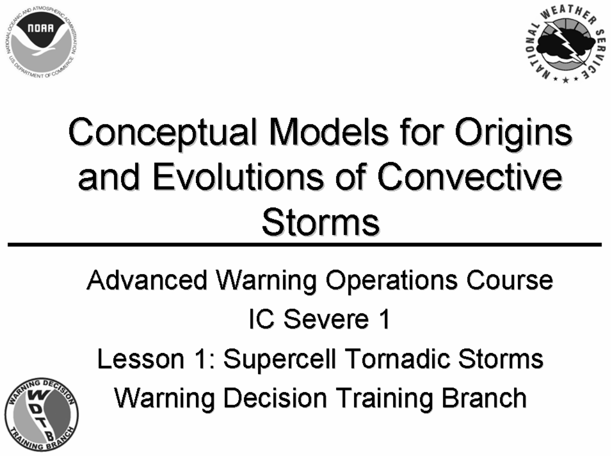
1. Conceptual Models for Origins and Evolutions of Convective Storms

Instructor Notes: 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.

Student Notes:



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

2. AWOC Severe Track Training Components

Instructor Notes: 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.

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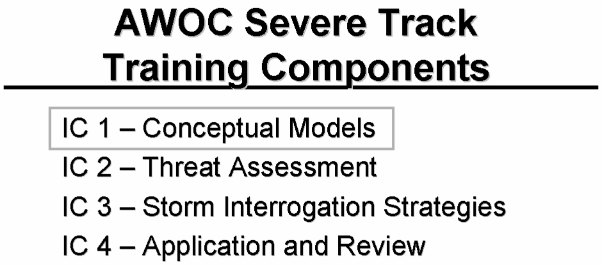

AWOC Severe Track Training Components

IC 1 – Conceptual Models
IC 2 – Threat Assessment
IC 3 – Storm Interrogation Strategies
IC 4 – Application and Review

3. IC1 Performance Objective

Instructor Notes: Performance objectives provide precise, measurable statements of the behaviors that training participants will be able to demonstrate on the job. They often specify the condition under which the behaviors will be demonstrated as well as the criteria for acceptable performance. The performance objective for this entire IC is that the trainee will demonstrate ability to incorporate the knowledge of conceptual models to help describe convective storm structure and evolution.

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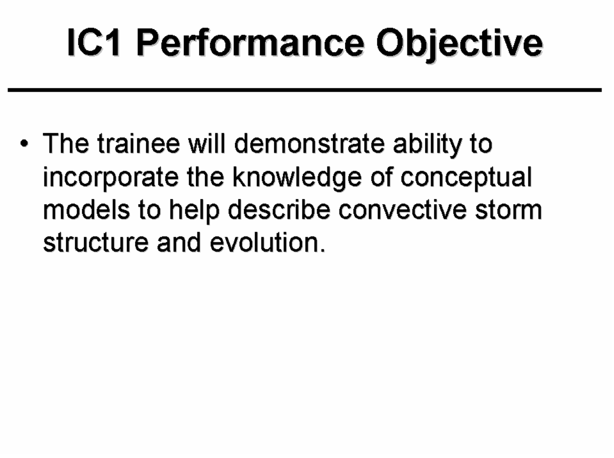

IC1 Performance Objective

- The trainee will demonstrate ability to incorporate the knowledge of conceptual models to help describe convective storm structure and evolution.

4. IC1 Lesson Plan

Instructor Notes: The instruction for IC1 is broken up into 6 lessons, with the following topics in each lesson: Tornadic supercell storms Squall line tornadoes Hail storms Organized multicell storms Flash flooding (meteorological and hydrological effects) Summary of learning objectives Individual learning objectives are designed into each Lesson and the IC test is on the objectives.

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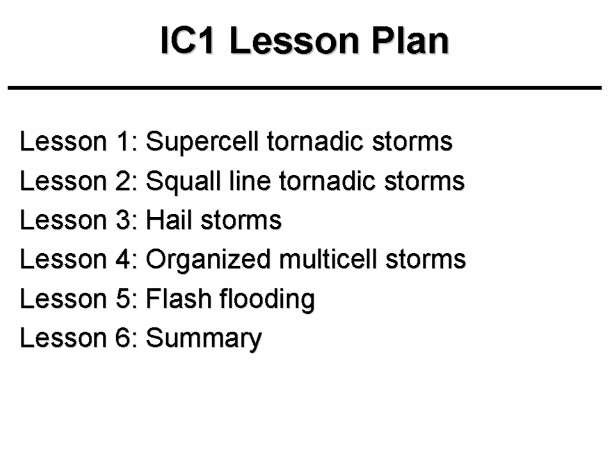

IC1 Lesson Plan

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

5. IC1 Learning Objectives

Instructor Notes: These are the learning objectives for lesson 1. There will be a test (20-25 questions) on the learning objectives for this IC.

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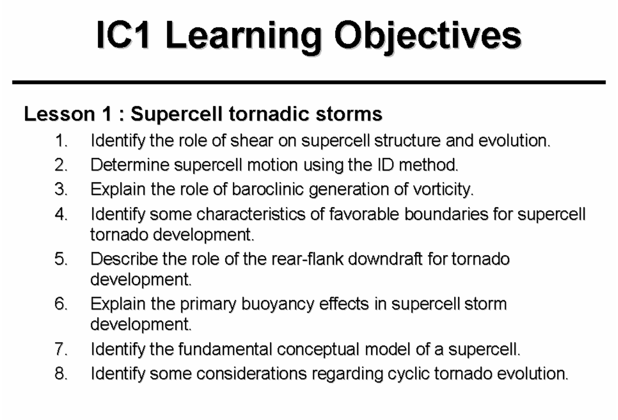


IC1 Learning Objectives

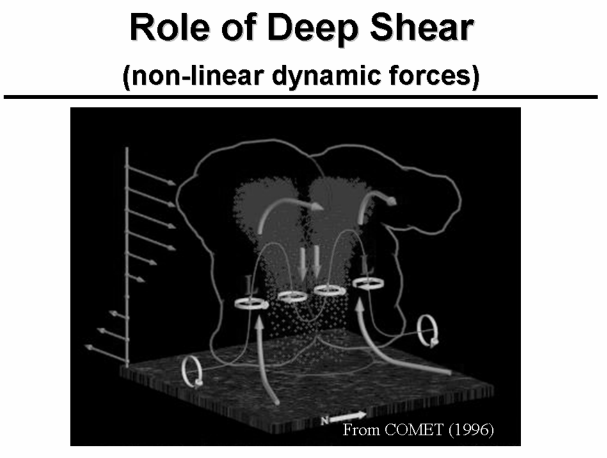
Lesson 1 : Supercell tornadic storms

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.

6. Role of Deep Shear (non-linear dynamic forces)

Instructor Notes: 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 streamwise vorticity into the updraft immediately produces vertical vorticity well correlated with the updraft. RKW theory also explains another internal dynamic force which affects supercell morphology.

