Storm Interrogation

AWOC – Severe Track

IC3-I-A

Location of weakly sheared updrafts

Welcome to the AWOC – Severe Track

IC3-I-A

Location of weakly sheared updrafts

This presentation is 33 slides long and should take 20 minutes to complete

Weakly sheared updraft location

- Objective:
  - Determine where to look for severe pulse storm updraft signatures based on the stage in its lifecycle.

This module shows several examples of where the updraft is most likely to be located depending on where in the storm is in its lifecycle. Not only clues in reflectivity and velocity can help us discriminate between updraft and downdraft within the mid- to upper-level of a convective cell but also at the source level of initiation, a level which is often overlooked during the cell's initial stages.

Weakly sheared updraft location

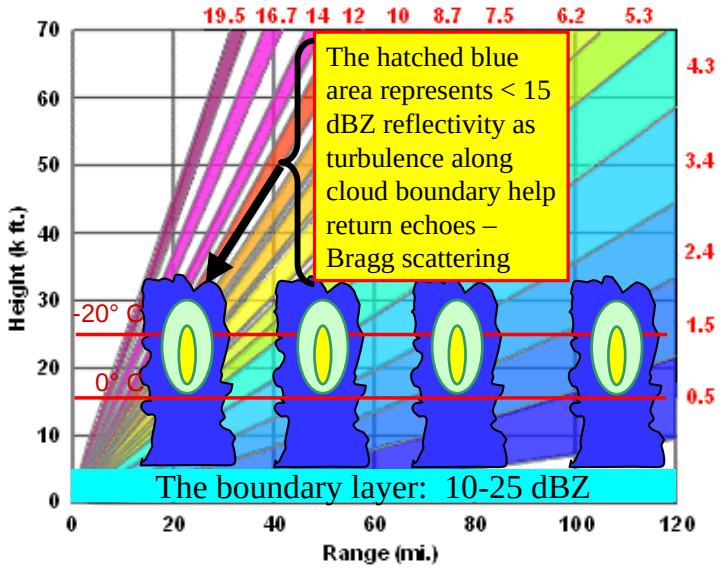
- Background
  - A pulse storm updraft is no steady state plume
  - Where to look for updraft signatures change during the life cycle of a thunderstorm
    1. Initiation phase where the reflectivity core is developing in the updraft
    2. Mature phase where the reflectivity core has reached its maximum vertical extent and downdraft occupied part of it
    3. Decaying phase where the core height and intensity decrease

A typical low shear thunderstorm updraft is more accurately pictured as a pulse of updraft air than a steady current of ascent. For example, a reflectivity core in an initiating thunderstorm indicate the presence of updraft. However, as the storm matures, the same reflectivity signature is more likely to be downdraft. Likewise, kinematic patterns that you'd look for where an updraft exists are transitory. Let's take a look at a couple scenarios.

1. Towering CU phase - reflectivity

Signatures

- <15 dBZ core (blue) marks the cloud region above the boundary layer
- >18 dBZ – increasing precipitation



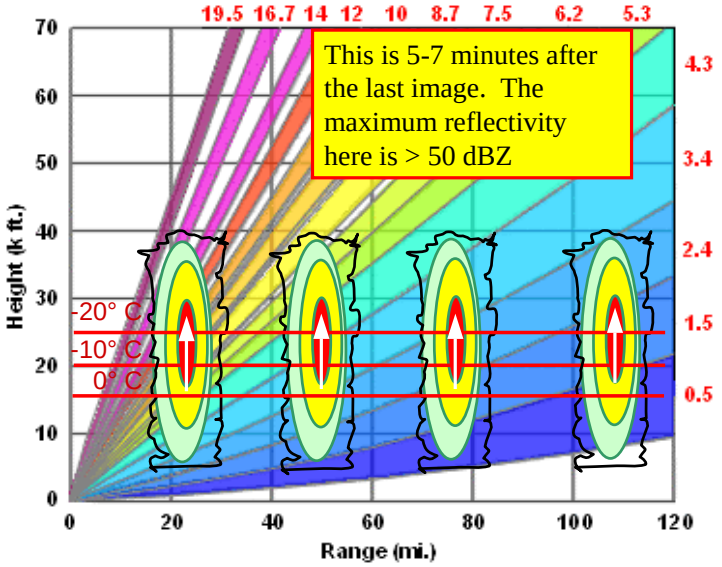
In the initiation stages before significant core develops, the towering cumulus itself returns echoes through a process called Bragg scattering. This mechanism comes about as temperature and moisture gradients embedded along the turbulent edges of a growing cumulus cloud act as a source for scattering incident microwave energy. It's not a very strong scatterer, but enough energy gets returned back to the radar to result in 15-20 dBZ echoes above the boundary layer. The cloud edges are the regions of strongest Bragg scattering and you would think there would be weak echo regions in the interior of towering cumulus clouds. However, there is very little of a typical towering cumulus cloud that could be said to have an updraft without any influence from dry air entrainment from the environment, and therefore, be completely homogeneous in temperature and moisture. Not much time passes before hydrometeors begin to fill the interior of a towering cumulus cloud, especially as it passes above the –10 to –20° C level. As the reflectivity of a towering cumulus exceeds 18dBZ, current conventional thinking is that the radar is detecting first hydrometeor formation.

The background chart shows VCP 11 elevation cuts and what slice you would expect to see reflectivities from towering cumulus from Bragg scattering and hydrometeor formation given your range from radar. This is for a typical environment given the height of the 0° and -20° C level labeled here. For colder atmospheres, you would need to supress the elevations of the developing hydrometeor cores so that they're relative to the lower freezing levels. In marine climates, or very humid environments, reflectivity cores would be more due to warm rain processes and thus the core altitudes would also be depressed.

1. Initiation phase - reflectivity

Height of initial core

- Reflectivity core is all updraft
- Stronger updraft pulses create higher cores



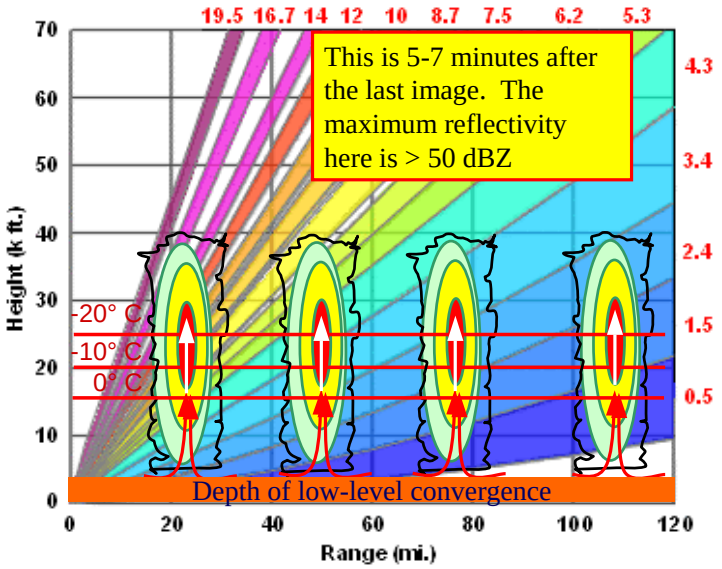
It only takes about 5-7 minutes from the previous image to produce significant reflectivities in the subfreezing air. At this point, the core is likely greater than 50 dBZ and completely elevated above the freezing layer. Stronger initiating cells produce cores that extend to higher altitudes.

The VCP 11 background chart shows that far range initiating cells may not show an initial elevated core between elevation slices. Switching to VCP 12 may help some in that event, although we would really need a slice < 0.5°.

1. Initiation phase - velocity

Low-level convergence

- Difficult to detect unless from a previous boundary
- Requires close proximity to the radar

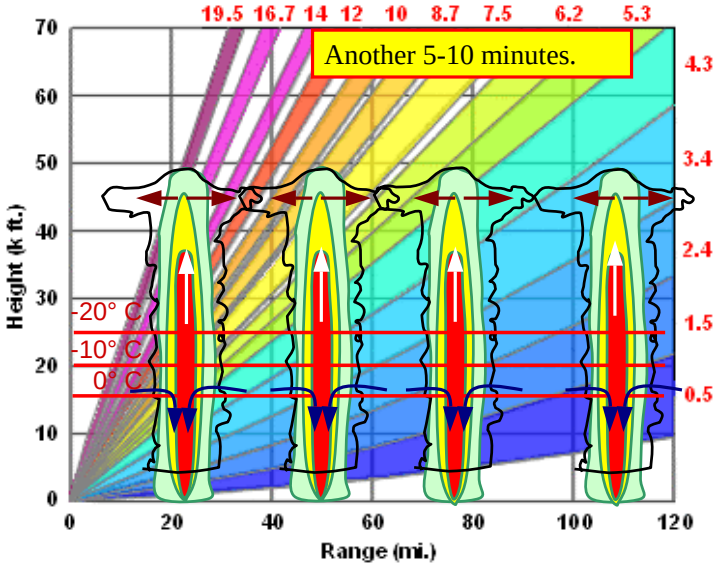


Low-level convergence exists in all cases of initiating Deep, Moist Convection,or DMC for short. Detecting the convergence is problematic because it's so weak. Typically it's on the order of 10^{-3} s^{-1}, or 2 kts of delta-V over a km when DMC initiates. The inflow into a typical pulse storm occurs over a fairly broad depth, and likewise, so is the convergence. When DMC initiates off of an outflow boundary, front or other convergence line, the source convergence is a bit more easy to see and can be more intense. Either way, the depth of the low-level convergence prevents us from detecting it beyond 40-60 nm.

2. Mature phase - reflectivity

Where the core is updraft

- Inside the core where it is colder than –20° C
- Anywhere lower and chances increase it is downdraft

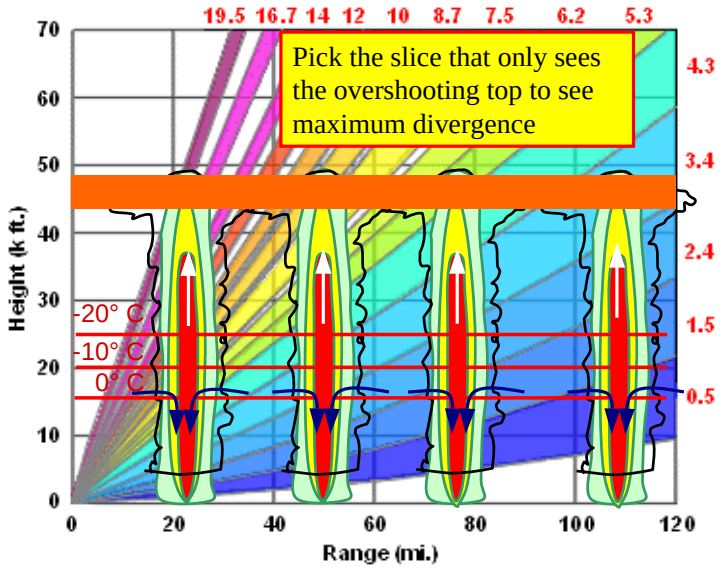


Another 5-10 minutes or 15-20 minutes after first echo, the mature cell's reflectivity core reaches ground with a downdraft. Now, the lower half of the core is occupied by downdraft and the other half, by updraft. In this stage, any intense core above the -20° C level is the most likely part of the core still in updraft. The top part of the downdraft is where midlevel velocity convergence can usually be detected. Anywhere between the significant midlevel convergence and the anvil-level divergence is where updraft would be located here.

2. Mature phase - velocity

Anvil-level divergence

- Occurs in a shallow layer maximized in the overshooting top

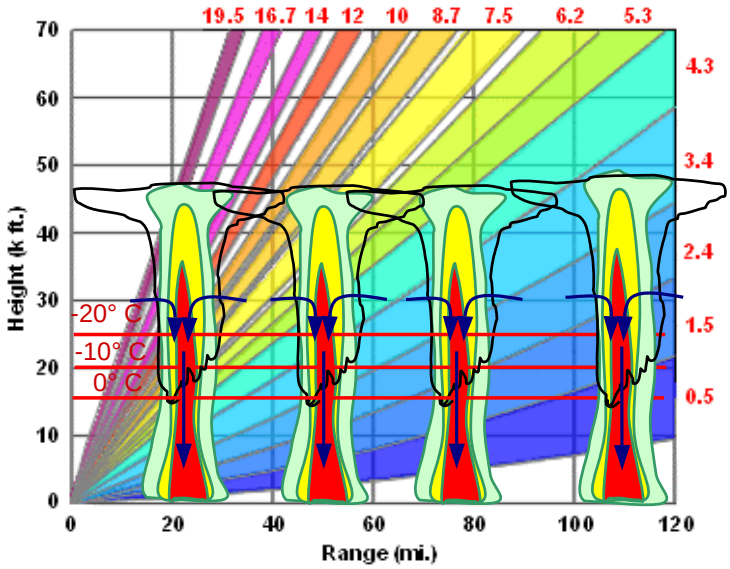


Anvil top divergence is shallow but still should be detected, even though the full magnitude of it may not be. The strongest stormtop divergence may be at the equilibrium level or slightly above. The equilibrium level is not that of the proximity sounding, but that of the storm itself.

3. Decaying phase -reflectivity

Where the core is updraft

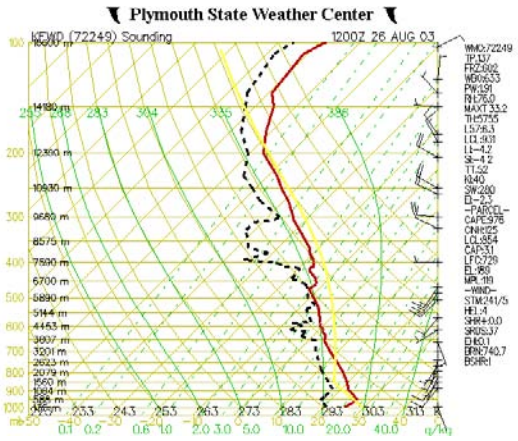
- Very high – just below updraft summit
- Decreasing reflectivities indicate updraft is elevating and weakening



The end cycle of the storm is when the upper-level reflectivities decrease, and the anvil-top divergence dies off. Usually the demise of anvil-top divergence is quite sudden, occuring within a volume scan.

Example 1

- 26 August 2003, FWD
- A weak pulse cell 15 nm from the radar
- Initiation from a cluster of towering cumulus with no analyzed boundary

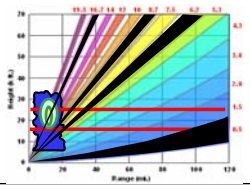


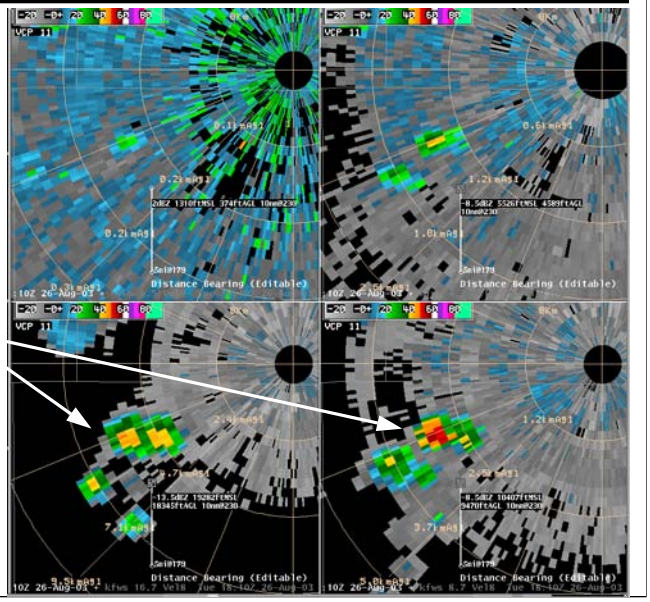
courtesy: http://vortex.plymouth.edu/uacalplt-u.html

Here are several examples taken from a typical low shear pulse thunderstorm day, in this case from the Dallas area. The first cell initiated from a cluster of towering cumulus without any obvious boundary in existence.

Example 1 of TCU phase

- First initiation on 26 Aug 2003 – 1800Z)
- The elevated core at the highest slice (lower left) marks location of updraft
- View slices at freezing and colder (lower 2 panels)



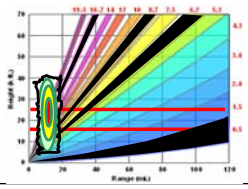


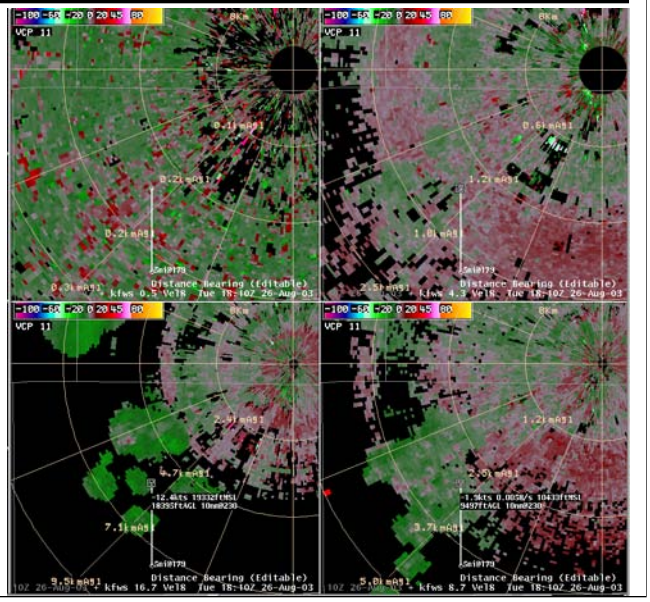
A nearby cell forms showing development of 50 dBZ, a 30 dBZ increase inside of 5 minutes from freezing to nearly –20° C.

For many of these sessions, the VCP chart shows an iconic thunderstorm pointing out its position relative to the radar and its slices. While there are many VCPs being used now, the VCP 11 chart is shown with the displayed slices darkened. The heights of the freezing and –20° C level are displayed as the two horizontal red lines on the chart. I will be emphasizing the heights of echoes, and their significance relative to these two isotherms. In a similar way, this is how the Hail Detection Algorithm works. More of this is discussed in the hail modules.

Example 1 of Initiating CB

- Velocity 5 minutes later
- No well defined convergence/divergence
- Cannot use velocity to infer updraft location here

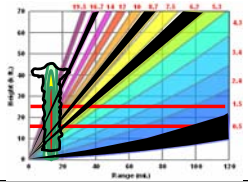


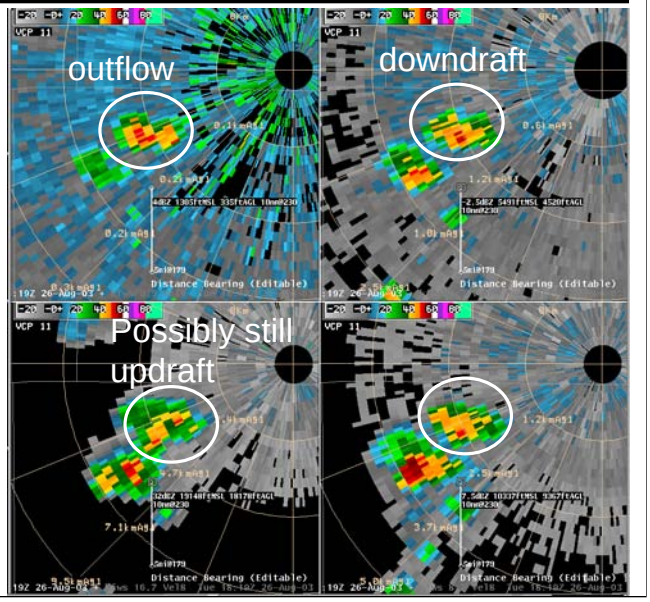


The initiating phase of this pulse storm shows no well defined low-level convergence. First pulse storms often fail to show the velocity convergence you'd think is necessary to compensate for the updraft above the surface. It is there, just very weak.

Example 1 mature stage

- 19 minutes later – 1819 UTC
- Lower core is occupied by downdraft
- Core above –10° C level is most likely updraft

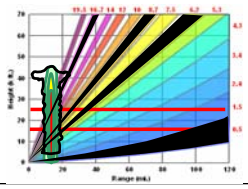


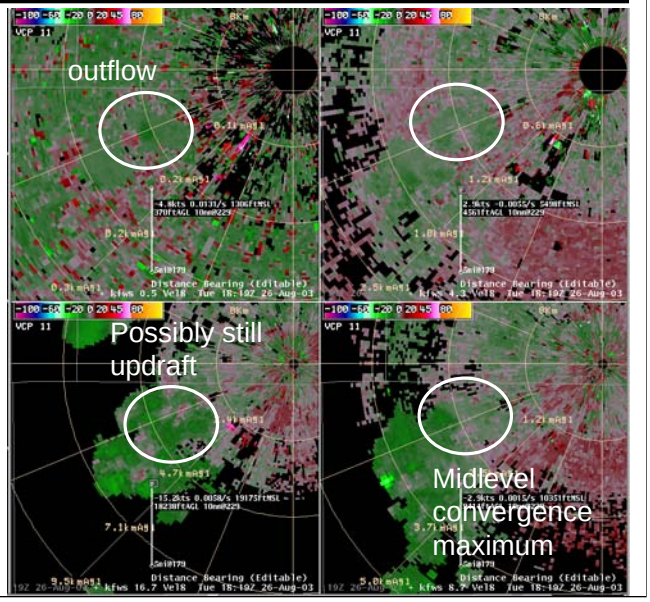


Nineteen minutes after initiation and the core with its downdraft have reached the surface.

Example 1 mature stage

- Velocity, 1819 UTC
- Outflow observed at lowest slice
- Updraft most likely above midlevel convergence maximum

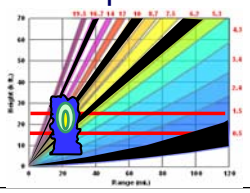


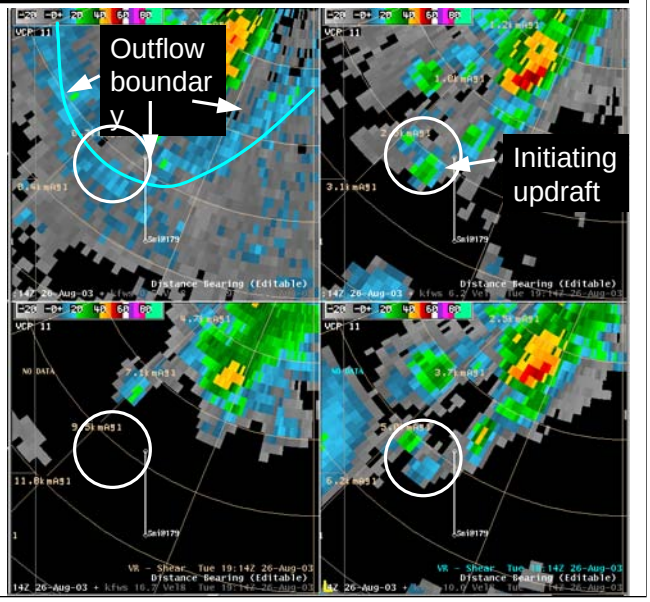


Divergence is visible as the downdraft reaches the ground with the core in the 0.5° slice (upper left). At 8.7°, weak midlevel convergence can be seen (lower right). Anywhere between the midlevel convergence and storm top, updraft is most likely to exist.

Example 2: TCU phase

- On 26 August 2003
- First storm sends out outflow boundary
- This storm initiates as towering cumulus intersects boundary
- More than one initiation point

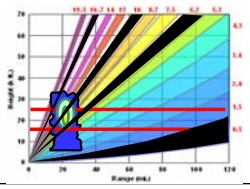


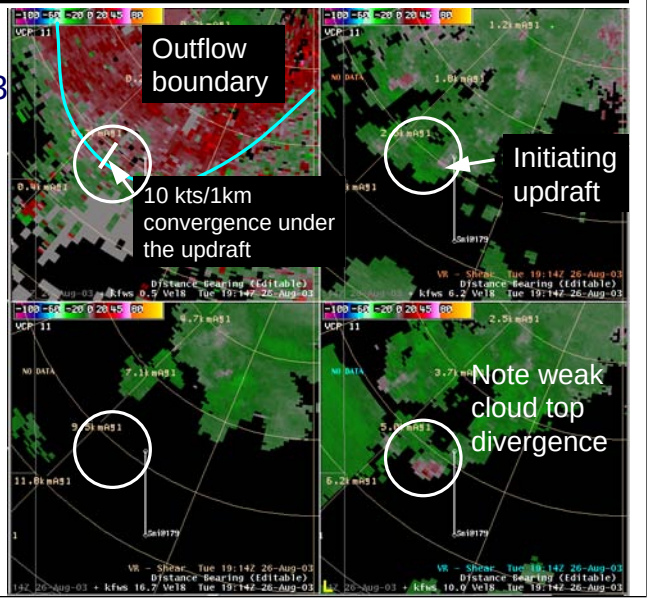


The first couple cells die out and in so doing, they send out a ring of outflow marked by a fineline seen in the 0.5° slice. This ring intersects another cluster of moderate cumulus a little further away from the radar. There are several towering CU that receive a boost of vertical velocity from the outflow boundary and start to develop elevated echoes. Here, the echoes are barely strong enough to be considered precipitation. Precipitation is likely responsible for the echo seen in the upper-right panel because the reflectivity is > than 20 dBZ. The lower-right panel is intersecting the top of the towering cumulus and here, Bragg scattering could be mostly responsible for the echo returns. Incidentally, the fineline echo at the lowest slice is probably a result of a combination of insects and Bragg scattering. Boundaries need a fairly strong density gradient and wind shear to cause Bragg scattering. Any boundary fineline echo over a large body of water is most likely a result of Bragg scattering since insects are typically confined to land.

Example 2: TCU phase

- Convergence = 10 kts over 1 km = .003
- If the same convergence is 1000m deep, the vertical velocity = 3 m/s (6kts) at 1km elevation (cloud base)

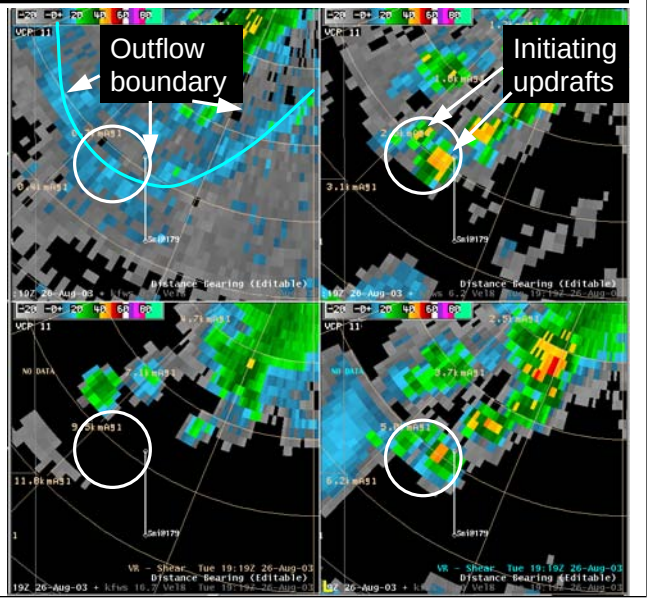


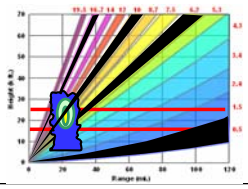


The outflow boundary shows a ΔV of 10 kts over about one km, or calculating out convergence, (ΔV/distance), results in a value of .003. Let's assume that is a mean convergence over 1000m depth. If I apply the continuity equation over that depth (sorry for the technicals), I get an extra 6kts of vertical velocity at 1km to supply to the towering cumulus and its vertical motion. The initiation should be stronger than with the first storm, all things being equal. Indeed, the 10° slice shows some weak but well formed cloud top divergence.

Example 2: TCU phase

- 5 minutes later
- The core is entirely updraft
- 50 dBZ at 5 km AGL ~ -10° C level

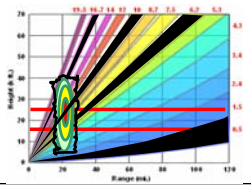


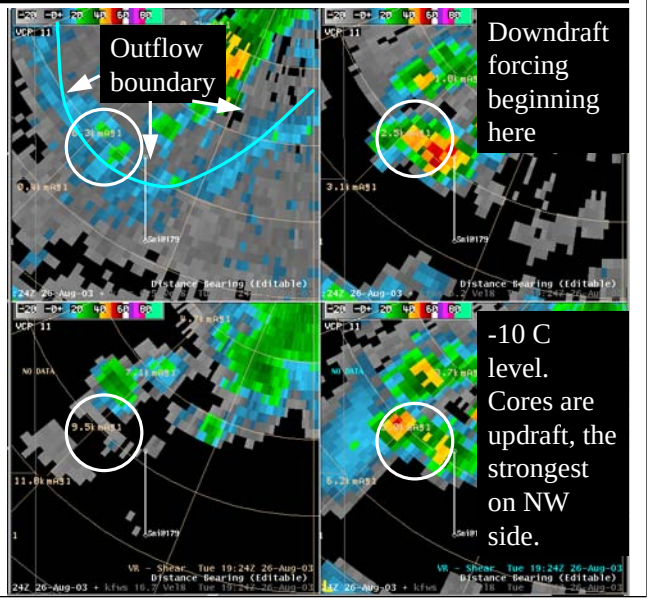


Five minutes later, the initial towering cumulus develop a respectable 45 dBZ echo at -10° C. An echo this strong in the dendrite formation zone probably means there is graupel and snowflakes mixing together and electric charge separation is underway. First lightning is probably going to occur within 5 to 10 minutes of this scan.

Example 2: Initial CB phase

- +10 minutes
- Core descends to the freezing level (upper right panel).
- Descent of core of 55 dBZ suggests downdraft forcing beginning at the freezing level

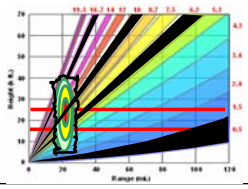


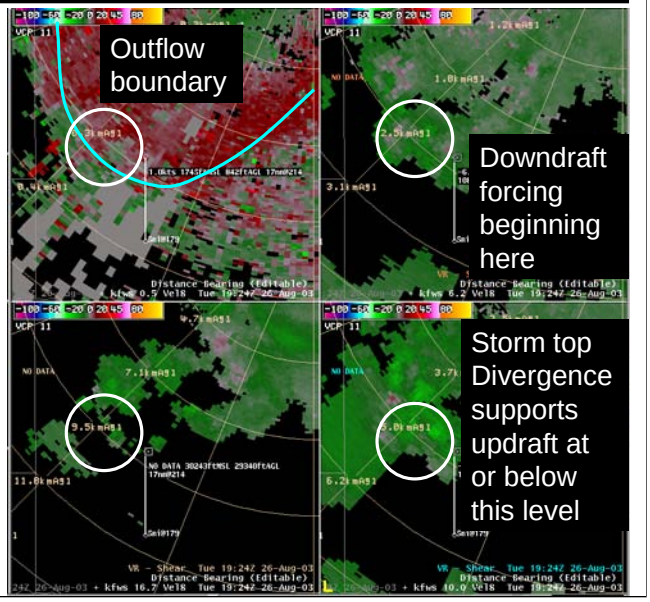


Add another 5 minutes and the core at the -10° C level is still updraft. More intense core is found just above the freezing layer (upper right panel), and it appears strong enough that downdraft may be inferred here.

Example 2: Initial CB phase

- +10 minutes
- The 6.2° slice indicates onset of weak convergence
- Downdraft forcing may be developing here and slowing updraft down within the core

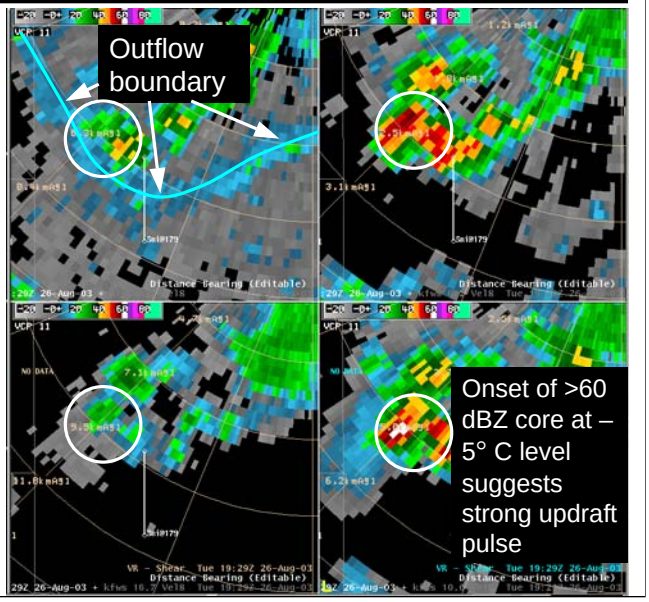


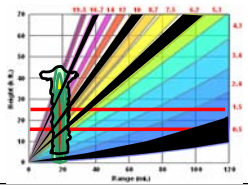


The velocity 4-panel for the same time indicates some weak convergence forming on the right side of the white circle at the 6.2° slice (or 15 kft and 0° C). Note the very weak outbounds in front of the broader inbounds. Downdraft is initiating within the 50 dBZ core. The outflow boundary in the 0.5° slice has not bypassed the storm yet. Updraft is still being forced above this level but below the descending core.

Example 2 of initiating CB

- 15 minutes later
- Increase in core intensity at –5° C level suggests strong updraft at that level

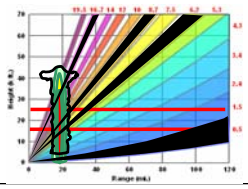


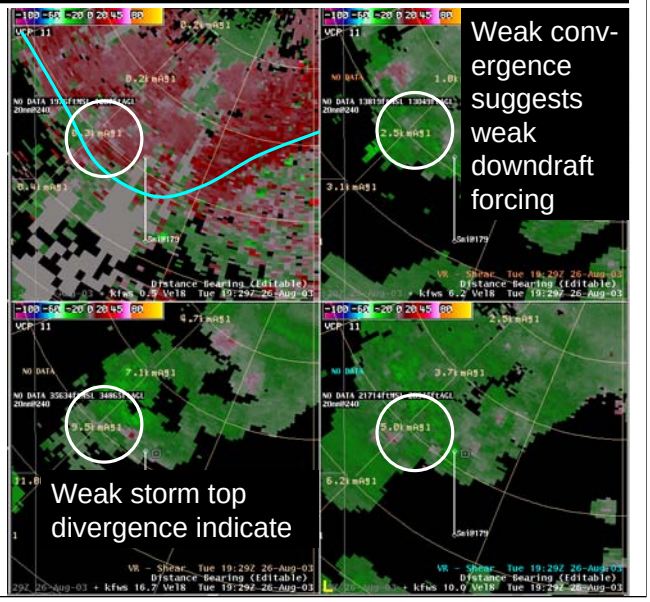


Add another 5 minutes, or 15 minutes after first elevated echo, and the core of the first updraft pulse is reaching ground. Also note that another adjacent towering cumulus has pulsed upward even more strongly and its core reached > 60 dBZ in the 10° slice. Not much echo has reached to the 16.7° slice. But I am guessing the next 2 volume scans will show strong reflectivities to that level.

Example 2 of initiating CB

- 15 minutes later
- Convergence off outflow boundary suggests continued updraft forcing at low levels
- Weak conv at 13 kft suggests weak downdraft forcing

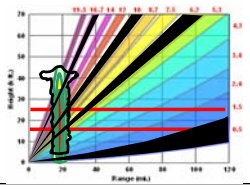


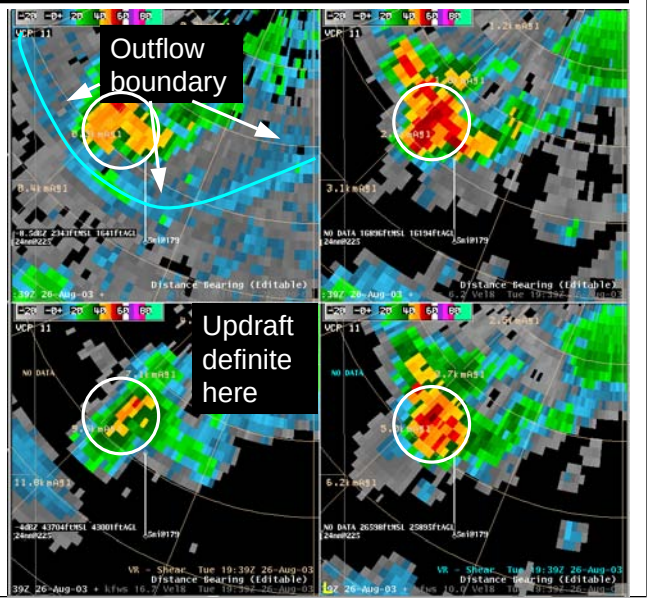


In fact, the storm top is at least at the 16.7° slice level, or 35 kft. There is storm top divergence there. Still weak convergence is visible at 6.2°, or 15 kft. Updraft is likely between 16 and 35 kft, and then above the surface outflow boundary. However, downdraft is coming down and a surface reflection will be visible shortly.

Example 2 mature CB

- Initiation + 25 min
- Updraft inferred at 31 kft slice as 50 dBZ core grows into this level
- Established core at midlevels infer downdraft

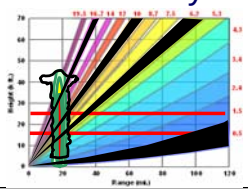


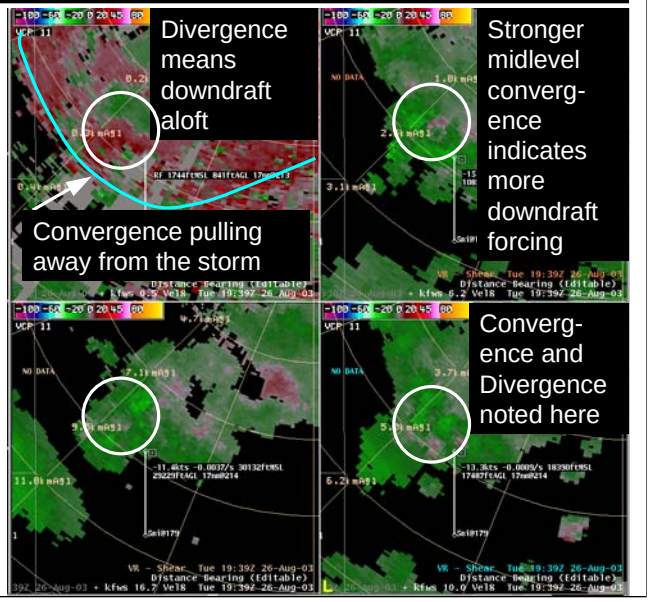


Let's add another 10 minutes so that we're at initiation +25 min. Now there's a solid core with its maximum vertical extent. The 16.7° slice now shows >50 dBZ core, which is most definitely occupied by updraft. I am not so certain that the 10° slice and below are still in updraft. The 6.2° slice is most definitely occupied by downdraft now. Let's take a look at the velocity.

Example 2 mature CB

- Initiation +25 min
- 6.2° convergence and 0.5° divergence infers downdraft from sfc to 13 kft
- 10° shows Conv/Div couplet, updraft and downdraft likely

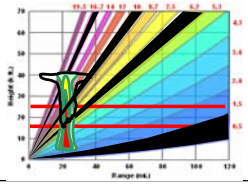


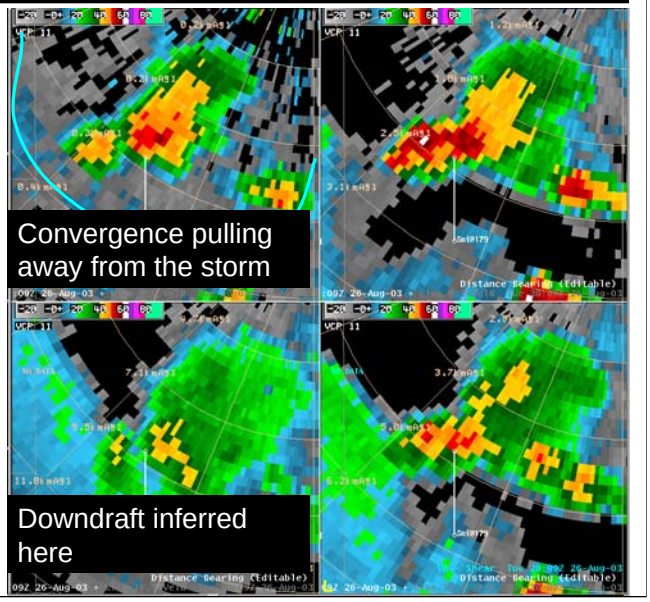


Now there is a divergent velocity couplet at 0.5°. Updraft is most likely sloping back from over the outflow boundary to the front side (southwest) side of the cell towards 6.2° (15 kft). But in the core up to at least 20 kft, downdraft is probably dominant. Certainly the 15 kft level, there is stronger convergence than before within the reflectivity core. A confusing pattern of convergence and divergence, with some shear does not give me much confidence that the core is dominated by either updraft or downdraft. Updraft is most likely above 20 kft within the core itself. The storm top divergence is above the slices depicted here.

Example 2 dissipating CB

- Initiation +50 min
- Several new cores developed but all are now weakening
- 10° (31 kft) shows weakening reflectivities indicating storm collapse

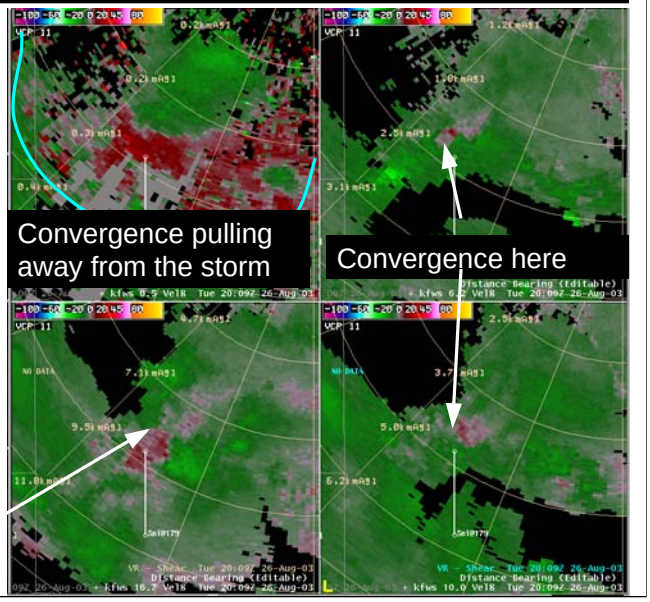




Fifty minutes after initiation, the upper-level core at 36 kft diminishes, a good sign that all is downdraft

Example 2 dissipating CB

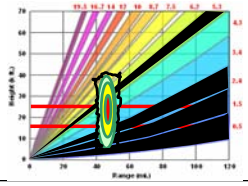
- Initiation +50 min
- Established 0.5° divergence
- Convergence from 6.2 ° (13 kft) to 10° (18 kft) indicates deep downdraft to the surface
- Weakening storm top reflectivity indicates downdraft there too despite weak divergence

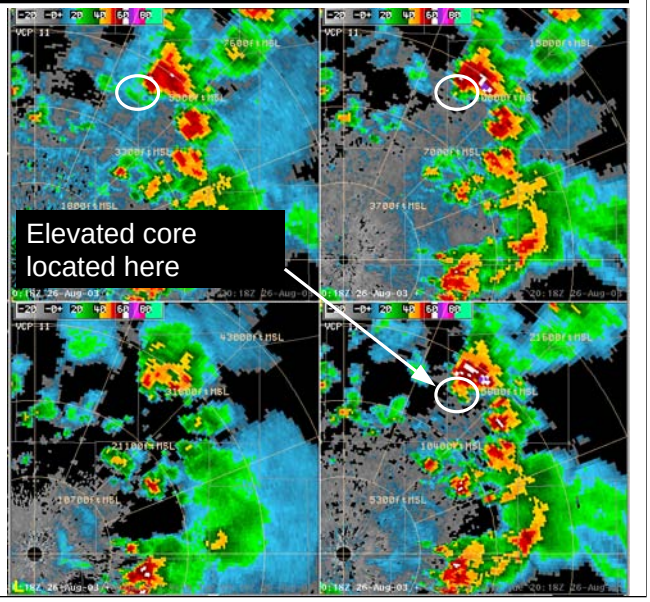


Convergence dominates most of the slices in the middle of the cell. At this stage, it is most likely that there is no updraft anywhere. Divergence is strongest near ground-level, and the outflow has spread wide enough to cut off any more source of lifting from the original outflow boundary.

Example 3 initiating CB

- Initiation +5 min
- Core is growing on the flanks of a larger multicell event

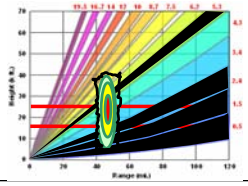


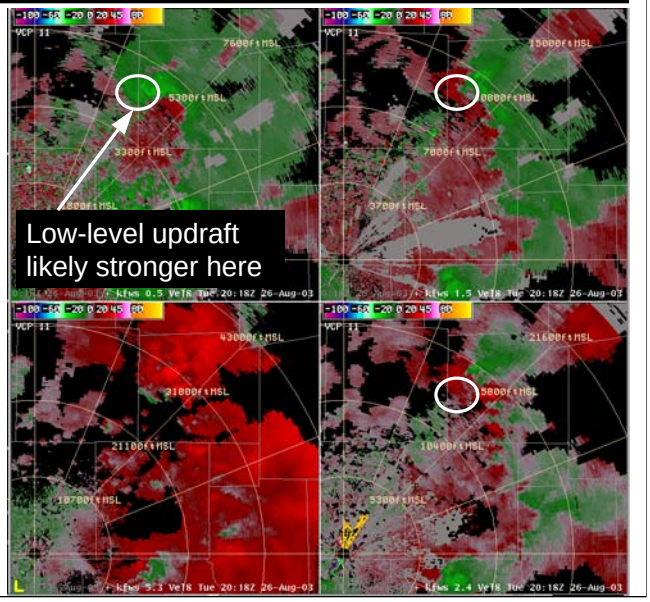


The third example shows a more strongly forced set of cells with the one highlighted inside the white circle. The low-level forcing from this cell comes from a deep outflow boundary sent out by the complex to its northeast.

Example 3 initiating CB

- Initiation +5 min
- New updraft developing on strong outflow convergence
- Low-level updraft boosted by strong convergence

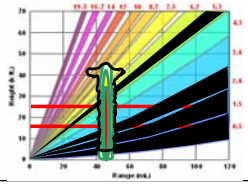


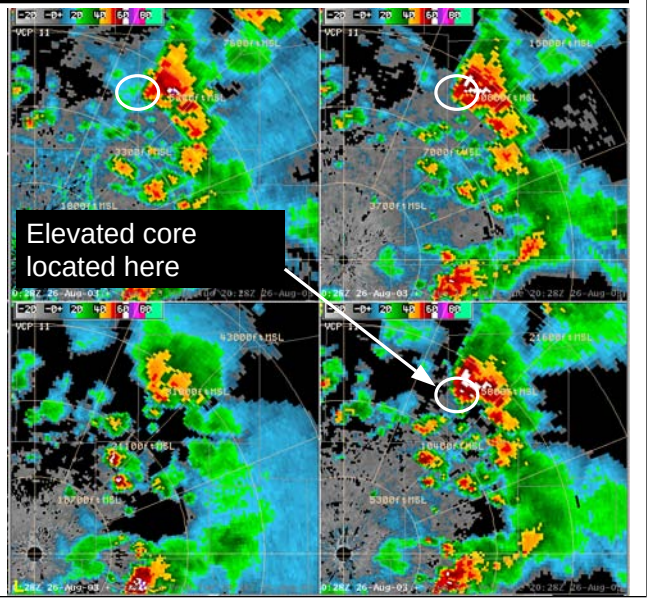


It's impressive to see strong velocity convergence in the 0.5° slice which is nearly 5 kft AGL. Initiation is likely to be strong with favorable consequences throughout its lifecycle.

Example 3 mature CB

- Initiation +15 min
- The core is now becoming the dominant storm

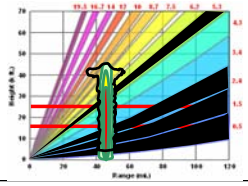


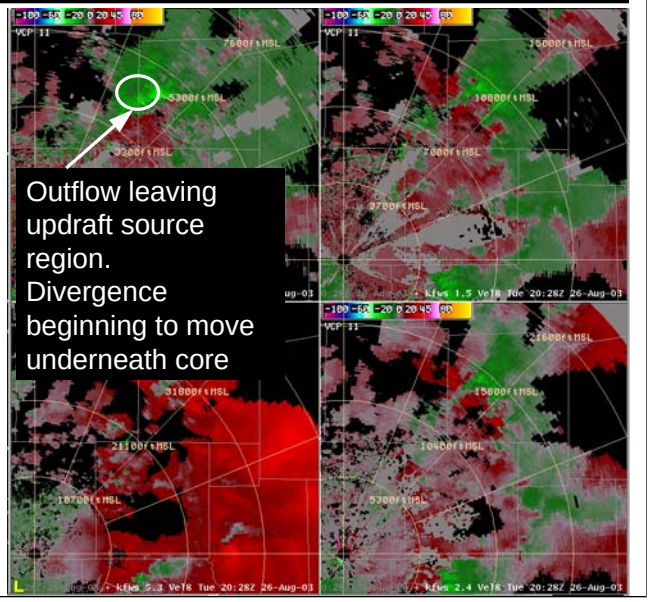


Fifteen minutes after initiation, there is a solid 60 dBZ elevated core at 13 kft AGL (lower right). This new core will become the dominant updraft in this multicell event.

