vorticity that is *streamwise* (i.e., vorticity and storm-relative velocity vectors parallel) produces net updraft rotation (Davies-Jones 1984) upon tilting. It is worthwhile to note that the tilting of *crosswise* horizontal vorticity (horizontal vorticity and velocity vectors perpendicular) also produces vertical vorticity. In the case of purely crosswise horizontal vorticity, integration of vertical vorticity over an entire updraft yields no net rotation; however, a pair of vortices, one cyclonic and the other anticyclonic, will result.

SRH is also critical. You'd like to see a large, looping hodo in the lowest 1 km because this means that the vector of the horizontal vorticity generated is directed across the buoyancy gradient (along the buoyancy isopleths). Therefore, for a wide range of typical storm motion, the generation of horizontal vorticity due to buoyancy gradients will increase SRH to the degree that the flow is also along the buoyancy (temperature) isopleths.

Key point: Horizontal vorticity generated at low levels along boundaries is an important vorticity source for low-level mesocyclones. Vertical vorticity along boundaries augments low-level mesocyclogenesis by producing enhanced streamwise vorticity.

Boundaries contain low-level horizontal vorticity due to generation of solenoidal effects from buoyancy gradients. Because of large accelerations in storm inflow, the baroclinically generated horizontal vorticity can be amplified by horizontal stretching (Brooks et al. 1993) even prior to reaching the updraft itself. A vigorous updraft, such as those that occur in environments with strong deep shear and sufficient convective available potential energy, can readily tilt and stretch the low-level horizontal vorticity present with the boundary (Weisman and Klemp 1982 ; Klemp and Rotunno 1983) if the updraft draws air from beneath the boundary interface.

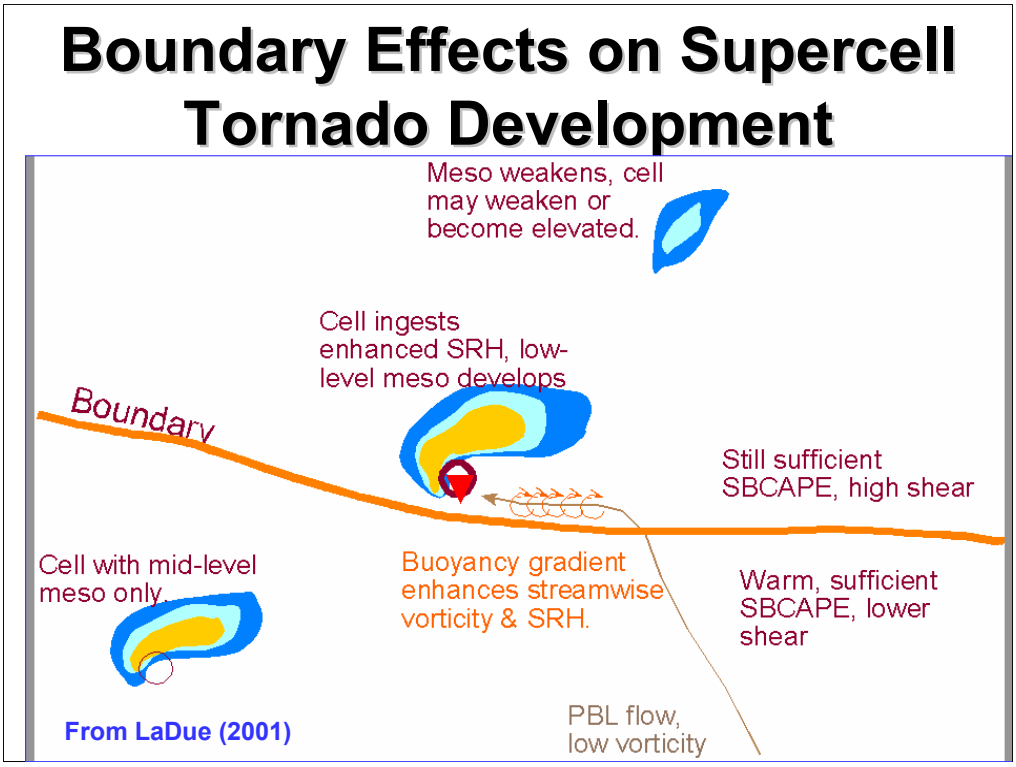
The black curve ("ambient" warm sector) in the figure to the right is the hodograph from the LBB special sounding at 2315 UTC. The blue curve is the hodograph from the special sounding at 2248 UTC near Lockney, TX that was 15 km toward the cool side of the pre-existing outflow boundary.



A schematic model summarizing the life cycle of the Garden City storm. (from Wakimoto et al., 1997) Cylindrical arrows depict the storm-relative flow. The location of the low-level and midlevel vorticity centers is shown by the ribbon arrows. The synoptic-scale trough is shown by the black dashed line. The rear- and forward-flank gust fronts are indicated by the frontal symbols. The occlusion downdraft, also known as the rear-flank downdraft (RFD), is shown by the black arrow.

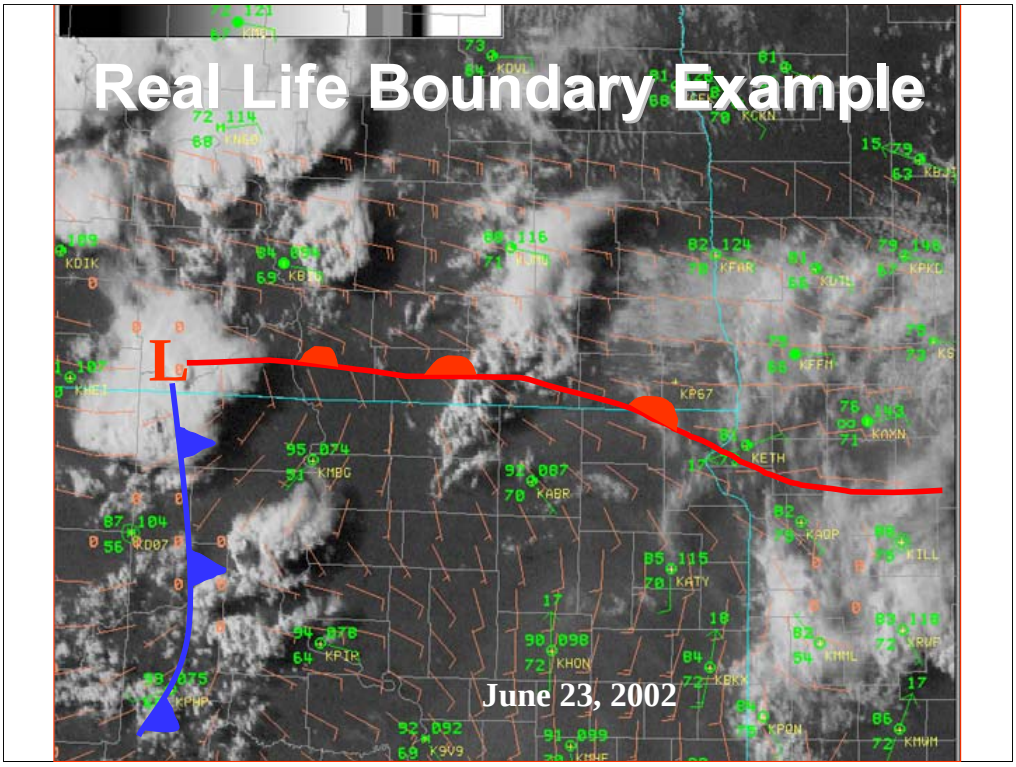
Pre-existing synoptic wind shift line, possibly interacting with HCRs helped to produce low-level updraft maxima/ vorticity stretching along the boundary. Interaction of supercell mesocyclone and one of these vorticity maxima was associated with tornadogenesis. This data from the Garden City, KS tornado in 16 May 1997.

The occlusion downdraft or RFD in the mesocyclone leads to a highly curved band of vorticity maxima reminiscent of the multiple vortex phenomenon in a tornado. One of these maxima develops into the Garden City tornado.

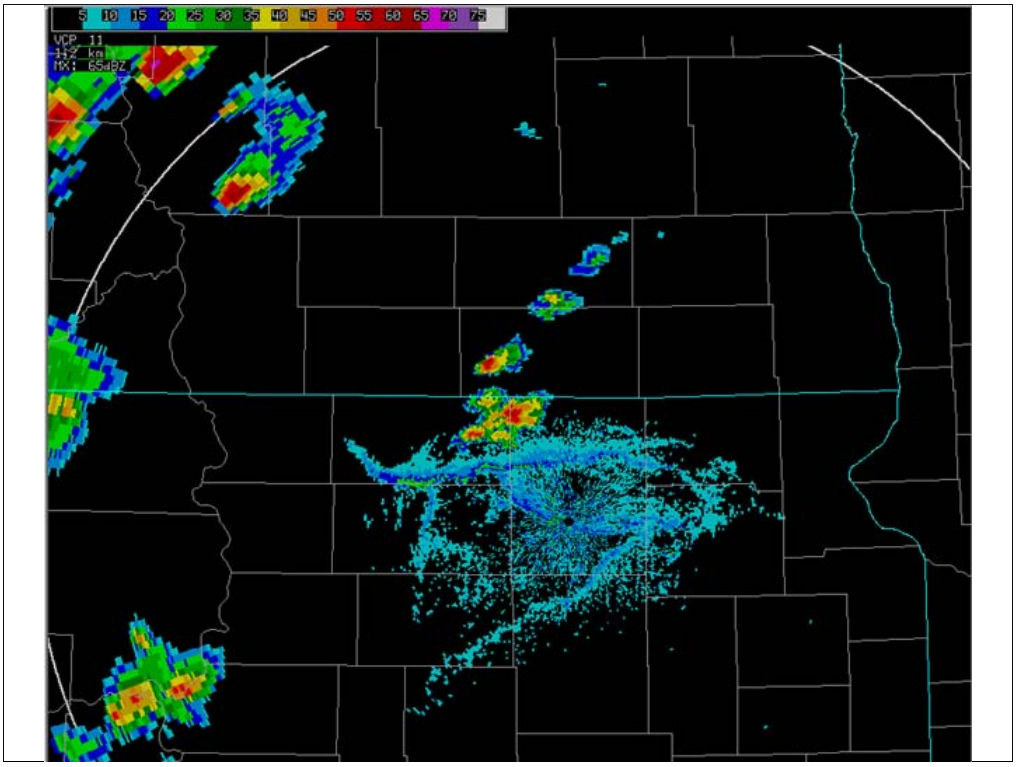


The animated flash graphic on this slide will help illustrate some of these key environmental considerations with boundaries and supercell tornadoes.

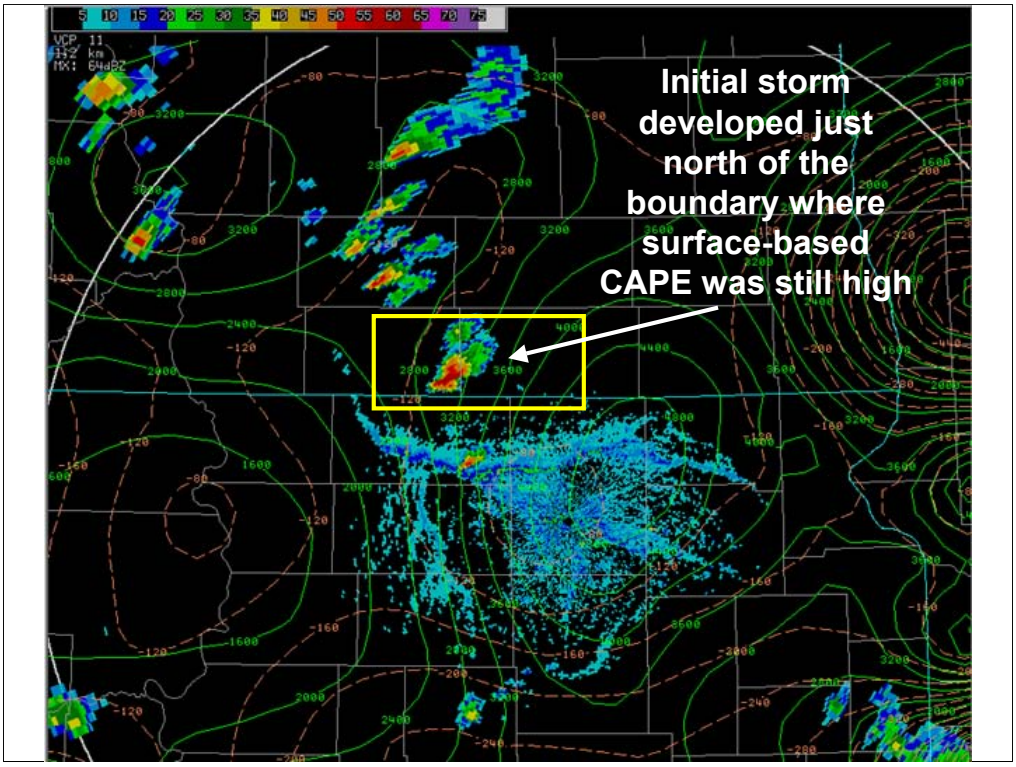
Boundaries that have shallow cold air, there is sufficient MLCAPE on the cold side, and the vertical pressure gradient generated by an updraft in low-level shear remains strong, would be a "good" boundary. Based on the VORTEX findings, the greatest tornado potential probably is located between no more than 10 km into the warm air to roughly 30 km into the cold air.



This is D2D imagery from 23 June 2002 near Aberdeen, SD.



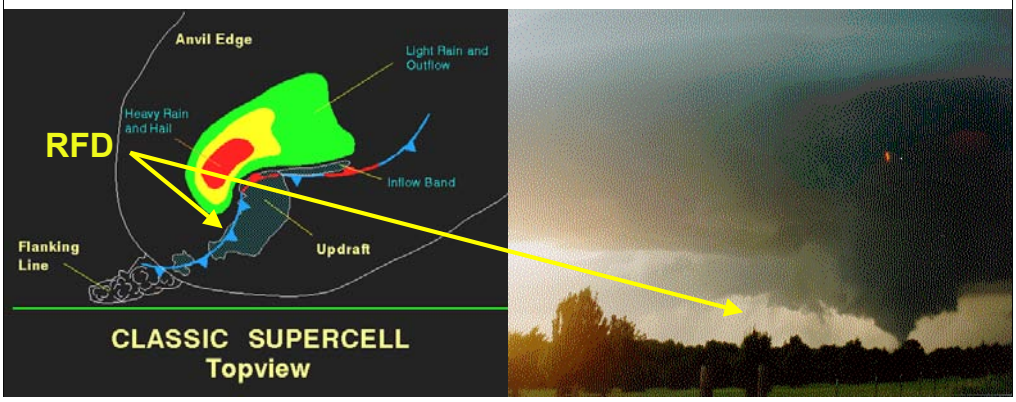
This is the 0.5 degree reflectivity data. Note 4 distinct boundaries. The one furthest north is the one which is the focus for storms.



Analyzed CAPE and CIN (Surface based) from the 22z LAPS analysis.

The Role of the RFD

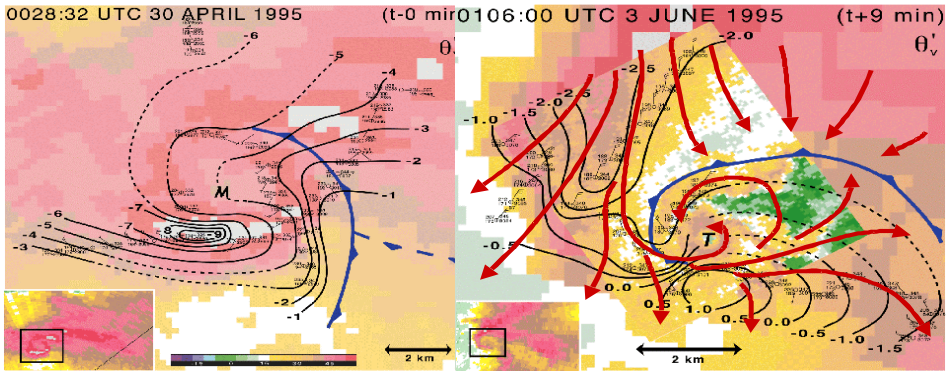
- Important factor in tornadogenesis process for supercells



Most supercells (tornadic and nontornadic ones) have circulations extending to the ground embedded in the outflow.

Some supercells have “cold” (relative to inflow air) RFD’s that keep the tornado cyclone from concentrating into a tornado, and that spread a great distance.

The Role of the RFD



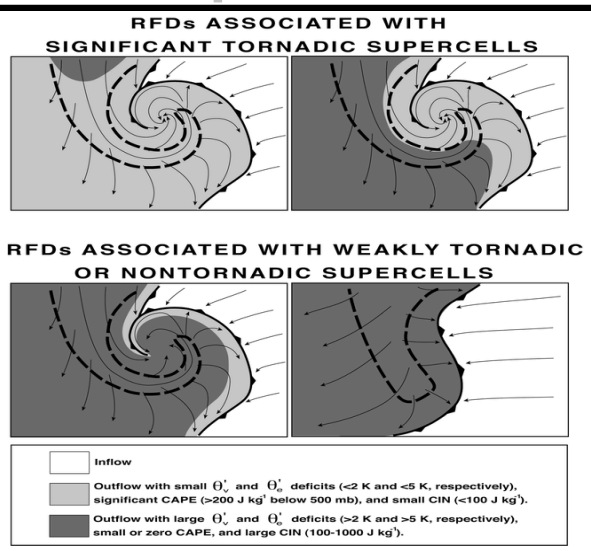
nontornadic storm
(less buoyant RFD)

Tornadic storm
(more buoyant RFD)

From Markowski et al. (2002)

Paul Markowski (2002) analyzed a large number of project VORTEX cases and found a strong correlation between Rear Flank Downdraft (RFD) potential virtual temperature deficit and the likelihood of a significant tornado (F2 or greater). Analysis in the figures show contours of θ_v departure from the pre-storm environment as sampled by mobile mesonet probe. Radar reflectivity is overlain, either from mobile radar or the nearest WSR-88D.

RFDs Associated with Tornadic Supercells

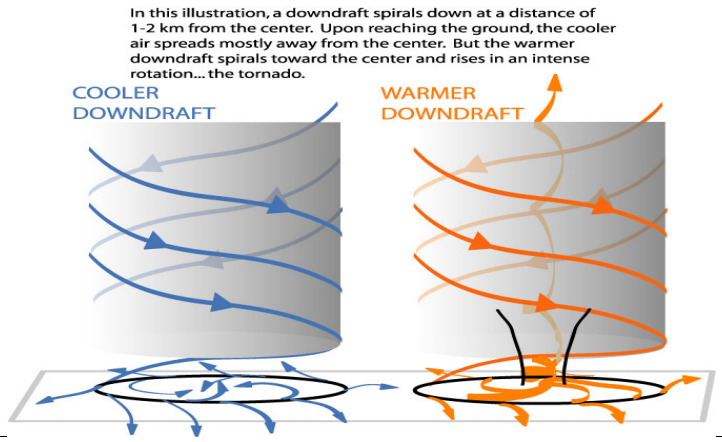


From Markowski et al. (2002)

More from Markowski et al. (2002), this is a composite diagram illustrating the general characteristics of RFDs associated with supercells that produce "significant" (e.g., F2 or stronger, or F0–F1 persisting >5 min) tornadoes vs RFDs associated with nontornadic supercells or those that produce weak, brief tornadoes. The thick, dashed contour is the outline of the hook echo, and thin, solid arrows represent idealized streamlines. In the bottom two depictions, the illustration on the left was representative of 11 of 12 tornadogenesis failures, while the illustration on the right depicts an evolution that was observed in only one nontornadic case.

Role of RFD

- Warm RFDs promote tornadoes; cold RFDs discourage them

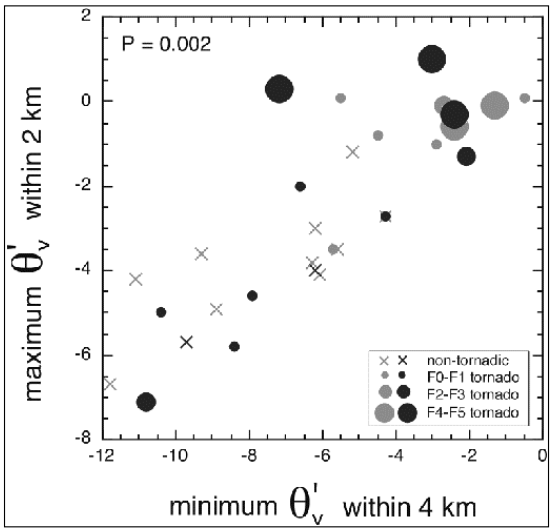


From Rasmussen et al. (2001)

(Note: There is a neat flash graphic on this slide.) Most supercells (tornadic and not) have circulations extending to the ground embedded in the outflow. Some supercells have cold RFDs that keep the tornado cyclone from concentrating into a tornado, and that spread a great distance. To elaborate on this concept, one of the most exciting findings of VORTEX and its successors was that rear-flank downdrafts in tornadic supercells seem to have a very unusual character compared to non-tornadic supercells and thunderstorm downdrafts in general. This finding comes from the Ph.D. dissertation research of Paul Markowski and collaborators. By examining mobile mesonet observations from beneath about 18 tornadic and 12 non-tornadic mesocyclones, the following was found: tornado cyclones~2-3 km diameter vortices… extended to the ground in all but one of the storms. The sample is biased towards storms that appeared to have good tornado potential, but suggests that mesocyclones that fail to produce tornadoes do not fail, in general, because of an "undercutting" by outflow. The notion of "outflow dominated" supercells may be much overused, and it is possible that many supercells have vortices extending to the ground embedded in the outflow below the updraft. In tornado cyclones that produce tornadoes, **the RFD reaches the ground with more CAPE, less CIN, larger equivalent potential, wet bulb potential, and virtual potential temperature than in tornado cyclones that do not produce tornadoes**.