Student Notes:



Role of Deep Shear

(non-linear dynamic forces)

From COMET (1996)

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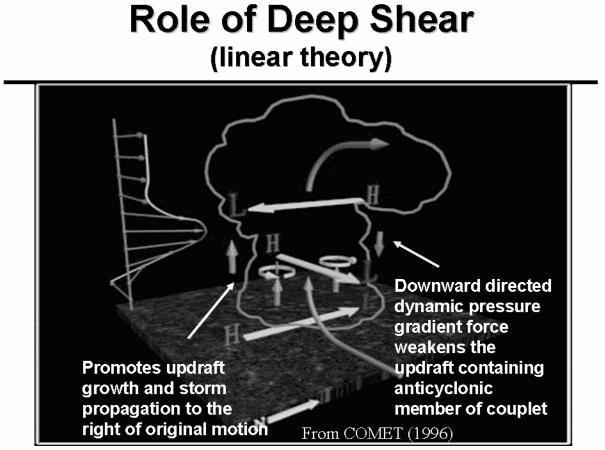
7. Role of Deep Shear (linear theory)

Instructor Notes: There 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 level. 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: 1) 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.

Student Notes:



Role of Deep Shear

(linear theory)

Downward directed dynamic pressure gradient force weakens the updraft containing anticyclonic member of couplet

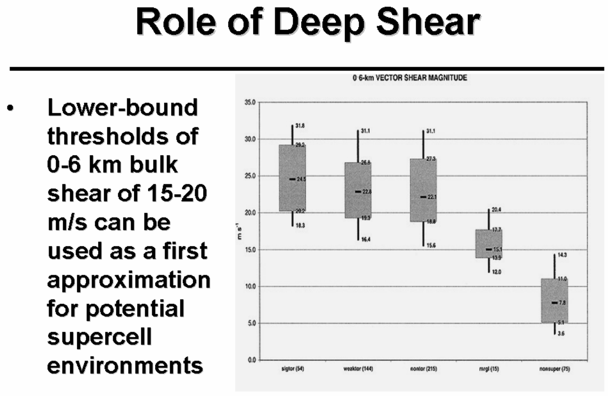
Promotes updraft growth and storm propagation to the right of original motion

From COMET (1996)

8. Role of Deep Shear

Instructor Notes: 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 0.001 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.

Student Notes:



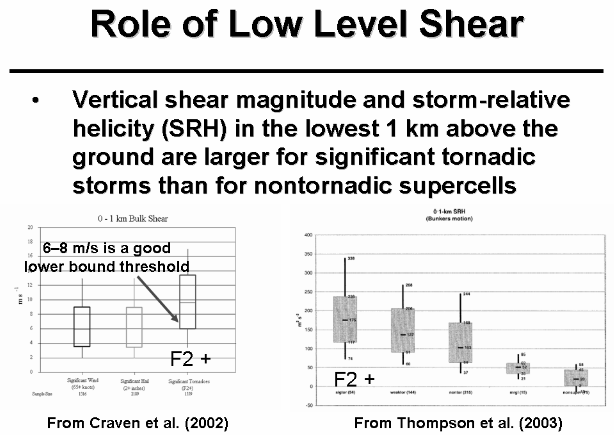
Role of Deep Shear

- **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**

9. Role of Low Level Shear

Instructor Notes: 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 hailstorms (2” diameter 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, around 6 to 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; and 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.

Student Notes:



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

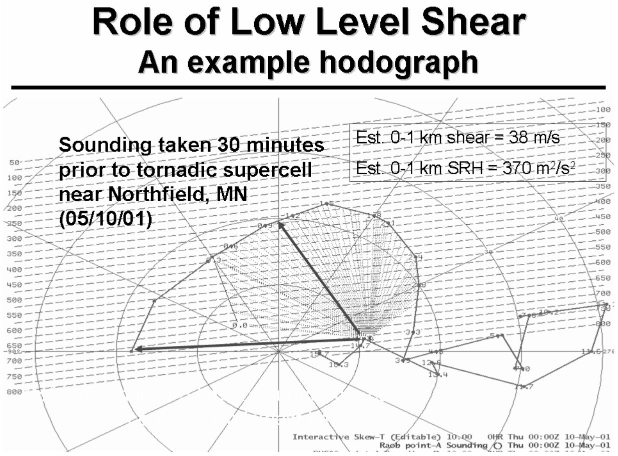
From Craven et al. (2002)

From Thompson et al. (2003)

10. Role of Low Level Shear An example hodograph

Instructor Notes: 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.

Student Notes:



Role of Low Level Shear

An example hodograph

Sounding taken 30 minutes prior to tornadic supercell near Northfield, MN (05/10/01)

Est. 0-1 km shear = 38 m/s

Est. 0-1 km SRH = 370 m^2/s^2

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11. Role of Low Level Shear

Instructor Notes: 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).

Student Notes:

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.

12. Role of Shear

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

Student Notes:

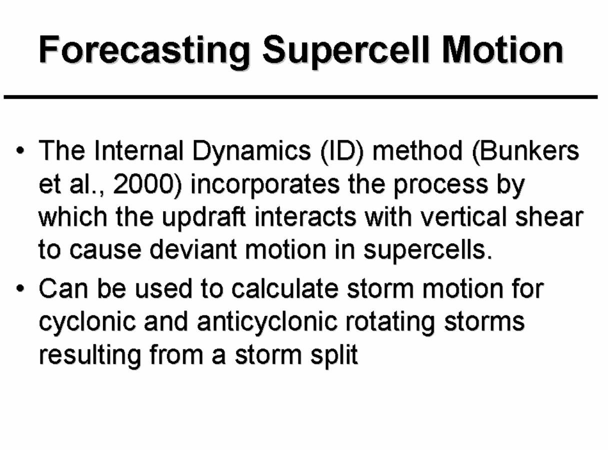
Role of Shear

- 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.

13. Forecasting Supercell Motion

Instructor Notes: 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.

Student Notes:



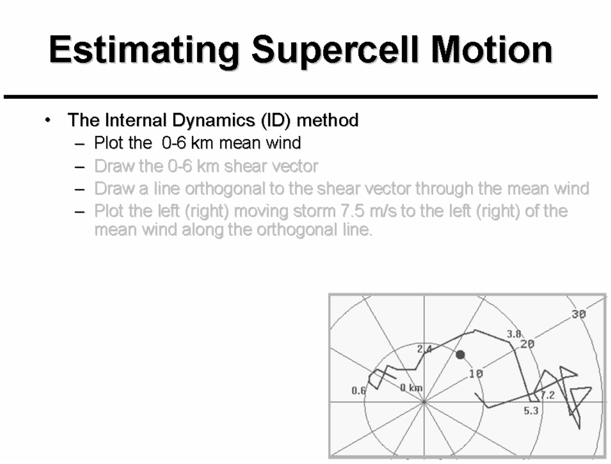
Forecasting Supercell Motion

- 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

14. Estimating Supercell Motion

Instructor Notes: 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.

Student Notes:



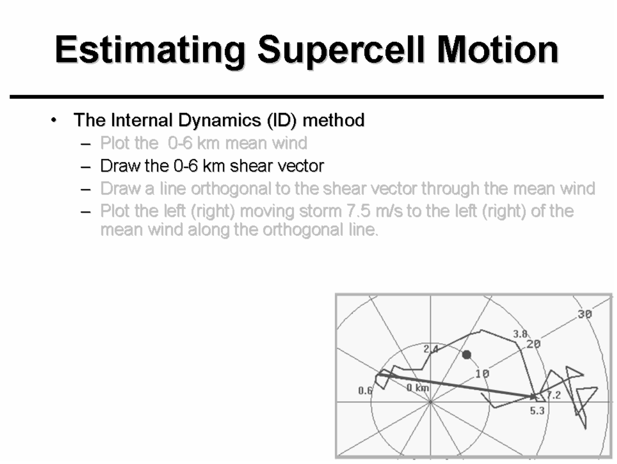
Estimating Supercell Motion

- 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.