Example 3 mature CB

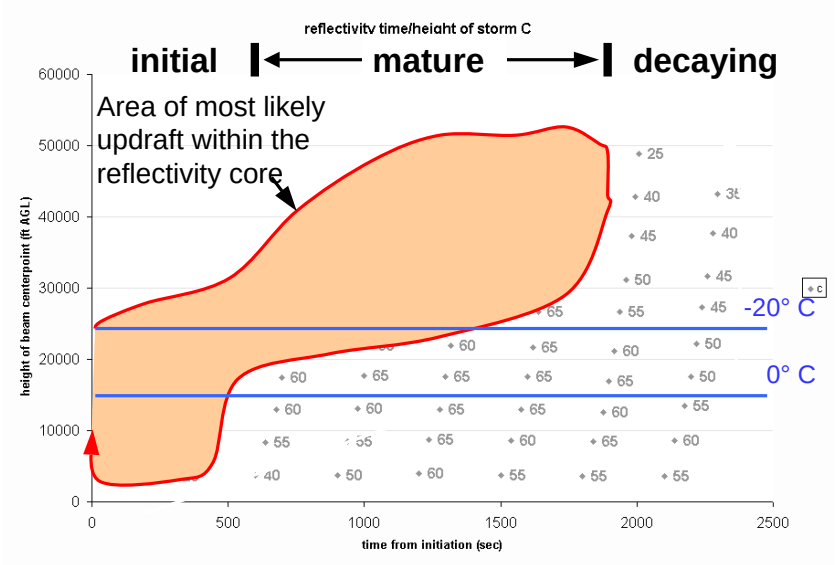
- Initiation +15 min
- New updraft developing on strong outflow convergence
- Low-level updraft boosted by strong convergence





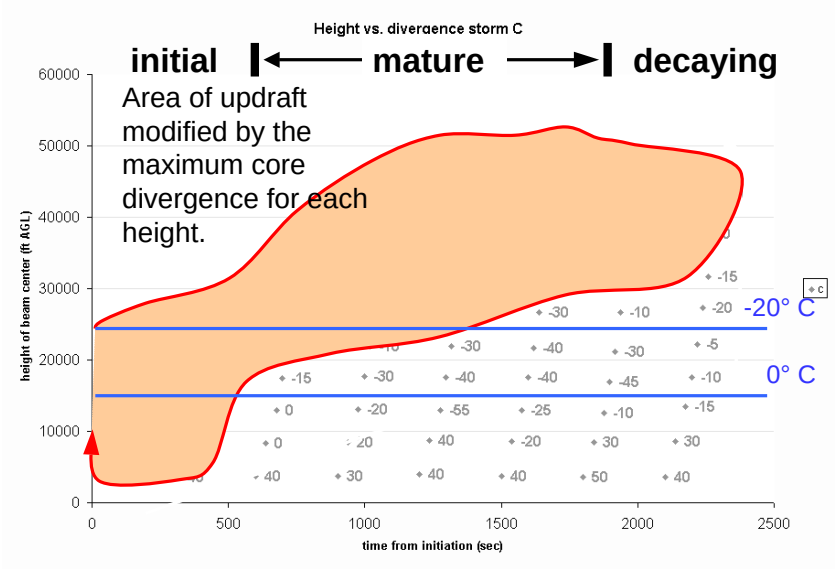
The deep cold pool boundary will soon pass away from this initiating cell but it has not done so yet.

Example 3 time-height reflectivity



A time-height reflectivity profile shows what part of the high reflectivities this cell is most likely occupied by updraft. In the first two volume scans, the updraft is likely occupying everywhere in the core and below. Once the intense core begins to descend, it is likely not occupied by updraft below about 20 kft AGL. However, at the same time, intense updraft, still partially forced by the departing outflow boundary, and buoyancy, continues to lift the upper reaches of the core until 1500 seconds after initiation. The last set of 4-panels was taken about 700 seconds after initiation.

Example 3 time-height velocity



Now we go to the time height cross-section of the maximum convergence/divergence (displayed as maximum ΔV) located within the confines of the 40 dBZ or greater echo. If updraft is likely anywhere above the level of maximum midlevel convergence, then the area of updraft has been modified to show some even after the maximum height of the reflectivity core begins to diminish. However, note that the storm top ΔV, once at 70 kts diminishes even though it's still positive through this figure.

Summary: Pulse storm updraft location

- Reflectivity
  - Updraft is colocated with cores at these locations
    - Under and within new elevate cores
    - Within the top of strong growing echoes (e.g., top of the 55 dBZ echo)
    - In growing strong echoes at temperatures < -10° C
  - Updraft is not colocated with these cores
    - descending high reflectivity cores
    - High reflectivity cores (growing or not) at temperatures > -10° C

Summarizing, Reflectivity

Updraft is colocated with cores at these locations

Under and within new elevate cores

Within the top of strong growing echoes (e.g., top of the 55 dBZ echo)

In growing strong echoes at temperatures < -10° C (this height rises though, in the late lifecycle of a pulse storm)

Updraft is not colocated with these cores

descending high reflectivity cores

High reflectivity cores (growing or not) at temperatures > -10° C

Summary: Pulse storm updraft location

- Velocity
  - Updraft is located
    - Above the zone of maximum low-level convergence in a developing storm
      - Low-level convergence difficult to spot without gustfronts
    - Between the maximum midlevel convergence and anvil-level divergence in a mature storm
    - From the low-level gustfront convergence sloped to the core's periphery at midlevels for a mature storm

Velocity

Updraft is located (Remember this is most likely located)

Above the zone of maximum low-level convergence in a developing storm

Low-level convergence difficult to spot without gustfronts

Between the maximum midlevel convergence and anvil-level divergence in a mature storm

From the low-level gustfront convergence sloped to the core's periphery at midlevels for a mature storm

For all of these pieces of evidence, none of them are direct measurements of vertical velocity. Also, as a cold pool

spreads out from its axis upon the core reaching the ground, updrafts may grow on a preferred flank of the parent cell,

resulting in a sloped updraft appearance. It is too simplistic really to show a time height diagram of maximum reflectivity and

convergence and say specifically that the entire core is either updraft or downdraft. The flanks of a midlevel core can certainly

be occupied by updraft while its center, downdraft. This is certainly true during the mature stages of a cell. Within the core, what

I can say is that it is likely the core is dominated by either updraft or downdraft.

Storm Interrogation

AWOC Severe Track

IC 3-I-B: Updraft location in a sheared convective cell

Storm Interrogation – Updraft location in a sheared convective cell

This lesson is 16 slides long and may take 15 minutes to complete.

Sheared storm updraft shape and location

- Objective: Determine where and what shape the updraft is in a sheared convective cell
  - Specifically, locate the part of the Weak Echo Region occupied by updraft
  - How to determine if a WER exists in fast moving storm

This module builds on the one in which we determine the location of updrafts in pulse storms. Locating the updraft in sheared storms is something that is frequently done by warning forecasters. In this session, we show a methodology that may help your skills in discriminating the updraft size and shape at different altitudes. In addition, we discuss what a real echo overhang and underlying weak echo region is from that which is artificially generated by the volume scan with a moving storm.

Then we show a case emphasizing where in a weak echo region may lie the main updraft of a sheared cell.

Sheared storm updraft shape and location

- Motivation
  - Greatest severe weather potential adjacent to updraft/downdraft interface
  - Inform spotters of updraft location
  - Size matters for hail severity, rainfall

Why locate an updraft? For one, the updraft is the 'business end' of a sheared severe storm, or in other words, the end of the storm where most of the severe weather is likely to be adjacent or within. Also, determining which side of a reflectivity core lies an updraft gives you information on the structure and morphology of the cell (e.g., whether the severe weather will be most likely ahead or behind most of the precipitation). Giving information to the spotters on the updraft nature of the storm may allow them to better position themselves to report what's there. It is not only the location of the updraft, but its shape that's also important. As an example, for hail size, the size of the updraft is important, as is its shape. Is the updraft elongated in such a way to maximize residence time for growing embryos? This kind of question makes knowing the shape of an updraft as important as anything else if you want to improve your skills over that of the algorithms.

Sheared storm updraft shape and location

- Less dependent on point in storm lifecycle because
  - updraft lasts longer than the transit time of air parcels from base to top of the convective layer

What we mean by a sheared cell is one whose updraft is experiencing vertical wind shear of such a degree that

the updraft persists longer than any individual parcel resides in the updraft. The storm is persistent, and more steady

state than a typical pulse cell, and includes supercells, and persistent updrafts even if there is no significant mesocyclone.

Low-shear cell updrafts (pulse storms) exhibit an updraft that's more akin to an explosion than that of a chimney flue.

In an explosion, there is almost no steady state draft. The updraft rises as a bubble with no follow through parcels.

Contrast that to a high shear cell (including supercells), where the updraft is more analogous to a chimney flue or a

plume where the updraft persists longer than any individual air parcel. This allows features such as echo overhangs

to persist longer than the time allowed for the hydrometeors to fall from high altitudes, and therefore be identified

with strong, persistent updraft plumes.

Sheared storm updraft shape and location

- Low-level updraft definition
  - Is near the sharp reflectivity gradient facing storm-relative inflow at updraft base
  - Over and in the inflow notch or concave regions of sharp reflectivity gradient
  - Somewhere within the WER.
  - Updraft will be above region of low-level convergence
  - When present, low Spectrum Width values helps define updraft
  - Mesocyclone*

We break updraft signatures in radar to those that occur at low-levels, say warmer than -10° C, and those that occur at colder temperatures.

The kinematic signatures may not be so dependent on actual temperature as they are on height relative to the ground and the equilibrium level.

As you look at all the signatures, here are some things to consider:

Preferentially sharp reflectivity gradient, concave regions, and inflow notches are the most range-independent updraft signatures. Even at far ranges with broad beam widths, these features tend to stand out in varying degrees. It's no surprise that the sharp reflectivity gradient is a deep feature. It stands at the interface between up and downdrafts anywhere from the midlevels and down. The concave region embedded in the enhanced reflectivity gradient is either the region of enhanced low-level inflow, or simply reflectivity core partially surrounding a midlevel updraft.

The WER is also quite range independent provided the lowest beam intersects the storm lower than around the -10° C level. Above that level, and you stand to just sample the core embedded in updraft at upper-levels. Any Bounded Weak Echo Region at that distance is unlikely to be detected as will be seen later.

Low-level convergence signatures can be detected at farther ranges than for typical pulse cells for some of the more severe sheared cells. Deep convergence zones are discussed in more detail in another module. However, this signature fails to be reliably detectable as far as the reflectivity-based signatures above.

Low spectrum width values sometimes occur within the core of updrafts. If an updraft is much larger than the individual beams sampling it, and it has a core of undiluted ascent inside its turbulent borders, and its presence is not obscured by a three body scatter spike, there is a chance of this feature being visible. Undiluted updrafts are typically free of turbulence which may explain the low spectrum widths.

One final signature I failed to note is the presence of a mesocyclone. Mature mesocyclones are split between updraft and downdraft in the lower half of supercells. Be sure to pick the inflow half.

Sheared storm updraft shape and location

- Upper-level updraft definition
  - Partly occupies the echo overhang > 45 dBZ
  - Intense core below the -15° C level is likely occupied by updraft
  - The BWER pinpoints the updraft when present

  - Below storm top divergence center
  - On the inflow side of deep convergence zones
  - In areas of low spectrum width that are colocated with the signatures above
  - Mesocyclone*

Reflectivity signatures colder than -10° to -15° C are a little different. than the lower level counterparts. Instead of the WER, you look for the echo overhang, although one depends on the other for its existence. Intense elevated cores is one feature that is ubiquitious to low and high shear cells. It is also the most range independent feature of all the updraft features; the only twist being that it's the first to fail owing to

cone of silence issues. That is one reason to pick an alternative radar to examine near range storms. The BWER is the most range limited upper-level reflectivity updraft signature. We will show how range limited this feature is owing to its small size.

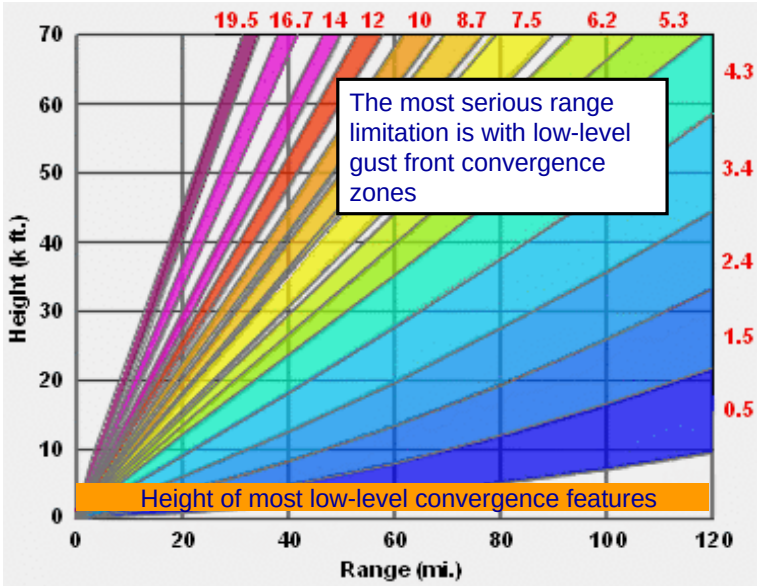
Velocity signatures in upper-levels for updrafts concentrate near the equilibrium level of a particular cell through its anvil-level divergence values. Consider that the center of divergence need not necessarily be the location of the zero isodop. It is the center of maximum divergence or ΔV. Deep convergence zones are rare that they reach well into subfreezing air. However, some of the most damaging HP supercells will have these extending to altitudes > 20 kft or -10° C. Remember that a deep convergence zone is only deep relative to the storm top for which it resides. However, the maximum detection range is absolute. That means a shallow topped storm with a deep convergence zone may be just as significant as its tall storm counterpart but the radar range limitations are much more significant.

Low spectrum width in upper-reaches of an updraft are probably harder to come by because of the proliferation of large hydrometeors occupying its core.

The real confidence of locating the updraft increases when more of these signatures become colocated, both in lower and upper regions of a sheared cell.

At upper-levels, most mesocyclones should be occupied by updraft. However, that may not be the case, and picking the threshold at which a downdraft partly occupies a mesocyclone to a level in which it doesn't may be extending our detection ability beyond reason. Therefore, I will say that use the mesocyclone to help confirm other updraft signatures.

Sheared storm updraft shape and location

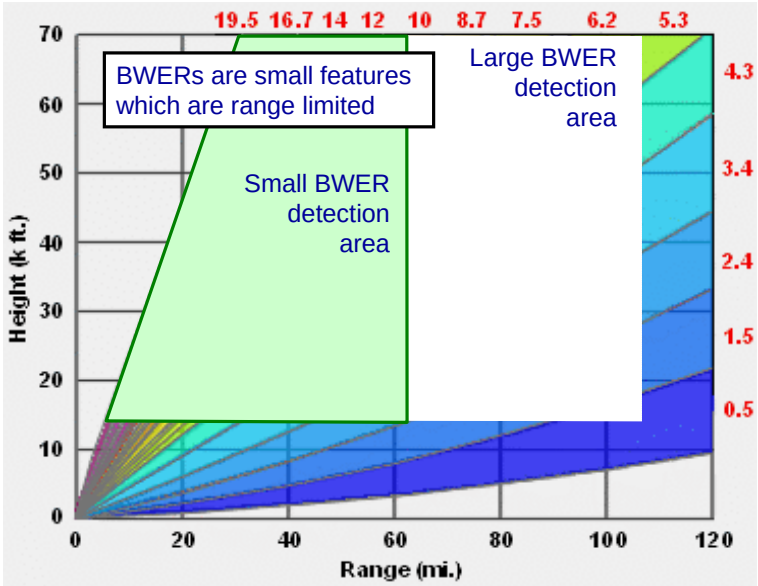


Here is an illustration of the range limitations for most low-level convergence signatures that can help you isolate updraft

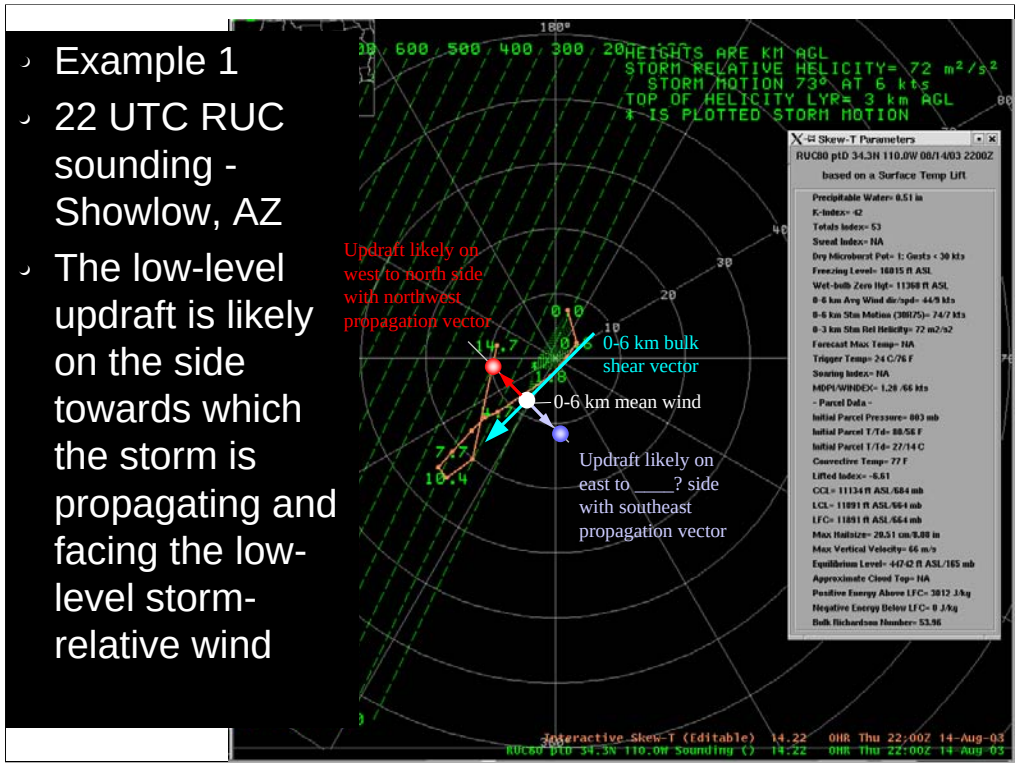
regions. Most convergence signatures are less than 6000' deep. If there is no deep convergence zone, then this signature

fails to provide any information beyond about 60 nm range.

Sheared storm updraft shape and location

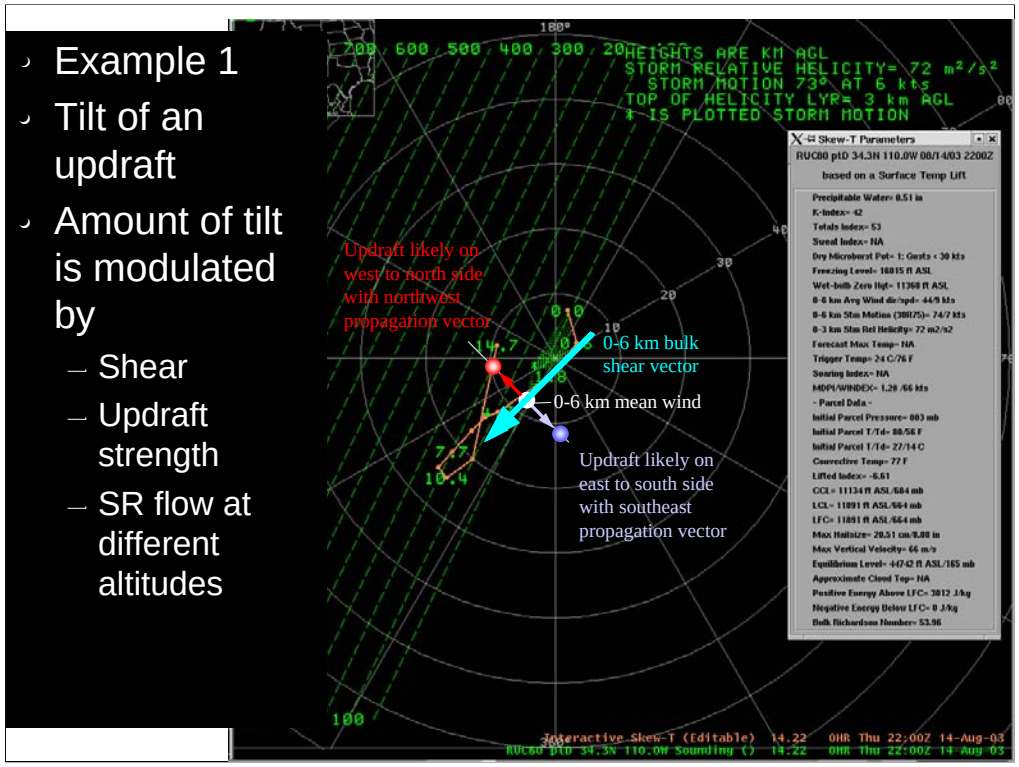


BWER detection is also highly range limited. Most BWERs become undetectable beyond 80 nm. Even the larger ones (longest dimension=5mi) are undetectable much beyond 90 mi. Thus, this figure is being very generous. As a note, small BWERs are anything about 2mi and less in its longest dimension. Note the inner range limitation. Do you have an alternative radar that can detect a BWER straight overhead?



Let's use an example to apply all the signatures we see to an interesting case of a strong easterly wave passing through Arizona as part of a monsoon event. The skewt is from the 80 km RUC at 22 UTC for Showlow, AZ. It is pretty representative of the environment on this day. This event is analogous to the typical springtime severe storm events east of the Rockies in which an elevated mixed layer is advected off the high terrain to supply regions with high lapse rates and large CAPEs, only in this case, the easterlies are advecting the mixed layer westward.

Zooming in on the hodograph, there is more than adequate shear for supercells with a 0-6 km shear of 25 m/s. Applying the ID method to derive storm motion, a right-mover (left-mover) should move straight west (south) at 10 (13) m/s. A right-mover (left-mover) would experience low-level Storm-Relative (SR) flow from the west (south). Somewhere on that face should lie the updraft base. For a right-mover, that is from the west to north. How about the left mover?

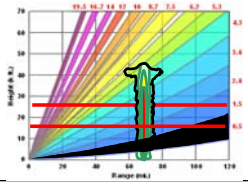


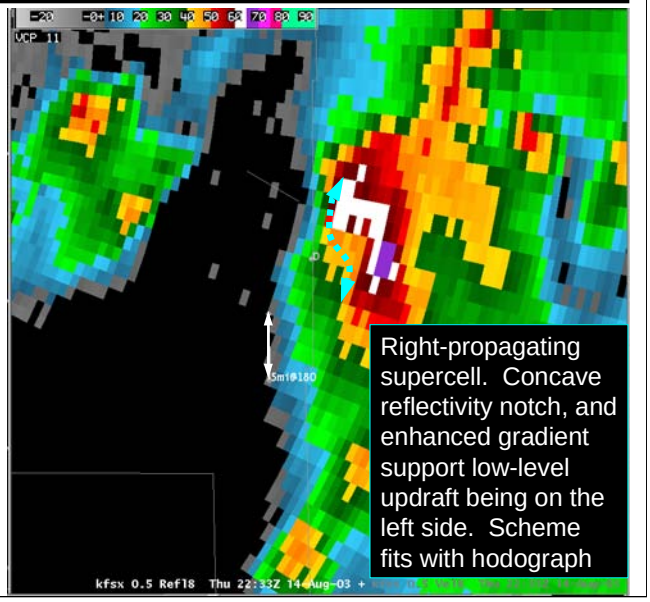
Given the orientation of the shear vector, the SR flow and its strength should give us an idea of its tilt. Both updrafts will tend to tilt toward the arrow head of the shear vector if the storms are moving off the hodograph. If a storm is moving along with the hodograph, its tilt will be directly down the shear vector.

An answer to the question on the previous page, note that the low-level updraft for the left mover is most likely to be on its east to south side.

Sheared updraft shape and location

- Example 1
  - Midrange Reflectivity considerat-ions
  - Lowest slice loop





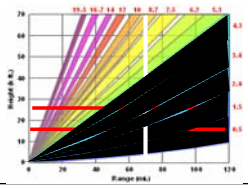
Right-propagating supercell. Concave reflectivity notch, and enhanced gradient support low-level updraft being on the left side. Scheme fits with hodograph

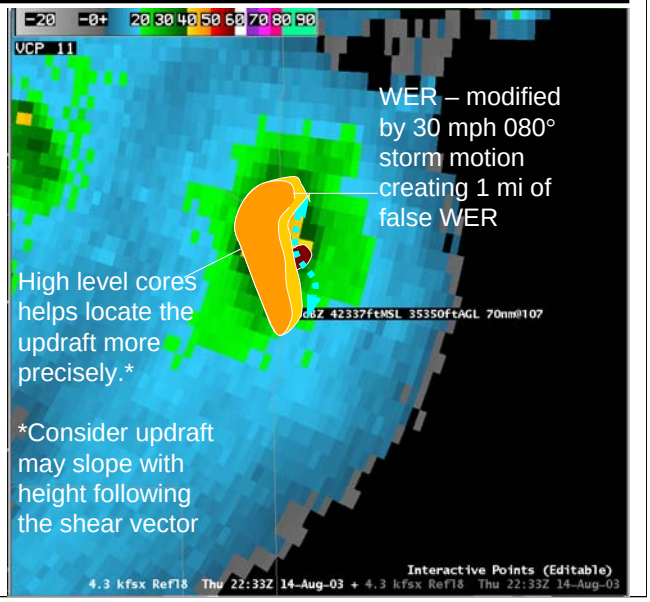
Here is a short time loop for one of the right-moving supercells on the Mogillon rim near ShowLow, AZ. The distance from the radar means that we may have difficulty viewing some low-level signatures and the BWER. The lowest scan is near 7000' AGL.

You can see that as this loop is stepped forward in time, the cell is moving westward. The concave reflectivity notch and enhanced gradient suggests the updraft is west of the core and leading it.

Sheared updraft shape and location

- Example 1
  - Midrange reflectivity considerat-ions
  - All-tilts





In this example, we discriminate the updraft area by applying the reflectivity signatures for low and high levels that we listed. At the lowest slice, this storm exhibits locally enhanced reflectivity gradient in a concave shape on its western side. We'll highlight it with a blue dashed line

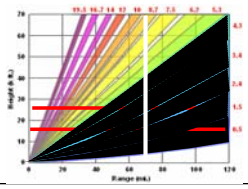
Advancing upward by two slices, we reach the intense echo overhang around 20 kft, or about -10° C. However, because the updraft is preceding the main core of this supercell, and because the supercell is moving westward at 30mph, the supercell echo overhang advanced forward approximately one mile in the time the radar took to reach this altitude. The effect is an spuriously large WER. We will shave about one mile off the width of the WER, still leaving a significantly large real WER.

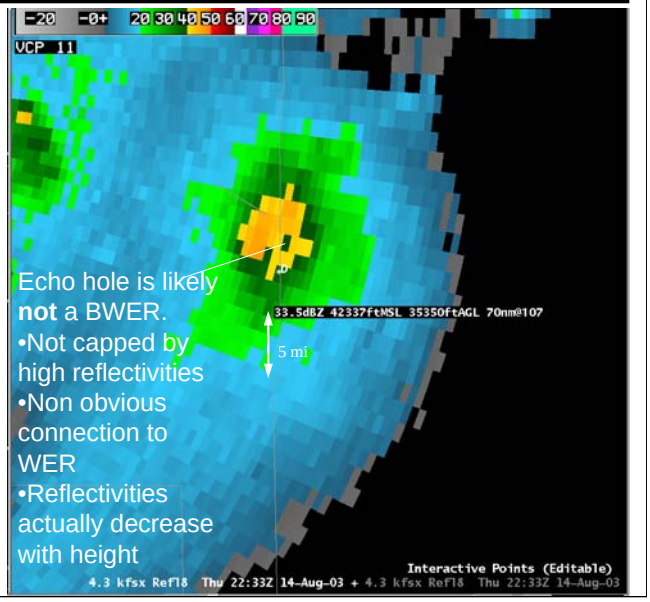
Going upward in height above the -20° C level means the actual reflectivity core is more likely in updraft. The highest slice is fairly near the storm top and here we mark it as updraft.

Note that the highest two slices have a weak echo hole. Is this a BWER? A BWER associated with a core of extremely strong updraft should be connected to the WER below and extend upward underneath the overshooting top. Reflectivities should begin as low as the WER within the lower parts of the BWER, and then gradually increase as hydrometeor production and entrainment commences. High reflectivities in the storm summit should cap off the top of the BWER, although in some cases, the BWER may extend very close to the storm summit. We'll consider whether this is a BWER in the next page.

Sheared updraft shape and location

- Example 1
- Is the echo hole a BWER?



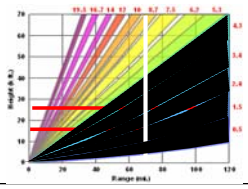


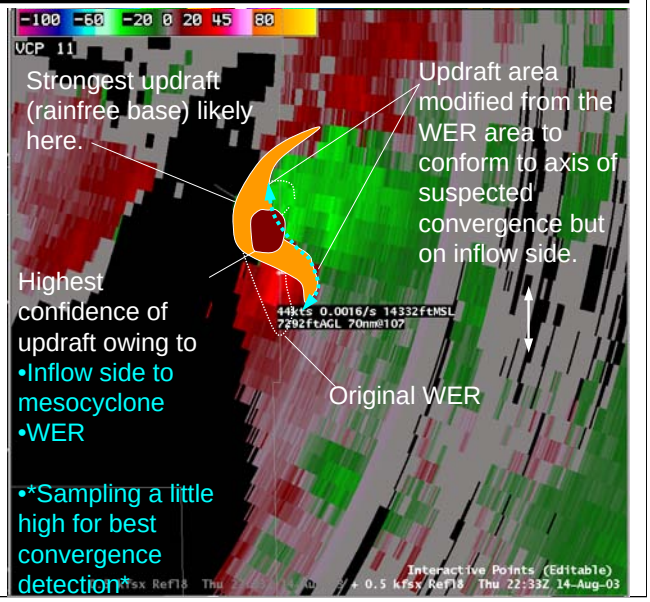
This echo hole is not capped by very high reflectivities. The reflectivities decrease with height, and there's no obvious connection with the WER.

These are three strikes against calling this feature a BWER associated with intense updraft. Most likely, the updraft is northwest of this echo hole and the BWER is really a weak echo region between two main updrafts. This would explain why reflectivities decrease with height.

Sheared updraft shape and location

- Example 1
  - Velocity considerat-ions
  - Low-levels (7200ft AGL)



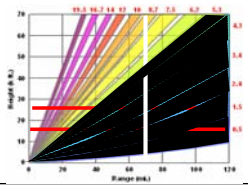


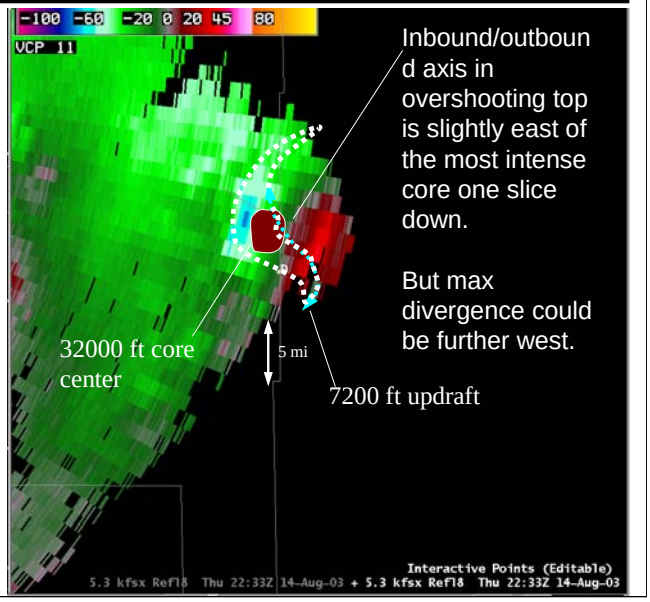
We're not done discriminating updraft region yet until we look at volumetric velocity. Starting where we left off with the reflectivity, adding the lowest velocity scan shows a classic mesocyclone with almost pure rotation. However, there is evidence of strong convergence on its northern flank, due west of the Rear Flank Downdraft and marked by the orange overlay.

Care must be taken not to confuse the decrease in radial velocity where outbound goes to inbound with increasing range with that of onvergence. If you have a pure rotational velocity couplet, you will see radial velocities decrease with increasing range. The convergent signatures should show more abrupt velocity gradients than that associated with pure circulation.

Sheared updraft shape and location

- Example 1
  - Velocity considerat-ions
  - high-levels (4400ft AGL)





Going up in altitude to storm summit, the strongest divergence is located a little west of the zero isodop. Therefore, the upper-level updraft is most likely in the location marked by the rough circle.

Putting all the pieces of evidence together, this storm has a low-level updraft roughly paralleling the gustfront, coinciding with the inflow portion of the mesocyclone, and then and upper-level updraft where the strongest storm summit divergence is located. Coincidentally, the storm summit divergence overlies the strongest portion of upper-level reflectivity core.

Summary: Sheared storm Updraft location

- Low-levels
  - Facing low-level SR flow side
  - Tight reflectivity gradient
  - Concave shape reflectivity gradient
  - Enhanced velocity convergence
  - WER
- High levels
  - Intense echo overhang (>45 dBZ)
  - On inflow side to mesocyclone
  - Storm summit divergence and echo center
  - BWER core
  - Low spectrum width

To summarize, the updraft location in a sheared storm is more likely than not to tilt with height. Therefore, look for reflectivity and velocity signatures at both low and high altitudes to gain a better understanding of the nature of particular storm's tilt.

At low-levels, you want to look for the updraft on the side roughly facing the low-level storm-relative inflow where there is a tight reflectivity gradient, preferably in a concave shape. You should see enhanced velocity convergence if your lower slices are below 4 to 5000 feet AGL. This area may lie in a weak echo region capped by intense reflectivity overhang. Recall that the echo overhang is not entirely occupied by low-level updraft. But the coincidence of more pieces of evidence at any point, does lead to higher confidence that the echo overhang is updraft.

At higher levels, the intense echo overhang, below an upper-level reflectivity maxima, under the region of strongest storm summit divergence gives you most of what you need to call the area an updraft. Your confidence increases if this area is in a BWER overlaid by high reflectivities, and in the vicinity of a mesocyclone. Remember that mature mesocyclones are partially occupied by rear flank downdraft, even at high altitudes.

Storm Interrogation

AWOC severe track

IC 3-I-C

The nature of the Weak Echo Region

AWOC severe track IC 3-I-C : The nature of the Weak Echo Region (WER)

This lesson is 11 slides long and will take 15 minutes to complete. This is a special session featuring Les Lemon as a guest in conversation with Jim LaDue.

The nature of the WER

- Objective:
  - Understand the characteristics of a WER
    - Specifically, determine the relationship between the WER and the updraft shape and location
- Motivation: The WER is a critical feature for
  - Determining updraft location
  - Estimating updraft severity

The Weak Echo Region is a storm signature commonly used to assess the severity of and to locate a convective updraft. But exploring the nature of the WER is the objective to be satisfied in this lesson. And specifically, what is the updraft shape and location with respect to the WER?

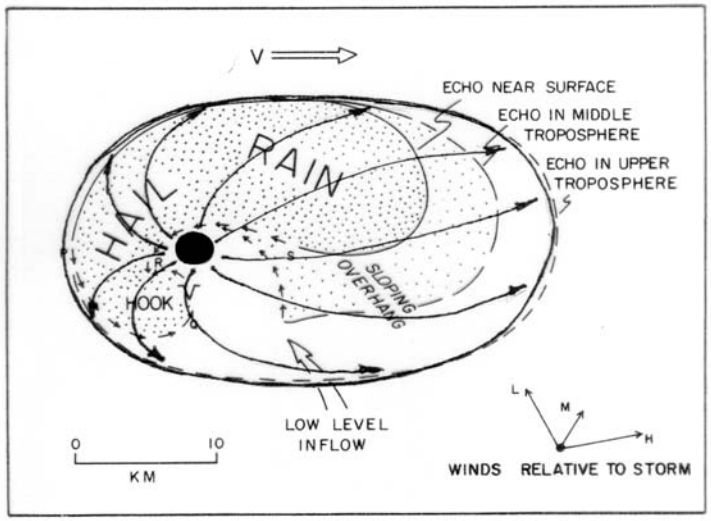


Figure 15.5. Schematic diagram showing horizontal sections at three levels through the radar echo from an SR Storm supercell (equivalent reflectivity factor about 10^3 mm^6 m^{-3}). The heavy black spot marks the position of the highest echo top and also the position of the vault at lower levels. Environmental winds relative to the storm in low, medium, and high levels of the troposphere are represented by the three vectors L, M, and H. When a tornado occurs, it is situated near the leading edge of the hook echo; hail falls from the echo surrounding the vault, and sometimes but not always below the hook itself, and the rain area extends ahead of this region within the storm's left forward quadrant.

This is a paraphrased version of the recordings in this talk and therefore captures the intent but not every word of the conversation.

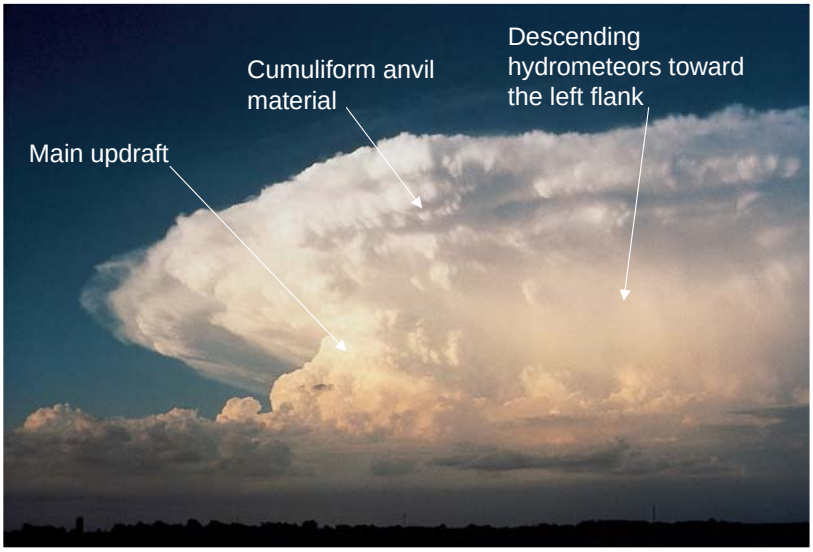
Jim: Les, How does this graphic help explain where the Weak Echo Region (WER) occurs?

Les: This is an old graphic from Browning (1964) but it illustrates the structure of the WER in showing the echo in the Upper, mid and lower troposphere and he called the echo overhang the sloping echo overhang because all winds are approaching the right flank of the storm thus the echo overhang cannot be explained by the ambient wind field. The precipitation in the echo overhang has to arrive in that position by vertical shear.

Jim: When I overlay the streamlines onto Browning's model, I see an awful lot of divergence. How strong is that divergence?

Les: It is not often appreciated how much mass is being transported upward in an updraft. The velocity difference across an updraft summit of roughly 20 km can be as high as 150 m/s (300kts). That large amount of divergence brings with it a high density of precipitation that goes on to form an echo overhang. The precipitation as it descends in the echo overhang is swept along by the storm-relative flow as it falls eventually forming a sloping echo overhang. The precipitation finally descends to the surface to form the edge of the low level echo.

The physical appearance of the WER

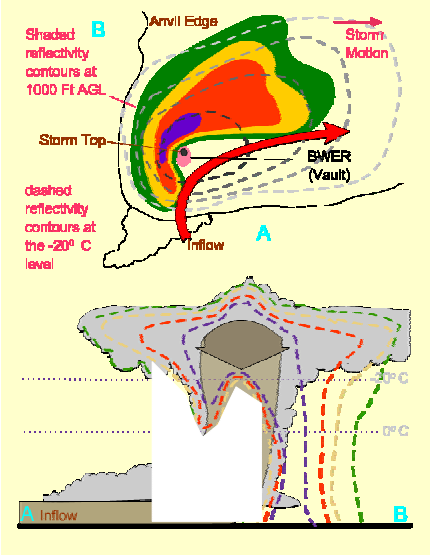


Jim: Here is a classic picture of a supercell from the distant southeast. Strong anvil-layer flow is coming in from the left and still the supercell is able to push a lot of anvil material upwind of its updraft. From this picture, Les, where would the WER be?

Les: You can actually see the WER in that you can see the cumuliform anvil (upside down convective bulges). The main updraft is located under the anvil and the foggy area right of the updraft tower is the descending precipitation that marks the sloping echo overhang. The highest reflectivities in the echo overhang are in the cumuliform anvil and then they slowly decrease as the hydrometeors descend and move toward the left flank of the storm.

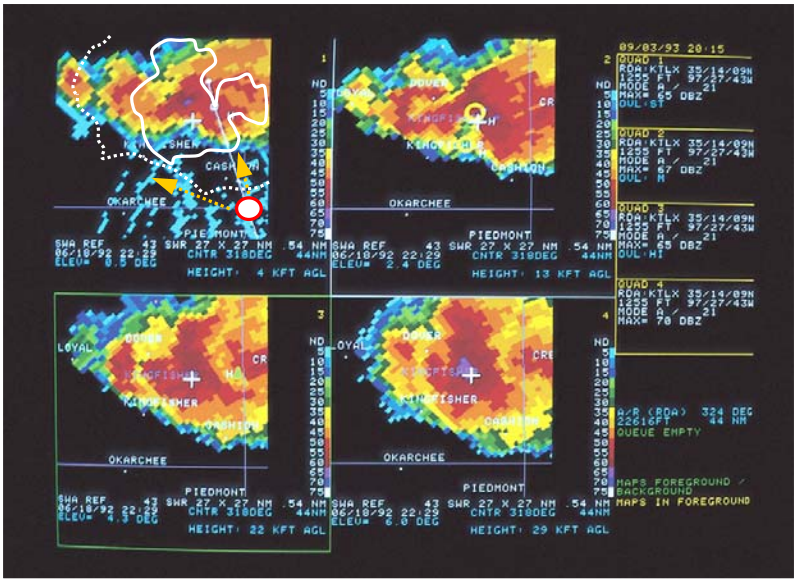
Background

- The WER
  - Is the region of weak echoes underneath the sloping echo overhang (> 45 dBZ)
  - Persists longer than it would take for hydrometeors above the WER to fall to ground



If I were the photographer who took the picture in the previous page, I would be standing at point A depicted in light blue in the horizontal cross-section of this supercell schematic. The WER is a region of weak echoes underneath the sloping echo overhang whose reflectivities are generally above 45 dBZ. The WER should persist longer than the transit time for hydrometeors to reach the ground. This second requirement eliminates the temporary WERs associated with the updraft phases of low shear pulse convective cells.

Note that only part of the WER(in white) is occupied by updraft in the vertical cross-section.



Jim: Here's a classic 4 panel image of the Cashion supercell from back in June 18, 1992 where the upper-left panel is at 4 kft, upper right is at 13 kft, lower left is at 22 kft and the lower right is at 29 kft MSL. Les, this storm does not have a clearly defined hook echo but it still has all the features associated with a severe storm such as a WER. What do you see?

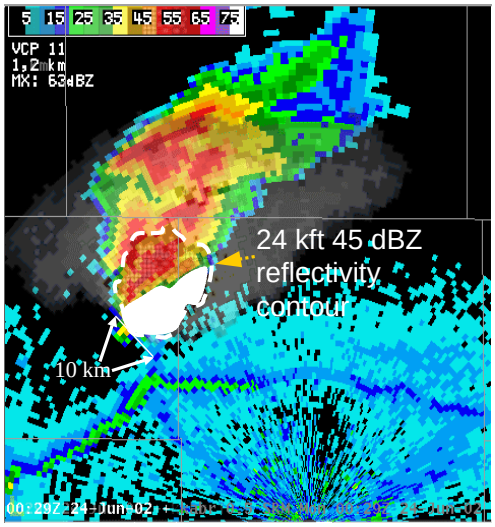
Les:The storm is moving to the SSE and we can see along the leading edge of the storm a high reflectivity gradient and an echo notch. That's outlining the region where the inflow is feeding into the base of the updraft. In the upper right, we can see the BWER and in the lower right, you can see the echo core aloft. Those features where the cursor is located outlines the three-dimensionality of the updraft.

Now we can see the echo overhang of 45 dBZ or greater within the solid white contour. That again is the precipitation out over the front flank of the storm forming the top of the WER. Note the location of the photographer as the white, red bordered circle in the upper left panel. The photographer turned his camera almost straight up to image the outer edge of the anvil. That edge essentially marks the outer edge of the reflectivity echo marked by the dashed white contour.

Jim: Spotters in the field often note how sharp the anvil edges are with severe storms. We've seen such an example with the previous 4 panel by noting how close the 45 dBZ and 0 dBZ echoes are located to each other in the anvil. This picture is from the photographer's site highlighted in the previous 4 panel .

The Weak Echo Region

- WERs are elliptical in shape
- Is that the shape of the updraft?



Here is a more recent example of a WER in a supercell from 24 June 2002 in South Dakota. The lowest slice is depicted by the bright reflectivities near the ground. Overlaid on top of that is a region of greater than 45 dBZ echo at about 24 kft above ground within the dashed white contour. The dull grey reflectivities outside the low-level echo represent weaker reflectivities at 24 kft. Where the strong reflectivities overlay the weak echoes below carve out an elliptical WER.

WER Summary

- In moderate to strong shear, the WER is partly due to
  - intense storm summit divergence
  - And the updraft itself
- More is needed to locate the updraft in sheared convection

Jim: In moderate to strong shear, the WER is partly due to strong storm summit divergence advecting hydrometeors horizontally into the anvil canopy, and it is partly due to the updraft suspending hydrometeors above the ground. However, in order to locate the updraft itself, we have to do more than solely identifying the WER location. Other sessions in storm interrogation focus more detail on updraft location.

Storm Interrogation

IC 3 Lesson 3

Updraft location of a sheared cell by satellite

Storm Interrogation, Updraft location of a sheared cell by satellite

This lesson is 17 slides long and should take 20 minutes to complete.

Sheared storm updraft location via satellite

- Objective
  - As a compliment to, or without radar data, use satellite data to locate an updraft to deep, moist convection in a sheared environment
    - Be able to use satellite data during the day or night

This lesson looks at how to interpret storm top brightness temperature information from GOES to locate the storm top in an environment with significant vertical wind shear. This process may seem straightforward if there is a unique relationship between storm height and brightness temperature. However, that is often not the case. We will look at how you can locate a storm top even if cloud height and brightness temperature are not colocated.

Sheared storm updraft location via satellite

- Motivation
  - Uncertain radar presentation of storm structure requires interpretation from independent sources
  - No radar data available
  - No spotters
  - No web cams

Why do you want to use satellite to locate a storm top? Satellite data can compliment radar in cases where the radar data are poor in quality or you just need some confirming piece of evidence as to the location of a storm. More likely than not, poor radar data, or even lack of radar data provides a strong incentive to use satellite data as a backup.

Sheared storm updraft location via satellite

- Locating updraft summits with GOES 0.6 and 10.7 μm data
  - Assume that the updraft location is at the summit of an overshooting storm top
  - Most of the time, cloud height and brightness temperature are related
  - However, not always, and this complicates locating the updraft summit

In this lesson, we will assume that the upper-level updraft is near the location of an overshooting top that is depicted well in visible imagery. As we mentioned before, the cloud top summit and the brightness temperature minimum can be occasionally displaced from each other, especially in sheared storm environments.

Sheared storm updraft location via satellite

- Brightness temperature can be uncorrelated from storm top height because
  - Elevated cirrus over storm top
  - **Resolution of IR imagery**
  - **Mixing warm air above the tropopause**

Research has theorized three possible contributions for why brightness temperature and storm top summits may be uncorrelated.

1. There could be a plume of elevated cirrus over and downwind of the storm top. If the temperature at the elevated cirrus is warmer than the storm top summit, as may be the case in an inversion, then the storm top may appear warm.
2. The storm top summit may be too small to be adequately resolved.
3. The most likely scenario is that the storm summit cloud boundary contains strong mixing resulting in the cloud edge taking on the properties of the environment around it, including its temperature.

Let’s examine the bottom two possibilities in more detail

Sheared storm updraft location via satellite

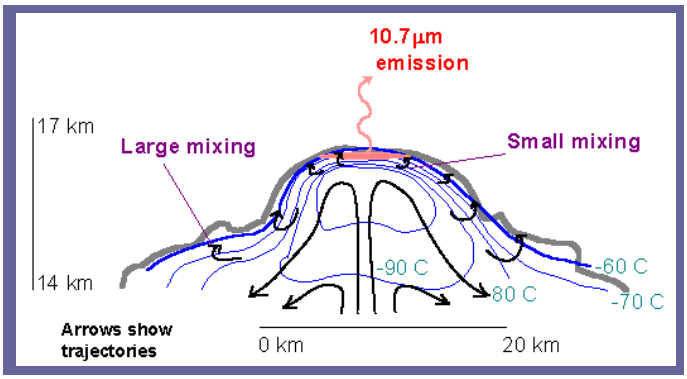
- IR Resolution
  - 2 X 4 km Instantaneous Field of View (IFOV) at nadir is too large to resolve small overshooting tops.
  - Downwind anvil Tb may be lower than at updraft summit.