RFD Characteristics Related to Tornado Occurrence

- Evidence builds that unstable RFDs favor more significant supercell tornadoes



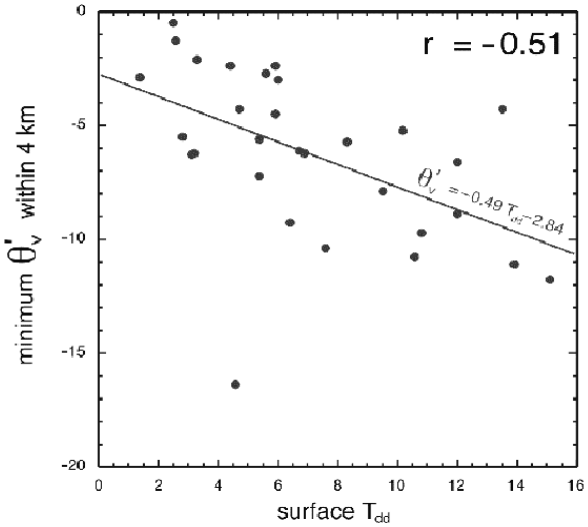
Markowski et al. (2002)

These observations were taken by mobile mesonets within RFDs. These results suggest that unstable RFDs implied plenty of CAPE available to aid vortex stretching. To account for sampling errors, the maximum and minimum θ_v' for each RFD is plotted on two axis.

Researchers speculate that the following description summarizes why buoyancy may be important in an RFD. The RFD is known to descend in an annular, or semi-annular region roughly centered on the axis of maximum low-level rotation. i.e., it descends around the developing vortex. (The degree to which the RFD is driven by thermodynamic/microphysical forcing, and/or dynamic forcing through vertical pressure forces, remains to be resolved.) Upon reaching the ground, some of the RFD air flows toward the axis, and some flows away from the annular region and thus away from the vortex. It appears that the vigor of the down-in-up flow vs. the down-out flow is related to the buoyancy present in the RFD air. If it is relatively buoyant, more air flows toward the axis with subsequent convergence and stretching leading to tornado formation. In this illustration the cool downdraft spirals down at a distance of 2-3km from the center. Upon reaching the ground, the downdraft spreads mostly away from the center. But the warmer updraft spirals toward the center, and rises in an intense rotation, the tornado. Future research in this area will likely center on understanding what governs the thermodynamic character of the RFD. Rasmussen and others' hunches are that the RFD is strongly related to both low-level humidity, and the sizes and types of precipitation particles comprising the hook-echo, or rear-side supercell precipitation cascade. A further complication is the degree of entrainment of dry environmental air, if present.

Humid Boundary Layer

- Of all major environmental parameters, surface dewpoint depressions are most related to RFD buoyancy
- Still a bit of uncertainty



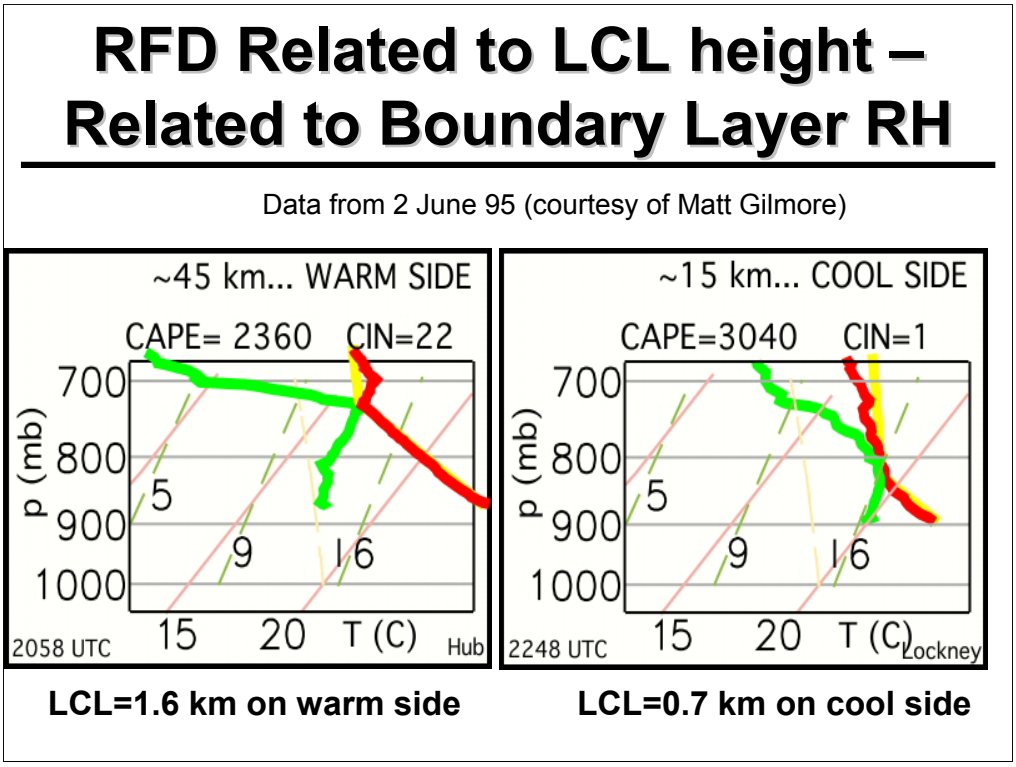
After Markowski (2000)

RFD buoyancy was compared to the best performing environmental parameter. Tdd was the highest correlated parameter to minimum Theta-V (the RFD proxy).

In fact, equivalent potential temperature in tornadic circulations is about the same as the supercell inflow, while in non-tornadic circulations it is colder. Note that all three potential temperatures are correlated with each other. These are very significant findings in our effort to understand and forecast tornadogenesis. Unfortunately, when Markowski examined proximity soundings to all of these events, there were only very weak signals at best. The one environmental measurable that was reasonably well correlated with RFD character and with tornado production was the surface dewpoint depression in the airmass the storm was moving through. This is completely consistent with the strongest predictor found in the 1992 climatological study of Rasmussen and Blanchard: LCL height.

From a forecasting perspective, large low-level humidity (i.e., small dewpoint depressions, low LCLs) in the presence of sufficient CAPE is a red flag that the threat of significant tornadoes is enhanced. Note that it is a rare occurrence in the atmosphere to have small dewpoint depressions and still have CIN small enough, and CAPE large enough, for supercells. It is much more common to have humid low-level conditions in which CIN is large and CAPE is small or nonexistent. Also note that humidity is higher on the cool side mesoscale outflow boundaries, where SRH is enhances as discussed previously. This means that boundaries may play a role in tornado production beyond the enhancement of SRH.

The situation of tornado threat in relatively drier low-level environments is much more complicated and will require additional research into the conditions in which the RFD can reach the surface with sufficient CAPE and reduced CIN for tornado formation. Right now, we think that a dry environment means that the precipitation in the hook echo must be “just right” to prevent too much evaporation, while a humid environment affords much more latitude in the amount/type of precipitation in the RFD. In a nutshell, some air goes toward the axis and some flows away.



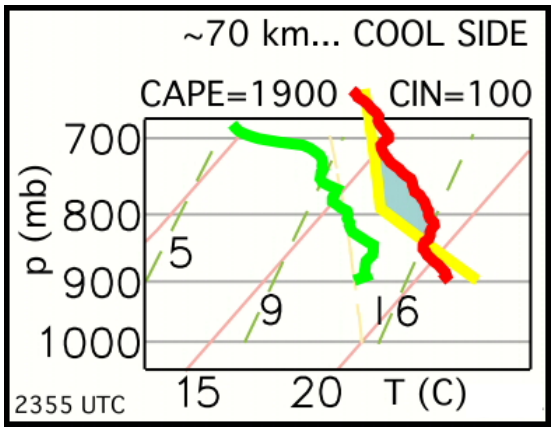
Just as ∇T can enhance SRH, cold/dry outflow can be modified to cool/moist outflow. These soundings were taken on 2 June 95, one of the VORTEX days. Note the difference in LCL height, surface based CAPE and CIN. The most low-level CAPE and least CIN was .7 km north of boundary.

This "moisture pooling" N of fronts (low LCLs) is the mode for tornadoes in the N. Central Plains (Johns et al. 2000).

Johns et al. (2000, Severe Storms Conference) found that intense tornadoes most often occurred to the cool side of stationary or warm fronts (46 years of cases from 1953-1999, N Central Great Plains of the US) where LCL heights were low and moisture pooling was occurring. In contrast, LCL heights in the warm sector were most always higher and tornadoes were rare.

Special RFD : Enhancing Boundary Layer RH

- Further north of the boundary, however, the moisture was not modified as much.
- It is no wonder that all tornadoes occurred within 40 km of the boundary!

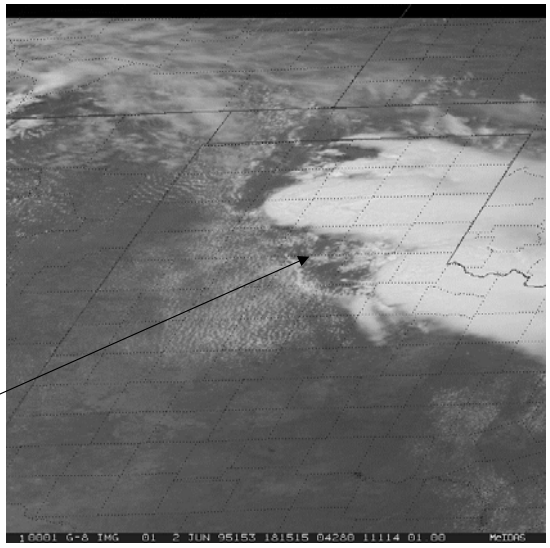


LCL=1.1 km

There is some low-level CAPE but more CIN deeper (1.1 km) into the cold air.

Special RFD: Enhancing Boundary Layer RH

- Early convection created cold /dry outflow boundary
- The outflow modified with time to become cool & moist
- Increased moisture ⇒
  Lower LCL,
  larger CAPE,
  smaller Tdd



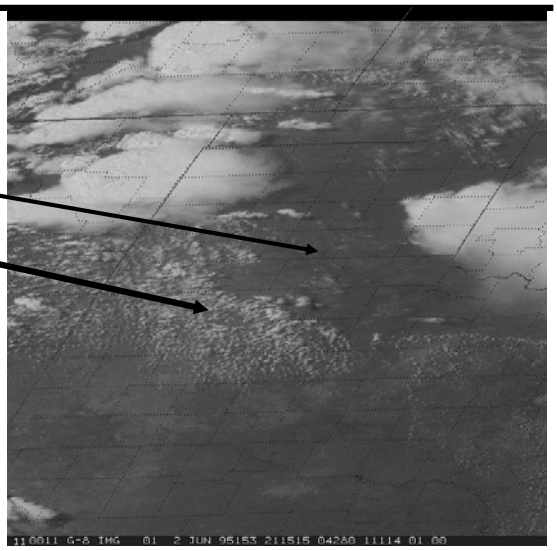
1815 UTC

This is the area where severe thunderstorms erupted.

Special RFD: Enhancing BL RH

How did the cool side evolve?

- Cool side ~ few clouds
- Warm side...cloudy

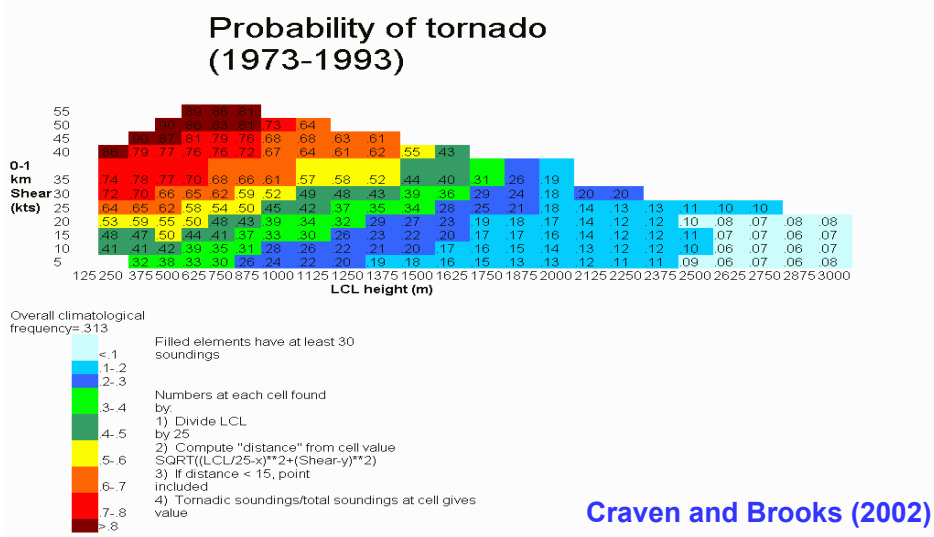


2115 UTC

Note that this proposed evolution is different from how the warm sector would be expected to mix-out moisture during the day (as shown by McGinley in "Nowcasting Mesoscale Phenomena", Chap 8 of the Mesoscale Meteorology and Forecasting book edited by P.S. Ray.(1986). See pg. 667 of that book. McGinley does not treat the special case of airmass modification.

Assuming equal insulation and vegetation on both sides of boundary, moisture could be boosted on the cool side due to: 1) Enhanced moisture fluxes owing to stronger surface winds, 2) "Trapping" of surface-based thermals in the internal boundary layer (BL) due to stability above, 3) Detraining of thermals in lower BL via stronger shear, and 4) Rotor circulation. Moisture is lost on the warm side due to thermals reaching their LCL - (boundary layer convective rolls) and deeper boundary layer mixing.

Combining Effects of LCL Height and Shear



This is from Craven and Brooks (2002). Graph shows that tornado likelihood greatly increases as 0-1 km shear AND LCL height decreases. Note that these are conditional probabilities and are only using 1800 LST soundings.

Other parameters that take into account low-level CAPE and Shear are EHI, VGP, and the Significant Tornado Parameter (STP). See SPC's Mesoanalysis page for more details (http://www.spc.noaa.gov/exper/mesoanalysis/s3/index2.html).

Unanswered Questions

- Failure modes
- Tornado scale affects (how & why do tornadoes form?)
- In-observables
- What are the roles of entrainment and microphysics in determining the thermodynamic character of the RFD?

Future research such as VORTEX 2 may help to explore answers to these questions.

Buoyancy Effects

- Buoyancy can help stretch the vortex associated with supercells
  - Especially when CAPE is compressed into lower levels (note: pressure gradient forcing from shear is still major acceleration factor below 500 mb)
- Related to CIN, LCL height , and LFC height
- Mean layer lifting process most representative in proximity soundings

Research has shown that low-level CAPE and or corresponding low-level CIN may have relevance to tornado production. More CAPE in the lowest levels (and thus lower LCF heights) above the ground suggests stronger potential for large low-level vertical accelerations and enhanced low-level mesocyclone intensification, and thus increasing likelihood of tornadoes in supercells. In a recent study, Davies (2004) showed than stronger tornadoes (≥F2) tended to have more MLCAPE, less MLCIN, and lower MLLFC heights than weaker tornadoes and non-tornadic supercell storms.

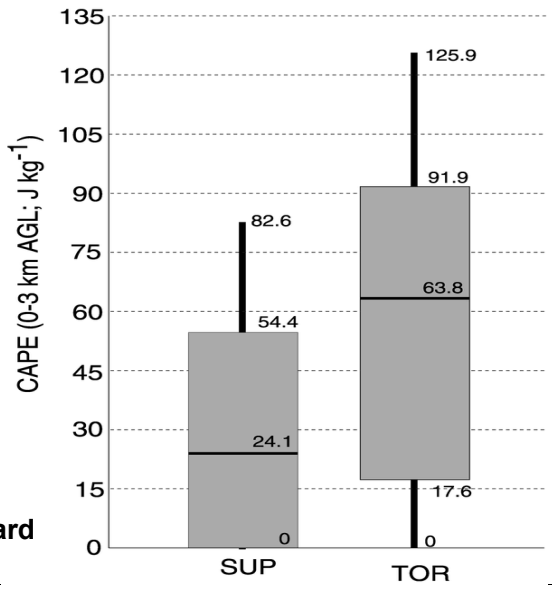
Simulations of storms with small CAPE (~ 800) squashed into the lowest 5 km indicate that pressure gradient forcing from rotation in mid levels is the primary force for accelerations below 500 mb. Above 500 mb, buoyancy forcing becomes more important (Wicker and Cantrell, 1996).

Low-level buoyancy is also related to LCL/LFC heights (RFD characteristics).

Buoyancy Effects

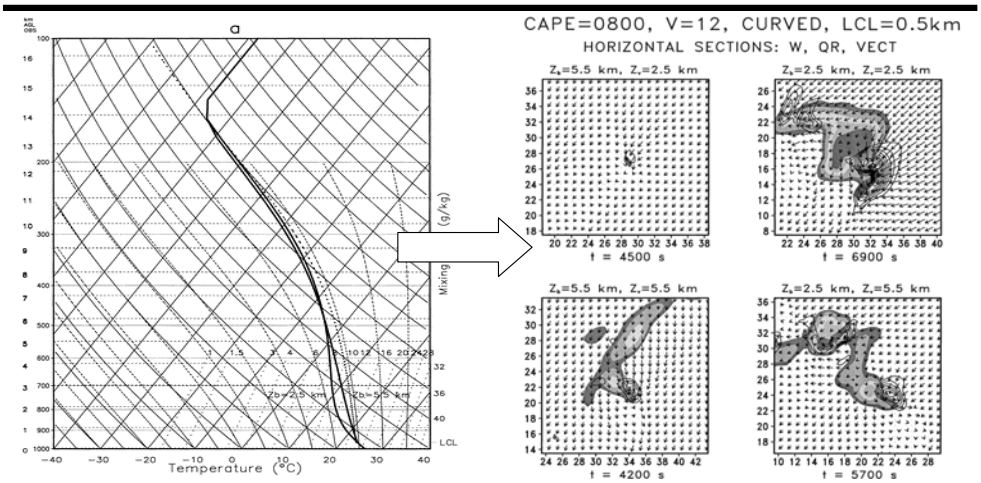
- Increases stretching
- Larger for significant tornadic supercells
- Lots of overlap

Rasmussen and Blanchard (1998)



From Rasmussen and Blanchard (1998), and Rasmussen (2003) research have shown that low-level CAPE may have relevance to tornado production. More CAPE in the lowest levels above the ground suggests stronger potential for large low-level accelerations and enhanced low-level mesocyclone intensification. LCL height and MLCIN are likely better indicators for low level vortex stretching potential. Also, boundaries could provide pre-existing vertical vorticity even without strong low-level buoyancy.

Buoyancy Effects



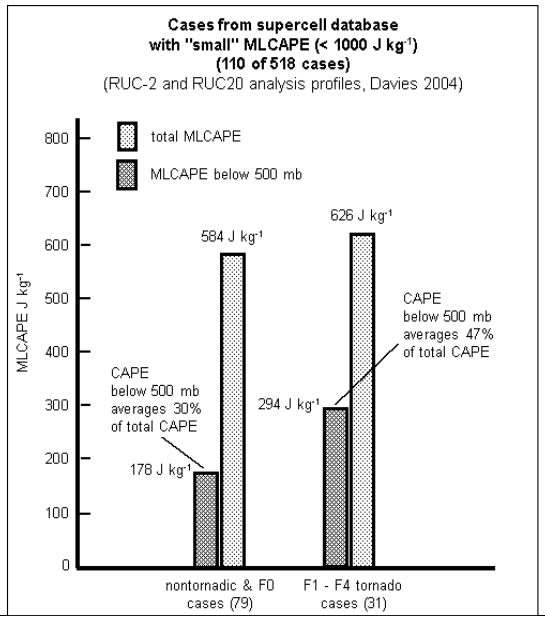
- When buoyancy and shear are concentrated in the lowest levels of the lower troposphere (e.g.., tropical land falling systems), updrafts can be intense and long-lasting (from McCaul and Weisman , 2001).

McCaul and Weisman's study (2001) showed that there are variations in buoyancy that need to be available in storms with given amounts of shear. They found that the effect of the buoyancy profile shape on convection is quite strong for small bulk CAPE, where the buoyancy profile is susceptible to specification in a wide variety of ways, but gradually weakens as CAPE assumes larger and larger values. Also, they found that increases in the low-level lapse rate tended to produce both stronger updraft rotation and colder surface outflows, and more rapid storm cell propagation relative to the low-level ambient wind, at least for the cases where supercells were found.