15. Estimating Supercell Motion

Instructor Notes:

Student Notes:



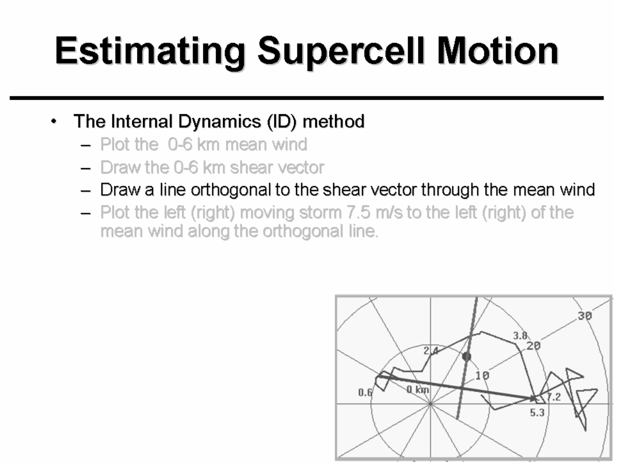
Estimating Supercell Motion

- 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.

16. Estimating Supercell Motion

Instructor Notes:

Student Notes:



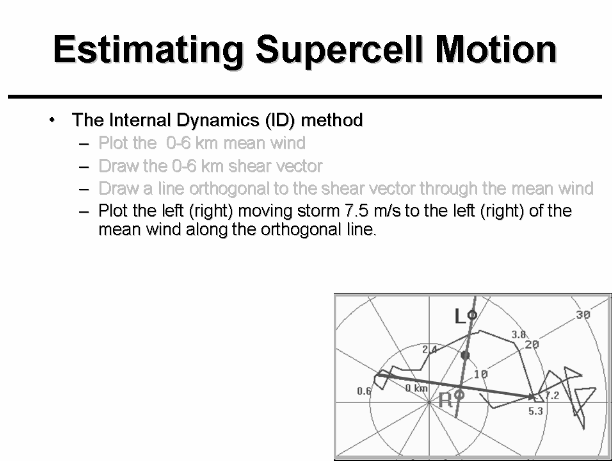
Estimating Supercell Motion

- 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.

17. Estimating Supercell Motion

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

Student Notes:



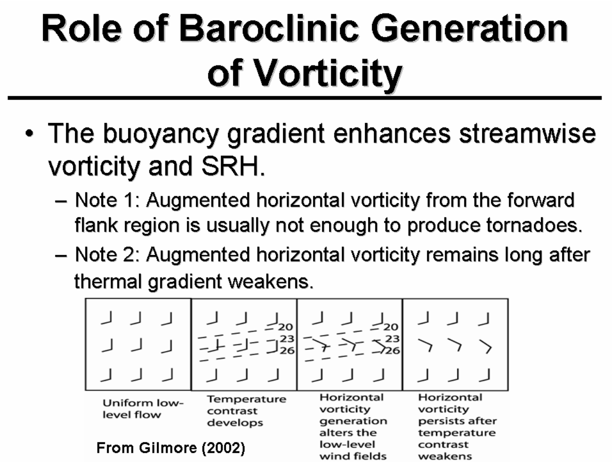
Estimating Supercell Motion

- 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.

18. Role of Baroclinic Generation of Vorticity

Instructor Notes: 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.

Student Notes:



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)

19. Effects of Low Level Shear (vorticity stretched into updraft)

Instructor Notes: 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 discernible 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 × 10 2 s 1 or greater or storm-relative helicity of 500 m2 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.

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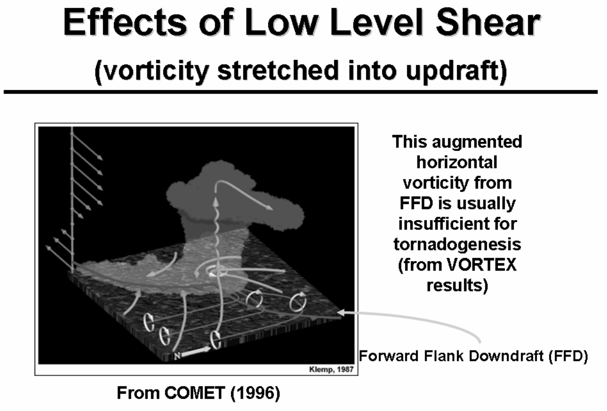


Effects of Low Level Shear

(vorticity stretched into updraft)

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

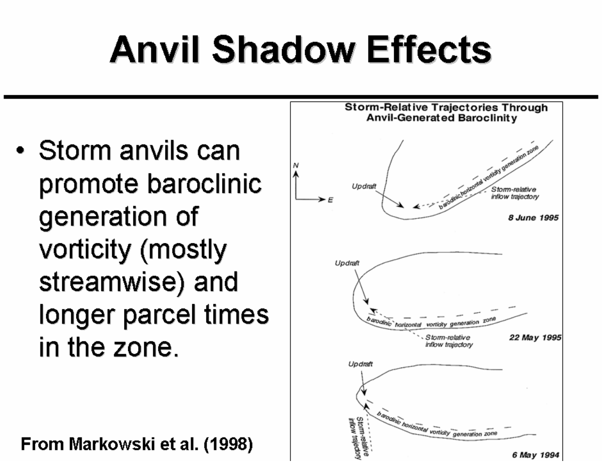
Forward Flank Downdraft (FFD)

From COMET (1996)

20. Anvil Shadow Effects

Instructor Notes: 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.

Student Notes:



Anvil Shadow Effects

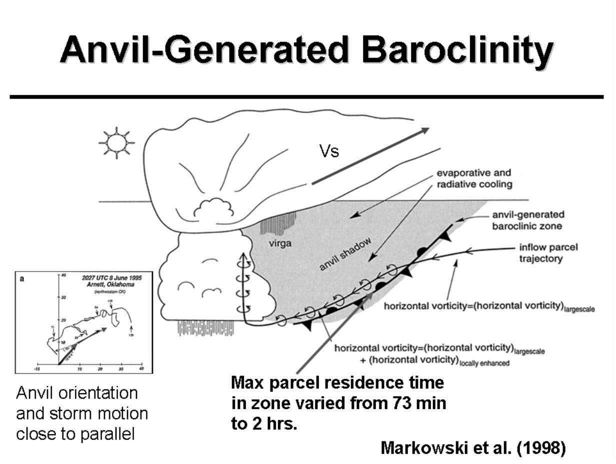
- Storm anvils can promote baroclinic generation of vorticity (mostly streamwise) and longer parcel times in the zone.

From Markowski et al. (1998)

21. Anvil-Generated Baroclinity

Instructor Notes: 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.