Most overshooting storm tops are large enough to be resolved even by the GOES IR imager. But a significant minority of storm tops may be too small for detection compared to the surrounding anvil brightness temperature. The result is that the anvil brightness temperature may be lower than the storm summit, since the anvil is a large, relatively flat expanse much larger than the Instantaneous Field Of View or IFOV from the GOES satellite. In order to properly resolve any overshooting top, the GOES IR imagery will need to decrease this size of its IFOV to about 1 km. This requirement will be met by the time GOES-R is launched within the next several years.

The 2X4 km IFOV at nadir refers to the point directly below the satellite. If you want to figure out the resolution for any area of your choice, consider reviewing the lesson on satellite data quality in the section on data quality in AWOC. We show you a simple method to determine the satellite resolution anywhere within view of a GOES satellite.

Sheared storm updraft location via satellite

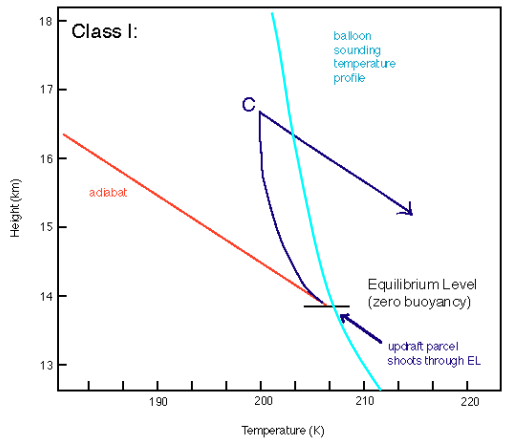
- Mixing along the top of the updraft dome mixes environmental air with cloud air



The most likely explanation for decorrelating storm top height and brightness temperature involves mixing the edges of the overshooting top with the relatively warm environmental air. Note that the 10.7 µm radiation is emitted mostly right at the cloud top edge in the region of thermal gradient between the extremely cold undiluted updraft air and the environment. The stronger the mixing along this edge, the more diluted the temperature gradient, and the more likely the thermal IR emissions are closer to that of the environment. Now imagine that the overshooting top is penetrating into a thermal inversion. It is quite conceivable that the mixing may cause the cloud edge to actually warm with height. This is the most likely explanation available and it seems to fit the conditions required, that is a thermal inversion. Let's go on and explore this some more.

Sheared storm updraft location via satellite

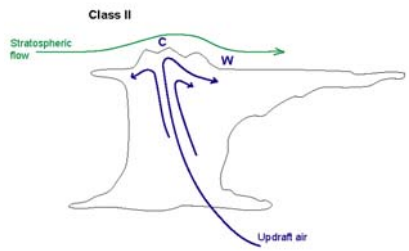
- If the temperature keeps falling above the EL, the brightness temperature (T_b) minima and cloud top height are correlated

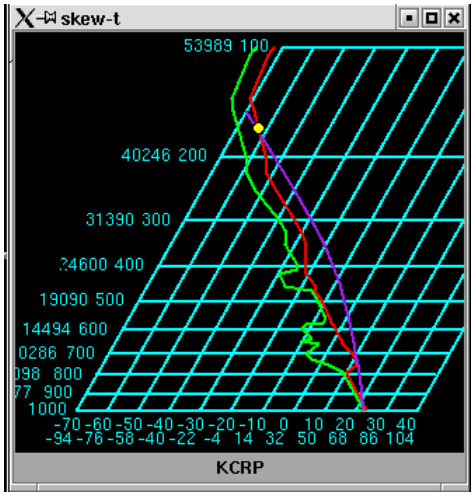


The figure to the right shows the temperature vs. height track of a theoretical air parcel marked as a blue curve as it passes above its equilibrium level, reaches its maximum altitude and descends. In this case, the temperature lapse rate is still positive (temperature decreasing with height) across the equilibrium level as shown by the cyan line. Therefore, as the parcel continues its slowing ascent, the parcel cools. The rate of cooling decreases as mixing commences with the environment but temperature still cools with height until it reaches its maximum altitude located at “C”. This is the case where the overshooting top and brightness temperature minimum are colocated.

Sheared storm updraft location via satellite

- The EL is below the tropopause
- This means good correlation most likely between updraft summit and T_b minimum

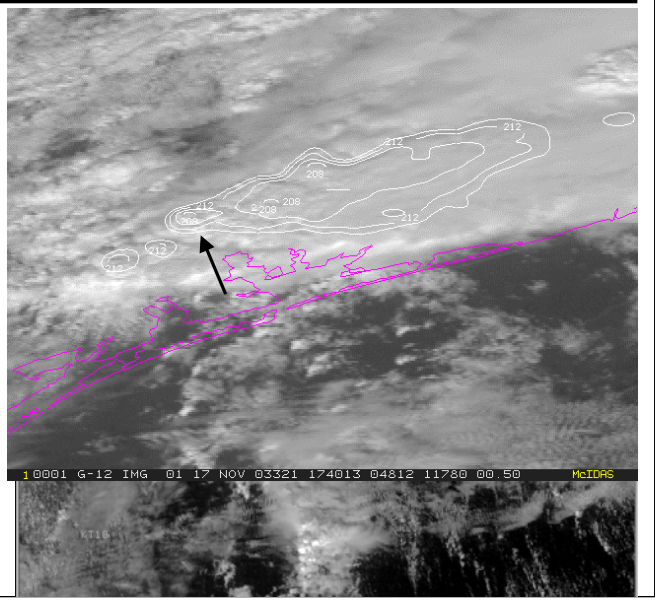




Here is a case from South Texas from a cool season severe weather event with supercells. The nearby Corpus Christi sounding showed that the equilibrium level is below the tropopause and positive lapse rates exist above it. This environment suggests that we stand a good chance of picking out the storm top location at its cold point “C”. Any warm wakes “W” may lie downwind of the storm top.

Sheared storm updraft location via satellite

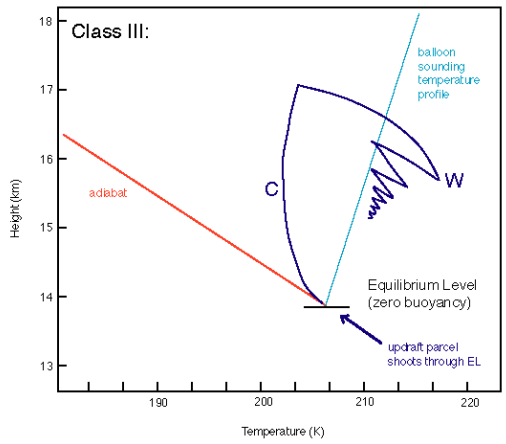
- The EL is below the tropopause
- This means good correlation most likely between updraft summit and T_b minimum



Comparing the visible imagery with the IR, we see that the brightness temperature minima just northwest of the black arrow is right where the brightest cumuliform cloud top shows up in the visible imagery.

Sheared storm updraft location via satellite

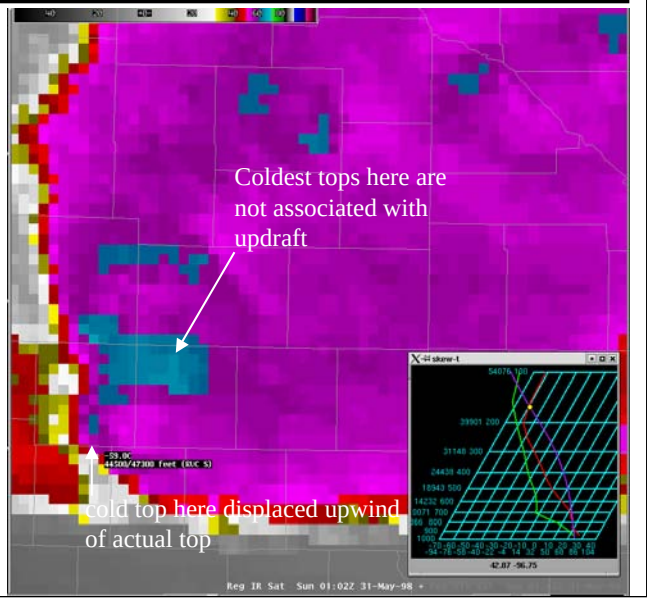
- If the temperature rises above the EL, the brightness temperature (Tb) minimum and cloud top height become displaced



When the EL is in an inversion, mixing causes the cloud top to actually start warming with height. This causes a displacement between the highest cloud and the coldest temperature. The cold spot is displaced upwind of the highest point. The cloud sinks downwind of the highest point warming nearly adiabatically until it settles to a level closer to the environmental EL.

Sheared storm updraft location via satellite

- Displaced cold top example
- Cold Tb top is displaced upwind of physical top
- or little relation between Tb and cloud height



The Spencer, SD tornadic storm on 31 May 1998 exhibited a typical upwind displacement of the coldest tops. In fact, the overshooting top was warmer than the rest of the anvil. The coldest top visible here is actually a collision of two anvils between two storms and has nothing to do with updraft.

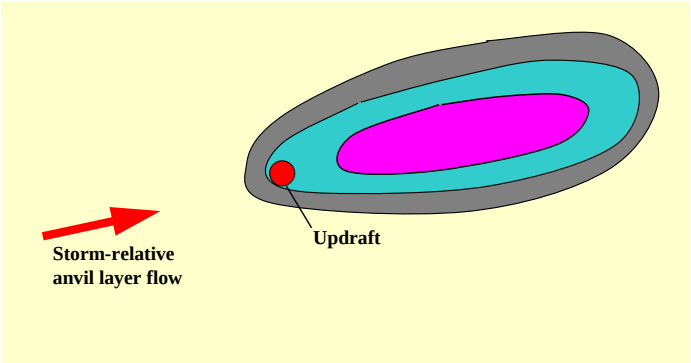
Sheared storm updraft location via satellite summary

- If the EL is in a positive or neutral lapse rate, the Tb minimum is located over the updraft summit
- If the EL is in an inversion, the updraft summit may lie between the Tb minimum and the warm wake
- You may compare to visible imagery during the day

To summarize, if the EL is in a positive lapse rate, the T_b minimum is well correlated with cloud height. Once the EL becomes embedded in a neutral or inverted lapse rate, the cloud actually begins to warm with height creating features such as the warm wake, the enhanced-V, and decorrelating the relationship between T_b and cloud height.

Sheared storm updraft location via satellite summary

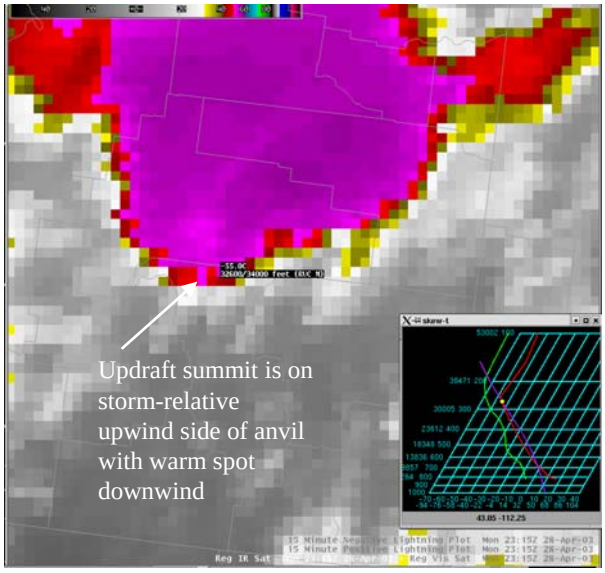
- For small storms, the updraft summit will be at upwind edge or point



Small overshooting tops from small storms may be completely unresolved by GOES. Or a storm struggling in high wind shear will have no overshooting top. The result is an anvil whose lowest T_b is in the flat anvil well downwind from the updraft. In these cases, the updraft will be at the extreme upwind location of the cold anvil.

Sheared storm updraft location via satellite

- Resolution problems
- 28 Apr 2003 - PIH
- Small updraft overshooting top in visible is lost in IR

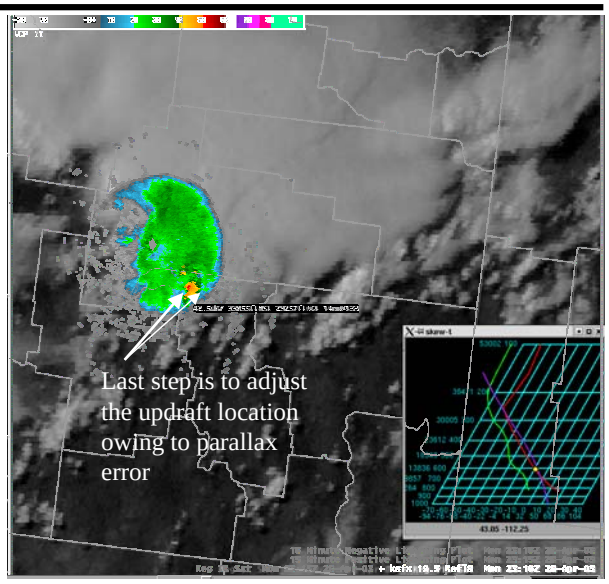


On 28 April 2003, a supercell southwest of Pocatello, ID exhibited a very small overshooting top that was unresolved by the GOES satellite. However, there is a warm wake since the EL is in a near isothermal layer. Both of these factors contribute to difficulty in finding the updraft summit by satellite. Two things help to make an educated guess as to where the updraft is located:

1. Look to the upwind wide of the anvil with respect to the storm-relative anvil-layer flow.
2. Upwind of the warm wake.

Sheared storm updraft location via satellite

- Resolution problems
- 28 Apr 2003 - PIH
- Small updraft overshooting top in visible is lost in IR



Overlaying the high level reflectivity core shows good agreement between satellite educated guess and the radar observed location of the upper-level updraft. Note the parallax correction.

Summary: Sheared updraft detection by satellite

- Positive lapse rate above EL
  - Updraft summit height and IR brightness temperature well related
- Negative lapse rate above EL (inversion)
  - Updraft summit height and IR brightness temperature may **not** be well related
- Small overshooting tops will be poorly resolved by 4km GOES IR
- Parallax correction needed

When there are positive lapse rates above the EL, there is good agreement between updraft summit height and IR Tb.

When the lapse rates become negative (inversion), the Tb minimum gets displaced upwind. In some cases, there might not be a Tb minimum.

Small overshooting tops are likely to be unresolved by satellite and therefore, you need to look at the upwind side of the anvil relative to the storm-relative anvil layer flow.

Storm Interrogation

AWOC Severe Track

IC3-II-A

Upper-level reflectivity core height and intensity

This lesson examines aspects of updraft intensity as a function of the height and intensity of the upper level reflectivity core. This is approximately 19 slides long and should take .

Upper-level reflectivity core height and intensity

- Objective
  - Provide guidance on assessing the potential for an updraft to produce severe weather based on the height and intensity of the upper-level reflectivity core

The primary objective of this lesson is to provide you guidance on assessing whether an updraft may lead to severe weather based on the height and intensity of the upper-level reflectivity core.

Much of the guidance will be based on the same principles on which the Hail Detection Algorithm or HDA, is based. I believe you will find this useful since this technique uses the height and intensity of the reflectivity core above the 0° and -20° C levels, and therefore helps to account for widely varying severe weather scenarios.

As a companion to this lesson, we have provided you a tool in which you can enter in your own reflectivity values, the heights of those values, the 0° and -20° C heights, and the height of your radar so that you can use this tool to help determine how to apply this lesson to real world examples in your CWA.

Upper-level reflectivity core height and intensity

- Motivation
  - Simplest and most common form of assessing updraft intensity

The motivation for this session is that estimating updraft intensity from using the height of the intense reflectivity core is the most common technique used by warning forecasters. In this lesson, however, we will look at this technique with respect to heights relative to critical temperature levels and not just height alone.

Upper-level reflectivity core height and intensity

- Two major considerations
  - Height of the peak reflectivity
  - Maximum height of specific reflectivity isosurfaces relative to the 0° and -20° C level
    - 45, 50, 55, 60, 65 dBZ

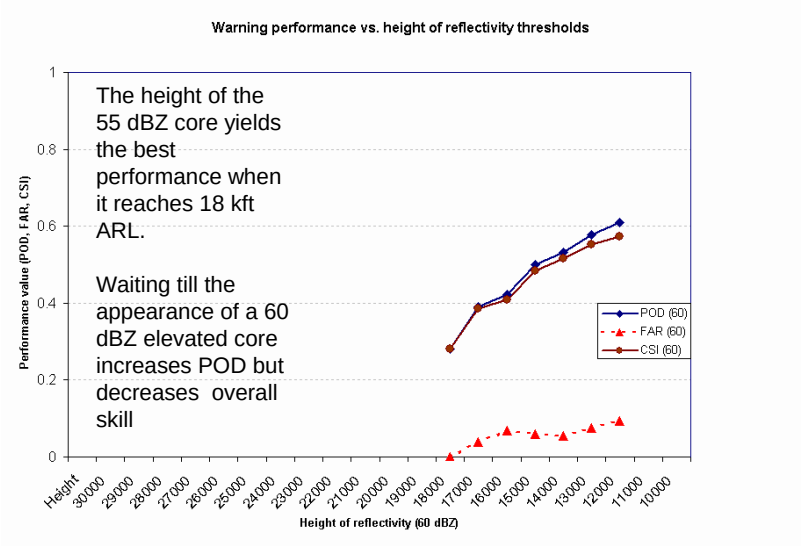
When estimating the potential intensity of the updraft, the premise is that the more intense the updraft, the higher the height of the peak reflectivity will be as well as the maximum height of specific values of reflectivity. We usually look at reflectivity values exceeding 45 dBZ, and especially, 55 dBZ. We will consider heights alone and then add heights relative to the 0° and -20° C levels.

Reflectivity height for pulse storms

- Key parameter to assess severe potential
- Results based on Northeastern US storms (Cerniglia and Snyder, 2002)
  - Warning scores based on severe storms parameters (e.g., VIL, dBZ height, ET)
  - Verifies either by wind or hail

For pulse severe storms, or storms in environments with low 0-6 km wind shear, the height of the intense reflectivity core is the most commonly used parameter to estimate updraft intensity with respect to its capability to produce severe weather. Cerniglia and Snyder (2002) examined a large number of pulse storms in the Northeastern US for the skill of many parameters, including reflectivity height, in anticipating severe weather (either wind or hail). We will show their results next.

For weakly sheared storms



Adapted from Cerniglia and Snyder (2002)

There are three graphs in this slide which shows the skill scores of the 50, 55 and 60 dBZ maximum heights in a storm in anticipating severe weather. Cerniglia and Snyder (2002) calculated the False Alarm Rate (FAR), the Probability of Detection (POD), and the Critical Success Index (CSI) by thresholding the height of a specific threshold reflectivity, then calculating each parameter by comparing wind and hail reports vs storms that succeeded, or failed to succeed in reaching or exceeding the two thresholds. The first graph shows the results for the 50 dBZ echo height. Note how the POD continuously decreases as the height of the 50 dBZ core increases. This is not surprising. For example, a warning forecaster that warns on any storm with a 50 dBZ echo at a low height will detect virtually all severe weather events. However, such a liberal warning threshold also results in a high FAR. On the other hand, a warning forecaster who stringently waits for the 50 dBZ echo to reach a high altitude experiences a lower POD, which is undesireable, but also achieves a desireably low FAR. Somewhere in the middle, the combination of POD and FAR will reach the most favorable combination, represented by a peak in the CSI. That peak comes when the warning forecaster waits till the 50 dBZ echo reaches or exceeds 19 kft ARL.

However, the next graph shows that the CSI for the 55 dBZ threshold height of 18 kft actually gives a higher peak in CSI than that of 50 dBZ. Perhaps waiting for the 55 dBZ to reach this altitude is a better strategy for improving warning performance.

What about using higher reflectivity thresholds? As it turns out, when Cerniglia and Snyder (2002) tested the 60 dBZ echo CSI, the CSI continuously rose with progressively lower altitudes. In other words, the presence of 60 dBZ anywhere in the storm was sufficient by itself to be associated with severe reports. Unfortunately, waiting for the 60 dBZ echo to reach a increasing altitudes resulted in more missed detections.

Remember that Cerniglia and Snyder's study chose only pulse, low vertical wind shear storms in New York, Pennsylvania and further east during the summer months. It would be dangerous to apply their specific thresholds of maximum CSI to other situations since the thermodynamic environment may be warmer or cooler than theirs. However, the point of their results does apply; that convection is more likely to be severe as the heights of intense reflectivities > 50 dBZ increased.

Upper-level reflectivity core height and intensity

- A more geographically independent approach
  - Would look at echo mass above the 0 and -20° C level
  - Science behind the Hail Detection Algorithm
  - More generic to all storm types
  - Unveiled as an interactive webpage
    - See the link at http://wdtb.noaa.gov/courses/awoc/icsvr3/

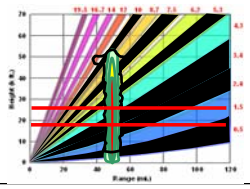
In order to generalize Cerniglia and Snyder's height-based results to more general cases, we will use the methodology behind the Hail Detection Algorithm (HDA) to account for the changing thermodynamic profiles for a couple cases.

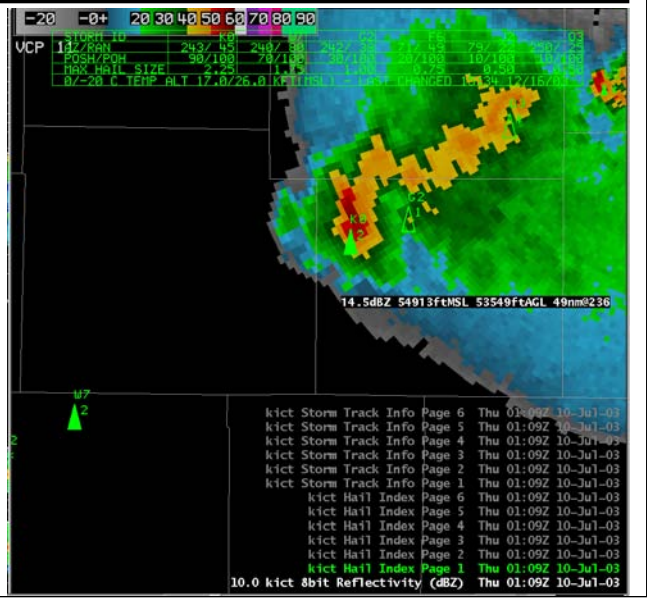
This approach should be more geographically independent since it looks at the mass of echo above the 0° and -20° C levels, and has a broad verification database that is used in the HDA. It should be more generic to a larger spectrum of storm environments and geographic locations. The methodology behind the HDA is revealed using a tool that is available at the website listed in this section. You will be able to enter in the reflectivity heights and values, the 0° and -20° C level, and the radar height to come up with similar values for these cases.

One word of caution, I should mention. This technique's verificaiton is based on hail reporting only. There is no verification on severe winds as there is with Cerniglia and Snyder. As will be discussed in another lesson, pulse storm downdrafts depend mostly on the total potential energy derived from negative buoyancy owing to evaporational cooling potential and precipitation loading. Most storms generate enough precipitation for evaporational cooling down to ground, even from weak updrafts. However, it is the precipitation loading potential that increases as the volume and intensity of the reflectivity core increases. This is especially true for reflectivity values exceeding 60 dBZ. Therefore, updraft intensity should have a significant effect on eventual downdraft intensity. Just remember that updraft strength is not the only forcing for downdraft strength, thus this caution also applies to any technique comparing severe winds to the height of reflectivity values.

Case 1: July 10, 2003 very severe reflectivity profile

- Let's examine the reflectivity profile of storm K0 and compare it to the Severe Hail Index as determined by the previous page



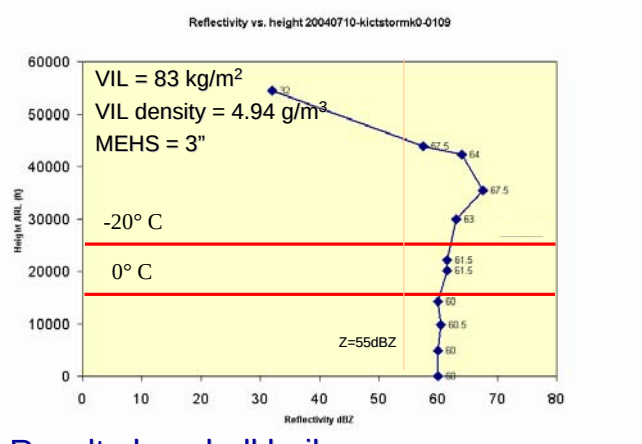


Here is a case with storms in a warm environment characterized by steep midlevel lapse rates, moderate shear (0-6 km = 30 kts), and a high equilibrium level over central Kansas. Note how close the 0° and -20° C levels are on the VCP chart inset (these levels are marked by the two horizontal red lines)

The HDA output is overlaid on an all-tilts scan for storm K0 (center), located about 45 nm from the radar. Going through the all tilts scan, this storm shows all the characteristics of a severe updraft including a Weak Echo Region, even a Bounded Weak Echo Region (BWER). In addition, intense reflectivities extend to very high altitudes.

Case 1: July 10, 2003 very severe reflectivity profile

- 0109 UTC
- Deep, high reflectivity well above/below –20 C level
- VIL density/SHI both agree



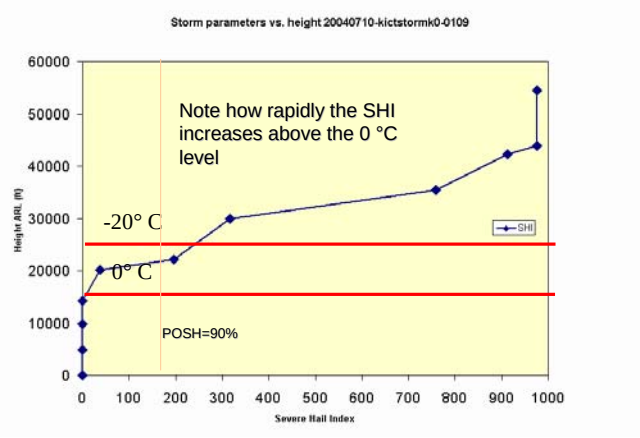
Result: baseball hail

Here is a vertical reflectivity profile taken off the all-tilts scan for storm K0. Reflectivities stay high nearly to the storm summit. Values are highest above the -20° C level reaching up to 67 dBZ at 35 kft. Using the HDA/VIL tool on the webpage, including the freezing and -20° C heights, and the height of the radar, we derive very high VIL, VIL density and Maximum Expected Hail Sizes. Baseball hail was reported with this storm.

The HDA derives its Probability of Severe Hail, or POSH, and the Maximum Expected Hail Size (MEHS) from a parameter called the Severe Hail Index (SHI). The SHI increases slowly at first for reflectivities between 40 and 50 dBZ for temperatures between 0 and -20° C, then rapidly increases for reflectivities exceeding 50 dBZ below -20° C. Take a look at the next page to see the vertical profile of SHI for this storm.

Case 1: July 10, 2003 very severe reflectivity profile

- 0109Z
- Values are integrated upward
- The SHI used by the HDA is the top most value

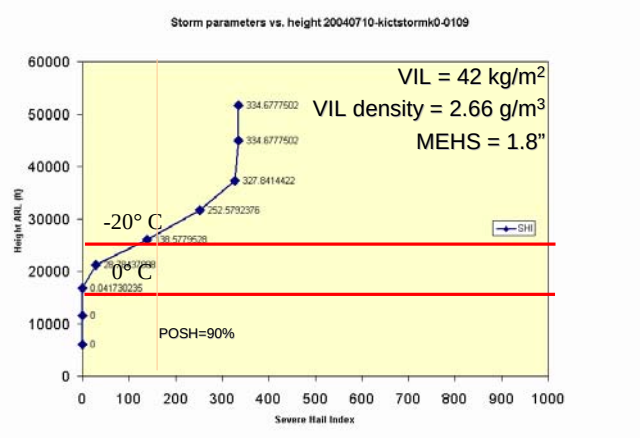


The HDA works by integrating upward in height and accumulating the SHI values until it reaches the highest slice with reflectivities > 40 dBZ. We can calculate for any atmosphere given the heights of the 0° and -20° C level, a threshold SHI for a high POSH, in this case the 90% POSH is marked by the vertical amber line. This storm exceeds that by a long ways. If this storm does not have a warning out for it, one should be ready to go for very large hail. Given the steep lapse rates and intense reflectivities, any downdraft has good potential to be severe as well.

As shown in the all-tilts scan, other reflectivity and velocity signatures of a severe supercell storm add confidence that this storm is very severe. Tornado potential, on the other hand, depends on other characteristics of this storm that are outside this lesson.

Case 1: July 10, 2003 very severe reflectivity profile

- 5 min earlier
- Top heavy reflectivity profile for cell K0 SW of ICT
- VIL and VIL density <u>underestimate</u> severe potential
- Elevated Z profile gives an earlier heads-up when using HDA technique

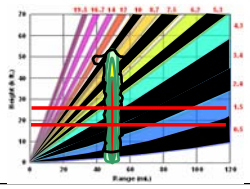


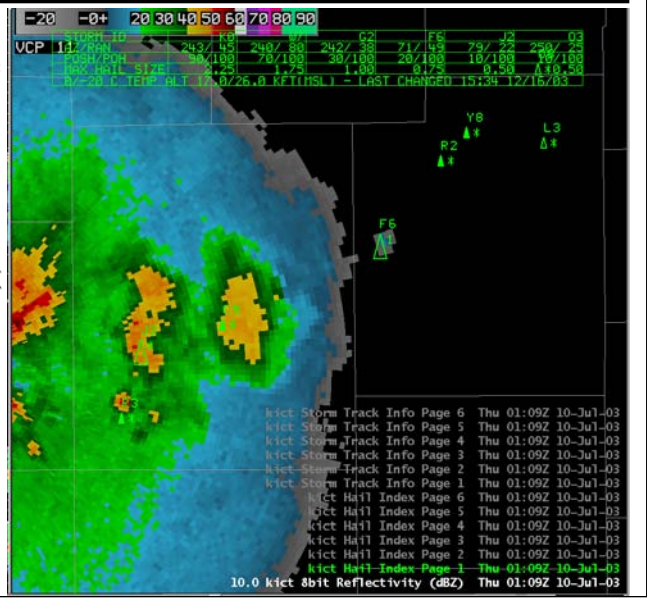
Result: Severe winds, baseball hail, nonmesocyclonic tornadoes

Just 5 minutes earlier, this same storm was too young for its precipitation core to have reached the ground. Note the elevated reflectivity core with intense values, all above the freezing level. Going to the SHI plot, we can see SHI values are still high and exceeding the 90% POSH threshold. However, the VIL and VIL density are still low enough that a warning forecaster may not think about issuing a warning solely based on their values. Here is where waiting for VIL or VIL density to reach warning threshold will cost a warning forecaster several minutes and may result in zero leadtime.

Case 2: July 10, 2003
Nonsevere updraft

- Let's examine the reflectivity profile of storm F6 and compare it to the Severe Hail Index as determined by the HDA worksheet

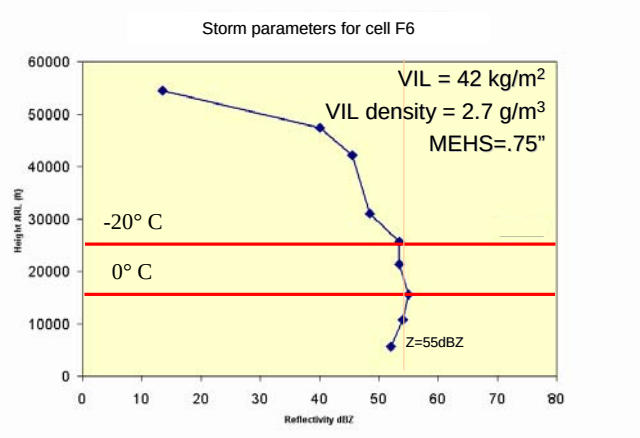




Not all similar environments produce similar storms. A case in point is storm F6 northeast of the KICT radar on the same day. The vertical reflectivity profile here is quite anemic and the HDA results in only 1" hail.

Case 1: July 10, 2003 nonsevere reflectivity profile

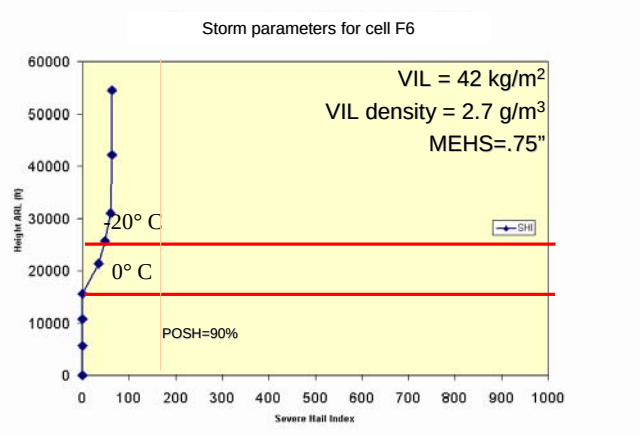
- 0109 Z
- Bottom-heavy and weak reflectivity storm F6
- Both VIL density and SHI are low



Comparing the massive storm to the southwest with this one, we find this bottom-heavy reflectivity profile shows marginal 50 dBZ in the sub - 20° C air.

Case 1: July 10, 2004 nonsevere reflectivity profile

- July 10, 2003 – Wichita
- Note that SHI responds exponentially less given 10-15 dBZ lower reflectivities in this storm

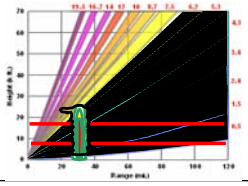


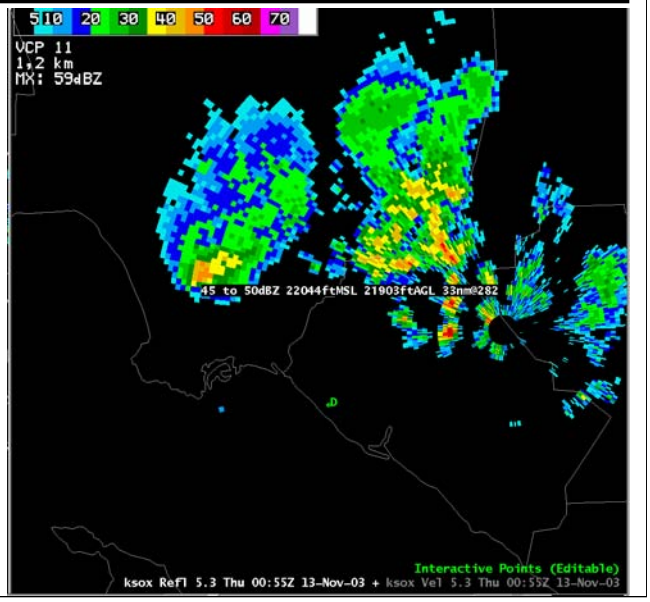
Result: no severe reports

SHI values are much lower, almost 10 times lower given a 15-20 dBZ lower reflectivity profile in the sub -20° C air. VIL, VIL density, and the HDA output all agree that this storm is below severe limits. This storm still could produce severe downdrafts if the DCAPE was high enough.

Case 2: Nov 12, 2003 Cold core reflectivity profile - LAX

- Cold core low – note depressed freezing levels
- Compare dBZ profile to the Severe Hail Index, VIL, VIL density

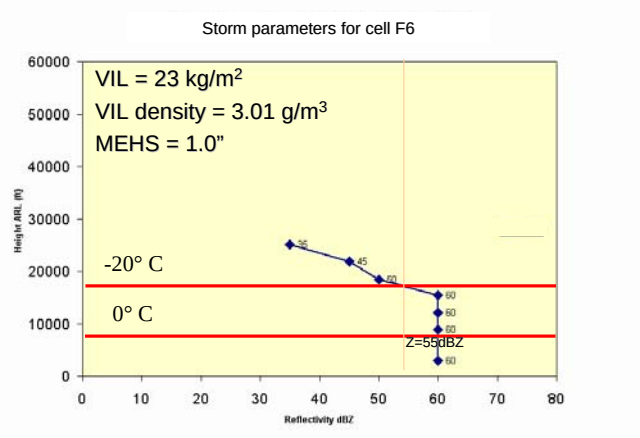




This second example represents a completely different convective environment from our Kansas one. This is a cold core convective case in the Los Angeles basin where a cell is anchored to converging seabreezes and east of the hills at the Rolling Hills Estates. Note the depressed 0° and -20° C levels.

Case 2: Nov 12, 2003 Cold core reflectivity profile - LAX

- Bottom-heavy but high reflectivity > -20 C level
- VIL density decreased from low elevated reflectivities



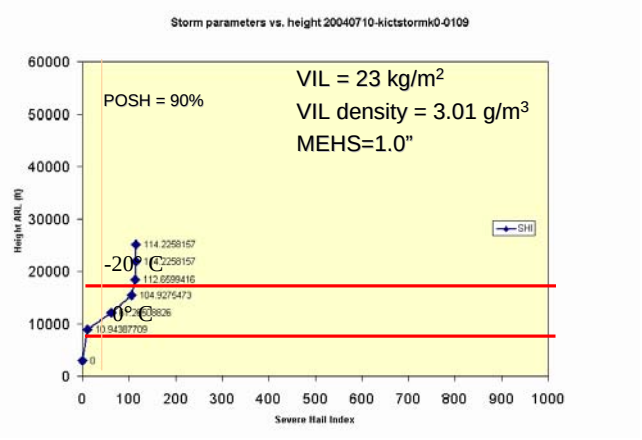
Reflectivities are somewhat bottom heavy in this case but the values are 60 dBZ in the 0° to -20° C layer. Because of the decreasing reflectivities well below storm top at this time, the VIL density is fairly low. At the time of this all-tilts scan, this storm appears to be below severe limits. The MEHS is still giving 1" hail size, mainly because of the low freezing level.

About 90 minutes earlier, a significant updraft pulse resulted in a more top heavy reflectivity profile and a much greater chance of severe hail.

Given the cold thermodynamic profile, and relatively little dry air or CAPE, the DCAPE was fairly low. We examine this case with respect to downdraft potential in another lesson.

Case 2: Nov 12, 2003 Cold core reflectivity profile - LAX

- SHI yields high likelihood of large hail
- Not quite severe HDA technique slightly high



Result: Large amounts of dime size hail in SC Los Angeles

Note that the SHI for 90% POSH is very low. The actual SHI is much larger along with the MEHS. In this case, the upper-level reflectivity profile is rather weak and the HDA is keying off the high reflectivities between the 0° to -20° C layer. Such a profile in SHI and upper-level reflectivity at levels colder than -20° C but well below the equilibrium level suggest that this is a case where the updraft is likely not very strong and the core is descending.

Perhaps this example shows why a single time is not adequate to assess whether or not there is a strong updraft. Earlier, there was a strong updraft pulse which may have led to this descending core of hail.

This storm produced large amounts of dime size hail, not necessarily severe but given the huge amounts of hail due to the depressed freezing level and long duration over South Central LA, the economic impact of the hail, not including the rain, was rather extreme. Recall the pictures in the news of front end loaders clearing out three foot deep hail drifts and impounded vehicles.

Interim summary

- Updraft intensity likely stronger as the height of 50, 55 dBZ core increases.
  - Warning performance (CSI) peaks at a certain altitude
  - That altitude depends on your thermal profile
- Presence of > 60 dBZ above the freezing level give strong likelihood of some type of severe
- Use the HDA worksheet to account for
  - different thermal profiles
  - Storm updraft dominant phase

To summarize, we've seen strong evidence of how strong the relationship between severe weather likelihood and the height of the upper level reflectivity core can be. We've also seen a case where a strongly initiating storm results in a large hail indication as a function of its intense upper-level reflectivity core and yet VIL density understates the storms intensity. Conversely, we've seen a storm with a high hail signal but where the reflectivity profile falls off in the sub -20° C air resulting in a low VIL density, and perhaps correctly.

In either case, a strong updraft should contain strong reflectivities, and those reflectivities should extend well into the sub -20° C air and close to the equilibrium level.

Summary contd

- Updraft intensity that governs potential for severe
  - Hail size through lofting larger hailstones
  - For severe winds, precipitation loading
- Updraft intensity not the only factor
  - Hail size also a function of updraft width, trajectory paths
  - Severe microbursts a function of DCAPE even more than CAPE

Updraft intensity increases the odds of severe weather as it is capable of lofting larger hailstones, and increasing downdraft intensity through heavy precipitation loading.

Remember that updrafts evolve through time and looking at storm trends to discern when the maximum updraft intensity is the most important consideration. Also note that hail takes time to grow, and in the process traverse through complicated 4 dimensional paths, something that the HDA or these techniques do not consider. And remember that downdraft and outflow intensity is not solely a function of updraft intensity.

Contact info

- If you have questions write to this group e-mail to ensure a quick response
  - icsvr3@wdtb.noaa.gov

Storm Interrogation

AWOC Severe track

IC 3-II-B

Updraft strength from low-level convergence

slide 1: AWOC Severe Track. IC3-II-B Storm Interrogation - Updraft Strength from Low-level Convergence. This lesson covers detecting and estimating the effects that low-level convergence has on updraft strength. There are 17 pages in this lesson and it should take about 20 minutes to finish.

Updraft strength– Low-level convergence

- Objective
  - Understand the contribution of low-level convergence to CAPE on updraft intensity

At the end of this presentation, you should understand the contribution of low-level convergence to CAPE on updraft intensity

You may not be able to provide specific values on how strong an updraft is likely to be, but you will have gained an appreciation in how updraft strength can be significantly enhanced beyond what the theoretical CAPE can provide in certain situations.

Updraft strength – Low-level convergence

- Consider this
  - Example of updraft strength after gustfront collision.
  - Strong enough to create hail and split charges if cold enough
  - From Mahoney, 1988, MWR vol 116, pg 1474

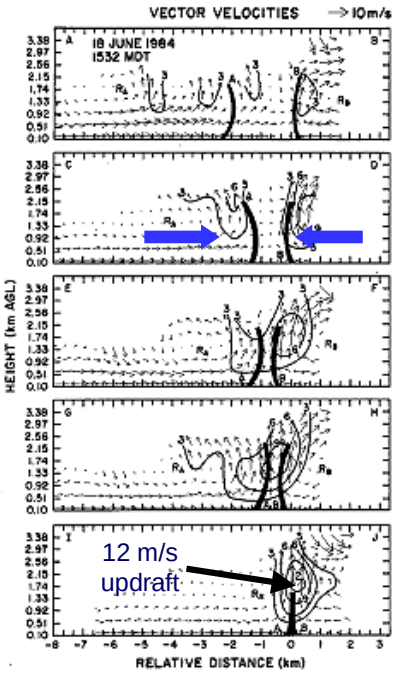


FIG. 9. Vertical cross sections of the ground-relative vector velocities. The grey, thick lines are the estimated frontal locations, and the dark, thin contours are updraft velocities in m s^{-1}. The circulation centers are marked R_A and R_B for fronts A and B, respectively.

Consider this example of dual-Doppler derived velocities of a colliding gustfront visualized in this cross-section taken from Mahoney (198???). A gustfront one km deep colliding at a combined speed of 13 m/s can produce an updraft of similar strength at 3 km above ground. Cloud physics and storm electrification research (See papers by Zipser and Marwitz) suggest storm electrification begins wen updrafts exceed 5m/s. Without any CAPE, we could've initiated lightning had the atmosphere been cold enough to produce graupel. This is not the case since this updraft forcing is too shallow to extend into cold enough air, however it does show that if this lowlevel forcing were to occur under a developing towering cumulus, the extra boost would give this cumulus a much greater initial updraft strength than a neighboring cumulus away from this forcing.

Updraft strength – Low-level convergence

- Convergence parameters to affect updraft magnitude
  - magnitude
  - depth
  - residence time of DMC over convergence

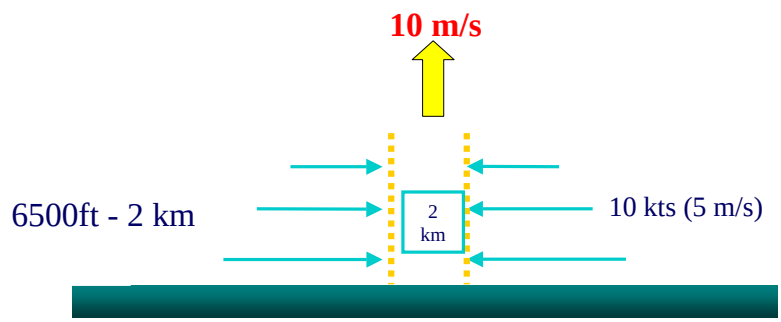
Several considerations need to be accounted for in determining how much of an initial boost to buoyancy convergence may give to a storm. The magnitude of convergence is one for obvious reasons, Stronger updraft results from stronger convergence. However, I could have a situation where an adjacent gustfront may be weaker in convergence magnitude but it's forcing deeper convergence. The second consideration, convergence depth, is equally important to magnitude when the final updraft speed is concerned.

Finally, when an airparcel responds to the forcing that has created the convergence, it starts to accelerate as long as that forcing is there. If the forcing is cutoff, the final vertical velocity of that parcel will have failed to reach its full potential.

One thing to remember, convergence is not a forcing mechanism. Something forces the convergence, and likewise the vertical velocity. This has implications for my scenarios coming in the following pages.

Updraft strength – Low-level convergence depth

Assuming a steady state convergence
Depth: ΔZ = 2 km
Boundary width = 1 km (one .54 nm range gate)
Mean convergence over 1 km: $\nabla \bullet V$ = 10m/s* 2000m = .005 s^{-1}
Updraft strength at 2 km W = $(\nabla \bullet V)\ \Delta Z$ = .005*2000 = **10 m/s**



. I will show a few examples of changing the convergence depth and magnitude across a boundary. The vertical velocity that arises out of the convergence, I estimate using the continuity equation greatly simplified so that you see the results more clearly. I mentioned before that convergence is not a forcing, it is just a diagnostic. What forced the convergence and its vertical motion field may be from a thermal gradient, or density gradient like you see across a gust front.

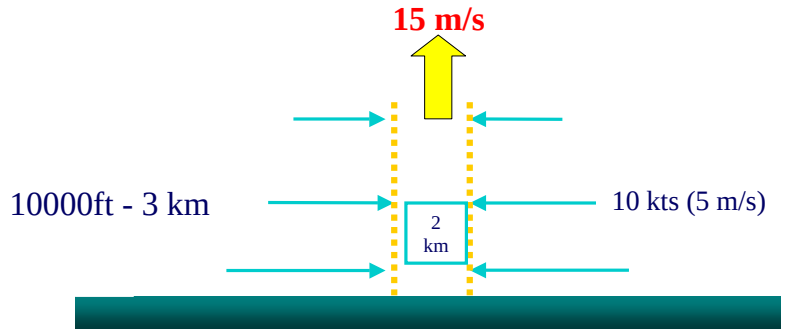
In this scenario, I have a 2km deep boundary where the average flow toward the center interface is 10kts. That means my velocity difference is 20 kts (10m/s). The boundary is roughly 2 km wide.

First, I estimate the mean convergence across the width of that convergence by dividing the velocity difference by the width of the boundary (all in meters and seconds). Then I multiply my convergence by the depth of the mean convergence (2000 m). My answer comes out to 10 m/s at 2 km altitude.

The boundary may be a bit deep but it's also a bit wider than a real boundary. Most fine lines are 2km wide or less.

Updraft strength – Low-level convergence depth

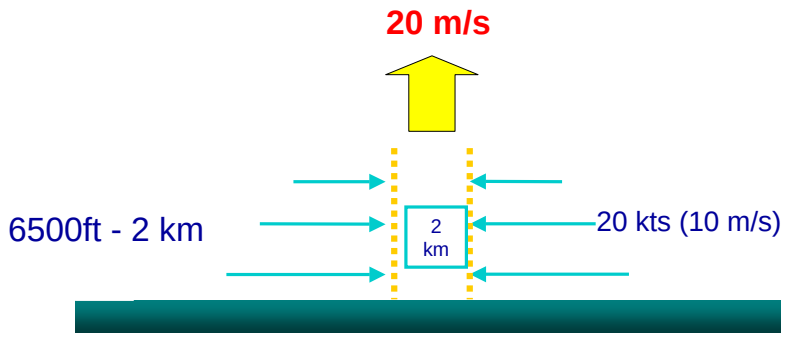
Assuming a steady state convergence
Depth: ΔZ = **3** km
Boundary width = 1 km (one .54 nm range gate)
Mean convergence over 1 km: $\nabla \bullet V$ = 10m/s* 2000m = .005 s^{-1}
Updraft strength at 2 km W = $(\nabla \bullet V)\ \Delta Z$ = .005*2000 = **15 m/s**



If I change my boundary depth to something deeper, maybe a deep convergence zone along a squall line gust front, my final vertical velocity at the top of my convergence (3 km) is 15 m/s, certainly strong enough to generate hail if the air temperature was cold enough.