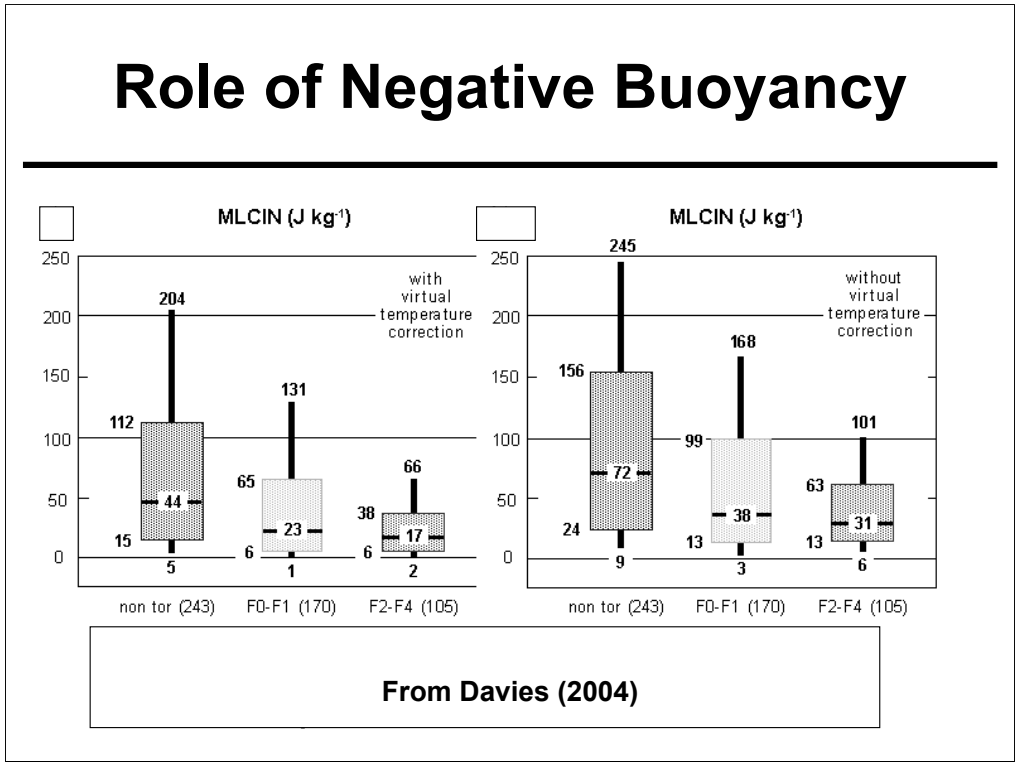
In this figure, they have maps of simulated updraft velocity w at z = 1.71 km (contoured at 2 m s^{-1} intervals), rainwater mixing ratio q_r at z = 0.127 km (shaded starting at 0.5, 1.0, 2.0, 3.0, and 4.0 g kg^{-1} values), and horizontal storm-relative wind vectors (every other vector removed) at z = 0.127 km for a simulation with 800 j/kg of CAPE and a curved hodograph with 12 m/s of shear. Coordinates relative to the full simulation domain are marked at 2-km intervals along the sides of the plots. Vectors are scaled so that a length of 1 km on the plots corresponds to a wind speed of 12.5 m s^{-1}. All plots are taken from the second hour of the simulated storms at selected times (see markings beneath each panel) deemed representative of mature storm structure.

MLCAPE Distributions

- Tornadic storms in small CAPE settings with moderate to strong shear are associated with CAPE that is mostly below the midlevels of the atmosphere (Davies, 2004)



This is from Jon Davies' study of 110 RUC-2 and RUC20 soundings.



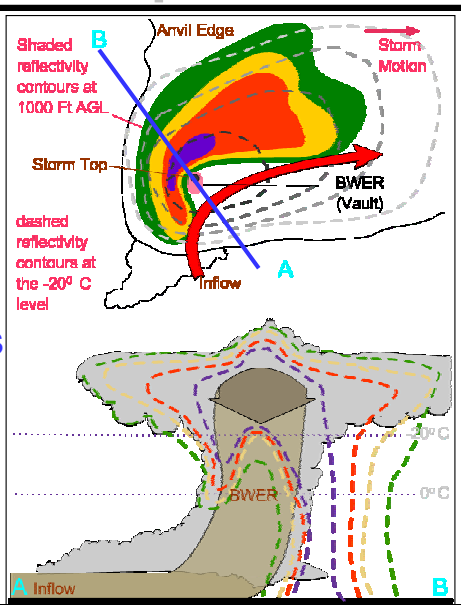
In another recent study, Davies (2004) showed than stronger tornadoes (≥F2) tended to have more MLCAPE, less MLCIN, and lower MLLFC heights than weaker tornadoes and non-tornadic supercell storms.

Tornadoes are considered less likely to occur with "elevated" supercells found in storm environments where the only instability is from parcels that originate well above the surface (Rasmussen and Blanchard 1998) and Grant (1995). Elevated convection as defined by Colman (1990) has no surface-based convective available potential energy (CAPE, Moncrief and Miller 1976). But many thunderstorm environments have significant surface-based CAPE present above a deep layer of convective inhibition (CIN, Colby 1984), signified by a large area of negative buoyancy below the positive CAPE area on a thermodynamic diagram. Therefore, a distinction can be made between thunderstorm settings that have no surface-based CAPE, with positive CAPE associated only with lifted parcels from well above the surface and thunderstorm settings that involve positive surface-based CAPE located above a large layer of surface-based CIN associated with a relatively high level of free convection (LFC).

From a physical standpoint, an environment with large CIN and associated high LFC heights may inhibit low-level parcel ascent and stretching near the ground, reducing likelihood of tornadoes. It is also possible that tornadogenesis may in part be related to rapid upward acceleration and stretching within the layer containing largest helicity. If CAPE is not positive and large within the same layer where SRH is large (e.g., CAPE located above and vertically "disconnected" from a layer of large SRH), then tornado development may become less likely.

Conceptual Models of Supercells

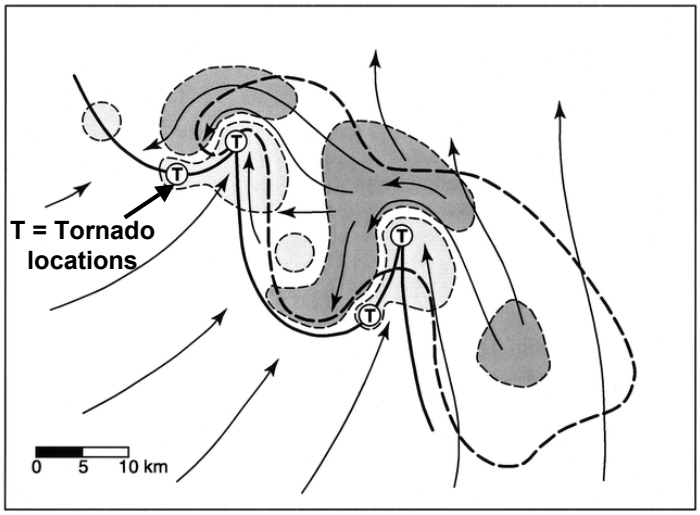
- Classic features identified from radar and visual observations



Modified from LaDue and Lemon (2004)

There will be more of this in IC3, but the main things to note conceptually are : tight low-level reflectivity gradients, the displacement of low level echo core, storm top slightly displaced on low level inflow side over the Bounded Weak Echo Region (BWER), pendent or hook echo on right, rear storm flank. Features are caused by the interaction of the rotating updraft in a sheared environment. Not all radar features are present in supercells.

Supercell model hybrids



From Ziegler et al. (2001)

Conceptual model of the mature Newcastle–Graham storm complex in the lowest 1 km, as inferred from the Doppler analyses and derived from classical conceptual models described in the text (from Ziegler et al., 2001) . Heavy solid curves are mesoscale cold fronts, heavy dashed contour denotes the precipitation shield, thin black arrows are airflow streamlines, and light and dark shading denote updraft and downdrafts areas, respectively. The circled "T" symbols indicate possible tornado locations.

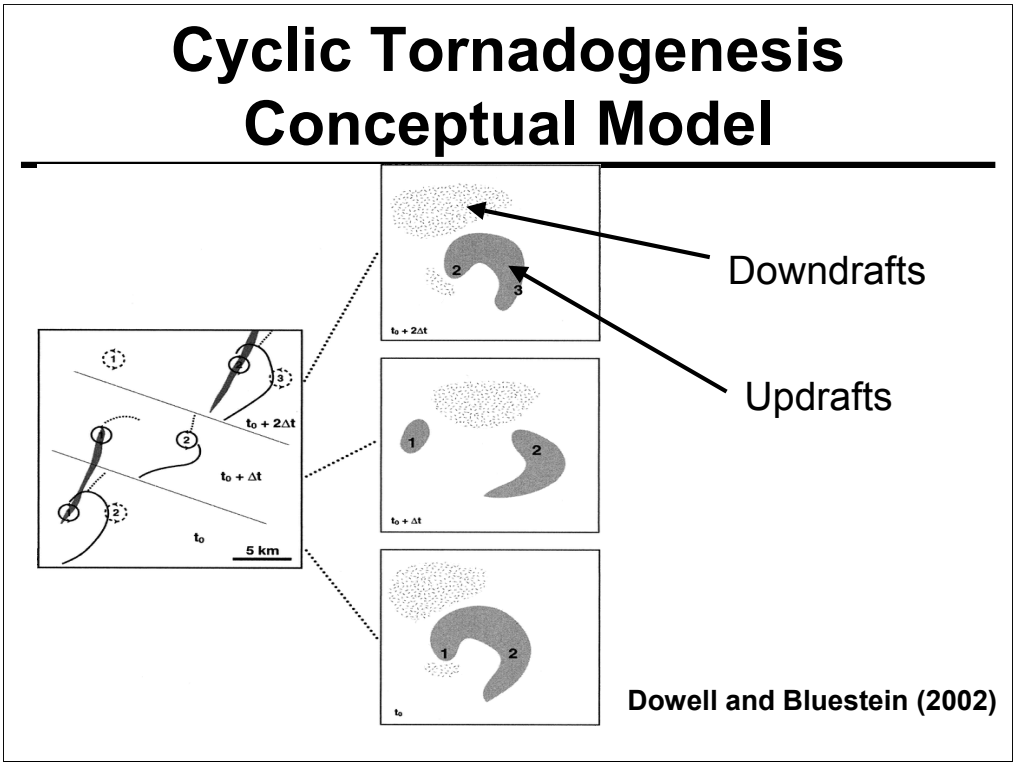
Supercell character, albeit rapidly evolving, was present prior to the Newcastle tornado. Mid-level mesocyclone developed through stretching. Subsequent low-level intensification through stretching; source of weak vertical vorticity not clear but parcels came from rainy area to the east. This data was from Newcastle, TX tornado from 29 May 1994.

Cyclic Tornado Process

- Occurs after RFD with a mature supercell surges forward and enhances convergence along leading edge
- Locally enhanced convergence promotes updraft and increases tilting of horizontal vorticity
- New supercell forms on head of RFD surge while “old” storm continues to left of initial storm track

See the flash graphic on the next slide that shows the cyclic process for tornadogenesis.

Subsequent tornadogenesis in a cyclic storm is typically observed to be somewhat faster than from the initial storm, but often these tornadoes can last the longest and be the largest.



From Dowell and Bluestein (2002). Circles and thick lines indicate vortices and wind shifts, respectively. Tornado tracks are shaded. (right) Shading indicates updraft, and the spotted pattern indicates downdraft. The time between successive tornadoes ($2\Delta t$) is 20 min.

Summary

- Review the 8 objectives on identification of aspects of supercell conceptual models.
- A summary of key points will be found in Lesson 6.

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- See the reference page

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Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 2: Squall Line Tornadic Storms

Warning Decision Training Branch

The title for the instructional component (IC) is "**Conceptual Models for Origins and Evolutions of Convective Storms** . This is the first IC in the AWOC Severe Track. Lesson 2 will be on conceptual models for squall line tornadic storms.

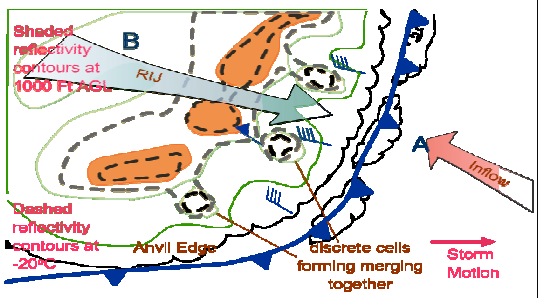
Lesson 2 Learning Objectives

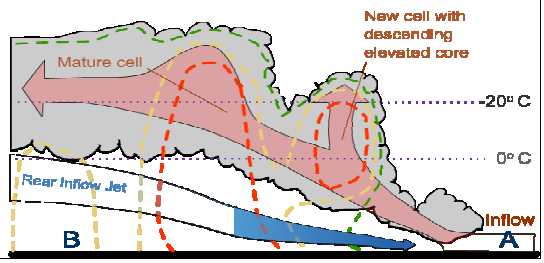
1. Identify characteristics of a severe linear squall line (SQLN).
2. Identify characteristics of SQLN tornado development process.
3. Describe how line-end vortices develop.

These are the learning objectives for lesson 2. Squall line tornadoes account for up to 20% of all tornadic events nationwide (Tessendorf and Trapp, 2000). However, issuing warnings for squall line tornadoes is problematic.

Conceptual Model of a Nonsevere Linear System

- Characteristics
  - Descending RIJ
  - No MARC, DCZ
  - Shallow sloping updraft over top of cold pool with numerous discrete cells merging into a line



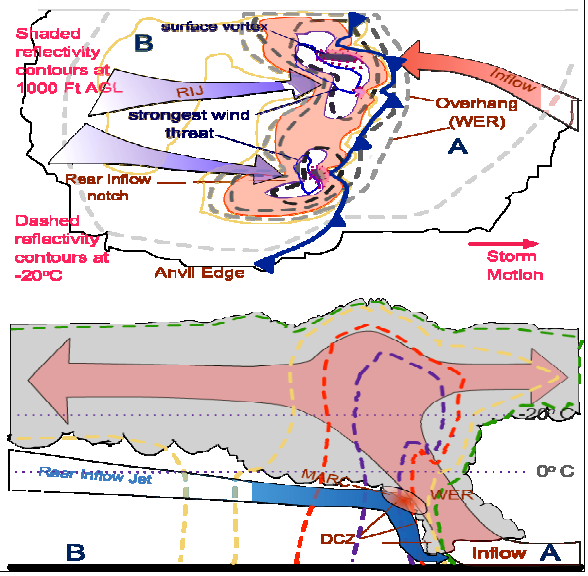


From LaDue (2004)

There will be more in IC 3 (storm interrogations) on this model. Essentially, the Rear-inflow Jet (RIJ) descends, due to cold pool imbalance with shear and lack of strong deep lifting along the gust front. Also, there could be insufficient storm-relative flow and/or surface based instability to feed the updrafts. There are no 3 dimensional features (line-end vortices, MARCs, DCZs, etc.) with these structures.

Conceptual Model of a Severe Linear System

- Characteristics:
  - Relatively nondescending RIJ
  - MARC, DCZ
  - Front end echo overhang with linear BWER ahead of the surface gust front



From LaDue (2004)

Note position of surface vortex (potential tornadic development location) just south of inflow notch and north of RIJ , manifested on radar by a rear inflow notch. That is where the low level velocity couplet–shear signature should be located. Others features are the Mid-Altitude Radial Convergence (MARC) signature (Schmocker et al., 1996), which is often a precursor to the descent of the elevated RIJ. The MARC feature is characterized by persistent areas of enhanced convergence just downwind of high reflectivity cores along the leading edge of the convective line. Persistent areas of MARC > 25 m/s at 3 to 5 km above ground level (AGL) can provide lead time for first report of wind damage before a well –defined bow echo develops (See Severe IC 3 for more details).

The Deep Convergence Zone (DCZ) (Lemon and Burgess, 1992) represents a deep zone of laminar flow at the interface of an erect updraft and the edge of the RIJ (or in the case of a supercell , the Rear-Flank Downdraft). See Severe IC 3 for more details.

Characteristics of SQLN Tornado Development Process

- 3 possible mechanisms at work
- Ambient vertical vorticity and horizontal convergence maximized in low-levels
- Nondescending tornadic vortex signatures (TVSs)

Squall line tornadoes account for up to 20% of all tornadic events nationwide (Tessendorf and Trapp, 2000). However, issuing warnings for squall line tornadoes is problematic. Supercell structures and attendant tornadoes are often observed during early stages of multicell systems when storms are still a bit isolated. During mature phase of squall line/multicell systems, supercells and their associated classical mesocyclone signatures generally are not identifiable, and in fact , are not considered important to the formation process . Thus, no clear relationship exists between midlevel line-end vortices that are located behind the leading-line convection and above the surface cold pool and subsequent tornadoes.

Numerical simulations and radar observations suggested that there were 3 possible mechanisms related to squall line tornado production. They all involve dependencies on strong (> 20 m/s) low-level shear (in lowest 2-5 km) and updraft which produces vertical vorticity in low-levels and a tornado vortex signature which develops and intensifies rapidly in low levels first as opposed to supercells (Weisman and Trapp, 2003).

Formation Mechanisms for SQLN Tornadoes

1. Horizontal shearing instability
   - Similar to nonsupercell processes (along leading edge of gust front)
2. Tilting of horizontal vorticity at intersection of a bow echo with preexisting boundary
3. Tilting of crosswise vorticity by convective-scale downdrafts
   - Tornadic Quasi-Linear Convective Systems (QLCS)

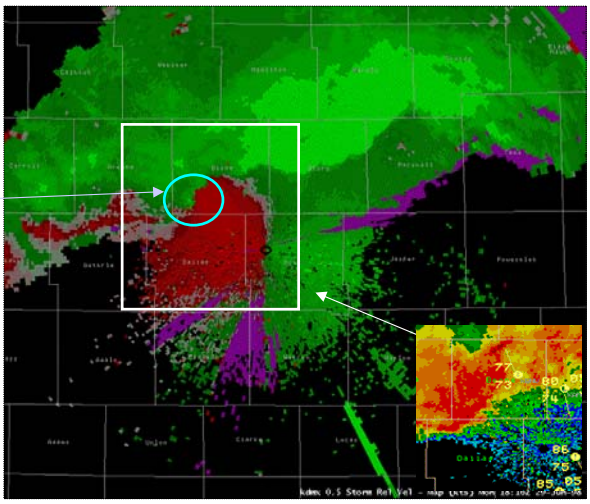
All of these are possible tornadic development mechanisms at work in SQLNs, but research remains uncertain as to which actually occurs in reality. The first mode occurs when horizontal shear vorticity is stretched locally by a vigorous updraft which is being enhanced by convergence and system-relative flow along the gust front. These vortices are usually short-lived.

2nd mode is tilting of horizontal vorticity at intersection of a bow echo with preexisting boundary (Przybylinski, 1995), or tilting upward of easterly shear. This is similar to supercell process but there is typically no long-lived rotating updraft above the low-level vortices associated with squall lines and bow echoes.

The third mode is downward tilting of westerly shear (Weisman and Trapp , 2003). This formation process, modeled in detail with numerical simulations (Weisman and Trapp (2003) includes the generation of both midlevel and low-level mesovortices via tilting of crosswise vorticity rather than streamwise vorticity (typical supercell process). The mesovortex associated with this type of QLCS develops a larger circulation with time than a supercell mesocyclone.

Example 1

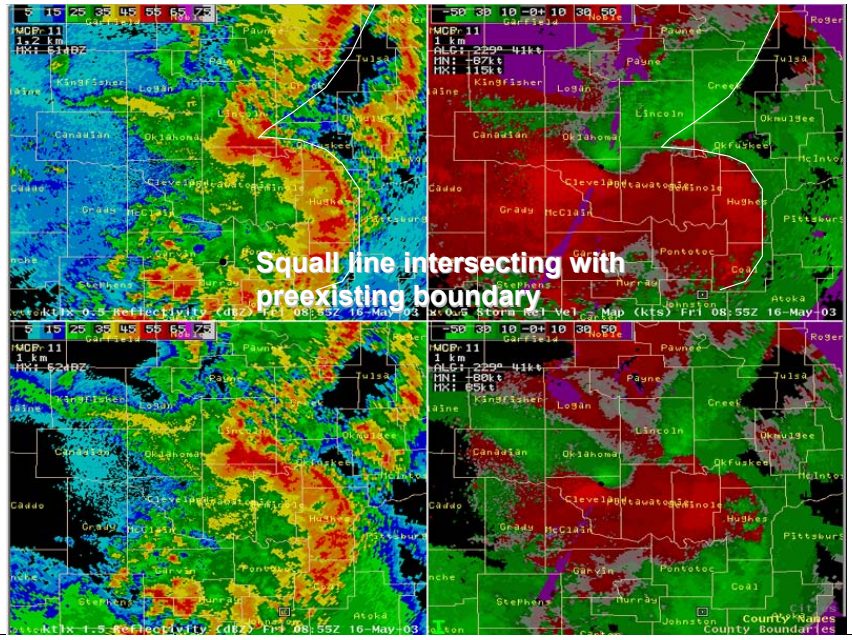
- "Kink" in the gust front signifies a mesovortex developing rapidly along squall line
- Likely location for a brief tornado or enhanced wind damage



This is from the 29-June 98 DMX WES case.