Student Notes:



Anvil-Generated Baroclinity

Anvil orientation
and storm motion
close to parallel

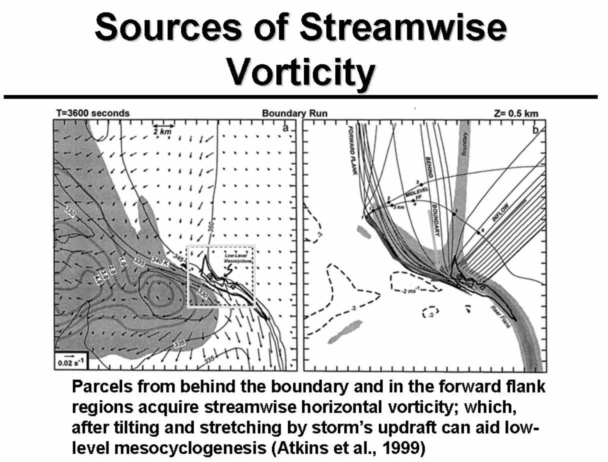
**Max parcel residence time
in zone varied from 73 min
to 2 hrs.**

Markowski et al. (1998)

22. Sources of Streamwise Vorticity

Instructor Notes: 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 θe (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 et al. (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.

Student Notes:



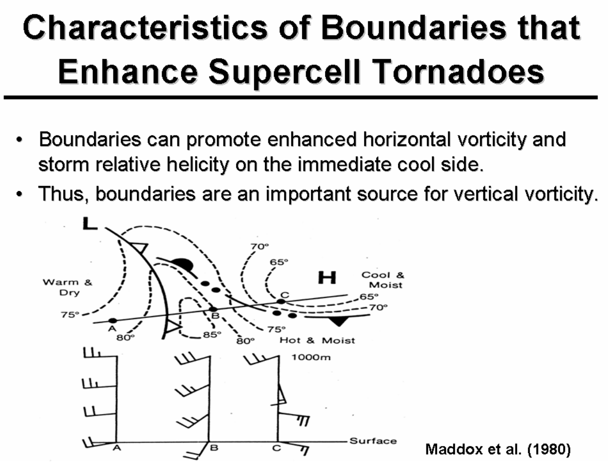
Sources of Streamwise Vorticity

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)

23. Characteristics of Boundaries that Enhance Supercell Tornadoes

Instructor Notes: 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 (esp. in low levels) fields in the vicinity of boundaries (from Maddox et al., 1980). Intense horizontal stretching occurs in the storm 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.

Student Notes:



Characteristics of Boundaries that Enhance Supercell Tornadoes

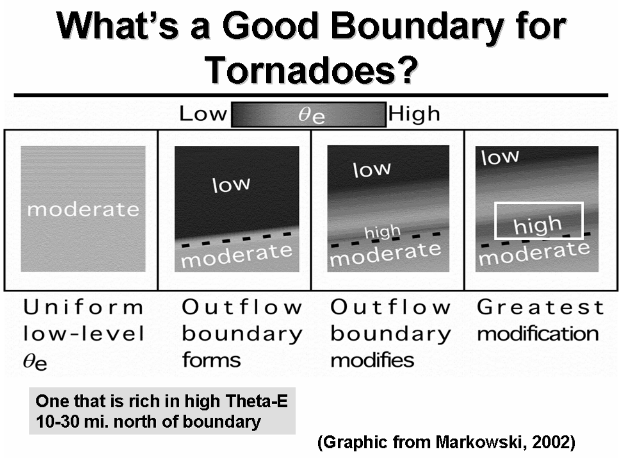
- Boundaries can promote enhanced horizontal vorticity and storm relative helicity on the immediate cool side.
- Thus, boundaries are an important source for vertical vorticity.

Maddox et al. (1980)

24. What's a Good Boundary for Tornadoes?

Instructor Notes: 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.

Student Notes:



What’s a Good Boundary for Tornadoes?

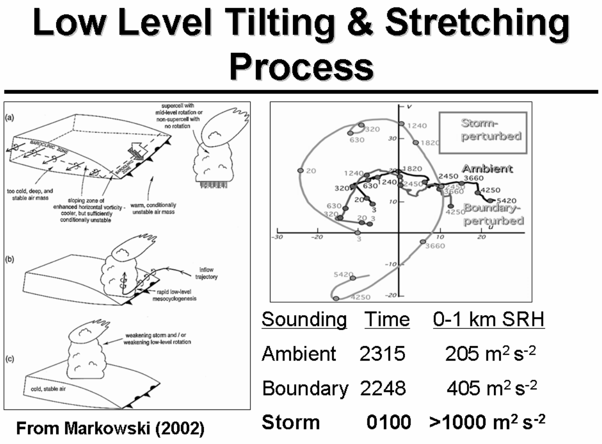
One that is rich in high Theta-E 10-30 mi. north of boundary

(Graphic from Markowski, 2002)

25. Low Level Tilting & Stretching Process

Instructor Notes: 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.

Student Notes:



Low Level Tilting & Stretching Process

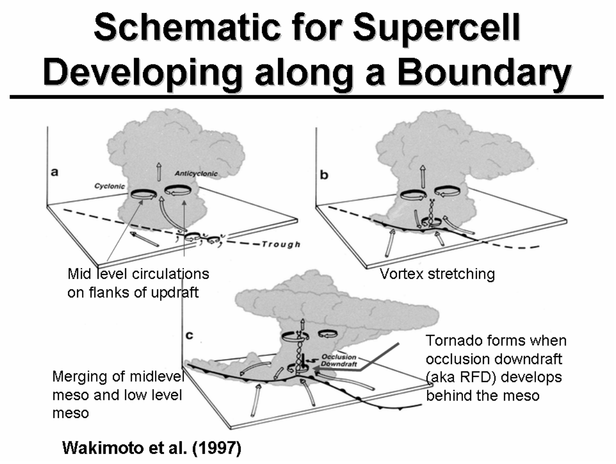
From Markowski (2002)

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

26. Schematic for Supercell Developing along a Boundary

Instructor Notes: 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.

Student Notes:



Schematic for Supercell Developing along a Boundary

Mid level circulations on flanks of updraft

Vortex stretching

Merging of midlevel meso and low level meso

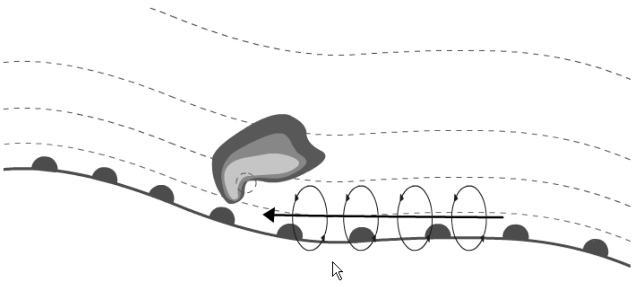
Tornado forms when occlusion downdraft (aka RFD) develops behind the meso

Wakimoto et al. (1997)

27. Slide 27

Instructor Notes: 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.