Updraft strength – Low-level convergence strength

Assuming a steady state convergence
Depth: ΔZ = 2 km
Boundary width = 1 km (one .54 nm range gate)
Mean convergence over 1 km: $\nabla \bullet V$ = 20m/s* 2000m = .01 s^{-1}
Updraft strength at 2 km W = $(\nabla \bullet V)\ \Delta Z$ = .01*2000 = **20 m/s**

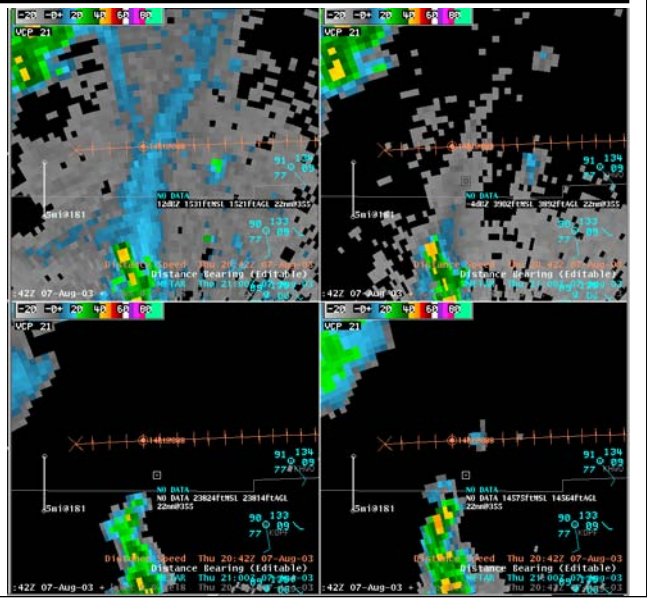


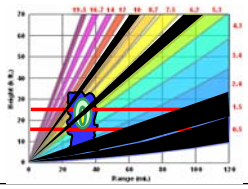
Going back to my 2 km deep boundary, now I double my inflow. Now I get a 20 m/s updraft at 2 km, that's double my previous 2 km deep boundary after doubling the inflow. This may be a realistic squall line gust front which is moving at 40 kts.

Remember, these are for illustrative purposes only. There are a lot of factors that may work against realizing these updraft numbers including the residence time of any parcel in the zone of convergence, entrainment, etc.

Case : Boundary collision

- 07 August 2003, Palm Beach, FL
- Two boundaries about to collide
- Collision speed 18 kts

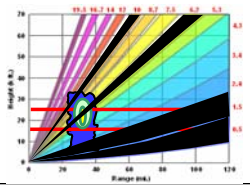


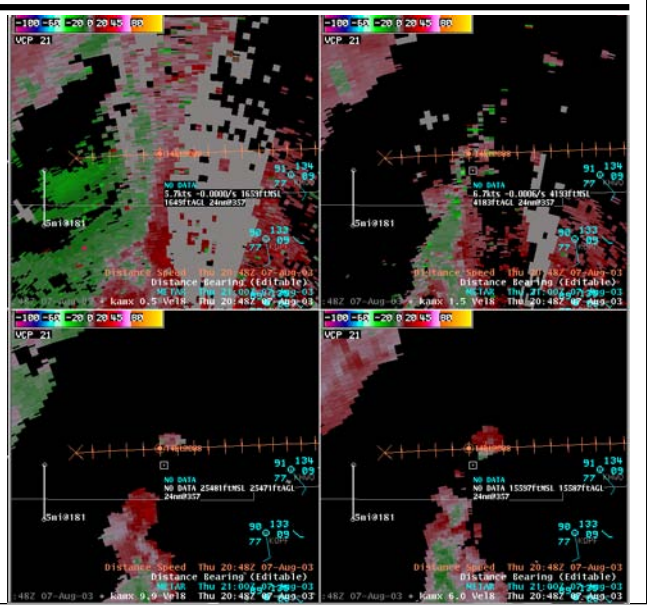


Here's an example from Florida of a boundary collision from 07 August 2003 near Palm Beach, FL. I tracked the motion of these two boundaries with the distance speed tool in AWIPS to get a combined collision speed of 18 kts. Looking at my 4-panel, I'm having trouble observing the boundaries above the 1.5° elevation slice, so I may have a good idea on the depth of the gust fronts. But what is the convergence?

Case: Boundary collision

- 07 August 2003, Miami
- Velocity is of limited use here owing to the angle of collision
- Flow is mostly tangential

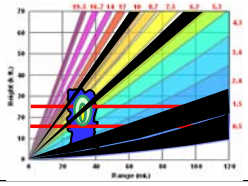


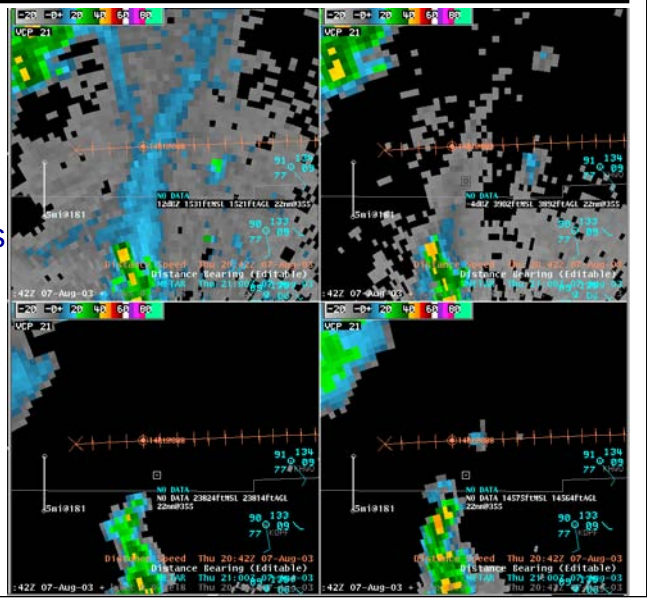


Looking at the velocity, I have a problem. The velocities are weak, probably because the winds in either cold pool are mostly tangential. I cannot use the velocity data to come up with an estimate on convergence.

Case: Boundary collision

- Implied convergence
- Each boundary moving 9 kts
- Closing speed 18kts
- Assume sfc wind = 1.4 X boundary motion = 13 kts



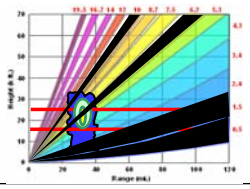


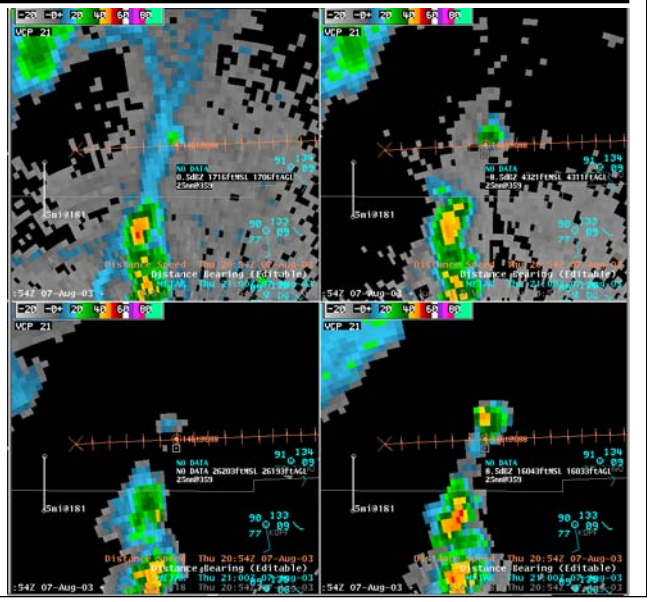
We will have to imply convergence based on an estimate of the winds behind each boundary. The closing speed of each boundary is roughly 18kts. Mahoney (1988) found that surface 10m winds behind a gust front was roughly 1.4 times that of the boundary motion after sampling a large number of boundaries. Apply that here to each boundary motion of 9 kts and we have winds roughly 13 kts in each boundary. After collision, the combined differential velocity may be 26 kts.

Note that the relation between boundary speed and maximum wind speed behind the boundary assumes a relatively calm pre-boundary environment. This relation works for this case. This relation needs to be revised for strong low-level wind events, .

Case: Boundary collision

- Upon collision, boundary width is the width of the fineline ~ 3 km
- Convergence of 26 kts (13 m/s) over 3 km is .0043 s^{-1}

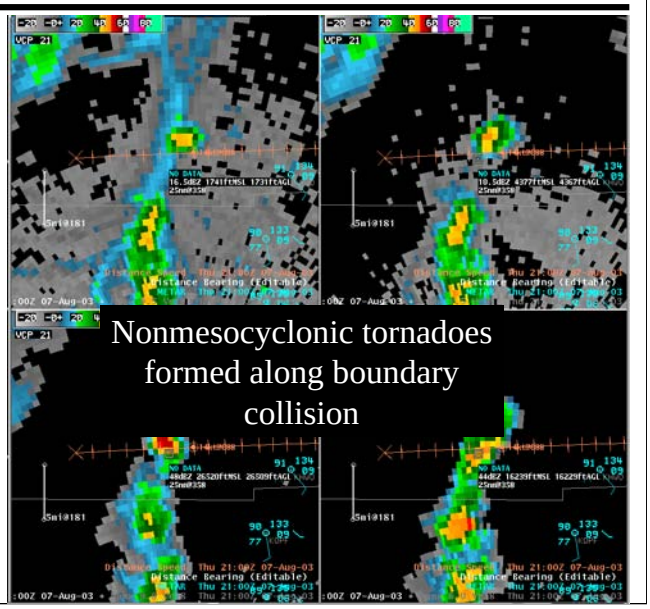




Radar observed the fineline after collision to be around 3 km wide. Dividing 13 m/s (26 kts) by the width of the fineline in meters gives me a convergence of .004 /s. This is going to be the maximum convergence near ground level. That convergence should be weaker going up in altitude. But let's keep this convergence for the lowest one km above the ground.

Case: Boundary collision

- Boundary depth is roughly 1 km deep
- Updraft at top of boundary (1 km) = $(\nabla \bullet V)\ \Delta Z$ = .004*1000m = 4.3 m/s
- Extra boost of updraft from collision can assist buoyancy for a more intense updraft



By the simplified continuity principle, multiple the convergence by its depth of one km and we get an updraft speed of 4.3 m/s at the top of the boundary. A developing towering cumulus is likely and initiation will be strongly forced compared to a other developing convection from most other initiation mechanisms this day. As can be seen, convective cells rapidly developed along and after the collision.

Summary: Case 1 – Pulse storm updraft

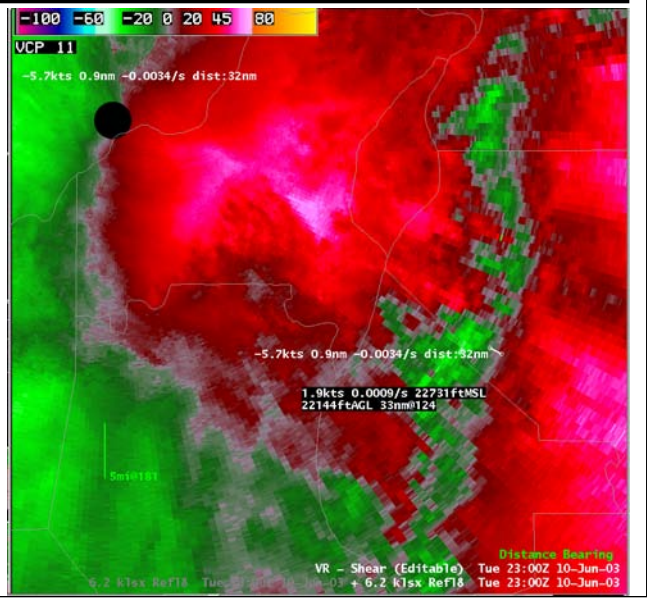
- Convergence adds vertical velocity to the peak updraft expected from buoyancy alone
- Convergence depth and magnitude modulate the strength of the updraft
- Caveats
  - Updraft must reside over convergence to realize its vertical velocity
  - That means boundary-relative storm motion needs to be small

To summarize this event, the boundary collision may have added up to 8 kts of vertical velocity to the base of the convective updrafts. In addition, large plumes of moisture have been advected upward to produce a much stronger base for buoyancy to continue the initiation process. The result was a more intense set of thunderstorm updrafts than the initial storms that created the original cold pool boundaries in the first place.

There are some caveats to everything. First, the convective layer steering flow must be such as to minimize boundary-relative storm motion in order to generate the strongest, deepest updraft possible. Deep layer shear should be optimally balanced with the motion of the gust front to generate a deep overturning convective current. In this event, shear is not a consideration in the environment, storm motion was small, and the updraft generated by the boundary collision was likely upright and deep.

Case 2: Deep convergence from sustained severe storm

- Convergence of .01 s^{-1} in a 3 km deep layer
- Followed by weaker divergence above 3 km
- Yields updraft of **~30 m/s** at 3km
- ~**25 m/s** at 4.7 km



Here is a case of a severe quasi-linear multicell event with a deep convergence boundary along the gust front. The gust front motion was nearly 50 kts resulting in some very strong convergence. Since velocity is likely mostly radial here, I use the VR-shear tool to estimate convergence across the width of the convergence zone, roughly 1.5 km. The actual zone was probably even narrower than that. This convergence was maintained through the lowest 3 km (10kft). This may be an overestimate but multiplying this convergence through the lowest 3 km resulted in an updraft of nearly 30 m/s at 3 km. Whether or not this is actually the case, the updraft generated here is nearly an order of magnitude higher than the Florida boundary collision case. Imagine this kind of boundary even in a situation where the linear system runs low on CAPE. One could easily imagine this system maintaining itself on its low-level convergence for awhile longer than expected.

Summary: Case 2 - Strong shear severe storm

- Updraft strength profile is maximized due to
  - Strong convergence (ΔV>50 kts over a few km)
  - Deep convergence (>3 km or 10 kft)
  - Low boundary-relative storm motion
    - Storm matching cold pool speed

Summarizing, this boundary moving at 50 kts resulted in some incredible convergence, especially considering that the ground-relative low-level inflow was out of the southeast. This convergence was also deep (3 km) and the matching vertical velocity was calculated at 30 m/s at 3 km. The convective layer storm motion allowed the deep updraft to maintain its footing close to the vertical velocity generated by the convergence zone and the result was a deep overturning updraft capable of generating all the features associated with a high end severe squall line including tornadoes, severe low-level winds and excessive rainfall rates. Very severe hail was not something found in this event for many reasons. One of them may be that squall line updrafts tend to flatten out at lower altitudes than for more isolated modes of convection in similar environments.

Summary: distant storms

- Estimating low-level convergence for distant persistent storms
  - Use the storm motion and calculate storm-relative low-level inflow
  - Storms with large, intense, persistent core are likely to have strong enough gust fronts to ‘block’ the storm-relative inflow providing strong convergence

Estimating low-level convergence from distant, persistent convective modes is a bit more problematic and relies on circumstantial evidence. Let's assume a cluster or supercell is moving along at a speed and has a large, intense core. As long as you can say this event has an intense gust front capable of forcing the storm-relative low-level inflow upward through convergence, you could use the forward motion of the storm and estimate its convergence as it moves into the low-level inflow. Be careful, it is hard to say what the storm-relative winds within the cold pool are when all you know is the storm motion.

Storm Interrogation

AWOC Severe Track

IC 3-II-C

Severe updraft storm structure signatures

Welcome to the AWOC Severe Track lesson IC3-II-C on examining severe convective updraft structural signatures. This lesson is 19 slides long and should take 20 minutes.

Severe updraft structural signatures

- Objective: Understand how the following signatures are an indication of, or contribute to severe updrafts in convection
  - WERs
  - BWERs
  - Stormscale velocity

This session adds onto the session on the height of reflectivity profiles. For severe storms, however, signatures appear that are unique to this class of convection beyond that of vertical reflectivity profiles. The objective in this lesson is to understand the signatures in reflectivity and velocity that indicate a severe updraft is in progress. Again, what is meant by severe updraft is one that is often accompanied by large hail and severe straight line winds. As a performance objective, you should understand how Weak Echo Regions, Bounded Weak Echo Regions and stormscale velocity patterns contribute to recognizing a severe storm.

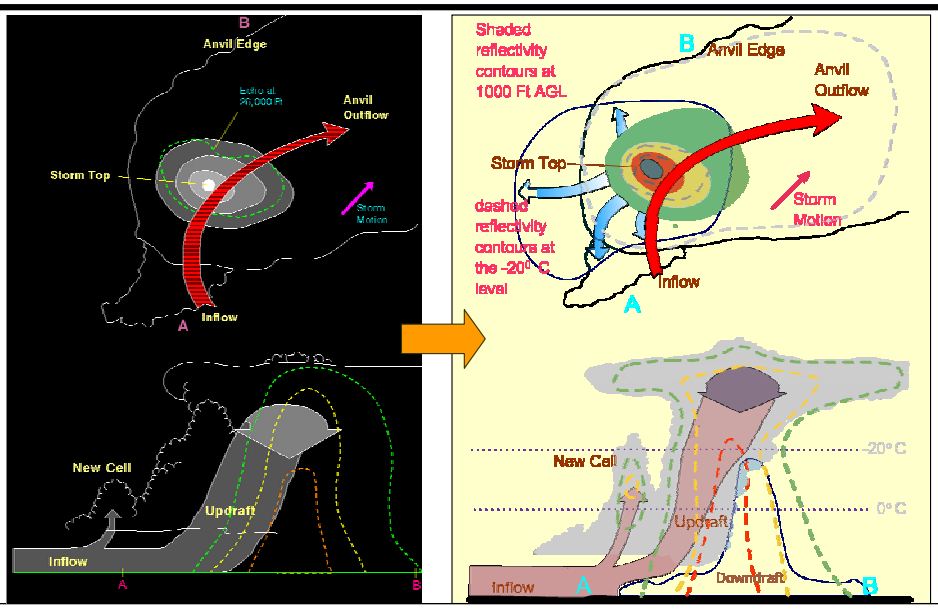
*Note that some conceptual models have been revised from previous training materials.

Severe updraft structural signatures

- Motivation
  - The Lemon technique has been revised, find out why
  - Integrate velocity into the Lemon technique

As a motivator, this lesson introduces a revised stormscale conceptual model that Lemon (1977) introduced and is widely used today. Velocity is also integrated into the Lemon (1977) technique and an analogous conceptual model is also introduced to discriminate severe and nonsevere linear convective systems.

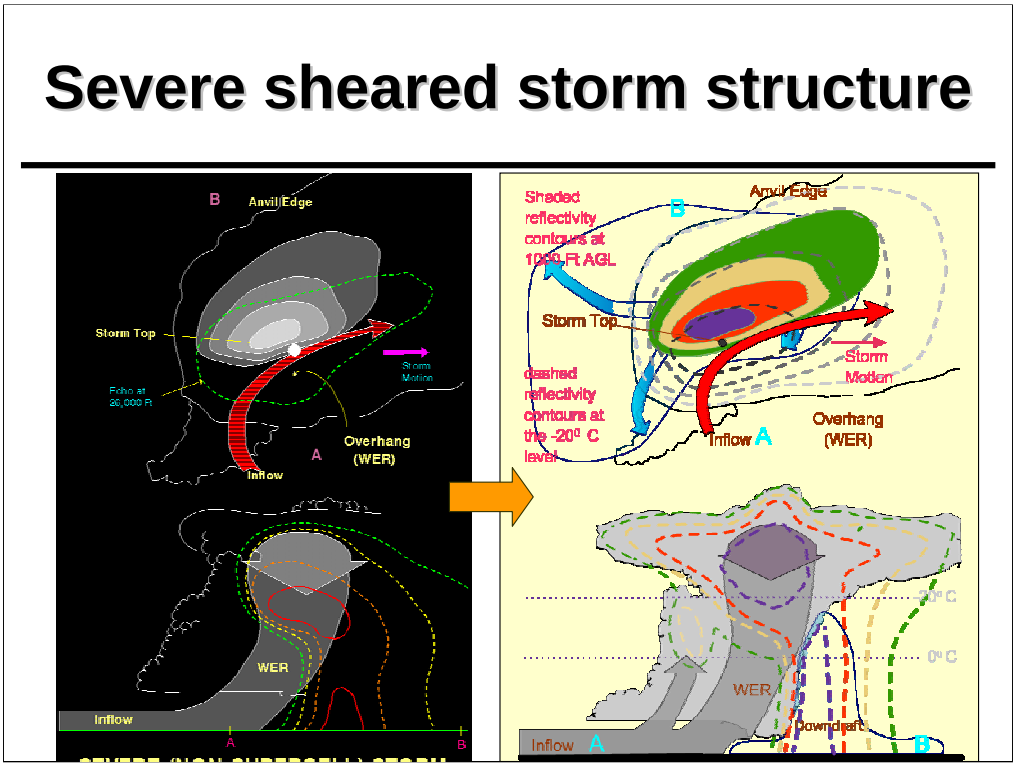
Nonsevere storm structure



We compare the classic nonsevere convective cell conceptual model with the revised version. There are several changes which corrects subtle features.

1. Heights of the upper-level reflectivity contours (dashed) in the horizontal cross section are with respect to the -20° C level. We also placed temperature contours on the vertical cross section to emphasize that features in the reflectivity core depend on the temperature more than some fixed arbitrary height. This change in thinking helps account for sheared convection in diverse thermodynamic profiles.
2. Note the reflectivity contours nearly match the cloud boundaries above the -20° C level. The anvil is composed of snowflakes and graupel with the precipitation particle sizes decreasing with increasing distance from the updraft core. Anywhere there is anvil cloud, there is at least 0 dBZ reflectivity and most likely values in the teens.
3. The downdraft and cold pool region have been added to show that the gust front severely undercuts the updraft base.

Otherwise, both diagrams reflect the lack of an echo overhang, and the multicell nature of nonsevere convection. The upper-level reflectivity core and storm summit are located over the lower level core centroid. Note that the reflectivity values fall off well below the updraft summit. With respect to velocity, the nonsevere sheared shows weak low-level convergence and upper-level divergence with no significant rotation, though some weak shear may exist in the updraft at midlevels. There is shallow convergence at the base of the updraft.



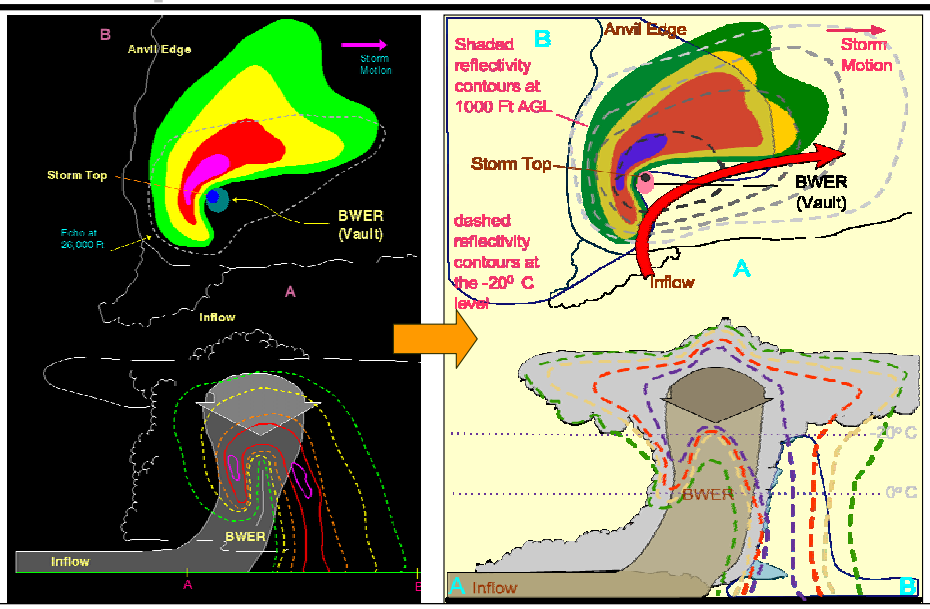
Increasingly intense storms may still exhibit multicell behavior, however, the initiation of new cells occur close enough to the primary cell so as to appear like the storm is more steady state in nature. A WER may be more persistent as new cells contribute to a more steady state intense echo overhang. The anvil is sharper and contains higher reflectivities than with the nonsevere cell. Some of the echo overhang occurs as echoes > 45 dBZ spread into the anvil outside the lowerlevel udraft. The updraft summit is displaced over the WER and the low-level reflectivity gradient. Higher reflectivities press upward closer to the storm summit than with the nonsevere storm. The session "The Nature of the WER" applies to these kinds of storms and supercell reflectivity morphologies.

Note in the newer version, there are actually three cells in different stages in their lifecycle, the old cell being the descending intense reflectivity core (purple), the middle one containing an elevated intense core, and the new one just beginning to develop a core. The three cells contribute to give the appearance of one strong semi continuously propagating cell.

The cold pool boundary remains closer to the main updraft but there is still some low-level outflow undercutting the lowering or wall cloud.

In velocity, these storms may contain short-lived but significant mesocyclones, strong and more persistent updraft summit divergence, and strong low-level convergence ahead of the gust front. This convergence may be deeper than with nonsevere storms, though not always so.

Trailing mesocyclone supercell updraft storm structure



Going to a supercell signature, we add the classic reflectivity signatures that indicate significant rotation to those associated with a severe nonsupercell storm. Here we define a supercell as that kind of cell that contains significant rotation, at least partly correlated with updraft, and the updraft is quasi persistent for much longer than the transit time of any air parcel through the updraft. The reflectivity envelope in the early version of the Lemon diagram has been lifted such that even the highest reflectivity values reach nearly to the updraft summit. The BWER remains the same but now the top of the BWER extends just a bit above the -20° C level. In some supercells, the top of the BWER may extend higher but it is generally capped by intense reflectivities no matter the height of the BWER.

The cold pool boundary bends back toward the low-level updraft region in response to strong inflow into the updraft side of the mesocyclone. The cold pool swirls around the back side into the RFD region

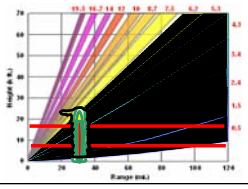
Interim summary: Revised lemon technique

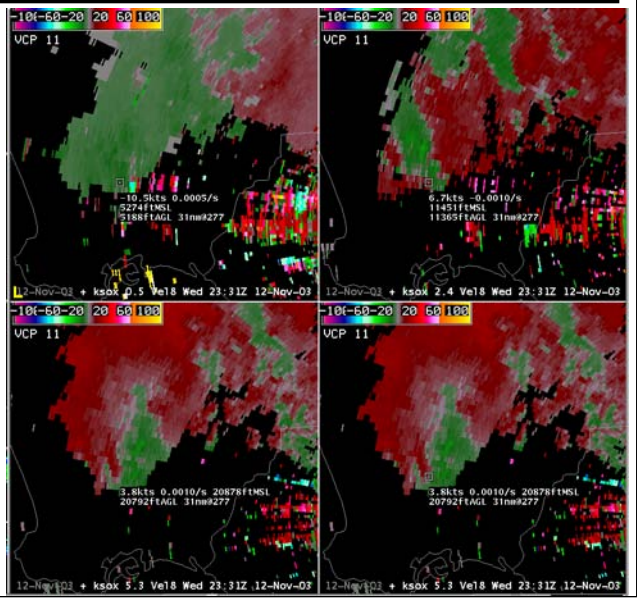
- Modifications to the Lemon Technique
  - Increased reflectivities in the anvil region in the echo overhang region overlying the WER
  - Increased reflectivities closer to the top of the overshooting top. Increases the overall density of hydrometeors from storm bottom to top to reflect reality.
  - Upper-level core is labeled with respect to the temperature coordinates (height of the -20° level), not in height coordinates

To summarize the modifications to the Lemon (1977) technique, we increased the reflectivities in the anvil region to account for part of the anvil comprising the intense echo overhang above the WER. Reflectivities have been increased near the storm summit for the severe storm updrafts. Finally, any references to height coordinates in describing upper-level reflectivity cores have been changed to temperature so as to increase the relevance of these diagrams for a wide variety of storm environments.

Example of a nonsevere sheared storm

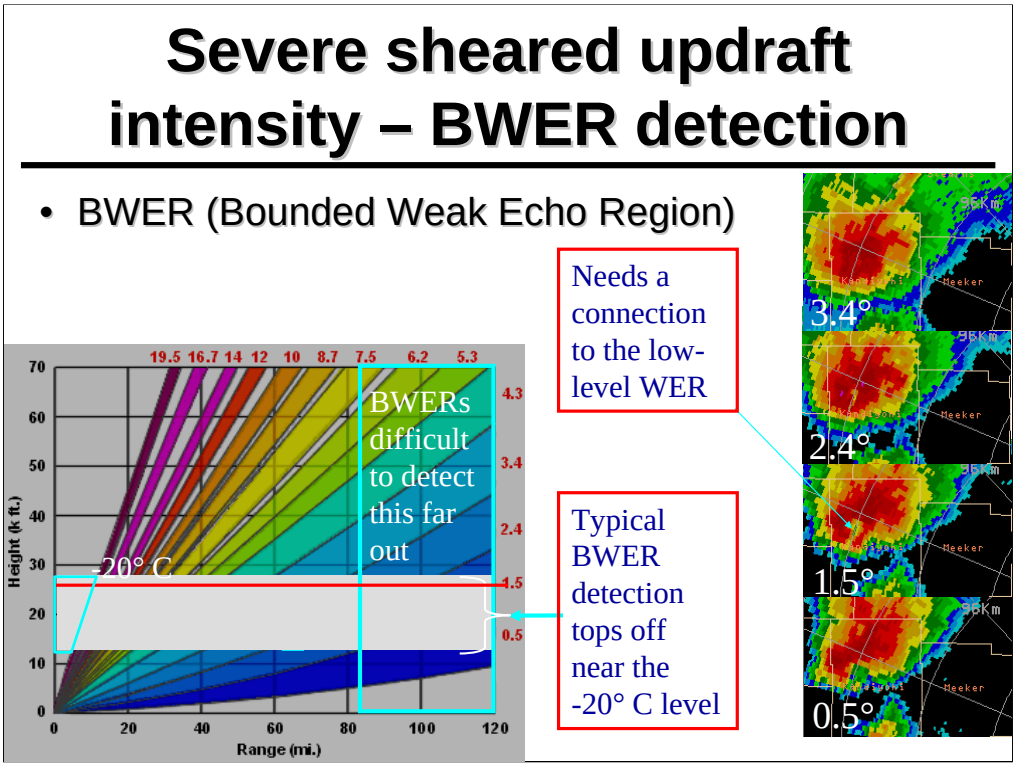
- KLAX 20031112
- Marginally severe with large amounts of dimes
- 2331 UTC shows small echo overhang of .54 nm
- Overhang is not persistent





This is a single image captured from a continuously evolving low topped multicell in a marginal shear environment (0-3km shear - 15-20 kts, equivalent to 30-40kts of 0-6 km shear). This storm exhibited little in the way of a sustained WER. Any initial elevated reflectivity core quickly descended to ground within one or two volume scans. In most times, the reflectivity core weakened with height well before the storm summit suggesting a relatively weak updraft most. Updraft summit velocity difference was weak, about 40-50 kts. This same case is presented in the lesson on "Updraft reflectivity height"

This storm produced dime size hail but since it was anchored to a boundary triple point, the storm produced huge amounts of hail and large rainfall totals, both leading to quite a bit of disruption to communities.

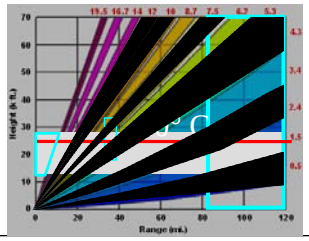


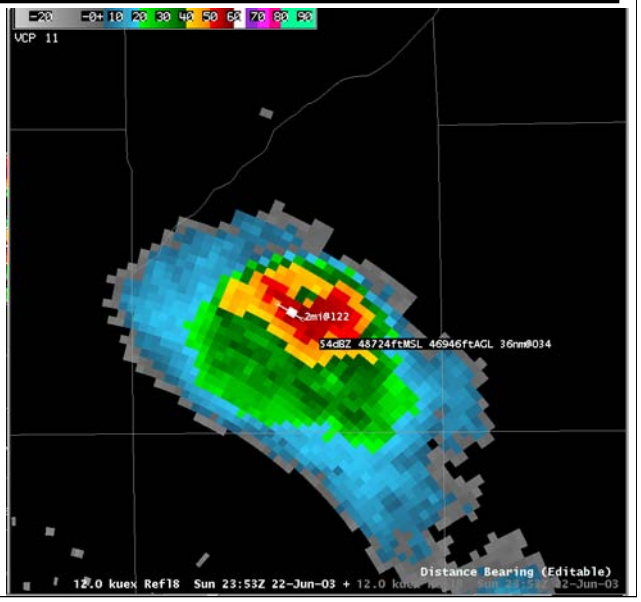
BWERs are fickle features to detect by radar owing to their relatively small sizes, and many false BWERs that exist. This VCP chart is overlaid with a light gray zone indicating where BWERs typically exist. The example on the right represents a storm with a range of about 63 mi and is marked by the rectangle where the BWER was found. This storm example was taken from June 11, 2003 in northern Minnesota and produced baseball hail and 90 mph winds.

To avoid the false BWER detection, make sure that a BWER is an upward extension of a WER and that it is capped by high reflectivities in higher elevation slices. The BWER usually reaches up to just above the -20° C level whatever its height, but significant variability exists in its vertical dimensions. BWERs are typically too small to be viewed much beyond 80 miles .

Classic severe updraft signature case

- Trailing updraft
- Normal width
- Produced a few record sized hailstones

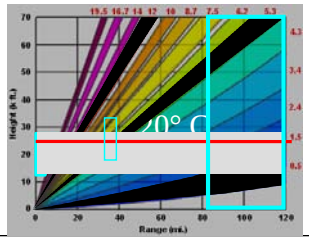


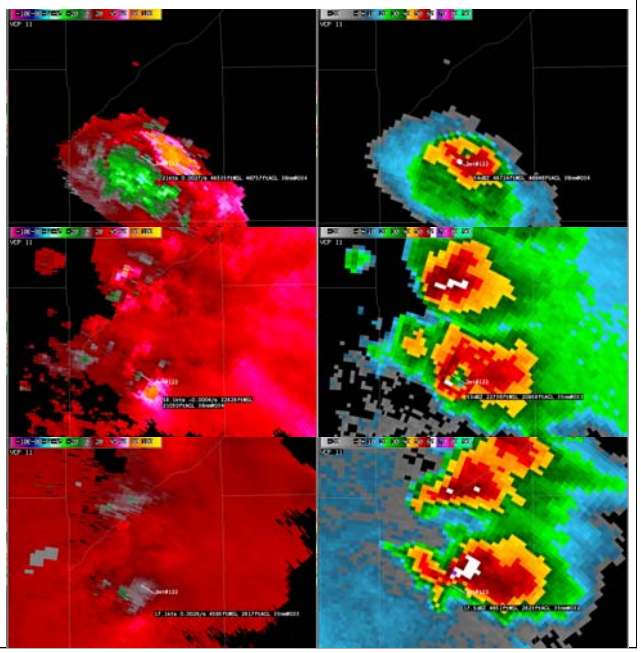


This all-tilts scan shows shows a supercell in the middle of it producing extreme sized hail. You may recall the hailstone diameter record being broken in Aurora, NE on June 22, 2003. This is what the storm appeared to warning forecasters about 5-10 minutes before the record hail fell on the town. This is a classic supercell with normal horizontal dimensions and a BWER approximately 2 mi in diameter. What is unusual in this case is that the BWER appears to extend to 45 kft and above the highest scan presented here. This BWER is an upward extension of the WER below but the high reflectivities over the top of it is not shown here. Given the vertical continuity of this echo hole and the fact that it's coexistent with other intense supercell reflectivity features, the echo hole is likely a BWER with intense updraft to extreme altitudes.

Classic severe updraft signature case

- Velocity

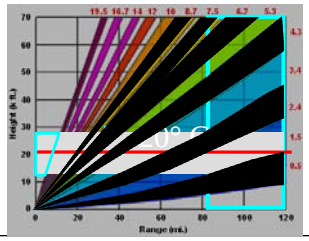


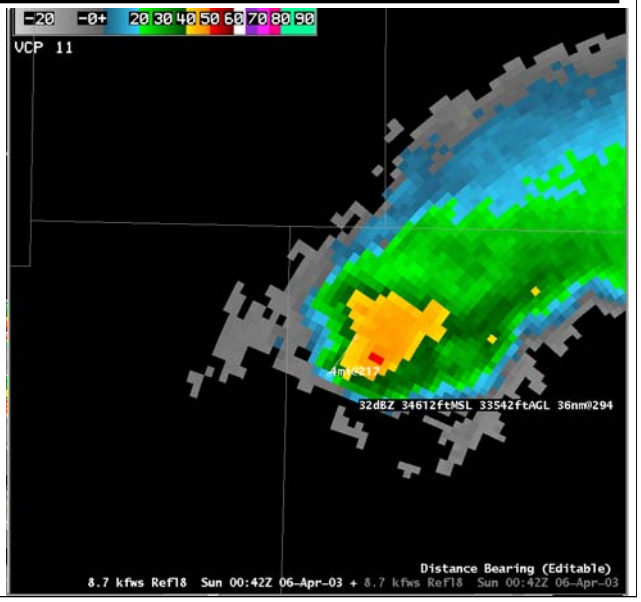


At the storm summit, top diagram, the divergence center appears to be more colocated with the high reflectivity core just south of the BWER suggesting it is not associated with the most intense updraft at this altitude. Note that the velocity difference between the maxima on both sides is above 150 kts, a good confirmation to the severity of the updraft suggested by the reflectivity structure.

Wide, lower topped supercell updraft

- Leading updraft
- Very wide updraft
- Prolific baseballs and 90mph winds



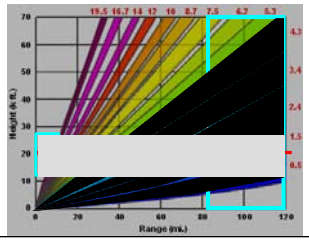


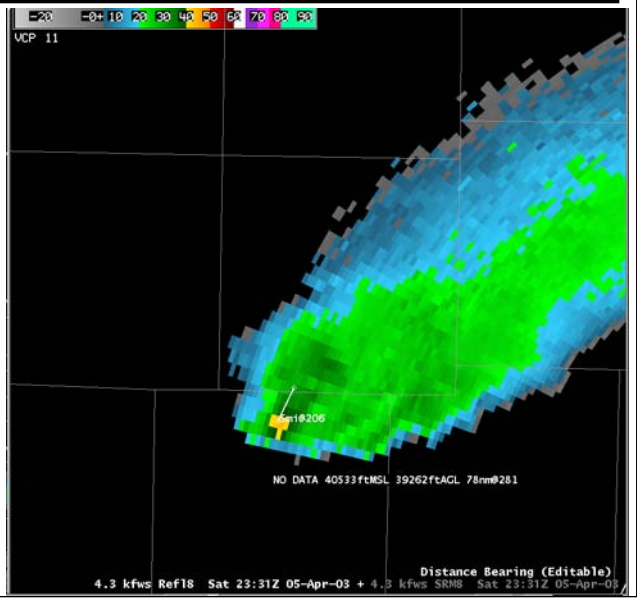
A different case shows what an extremely wide BWER appears to be at similar ranges to this radar as the Aurora, NE storm is to the Hastings, NE radar. The small vertical rectangle in the VCP inset shows the vertical dimensions of this BWER. It is in the right spot of where BWERs can be sampled. In this case, the soon to be Ft. Worth hailstorm of 2003 shows a classic BWER, with a long dimension northeast-southwest of 4 mi. The BWER is an extension to a large WER and is capped overhead by high reflectivities. An elongated BWER like this has been suggested by some researchers to be an especially favorable signal for large amounts of extreme hail.

Note, however the storm summit is only a little above 33 kft. This storm produced almost $1billion in damage in the Ft. Worth, Dallas metroplex.

Same supercell at max BWER detection range

- Large BWER of 5nm is barely visible at only 80 nm

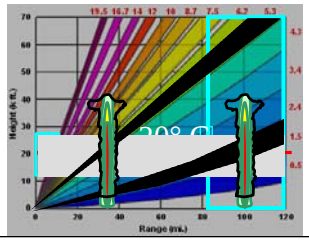


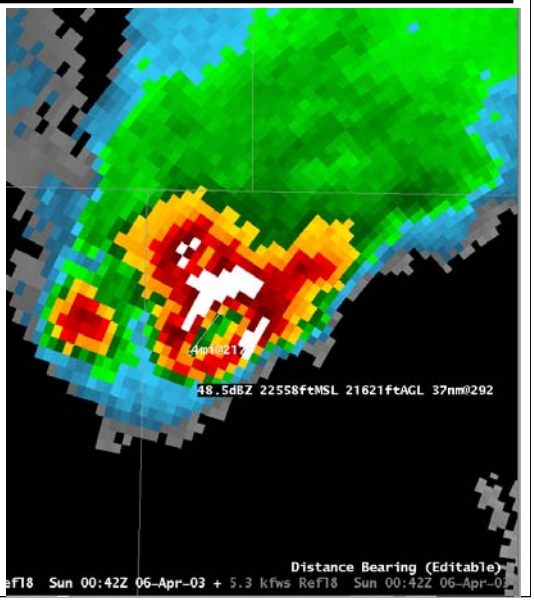


75 minutes earlier, this same supercell was located 78 nmwest of the radar, and was producing especially damaging hail here too. This is the first scan in which a BWER was detected by the Ft. Worth radar and it appeared to be of similar size as when it closed within 40 nm of the radar. This graphic shows that even large BWERs are difficult to detect beyond even 75 nm from the radar. Note that the VCP chart ranges are in statute miles while the cursor readout is in nautical miles.

Same supercell at two very different ranges

- KFDR only shows hint of an inflow notch

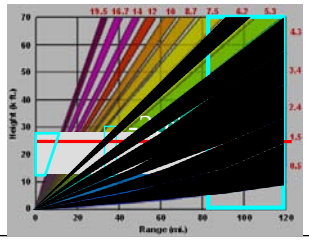


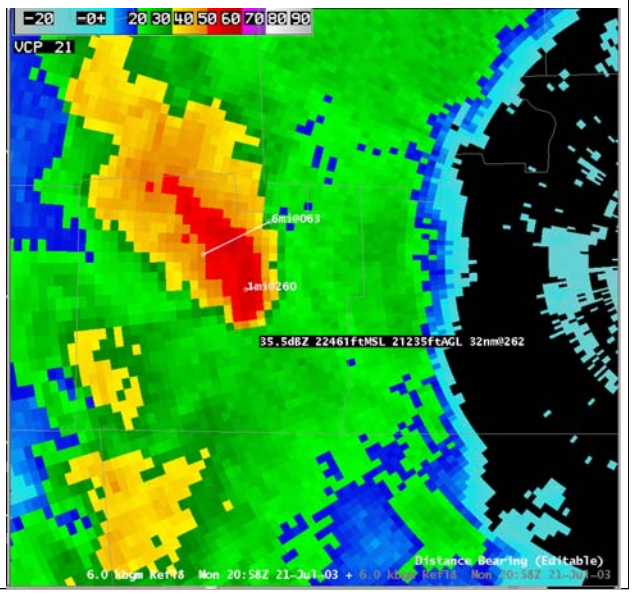


Multiple radars were viewing this storm from a wide variety of ranges. Going back to the 0042 Z timefame as the storm was within 40 nm of the KFWD radar, the storm was also being viewed by the KFDR radar from nearly 90 nm away. This large BWER is clearly outside the range of detectability from KFDR. There are fewer BWERs larger than this one on record.

Can you apply the Lemon technique here?

- Squall line moving 52 kts
- Storm top 26 kft AGL

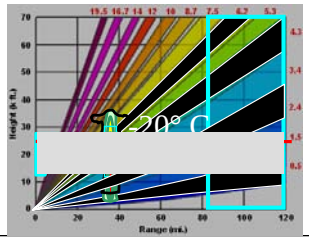


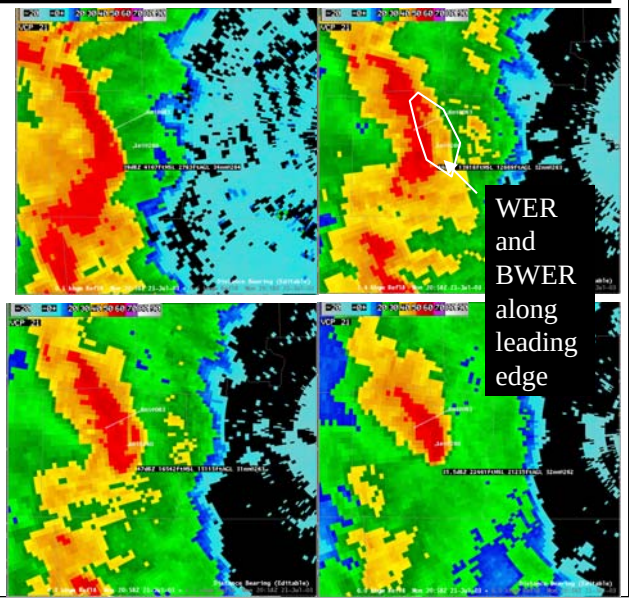


Can the traditional Lemon technique, or even a revised one be applied to assess the severity of a linear multicell system? Here is a case of a severe squall line west of Binghamton, NY on 21 July 2003. This segment of the line is just about to begin its bowing out process. The stom summit is shallow but there are several signatures suggesting the updraft below is very intense. There is a front-end WER, sharp reflectivity gradient, even a suggestion of a BWER, to indicate an upright updraft strong enough to create these features.

Can you apply the Lemon technique here?

- Yes, accounting for storm motion, a WER and BWER can be detected

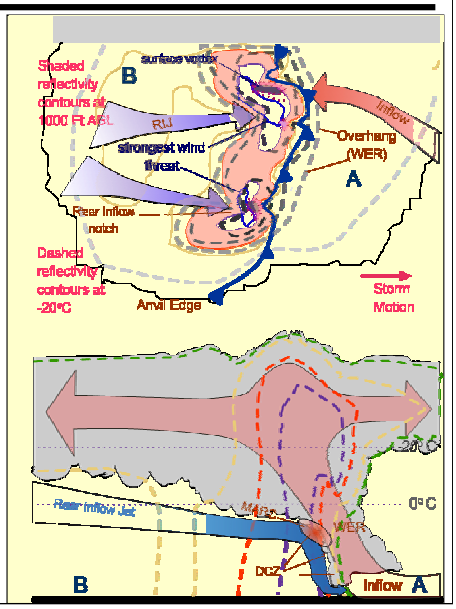




Discerning a WER on the leading edge of a squall line has the complication that you have to remove any spurious echo overhangs as the squall line moves forward during the volume scan completion time. This artificial WER becomes more exaggerated closer to the radar site since the radar needs to scan more elevation slices before getting to the echo overhang. A line moving at 55 kts may create up to 5 miles of artificial echo overhang. Still, a real echo overhang jumps forward rapidly in a few thousand feet which is noticeable between the 3.4 deg slice (upper right) and 4.3 deg slice.(lower left) with even a linear echo hole at 4.3 deg on the front end of the intense bowing echo.

Conceptual model of a severe linear system

- Key things to note are the
  - Relatively nondescending RIJ
  - MARC, DCZ
  - Front end echo overhang with linear BWER ahead of the surface gust front



A conceptual model of a high-end severe linear system shows the same features we've seen in the example from New York. One is a leading edge WER and even a small linear BWER. The updraft is upright.for several km before sloping back over the cold pool dome. The leading gust front exhibits a steep slope and the Rear Inflow Jet (RIJ) behind it remains nondescending until within the heavy reflectivity core of the leading edge. However, the gust front remains underneath the low-level updraft providing a strong initial updraft through convergence. A Mid Altitude Radial Convergence Zone (MARC) is pronounced between 3 and 5 km above ground level and is the zone where the RIJ reaches the heavy convective line where it sharply turns downward. Differential velocities exceeding 50 kts are common in MARCs during and preceding localized severe wind events.

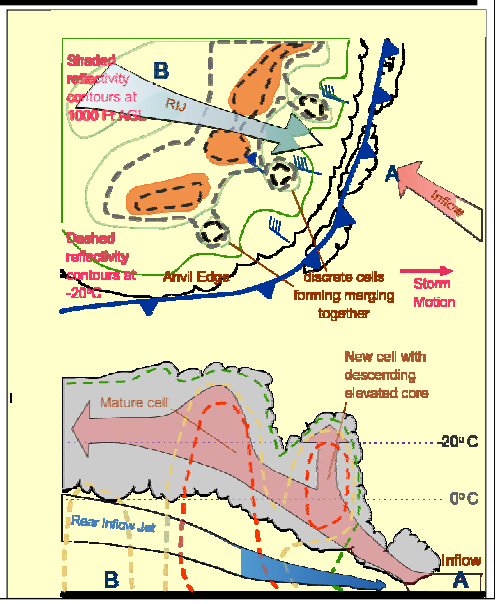
The MARC is a component of a Deep Convergence Zone (DCZ) which represents the interface between the ascending branch of air and the descending branch of the RIJ and deep cold pool.

Depending on the line-normal upper-level storm-relative flows, some anvil material may flow ahead of the line. This is not a requirement for a severe linear updraft.

The high end severe systems appear to consist of one unbroken leading edge updraft and trailing reflectivity core. You will see little evidence of discrete cellular behavior over the leading edge of the cold pool.

Conceptual model of a nonsevere linear system

- Key things to note are the
  - Descending RIJ
  - No MARC, DCZ
  - Shallow sloping updraft over top of cold pool with numerous discrete cells merging into a line



A weak linear system is depicted here as one that has **no** WER, or deep convergence (DCZ means Deep Convergence Zone) or Mid Altitude Radial Convergence (MARC). The gust front is shallow and quickly advances faster than the cells above it, leaving them behind and over the cold pool. As a result, you see multiple discrete cells forming over the gust front which congeals into a region of strong reflectivity in a roughly linear shape well behind the surface gust front.