Brief F1 tornadoes and extreme wind damage were reported as the line swept into Des Moines area.

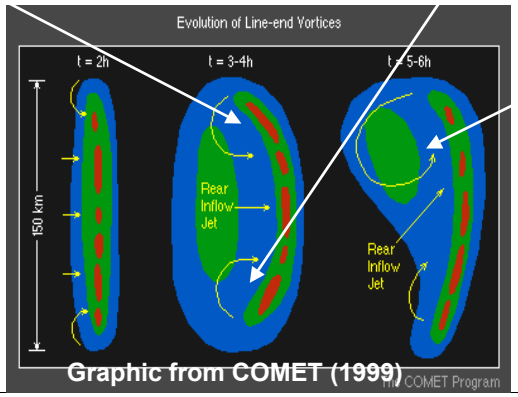
Example 2



There's a loop with this example. The F1 tornado briefly touched down in SE Lincoln Co. (very near the intersection of the squall line with the SW-NE boundary), approximately 14 min after this radar image.

How Line-end Vortices Develop

- Line-end vortices (or bookend vortices) typically develop over time (2-4 hours) along any portion of line (ends, breaks, other - where strong updraft/shear exists).
- Northern member cyclonic, southern member anticyclonic.



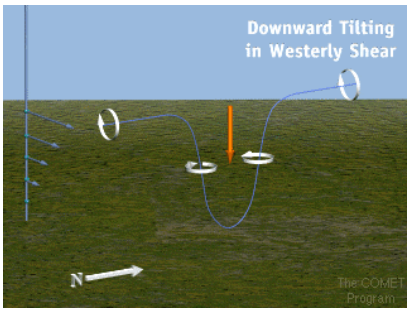
Graphic from COMET (1999)

- Cyclonically rotating vortex tends to become stronger and larger due to midlevel convergence and Coriolis forcing.

In the numerical simulations presented in the MCS module (http://meted.ucar.edu/convectn/mcs/), the line-end vortices developed 2-4 hrs. into the lifetime of the convective system, just behind the zone of active convection. The northern vortex had cyclonic rotation while the southern end of the line rotated anticyclonically. The northern member is the one that usually is stronger and longer- lasting and can enhance the RIJ sufficiently to help spin up a tornado. Note that bookend vortices are downdrafts - tornadic circulations along squall lines form typically along the leading edge of the system outflow or when the outflow intersects a pre-existing boundary.

How Line-end Vortices Develop

- A new conceptual model by Weisman and Trapp (2003)
- Downward tilting of westerly shear

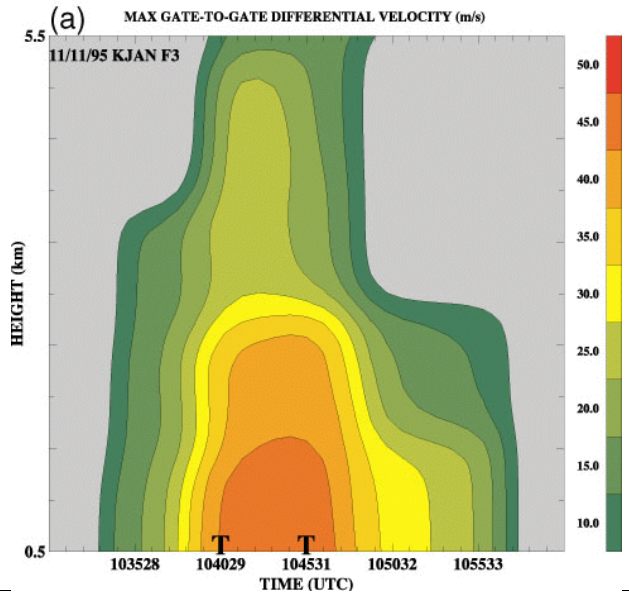


Note in the flash graphic counter-rotating vortices which develop below the horizontal vorticity streamlines which are bent downward. The (red) one to the south rotates cyclonically and is stronger, and longer lasting than the anticyclonically (purple) rotating one. Also, note Coriolis Force (CF) effects get stronger with time - actually the graphic tries to imply the impacts of midlevel convergence in the presence of the CF squall line which acts to strengthen the cyclonic vortex with time. This forcing helps to produce the asymmetric evolution that characterizes most long lasting MCSs.

Nondescending TVS Paradigm

- Mode prevalent in QLCSs
- The T is tornado time
- Short lead times to max velocity differentials and tornado

Trapp et al. (1999)



The non-descending TVS paradigm is found in QLCS structures. The mode of development is bottom-up from crosswise vorticity that is tilted by storm scale downdrafts (Trapp et al., 1999).

Summary

- Review the objectives

The 3 objectives are:

1) Identify characteristics of a severe linear squall line (SQLN)
2) Identify characteristics of SQLN tornado development process
3) Describe how line-end vortices develop.

The test over IC 1 will include a few questions on this Lesson's objectives.

References

- See handout list or AWOC Severe Track web page

See the reference list.

Severe Track IC 1
Lesson 2 References

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Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 3: Hail Storms

Warning Decision Training Branch

The title for the instructional component is "**Conceptual Models for Origins and Evolutions of Convective Storms** . This is the first instructional component in the AWOC Severe Track. Lesson 3 will be on conceptual models for hailstorms.

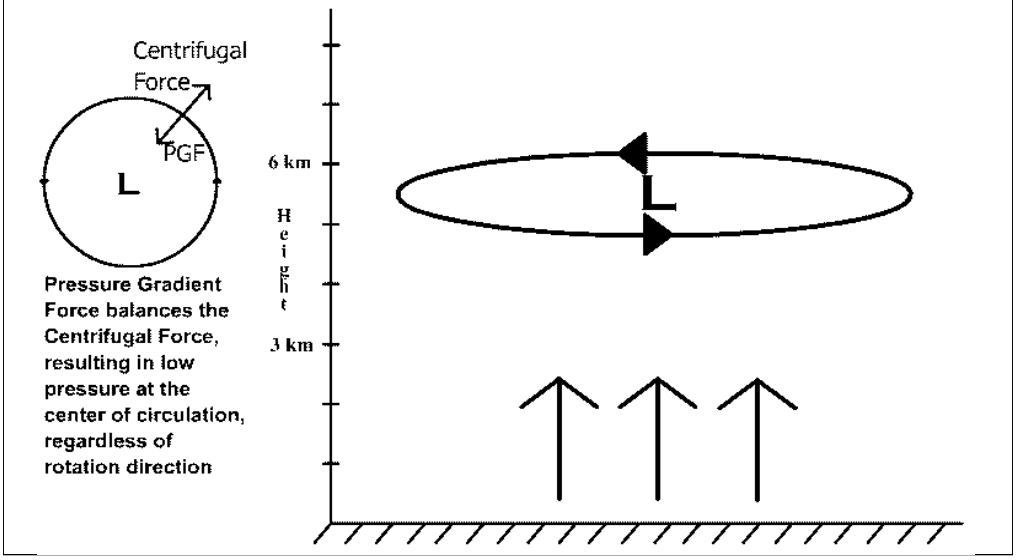
Lesson 3 Learning Objectives

1. Determine the role of shear and midlevel rotation on updraft strength.
2. Determine the roles of buoyancy and steep lapse rates in hail growth zone.
3. Identify the effects of melting.
4. Identify favorable hail growth trajectories.

Lesson 3 Learning Objectives

5. Identify favorable hail embryo source regions in convective storms.
6. Identify favorable soundings for surface based updraft hail and elevated updraft hail.
7. Identify characteristics of the hybrid Multicell-Supercell Hailstorm.

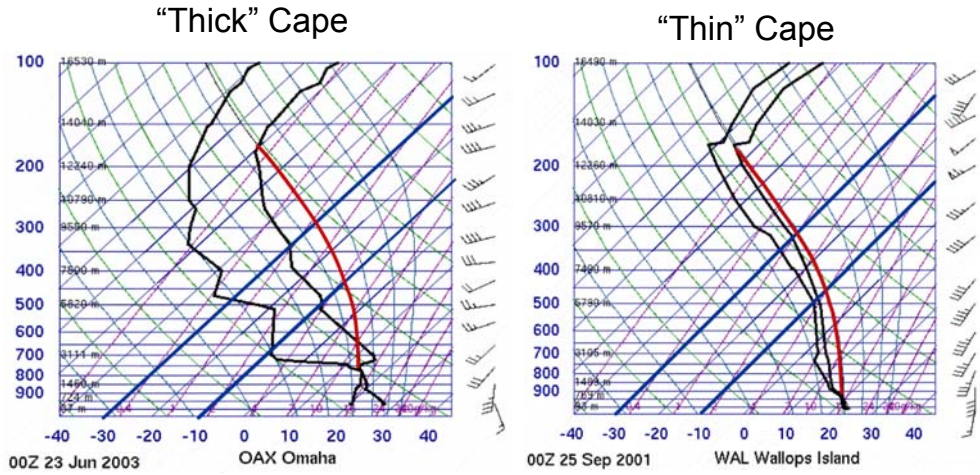
1. Role of Shear and midlevel rotation on updraft strength



As seen in the section on supercells, wind shear produces horizontal vorticity that can tilted into vertical in convective updrafts. Vertical vorticity is associated with mid-level rotation. Many times rotation is strongest in mid-levels of a storm. Regardless of the direction of spin of the rotation, whether cyclonic or anti-cyclonic, there is going to be a centrifugal force associated with the rotation. The stronger the rotation, the stronger the centrifugal force. To keep the forces balanced, an opposing pressure gradient force must be present. Again, both cyclonic and anti-cyclonic rotations will have an inward directed pressure gradient force, in turn leading to a dynamically induced low pressure in the center of the circulation. Low pressure in mid-levels lead to an upward directed pressure gradient force below the circulation, and thus stronger vertical motion. It has been shown mathematically that the dynamically induced (via mid-level rotation) contribution towards total updraft velocity can be as large as the contribution due to buoyancy. With regards to hail, stronger updrafts have the ability to support larger hail stones, thus the presence of mid-level rotation can signal stronger updrafts within a storm, and thus a higher threat of severe hail with all other environmental factors being equal.

Key Point: A storm exhibiting mid-level rotation is more likely to contain severe hail than one without rotation in identical environments with all else being equal. This is because mid-level rotation can enhance updraft strength due to a dynamically induced vertical pressure gradient force.

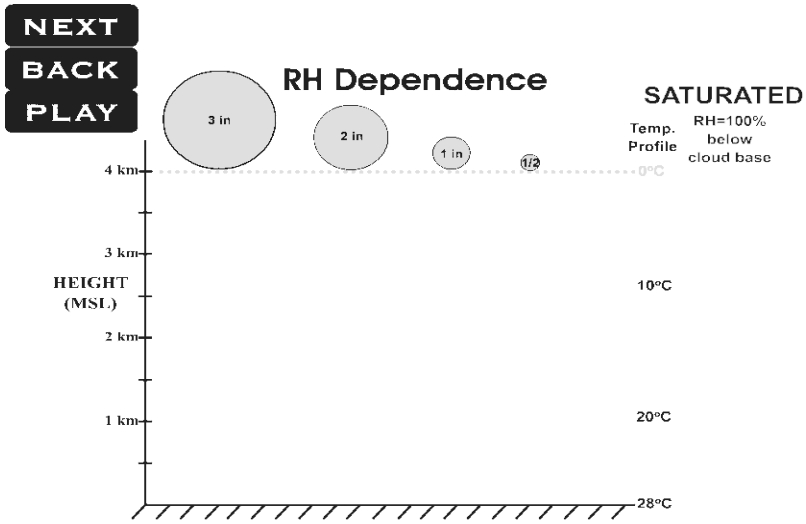
2. Buoyancy and steep lapse rates in hail growth zones



Steeper lapse rates aloft increases the overall instability of the atmosphere. Greater instability allows for more buoyant parcels of air if enough lift is present to overcome any cap that may be in place. Intuitively, more buoyant air (and thus lapse rates) within the –10 to –30 ^{o}C layer, corresponding to the maximum hail growth zone, would mean stronger updrafts in the growth zone. All other factors being equal, larger stones would have the ability be suspended longer in the prime growth zones, thus growing even larger. To date, no studies have been done to verify the usefulness of this concept…currently it is just a conceptual picture of an ingredient for simplified hail growth trajectories.

Key Point: instability and thus strong updrafts are preferential to large hail growth in the hail growth zone, between about –10 and –30 ^{o}C.

3. Melting Effects



Melting affects hail most significantly affects smaller hail sizes as they fall through the 0°C level. All other factors being equal, small hail will melt proportionately more than large hail for 2 reasons: 1. larger hail has a higher terminal velocity and spends much less time in the melting layer before reaching the surface and 2. surface area is related to the radius of the hailstone, squared, while volume of rainwater loss is related to the cube of the radius. Thus, smaller hailstones will have a proportionately larger surface area exposed to melting conditions than larger stones, and thus proportionately melt faster than larger stones as well. Certain atmospheric conditions favor more rapid melting as well, with the amount of melting always dependent on the initial size of the hailstone. Conditions within the melting layer that favor melting are relative humidity (higher RH promotes greater melting and/or the presence of liquid drops falling with the hail), temperature profile (higher freezing level and warmer temps favor greater melting). Low relative humidity allows for a delay in the onset of melting by providing favorable conditions for the hailstone surface to remain dry. In melting layers with 50% or less relative humidity, melting has been found to proceed when the stone reaches air with +5 ^{o}C, obviously diminishing the amount of time the hail falls through the melting layer. Additionally, low RH hinders melting even if the stone is coated in water, since the layer of water is more likely to evaporate off the surface, cooling both the hail stone and the surrounding environment, further slowing the melting process. Having a warmer temperature profile intuitively results in more rapid melting, as heat transfer from the atmosphere to the hailstone is larger in a warmer environment.

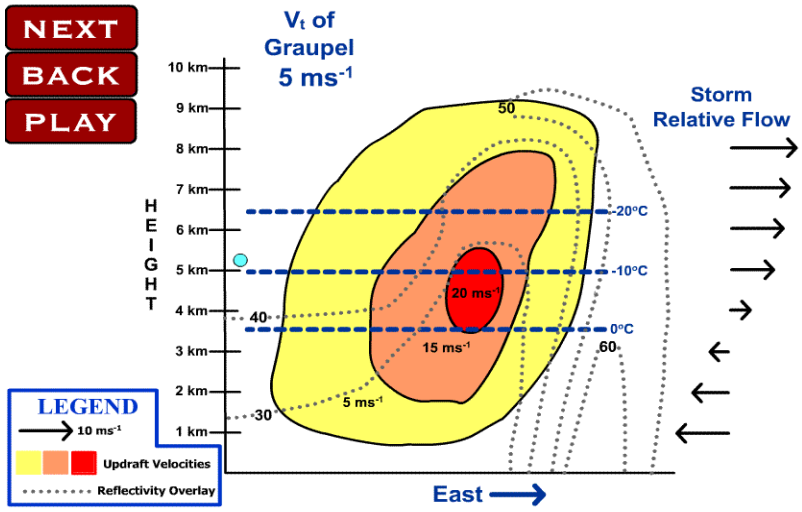
Another factor not mentioned above deals with hailstone ice density. Low density hail (common on the high plains), typically with graupel cores, melts much more effectively than high density hail. It is also strongly size dependent, but it is very important to not that low density hail is easily the most important factor when dealing with melting. The problem is that we currently have no way of knowing if low density hail exists in a storm, nor what proportion of the total hailfall consists of low-density stones.

Finally, microphysical differences between the makeup of all the stones in a hailfall can also influence melting, although these differences have not been studied nor can they be measured at this time. Some of these differences are shape of the hailstone, hailstone size spectrum within a particular hailfall, and direct influences of surface hailstone heat transfer, among others.

Key Point: Smaller hail melts proportionately more than larger hail because of differences in surface area and terminal falls speeds. Thus, hail that is large in-cloud will remain large at the surface. Relative humidity, temperature profile, and hailstone density all play important roles in the amount of melting a stone undergoes falling through the melting layer.

4. Hail Trajectories

Residence Time Example



Hail trajectories have been found to be extremely diverse within convective storms. The diversity of the trajectories becomes even more complicated when the size of the storm and the strength of the updraft/wind shear increases. A single trip up an updraft in a pulse storm can grow a hailstone up to about golfball size (Knight and Knight 2001), and the updraft necessarily has to have an ideal vertical velocity profile such that the hail stone spends as much time as possible in the updraft. An updraft too weak won't allow a sizable stone to grow, and an updraft too strong will eject the hail embryo too quickly before significant growth can occur.

Hail larger than about golfball in size can be produced with some form of recycling trajectories within a storm or complex of storms. Recycling can occur with multicelled convection where an older updraft produces hail that falls into or near the base of a newer updraft. Supercell convection allows for numerous recycling trajectories, but the bulk of the trajectory studies to date have found relatively simple paths through or around the main updraft, and nearly all of the growth occurs within a fairly narrow altitude and temperature range (-10 to -25°C). The largest hail tends to originate from embryos that find themselves on the southwest side of the large updraft. Upon entering the updraft these particles are then able to experience the longest growth time by traversing the full length of the updraft's long dimension (Foote 1984).

The importance of any hailstone trajectory lies in the amount of time the hailstone resides in an updraft, and this time period is referred to as "residence time". As residence time increases, so does the possibility for growth of large hail within a convective updraft. Residence time is increased when: The hailstone's terminal velocity is nearly balanced by an updraft, the updraft width is substantial, and storm relative flow across and through the updraft isn't too strong.

Key Point: A wide variety of trajectories exist that can produce large hail. The important concept is residence time within the updraft, the more the larger the hail. Wide updrafts and larger embryos lead to the largest hail sizes. .

5.. Favorable Embryo Source Regions

- 2 primary sources, 1 secondary source
  1. Nearby growing CBs, flanking lines
  2. Stagnation points
  3. Shed drops from growing/melting hail

     -- secondary source since hail already in storm

The main issue about hail embryo origins is how embryos arrive within the strong updraft that is capable of growing to large hailstones (Knight and Knight 2001). There is no real delineation between an embryo and small hailstone, thus some of the principles involved in transport are covered in other topics. A remarkable finding regarding hailstone embryos is that many analyses of hailstone collections from significant hailstorms from all over the world reveals mixtures of types of embryos. The importance of this is that either embryo delivery into strong updrafts straddles the freezing level or embryo sources are typically diverse: or both could be true. If embryos sources straddled the freezing level then frozen drops and graupel particles would equally be likely as embryos.

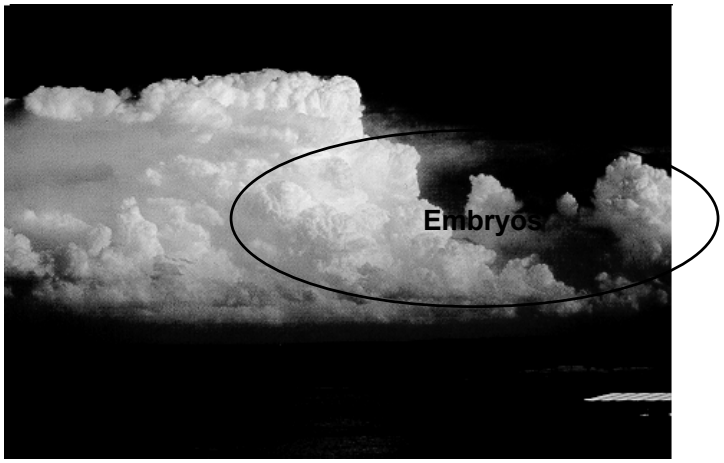
Though embryo sources are very diverse, there are 3 important sources of hail embryos within convective storms. The first is within developing cumulus towers on the flanks of parent storms or within newer updrafts within multi-celled convection. The embryos grow within the developing updraft early in the lifecycle when updraft velocities are ideally not so strong that all liquid water is advected too quickly vertically before significant growth can occur. Of course this mechanism works in single celled “pulse storms”, where embryos grow in a developing updraft, then as they are advected vertically, they grow such that their Vt increases at about the same rate that the updraft velocities increase, thereby significantly increasing residence time in the updraft growth zone. These storms, given the right environmental conditions and ideal updraft velocities, can produce over 1.00 inch diameter hail from the initial embryo.

The second favorable source of hail embryos is near stagnation points in the mid-levels of a convective storm with an intense updraft. The updraft is necessarily intense so that mid-level storm relative flow does not significantly penetrate the updraft not significantly tilt the updraft. A stagnation point arises when the strong updraft is an obstacle to the mid-level flow, resulting in a dynamically induced high pressure on the upwind side of the updraft and a region of little to no horizontal flow where the mid-level flow splits and is diverted around the updraft. Again, the updraft is porous, i.e., it isn't a "rigid" obstacle to the flow, it diverts a certain percentage of the mid-level flow, but some of the flow enters and mixes with the updraft. This region is important for embryo growth because it is on the edges of the main updraft in which the embryos can stay with the storm long enough to grow.

A third favorable source of hail embryos is from drops shed from growing or melting hail or below the 0°C level. This source assumes hail is already present in the storm. Hailstones that are greater than 9 mm in diameter have been found to shed liquid drops during either melting or wet growth processes. These shed drops then can become hail embryos when they freeze. The majority of hailstones within a severe thunderstorm with frozen drop embryos are likely to be formed through this process.