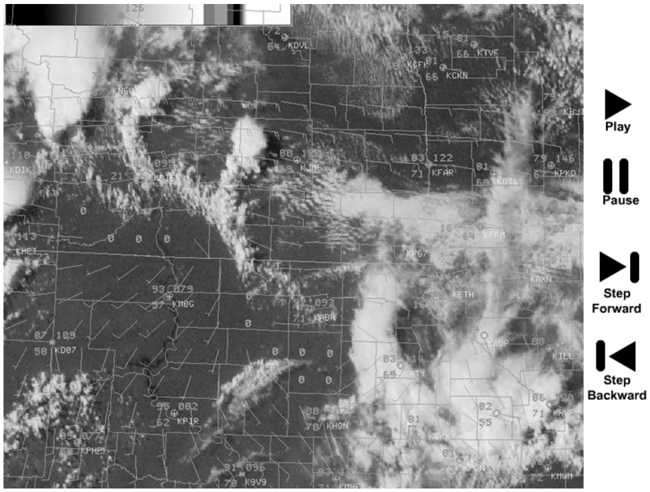
Student Notes:



28. Slide 28

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

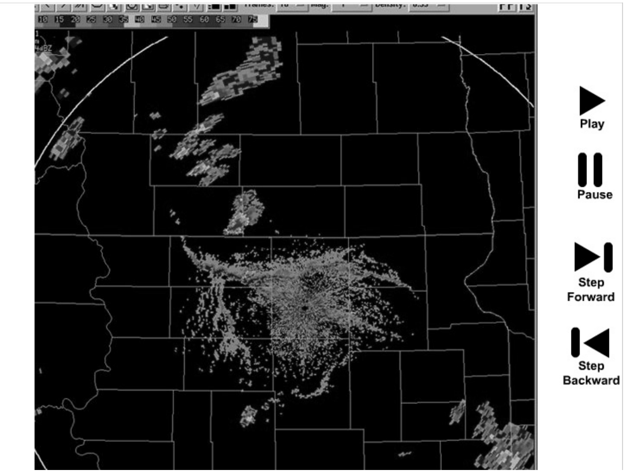
Student Notes:



29. Slide 29

Instructor Notes: 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.

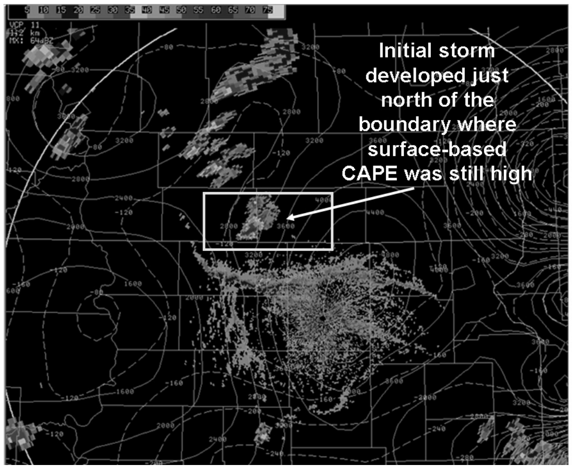
Student Notes:



30. Real Life Boundary Example

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

Student Notes:



Initial storm developed just north of the boundary where surface-based CAPE was still high

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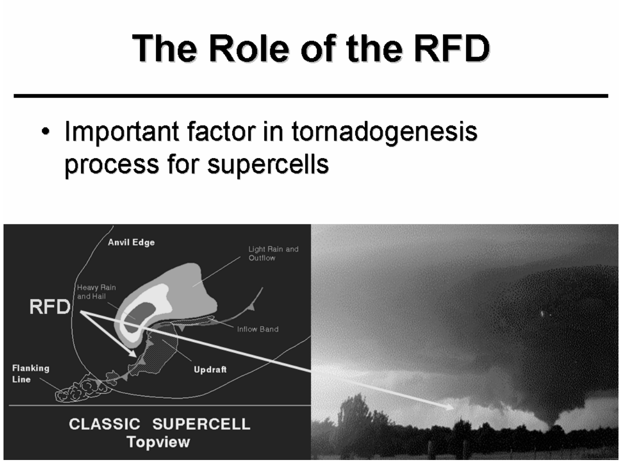
31. The Role of the RFD

Instructor Notes: 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.

Student Notes:

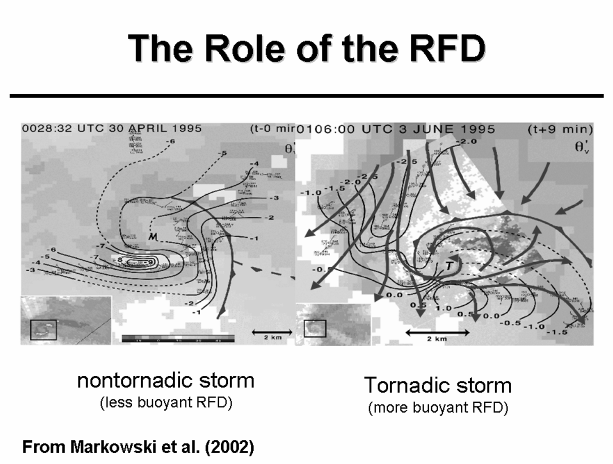


The Role of the RFD

- Important factor in tornadogenesis process for supercells

32. The Role of the RFD

Student Notes:



The Role of the RFD

nontornadic storm
(less buoyant RFD)

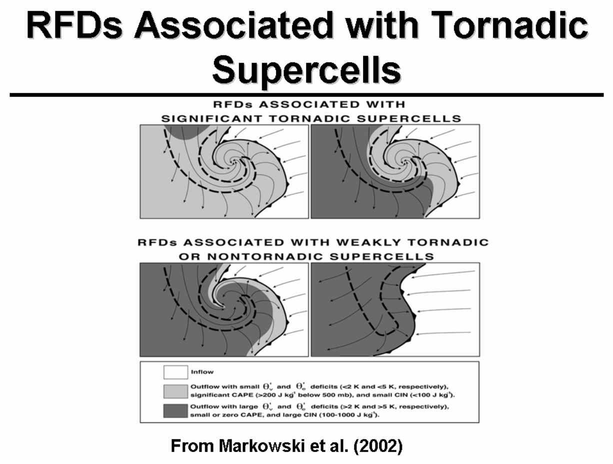
Tornadic storm
(more buoyant RFD)

From Markowski et al. (2002)

33. RFDs Associated with Tornadic Supercells

Instructor Notes: 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.

Student Notes:



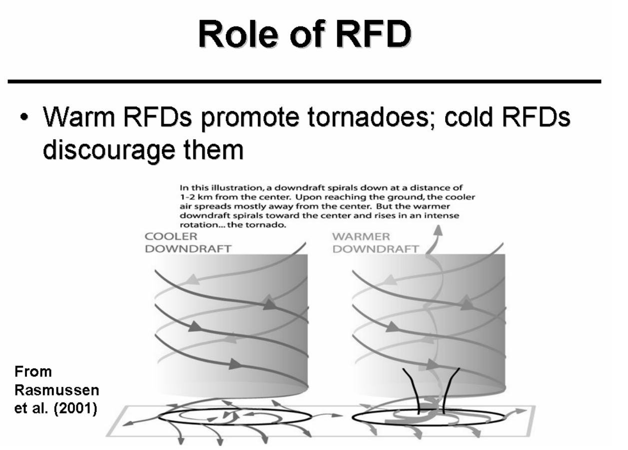
RFDs Associated with Tornadic Supercells

From Markowski et al. (2002)

34. Role of RFD

Instructor Notes: 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. Erik Rasmussen's long-standing work on tornadogenesis (See http://cimms.ou.edu/~erik/) was where I first saw the tornadic RFD conceptual model presented here (2001). There is a recent published paper (Paul M. Markowski, Jerry M. Straka and Erik N. Rasmussen. 2003: Tornadogenesis Resulting from the Transport of Circulation by a Downdraft: Idealized Numerical Simulations. Journal of the Atmospheric Sciences: Vol. 60, No. 6, pp. 795–823.) (Available from Allen Press) where these concepts are described in detail.