Remember that even a shallow sloped, weak updraft linear system may still produce severe winds. However, the high-end severe linear systems tend to have the structure presented to you in the previous page.

Summary: Severe updraft signatures

- severe updraft signatures common to all storms in order of most severe first
  - BWER
  - WER
  - Intense reflectivity core, and deep relative to the –20° C level
  - Storm top displaced over WER
  - Deep convergence zone

Summary: Severe Updraft Signatures

The most severe updraft signatures tend to have these features common, even for linear systems.

- BWER
- WER
- Deep, intense reflectivity cores * *Severe linear updrafts tend to have somewhat shallower cores than discrete severe updrafts
- A storm top displaced over the WER
- A deep convergence zone** **This is a weak requirement as many discrete severe updrafts may not exhibit this. For example, classic or Low Precipitation (LP) supercells mostly fail to show any deep convergence and yet have extremelyi ntense updrafts.

Contact info

- If you have questions write to this group e-mail to ensure a quick response
  - icsvr3@wdtb.noaa.gov

Storm Interrogation

AWOC Severe Track

IC3-II-D

Estimating updraft intensity with satellite: part 1

Slide 1: Storm Interrogation - Estimating updraft intensity by satellite - part 1

This presentation is 23 slides long and should take 20 minutes to complete.

Estimating updraft intensity with satellite: part 1

- Objective
  - Use satellite data to qualitatively estimate updraft strength in the absence of radar data based on
    - Cloud top growth rates determined from temperature and the D2D cloud height estimation tool
    - Temperature and height of the storm equilibrium level

As a motivation for this lesson, there have been times when offices are stripped of radar data for various reasons. Satellite data can provide a useful backup, or as a tool of confirmation.

The objective of this lesson is to qualitatively estimate updraft strength from satellite based on two major parameters that you have the capability to evaluate

1. The cloud top growth rate in terms of time trends of cloud top temperature and height.
2. Temperature and height of the storm Equilibrium Level (EL)

Both of these parameters, you can evaluate for yourself using the D2D cloud height estimation tool.

We will discuss this more later in this lesson.

Estimating updraft intensity with satellite: part 1

- Possible methods
  - Cloud Top Temp (CTT) cooling rates pre-anvilgenesis
  - CTT cooling rates post-anvilgenesis
  - Cloud top growth rate using the cloud height tool in AWIPS
  - Anvil equilibrium level temperature/height

There are many methods for evaluating storm intensity from satellite:

1. Cloud top cooling rates prior to anvilgenesis.
2. Cloud top cooling rates after anvilgenesis. Now we are talking about the cooling rate of the overshooting top
3. Cloud top growth rate using the cloud height tool in AWIPS. This technique simply converts cloud top temperature to height. Otherwise, the physical basis remains the same as 1 and 2.
4. Anvil equilibrium level temperature and/or height. In many ways, this technique is better to use than cloud top growth rates

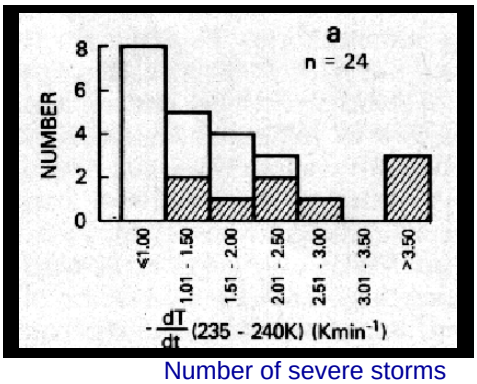
Estimating updraft intensity with satellite: part 1

- Recommended Prerequisite
  - Be familiar with the Interactive cloud height algorithm in D2D
  - Training is available at
    - http://www.cira.colostate.edu/ramm/visit/cldhgt.html

I mentioned that the D2D cloud top height tool is used in evaluating some of these techniques. This tool was developed by the Aviation Weather Center to help forecasters write convective sigmets around the world. Now that this technique is available to all, this tool should help you out in convective forecasting. The VISIT program has developed a training session for the general use of this tool at http://www.cira.colostate.edu/ramm/visit/cldhgt.html. The session is generic in the use of this tool. Here we provide some specific potential applications.

CTT cooling rate pre-anvil

- Note that cooling rates are ≳2° K/min for most severe storms based on limited samples
  - Prior to anvilgenesis
  - 2° K/min corresponds to only 4 m/s of updraft



Number of severe storms are shaded.

From Adler et. Al 1985

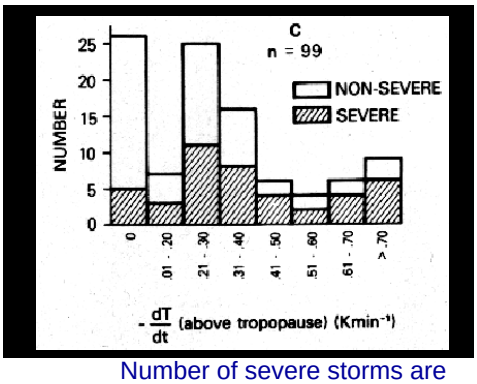
Satellite-based severe thunderstorm analysis research peaked in the mid 1980's prior to the advent of the WSR-88D because of the incentive to provide more information than the old radar system could provide. Some of the results from that time are still relevant today but there are caveats since we are now talking about higher resolution satellite imagery. Nevertheless, I present some of the techniques devised then in our current framework.

Adler et al 1985 approached discriminating severe from nonsevere storms using the cloud top cooling rate determined from rapid scan GOES imagery. After several severe storm outbreaks, they found a fairly good relationship between cooling rate and eventual severe weather reports.

This bar chart shows the maximum cooling rate found in a storm before it had a chance to produce an anvil. Note that the storms that went on to produce severe weather (gray shaded bars) tend to dominate when the cooling rates exceeded 2 degrees/minute. This only corresponds to a 4 m/s updraft. Poor resolution was blamed for the low values. GOES IR imagers before the advent of GOES 8 had a 4X8 km field of view at nadir (below the satellite). Now we have routine 2X4km imagery. Today's cooling rates are higher as a result and so this graph's purpose is to highlight the relationship, rather than specific thresholds.

CTT cooling rate post-anvil

- After anvilgenesis, overshooting top cooling rates are much smaller.
- If the cooling rates > 0.4° K/min severe storms were more likely in this dataset.



Number of severe storms are shaded.

Sampled from typical mid-western severe events

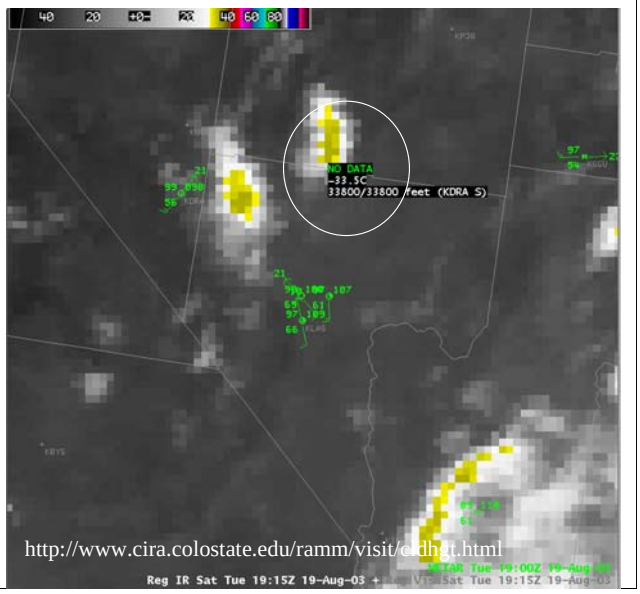
From Adler et. Al 1985

As the storm creates an anvil, and the overshooting top begins to extend above it, the cooling rate typically slows down. Following updraft surges also have slower cooling rates. The reason is that the overshooting top growth is in a region of negative buoyancy. Adler et al 1985 reflects this with much smaller cooling rates. Instead of 2 deg/min, now we are talking 0.4 deg/min as a strong severe/nonsevere thunderstorm discriminator. Again, these cooling rates reflect the maximum cooling rate found in the overshooting top prior to the severe report.

Another word of caution, their database was limited to major spring severe storm outbreaks with strong vertical windshear. We will look at multiple events as examples later.

Cloud top cooling rates example Storm A

- Initiation in pre-anvil stage north of LSV (Storm A)
- Use the cloud height algorithm to track cooling rate and cloud top growth



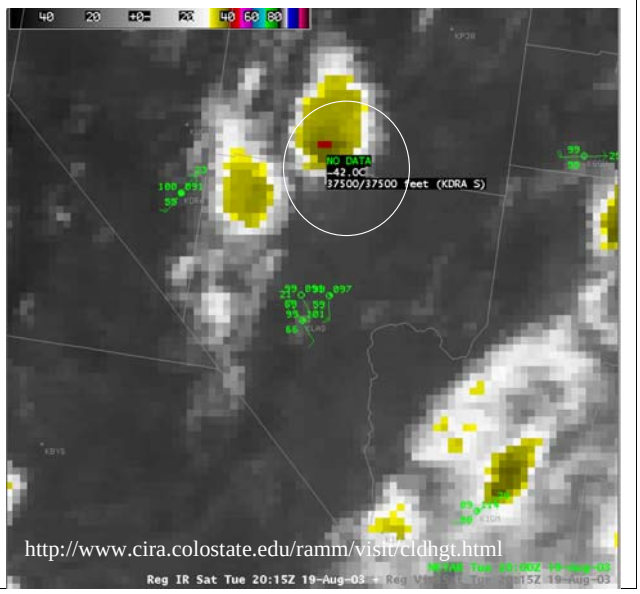
This storm is embedded in a monsoon environment with a shortwave trough moving northwest through AZ. It is generating off some high terrain north of LAS.
GOES-10 is in normal scan mode and the D2D cloud height algorithm is basing the cloud top height on the KDRA sounding at 12 UTC. It may be a bit on the dry side but should be fairly relevant when trending the cloud height and temperature.
Right away, notice the 6 deg temperature drop in the overshooting top in 15 minutes.

This is the pre-anvil growth stage of this storm.

See http://www.cira.colostate.edu/ramm/visit/cldhgt.html for the training on the AWIPS cloud height algorithm.

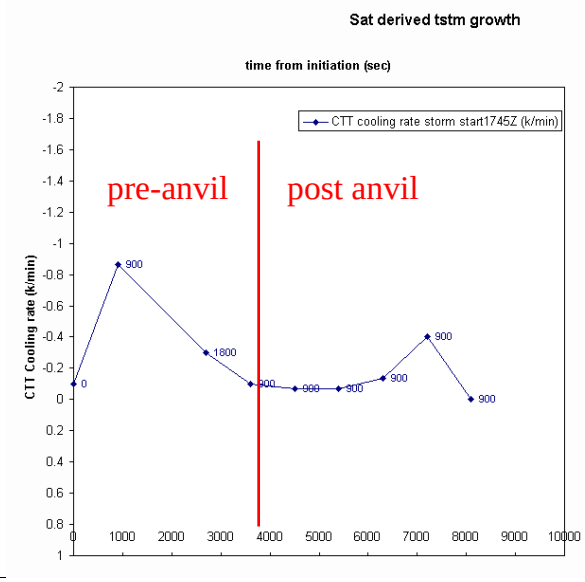
Cloud top cooling rates example Storm A

- post-anvil stage north of LSV (Storm A)
- Use the cloud height algorithm to track cooling rate and cloud top growth



In these three frames of this loop, this storm is now creating an anvil and any growth rate during this part of the storm growth can only be compared to the growth rates of storms after their respective anvils have formed.

Cloud top cooling rates example Storm A



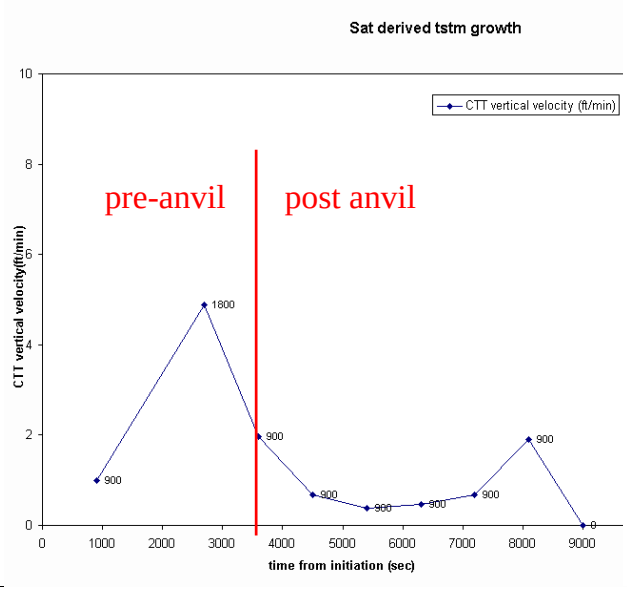
- Peak Pre-anvil cooling peaks at -0.9° C/min
- Peak post-anvil cooling = -0.4 C/min
- This is 15 minute data
- Adler's used 5 minute data

Time trends of temperature were taken of this storm from first cumulus to reveal this graph. Note there are large temporal gaps in the imagery which tend to overlook rapid growth spurts (see between 1000 and 2500 seconds). Still, the maximum temperature rate of –0.9 K/sec occurs in the first stages of the towering cumulus.

After anvilgenesis the peak cooling occurs as a followup updraft surge cools the overshooting top by 0.4 K/sec at 7200 seconds after initiation.

These rates are small compared to Adler's work. Adler et. al 1985 used 5 minute data, and if we had access to such, we would get higher rates. However, our higher resolution imagery should produce higher rates than Adler et. al 1985. Do the competing differences cancel each other? We don't know.

Cloud top vertical velocity example Storm A

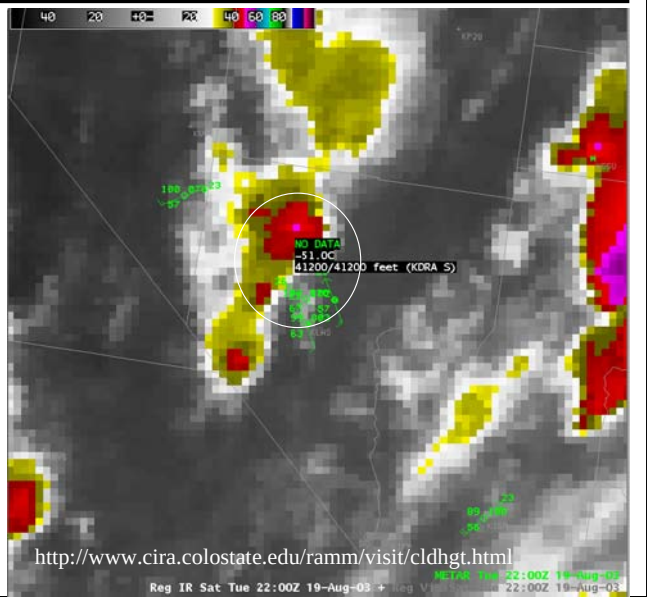


- Peak Pre-anvil cloud top vertical velocity = 5 mph
- Peak post-anvil cloud top vertical velocity = 2 mph

Converting temperature rate to growth rate of storm top height gives us maximum vertical motions of 5 (2) mph for the pre- (post) anvil stage respectively. To create this graph, I simply read off the maximum cloud height found nearby the cursor using the D2D cloud height algorithm (see the altitude on the right in the cursor readout) These results agree with Adler's results very nicely. We'll compare this storm with another one that formed closer to Las Vegas.

Cloud top cooling rates example Storm B

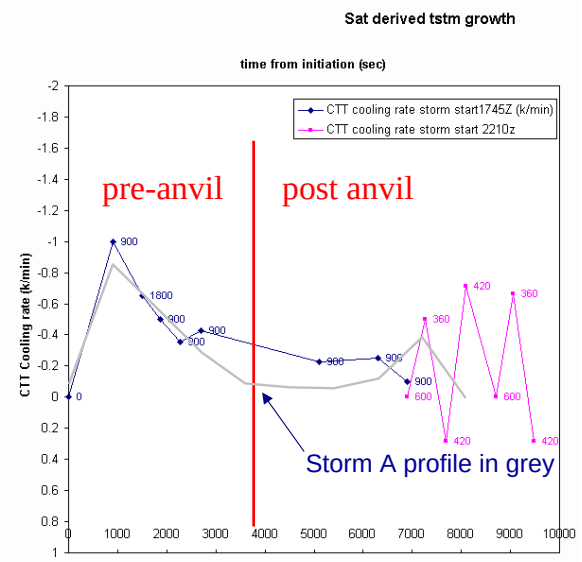
- Storm B initiates on high terrain and outflow from the west
- Let's compare with storm A



Storm B initiates on the high terrain northwest of the city's northern Suburbs near an implied outflow boundary (inside the white circle). Now we have RSO operations going on GOES-10. I cannot emphasize enough the importance of having RSO imagery should you try any of these techniques. Note the cloud tops are taller with this storm.
There are two separate updraft surges within this multicell. This loop shows only the first surge, mostly prior to anvil production.

See http://www.cira.colostate.edu/ramm/visit/cldhgt.html for training on the AWIPS cloud height algorithm

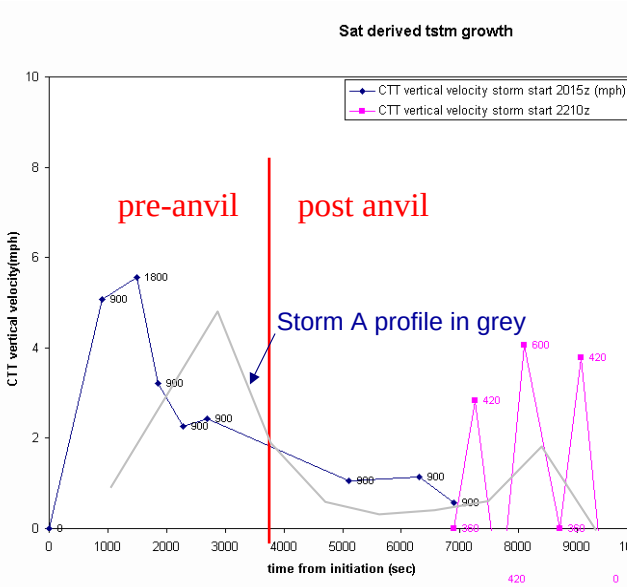
Cloud top cooling rates example Storm A



- Peak Pre-anvil cooling peaks at –1.0° C/min
- Peak post-anvil cooling = -0.7 C/min
- RSO begins at the purple time trend for the 2nd updraft surge

This graph compares storm A and storm B, where the storm A profile is set in a grey background. Both have also been set so that the timeline is time from initiation for both storms. Note that both of them exhibit a rapid growth but that storm B is a little more rapid than storm A, given the same image frequency. Storm B continues to show the same or more rapid cooling through its pre-anvil stage. During the post-anvil stage, the overshooting top is also more rapid than storm A. A second updraft surge, shown in purple, exhibits wild fluctuations in cooling rate but that the highest values are higher than with storm A.

Cloud top vertical velocity example Storm B



- Peak Pre-anvil cloud top vertical velocity = 5.7 mph
- Peak post-anvil cloud top vertical velocity = 4 mph for secondary pulse (purple)

Similarly, using the AWIPS cloud height estimator, peak updraft speeds are up to 5.7 (4) mph prior (after) to anvilgenesis.

Actual updrafts are much higher given:

1. that the satellite field of view is larger than individual updraft pulses,
2. that the IR imager only senses cloud edge in the zone of mixing, and not parcel core temperature
3. After anvilgenesis, updraft strength converts mainly to anvil-level divergence owing to adverse buoyancy gradients

Therefore 5.7 mph, or 501 ft/min is a significant number in the towering cumulus stage, and 4 mph or 352 ft/min is quite big.

Interim summary: cloud top cooling rates

- Storm B produced 1.25” hail and 70mph winds over LSV
- Storm A had no reported severe weather
  - Low population density
- The peak cloud top cooling and ascent rate for the storm should be used
- Different criteria before and after storm produces an anvil

Storm B went on to produce 70 mph winds and 1” hail. No reports came in for Storm A, although I caution that storm A originated over relatively unpopulated territory and there may have been unreported severe weather at the surface.

Note that we used the peak cooling rates prior and after anvilgenesis for the lifetime of a particular single or multicell event.

Remember that cooling rates pre- and post-anvil are distinct and should be treated separately.

Interim summary: cloud top cooling rates (contd)

- Cooling rates are dependent on image temporal frequency
  - Faster scans usually result in higher growth rates
  - Really need 30 second scanning to capture individual updraft growth spurts
- Best to make relative comparisons
- Another technique next

There are real problems using this technique, the worst of them is the uncertain image time interval. Cooling rates can be more a function of image frequency than anything real. A good check

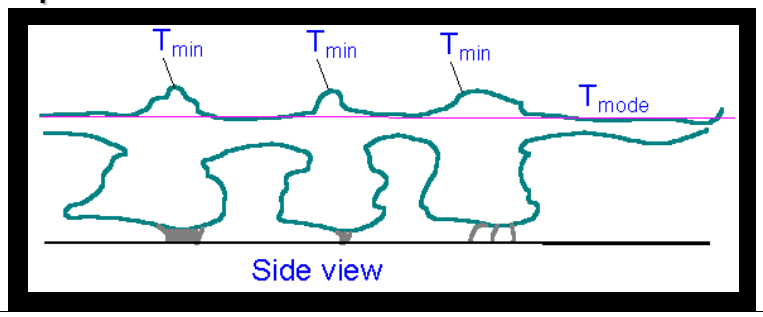
The optimal frequency should be 30 seconds, which the GOES satellites have done under research operations.

Probably the best way to assess cooling rate is to compare cooling rates between storms in a similar environment.

The next satellite-based updraft intensity technique may help a bit to account for image frequency problems.

Anvil equilibrium temperatures

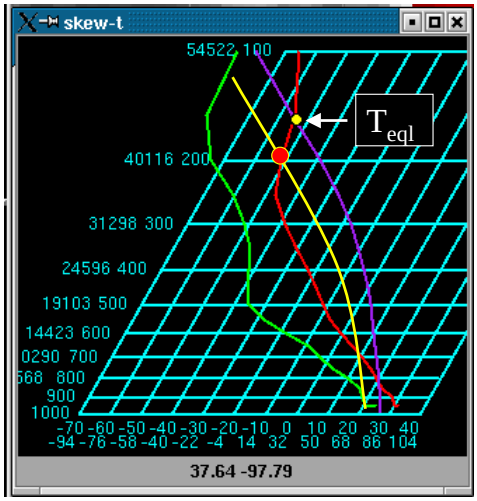
- Each convective cell has its own equilibrium level height which is visualized on satellite data as relatively flat areas of anvil.
- Represented by the mode of the brightness temp



When a thunderstorm updraft does reach its own equilibrium level (EL), anvil material spreads out to form a relatively flat region around the updraft overshooting top. This flat region is relatively large, larger than the field of view of the GOES imagery, and therefore, its temperature is easily resolved by the imager. Quantitatively, the mode of the brightness temperature reveals the flat region of the anvil.

Anvil equilibrium temperatures

- The standard parcel theta-E (purple) gives an equilibrium temperature (T_{eql}) of -55° C
- However, if the storm is entraining dry air, or is elevated, the actual theta-E realized (yellow) may give a warmer T_{eql}



Every convective cell has its own equilibrium level, quite distinct from what your RAOB or model sounding may tell you.

There are a million reasons for this to happen, the most frequent may have to do with dry air entrainment with updraft parcels. Another reason may be that the parcel originated at a level or incorporated air at different levels than the chosen method of deriving the theoretical parcel.

As a forecaster, you can sample the brightness temperature of areas that appear flat around the overshooting domes. The equilibrium level brightness temperature can be theoretically converted to the updraft parcel θ_e for the storm by looking on the sounding to where the EL . Then comparing θ_e based off the satellite EL to that of a representative sounding should provide an impression as to how close to the sounding θ_e the storm in question realized. A storm that is utilizing all of the potential θ_e shown in the sounding should have an EL brightness temperature close to the EL temperature in the sounding (purple curve with yellow EL). Storms experiencing loss of updraft θ_e through dry air entrainment, or a different level or parcel origin should show a warmer EL brightness temperature than the sounding suggests (yellow curve with red EL).

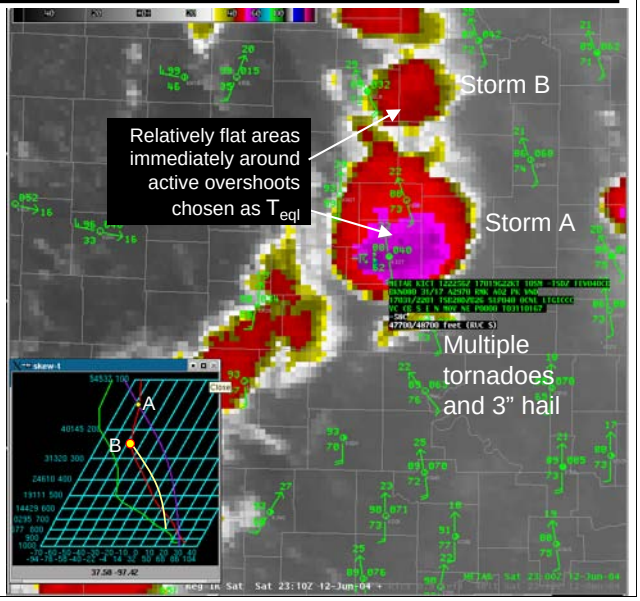
In theory, this technique appears straightforward but there are complications as follows:

1. The comparison environmental sounding is wrong
2. Storm anvils modify the upper-level temperature environment and change your sounding. Anvils warm the environment at their bottoms and cool the environment at the top. Large contiguous anvils push the tropopause upward and cool it down so that subsequent updrafts are able to reach cooler brightness temperatures without necessarily being more intense.
3. An inversion at the EL may complicate the relationship between cloud height and brightness temperature. As stronger updraft pulses create a higher EL, the brightness temperature may not change or even show warmer values.

Overall, this technique should be better than attempting to find the height of an overshooting top and comparing that to the sounding. The reason is that resolution, and cloud edge

T_{eql} example

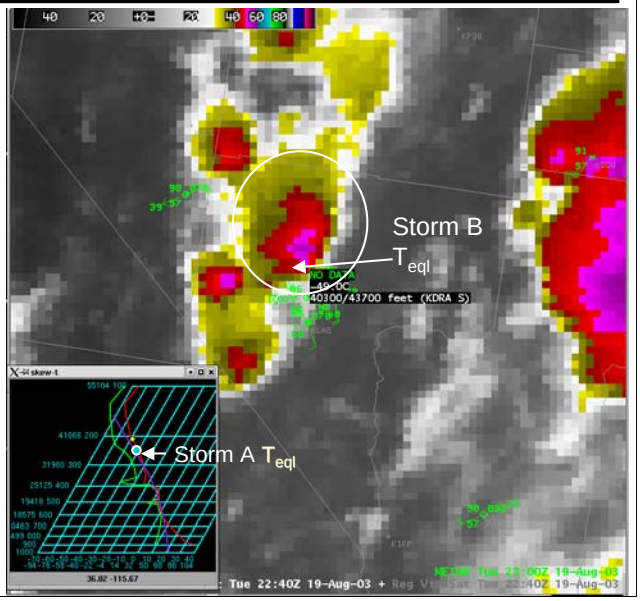
- 12 June 2004
- Storm A appears to be realizing all available SBCAPE
- Storm B is **not** realizing the available SBCAPE



A good example of the application of this technique is to examine storm behavior in a comparitive sense. On 12 June 2004, two storms in Kansas formed along a dryline. Given similar surface dewpoints, storm B looks relatively anemic vs. Storm A. Investigating the areas of relatively flat brightness temperature around the overshooting gives me an idea that the two storms have highly different EL temperatures. Storm A appears to be realizing all the SBCAPE found in the RUC model data in its proximity (see "RUC" in the AWIPS cloud height cursor readout). Storm B appears to be grossly underutilizing the SBCAPE available to it, and therefore realizes a much smaller θ_e . Storm B eventually dissipated while A went on to produce all sorts of severe weather.

T_{eql} example 2

- Back to LSV
- Storm B T_{eql} is colder than Storm A.
- Storm B is likely accessing higher theta-E air from near LSV

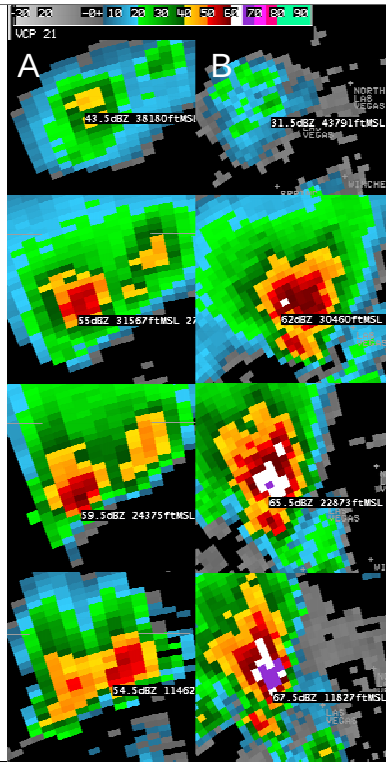


Going back to the LSV example, storm B is the storm that struck LSV with hail, strong winds, and flooding. Note that Storm A has a much lower EL temperature than Storm B. It is likely that Storm B is accessing higher θ_e air from the Colorado River Valley than Storm A. Or Storm A never realized the low-level θ_e air available to it. Either way, storm A likely has a weaker updraft than B.

http://www.cira.colostate.edu/ramm/visit/cldhgt.html

T_{eql} example 2

- Compare the storm A (left) and B (right) to note the relatively larger and more intense core that corresponds to the higher anvil equilibrium level



We can add evidence to the conclusion by noting that Storm B (right column) has a much stronger core with higher reflectivities.

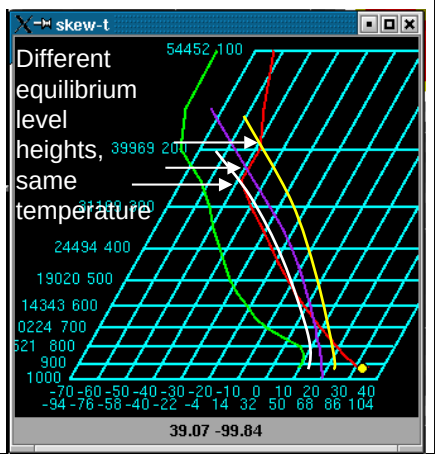
Interim summary: Anvil T_{eql}

- Strengths –
  - Allows you to approximate the theta-E the updraft is realizing.
  - Relative strengths between storms
- Limitations
  - Required anvil exposure to undisturbed environment
    - Storm complexes push the equilibrium level higher
  - T_{eql} and height ambiguity in isothermal layers and inversions at the equilibrium level

To summarize, assessing the satellite based EL temperature can give you clues as to the θ_e in the updraft column, and therefore how well the storm is utilizing the θ_e found in its environment. Use this technique to assess relative updraft strengths between adjacent storms. But be careful. The storm anvil should be exposed to undisturbed environment free of pre-existing anvils. Equilibrium temperatures may also lose their relation to anvil height where isothermal layers or inversions exist across the EL.

Interim summary contd: Anvil T_{eql}

- Limitations: T_{eql} and height ambiguity contd.
  - Isothermal layer on right may result in ambiguity of equilibrium level height



This is an example of the EL temperature and height ambiguity in an isothermal layer. All three parcel θ_e profiles give out the same EL temperature. I'm sure the updraft strengths would not be the same, however.

Other satellite-based severe convection training materials

- Enhanced-V's and what they mean
  - http://www.cira.colostate.edu/ramm/visit/ev.html
- More on how Enhanced-Vs are formed:
  - http://www.nssl.noaa.gov/istpds/icu624/
- Interpreting Rapid Scan Operations data
  - http://www.cira.colostate.edu/ramm/visit/rso3.html
  - http://www.cira.colostate.edu/ramm/visit/newrso.html

Here are some extra satellite-based training sessions that address severe storms detection. There is another session centered on a case that illustrates the supporting role of satellite data while interrogating storm structure.

Contact info

- If you have questions write to this group e-mail to ensure a quick response
  - icsvr3@wdtb.noaa.gov

Storm Interrogation

AWOC Severe Track

IC3-II-E

Estimating updraft intensity with satellite: part 2

Storm Interrogation: Estimating Updraft Intensity with Satellite – Part 2

This session is a followup to part 1 of estimating updraft intensity with satellite data. It is short with 11 slides and should take 15 minutes to complete.

Estimating updraft intensity with satellite: part 2

- Objective
  - Utilize the following satellite signatures to assist radar in estimating updraft strength and severe storm potential
    - overshooting top characteristics,
    - presence of an enhanced-V,
    - anvil shape vs. storm-relative anvil-layer flow,
    - and anvil top temperatures.

This objective uses a case to highlight how the following signatures can be used to assist radar in estimating updraft strength and severe storm potential. We will mention:

•Overshooting top characteristics,

•enhanced-V signatures,

•anvil shape vs. storm-relative anvil-layer flow,

•and Anvil top temperatures.

We will also look at the radar presentation of this storm and some near storm environmental information.

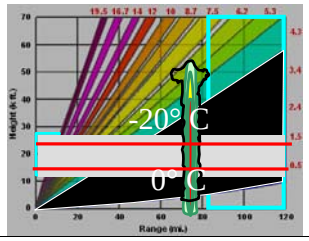
Estimating updraft intensity with satellite: part 2

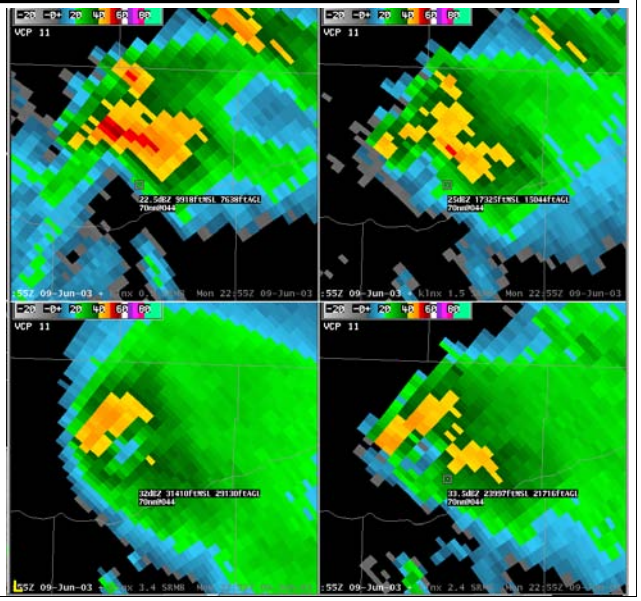
- Suggested prerequisite
  - Part 1 of Estimating updraft intensity with satellite

This is a followup to part 1 of estimating satellite updraft intensity. Because of this, many satellite-based signatures will be mentioned but not explained in any detail. If there is anything that confuses you, refer to part 1 of this session.

Example case

- Northern Nebraska
- Is this updraft severe enough to put out a warning?
- If so, what kind of weather do you expect?





This is a developing storm in northern Nebraska on 09 June 2003. It just recently formed ahead of a dryline bulge near or just south of a warm front. A fairly significant 500mb short-wave trough is coming in from the west and SPC has a MDT risk out for the area.

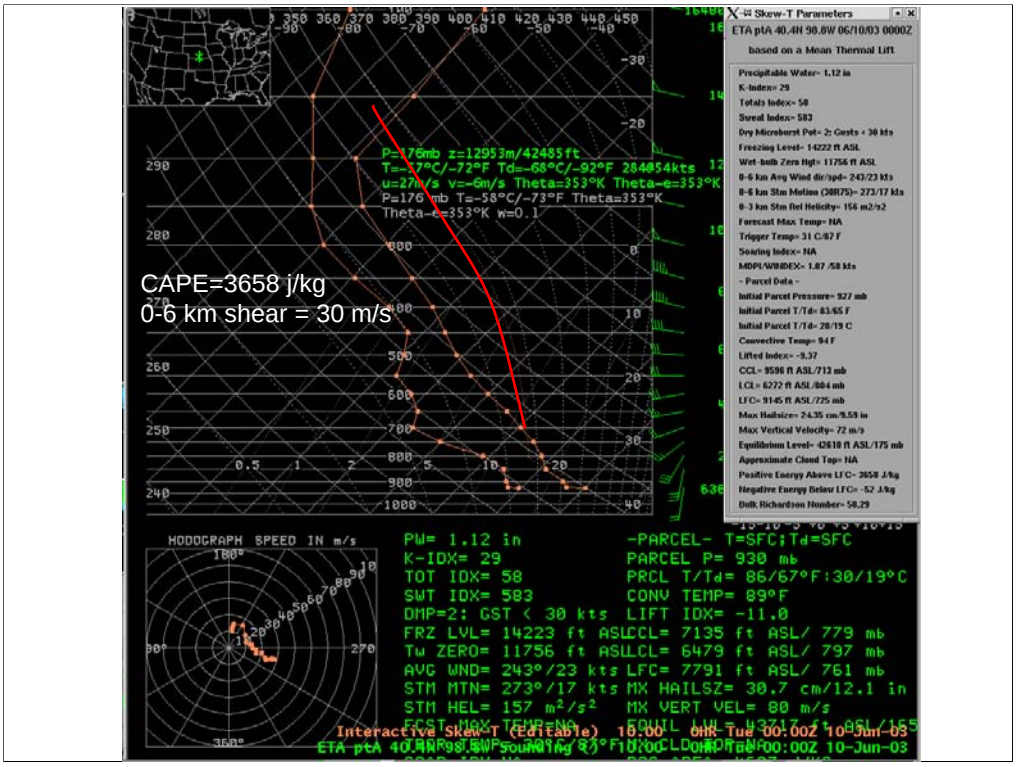
The three frames of this loop show what appears to be a supercell structure with a low-level sharp concave reflectivity gradient, and what appears to be a BWER at 2.4° and 3.4° in elevation, or 21 to 25 kft AGL. However, the surrounding reflectivity is extremely weak at high altitudes. The only reflectivities > 60 dBZ are located at the lowest slice, well below the freezing level.

Is this echo hole a true BWER, one with intense updraft or is it a gap between two cells?

What is this cell capable of doing?

Would you issue a warning based on this data alone?

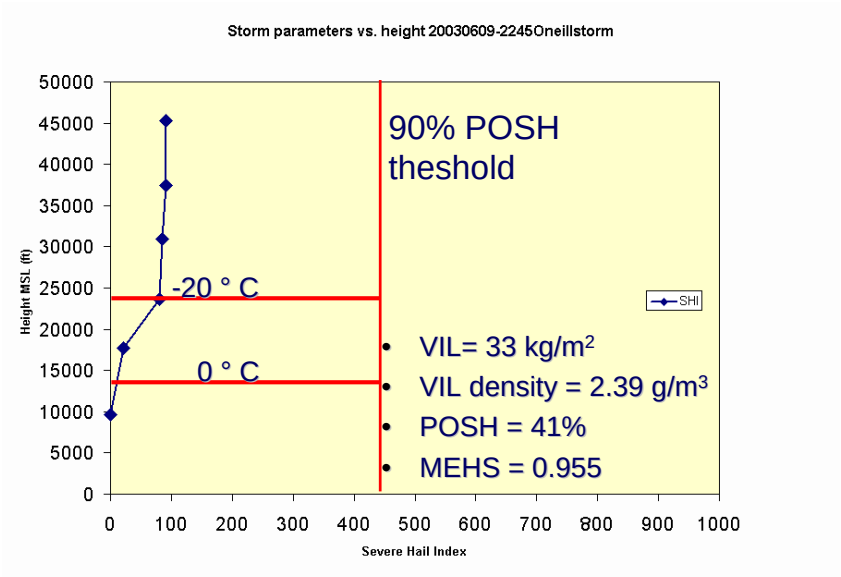
Let's take a look at some more information.



Since this storm is not near any RAOB sounding, I chose to pick an ETA analysis sounding at 00 UTC. During the actual event, this would've been impossible but a RUC or LAPS sounding showed a similar sounding profile to this one. This sounding shows strong 0-6 km shear of 30 m/s, more than enough for supercells. Steep lapse rates and high CAPE means any storm could go severe quickly and be supercellular in nature.

The environments support the radar structure to be more supercellular than two components of a multicell. But what about the low reflectivities?

Vertical storm profile 2245Z

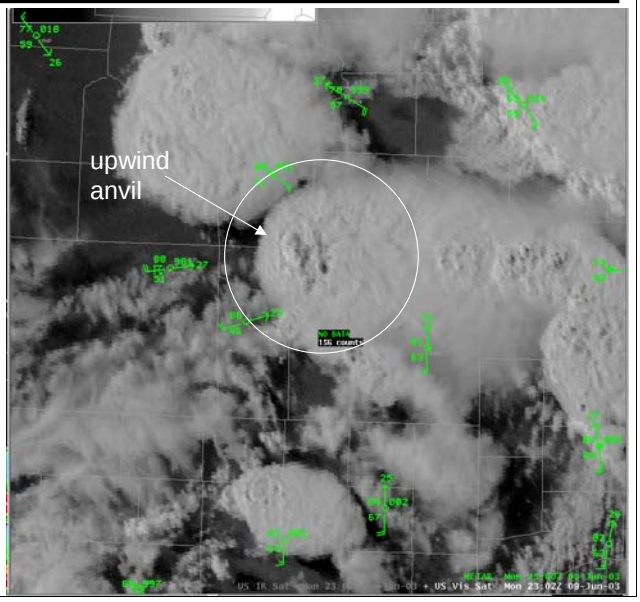


If I take the vertical reflectivity profile for this event, and apply the HDA/VIL tool discussed in the lesson on updraft intensity and reflectivity core heights, I see a slowly decreasing profile of reflectivities, especially where it is needed to increase the Severe Hail Index (SHI). VIL reaches only 33 kg/m^2, VIL density is only 2.39 g/m^3, and SHI is far less than what's needed for a Probability Of Severe Hail (POSH) of 90% (it is only 41%). The Maximum Expected Hail Size (MEHS) seems a bit high given this profile but it is barely over severe limits.

The reflectivity profile does not support any warning, and hasn't in all three volume scans.

Visible images 2245&2300 UTC

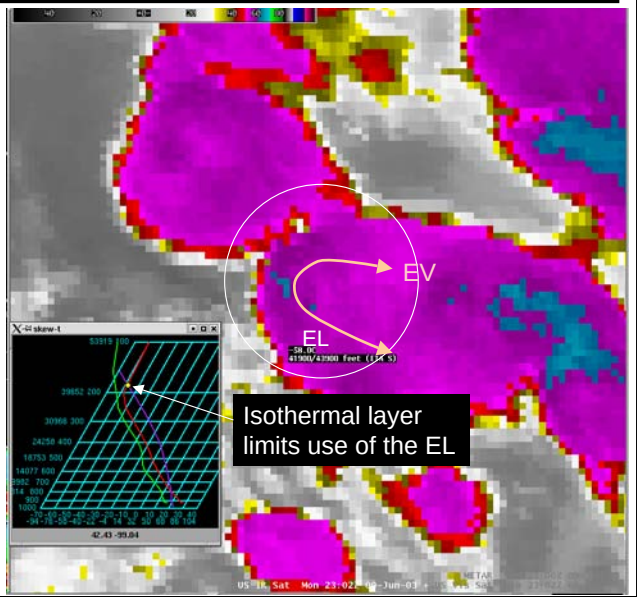
- Strong overshooting top clearly visible
- SR anvil layer flow ~ 20 m/s
- But upwind anvil growth evident



The GOES-12 visible imagery shows a well defined overshooting top with a long anvil downwind and yet, significant upwind anvil growth. The Storm Relative anvil layer flow is about 20 m/s which is in the range to support classic supercells according to Rasmussen and Blanchard (1998). The presence of upwind anvil growth and the classic oval shaped anvil in the face of 20 m/s SR anvil layer flow supports the shape and morphology of the radar structure implying a severe updraft.

Visible images 2245&2300 UTC

- IR shows a weak enhanced-V
- T_{eql} indicates boundary layer moisture being accessed
  - However the layer is isothermal
  - A lower equilibrium level still gives the same T_{eql}



The GOES-12 IR imagery indicates that the brightness temperature EL based on the AWIPS cloud height tool is about where the ETA analysis expects it to be. However, note that there is an isothermal lapse rate across the EL. This means that a fairly broad range anvil EL heights may give similar brightness temperatures. We will not use the EL method here. However, the presence of a weak Enhanced-V and a cold overshooting top supports the visible imagery and the radar reflectivity shape that this storm is a supercell.

Summary of this case

- Radar
  - Weak reflectivities
  - evidence of BWER and WER but no marginal echo overhang reflectivities
- Satellite
  - Evidence of Enhanced-V
  - Strong overshooting top
  - Upwind anvil growth against 20 m/s SR anvil layer flow
- Decision?

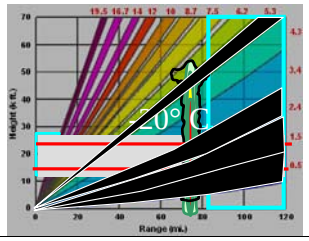
To summarize, the radar showed weak overall reflectivities. The HDA and techniques using the vertical reflectivitiy profile of this storm fail to indicate the potential for severe weather. The presence of a WER is suggested but the classic definition of a WER is one that is overlaid by an intense echo overhang. This is not a classic WER and the same logic applies to the BWER presented here.

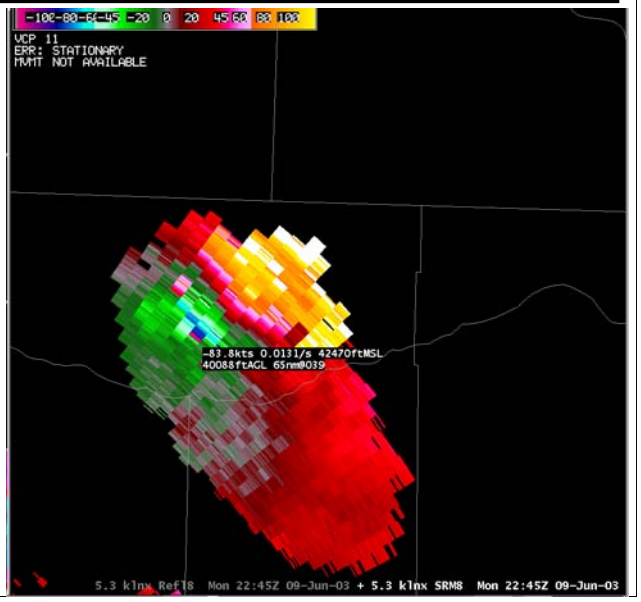
The GOES 12 IR/VIS data support the argument that the WER and BWER are legitimate indicators of a severe updraft, even if they are not surrounded by high reflectivities aloft. The enhanced-V indicates the presence of a strong, persistent updraft in a sheared environment. Evidence of an overshooting top and upwind anvil growth against 40 kts of SR anvil layer flow both add additional support for a severe updraft.

The storm appears to be a supercell with a strong updraft. This is not a high end updraft capable of creating baseball hail but it appears at least strong enough to support golfball hail. The lack of intense reflectivities suggest an LP supercell in appearance and probably has difficulty in developing any kind of severe downdraft. I will go for golfballs in this storm and they are likely to be widely scattered otherwise high reflectivities would show up throughout the storm.

Example case

- This velocity all-tilts scan should help
- What is your decision?





I purposely kept the velocity from entering into our analysis until now. But upon showing it, this storm clearly has a classic midlevel mesocyclone and intense updraft summit divergence of nearly 160 kts. This only adds evidence and confidence that this updraft is significantly strong.

At 2300 UTC, golfball hail was observed by storm chasers from a supercell with visually LP appearance.

Summary

- Low Precipitation supercell
- Severe hail potential higher than weak reflectivities suggest
- Structure analysis along with impressive satellite appearance suggests greater severe potential than the hail algorithm suggests
- Golfball hail reported at 2300 UTC

This is a low precipitation supercell that has a higher severe hail potential than any VIL or HDA products can estimate. There is a BWER and the proper shape of a supercell but the criteria that the BWER must be surrounded and capped by high reflectivities not being met might cast a bit of doubt about the structure indicating a severe updraft. However, the presence of an enhanced-V, large overshooting top, and the velocity structure showing a strong mesocyclone and storm top divergence adds credibility to the fact that this storm's updraft is very strong.

Golfball hail was reported by storm chasers at 2300 UTC.

Storm Interrogation

AWOC Severe Track

IC3-III-A

Tornado Warning Guidance – Mesocyclone analysis and sampling

Welcome to AWOC Severe Track

IC3-III-A

Tornado Warning Guidance – Mesocyclone analysis and sampling

It is about 18 slides long and should take 20 minutes to complete

TWG: mesocyclones

- Objectives
  - Interpret mesocyclones and how they fit into providing the necessary tornado ingredients given radar sampling limitations
  - Know how the overall tornado warning skill scores may be related to mesocyclone strengths
  - Understand the impacts of radar sampling on mesocyclone strength and strength trends

The main objectives center primarily on how mesocyclones fit into satisfying the ingredients for tornadogenesis, what the most effective parameter is, and how effective it is at discriminating tornadic from nontornadic mesocyclones, and how sampling affects its strength and when to know If a trend in rotational velocity is real.