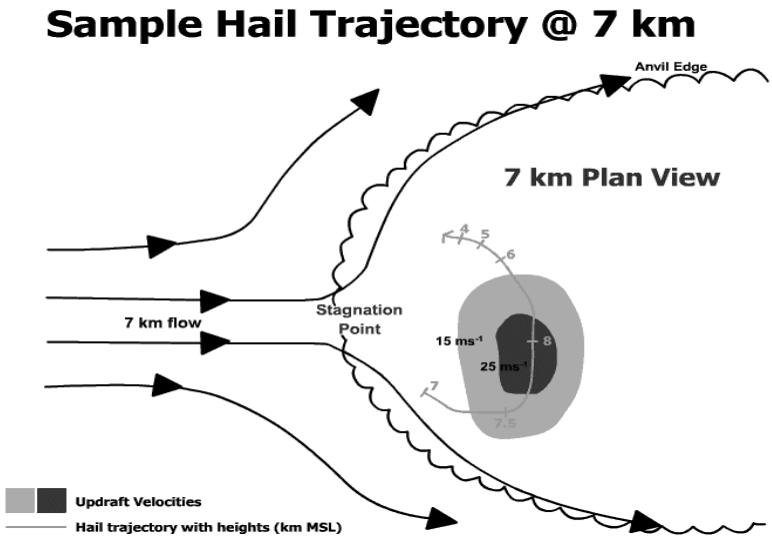
Key Point: Understand that where embryos come from is relatively unimportant, but what is important is where (and if) they are input into the updraft. Know three important areas for embryo growth: stagnation points in the mid-levels of an updraft, within growing cumulus towers on the flanks of the parent storm or within multi-celled convection, and from drop shedding. Additionally, all 3 sources may be working within a given convective storm.

5. Favorable Embryo Source Regions

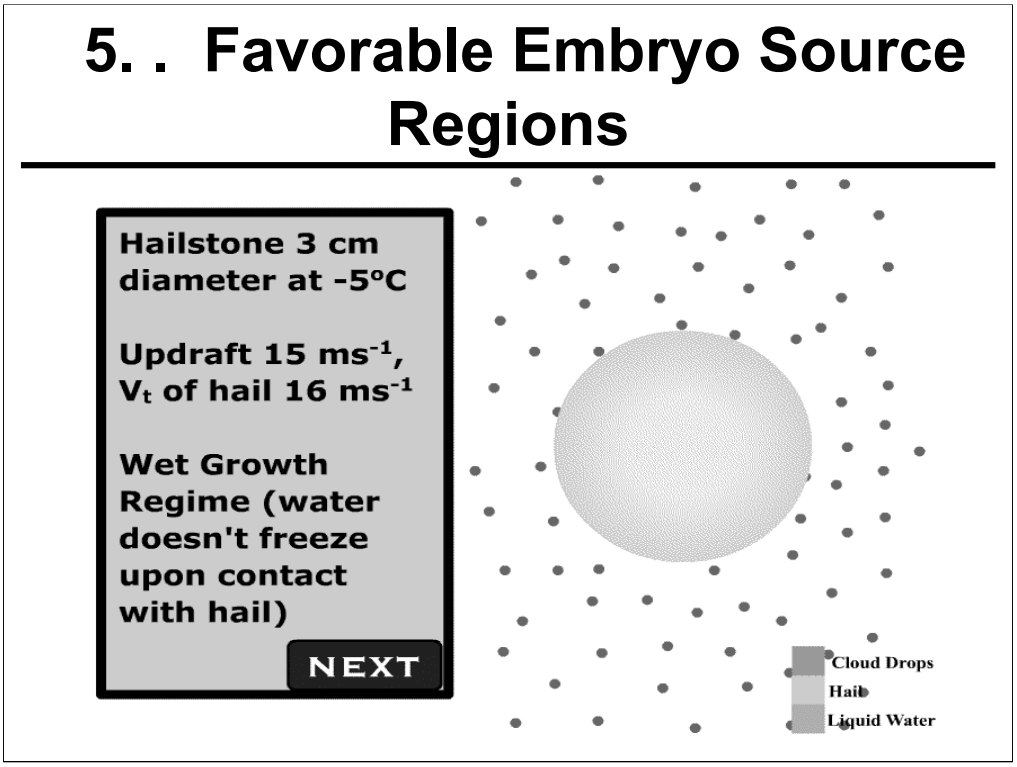


Source region #1: growing cumulus towers or flanking lines

5. Favorable Embryo Source Regions



Source region #2: stagnation points: very weak horizontal flow (and vertical flow), thus allowing depositional/collection growth for embryos, typically graupel



Source region #3: shed drops, which is a secondary source. This animation will demonstrate hail in a wet growth regime and how drops are shed from the ice core.

6. Hail Soundings

- 20 soundings, from all across the country, from surface based to elevated, to ones with thin CAPE, thick CAPE, no shear to high shear, etc. These are located for review the following link:

Hail Soundings

This is almost like a summary point, where we could show a wide variety of hail/non-hail soundings, making the point that RUC soundings near the inflow of storms, especially those near the initialization times, can be decent representations of the near storm environment, especially given the poor density of the rawinsonde networks.

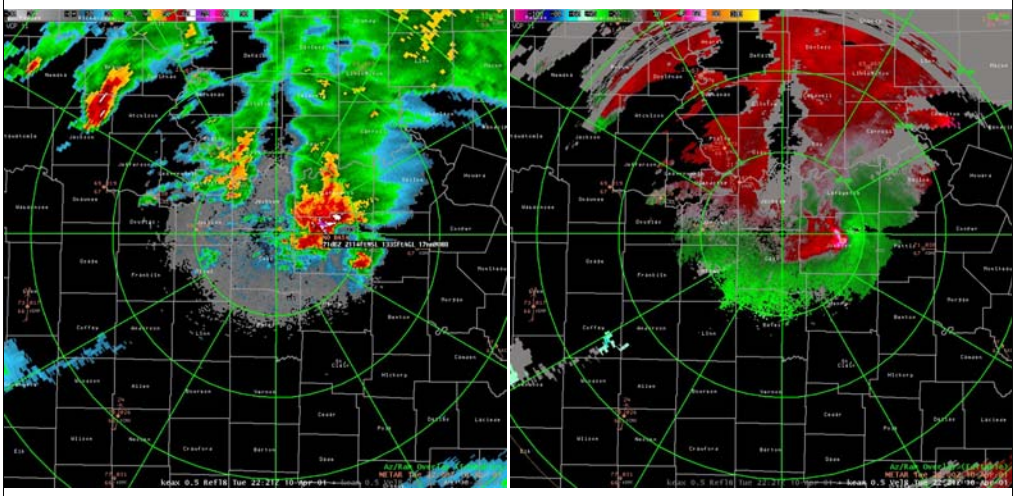
Key Point: Look for thick CAPE, good deep layer wind shear, lapse rates aloft. Much like for supercell and tornado environmental assessment, but without any low level shear and LCL/LFC considerations.

7. The "Hail Monster”

- Nelson (1987) studied hybrid multicell-supercell storms that dropped not only enormous hail, but the enormous hail covered a large area and these storm persisted for several hours
- Characterized by a Deep Convergence Zone (DCZ), huge reflectivity cores along the southern flank and forward flank, few if any tornadoes, tremendous straight line winds

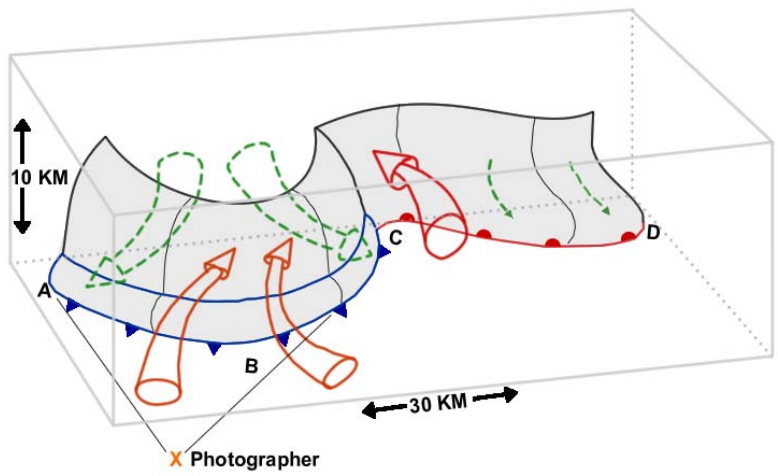
Hybrid multicell/supercell hailstorms produce not only unusually large hail in high quantities, but the hailswaths containing the large hail cover an extrodinary amount of land, leading to destruction over a large area. These storms are characterized with intense gust fronts on their rear flank, and very deep zones of moist convergence along the leading edge of the rear and forward flank gustfronts. these storms tend to move very fast, to the right of the mean wind, and persist for several hours. They are typically non-tornadic or very weakly tornadic, both in strength and amount of time. The huge region of deep, moist convergence along the rear flank allows for a very wide region of updraft, not necessarily one single updraft, but likely many updrafts which collectively form a wide region of rising motion. Very broad updrafts have already been discussed as allowing a high amount of residence time for hail to grow. The deep and broad convergence zone accounts for the sheer size of the hail cores. Hybrid hailstorms typically have very high Z all along south, west, and north sides of the mesocyclone.

7. The “Hail Monster”



April 10, 2001 Supercell that tracked all the way across Missouri, turned out to be the costliest hailstorm in US history. Notice the tremendous size of the reflectivity cores on NW of the inflow notch and to the south, typical of these hybrid multi-supercellular hailstorms. True to form, this storm produced only a few very weak, brief tornadoes, but golfball to baseball size hail across entire counties occurred, with very high amounts of this large hail.

7. The "Hail Monster"



This is an example of a deep convergence zone along the rear flank. The X marks the approximate location of the photographer in the next image

7. The “Hail Monster”

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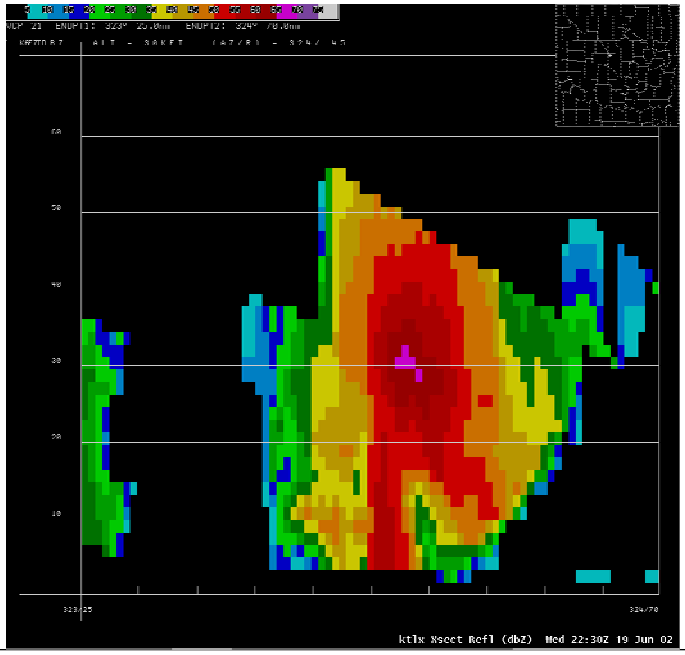
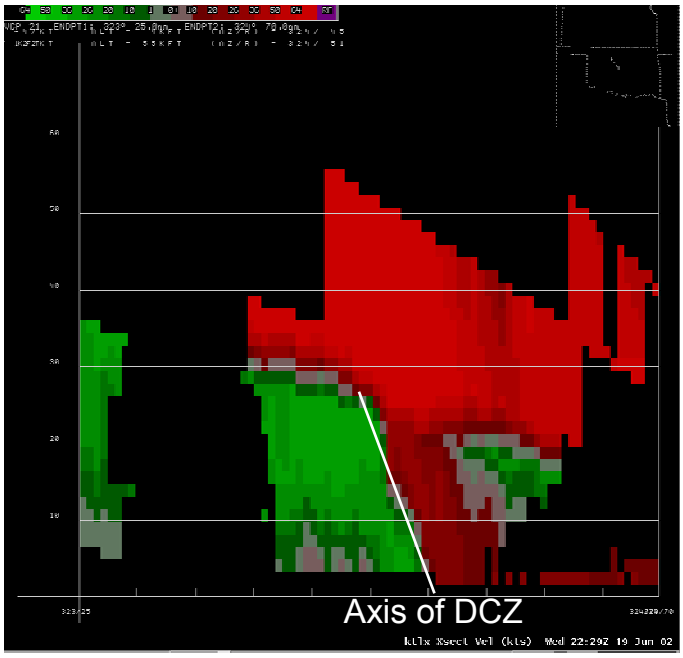


This is an example of a BWER of a storm with a DCZ.

7. The “Hail Monster”



Velocity images of the DCZ from previous reflectivity image. Notice the extreme depth of the zone of convergence.

Hail Ingredients Summary

Large Hail:

Microphysics	Kinematics
High supercooled LWC	Light SR flow through updraft
Wet growth in mixed phase region	Large contiguous updraft, 20-40 m/s
Low density growth	Optimal trajectories
Large embryos	Favorable horizontal updraft gradients

Large *Amounts* of Hail:

Microphysics	Kinematics
High embryo concentration	Large contiguous updraft, 20-40 m/s
Ample supercooled LWC	Flow that injects embryos across a broad updraft front

Summary of ingredients for large hail and large amounts of hail, but unfortunately in many cases we don't have any way of measuring these things for operational usage.

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Nelson, S. P., 1987: The hybrid multicellular-supercellular storm—an efficient hail producer. Part II: General characteristics and implications ofr hail growth. *J. Atmos. Sci*, **44**, 2060-2073.

Rasmussen, R. M, and A. J. Heymsfield, 1987: Melting and shedding of graupel and hail. Part II: Sensitivity study. *J. Atmos. Sci*., 44, 2764-2782.

Lemon, L. R., and D. W. Burgess, 1993: Supercell associated deep convergence zone revealed by a WSR-88D. Preprints, 26th Conf. on Radar Meteorology, Norman, OK, Amer. Meteor. Soc., 206–208.

Lemon, L. R., and S. Parker, 1996: The Lahoma storm deep convergence zone: Its characteristics and role in storm dynamics and severity. Preprints, 18th Conf. on Severe Local Storms, San Francisco, CA, Amer. Meteor. Soc., 70–75.

Witt, A., 1996: The relationship between low-elevation WSR-88D reflectivity and hail at the ground using precipitation observations from the VORTEX project. Preprints, 18th Conf. on Severe Local Storms, San Francisco, CA, Amer. Meteor. Soc., 183-185.

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____, M. D. Eilts, G. J. Stumpf, J. T. Johnson, E. D. Mitchell, and K. W. Thomas, 1998: An enhanced hail detection algorithm for the WSR-88D. *Wea. Forecasting*, 13, 286-303.

Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 4: Organized Multicell Storms

Warning Decision Training Branch

The title for the instructional component is "**Conceptual Models for Origins and Evolutions of Convective Storms"** . This is the first instructional component in the AWOC Severe Track. Lesson 4 will be on conceptual models for organized multicell storms.

Lesson 4 Learning Objectives

1. Identify 3 distinct modes of linear Mesoscale Convective Systems.
2. Identify the primary factors influencing the evolution of organized multicell storms.
3. Identify the role of storm-relative winds on multicell storm propagation.
4. Identify the effects of cold pool strength in squall line evolution.
5. Determine the role of the rear-inflow jet on squall line longevity.

These are the learning objectives in this lesson.

Lesson 4 Learning Objectives

6. Distinguish between the effects of positive shear and cold pool lifting based on RKW theory.
7. Identify the effects of instability on multicell propagation.

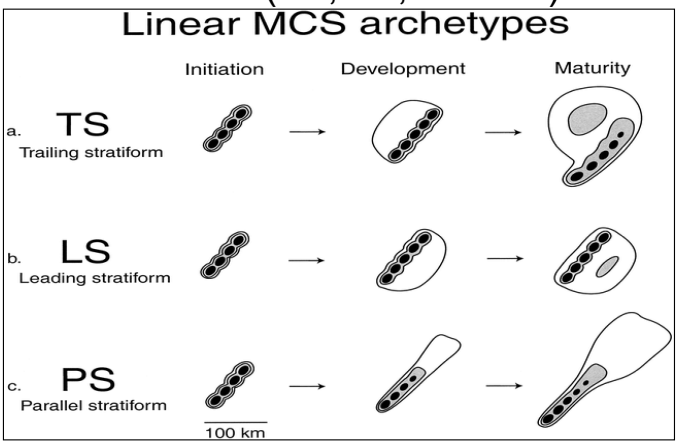
Multicell Storms

- Morphology and evolution of organized wind storms in multicells
- Environment of organized multicell wind storms
- References

Damaging wind storms can occur from supercells and even pulse (or ordinary) storms, but the majority of damaging events occur from organized multicell systems. We will discuss some of the factors influencing the morphology and evolution of organized wind storms in multicells.

Morphology and Evolution

- Role of air flows in complex multicell system
  - 3 distinct modes (TS, LS, and PS)



Parker and Johnson (2000)

This is Parker and Johnson's (2000) schematic reflectivity drawing of idealized life cycles for three linear MCS archetypes: (a) TS, (b) LS, and (c) PS. Approximate time intervals between phases: for TS 3–4 h; for LS 2–3 h; for PS 2–3 h. Levels of shading roughly correspond to 20, 40, and 50 dBZ. Their study found that there exists three distinct modes of linear MCSs: trailing stratiform (TS, 60% of the cases), leading stratiform (LS, 20% of the cases), and parallel stratiform (PS, 20% of the cases).

The TS MCSs experienced front-to-rear storm-relative winds throughout their depth, moved rapidly, and were the longest lived of the three classes. The LS MCSs experienced weak middle- and upper-tropospheric rear-to-front storm-relative winds, moved slowly, and persisted for approximately half as long as TS MCSs. The PS MCSs experienced significant middle- and upper-tropospheric line-parallel storm-relative winds, moved more rapidly than LS MCSs but less rapidly than TS MCSs, and persisted for approximately half as long as TS MCSs. At some point in their life cycle, a majority of MCSs evolve toward TS structure. The synoptic conditions associated with linear MCSs in this study largely resembled those discovered by previous authors (e.g., Maddox, 1983, Bluestein and Jain, 1985, Kane et al. 1987). In addition to a nocturnal maximum in linear MCS frequency, a secondary near-sunrise mode existed similar to that documented by Geerts (1998).

One case study suggests that for PS MCSs, the orientation of a linear trigger to the tropospheric wind profile may be of first-order importance, while another suggests that LS MCSs may be sustained in a variety of ways, including inflow from the rear.

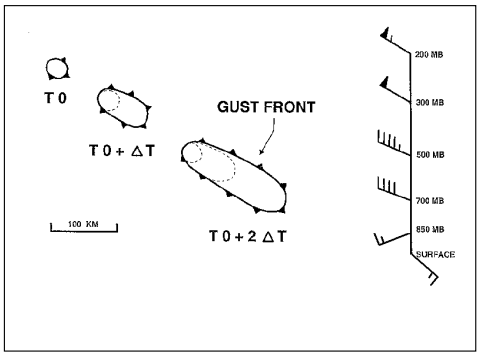
Factors Influencing Evolution of Organized Multicells

- Environmental winds (all levels)
- Storm-relative wind distribution
- Cold pool strength
- Orientation of gust front relative to storm low-level inflow
- Instability gradients
- Boundary interactions

As you can see, there are multiple mechanisms governing movement and subsequent evolution of multicells.

Effects of Cloud Bearing Wind

- Affects gust front speed and resulting system movement

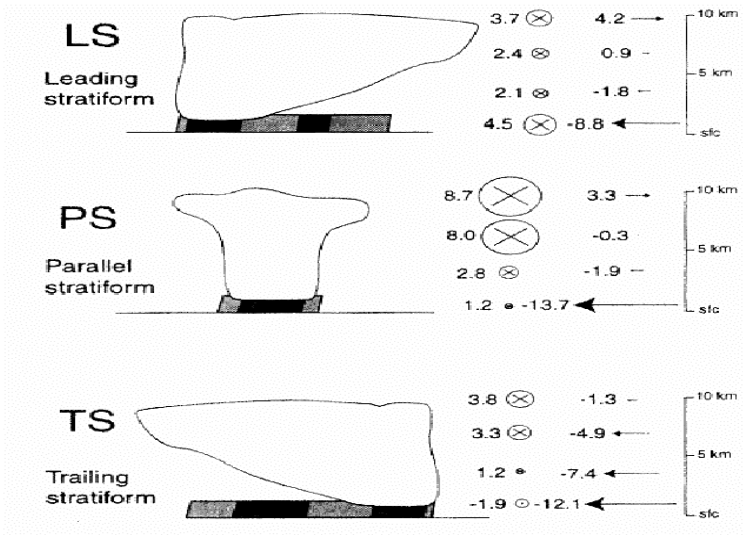


From Corfidi (2003)

The strength of the mean wind helps determine motion and stratiform precipitation distribution. The mean cloud layer winds help to advect systems downstream. Propagation effects are a result of many factors which we will discuss later.The strength of the environmental winds and resulting cold pool speed determines to a large degree the intensity and longevity of the multicell system.