Student Notes:



Role of RFD

- Warm RFDs promote tornadoes; cold RFDs discourage them

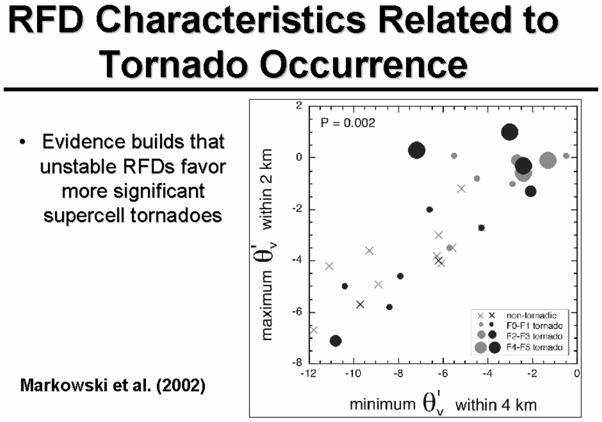
In this illustration, a downdraft spirals down at a distance of 1-2 km from the center. Upon reaching the ground, the cooler air spreads mostly away from the center. But the warmer downdraft spirals toward the center and rises in an intense rotation... the tornado.

From Rasmussen et al. (2001)

35. RFD Characteristics Related to Tornado Occurrence

Instructor Notes: 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 θv’ 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.

Student Notes:



RFD Characteristics Related to Tornado Occurrence

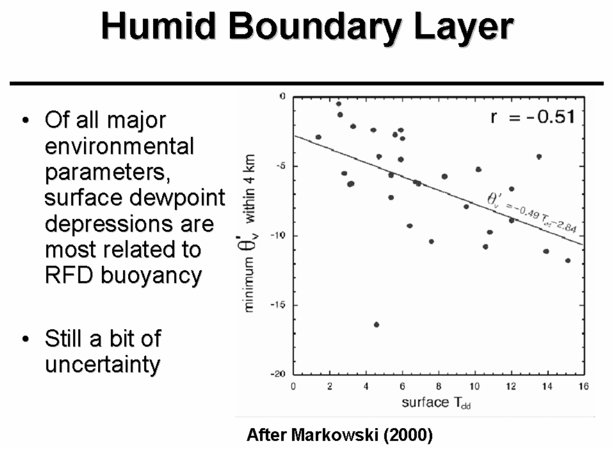
- Evidence builds that unstable RFDs favor more significant supercell tornadoes

Markowski et al. (2002)

36. Humid Boundary Layer

Instructor Notes: 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.

Student Notes:



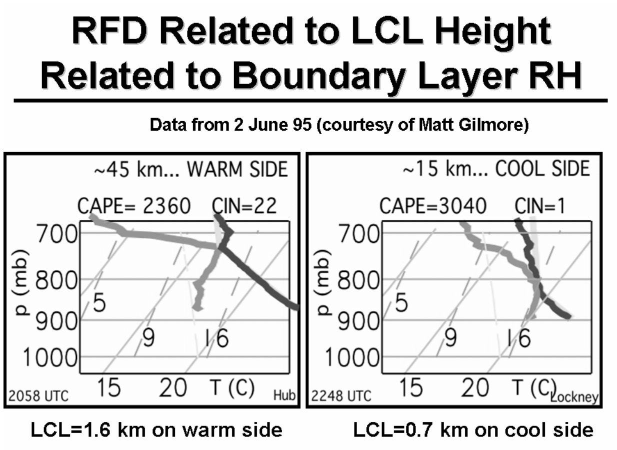
Humid Boundary Layer

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

After Markowski (2000)

37. RFD Related to LCL Height Related to Boundary Layer RH

Student Notes:



RFD Related to LCL Height Related to Boundary Layer RH

Data from 2 June 95 (courtesy of Matt Gilmore)

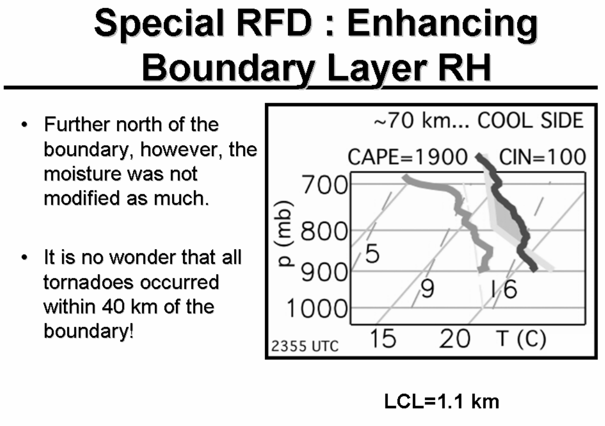
LCL=1.6 km on warm side

LCL=0.7 km on cool side

38. Special RFD: Enhancing Boundary Layer RH

Instructor Notes: Note there is some low-level CAPE, but more CIN deep in the cold air.

Student Notes:



Special RFD : Enhancing Boundary Layer RH

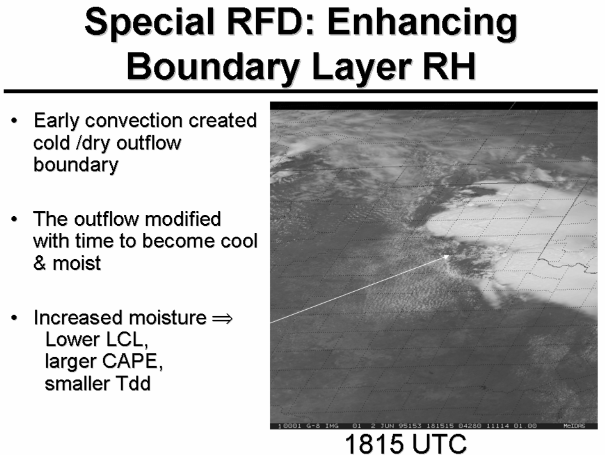
- Further north of the boundary, however, the moisture was not modified as much.
- It is no wonder that all tornadoes occurred within 40 km of the boundary!

LCL=1.1 km

39. Special RFD: Enhancing Boundary Layer RH

Instructor Notes: This is the area where severe thunderstorms erupted.

Student Notes:



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

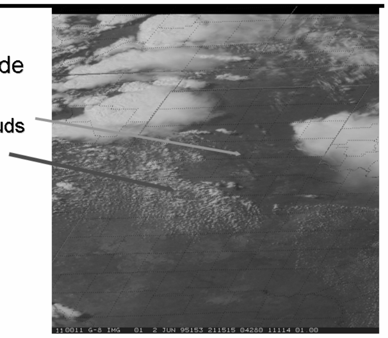
40. Special RFD: Enhancing BL RH

Instructor Notes: 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.