TWG: mesocyclones

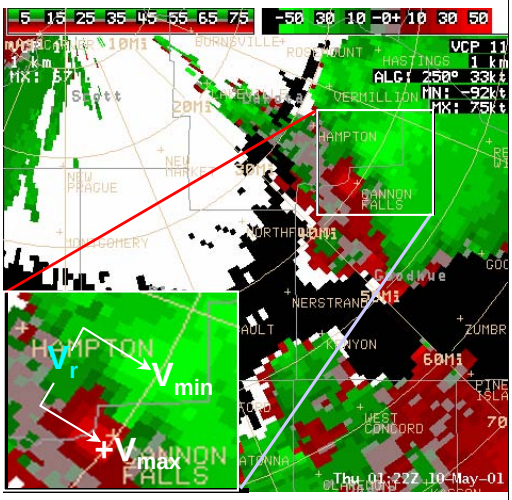
- Motivation
  - Weakening mesocyclones may just be a radar artifact
  - The impact of range on tornado warning performance based solely on mesocyclone low-level rotational velocity is not as simple as previously thought

All too often I am tempted at discontinuing a tornado warning when a mesocyclone begins to weaken. Is the mesocyclone truly weakening or is it a radar artifact? This session may help you in your decision.

A second motivation puts into light the difference that range from radar has on mesocyclone rotational velocity and tornado discrimination performance. They do not necessarily coincide and we show you how they differ.

Mesocyclone - review

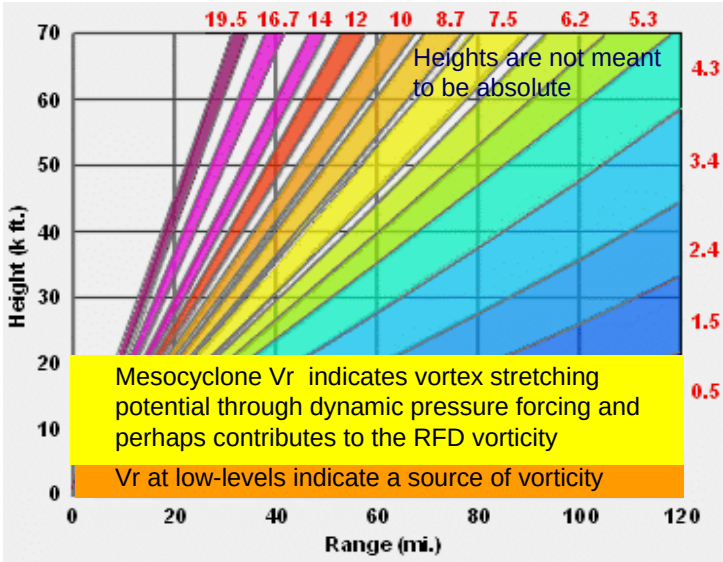
- Core diameter from **V_{min} to V_{max}** should not exceed 5 nm
- Rotational Velocity $V_r = (|\mathbf{V_{min}}| + |\mathbf{V_{max}}|)/2$ exceeds user thresholds
- Vertical continuity above the low levels adds confidence mesocyclone has some correlation with an updraft



As a refresher, when we define rotational velocity (V_r), it is the average of the absolute magnitudes of the maximum and minimum velocities found at some distance from the center of rotation. A mesocyclone contains azimuthal runs of continuously increasing velocity between the peak minimum and peak maximum velocities. Sometimes that run of adjacent range gates with increasing velocity is very short, especially when the mesocyclone is not much larger than the widths of the individual gates. This is where sampling issues come in when measuring V_r .

A mesocyclone should have vertical continuity and this leads to a mesocyclone having V_r measured at multiple elevations. The lowest elevation V_r is the one we will measure most often when assessing its potential for tornadogenesis.

Mesocyclones and tornado ingredients



This is what we do know:

Mesocyclones depicted on radar contribute to the ingredients for tornadogenesis either by showing the source of low-level vorticity available for stretching into tornadic scales or by showing where nondynamic pressure deficits act to enhance upward parcel accelerations, and vortex stretching below the mesocyclone detection level. This level may be very low.

What we do not know:

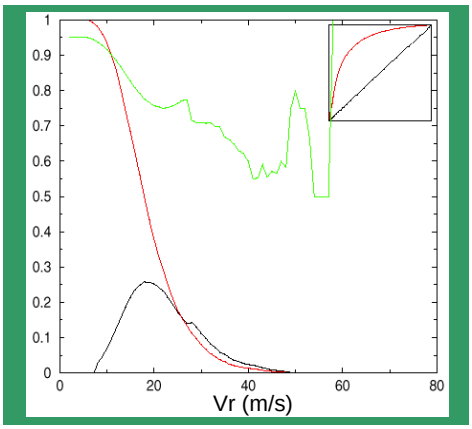
How does the mesocyclone serve the Rear Flank Downdraft (RFD) in vorticity transport? We know the RFD is rich in horizontal vorticity which then tilts into the vertical as it reaches ground. But the evolution of the vorticity from the front flank of the updraft, tilted into the mesocyclone and then its possible contribution to the RFD is unknown at this point.

Mesocyclone best predictor

MDA = Mesocyclone Detection Algorithm available in AWIPS OB4

This parameter is testable by user

MDA low-level rotational velocity: V_r (m/s)



FAR = green line
POD = red line
HSS = black line

Inset = POD vs FAR

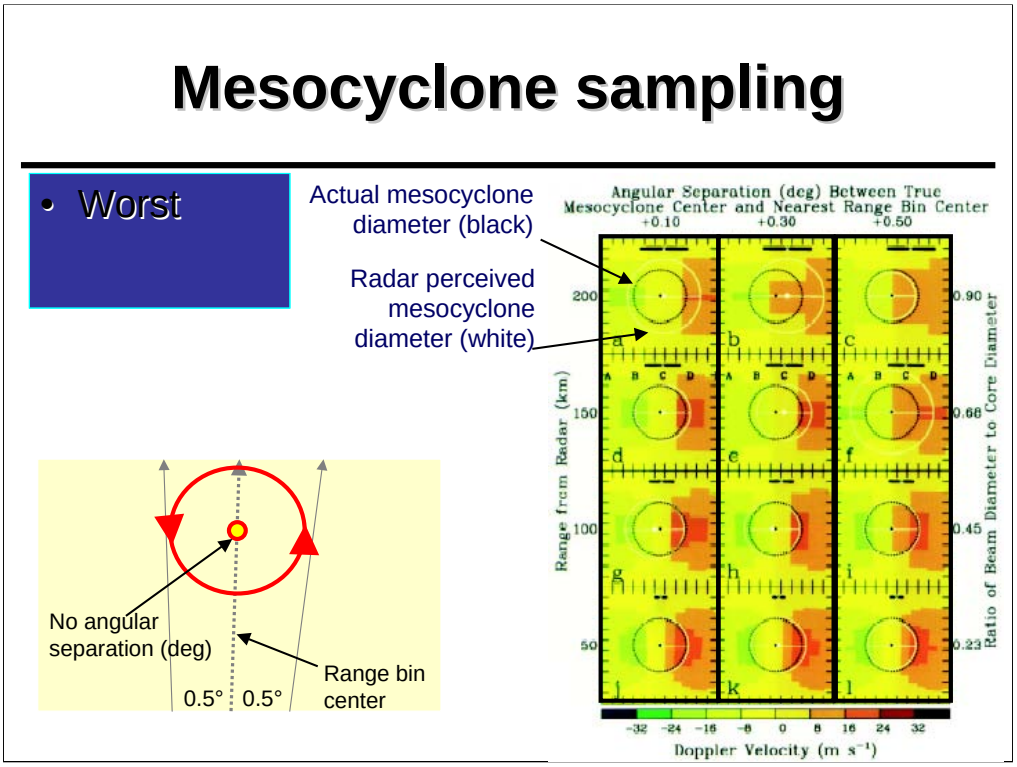
http://www.wdtb.noaa.gov/resources/PAPERS/twg02/index.html

A project between NSSL and WDTB was conducted in 1999 and 2002 to determine the skill scores of multiple radar and near storm environment parameters in discriminating tornadic and nontornadic radar detected mesocyclones and Tornado Vortex Signatures (TVS). The scope of the study went on to generate a neural network incorporating hundreds of parameters describing the mesocyclones and TVSs and near storm environment data. Results were mixed, however several important findings came out of the study.

For radar-based parameters describing mesocyclones, one of the best tornado discriminators wound up being low-level V_r. Using low-level Vr as a threshold and varying that threshold incrementally, we generated a graph of its skill in tornado discrimination. For example, at time T, the low-level Vr was evaluated by the mesocyclone detection algorithm (MDA). If the mesocyclone was within T-20 minutes to T+5 minutes of a tornado, that particular measurement of low-level Vr would be considered a hit. Otherwise, it would be a miss. After thousands of detections from many years spanning the country, statistics were created for low-level Vr, amongst hundreds of other parameters.

Note that the FAR remains high, never falling below 60%, and staying above 70% for most values of Vr. The POD drops off considerably as low-level Vr increases beyond 15 m/s (30kts). The black curve represents the Heidke Skill Score (HSS), a better skill score than Critical Success Index (CSI). The HSS accounts for correct null decisions (forecast of no and none observed) which the CSI does not. Note that the HSS peaks at roughly 20 m/s (40kts). However, there is a broad range of good HSS skill scores. If you waited till the Vr reached 20 m/s before issuing a tornado warning, your skill scores would be maximized. Just remember though that these skill scores don't have to answer to asymmetric penalty ratios, or take into account different environments with different sized mesocyclones. All mesocyclones of all sizes in all environments were lumped into these results.

I mention that low-level Vr is one of many parameters describing a mesocyclone. In actuality, there are other parameters that are slightly more skillful than this one. These include ones such as integrated rotational velocity, and mesocyclone strength rank. Both of these parameters cannot be easily evaluated by manual inspection of base data. They are available, however, in the MDA. The MDA will replace the current mesocyclone algorithm by AWIPS OB4.



Any mesocyclone velocity-based parameter suffers from sampling limitations owing to:

1. the ratio between the mesocyclone diameter and the beam width,
2. and the location of the mesocyclone center with respect to the beam center (measured by angular separation).

Note that the angular separation is zero when the mesocyclone center is located on the beam centerline, and rises to 0.5° when the mesocyclone straddles the edge of a beam. A mesocyclone is optimally sampled if the angular separation is 0.5°, or when none of the beams samples both sides of a mesocyclone and average out its velocities. Meanwhile the mesocyclone is large compared to the beam width when the ratio of beam diameter to mesocyclone core diameter is small. Look on the vertical axis to the right of the 12 panel and you will see this ratio appear small when the mesocyclone is large compared to the beamwidth and is well sampled. The smaller this ratio is, the less important angular separation becomes since a smaller portion of the mesocyclone velocities are affected by angular separation.

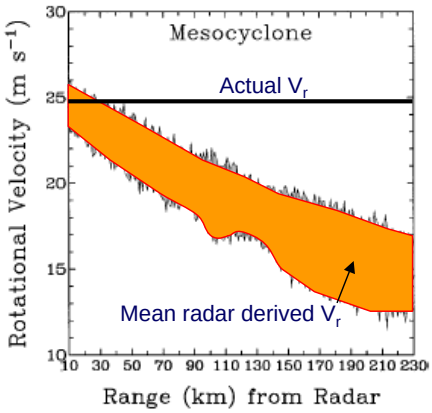
Results from a sampling study conducted by Wood and Brown (1997) show how these two considerations interact to reduce the maximum velocities and change the appearance of a mesocyclone. The 12 panel image on the right shows how a theoretical mesocyclone with a diameter described by the black circle and a Vr of 25 m/s changes according to angular separation and distance from the radar. The theoretical mesocyclone is 3.5 nm in diameter. But note that the radar's interpretation of the mesocyclone diameter (white circle) starts to change as the mesocyclone becomes smaller relative to beam width.

Look at the top row (range=200 km) where the mesocyclone diameter is just a little larger than the beam width. Three scenarios are presented:

1. An okay angular separation of 0.3° leads to a gate-to-gate signature similar to that of a TVS but the mesocyclone diameter is too high (see white circle) and a little off center.
2. The next slide shows the best condition where there is no angular separation and the mesocyclone is seen by the radar to be in the correct place and size. Vr is a little low since the maximum velocities exist in an area too small for adequate resolution.
3. Now, if the mesocyclone is sampled by the next volume scan with an angular separation of 0.5°, the velocity minima and maxima are averaged out to reveal near zero velocities. The adjacent beams can only pick out the weakening velocities outside the mesocyclone diameter. The mesocyclone will have appeared to weaken.

Mesocyclone sampling vs trends

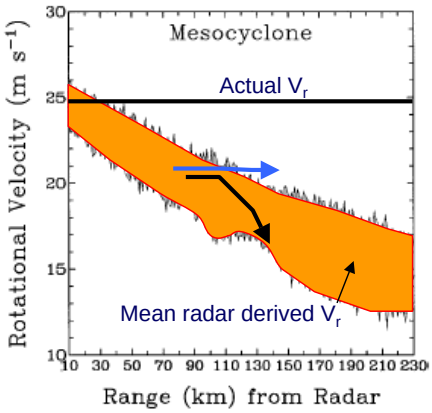
- Vary the angular separation between beam centerpoint and meso center
- Add radar data uncertainty
- Do this for all ranges
- Result is uncertainty for Vr for a 3.5 nm wide mesocyclone for all ranges
- Suspect any trends that fail to exceed the uncertainty envelope



Wood and Brown (1997) incremented the angular separation enough to graph the Vr in 50 steps for each range from the radar. Instrument noise was added to better simulate the velocity returns from the WSR-88D. The result is a picture of the uncertainty of how the WSR-88D depicts a true mesocyclone of 3.5 nm in diameter and a Vr=25m/s. Note that the uncertainty increases with range around a slowly diminishing average Vr depicted by the radar.

Mesocyclone sampling vs trends

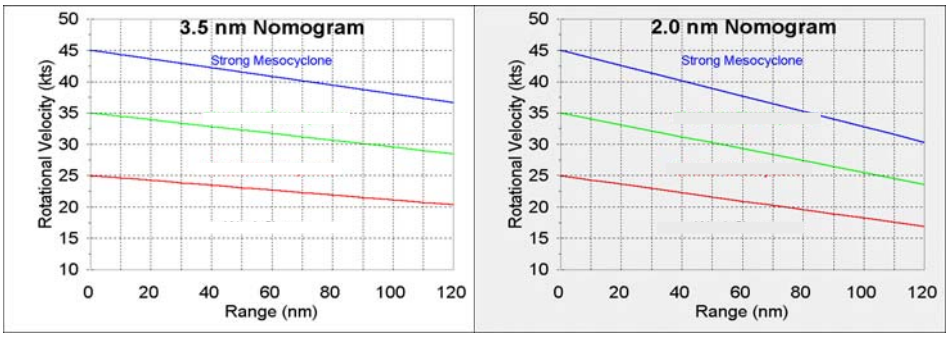
- The V_r trend in black is not strong enough to rule out radar sampling
- The V_r trend in blue, may indicate actual meso is intensifying
  - If the mesocyclone has moved away from the radar the same distance indicated here



When thinking about radar uncertainty and Vr degradation with respect to range, you may have a good picture of what kinds of mesocyclone trends may be real. Remember that this plot was created with a true mesocyclone Vr of 25 m/s across 3.5 nm. The range degradation of Vr would be sharper for smaller diameter mesocylones. A mesocyclone appearing to have constant Vr but is increasing in range is probably actually intensifying like the trend in the blue line. A mesocyclone appearing to be abruptly weakening by 3 m/s (6kts) while also increasing in range with time might not actually be weakening (black line).

Mesocyclone sampling effects with range

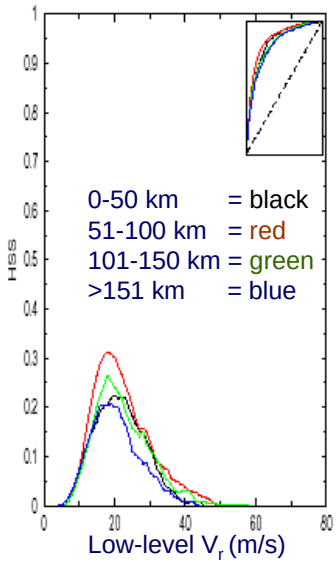
- Wood and Brown's results agree with the trends of V_r with range shown here.
- However…



The Wood and Brown (1997) results show the same Vr degradation with range as the classic mesocyclone nomograms we have preached to use for many years. There is one issue. What is a strong mesocyclone, a moderate, a weak mesocyclone with respect to its potential for a tornado discriminator? The HSS plot of low-level Vr suggests that tornado warning skill does not linearly increase with increasing Vr. There is a peak, after which the chances of missing tornadoes increases. How do the skill scores change with increasing range? The results are in the next page.

Mesocyclone low-level rotational velocity vs. range

- Heidke skill score shows the highest performance of low-level V_r at 51-100 km range
- Overall degredation in performance is not consistent with range



http://www.wdtb.noaa.gov/resources/PAPERS/twg02/index.html

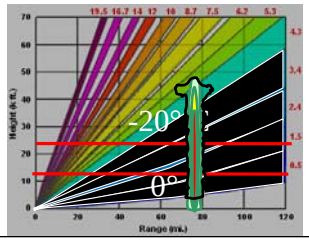
The TWG study broke all parameters that are radar range dependent into 50 km bins and recalculated their tornado discrimination potential. Note that for the low-level Vr, the best skills in HSS are achieved at an intermediate range of 51-100 km (27 – 53 nm).

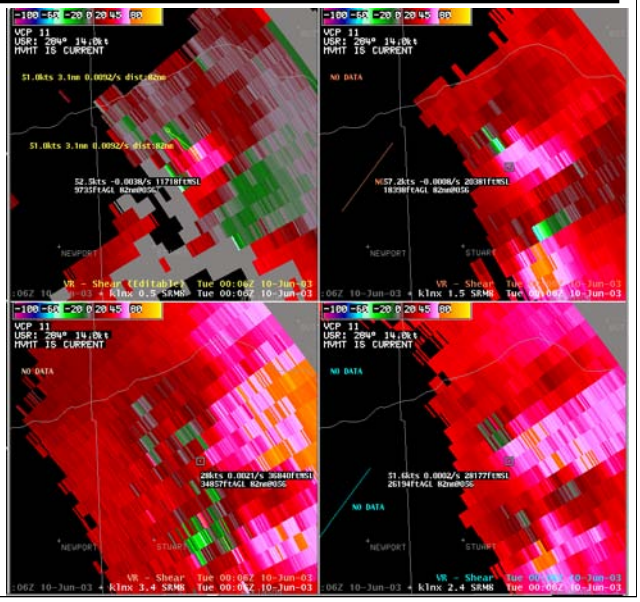
Then the HSS decreases somewhat at higher ranges. Note though that the HSS never drops drastically, even for ranges greater than 80 nm. The small changes in range probably represent the large compilation of all types of mesocyclones and that many are of fairly normal size (diameter=3.5 nm).

The low HSS skill scores of low-level Vr at the closest ranges <51 km, may be a result showing that many mesocyclones are strongly convergent at low-levels and therefore, have a lower rotational component to their total velocity. This is mostly speculation at this point. We do have a lesson on close range tornado warning guidance.

Example: Classic distant meso

- Typical size supercell at 78 mi
- Some uncertainty about measuring the same mesocyclone as its Vr increases and onset of gate-to-gate shear





Now to some examples.

The first one goes back to the 09 June 2003 northern Nebraska storm. It is a standard size supercell, and has the unusually low reflectivity values as of 2345 UTC. See the lesson on updraft strength from radar and satellite IC3-II-E. The storm continued to intensify and the reflectivities increased to more “normally” what is expected.

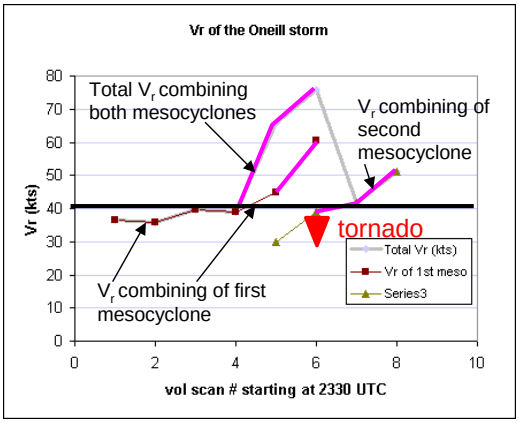
This four panel velocity loop extends into 0005 UTC the next day.

At 2335 UTC, there are huge outbounds on the north side of the mesocyclone. Is this velocity dealiasing? Yes, most likely

At 2350 UTC, I move the 4 panel further east and at the same time, the Vr increases abruptly. However, it is not clear whether or not I may be sampling inbounds of one mesocyclone and outbounds of another further southeast. My uncertainty remains until I see a more coherent velocity structure at the end of the loop. Vr values are very strong for this range and the mesocyclone is a bit larger than 3.5 nm. I will plot my total Vr assuming this is one mesocyclone we are tracking but I will also split the Vr into what I think may be two mesocyclones as well.

Vr trends

- From the Vr uncertainty chart, and the distance of 78 nm, I estimate a 5 m/s (10 kt) uncertainty in any trend



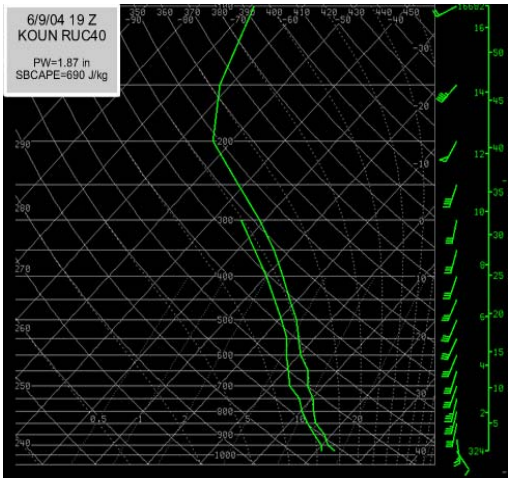
The purple line segments indicate increase in V_r above my 10kt uncertainty using the start points as my initial strength.
The black line indicates optimal Vr for best tornado warning skill based on TWG results.

Both the total Vr of what may be two mesocyclones are plotted. But with my uncertainty about whether I am seeing one or two mesocyclones, I will make my best guess as to the Vr for each one. Either way, note that there are fluctuations in low-level Vr but I am not calling these fluctuations real until I see a change of at least 10 kts from the start time of this loop. If I look at the Vr of the first mesocyclone only, not the combined ones, I get a one volume scan leadtime before the reported tornado. It is most likely the tornado came from the smaller velocity gradient on the northwest mesocyclone, or the northwest side of the combined mesocyclone.

If my uncertainty confuses you, it should given that this mesocyclone is at 80 nm and at that range, poor velocity sampling could inadvertently lead you to accidentally combine two mesocyclones into one.

2nd Example: Mini supercell

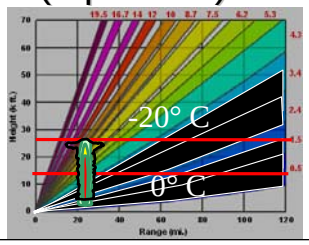
- Shallow CAPE
- Good low-level curvature
- Typical of tropical storm environments but with a subtropical system

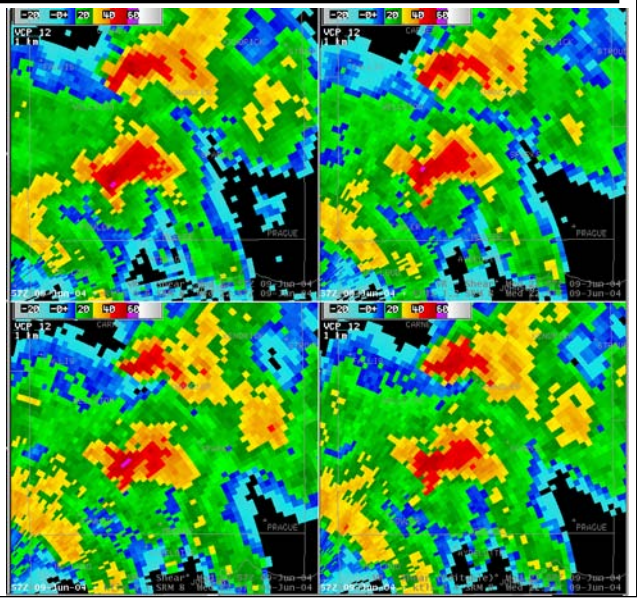


This case is not like the last one in that we are looking at a shallow CAPE, tropical type environment. There is good low-level turning below 2 km AGL and not much speed shear above that. Given my nearly saturated environment, and good 0-3 km CAPE, I might expect some minisupercells and a small tornado potential. At the time of this event and without 20/20 hindsight, this day presented itself as a challenging situation given the initially widespread areas of heavy rain, eventually breaking up into isolated modes of convection.

2nd example

- Close range, starting at 13nm and ending at 27 nm
- Tornado time is at 2257 UTC west of Chandler (top storm)

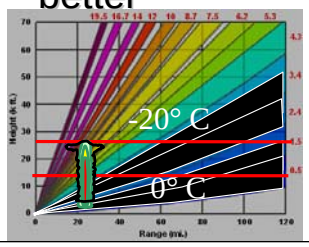


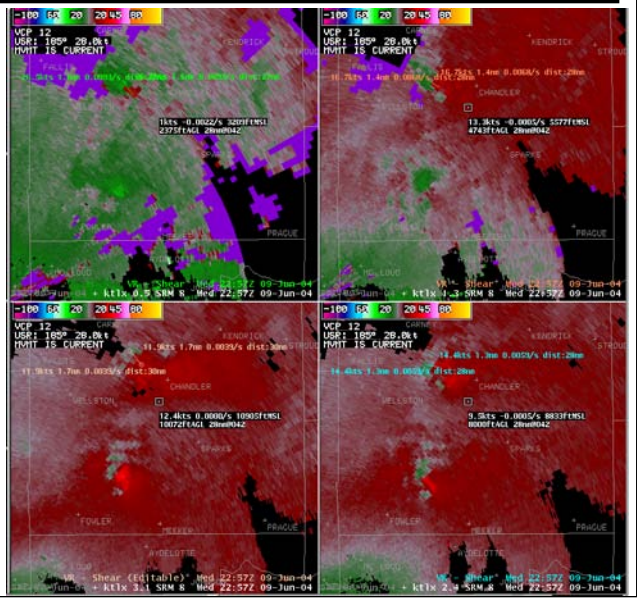


From a close range averaging 20 nm, the radar in VCP 12 shows two minisupercells. This 4-panel is zoomed to the same scale as the one in the previous case. Note in the VCP chart, the large separation between the 0 and –20 C levels indicating a weak lapse rate. The storm top barely made it to –20 C. None of these storms produced hail, however the rainfall rates were extremely high.

2nd example

- Small mesocyclone (2nm)
- Yet still smaller V_r than the Oneill storm
- Sampling much better



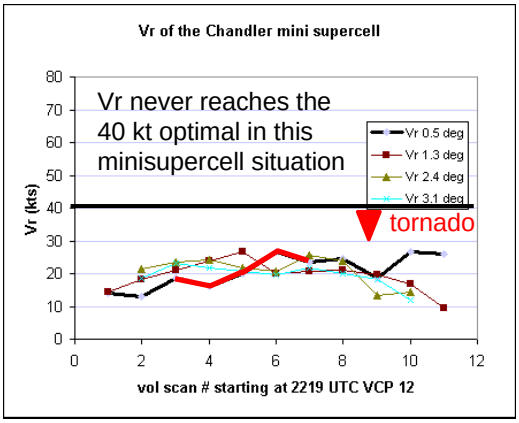


This 8 bit SRM imagery shows the mesocyclones on the same zoom level as the previous example. I am tracking the northern supercell mesocyclone. Despite the small size of the mesocyclone (<2nm in diameter), the close proximity to the radar allowed for good sampling. We should not have the same problems with angular separation as with the previous case.

Note in the first few frames of the loop, the lowest slice (upper left) mesocyclone structure is mostly convergent and experiences a lower Vr than even the very next slice, only 1500 ft higher. This is an example where the near range low-level Vr may be reduced since most of the velocities are convergent instead of rotational. The mesocyclone appears to shrink later in the loop and although the 0.5° slice shows more rotation, the Vr remains small. The tornado was reported in the last frame in the loop, or at 2257 UTC.

Vr trends

- From the Vr uncertainty chart, and the distance of 20 nm, I estimate around 3 m/s (6 kt) uncertainty in any trend
- Owing to good sampling, the velocity uncertainty is small



The red line segments indicate increase in the 0.5° V_r above my 6 kt uncertainty using the start points as my initial strength.
The black line indicates V_r for best tornado warning skill based on TWG results.

Starting with the Vr time trend from the previous caes, I add the current case and overlay the Vr at which the TWG study's HSS skill score peaks for low-level Vr. The minisupercell Vr never reaches close to that level.

I plotted the Vr time trend of all slices at once. The dark black trend represents the low-level Vr. Here with my decent mesocyclone sampling, I allow myself a lower threshold of velocity change in time before calling it a legitimate trend. The thick red line represents where that trend has occurred relative to the beginning of this trend. Note that the values increase, then level off and actually decrease a bit before the tornado report.

Summ: Mesocyclone sampling

- Radar observed mesocyclone rotational velocity decreases as range of a constant intensity mesocyclone increases
- Uncertainty of trends in rotational velocity increases with increasing range
- However, the best warning performance using thresholds of rotational velocity seem to peak at 51-100km (30-65 mi) range.

In summary, radar observed mesocyclonic V_r decreases with range.

Uncertainty in V_r trends increases with range as the angular separation becomes more important.

Tornado discrimination potential of low-level V_r represented by the Heidke Skill Score, HSS peaks at 51 to 100 km in range.

It is important to know what is a real change in mesocyclone strength trend and what is a spurious artifcact of radar sampling.

Remember though that the mesocyclone diameter also can change with time and this fact will influence further what a real trend may be. Meoscyclones often contract prior to and during tornado time. The impact on sampling may result in the appearance of a mesocyclone weakening or going through more volatile trends during this contraction. Be mindful of this when it does happen.

Storm Interrogation

AWOC Severe Track

IC3-III-B

An overview of storm scale signatures considered in tornado warnings

Welcome to the

AWOC Severe Track

IC3-III-B
An overview of storm scale signatures considered in tornado warnings

This lesson is 23 slides long and should take about the same number of minutes to complete.

Storm scale signatures considered in tornado warnings

- Objectives
  - This lesson is intended to be an overview of common storm scale signatures associated with tornadogenesis. In particular:
    1. Discuss the ingredients for tornadogenesis
    2. Determine the range of low-level velocity difference that leads to good tornado discrimination in a TVS signature

This is intended to be a review of tornado precursor signatures for the most part. As a first objective this lesson presents the signatures and how they relate to the ingredients for tornadogenesis. In some contexts, the storm scale signatures we can detect are directly related to the ingredients for tornadogenesis. In other contexts, the role of these same signatures in contributing to the ingredients for tornadogenesis are still in the realm of the unknown.

As a second objective, this lesson covers the range of low-level velocity difference that lead to good tornado discrimination in a TVS signature based on the Tornado Warning Guidance (TWG) project conducted by the National Severe Storms Laboratory (NSSL) in 2001 and 2002. The results for the TVS velocity attributes were also extended to mesocyclone signatures, and near storm environment parameters. This lesson also mentions the ability of mesocyclone rotational velocity to discriminate tornadic from nontornadic storms. However, another lesson in IC3 delves into mesocyclone signatures and sampling in more detail.

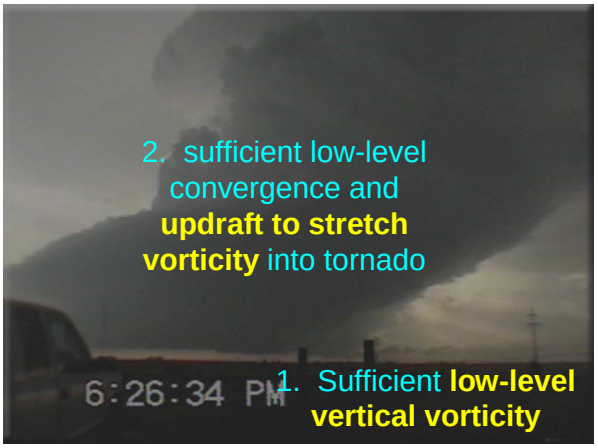
Storm scale signatures considered in tornado warnings

- Objectives (contd)
  3. Determining the relationship between the TVS and the tornado cyclone
  4. Recognize signatures conducive to vortex stretching
  5. Recognize common storm interactions observed with tornadogenesis in the past
  6. Understand what is not known in the relationships between the storm scale signatures in this lesson and ingredients for tornadogenesis

This talk also covers the relationship between the TVS signature and the tornado cyclone, and recognizes the signatures conducive to vortex stretching (e.g., updraft signatures). I devote some discussion to a topic of growing interest amongst researchers: the role interstorm interactions have on tornadogenesis.

Finally, we will discuss what we do not know about storm scale and near storm environmental signatures in regards to how the contribute to the tornado ingredients at the end of the lesson.

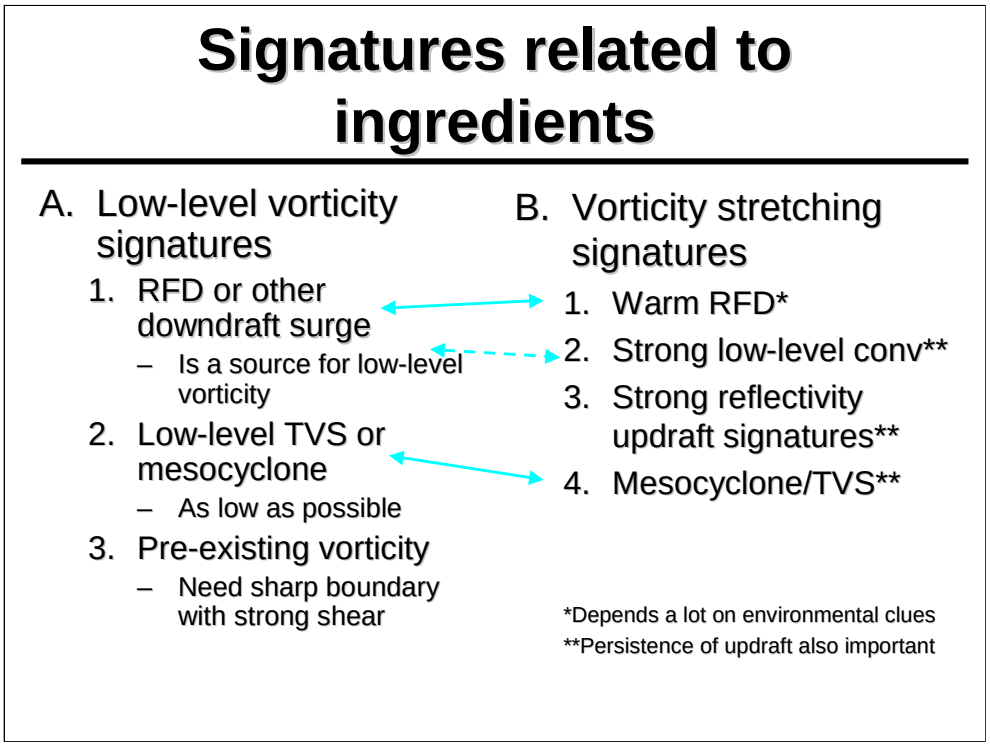
Tornado ingredients



The ingredients for tornadogenesis are deceptively simple:

1. There has to be a sufficient amount of low-level vorticity available as a source for rotation in a tornado. The magnitude of vorticity is important in that it helps affect how much time some updraft needs in order to concentrate that vorticity into tornadic magnitudes. Also, the available pool of circulation (vorticity integrated over a closed path) for tornadogenesis is a contributor to the aspects of a tornado such as size, strength and longevity.
2. In order for the vorticity to concentrate into tornado scales, a sufficient horizontally localized upward acceleration of air must overlay the low-level vorticity (e.g., a cumulus updraft or enhanced convergence along a gust front). Convergence is necessary down in the vorticity pool in order to concentrate. Both updraft and convergence accompany each other since one cannot exist without the other in the world of kinematics. The upward acceleration needs to be localized or else all the vorticity is lofted without any concentration.

Remember that we know the ingredients for tornadogenesis. The problem is, knowing to what extent the ingredients must magnify, and how do the signatures that we use to assess tornado probability contribute to tornadogenesis. When I discuss any signatures considered in tornado warnings, the signatures may or may not be direct observations of the presence of tornado ingredients. I will let you know how much we are seeing ingredients when we detect a certain signature.



How are the storm scale signatures used in tornado warnings related to the ingredients for tornadogenesis? Many of the signatures we use are known to supply a little of both a low-level vorticity pool and a source for stretching that vorticity. Some appear to be related more to one ingredient.

For example, the consensus in the research community suggests that the Rear Flank Downdraft (RFD) is the primary source of low-level vorticity in mesocyclonic tornadogenesis. At the same time, significant mesocyclonic tornadoes are favored when the RFD is warm and buoyant. This is an example of the dual role that this feature provides to the ingredients for tornadogenesis.

Consider strong low-level convergence. It is associated with strong stretching potential of background vorticity. RFDs do provide for strengthening low-level convergence but the RFD is not the only source of strengthening low-level convergence. A boundary intersection can also provide this function as well.

Note that the presence of a mesocyclone and or a Tornado Vortex Signature is something that we all use as critical signatures for tornado warning decisions. The presence of such a signature at very low levels may be an actual detection of the pool of vorticity available for tornadogenesis at low levels. However, a detection of these features at higher levels serves as a mechanism for strong updraft acceleration

Evidence of ingredients coming together

Probability of a Tornado

all ranges →	**TWG01**	**TWG99**
MDA	.05	.03
TDA	.09	.05
MDA'	.19	
TDA'	.29	
MDA + BWER	.09	.09
TDA + BWER	.09	.09
MDA' + TDA'	**.34**	**.31**
MDA'+TDA' +BWER	**.38**	**.38**

MDA'
Equivalent to a moderate mesocyclone in the current mesocyclone algorithm

TDA'
typical to the default values (LLDV>25 m/s, MDV> 36 m/s).

Note* These are apriori probabilities. $P_t=N_t/N$, where N_t is the number of detections considered tornadic and N is the total number of detections

The more evidence that ingredients are coming together is highlighted best by the results shown here from the TWG where research algorithms from NSSL were tested for their tornado discrimination capability. This study documented all automated detections of mesocyclones (MDA algorithm), TVSs (TDA algorithm), and BWERs (BWER detection algorithm) from around the country for several years and then classified them as to whether or not they were associated with a tornado (within 20 minutes). Here we show that the stronger mesocyclones and TVSs (labeled MDA' or TDA') provide a stronger probability of a tornado. However, the probabilities are a lot lower than with strong simultaneous detections of both signatures.

A triple detection of a strong mesocyclone, strong TVS, and a BWER provide the best probability of a tornado occurrence of all. Both studies, TWG in 2001 (TWG01), and the TWG in 1999 (TWG99) support this result.

Now, there is no attempt to infer how these signatures play into providing for tornado ingredients. Some of the TVS detections may have been low enough to the ground to be a direct estimate of low-level vorticity. Higher level rotational detections along with the BWER detections are probably strong evidence of vortex stretching potential. There are however, the unknown relationships that we must consider too.

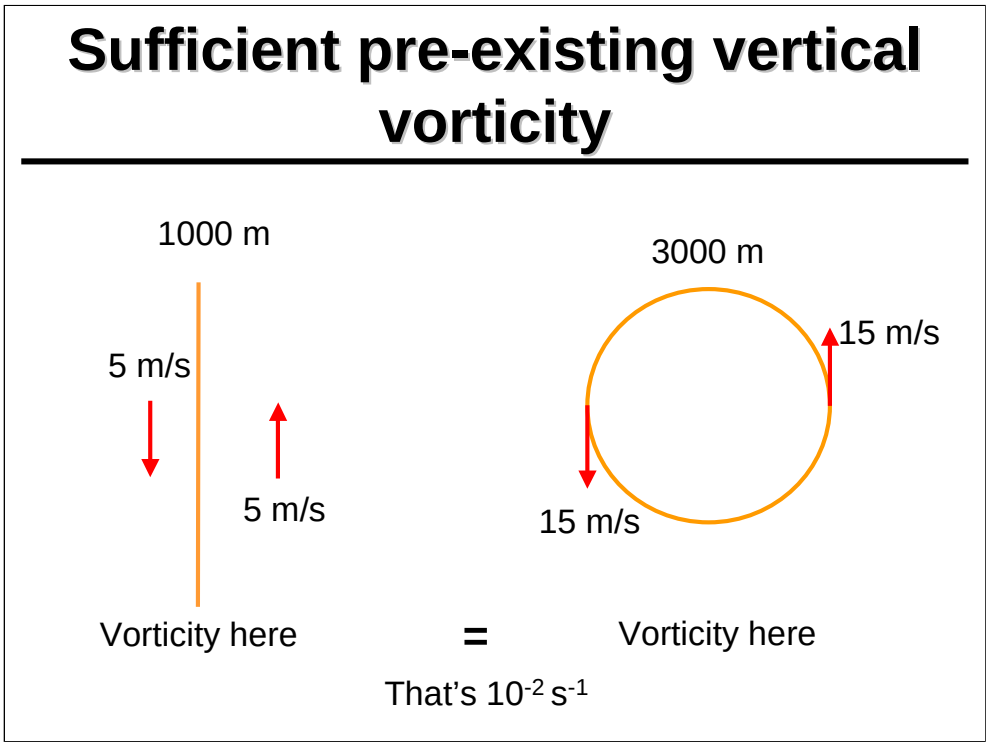
Low-level vorticity detection

- Do I have the detection of at least mesocyclonic vertical vorticity in association with the storm or at least storm induced?
  - Mesocyclone
  - Tornado Vortex Signature (TVS)
  - Strong shearing along a boundary
- And is that detection at low-levels?
  - As low as possible (< 1.5 km)

Here are some questions that you can assess if you are faced with a tornado warning decision that play into whether or not you are detecting strong low-level vorticity. Are any of the signatures, mesocyclone, TVS, or vertical shearing vorticity along a boundary strong enough to reach mesocyclone values? Mesocyclonic vorticity is on the order of .01 s^{-1}. If you have that or more while still following the technique for determining the rotational velocity of a mesocyclone, or differential velocity of a TVS for example, then you can answer this question except for one more question to answer.

That second question is: Is your vorticitiy detection as low as possible? If your detection is above 1.5 km AGL, you are probably not looking at the low-level pool of vorticity. The lower you can view velocities (metar, mesonet data included), the greater the chance is that you directly detecting the low-level vortex pool that can be the supply for tornadic vortex formation.

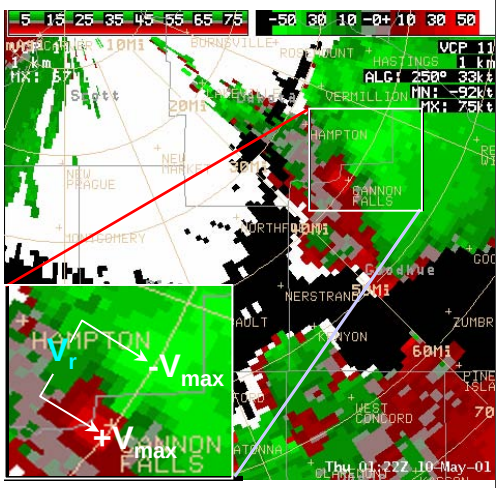
As a note, an RFD can generate vertical vorticity on short time scales (<5 minutes) and your opportunity to see it will be short lived. See the lesson on viewing tornadogenesis from close ranges.



An example of low-level vorticity detection may be that which can form across a sharp boundary. Note in this slide that not much velocity difference is needed for mesocyclonic vorticities to occur. There is another lesson on nonmesocyclonic tornadoes in this IC.

Mesocyclone: review

- Core diameter from **$-V_{max}$ to $+V_{max}$** should not exceed 5 nm
- Rotational Velocity $Vr = (|-V_{max}| + |V_{max}|)/2$ exceeds user thresholds
- For low-levels, I'd prefer to see this strength vorticity in the lowest elevation slice, especially when close to the radar.
- Vorticity is actually going to be $2V_r$ / distance or ΔV/distance.



Remember that vorticity is not just a function of velocity difference but also a function of the distance between the two velocities you measure. When you assess whether or not you have .01 s^{-1} vorticity in a mesocyclone, refresh your memory on where you should select your velocities, such as with the V_r shear tool. The end points in the V_r shear tool should be at the peak in the velocities, where the solid body flow becomes potential flow. When you calculate V_r from the Vr shear tool, multiply it by 2 and divide by the distance of your baseline. Since the units for distance need to be in meters to calculate vorticity, you can take your baseline in nm, divide it by 2 to get kilometers, multiply kilometers by 1000 to get meters. Your velocity units in knots can be divided by 2 to get m/s.

Factoring in the units and conversions, I get

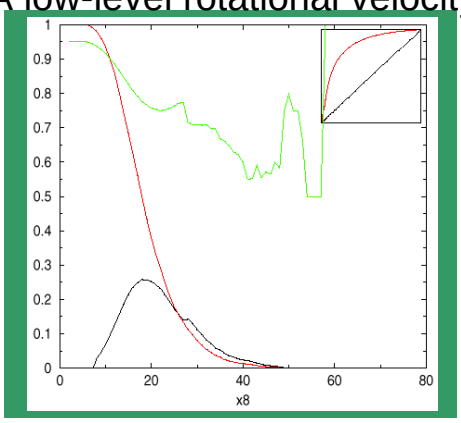
Thus vorticity = 2Vr (kts) / dist (nm) * 1000

Let's keep things simple and stay with low-level Vr though when we view the next slide.

Mesocyclone rotational velocity: low-level vorticity

The best mesocyclone parameter from a study by NSSL in 2001

MDA low-level rotational velocity (m/s)



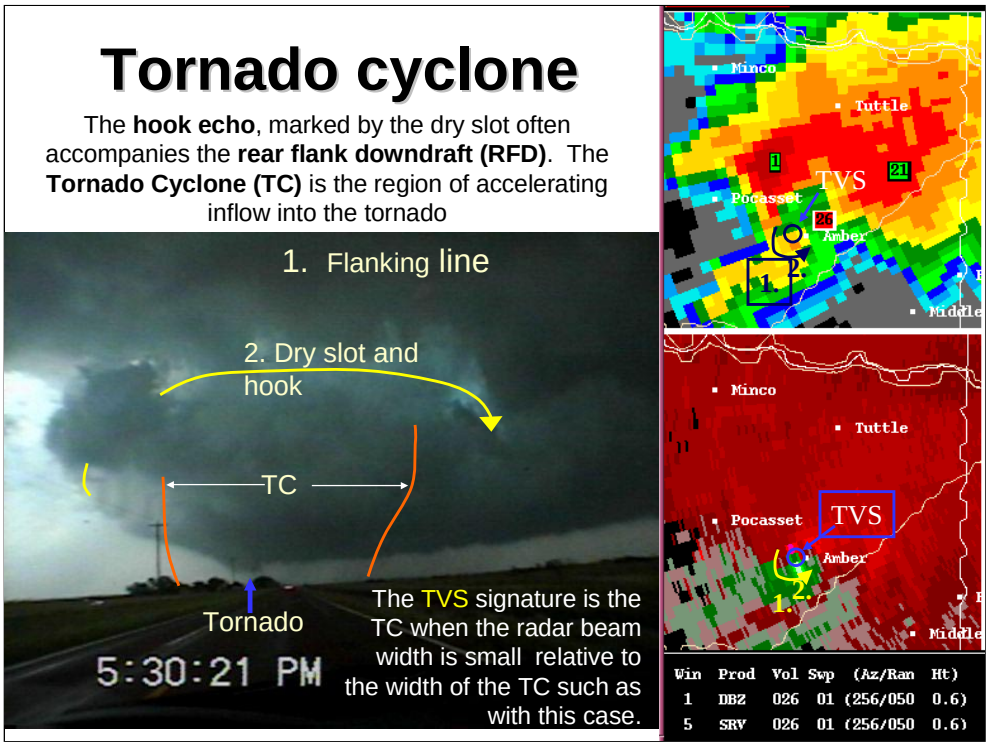
FAR = green line
POD = red line
HSS = black line

Inset = POD vs FAR

See http://www.wdtb.noaa.gov/resources/PAPERS/twg02/index.html

This graph was constructed from 1000's of mesocyclone detections from the Mesocyclone Detection Algorithm (MDA) developed by NSSL. Detections were labeled as tornadic only from –20 min to +5 min of a particular detection time. Hundreds of parameters in the MDA were tested for their skill at detecting the tornadic phase by stepping each parameter upward in its strength and then creating the skill score parameters seen on the right. The best parameter was the low-level rotational velocity (low-level defined as that detection found on the 0.5° slice). The Heidke Skill Score (HSS), peaks where this parameter offers the best skill in tornado discrimination.

Note that there is good skill across a fairly broad range and the peak in the HSS is meant to be a warning threshold.



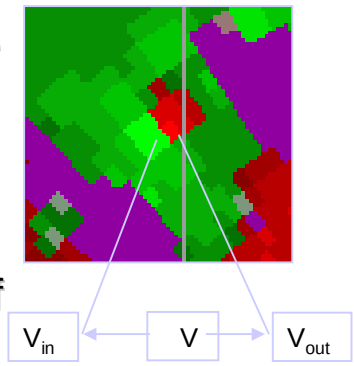
In order to generate vertical vorticity at ground level, a downdraft must bring and tilt elevated horizontal vorticity towards the vertical. The formation of the RFD usually indicates that the mesocyclone is developing downdraft within it, causing a bifurcation in the original simple rotational structure of the mesocyclone. The mesocyclone inside the curling RFD often called the tornado cyclone,is a smaller circulation than the original rotating updraft, containing strong vertical vorticity within it. If that vertical vorticity is continuous to near ground, then one of the tornado ingredients, low-level vertical vorticity supply is coming into existence. However, if the tornado cyclone is stronger aloft, it could mean that it is a potentially strong stretching source through the nonhydrostatic pressure forcing.