Evans and Doswell (2000) also showed a relationship between mean winds in the 0-6 km layer and the 0-2 km system-relative inflow when trying to distinguish between derechoes and non-derecho multicell systems. Observations have shown that new cell development most often occurs where the ambient low-level inflow relative to the boundary is greatest. This is where low-level convergence is maximized. Often, this is the region that is governed by the position of the low-level jet. Even when the low-level jet is not favorably positioned away from the boundary, if sufficient relative motion exists between a gust front and the low-level environmental wind, convergence maxima may develop. Propagation in the downwind direction may result if surface based instability is present as well. Momentum transfer also contributes to gust-front motion and speed.

Effects of Storm-Relative Flow



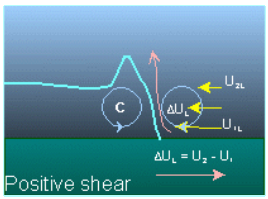
From Parker and Johnson (2000)

From Parker and Johnson's study, vertical profiles of layer-mean storm-relative pre-MCS winds for linear MCS classes. Wind vectors depicted as line-parallel (X) and line-perpendicular (arrows) components in m s^{-1}. Layers depicted are 0–1, 2–4, 5–8, and 9–10 km. Typical base scan radar reflectivity patterns (shading) and hypothetical cloud outlines are drawn schematically for reference. MCSs' leading edges are to the right.

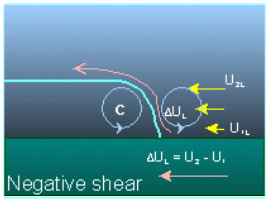
For each linear MCS, they selected nearby NPN wind profiles from three times at which the reflectivity structure best resembled the case's predominant organizational archetype. These profiles were then composited to produce mean wind fields for each linear MCS mode. The TS cases' mean line-perpendicular storm-relative wind components, as constructed from the profiler data, were significantly different from those of the LS and PS classes. The TS class mean exhibited negative line-perpendicular storm-relative winds at every level. Above 2 km, TS cases exhibited significantly larger rearward storm-relative winds than those observed for the LS and PS classes. This result is consistent with rearward advection of hydrometeors by the mean flow, which has been argued to explain trailing stratiform precipitation regions (Houze et al., 1990). In contrast, the LS and PS classes were nearly indistinguishable from one another in most of the line-perpendicular fields, exhibiting weak middle-tropospheric storm-relative winds and modest rear-to-front storm-relative winds at upper levels. The notable exception was the 0–1-km layer, in which the magnitude of line-perpendicular flow for the PS cases was, on average, greater than that of the TS cases. The lower-tropospheric line-perpendicular winds near PS cases were quite strong within a shallow layer. Above 2 km, PS MCSs exhibited deep line-parallel storm-relative flow, such that the middle-tropospheric advection of hydrometeors was largely along the line. In the 5–8-km layer, in which Rutledge and Houze (1987) found bulk transport of MCS hydrometeors to be focused, PS cases exhibited almost purely line-parallel storm-relative winds. The line-perpendicular storm-relative winds attending LS cases were not remarkably distinct from those in PS cases, although the line-parallel winds were much weaker. Thus, in LS cases there was a greater average rear-to-front component of the storm-relative flow aloft, which may help to explain the forward advection of hydrometeors. The 5–8- and 3–10-km mean line-perpendicular storm-relative winds were by far the most statistically significant differentiators among the three classes in this study, suggesting that the middle- and upper-tropospheric storm-relative flow field is of primary importance in determining the organizational mode of linear mesoscale convection.

Cold Pool Effects
RKW Theory

- Positive shear case
  - Promotes deeper lifting along downshear side



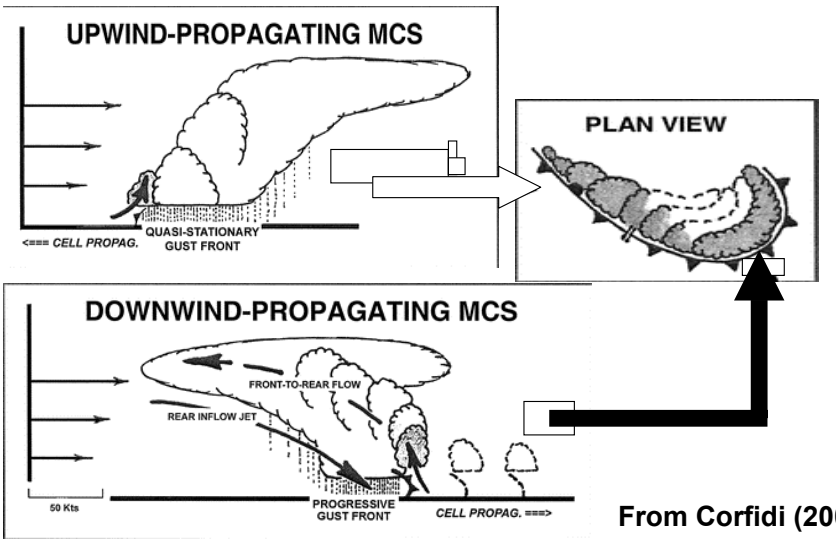
- Negative shear case
  - Decreases net lifting



Adapted from COMET (1996)

In the framework of RKW theory (Rotunno, Klemp and Weisman), new cell growth is favored on the downshear side of a multicell cold pool. The depth of the shear layer needs to be calculated when considering this theory in operations.

Cold Pool Effects Movement of Systems



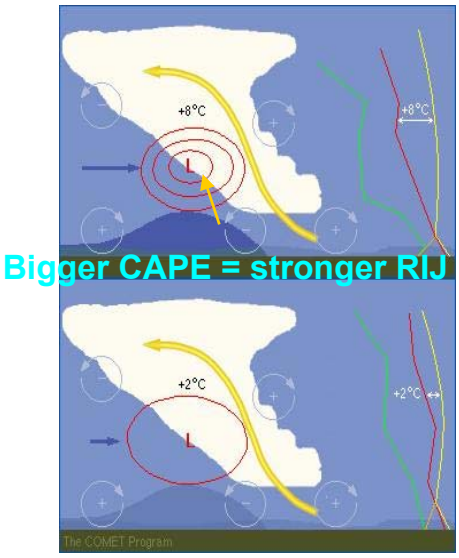
From Corfidi (2003)

Main points from Corfidi (2003) were:

- A cold pool will elongate in the direction of the mean cloud-layer wind as a result of momentum transfer.
- The degree of elongation increases as the wind profile becomes more unidirectional, and this effect occurs on all time- and space scales.
- Propagation, or new cell development relative to existing storms, occurs most readily on the periphery of the cold pool (i.e., along those portions of the gust front), where the relative inflow is strongest and where surface-based convective instability is present.
- Upwind-developing MCSs are most favored along quasi-stationary (mean flow parallel) portions of the gust front, and
- Downwind-developing MCSs are favored on the more progressive (mean flow perpendicular) parts of the boundary.
- Thermodynamic factors modulate the role played by gust-front orientation and motion: a) upwind-developing environments are characterized by comparatively moist conditions through the low to midtroposphere and, therefore, relatively weak convective-scale downdrafts, and (b) downwind-developing environments are characterized by comparatively dry conditions at midlevels and/or in the subcloud layer and, therefore, a tendency to produce strong convective-scale downdrafts.

Role of Rear-Inflow Jet (RIJ)

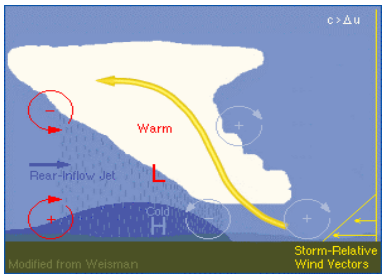
- Produced by perturbation hydrostatic pressure gradients from buoyancy differences across the updraft, esp. in anvil
- Rear to front flow orientation
- Modulated by strength of cold pool and shear

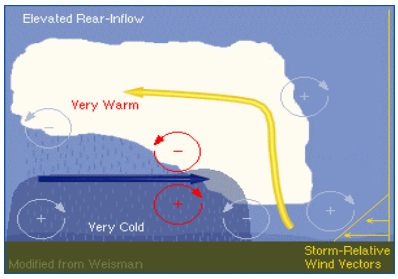


Stronger RIJ is due to larger CAPE, steeper lapse rates, larger theta-E differences from surface to midlevels. Given the same buoyancy for updrafts and cold pools, shear can help to modulate the intensity of the RIJ. Thus, according to Weisman's numerical simulations, the longevity of a squall line depends on the rear-to-front slope of the RIJ. This has not been verified operationally.

RIJ Schematic

- Results in upshear tilted structure
- If RIJ remains elevated, it can help to restore balance of cold pool with environmental shear and allow squall line updraft to remain vertically erect for longer periods (Weisman, 1993).

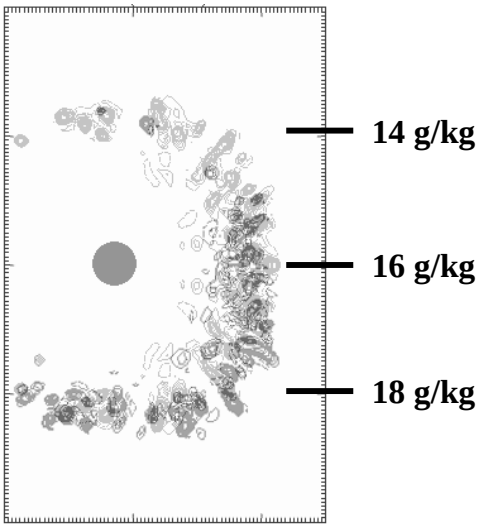




More on the MCS web site at http://meted.ucar.edu/convectn/mcs/

Instability Effects

- Instability effects
  - Can modulate propagation of multicells toward areas of higher instability

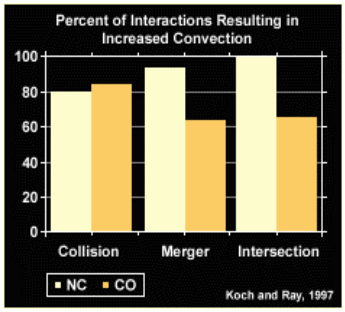


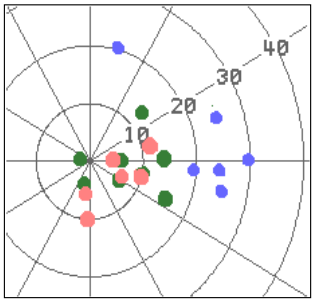
From Richardson (1999)

Simulated storms moved toward higher areas of low-level moisture and I suspect, greater instability. Surface based instability has been shown to influence MCS movement.

Boundary Interactions

- Modulates/enhances development of new convection



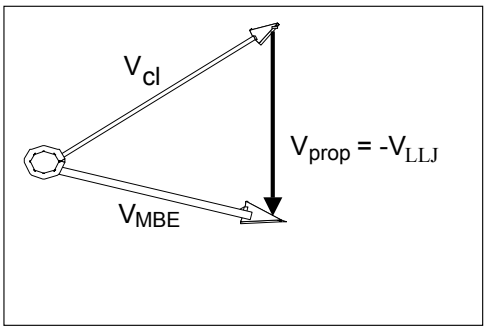


Blue = steering layer flow
Green=triple pt motion
Red = multicell motion
(Weaver, 1979)

Boundary location can override the other factors by modulating the convergence.

Quantifying Effects of Propagation

Quantifying propagation of multicells (after Corfidi, 1996 and 2003)

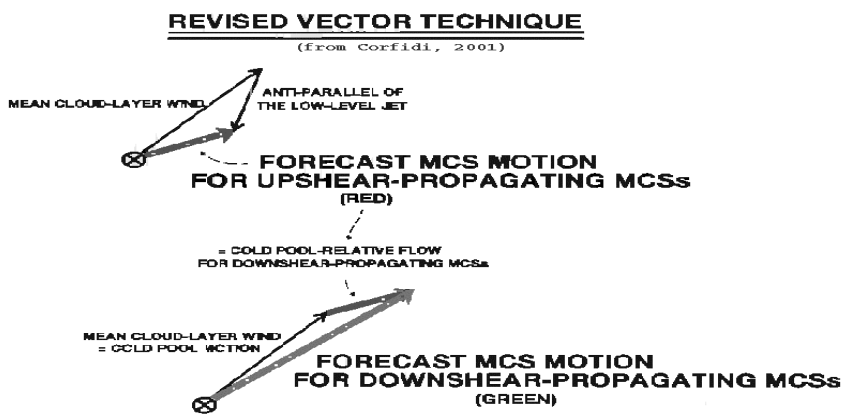


This technique works well for backbuilding events

The V_{prop} is the anti- parallel vector of the low-level jet. V_{mbe} is the resulting movement of the mesoscale beta element – centroid of the MCS.

Quantifying Effects of Propagation

- For Forward Propagation (Corfidi, 2003)



For forward–propagating MCSs, you need to take into account the cold pool relative flow. This makes the resulting forecast Vmbe motion much larger.

Summary

- Organized multicell storms
- Review objectives
  - Morphology and evolution of organized multicells
  - Environment
  - Multiple factors influencing organization and evolution

The objectives for this lesson are:

1) Identify 3 distinct modes of linear Mesoscale Convective Systems.
2) Identify the primary factors influencing the evolution of organized multicell storms.
3) Identify the role of storm-relative winds on multicell storm propagation.
4) Identify the effects of cold pool strength in squall line evolution.
5) Determine the role of the rear-inflow jet on squall line longevity.
6) Distinguish between the effects of positive shear and cold pool lifting based on RKW theory.
7) Identify the effects of instability on multicell propagation.

References

- See handout reference list or refer to AWOC Severe Track web site

Severe Track IC 1
Lesson 4 References

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Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 5: Flash Flooding

Warning Decision Training Branch

The title for the instructional component is "**Conceptual Models for Origins and Evolutions of Convective Storms** . This is the first instructional component in the AWOC Severe Track. Lesson 5 will be on conceptual models for flash flooding, both meteorological and hydrological factors.

Lesson 5 Learning Objectives

1. Identify meteorological conceptual models concerning heavy rainfall

2. Identify hydrological ingredients favorable for flash flooding

3. Identify the possible watershed responses to excessive rainfall and problems with flash flood guidance

Lesson 5 Learning Objectives

4. Identify the primary parameters that help determine precipitation efficiency

5. Identify characteristics of the flash flood potential in supercells

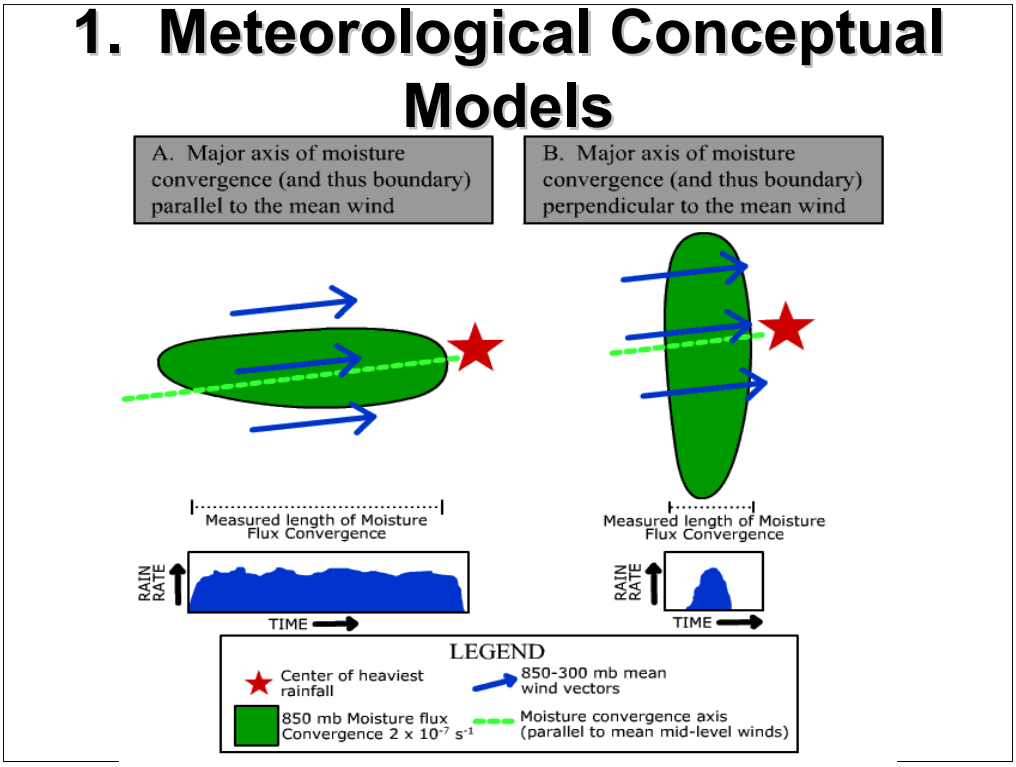
6. Identify the effects of advection and propagation and their significance to flash flooding

1. Meteorological Conceptual Models

- Maddox (1979): 4 flash flood types from a meteorological standpoint
- More recent work (Junker et al. 1999) has focused on the moisture field and location of surface boundary to distinguish the most extreme heavy rainfall events

Maddox FF events is a review and will not be covered in AWOC. The point is that each type deals with a low-level boundary of some type, increased moisture/instability, and relative movements of convective elements whether they are training or nearly stationary

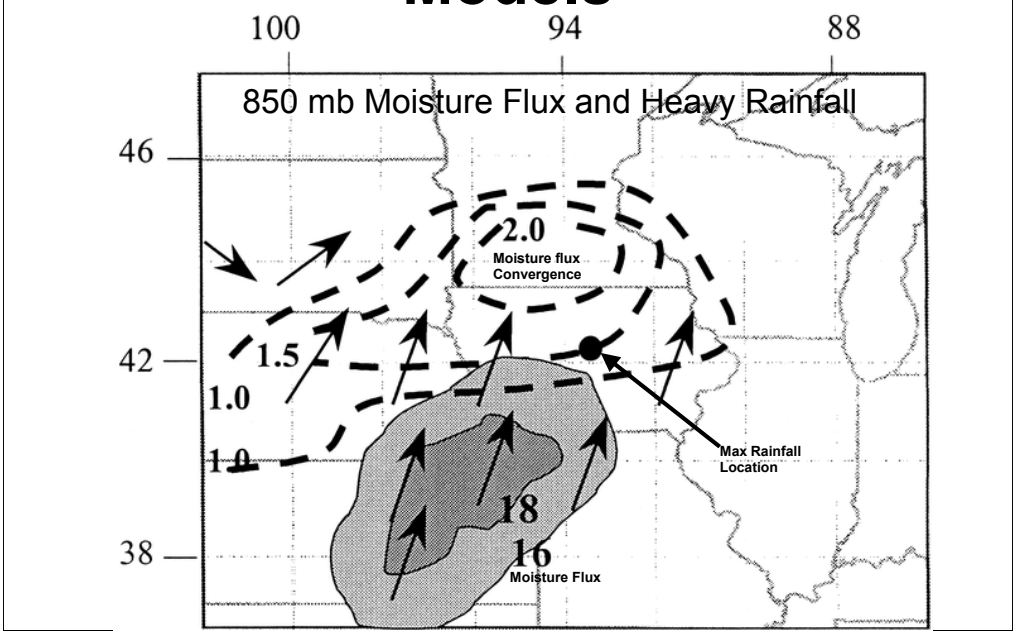
Junkers studied MCSs from the Midwest during the great flood of ’93. He found differences between MCSs that produced extreme rainfall and those that were “ordinary”, and those differences will be discussed here



Obviously case A led to extreme rainfall events in theJunker (1999) study, while case B led to must less extreme rainfall

•A larger scale of forcing and a longer duration of intense rainfall are possible when a long axis of moisture flux convergence coincides with the mean wind.