Student Notes:

Special RFD: Enhancing BL RH



How did the cool side evolve?

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

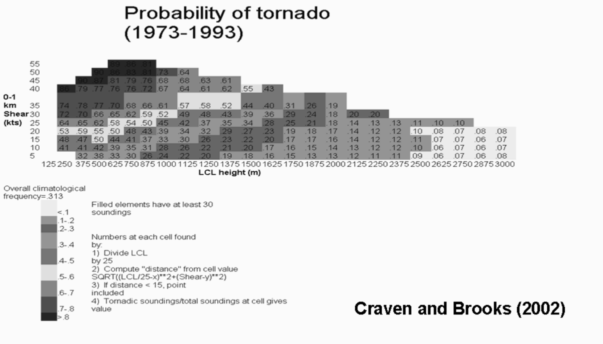
2115 UTC

41. Combining Effects of LCL Height and Shear

Instructor Notes: This chart, from Craven and Brooks (2002) shows a smoothed probability of a tornado as a function of LCL height (m) and 0-1 km shear. The data was obtained from observed 1800 LST soundings on the condition that CAPE was present. The results are based on 20 yrs. of climatological data. The graph indicates the following relationship: tornado likelihood greatly increases as 0-1 km shear increases AND LCL height decreases. 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) on STP.

Student Notes:

Combining Effects of LCL Height and Shear



Probability of tornado
(1973-1993)

0-1 km Shear (kts)	125	250	375	500	625	750	875	1000	1125	1250	1375	1500	1625	1750	1875	2000	2125	2250	2375	2500	2625	2750	2875	3000
55					.89	.86	.81																	
50				.90	.86	.83	.81	.73	.64															
45			.90	.87	.81	.79	.76	.68	.68	.63	.61													
40		.86	.79	.77	.76	.76	.72	.67	.64	.61	.62	.55	.43											
35		.74	.78	.77	.70	.68	.66	.61	.57	.58	.52	.44	.40	.31	.26	.19								
30		.72	.70	.66	.65	.62	.59	.52	.49	.48	.43	.39	.36	.29	.24	.18	.20	.20						
25		.64	.65	.62	.58	.54	.50	.45	.42	.37	.35	.34	.28	.25	.21	.18	.14	.13	.13	.11	.10	.10		
20		.53	.59	.55	.50	.48	.43	.39	.34	.32	.29	.27	.23	.19	.18	.17	.14	.12	.12	.10	.08	.07	.08	.08
15		.48	.47	.50	.44	.41	.37	.33	.30	.26	.23	.22	.20	.17	.17	.16	.14	.12	.12	.11	.07	.07	.06	.07
10		.41	.41	.42	.39	.35	.31	.28	.26	.22	.21	.20	.17	.16	.15	.14	.13	.12	.12	.10	.06	.07	.06	.07
5			.32	.38	.33	.30	.26	.24	.22	.20	.19	.18	.16	.15	.13	.13	.12	.11	.11	.09	.06	.07	.06	.08

LCL height (m)

Overall climatological frequency=.313

Filled elements have at least 30 soundings

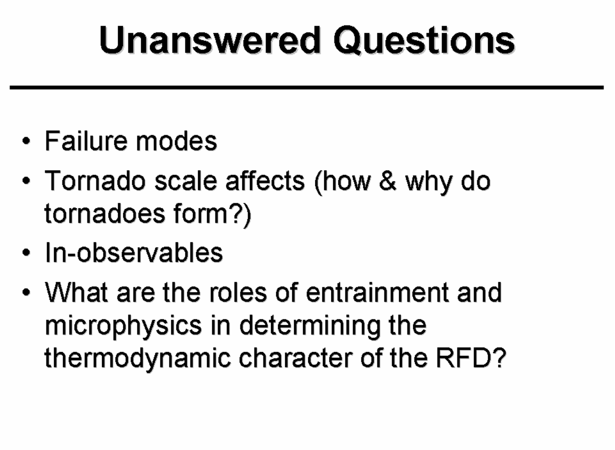
Numbers at each cell found by:
1) Divide LCL by 25
2) Compute "distance" from cell value SQRT((LCL/25-x)**2+(Shear-y)**2)
3) If distance < 15, point included
4) Tornadic soundings/total soundings at cell gives value

Craven and Brooks (2002)

42. Unanswered Questions

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

Student Notes:



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?

43. Buoyancy Effects

Instructor Notes: 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, 1994). Low-level buoyancy is also related to LCL/LFC heights (RFD characteristics).

Student Notes:

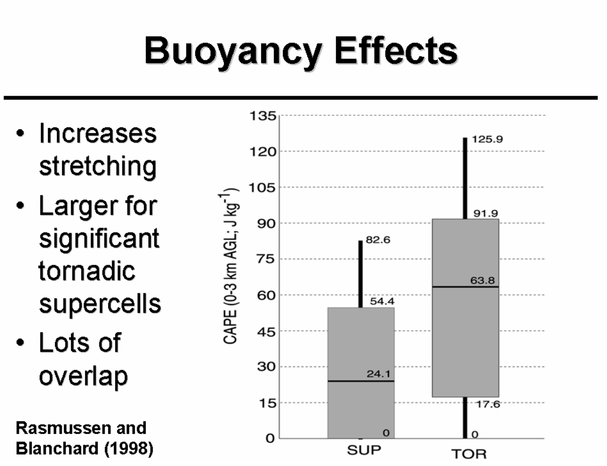
Buoyancy Effects

- 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

44. Buoyancy Effects

Instructor Notes: 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.

Student Notes:



Buoyancy Effects

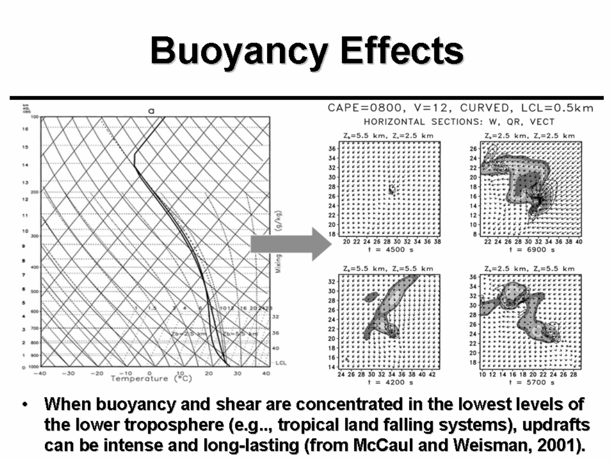
- Increases stretching
- Larger for significant tornadic supercells
- Lots of overlap

Rasmussen and Blanchard (1998)

45. Buoyancy Effects

Instructor Notes: 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 qr 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.