A distant view of the tornado cyclone by radar means you are seeing this feature mainly aloft, and therefore, is more likely providing a source of strong vortex stretching. In this range of roughly 30 to 70 miles, you need to know if the RFD is likely to be buoyant so that the pressure forcing previously mentioned can result in improved vortex stretching potential. What you do not know is whether there is any vorticity near the surface. This is the range in which your TVS signature, if you have one, could be sampling the tornado cyclone because the beam width is still relatively small on most occasions.

At greater ranges > 70 mi, the TVS signature you detect may only be that of the larger mesocyclone associated with the storm updraft. Your detection of the tornado cyclone depends on its size compared with that of your beam width.

Tornado Vortex Signature: low-level vorticity signature

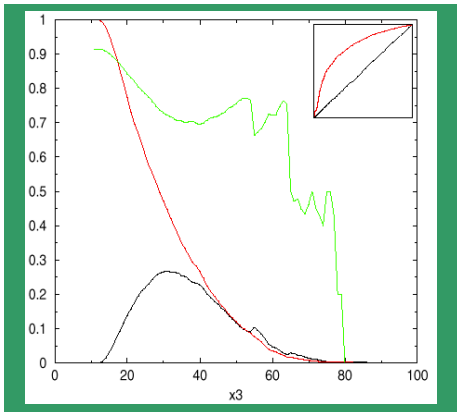
- Tornado Vortex Signature (TVS) strength is partly estimated by measuring the velocity difference, V, for each elevation slice
  - $V = |V_{in}| + |V_{out}|$
- A TVS is not definable beyond about 60 nm, thus if one exists, it is primarily a low-level feature



As a refresher, TVSs are measured for their strength using the velocity difference across two azimuthal gates. The next slide will show how this Low-Level Delta Velocity (LLDV) is related to its discriminating potential based on the TWG study.

TVS strength vs tornado probability

TVS low-level gate-to-gate velocity difference, LLDV (m/s)



FAR = green line
POD = red line
HSS = black line

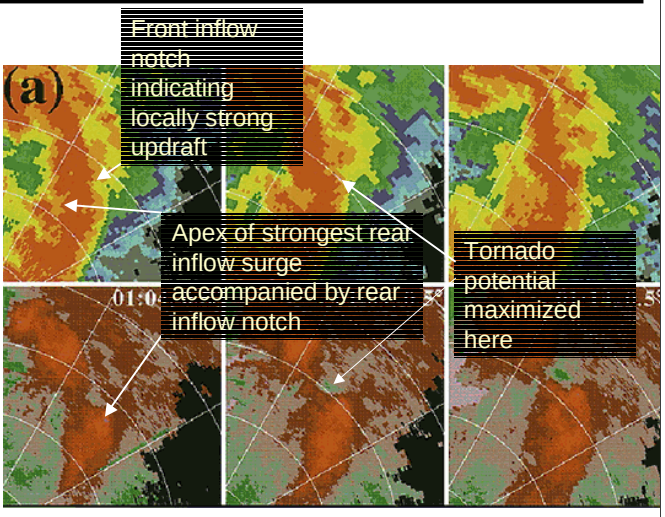
Inset = POD vs FAR

Note that the HSS (black line) is relatively high across a broad range of LLDV values, here in m/s. We used to define a TVS as one when the gate-to-gate ΔV exceeds specific thresholds (e.g., 70 kts for certain ranges). However, given our broader experience of these signatures and the weather that was associated with them, and given these results, we see that TVS strengths are quite diverse and show relatively good warning performance even if a smaller LLDV is used (e.g., 25 m/s or 50 kts).

This should remind you that the TVS strength is one of many considerations when a tornado warning decision is being made.

Vertical vorticity along gust front of a squall line

- Low-level vortex formation behind leading edge
- Vertical vorticity phases with strong updraft signature



Quasi linear systems also provide for strong low-level vorticity.

Provided that the updraft can keep up with the outflow surge (often needing strong deep layer shear), the left side and apex of the surge will contain a strong likelihood of tornado formation.

Vortex formation usually begins at low-levels and then builds up with time.

It is not precisely known where the contributions to low-level vertical vorticity originate but there are some interesting theories proposed by Trapp and Weisman (2003) in Monthly Weather Review. Another lesson in IC3 covers Quasi Linear Convective System induced low-level vortices and tornadoes in more detail.

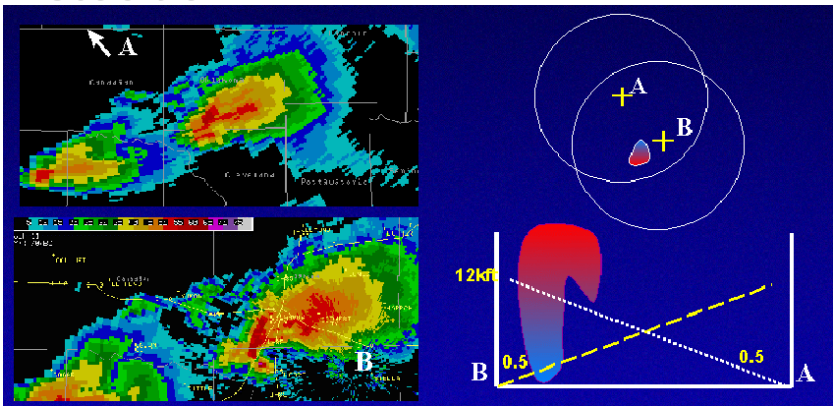
Strong Updraft Signatures

- Strong signals favoring low-level vortex stretching
  - i. Locally sharp concave reflectivity gradient facing the inflow
  - ii. Inflow notch
  - iii. Mesocyclone
  - iv. WER
  - v. BWER
  - vi. Low-level velocity convergence and accelerated low-level inflow

A lot of the same signatures from which the presence of low-level vorticity can be inferred can also infer the presence of strong updrafts. In addition, there are other velocity and reflectivity signatures to infer strong updraft forcing and vortex stretching potential.

Strong Updraft Signatures – Concave sharp Z gradient

- Note that this shape can be detected even from relatively far away. This gradient often marks one side of the WER.



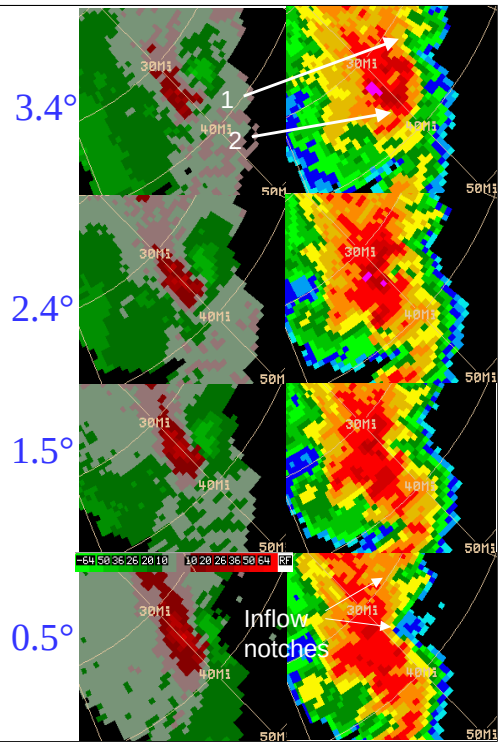
Note that this shape can be detected even from relatively far away. This gradient often marks one side of the WER. The locally concave feature is one of the most common amongst storms with intense updrafts.

If the concavity of the sharp reflectivity gradient tightens, then we have an inflow notch.

Both of these indicate strong updraft in low- and midlevels.

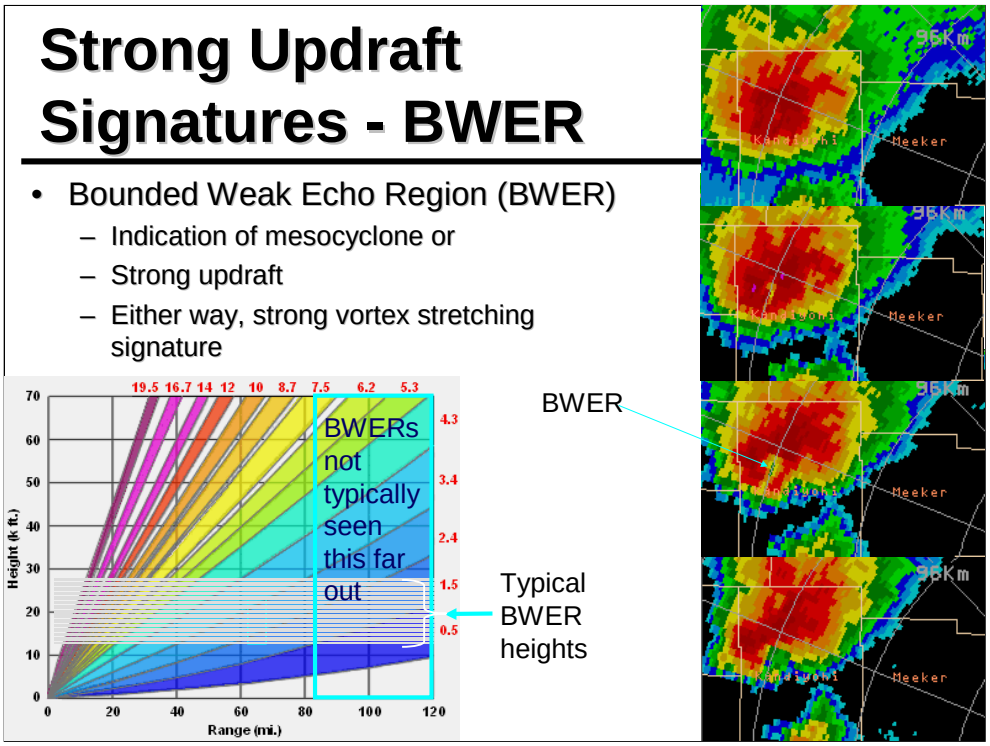
Strong Updraft Signatures – inflow notch

- Two inflow notches noted
- Watch for the one with the sharpest reflectivity gradient, and associated with a mesocyclone.
- The colocation of the notch and low-level vortex suggests strong stretching potential.



Note that the 0.5 deg slice shows two inflow notches, one in the center, the other, top center. Which one is most likely associated with an intense updraft? The notch with the sharpest reflectivity gradient, and associated with a mesocyclone is the answer. Note the top center notch has no velocity signature, no WER or BWER. The middle notch has all these other features to add confidence of a strong updraft there.

The colocation of the notch and low-level vortex suggests strong stretching potential.

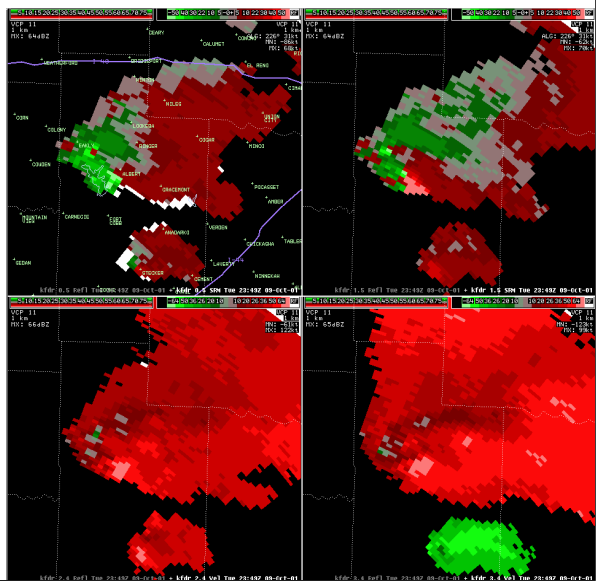


The BWER, as noted by the TWG study, when colocated with a mesocyclone and TVS increase the odds of a tornado being associated with the two rotational signatures.

IC 3 has a session on strong updraft signatures in vertically sheared storms which is a highly recommended lesson with more examples of BWERs.

Strong Updraft Signatures – mesocyclone

The stronger the mesocyclone, the more likely there is stronger nonhydrostatic pressure forcing of the updraft into the core of rotation.

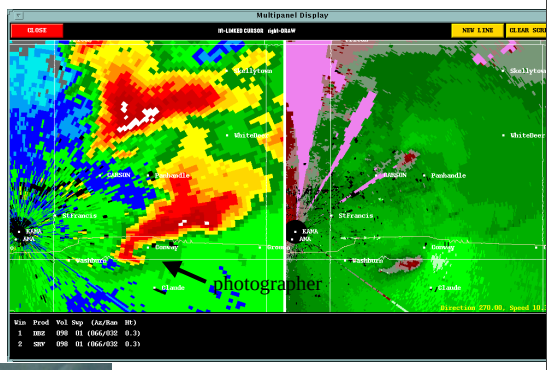


Midlevel mesocyclones provide a updraft forcing as a strong upward directed nonhydrostatic pressure gradient forcing forms beneath significant rotation aloft. The mesocyclone aloft may also have other relationships to providing for the tornado ingredients that we do not know of yet.

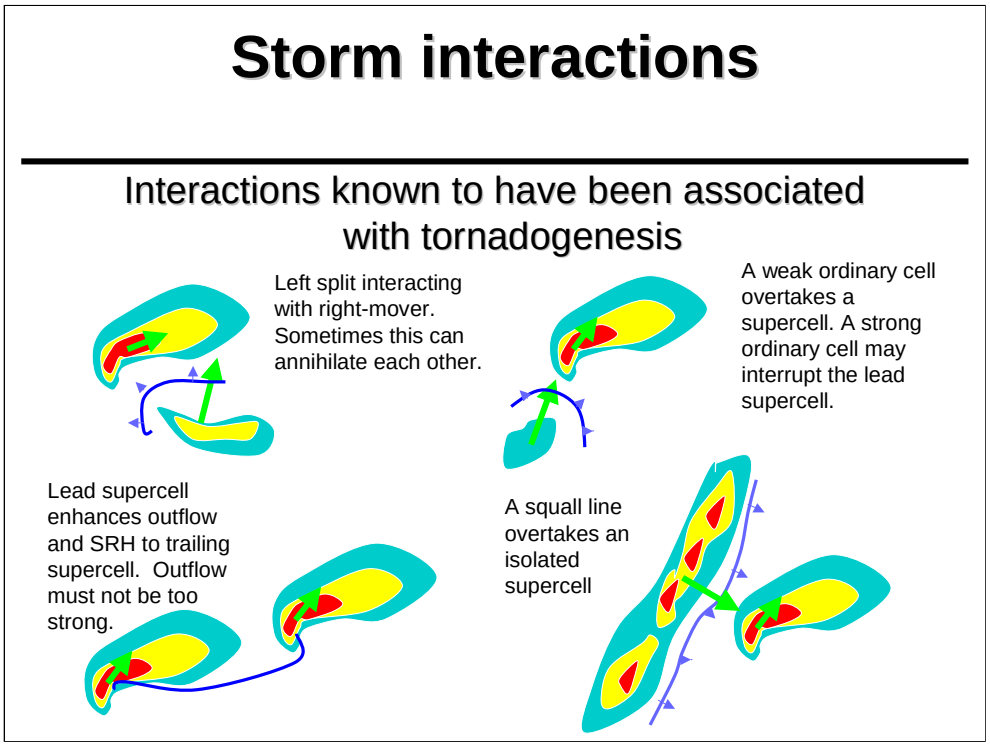
Remember that a mesocyclone also contains part downdraft during its mature phase. Most of the upward directed nonhydrostatic pressure forcing occurs in the updraft flank of the midlevel mesocyclone, usually on the right and front sides, perhaps extending beyond the visual cloud boundary.

Vortex stretching – accelerated low-level inflow and convergence

- Inflow acceleration
  - Strong pressure deficits in the updraft core induce inflow acceleration
  - Indirect indication of vortex stretching potential
- Low-level Convergence
  - More direct indication of vortex stretching potential



The radar is ideally located to see all the low-level inflow into the storm to the SE of the radar. With the strong convergence, strong vortex stretching potential is likely there. However, strong low-level vorticity is not seen at this time. The radar is not ideally suited to see the low-level inflow to the northern storm. Yet there is more low-level vorticity there. The northeastern storm is the tornadic one. The low-level inflow is only one of many signatures for which to look. Both storms have strong updrafts, but the northern one has a low-level vortex initiating.



Interstorm interactions are becoming recognized as more influential in the timing tornado formation by the research and forecast communities. This topic is in great need for further study to determine a storm interaction climatology vs. tornado occurrence, and the nature of how storm interactions contribute to tornadogenesis.

I present four common modes of storm interactions that have been observed to be linked to tornado formation in past case studies, and personal experience.

The upper left case is perhaps the most common storm interaction when the deep layer shear vector is directed orthogonal to a broken line of developing supercells. The left-moving supercells collide with right-movers in this shear configuration. In some cases, the storm collision results in tornadogenesis through the interaction of the left-mover's gust front with the right-moving supercell. Cases that have resulted in tornadogenesis include that of Granite Falls, MN on July 25, 2000, where a weak left mover intersected a right-moving supercell and a tornado occurred immediately afterwards. On the other hand, numerous left- right-moving supercell collisions resulted in the destruction of both storms. No studies have been done to provide any guidance on determining the future evolution of the right-mover after such a collision with a left-mover supercell.

Interaction type #2, lower left, is when a lead cell of any type extends an outflow boundary and a following storm rides the boundary feeding off the convergence and enhanced horizontal vorticity available to it. Recently, an intense tornadic storm formed near Mulvane, KS on 12 June 2004 from trailing supercell in a similar configuration as this conceptual diagram. The trailing supercell does have the danger of moving too far into the cold wake of the lead storm resulting in high CIN at low-levels.

Interaction type #3, upper right, often produces a tornado when a weak shower overtakes a lead supercell and tornadogenesis quickly follows. If the shower becomes too strong, it could eventually swallow the lead supercell, or cause it to go into an high precipitation mode.

Interaction #4, lower right, is relatively well documented by Przybylinski, Knupp and others. The isolated nontornadic supercell becomes tornadic as a squall line approaches from its back side. The interactions between the supercell and the squall line outflow boundary may be responsible for tornadogenesis.

StormscaleTornado ingredients: major unknowns

- Low-level vorticity signatures
  1. How does the RFD acquire horizontal vorticity and reorient it to the vertical?
  2. How does the mesocyclone influence the RFD vorticity?
  3. How does vertical vorticity generate at the leading edge of a squall line?
- Vorticity stretching signatures
  1. What modulates the RFD thermodynamics?
     - ~40% variance of RFD buoyancy unexplained by pre-storm LCL heights
- Environmental clues
  1. How does low-level shear, buoyancy, humidity contribute to the tornado ingredients?

There are more unknowns than listed here as to how the tornado ingredients develop in a supercell. Perhaps the most important questions relate to the role of the RFD in organizing vertical vorticity, and acquiring its thermodynamic characteristics. Remember that 40% of the variance in RFD buoyancy is not explained by the height of the pre-storm LCL. Another important question details how vertical vorticity of sufficient magnitude can accumulate along the gust front of a QLCS system.

Summary: Tornado signatures

- Storm scale
  - Interstorm interactions
  - Relationship between radar observed signatures and tornado ingredients
    - Mesocyclone
    - TVS
    - BWER
- Near storm environment
  (Covered in storm interrogation, IC2)
  - Low-level (0-1 km) shear
  - Deep layer shear
  - Pre-existing vertical vorticity
  - CAPE
  - CIN
  - Boundary layer humidity

To summarize, we discussed the relationship between radar observed signatures and the two tornado ingredients: low-level vorticity supply and vortex stretching potential. We also discussed the interstorm interactions and the most commonly observed ones related to initiating tornadoes.

Keep in mind that we did not cover the near storm environment and the relation between the most common parameters and tornado ingredients, except for the presence of low-level vertical vorticity.

Storm Interrogation

AWOC – Severe Track

IC3-III-C

Tornado Warning Guidance – Stormscale induced storm relative helicity signatures

Storm Interrogation – Tornado Warning Guidance – Stormscale Induced Storm Relative Helicity Signatures

This lesson is relatively short, only 11 pages long. It should take 10 to 11 minutes to complete.

Stormscale enhancement to SRH

- Objective
  - Determine the likelihood that a storm is enhancing low-level SRH in its inflow
- Motivation
  - Some storms enhance SRH more than others from the base state environment

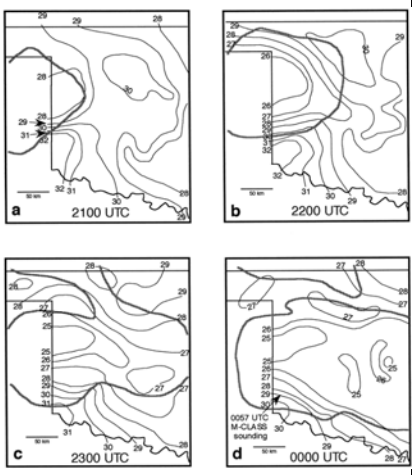
The objective of this lesson is to provide you considerations on how a potentially tornadic supercell may enhance Storm-Relative Helicities (SRH) in its stormscale environment. These considerations are based on results from recent project VORTEX experiments and other studies.

It is important to know which storms enhance SRH more than others due to factors that you cannot detect on the mesoscales.

Some storms may modify their local environment more than others and it is important to determine which ones may do so.

Anvil-induced baroclinicity

- Cooling along south anvil edge results from shadow. Baroclinity results leading to horizontal vorticity.
- Strongest 1 km SRH enhancement may occur when low-level inflow parallels anvil edge.
- Need sunlit ground right of anvil.



Markowski, MWR 1998, pg2924

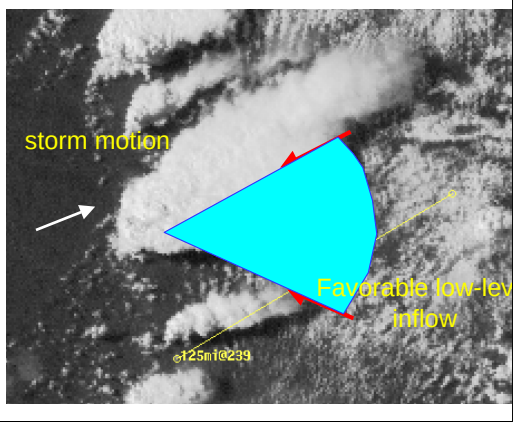
Anvil shading induced baroclinicity is a phenomenon that was proposed by Markowski 1998 after examining several cases, some going back to the early 1980's to several events from project VORTEX including the June 08, 1995 tornado outbreak in the Texas Panhandle. In these cases, Markowski noted significant surface temperature drops induced by the loss of solar insolation under the forward anvils of supercells. The June 08 case shown above is an analysis of surface temperatures from the Oklahoma mesonet. Note the significant temperature gradient forming under the southern anvil edge. After a scale analysis of horizontal vorticity production resulting from this temperature gradient, Markowski found that mesocyclonic vorticities can develop in as little as 20 minutes for air parcels residing in this anvil shadow induced temperature gradient.

Three features are needed to support evidence of horizontal vorticity production by anvil shading:

1. The low-level inflow needs to be roughly parallel to the anvil-layer SR flow so that the low level flow parallels the anvil edge.
2. Solar insolation must reach the ground away from the anvil to set up the relative cooling under the anvil.

Anvil-induced baroclinicity

- Prefer low-level inflow to be nearly parallel to anvil-level SR flow.
- Anvil-induced baroclinicity is not a well documented mechanism for enhancing SRH.



This event, occurring on May 6, 2001 in Southern Oklahoma shows an anvil that may be a good candidate for anvil-induced horizontal vorticity production. The anvil layer SR flow and storm motion are nearly parallel. Low-level inflow is nearly opposite to the anvil layer SR flow. The anvil shadow edge should remain relatively fixed. Low-level air parcels acquire increasing horizontal vorticity in the anvil edge-induced thermal gradient the longer they remained in that region. Markowski found that 20 minutes residence time was sufficient to generate mesocyclonic horizontal vorticity of .01 s-1. The depth of shadow-induced cooling was found to be less than 200 m deep. However, the shallow layer shear is also the greatest tornado/nontornado discriminator for mesocyclonic tornadoes.

Perhaps there is some forecasting value to looking for anvil-induced enhancements to 0-1km SRH but the evidence to date is weak. This is certainly a parameter not to depend on to make your tornado warning decision. But if the situation presents itself favorably, you may want to take note.

Forward Flank Downdraft gust fronts?

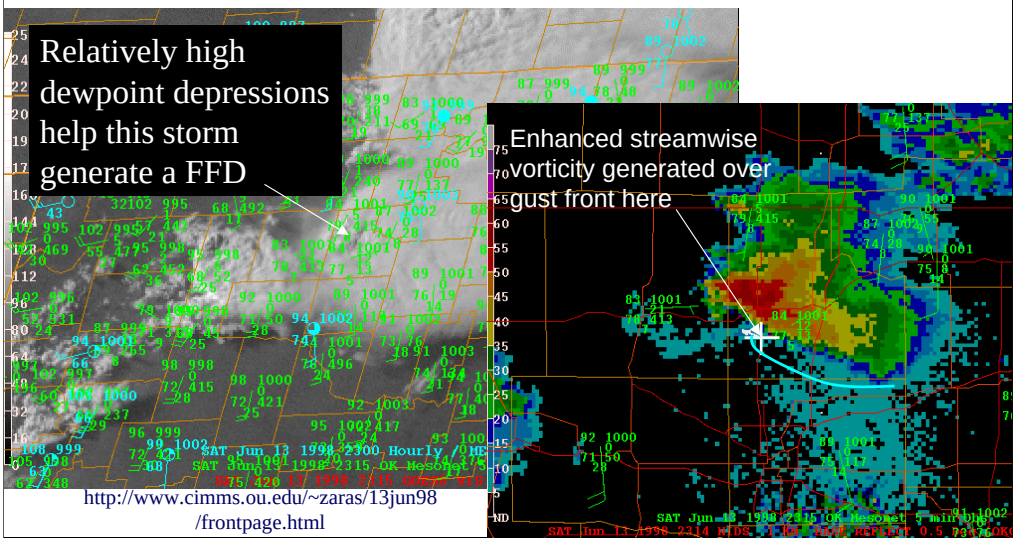
- Theory supports FFDs enhancing 1 km SRH and tornadogenesis through numerical analysis.
- VORTEX (1994-2000) observations unable to observe FFDs in most tornadic supercells.
- The role of FFDs in enhancing SRH and tornadogenesis may help in some cases but is not a necessary condition.

Forward flank downdraft gust fronts have long been recognized as a potential source of enhanced SRH through buoyancy gradient induced horizontal vorticity formation. Numerous stormscale numerical modeling studies continue to support the production of low-level mesocyclogenesis through tilting of forward flank gust front horizontal vorticity.

This mechanism had failed to show up for most VORTEX project cases in 1994 to 1995, and most cases afterwards that were sampled by mobile mesonets. Clearly the necessity of a forward flank gust front for tornado production was shown not to be true in general. However, do not ignore the presence of a forward flank gust front when one does materialize. There have been several documented events with marginal low-level pre-storm shear that likely were enhanced by the production of a forward flank gustfront horizontal vorticity.

Forward Flank Downdraft gust fronts?

Storm with a FFD



http://www.cimms.ou.edu/~zaras/13jun98/frontpage.html

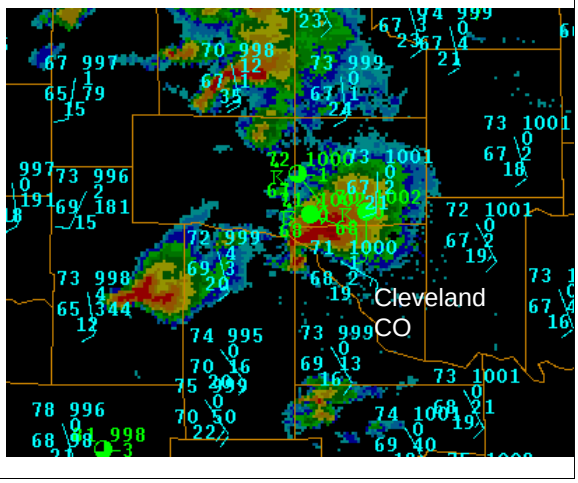
Low-level Forward Flank Downdrafts (FFD) and gustfronts are favored in environments with evaporational cooling potential from sufficiently large near surface dewpoint depressions. This event on 13 June 1998 is a strong candidate for this kind of event. On this day, there was strong deep layer shear and very large CAPEs. Dewpoint depressions averaged between 15 and 20° C.

Note 0.5 ° radar scan overlaid by mesonet data for the same time shows one mesonet with a northeast wind on the south side of the forward flank core. Horizontal vorticity, and SRH are likely to be enhanced in this region just south of the core upon which the updraft ingests this to assist in low-level mesocyclogenesis. Shortly after this image, an F1 tornado formed and lasted about 10 minutes.

Forward Flank Downdraft gust fronts?

Storm **without** a FFD

- Low dewpoint depressions in the environment
- Most VORTEX cases showed similar results.
- A FFD is not required to for tornadogenesis.

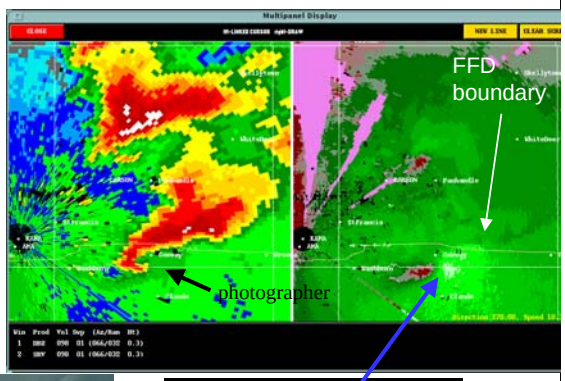


If an environment with 15 to 20 ° F dewpoint depressions can generate a FFD gustfront, then an environment with a nearly saturated boundary layer may inhibit FFD formation. May 3, 1999 provided a classic example. Here, dewpoint depressions were on the order of a few degrees. There was much weaker evidence of a significant FFD gustfront across the south edge of the forward flank core in northern Cleveland County.

Despite the lack of well defined FFD boundaries, this day produced exceptionally long tracked, violent tornadoes. Many of the VORTEX cases had similar environments.

Accelerated inflow

- A case with a forward flank gust front and…
- Inflow acceleration to increase SRH



Inflow acceleration seen best in this storm why?

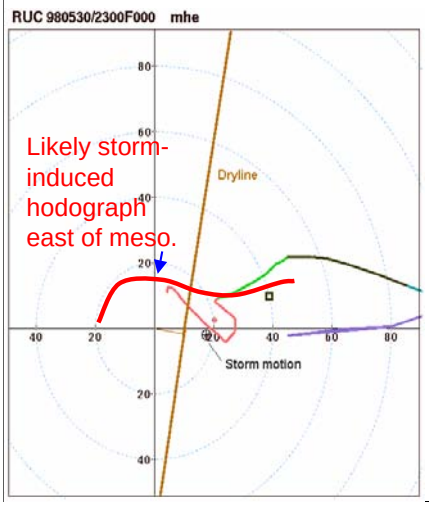
Mesocyclones, by virtue of their enhanced vertical pressure gradients, often assist buoyancy in generating a strong updraft, and consequently, enhanced inflow. Enhancing inflow speeds also enhances SRH given the same embedded streamwise vorticity.

The southern supercell shows very obvious enhanced inflow while the northern one does not. I will let you speculate as to why that is the case.

This event which occurred on 29 May 2001 east of Amarillo, TX produced several tornadoes, but only from the northern supercell.

Note that a FFD boundary shows up in the velocity product in the southern storm. This boundary is likely to reside along the inflow cloud band observed in the photograph.

Accelerated inflow

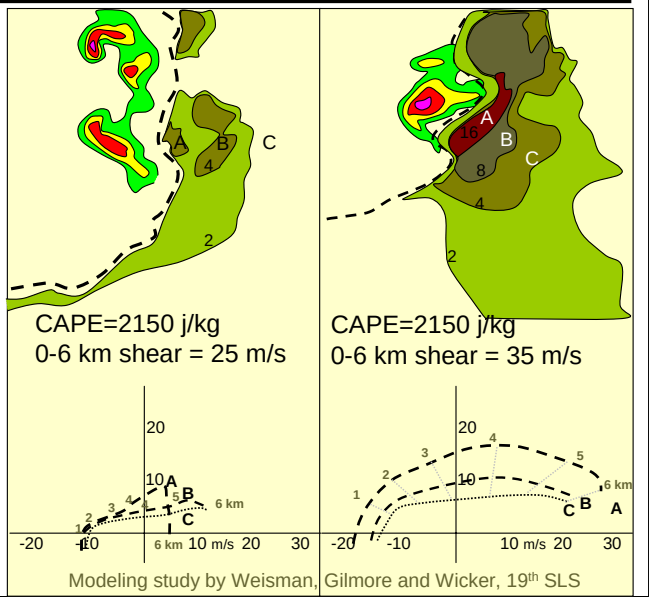


- Weak synoptic scale SRH is often augmented by enhanced inflow into supercells. Two examples are:
  - Spencer, SD 5-31-98
  - East Oklahoma 5-26-97
- Both had strong 0-6 km shear, very high CAPE (>4500 j/kg), low CIN and low LCL.

Accelerated inflow is often not just a shallow feature, and seems to be increase in strength as the deep layer shear increases. Observations from the field also suggest that supercells utilizing very high CAPE (>4500 j/kg) appear to have significantly stronger inflows than weaker CAPE storms. The hodograph on the left was taken from the RUC model sounding east of the Spencer, SD tornadic storm on 30 May 1998. Environmental low-level flow was almost nonexistent. However, there was extreme CAPE and very strong 0-6 km shear (50 kts). Spotters just ahead of the supercell reported inflow of at least 20 kts. Using a little artistic license, the hodograph has been modified in the lowest 6 km based on their observations and a small numerical study by Weisman et. al (2000).

Accelerated inflow

- Multicell in 25 m/s 0-6 km shear increase the shear another 4 m/s
- Supercell in 35 m/s 0-6 km shear increase the shear another 16 m/s



Weisman et. al (2000) ran several experiments where the pre-storm environmental 0-6 km shear was changed, and then the 0-6 km shear was analyzed during the lifecycle of the modeled convection. Their experiments show a large increase in storm-induced shear, with shear values increasing with decreasing distance from the storm (see sounding points C to B to A) on the right hand side. The earth colored shaded regions ahead of the reflectivity core of the storm show where the storm has affected the 0-6 km shear fields. Some of the shear is induced by accelerated low-level inflow, while some is induced by accelerated midlevel flow on the south and southeast sides of the mesocyclone.

Lowering the pre-storm shear produces nonsupercell storms and lower enhancements to the storm proximity shear (see the left side).

Summary: Low-level SRH enhancement

- Close to radar, can detect
  - Forward flank outflow boundaries in velocity
  - Storm-induced inflow acceleration in velocity
- Far from the radar, must infer
  - FFD boundary right of the reflectivity core
  - Adequately high dewpoint depressions
- Anvil baroclinicity
  - Anvil must extend ahead of anticipated storm motion
  - Adequate solar heating right of anvil edge

Low-level SRH enhancement can be detected close to the radar in the form of forward flank outflow boundaries, and storm-induced inflow acceleration.

Far from the radar, your information content goes down and the need for inference and intuition go up. FFD boundaries are most likely to become prominent when supercells produce long forward flank cores and there are adequately high dewpoint depressions in the boundary layer.

Another, less tested consideration, is the anvil baroclinicity. Look for this where the anvil extends ahead of the anticipated storm motion and there is solar insolation outside the anvil shadow.

Storm interrogation

AWOC Severe Track

IC3-III-D

Part 1: Near range tornadogenesis signatures viewed by the WSR-88D

Welcome to the AWOC Severe Track

IC3-III-D

Part 1: Near range tornadogenesis signatures viewed by the WSR-88D

This lesson is 18 slides long and should take 20-25 minutes to complete.

Part 2 of this duo examines near range tornadogenesis by the TDWR

Part 1: Near range tornadogenesis signatures

- Objectives
  - Recognize how tornado precursor signatures such as the mesocyclone and TVS appear in ranges less than 50 km
  - Interpret favorable signatures indicating a likely tornado that can only be detected at close ranges

The appearances of the classic mesocyclone and TVS are quite different when these features become large relative to the beam width. As we will see, the TVS may not represent the entire tornado cyclone, but perhaps an increasingly small part of it. The mesocyclone may not even look like a coherent rotational structure when smaller velocity structures within can be resolved.

On the other hand, it is these close ranges where radar data becomes by far the most useful tool because of the extreme detail it can portray.

There are two objectives in Part 1:

1. Recognize how tornado precursor signatures such as the mesocyclone and TVS appear in ranges less than 50 km
2. Interpret tornado signatures that can only be detected at close ranges.

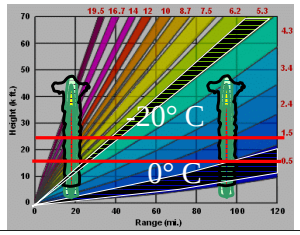
Part 1: Near range tornado signatures

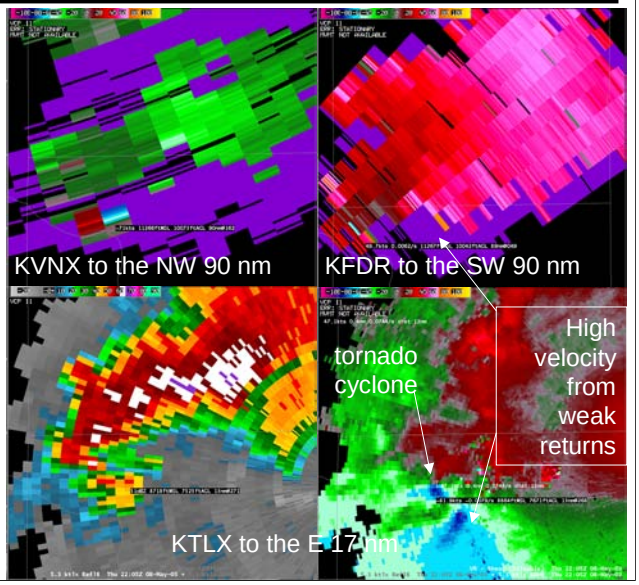
- TVS and mesocyclone appearance at close range
- Low-level convergence
- Hook echoes
- Debris

This lesson, using two cases that represent a growing number of documented close range tornadic events to radars, will show the appearances of a TVS and mesocyclone at close range, low-level convergence signatures, the finescale appearance of hook echoes, and debris signatures.

Mesocyclone comparison: distant vs. nearby radar

- 08 May 2003 – OK
- More scales of circulation appear at close range
- High velocities in low reflectivity fail to appear in KFDR





This case on May 8, 2003 resulted in an F4 tornado that struck Moore, OK and was observed at close ranges by KTLX WSR-88D, a nearby TDWR, and the experimental radars at NSSL and the ROC. All the radars observed the entire lifecycle of the tornado less than 15 miles in range.

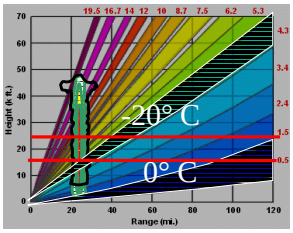
To start off, we show the appearance of this mesocyclone at approximately 10 kft AGL from two radars of different viewing angles but 90 nm away to that of KTLX, only 17 nm away just before the start of the tornado at 2205 UTC. To the northwest, KVNX lucks out and manages to sample the tornado cyclone with an almost 0.5° offset angle (See IC3-III-A) resulting in a gate to gate signature that easily is strong enough to be called a TVS if it has vertical continuity. None of the strong flow around the storms right flank can be detected because of weak returned energy. KFDR, 90 nm southwest, suffers from range folding problems in the area of the mesocyclone for the same reason. Other volume scan times show better resolved strong outbounds on the right flank of the storm and KFDR is well positioned to see the flow around the right side of the mesocyclone; some gates show > 100 kts of outbounds.. KFDR is barely able to resolve the gate to gate tornado cyclone signature.

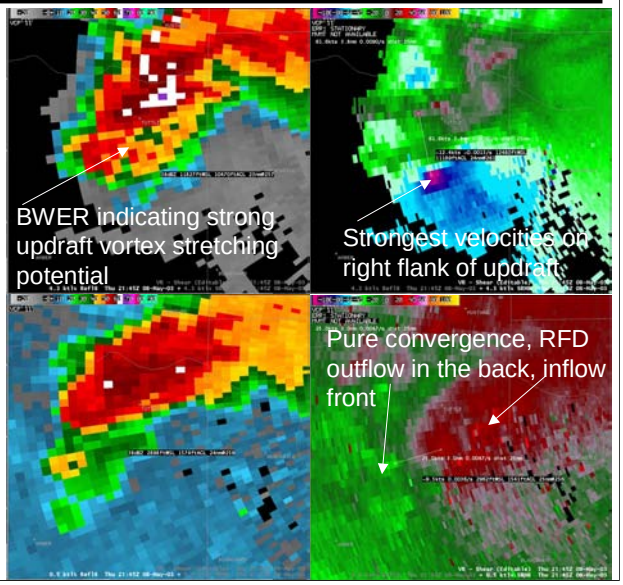
KTLX, 17 miles away, and with an elevation in the center of the 0.5° slices of the other radars, is close enough to resolve the low reflectivity, high velocity signature on the storms right flank. This is often visualized as rapid horizontal motion in the cloud bands to the right of the visual storm updraft at midlevels and comprises part of the mesocyclone as viewed from more distant radars. These high inbounds are nearly completely separate from the occluded portion of the mesocyclone (or tornado cyclone) within the hook echo and inside the rear flank downdraft.

Note that the tornado cyclone does not show the maximum velocities in this circulation in adjacent gates at this elevation angle. There is a 90 kt gate to gate velocity difference, but higher velocities exist at greater ranges from the tornado cyclone center. Sometimes a circulation may not even show up as a TVS at these ranges and yet be very tornadic.

Near range tornadogenesis signatures: 08 May 2003

- 2145 UTC
- Weak pure convergence at 0.5° (1kft)
- Mesocyclone at 4.3° (11 kft)





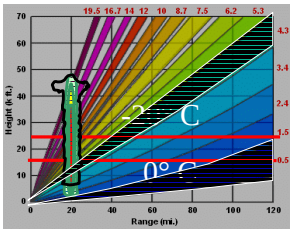
The environment on this day was very supportive of tornadoes, low LCLs, 0-1 km wind shear exceeding 25 kts, CAPE on the order of 4000 j/kg, no CIN and a strong dryline west. A PDS tornado watch is in effect and any supercell in the stage of development shown above is likely to have high tornado potential.

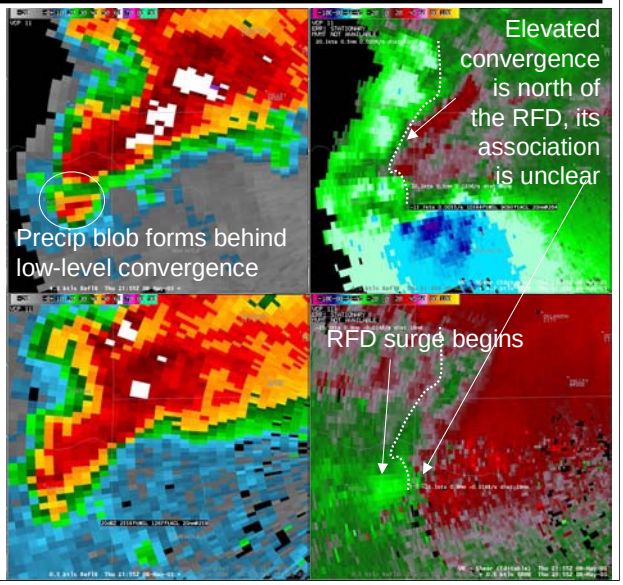
We'll take a walk through of common signatures at near range leading up to the tornado. We'll start at 2145 UTC, about 20 minutes before tornado time. Two slices are displayed, the lowest slice at 1 kft AGL, and the other at 11 kft AGL. As the storm approaches the radar, I will change elevations to keep sampling the storm between 8 and 11 kft for the upper slice.

Several precursor signals are coming together for tornadogenesis. The higher reflectivity slice shows evidence of a strong midlevel updraft signified by a BWER. Strong velocities aappear on the right flank of the storm updraft comprise a well developed mesocyclone, more evidence that air is accelerating strongly upward between the surface and 10 kft. Also at 10 kft, there are areas of separate inbounds and convergence which may indicate an RFD. Near surface velocities show almost pure speed convergence. But that convergence is under a mesocyclone further indicating some stretching potential is there for any near surface vorticity in the vicinity. At this time, there is no significant RFD outflow surge and low-level convergence is fairly weak. Given the elevated convergence, an RFD outflow surge may seem likely.

Near range tornadogenesis signatures

- 2155 UTC
- Mesocyclone at 4.3° (10 kft)
- Strong pure convergence at 0.5° (1kft)

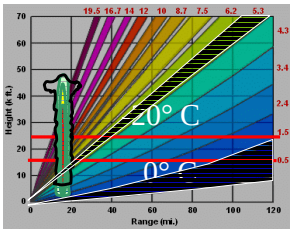


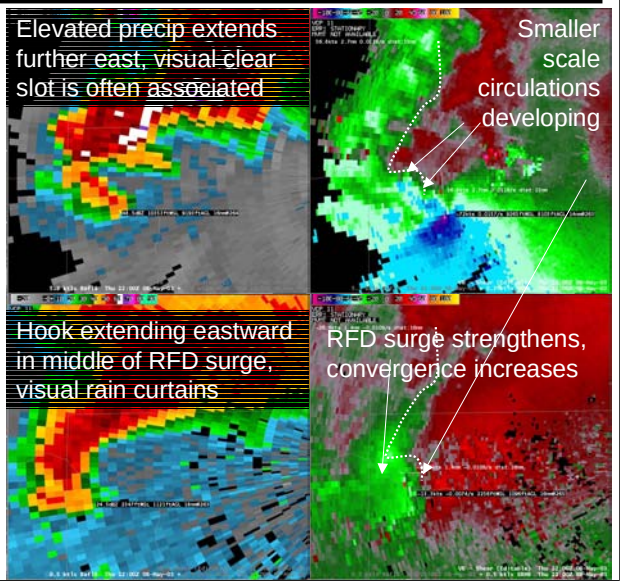


At 2155 UTC, 5 minutes later, the low-level velocity shows the RFD outflow surge may indeed be underway. Convergence at its nose ramps up considerably. But note there is no rotation. Above the RFD surge, note the inbounds and midlevel convergence increases a little behind the low-level convergence (accounting for system motion before the radar scans at 10 kft AGL) and is marked by the dotted white boundary. An area of precipitation forming above and behind the low-level RFD surge a feature that has been observed before prior to tornadogenesis and may have some relationship that has not been identified yet.

Near range tornadogenesis signatures

- 2200 UTC
- Mesocyclone at 5.3° (8.7kft)
- Strong pure convergence at 0.5° (1kft)

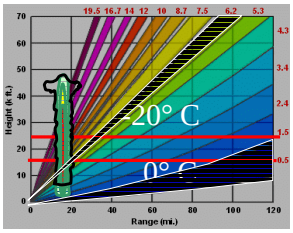


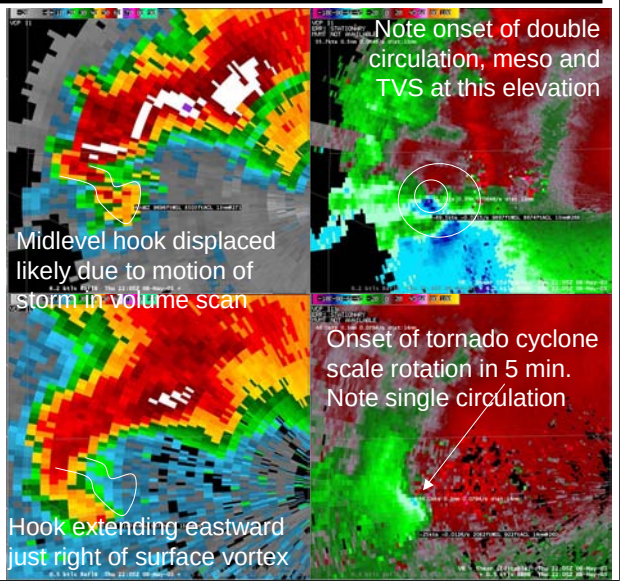


At 2200 UTC, the elevated precipitation blob connects with the low-levels to form the beginning of a hook echo. The part of the hook about to curl to the east lies in the middle to south part of the RFD surge. Strong convergence begins to broaden north to south just ahead of the hook echo. Note that the inflow into this convergence (visualized as outbound low-level velocities) increases too. At 8.7 kft AGL, small scale circulations begin to develop, nearly overhead of the low-level convergence. Developing rotation above strengthening low-level convergence, all underneath a strong echo overhang (not shown) signifies stronger and more immediate mesocyclonic tornado precursor signals.