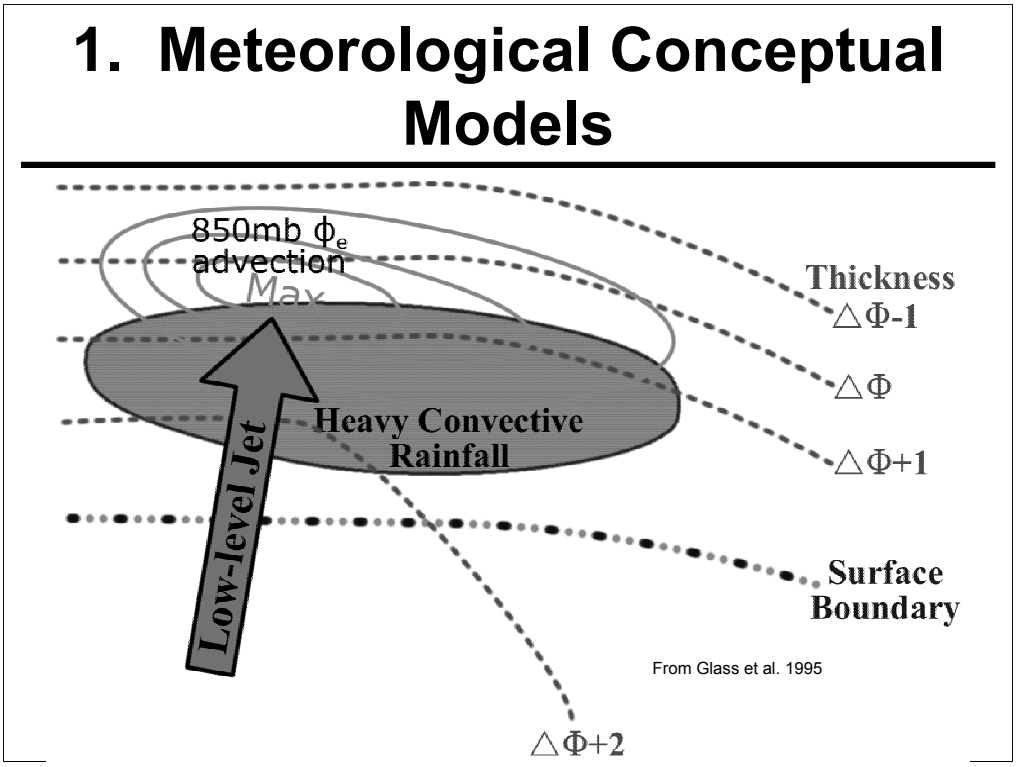
1. Meteorological Conceptual Models



From Junker et al. (1999), in a study of Midwest MCS's during Flood of 1993. This is a composite map of 850 mb moisture flux and moisture flux convergence and it's relation to location of maximum rainfall

•This favors upstream cell development, where forcing and instability remain strong, then track downstream with the mean flow. The low-level boundary focuses new cell development

•This is a good setup for backward propagating MCSs



•From Glass et al. 1995

•This is the proposed conceptual model of heavy convective rainfall north of an E-W oriented boundary. In the blue region of heavy convective rainfall, cell repeatedly develop and organize into small cores of heavy rainfall convection, then move downstream with the 850-300 mb cloud layer shear

1. Meteorological Conceptual Models: Ingredients Review

1. DMC (especially at night)
2. High moisture content (relative to normals) through a deep layer
3. Weak to moderate mid-level shear
4. Winds veer considerably with height (LLJ vs mid-level flow)
5. Large-scale forcing weak or negligible

1. Meteorological Conceptual Models: Review cont'd

6. LLJ moisture supply and focus for the convection: determines rainfall scale
7. Winds aloft parallel to low-level stationary boundary
8. Cells "training"
9. Upstream mesoscale wave moving into a long wave ridge

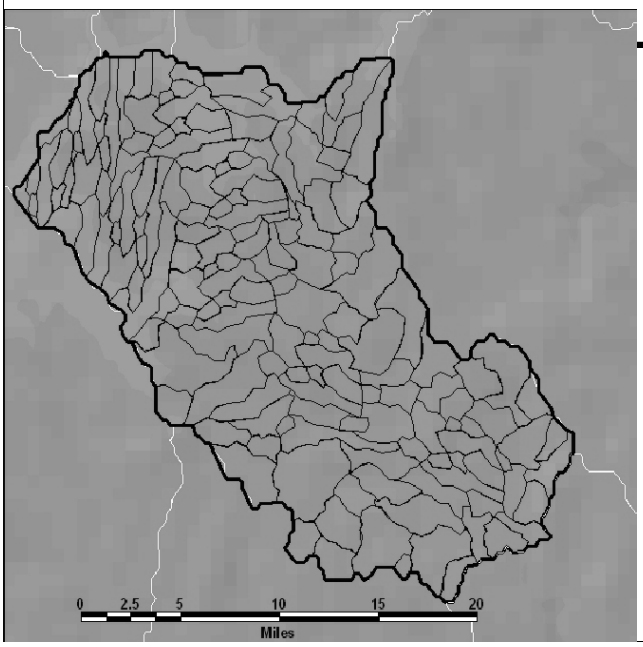
2. Hydrologic Ingredients

- Given an amount of rainfall and duration, 5 Flash Flood Threat Factors:

1. Size, shape, topography of basin
2. Size, shape, condition of stream channel
3. Infiltration capacity and saturation of soil
4. Vegetation and Land Use
5. Season

These conditions should be known as best as possible before any heavy rainfall begins. Hydrologic ingredients are every bit as important to flash flooding as meteorological ingredients

Watershed Characteristics



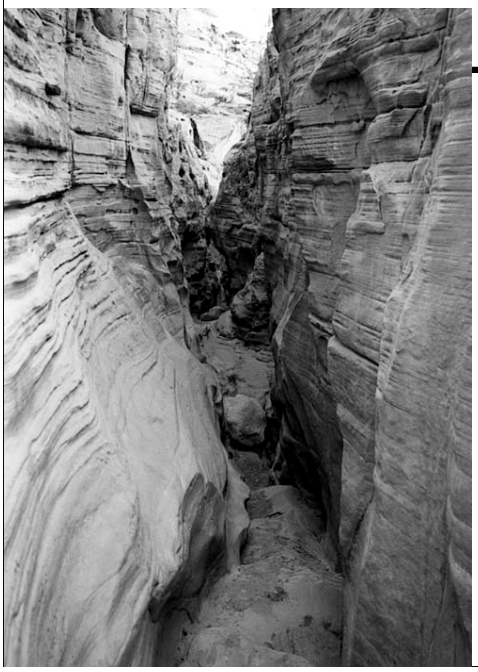
1. Size, shape, topography of basin

-- customize your FFMP basins if you haven't already done so.

Courtesy Bob Cox - MBRFC

The majority of flash floods occur in very small basins, mainly because the scale of the heaviest rainfall is also quite small, thus it is crucial that you have basins defined small enough that flash flooding rainfall will not be too "averaged" too much across the basin.

Stream Channel Characteristics



2. Size, shape, condition of stream channel

-- width, steepness, soil type

Steep terrain, soil type (such as rock), and narrow channels are all conducive to flash floods, meaning far less rainfall can produce siginificant flash flooding in basins with such makeup. The above is from Crack Canyon in Southeast Utah: probably a worst case scenario for stream channel condition and propensity for flash flooding

Soil Type and Condition

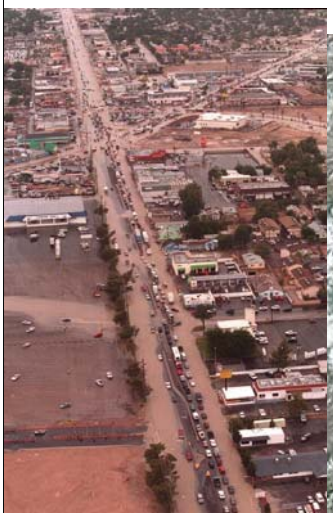
3. Infiltration capacity and saturation of the soil

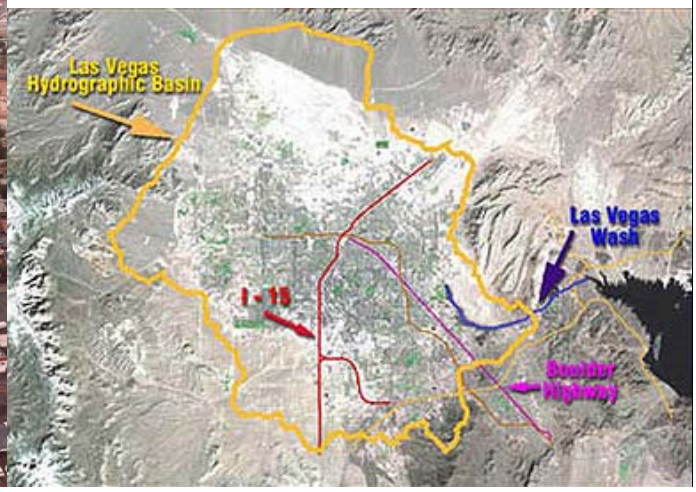
- Doswell et al. (1996) present a case of 180 mm (7 inches) rainfall in less than a day in Iowa Sep 1989, with only minor flooding
  - → Tail end of 2-year drought, soil could handle precipitation
  - → Soil type (infiltration) and saturation (soil moisture) differences can make the difference in any event

Soils that are heavily clay have a low infiltration capacity and thus more prone to runoff. Rocky soils likewise are prone to high levels of runoff. By the same token, soils that are saturated from previous rainfall are prone to high levels of runoff.

Vegetation and Land Use

4. Vegetation and Land Use





Vegetation intercepts rainfall, inhibits surface runoff, allowing more time for infiltration

•Las Vegas is one of the worst areas for flash flooding because the soil surrounding the city has very poor infiltration with next to no vegetation: thus nearly all rainfall is converted to runoff. Add to the fact that all the natural washes within the city are now paved over with city streets and the problem is exacerbated.

•Cities in general are very flash flood prone with all the concrete and poorly constructed drainage systems

Season

5. Season

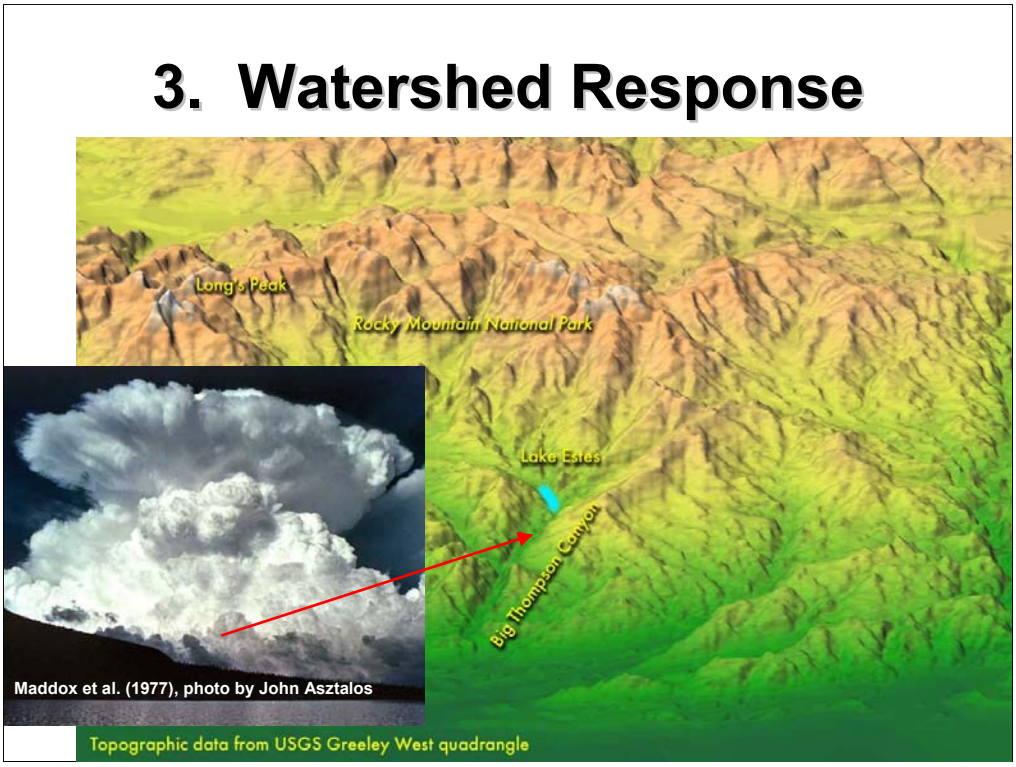
- Mainly impacts surface runoff potential

  → Vegetation growth stage

  → Lower temperatures, higher viscosity and lower infiltration

  → Frozen ground worst case

Dormant vegetation leads to less rainfall interception, less evapotranspiration (soil moisture high to begin with)

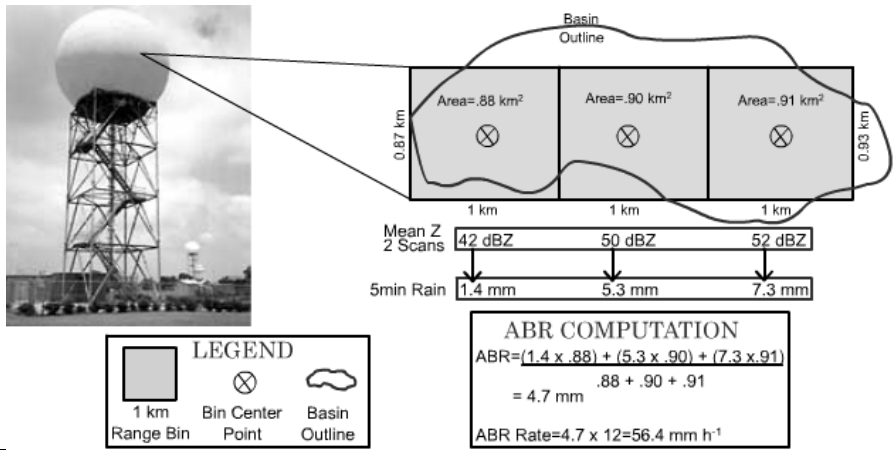


•We've discussed the meteorological and hydrological ingredients for flash flooding. Now let's look at what happens when heavy rainfall occurs across a watershed. What is the response of the watershed to the rainfall and how can we measure this response?

•The above is the Big Thompson Storm and topo map

3. Watershed Response: ABR

- Average Basin Rainfall: In a flash flood, the *RATE* is more important than the *AMOUNT* of rainfall, thus need accurate rates



•4 inches of rain in 4 hours is much different than 4 inches in one hour for a basin

•The gray area is with very high rate AND small amount, meaning a very quick burst of heavy rainfall. That's tougher to gage FF threat.

•Size of watershed and size of heaviest rainfall important

•How ABR is computed:

1.Z of each radar 1 km polar bin is converted to a 5 minute rainfall amount, then multiplied by the area of each bin to get a rainwater volume per bin

2.Only the rainfall volumes of each bin that have a *center point* falling within the watershed are summed

3.Summed rainfall volumes are divided by the total area of all used radar bins in the watershed to determine ABR: a total precip for 5 minutes across the basin

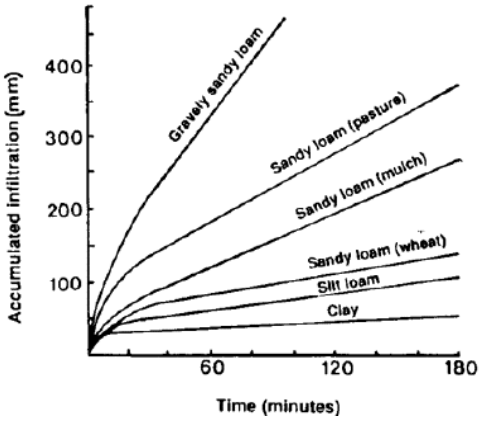
4.ABR *rate* is calculated by multiplying the calculated 5 minute ABR by 12 (hourly rate)

3. Watershed Response: Runoff

- Need to know how much ABR goes into runoff

INFILTRATION:

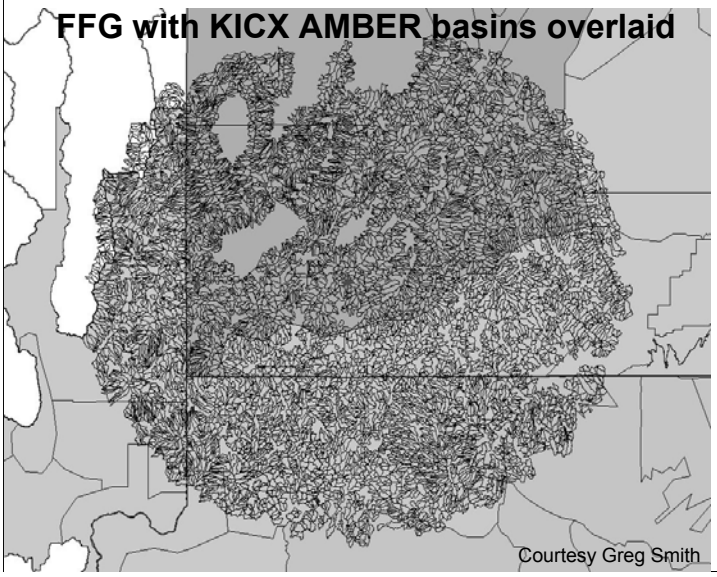
- **Soil type, moisture, and vegetation**



- Max runoff occurs when infiltration capacity is used up
- Saturated soils just as efficient as rock at converting rainfall to runoff
- Need to quantify runoff potential into a useful quantity: FFG

•A small portion of ABR may be lost due to evaporation, transpiration, and depression storage, but compared to the ABR rate related to flash flood producing rainfall, these losses are minimal

3. Watershed Response: FFG



- FFG updated once a day by CWA zones in the Western U.S., twice per day in other regions
- Diversity of basins in each zone

•Terrain, soil and other basin characteristics vary widely within many counties and forecast zones across America, especially the Western U.S.

•No consistency on how to compute FFG from RFC to RFC

•Twice a day updates isn't frequent enough since antecedent precipitation can play a huge rule in flash flooding.

•Many flash floods quicker than 1 hour as well

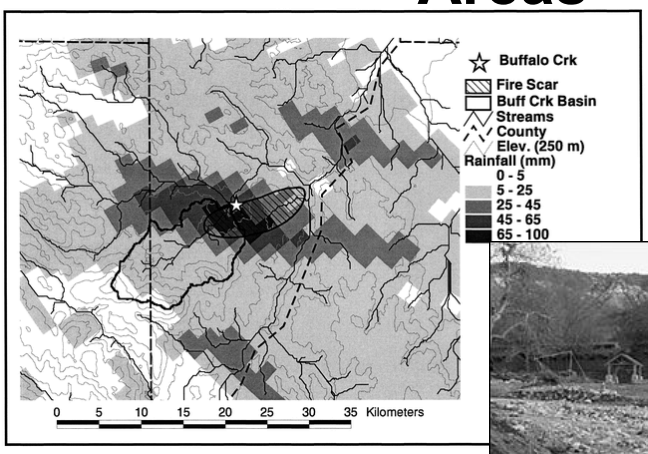
• What constitutes a significant flash flood? → Slot canyons can cause serious problems with just 30-50 cfs flow during a flash flood: different thresholds to floods and FFG doesn't address this. Tying thresholds to "bankful" not always a meaningful statistic

•FFG works best during an extended period of dry weather, worst with multiple rainfall events during previous 24-48 hours

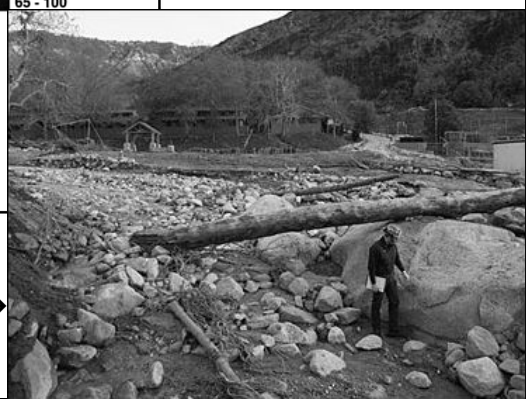
3. Watershed Response: Topography and Intensity

- Topography: The steeper the slope, the quicker surface runoff reaches the stream, with rapid stream response, and a higher crest
- Intensity: gentle slopes can still see significant flash flooding if rainfall intensity is exceptional

3. Watershed Response: Burn Areas



← Buffalo Creek



Waterman Canyon →

•All rainfall converted to runoff in burn areas, and the problem is especially severe the steeper the terrain

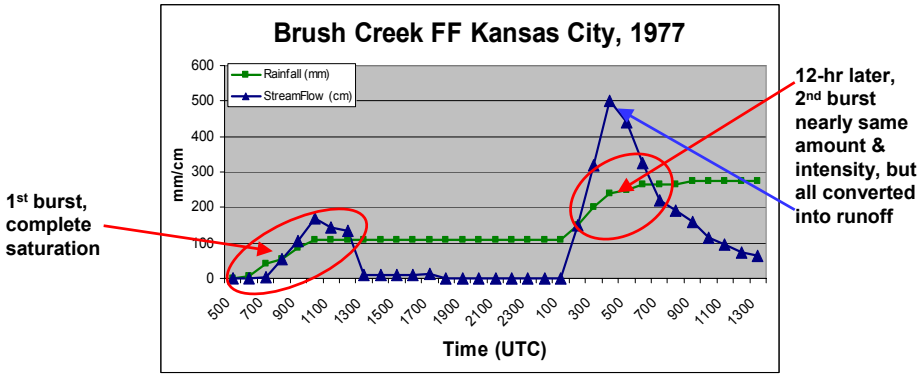
•Both these of these flash floods were a direct result of rainfall falling in a burn scar

•Buffalo Creek: 2 injuries but substantial structural/road damage in the area

- •Fei et al. 2001 also showed though numerical simulation that the burn area was actually preferred location for convection due to enhanced insolation

•Lytle Creek killed 15 after 2 days of moderate/heavy rains over a recent burn area, which led to tremendous flash flooding