Student Notes:



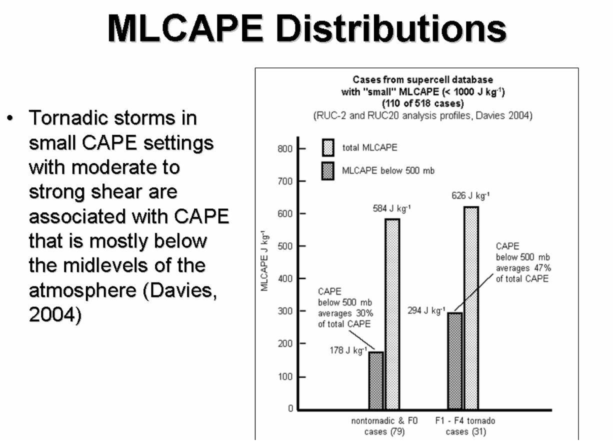
Buoyancy Effects

- **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).**

46. MLCAPE Distributions

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

Student Notes:



MLCAPE Distributions

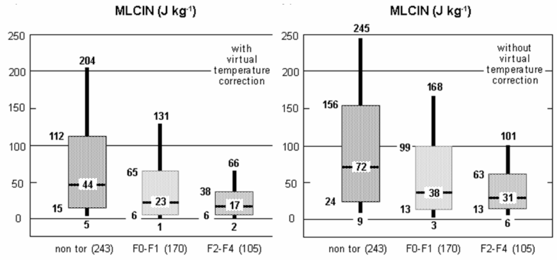
- Tornadic storms in small CAPE settings with moderate to strong shear are associated with CAPE that is mostly below the midlevels of the atmosphere (Davies, 2004)

47. Role of Negative Buoyancy

Instructor Notes: 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.

Student Notes:

Role of Negative Buoyancy

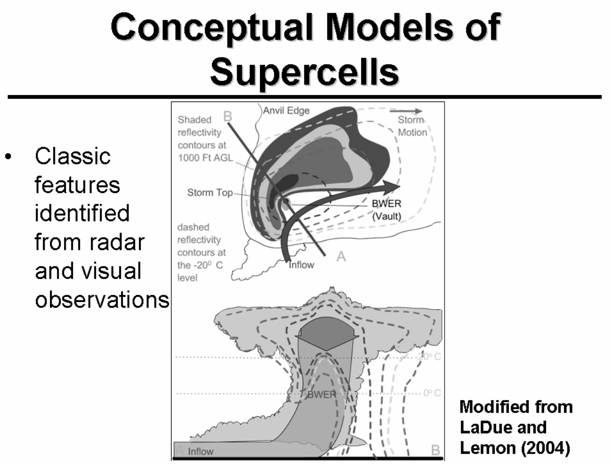


From Davies (2004)

48. Conceptual Models of Supercells

Instructor Notes: 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.

Student Notes:



Conceptual Models of Supercells

- Classic features identified from radar and visual observations

Modified from LaDue and Lemon (2004)

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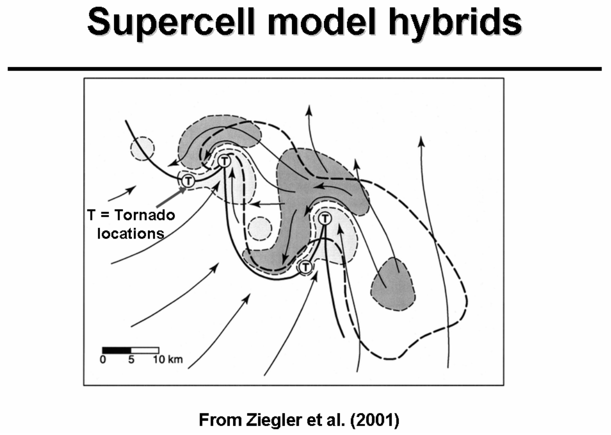
49. Supercell model hybrids

Instructor Notes: 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.

Student Notes:



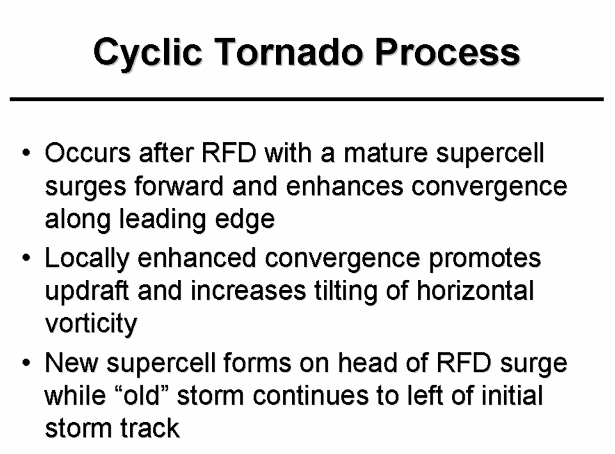
Supercell model hybrids

From Ziegler et al. (2001)

50. Cyclic Tornado Process

Instructor Notes: 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.

Student Notes:



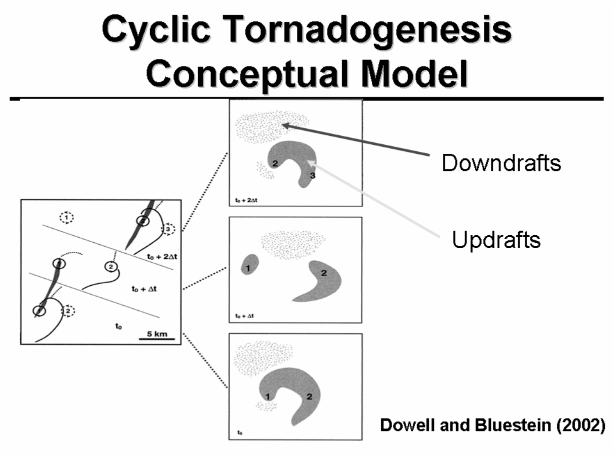
Cyclic Tornado Process

- 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

51. Cyclic Tornadogenesis Conceptual Model

Instructor Notes: 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 (2Δt) is 20 min.

Student Notes:



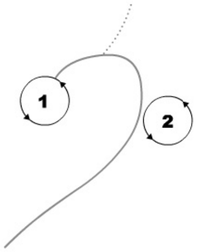
Cyclic Tornadogenesis Conceptual Model

Dowell and Bluestein (2002)

52. Slide 52

Instructor Notes:

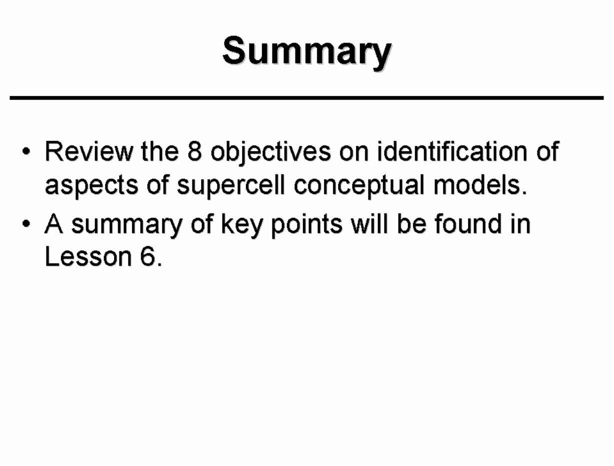
Student Notes:



53. Summary

Instructor Notes:

Student Notes:



Summary

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

54. References

Instructor Notes: Please see the reference page for AWOC Severe Track IC1 at http://wdtb.noaa.gov/courses/awoc/index.html

Student Notes:

References

- See the reference page