3. Watershed Response: Antecedent Precipitation



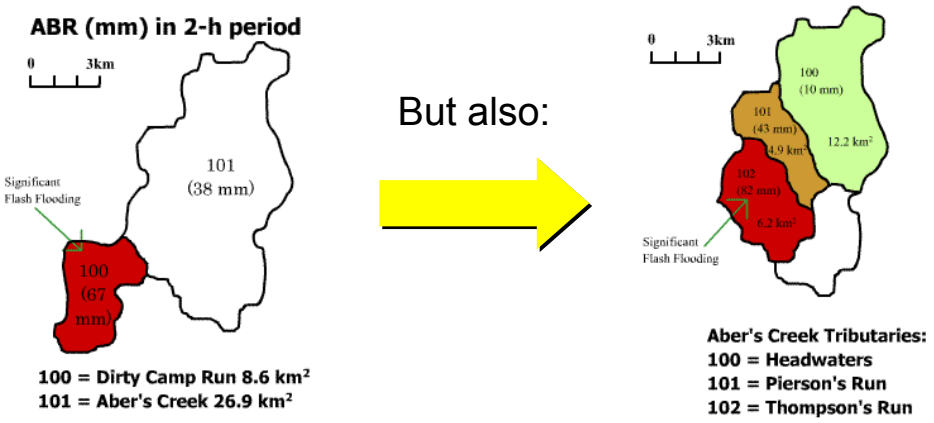
Moral: Soil moisture/saturation strongly influences surface runoff. Antecedent precipitation important to account for, and many times FFG doesn't capture it

•2 distinct periods of intense rainfall separated by 12 hours, claimed 25 lives in Kansas City. First rainfall saturated the soil, while the second rainfall went entirely into runoff, producing disastrous flash flooding

3. Watershed Response: Size

- 5-20 km^2 basin can be easily inundated by MGE elements, while basins 100-200 km^2 require training of some sort

→ Subdivided watersheds vital to detect FF



•These basins are 38-44 km from KPBZ

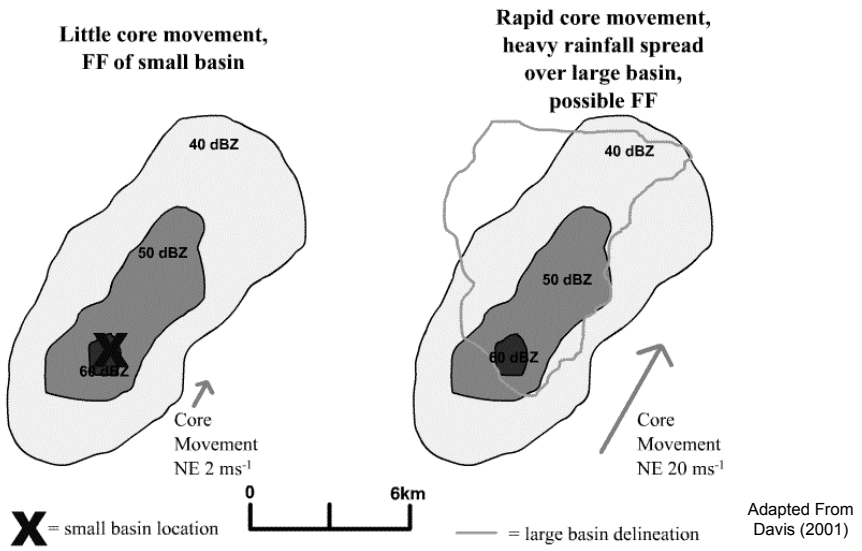
•MGE=mesoscale gamma elements, essentially individual heavy rain cores make up this scale of phenomena

•Evening of July 1, 1997

•The image on the left clearly shows the threat in Dirty Camp run, which did in fact verify after greater than 2 inches fell in 2 hours. Aber's Creek in the left doesn't appear to have much of a threat…until you subdivide it further into smaller tributaries. On the right, Aber's Creek watershed has a basin (Thompson's Run) at high risk, and indeed significant flash flooding occurred in that small basin

•This example shows the importance of dividing basins into smaller units so that rainfall is averaged over smaller areas.

3. Watershed Response: Rainfall Core Movement



Adapted From Davis (2001)

• Problem!: Fast cell movement complicates things

•Fast cell movement is problematic: not obvious where flash flooding will occur if at all, and fast movement means strongly sheared environment and thus a forecaster may be more concerned with other forms of severe weather

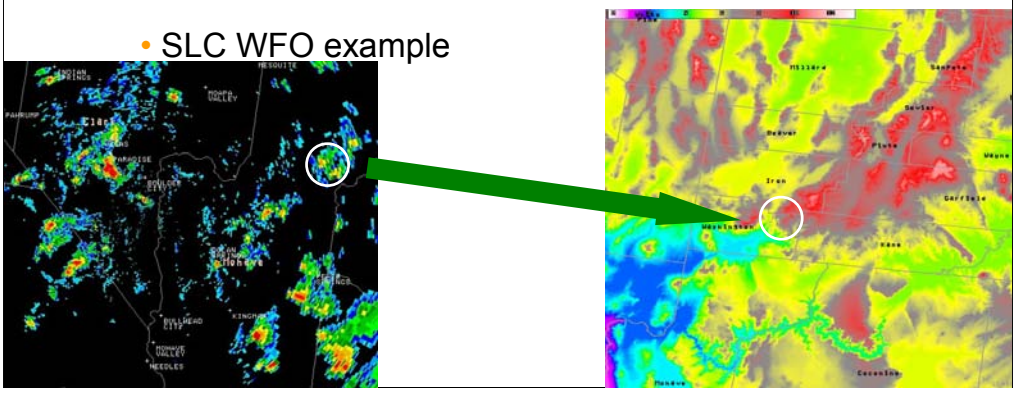
•With training, fast individual cell movement can lead to flash flooding with repeated development over the same areas, and would likely have to be the case with the scenario on the right: training could produce flash flooding in that large basin.

3. Watershed Response

- FF warnings should read like tornado warnings, with names of towns in threat area

  → Shouldn't be too hard since flash floods generally follow streams or dry arroyos: NBD stream database allows for this connection downstream

- SLC WFO example



•Zion National Park. No rainfall in the Narrows Section, but just upstream significant rainfall occurred. SLC issued a flash flood warning for the Narrows that saved 40 lives. SLC WFO used topo image and radar to determine where the heaviest rain was falling, then used stream connectivity to determine that the flood waters would enter the Narrows Section

•If storms move slowly along the downstream direction of the stream, flash flooding can be enhanced

•Future FFMP builds will have stream connectivity

3. Watershed Response

- rainfall easily converted to runoff in urban areas
- some cities have inadequate drainage systems
- Local WFOs should define their own urban drainage areas with FFMP, need to be divided into small segments no larger than 5 km^2
- FFG 1in/hr

Many offices across the U.S. have set FFG to 1 in/hr for highly urban areas.

4. Precipitation Efficiency

- Decreases:
  - → updraft strengthens, narrows
  - → excessive evaporation
  - → strong wind shear
- Increases:
  - → high RH everywhere, especially below LCL
  - → "Warm rain" processes
- Neither PE nor entrainment can be observed operationally, only *inferred*

•Entrainment significant when: RH decreases anywhere, but especially below cloud base. Also with very strong wind shear entrainment will be enhanced as updrafts are more tilted

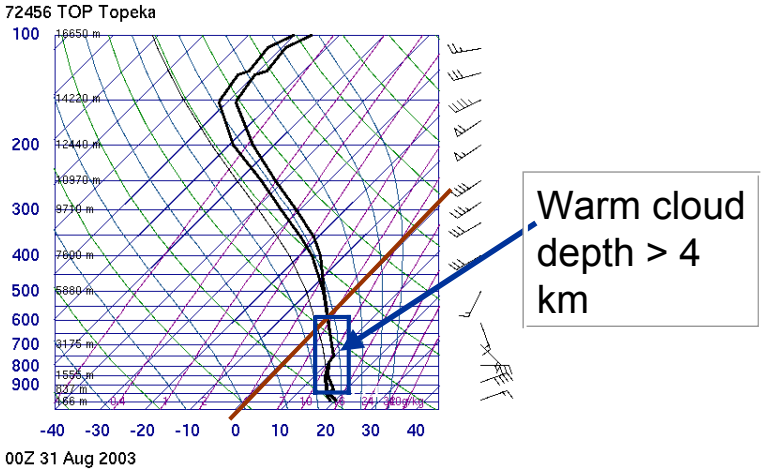
•Entrainment of dry air reduces PE because it introduces unsaturated air into the convection, which in turn promotes evaporation

•Very strong updrafts eject condensate out of the top before they can grow into precipitation size, leading to decreased PE. You'd really like to see "thin CAPE" profiles

Key Point: A deep warm cloud layer, high RH all levels but especially below LCL, low vertical wind shear, all increase precipitation efficiency. Narrow and/or very strong updrafts decrease precipitation efficiency. Highly efficient rain production is achieved through warm rain processes. It should be kept in mind that with supercellular convection and convection west of the Rockies precipitation efficiency is not important to flash flooding.

4. Precipitation Efficiency

- Infer high PE potential: Example
  → deep warm cloud layer, RH, CAPE, shear



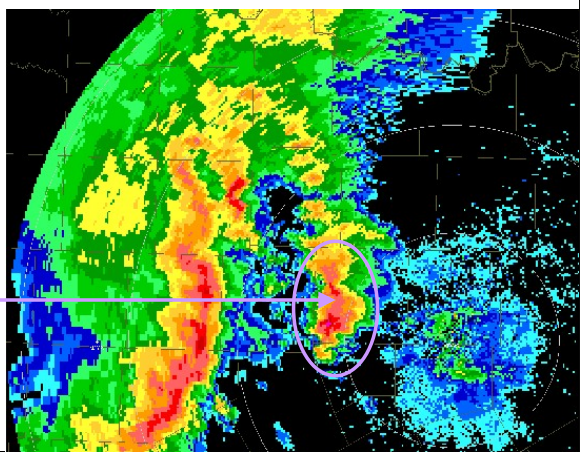
To maximize the effectiveness of warm rain processes, a deep "warm cloud" layer should be present. You can see these layers on soundings as the vertical distance between the LCL and where the moist adiabat from the LCL intersects the 0ºC isotherm. Depths greater than 3 km are considered to be "deep" warm cloud layers, but in tropical environments exceptionally deep layers should be 4 km or greater. Residence time in the updraft above freezing is maximized with weak to moderate updrafts within a warm cloud depth, allowing for larger drops and thus more collision/coalescence.

Also evident on this sounding is high RH at all levels, relatively weak vertical wind shear (although directional shear excellent)

5. Supercell Flash Flooding

- Significant low-level moisture inflow (+)
- "Loaded Gun Sounding" (-)
- Strong updrafts (-)
- Isolated (-)
- Movement Speed (+/-)

→ HP's

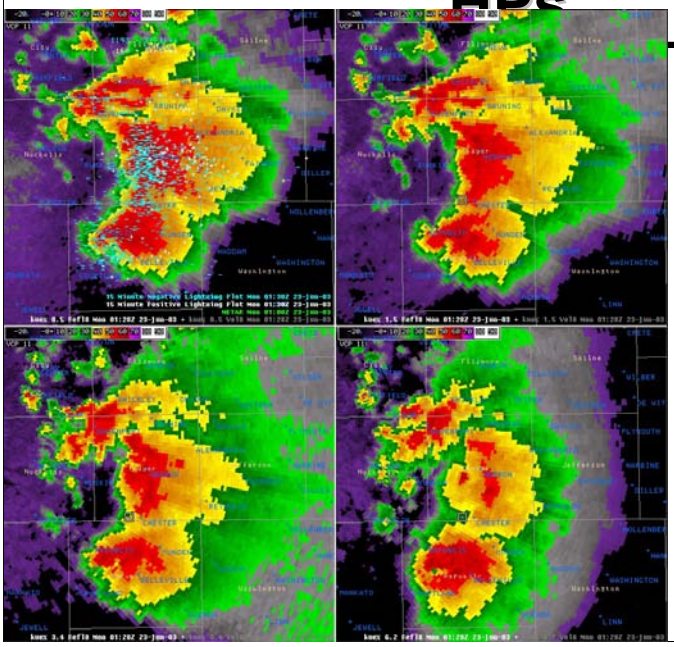


There are advantages and disadvantages to flash flood potential in supecells. Loaded gun sounding, isolated nature and very strong updrafts all are detrimental to flash flooding threat. However, very moist low level inflow and possibly speed of movement are both contributing factors to flash flooding. The single most important consideration for supercells is their movement. They are capable of producing tremendous rainfall rates, a key to flash flooding, but if they are not moving slowly, flash flooding becomes unlikely.

HP supercells are important to the flash flood threat, more so than classic and certainly more than LP types. HPs tend to be larger and move slower than other supercell types. Training supercells can also pose a high flash flooding threat. Though supercells are traditionally associated with low precipitation efficiency, this can be balanced, especially in HPs, by tremendous moisture inflow into the storm, as is shown in the ppt slides.

Key Point: Flash floods can occur with supercells, especially if HP in nature and if slow moving and/or training.

5. Supercell Flash Flooding: HPs

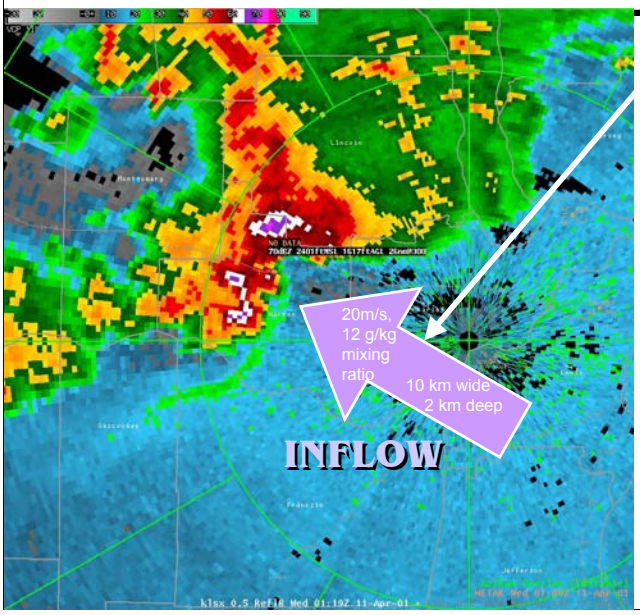


- HPs can cause significant flash flooding if they move sufficiently slow enough
- Limited studies, Smith et al. (2001)

•Smith et al. (2001) study:

- •There is currently no forecast methodology for HP's, and very little are known about them. We know that they move slower and are more efficient precipitation producers
- •HP's have unusually large precipitation cores, which are exceptionally intense
- •Contain some of the highest/richest moisture inflow of any known convective element

5. Supercell Flash Flooding: Moisture Inflow



- Given this realistic HP inflow setup, cloud water balance yields:
  → R~4 in/hr over 100 km^2 with a low 50% Precip. Efficiency
- **Moral of story**: even low PE associated with HPs and CLs can be balanced by large values of moisture inflow

This is the key to supercell flash flooding: understanding *why* supercells are such a threat despite poor precipitation efficiencies and at times swift movement.

•These are actual calculations from May 5, 1995 HP over DFW from Smith et al. (2001), although the above image is from an HP that hammered the STL metro in April 2001, with hail and flash flooding

•LP supercells cannot produce flash flooding.

6. Cell "Movement"

- Movement takes into account effects of:

1. Advection

   → cells travel with mean wind in cloud layer, easy to measure

2. Propagation

   → cell movement from the development and dissipation of individual cells, very hard to determine but usually related to moisture flux and instability axes

•Flash flooding can occur when these two effects cancel each other out leading to very little net movement of heavy rain cores.

•Back building MCSs are most prone to flash flooding because of "training of inidividual mature cells", which can happen when advection and propagation effects cancel each other out.

Techniques on how to determine which process will be dominant or if they cancel each other out will be discussed in Severe IC 2: Mesoanalysis

Conceptual Models for Origins and Evolutions of Convective Storms

Advanced Warning Operations Course

IC Severe 1

Lesson 6: Summary

Warning Decision Training Branch

The title for the instructional component is "**Conceptual Models for Origins and Evolutions of Convective Storms**". This is the first instructional component in the AWOC Severe Track. This lesson will be a summary of learning objectives for the the entire IC. It can be a helpful review of the objectives which are tested on the exam.

Performance Objective

- The trainee will identify aspects of recent (1994-present) research on conceptual models that describe convective storm structure and evolution.

The performance objective will be evaluated after the training is completed.

Review of Key Objectives

1. Role of shear
   - Important for developing organized deep rotation in supercells; determines propagation and movement: low-level shear correlated to significant tornado potential in supercells.
2. ID Method
   - Uses 0-6 km shear vector; 7.5 m/s left/right of mean wind along orthogonal line.
3. Role of baroclinic generation of vorticity
   - Increases streamwise vorticity in a zone through solenoidal effects; eventually updraft tilts this vorticity into vertical and is stretched via shear-induced pressure forces.

These objectives are in lesson 1.

Review of Key Objectives

4. Characteristics of favorable boundaries for tornadoes
   - Ones that have enhanced horizontal vorticity and storm relative helicity on the immediate cool side; important source for vertical vorticity.
5. Role of Rear-Flank Downdraft (RFD)
   - Helps to produce tornadoes if air possesses similar buoyancy to environmental inflow
   - Enhances boundary layer RH, lowers LCL
6. Buoyancy effects in supercells
   - Increases stretching, related to lower CIN, lower LCL, LFC heights

These objectives are in lesson 1.

Review of Key Objectives

7. Fundamental conceptual model of a supercell
   - Gust fronts, RFD, FFD, core, location of potential vortex
8. Tornadoes can be cyclic
9. Characteristics of a severe squall line
   - Leading reflectivity gradient
   - Front end echo, possible BWER, MARC, DCZ
10. Characteristics of line-end vortices
    - Develop in mature phase of squall line, bookend vortices develop on end or at line breaks, cyclonic member dominates
11. Characteristics of squall-line tornadoes
    - Nondescending TVS, surface vortex located on leading edge of line, south of front-flank notch, north of rear-inflow notch

These objectives are in lesson 1 and 2.

Review of Key Objectives

12. Mid-level storm-scale rotation can enhance updraft strength.
    - non-hydrostatic upward directed pressure perturbation in the center of the mesocyclone can increase the updraft strength
13. Steep lapse rates in the hail growth zone are favorable for large hail.
    - Hail growth zone basically between –10°C and –30°C
    - thick CAPE is more favorable for large hail than thin CAPE
14. Melting parameters should only be applied to small hail sizes.
    - RH, Temp., density of hail, all important to smaller hail

These objective are from lesson 3.

Review of Key Objectives

15. Hail growth trajectories vary widely from storm to storm.
    - Residence time in an updraft is the most important factor to large hail growth trajectories
16. 3 main sources of hail embryos in convective storms: Nearby flanking lines of growing Cbs, stagnation points, and shed liquid drops.
    - All 3 regions may operate in a single convective storm
17. Deep-layer shear, steep lapse rates, thick CAPE, are favorable sounding parameters for large hail.

These objective are from lesson 3.

Review of Key Objectives

18. Characteristics of the hybrid Multicell-Supercell hailstorm.
    - Deep convergence zone, huge size/depth of hail core, few and very weak tornadoes
19. There are 3 modes of linear MCSs
20. Factors governing evolution of organized multicells
    - Environmental winds and shear (all levels), storm-relative winds, cold pool strength, orientation of gust front relative to storm low-level inflow, instability gradients, boundary interactions

These objective are from lesson 3 and 4.

Review of Key Objectives

21. Role of storm–relative winds on multicells
    - Influences propagation via where updrafts will develop
22. Cold pool effects
    - Positive shear – deeper lifting along downshear side
    - Negative shear – diminishes lifting
23. Role of Rear-Inflow Jet
    - Produced by buoyancy gradients across updraft, enhances rear-to front with vorticity generated by cold pool, results in upshear tilted structure; if RIJ remains elevated, it can help to restore balance of cold pool with environmental shear

These objective are from lesson 4.

Review of Key Objectives

24. RKW theory (see cold pool effects)
25. Effects of instability on multicell movement
    - Convection will develop toward regions of higher surface based instability
26. Meteorological ingredients for heavy rainfall.
    - Max rainfall occurs just east of the maximum moisture convergence in low levels
    - Deep moisture, and lots of it
    - Weak wind shear, but strong turning with height favorable

These objective are from lesson 4 and 5.

Review of Key Objectives

27. Hydrological ingredients for heavy rainfall
    - Topography, size, condition of basin and/or stream channel very important
    - Antecedent precipitation can prime a basin for flash flooding and may not be included in FFG
    - Urban areas especially prone to flash flooding

These objective are from lesson 5.

Review of Key Objectives

28. Characteristics of the Watershed response to excessive rainfall
    - Rainfall rate more important than final rainfall amounts in most flash floods
    - FFG may not incorporate recent rainfall, and typically does not accurately represent actual basin characteristics due to differences in scale
    - Burn areas significantly enhance flash flood threat
    - Smaller basins flood much more easily than large basins
29. Precipitation efficiency can not be directly measured, but can be inferred: higher PE requires a deep warm cloud depth, high PW, low wind shear, “thin” CAPE.

These objective are from lesson 5.

Review of Key Objectives

30. Characteristics supercell flash flooding.
    - Slow movement most important, and moisture inflow into an HP more than makes up for low precipitation efficiency
31. Forward propagating MCSs far more likely to produce flash flooding

These objective are from lesson 5.

Contact Information

- For questions on this IC
  - Contact your SOO
  - WDTB focal points for Severe Track IC1
    - icsvr1@wdtb.noaa.gov