Near range tornadogenesis signatures

- 2205 UTC
- Mesocyclone at 5.3° (8.7kft)
- TVS at 0.5° (1kft)



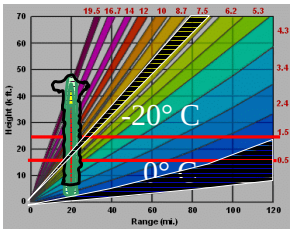


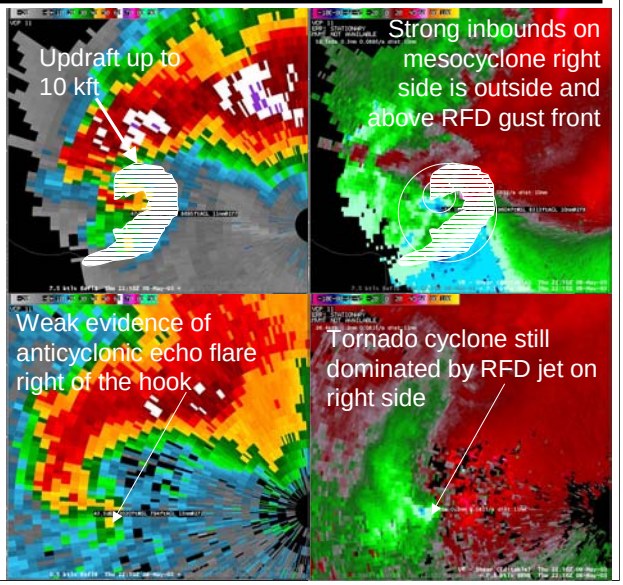
At 2205 UTC, the southern of the two circulations at 8.7 kft AGL consolidates and links with the rapid onset of circulation at the lowest level. This is tornadogenesis underway. The hook echo extends further east embedded on the strengthening RFD surge, now right of the circulation, now a tornado cyclone.

Note that the radar must complete many scans before adequately sampling the low- and midlevels of this storm. Meanwhile the circulation is progressing eastward causing an artificial tilt of all features in the direction of storm motion.

Near range tornadogenesis signatures

- 2210 UTC
- Mesocyclone at 7.5° (8.7kft)
- TVS at 0.5° (<1kft)



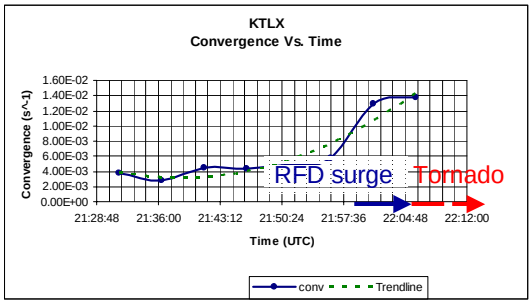


The tornado cyclone is still dominated by an RFD jet on its right side. At 8.7 kft AGL, note that the tornado cyclone (inner circle) still has the maximum inbound/outbound velocities away from the center. A TVS is present after noting the gate-to-gate shear of adequate magnitude. Some tornado cyclones at this range fail to show a TVS. The larger mesocyclone is still evident at 8.7 kft as a separate circulation from the tornado cyclone. Visually, the tornado cyclone is mostly RFD outflow swirling toward the cyclone center. The RFD air contains the hook echo. Part of that hook may be falling out of a deep dry slot carved out of the updraft (white shaded comma shaped region), which in turn, conforms roughly to the RFD gust front boundary. Thus the updraft becomes more horse shoe shaped. Not all updrafts will undergo this shape transformation to a horse shoe, but most will while low-level mesocyclogenesis commences.

One other interesting effect of the RFD surge is that an area of anticyclonic vorticity can accumulate on the right side of the surge. If the radar is close enough and the anticyclonic circulation is large enough, you may see it visualized in the reflectivity data as an anticyclonic flare echo. What you are seeing is the fact that the RFD echo is tilting horizontal vorticity downward, the cyclonic part of the resulting couplet concentrates within the developing tornado cyclone, the anticyclonic part of the couplet develops as a large sheet of anticyclonic vorticity along the right side of the RFD surge. Sometimes this sheet of anticyclonic vorticity coincides with the tail part of the updraft over the trailing gust front and anticyclonic tornadogenesis may be the result

Near range tornadogenesis signatures

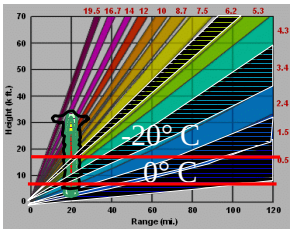
- WSR-88D shows increase in low-level convergence exceeding .01 s^{-1} prior to tornadogenesis
- Eastward RFD surge apparent at the same time

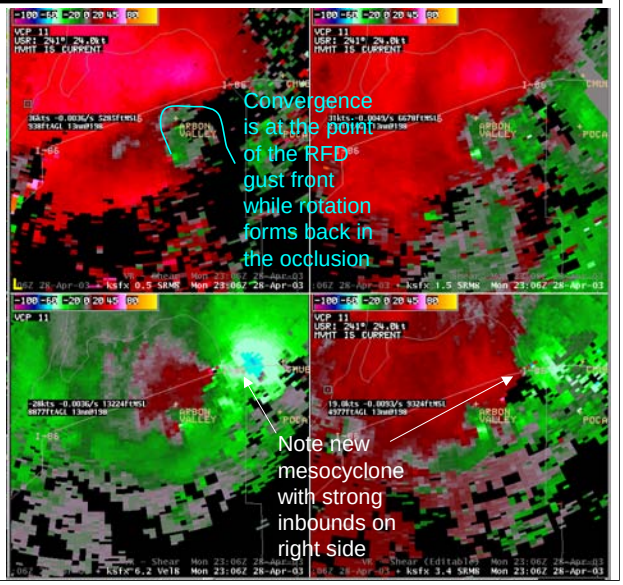


The RFD surge in combination with increasing storm-relative low-level inflow increases convergence rapidly just before tornadogenesis. Low-level convergence values rise above .01 s^{-1} across a one km baseline. There is perhaps a 1 to 10 minute leadtime before tornadogenesis in this case.

Another example of low-level convergence

- 28 Apr 2003, Pocatello, ID
- Low-level convergence
- Low-level TVS formation and tornadogenesis coincide

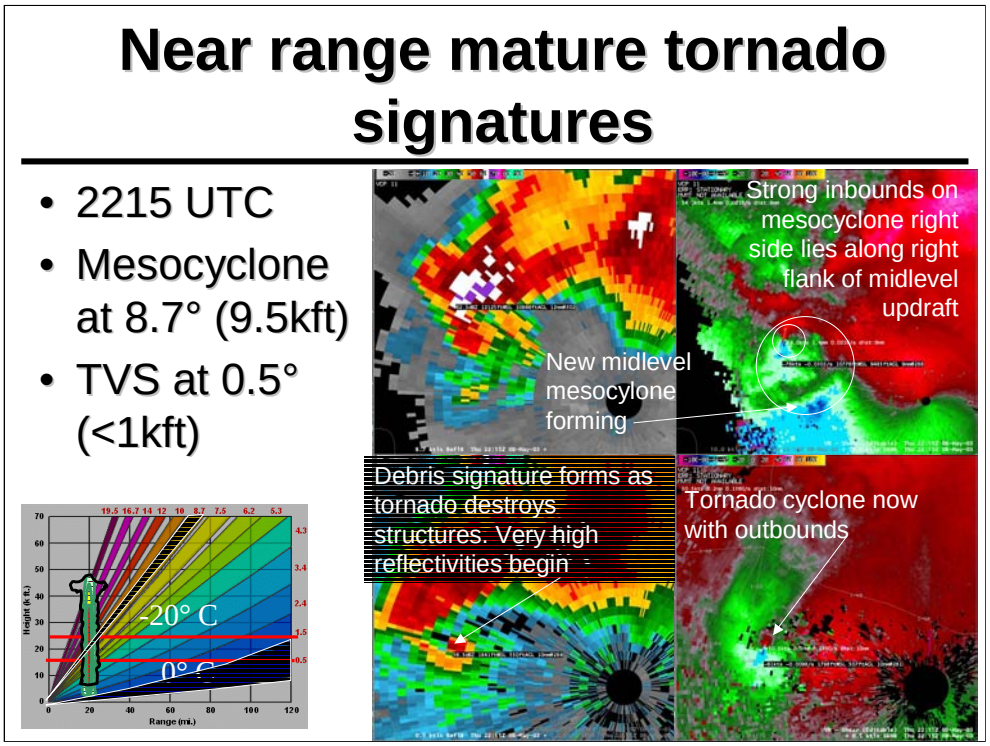




A close range tornadogenesis event occurred just south of Pocatello, ID on 28 April 2003. This time, the radar was left of the storm track, whereas on 08 May 2003, the radar was to its right. The different viewing angle precludes viewing the full strength of the RFD surge; it is directed more to the east instead of straight at the radar.

At 2251 UTC, the RFD gust front is evident as a horse shoe shaped region of convergence turning to shear on the left side. Given the ground clutter on the lowest slice, the convergence appears a little better at the 1.5° slice. The larger mesocyclone appears best at 10 kft AGL at 2251 UTC with more pure convergence below in the lowest two slices.

By 2256 UTC, a tornado cyclone forms at 10 kft AGL over the left side of the RFD horseshoe shaped gust front. The next scan at 2301 UTC shows the tornado cyclone extending to ground level and tornadogenesis commenced.



Going back to the 08 May 2003 tornado, we now look at some mature tornado signatures that show up only at near ranges.

The lowest velocity scan now shows a more symmetrical tornado cyclone, although the RFD inbounds still provide some asymmetry to the circulation.

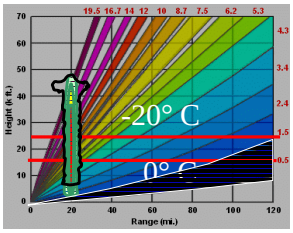
The RFD shows strong connection to the downdraft and outflow from the forward flank region of the storm's core.

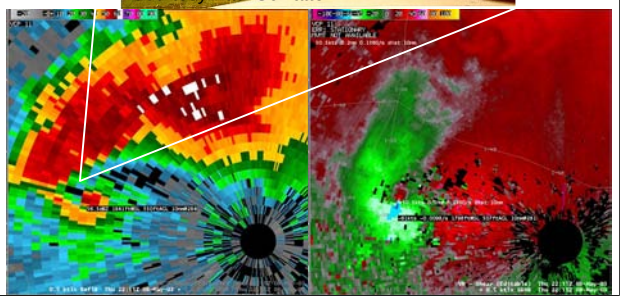
The tornado cyclone and larger mesocyclone still appear as separate circulations at 10 kft AGL. Note, however that on the right flank of the midlevel mesocyclone, a separate area of enhanced inbounds increase in strength that indicates the development of localized updraft rotation and the beginnings of a new separate mesocyclone.

Perhaps the most notable signature is the existence of a small area of strong reflectivities at the tip of the hook echo in the lowest scan. This small area of reflectivity appears just as the tornado destroys structures near I-35 in Moore. The reflectivity "ball" is the signature that the radar is detecting debris. The followup session to this shows another region of even more intense reflectivities viewed by the TDWR.

Near range mature tornado signatures

- 2215 UTC
- Mesocyclone at 8.7° (9.5kft)
- TVS at 0.5° (<1kft)

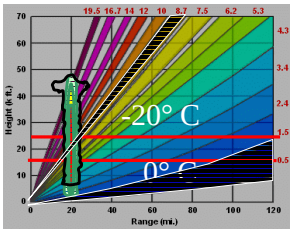


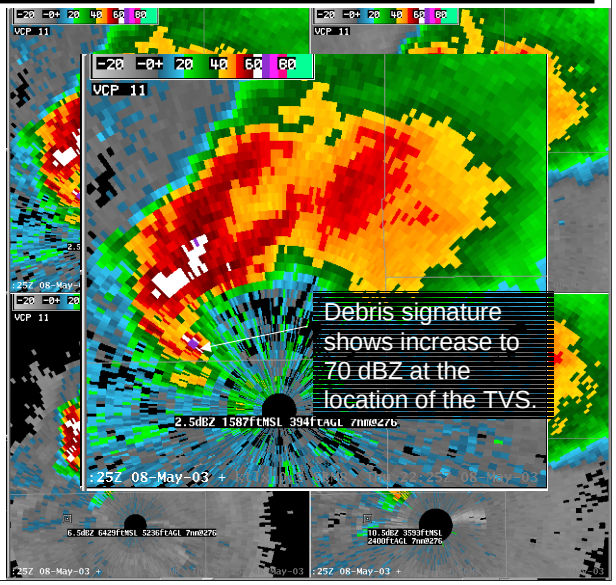


As observed from the ground to the northwest, and a couple minutes before the radar image, the tornado is beginning to loft debris several hundred feet into the air. At 16 miles range, large debris at this altitude is enough to be detected by the radar. Again, the debris needs to be large to present a significant radar cross-section. Dust particles alone are not enough to provide reflectivities that exceed normal reflectivities associated with the hook echo and other natural scatterers (e.g., insects).

Near range mature tornado signatures - debris

- 2225 UTC
- Debris signature near the time of impact on the GM plant



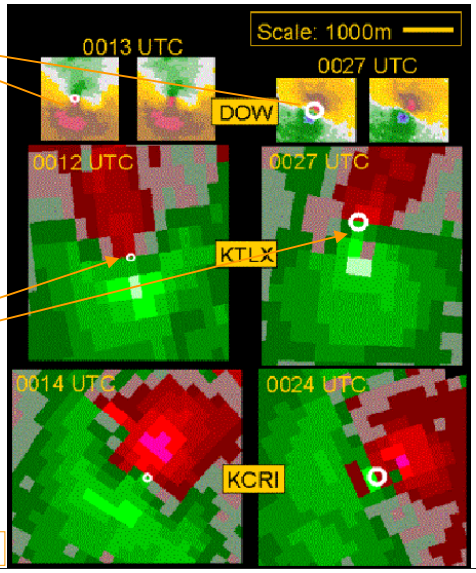


At 2225 UTC, the tornado impacted the General Motors plant in Southeast Oklahoma City resulting in a significant upward surge in debris.

Is the close range TVS a tornado?

Mobile radar directly observes tornado with a radius marked by the white circle. The radius is 100 to 500 m.

Overlay actual radius on KTLX (20 mi), or KCRI (12 mi) shows the TVS to be many times larger than the tornado.



Adapted from Burgess et al. (2001)

A question often arises as to whether the tornado core can be adequately sampled by the WSR-88D at close ranges. On May 3, 1999, the Doppler On Wheels (DOW) sampled a large tornado within a few km range. The small velocity couplet signature from the DOW that can be seen at two different times, 0013 UTC and 0027 was the tornado core. Its radius was chosen as the radius of maximum winds found around the tornado center. Superimposing the white circle at 0013 UTC, marking the tornado diameter on the WSR-88D from KTLX (20 miles range), and the test bed WSR-88D, KCRI (12 miles range), you can see that the tornado core is still far smaller than the individual gate sizes from both radars. Even when the radar was closer (16 miles from KTLX, 8 miles from KCRI) the tornado core diameter is still too small for the two radars to resolve it. Adequate tornado sampling requires about 4 azimuthal gates across the core.

Other factors also hinder adequate velocity sampling of the tornado:

1. The tornado offset angle from the beam centerline is too small, or a single range gate is sampling both sides of the tornado.
2. Most of the returned power to the radar comes from relatively slow moving debris. You don't see the velocity spectra, only the velocity from which the radar detects the greatest returned power.

Summary: Close range rotation signatures

- More complexity of rotation
  - TVS is the detection of the tornado cyclone
  - Mesocyclone scale shows less symmetry
    - strongest velocities are located at midlevels on the right flank of the updraft for cyclonically rotating mesocyclones
    - Difficult to discern mesocyclone rotation at low-levels

To summarize, close range rotation signatures are more complex in scales.

At close ranges, the TVS is the manifestation of the tornado cyclone.

The mesocyclone does not appear as symmetric as before, with most of the strong velocities displaced to the right side of the updraft for cyclonically rotating storms. At low-levels, the mesocyclone may not appear at all.

Summary: Close range tornadogenesis signatures

- Lowest level velocity signatures
  - RFD surge
  - strong convergence under higher level rotation and other updraft signatures
  - Increase in convergence with time
  - Rotation onset at tornado time
- hook echo
  - Rapid extension associated with RFD surge
  - Perhaps an elevated descent of reflectivity core into back side
  - Occasionally an anticyclonically shaped flare south of the hook

Remember that these signatures apply best to mesocyclone induced tornadoes.

Tornadogenesis signatures appear at low-levels as the RFD begins to develop. Convergence increases dramatically at low-levels and should appear under a midlevel mesocyclone and other strong updraft signatures. Only immediately before tornado formation is there any appearance of a tornado cyclone at low-levels. The convergence signature gives you on the order of 5 to 10 minutes of lead time. The onset of an intense tornado cyclone may only appear within a minute of tornadogenesis.

The hook echo may appear to extend in length and definition as the RFD develops. More recent research work has suggested that a descending 'blob' of reflectivity on the back side of the storm may contribute to RFD genesis.

As the RFD matures and begins to develop low-level rotation, an anticyclonic flare echo may be detected right of the main hook echo. Anticyclonic tornadoes are most likely if this anticyclonic flare coincides with the gust front underneath strong updraft.

Summary: Close range mature tornado signatures

- Lowest level velocity signatures
  - TVS likely, sometimes not visible as a gate to gate signature – too close for a TVS
  - RFD gust front with other vortices along interface
- Reflectivity
  - Debris appears as a ball of very high reflectivity

Close range radar signatures of a mature tornado include good sampling of the tornado cyclone. Sometimes, the sampling is such that no gate to gate TVS strength signature appears in the tornado cyclone. The RFD gust front appears well defined, and there may be other vortices appearing along its interface.

If the tornado is ejecting large debris (e.g., tree branches, building parts), a reflectivity debris ball may appear as a small region of very high reflectivities extending upward several thousand feet or more.

Storm interrogation

AWOC Severe Track

IC3-III-E

Part 2: Near range tornadogenesis signatures viewed by the TDWR

Welcome to the

AWOC Severe Track

IC3-III-E

Part 2: Near range tornadogenesis signatures viewed by the TDWR

This part follows part 1 of near range tornadogenesis signatures by the WSR-88D.

It is approximately 13 slides long and should take about 10 minutes to complete.

Part 2: Near range TDWR tornadogenesis signatures

- Objectives
  - Familiarize yourself with the applications and weaknesses of using Terminal Doppler Weather Radar (TDWR) for analyzing close range tornadogenesis signatures
  - Be familiar with the characteristics of the TDWR

As objectives, you should familiarize yourself with the applications and weaknesses of using the TDWR for analyzing close range tornadogenesis signatures. The same applications and weaknesses should apply to the interrogation of many meteorological features.

This lesson will also help you become more familiar with the characteristics of the TDWR.

At this point, development is underway to send TDWR data to WFOs on an operational basis. Thus for any site that has a TDWR in your CWA, this lesson will have more relevance to you.

Part 2: Near range TDWR tornado signatures

- TVS and mesocyclone appearance at close range
- Low-level convergence
- Hook echoes
- Debris

We will look at the similar events as with part 1, a close range mesocyclonic tornado formation case in Norman, OK, and a nonmesocyclonic case from Salt Lake City, UT. You will see how TVS signatures and mesocyclones appear in the TDWR, how low-level convergence signatures appear, how hook echoes become more complicated, and the sensitivity of the TDWR to debris signatures.

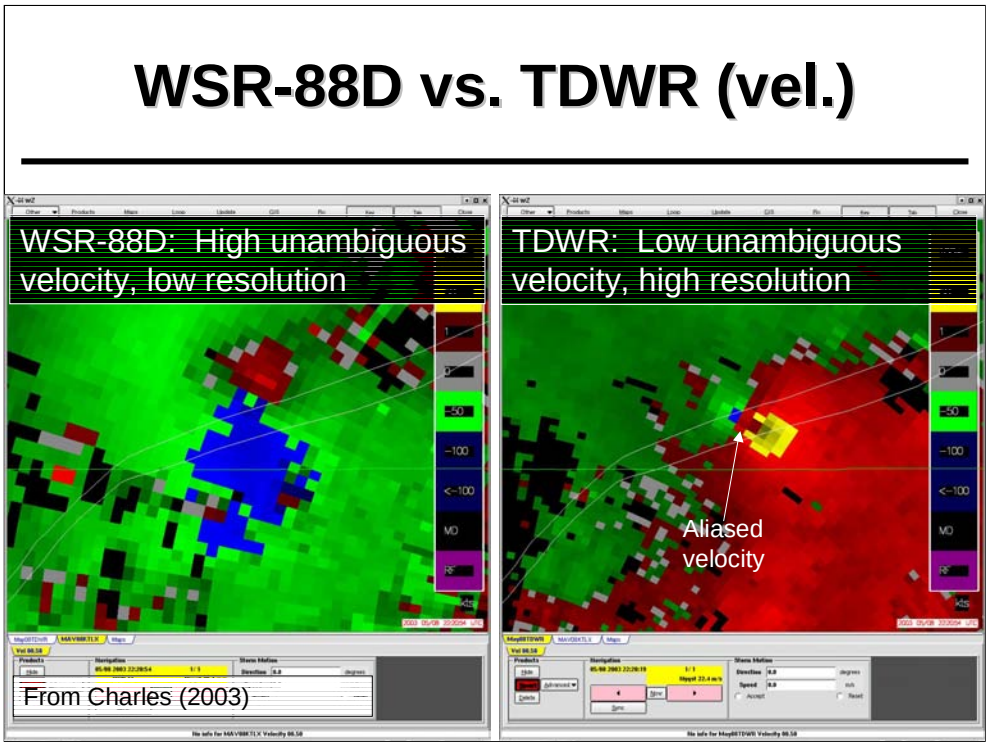
TDWR vs WSR-88D

	WSR-88D	TDWR
wavelength	10 cm	5 cm
Volume scan time	4 minutes in VCP 12	1 minute 0.5°, 2.5 min for other angles
Beam width	1.25°	0.5°
Range gate	.13 nm in velocity .54 nm in reflectivity	.067 nm
Max unambigious velocity	Up to 62 kts with a PRF = 1293.10 s^{-1}	20 - 30 kts

The TDWR operates at 5 cm and is more susceptible to attenuation in heavy precipitation. However, this wavelength is more conducive to detecting most nonprecipitating echoes such as insects.

One of the TDWR volume scan strategies allows for one minute sampling at the 0.5° angle while sampling other elevation angles on a 2.5 minute basis. The real advantage comes with the 1 minute sampling when a storm is undergoing tornadogenesis.

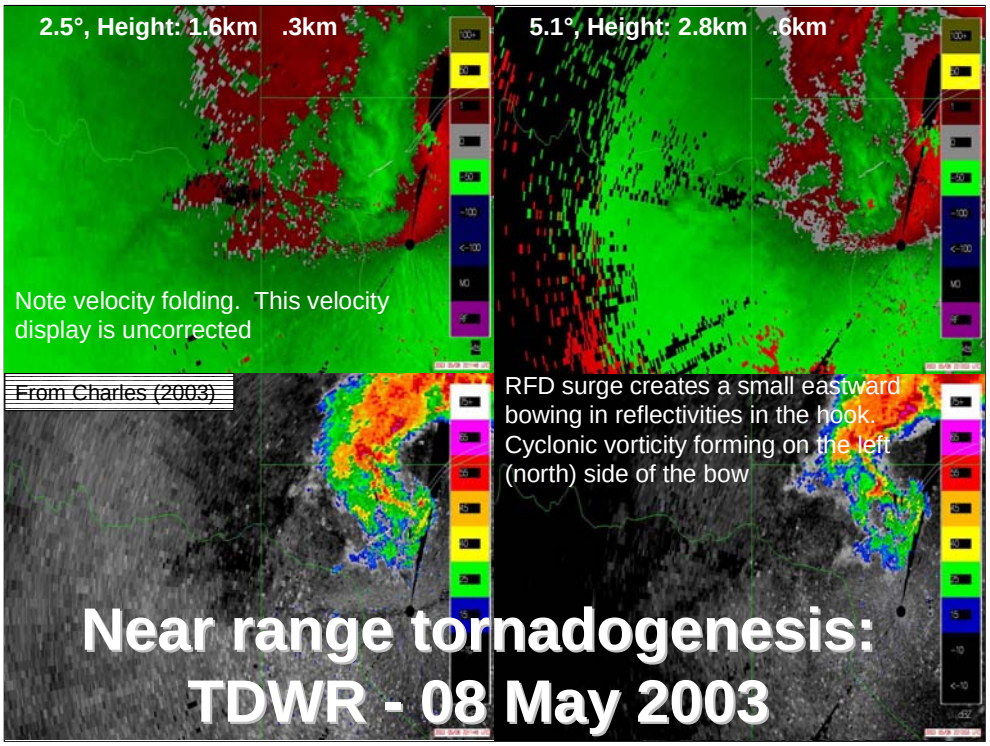
The beam width of the TDWR is half that of the WSR-88D. Add a shorter range gate due to a faster PRF, and the TDWR delivers much higher resolution, 8 times more data than a single range gate from the WSR-88D. The tradeoff is that the maximum unambigious velocity (from here on, V_{max}) is a lot lower for the TDWR. Examples will show the effects on real information coming next.



Here are two views of a mature tornado cyclone with a 8 mile range to radar. The WSR-88D, left adequately samples the high velocities associated with the right flank of the tornado cyclone but washes out the tight velocity couplet that should be there given that the tornado is in its mature stage.

The resolution of the TDWR produces a much tighter velocity couplet on the same order of size as the damage track being produced by the tornado (within the area bounded by the thin white perimeter). But notice that some aliased velocities exist near the circulation center, just on its left side. An even more clear example

Much of the May 08, 2003 results are from a paper by Mike Charles (2003) while working with the NWS OUN as a summer student in the Research Experiences for Undergraduates (REU) program and with Dave Andra, Dan Miller, and Mike Foster serving as mentors.

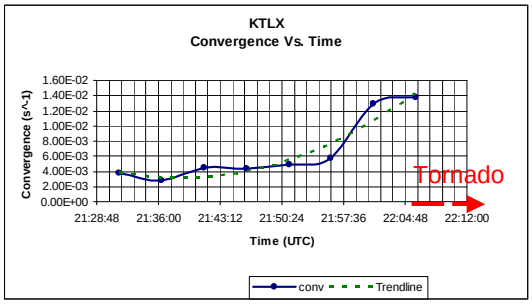


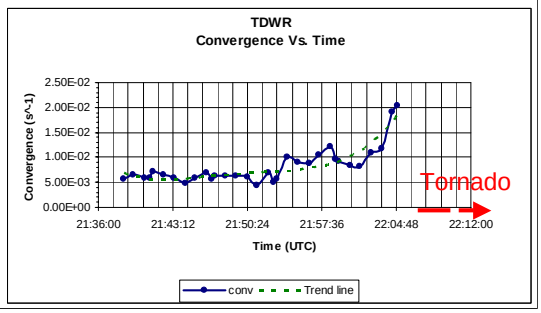
Displayed here is a 4 panel image of the

The first few times show the strong inbounds south of the developing hook echo, and above 1.6 km AGL. The inbounds are folded once to outbounds and then again to inbounds again in the

Near range tornadogenesis signatures

- Both radars show increase in low-level convergence exceeding .01 s^{-1} prior to tornadogenesis
- Values are higher for the TDWR





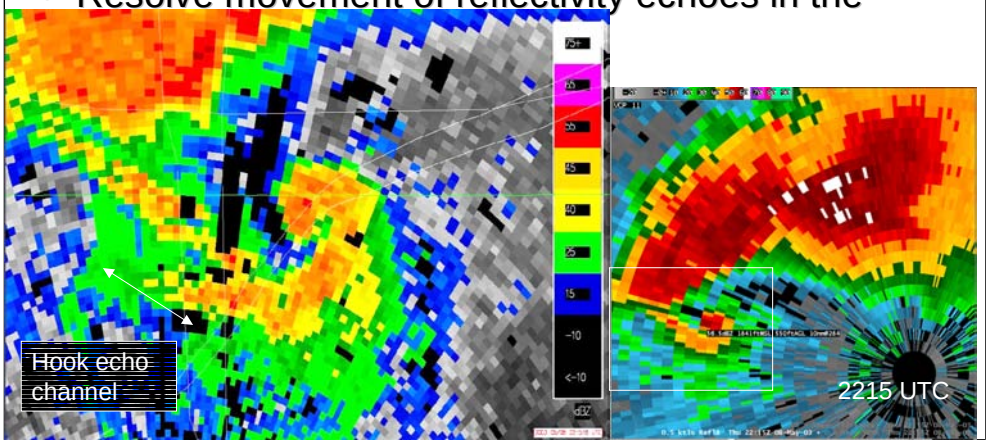
Adapted from Charles (2003)

An analysis of maximum convergence found at the lowest elevation from both radars show increasing values before first tornado. The improved TDWR temporal resolution results in more noise and sharper increases in the RFD convergence. Note that both show rapid increase in convergence less than 5 minutes before tornado time. Note that the trend line in the WSR-88D shows a false picture of slowly increasing convergence. Unfortunately, you only see the convergence represented by the data points and thus the WSR-88D gives you less lead time to convergence increase than the TDWR.

The TDWR maximum convergence exceeds .02 s^{-1}, a third higher than that of the WSR-88D.

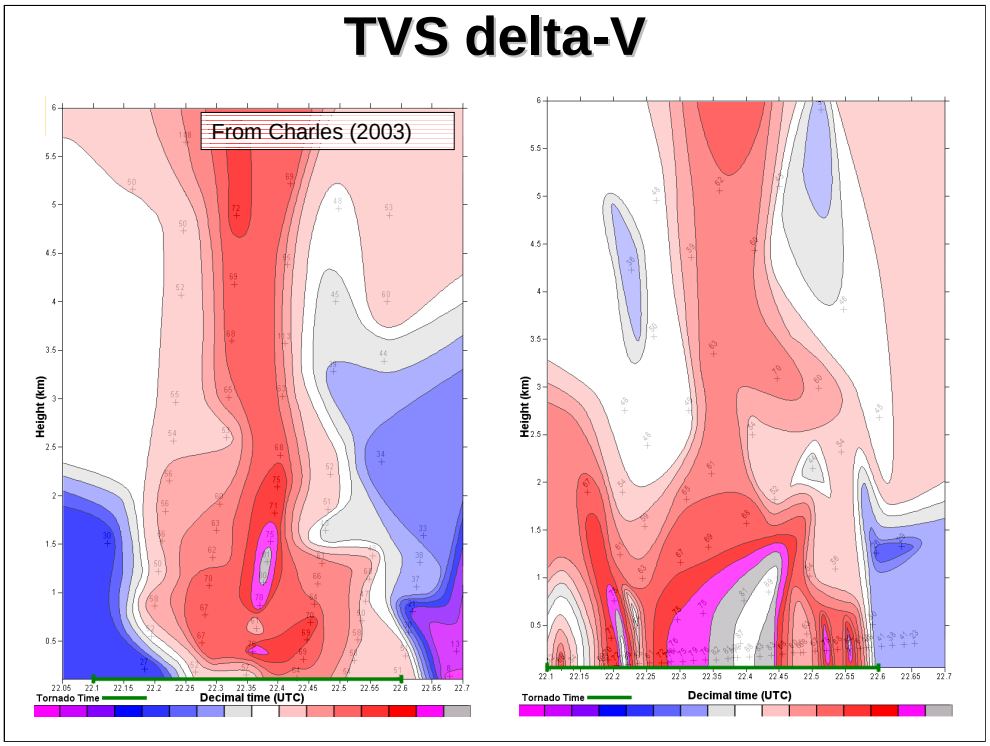
Near range tornadogenesis TDWR reflectivity signatures

- TDWR offers 1 minute scans at 0.5°
- Debris signature only resolved by TDWR
- Resolve movement of reflectivity echoes in the



The one minute resolution of the TDWR is just about enough to track individual reflectivity patterns northwest to southeast along the hook echo channel. As this loop proceeds, the onset of the debris signature in the TDWR occurs right as the damage track begins. The WSR-88D cannot detect it so early.

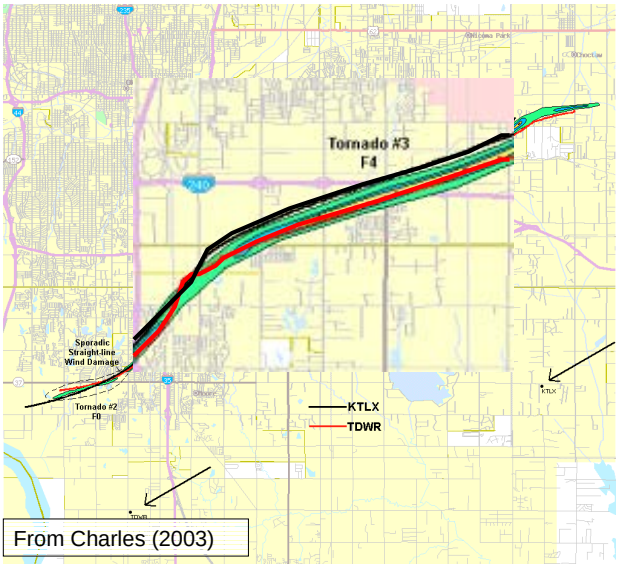
During the event, forecasters, and ham radio operators were able to relay minute by minute positions of the tornado as it plowed through Moore and South Oklahoma city. This level of communication helped emergency responders at a level not done before.



The TDWR should provides stronger values of velocity difference in the TVS signature than the WSR-88D. Stronger may not be necessarily better when assessing tornado potential since just about all TVS may appear stronger with finer resolution. However, the chance for early detection of a tornadic circulation is much sooner with the TDWR. Given the better temporal resolution, the structure of the time/height trends show more detail. In either case, both KTLX and the TDWR clearly show the TVS signature strengthen during the mature stages of the tornado.

Accuracy of WSR-88D and TDWR TVS track vs. damage

- WSR-88D in black
- TDWR in red
- Both are accurate < 1 km but the TDWR is more accurate

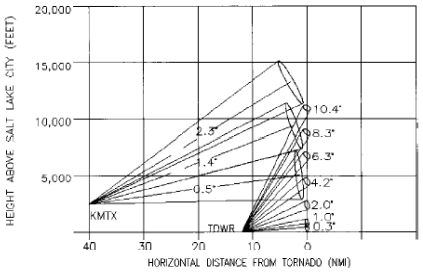


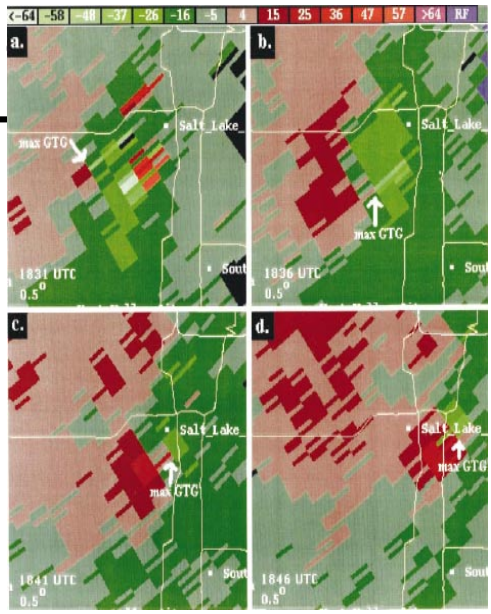
From Charles (2003)

Finer resolution does mean finer accuracy in positioning the tornado with the TDWR. Upon zooming in on the F-scale contour damage map, the lowest slice circulation center of the WSR-88D (black line) is a quarter mile off from the axis of worst damage. The TDWR track (red line) is just about dead center on the damage.

TDWR:

- 11 August 1999 – SLC
- Weak circulation noted in the 0.5° slice from KMTX



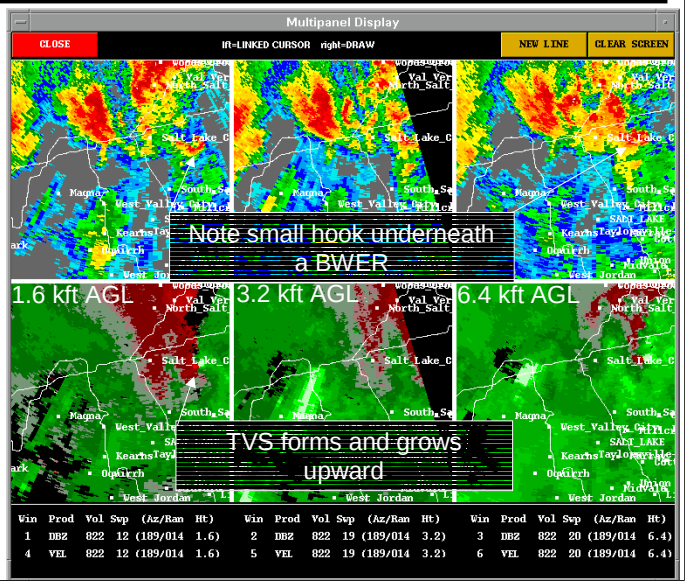


From Dunn and Vasiloff, 2001 (WAF)

Another case has been published in Weather And Forecasting by Larry Dunn and Steve Vasiloff where the TDWR data were compared to the WSR-88D for the Salt Lake City tornado. The differences in distance between these two radars is much greater, with the TDWR in close proximity to the damage track. The fine resolution and number of beams below the 0.5° slice of the KMTX WSR-88D make the TDWR there indispensable for analyzing small features in the Salt Lake Valley. The tornadic storm here barely showed any gate to gate signature, labeled as “max GTG” with the storm as it scoured a damage path through downtown.

TDWR case #2

- TDWR is closer and is able to show these that the WSR-88D could not
  - Boundary
  - TVS
  - Hook, BWER



The TDWR data, only 14 km (8nm) in range, and with numerous low slices below the lowest slice of KMTX, shows an accurate evolution of this tornado as a near surface-based vortex extending upward into the storm near 1840 UTC. A small hook echo feature and even a BWER forms around the vortex at the end of the loop. This TDWR did not have a one minute lowest slice sampling period but with its proximity, provided high quality information on the tornado vortex.

Summarizing: TDWR vs. WSR-88D in near range tornadoes

- WSR-88D
  - Poorer resolution
  - Good unambiguous velocities
  - Poor temporal frequency
  - Low attenuation
  - Good coverage
  - Poor siting on mountain tops
  - NWS control
- TDWR
  - Better resolution
  - Poor unambiguous velocities
  - Good temporal frequency
  - High attenuation
  - Poor coverage (20 cities)
  - None sited on mountain tops
  - FAA control

The TDWR offers you excellent resolution and temporal frequency. However, given other factors favoring the WSR-88D, the TDWR will serve as an enhancement to the current network, and certainly not a replacement. Note the strengths of each radar are colored in yellow. The WSR-88D's advantages lie in its coverage, high

It is not known at this time how the TDWR data will be made operational to the NWS forecasters. Work will need to be done that will be defined during the course of AWOC delivery. As the details are worked out on delivering the data to the field, WDTB will provide more training on the use of TDWR data.

Storm Interrogation

AWOC Severe Track

IC3-III-F

Nonmesocyclonic tornadoes

Welcome to the AWOC Severe Track

IC3-III-F

Nonmesocyclonic tornadoes

This lesson is 11 slides long and should take anywhere from 10 to 15 minutes to complete

Nonmesocyclonic tornadoes

- Objectives
  1. Given the example, show the conditions where pre-existing vertical vorticity is a significant tornado ingredient
  2. Determine the timing of greatest tornado threat given the superposition of
     - vertical vorticity and prestorm misocyclones
     - incipient updrafts
     - boundary intersections and/or collisions

The objectives of this lesson are two fold:

1. Show where pre-existing vorticity should be a significant tornado ingredient. This goes far beyond the analysis that is often shown in the SPC mesoanalysis web page using an objective analysis. Here, we go to the boundary scale using radar data, make some assumptions as to the nature of the wind field right up to the edge of either side of the boundary, then use the boundary width as a baseline from which to make an estimate of the background vorticity supply. This is probably as close as we can get to estimating what is really out there. However, note that boundary widths seem to decrease every time a newer higher resolution dataset becomes available.
2. Determine the timing of the greatest tornado threat given the superposition of vertical vorticity, perhaps prestorm misocyclones, incipient storm updrafts, and boundary intersections and/or collisions. Again, anticipating nonmesocyclonic tornadogenesis is very difficult when no significant rotational signatures appear on radar in advance of the event. Timing the convergence the tornado ingredients, vertical vorticity, vertical vortex stretching potential, based on what is detected by radar may help, along with spotter data, to provide some lead time.

Nonmesocyclonic tornadoes

- Considerations
  - They frequently occur in supercells
    - e.g., flanking line tornadoes
    - thus the term “nonsupercell tornado” is not accurate
  - Often no precursor velocity signature on radar
  - Occurrence not a function of LCL height
    - low CIN and steep lapse rates
  - Favored development from boundary interactions with other boundaries or horizontal convective rolls

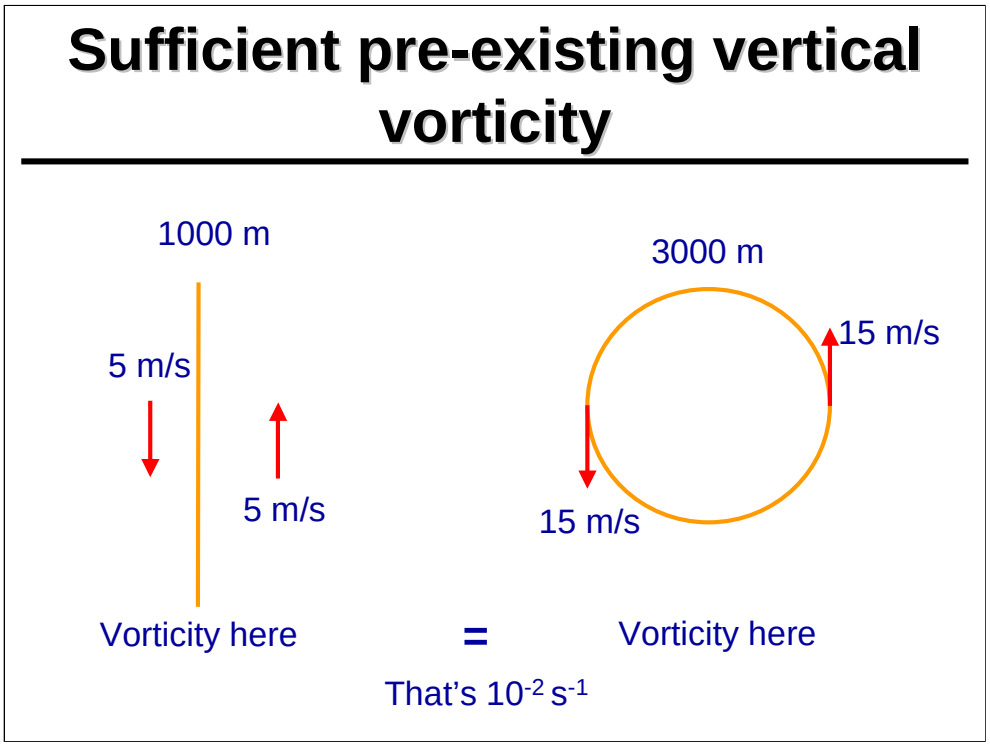
There are some considerations to consider: :^)

Nonmesocyclonic tornadoes is a term that is gaining more favor over nonsupercell tornado because the processes in how the ingredients arrive to produce these tornadoes can occur both in supercells and nonsupercell storms. Flanking line tornadoes along the rear flank downdraft gust front of a supercell is an excellent example of a nonmesocyclonic tornado.

No precursor velocity signatures on radar are common with these events. The pool of vorticity is often very small and close to ground. The misocyclones that may form when a vortex sheet breaks down into eddies are often too small to be detected. Even with mesocyclonic tornadoes, the actual pool of vorticity that directly feeds the tornado may not appear until the time of the tornado. All other vorticity signatures may be a more indirect contribution to tornadogenesis. That has yet to be determined with more research though.

LCL height is not a consideration with nonmesocyclonic tornadoes. There is typically no downdraft feeding vorticity to nonmesocyclonic tornado, and therefore, downdraft buoyancy is not a factor. But allowing for strong low-level stretching is important, and therefore, these events require almost no CIN and steep lapse rates up to at least the LFC.

A linear homogeneous boundary may carry very strong vertical vorticity across its interface, even mesoscyclonic in values, but it may not be enough to initiate a nonmesocyclonic tornado. Most events require some interaction with another boundary, perhaps horizontal convective rolls to ramp up the low-level vorticity even more, and perhaps provide additional stretching potential under an initiating cell.

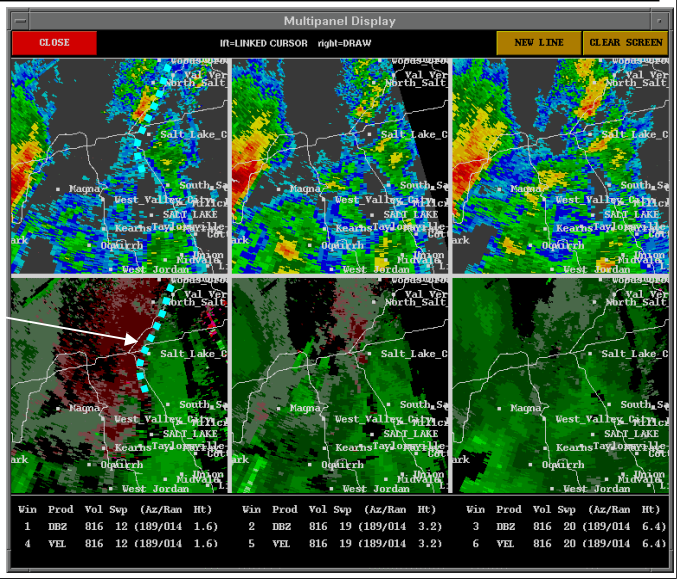


A typical well defined boundary may be one km (.54 nm) or less. Applying only 10 kts of wind in opposing directions across the width of that boundary provides the same vorticity as a 3km wide mesocyclone with a 30 kt rotational velocity. The SPC mesoanalysis plots of vertical vorticity peak out orders of magnitude less than what really is occurring.

We'll show an example coming up.

Pre-existing vertical vorticity

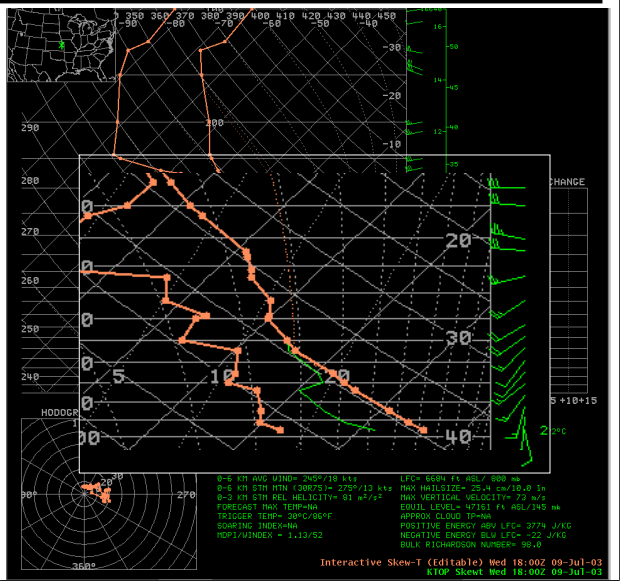
- Look for
  - Small boundary width = 1km
  - Strong shearing vorticity across the boundary
  - Young updraft over boundary



Pre-existing vertical vorticity here prior to the Salt Lake City tornado event occurred on scales of 1 km or less. The boundary is part outflow, part lake breeze effect. Regardless of its origins, the boundary showed good vertical vorticity observed from the TDWR. Note that it only existed up to about 2 kft AGL. A strong updraft initiating over the boundary resulted in the superpositioning of the background ingredients for tornadogenesis. The actual trigger to get tornadogenesis going was something that occurred on even smaller scales with little lead time observed by the TDWR. However, given the favorable background conditions, there needs to be a level of awareness that something could happen.

Another example: 09 July 2003, ICT

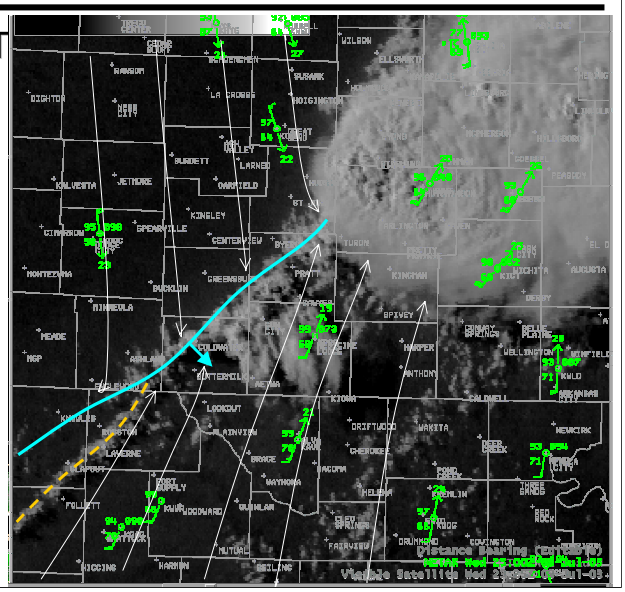
- KTOP skewt modified with PM temps around ICT
- Marginal deep shear, weak 0-1 km shear
- No CIN, steep lapse rates through LFC



An excellent example of nonmesocyclonic tornadogenesis occurred with a common synoptic setup over the Plains on 09 July 2003. A cold front moved south with little temperature gradient across the interface. Steep lapse rates and almost no CIN are apparent after modifying the 18 UTC KTOP sounding with the observed afternoon temperatures. The LCL is high and there is weak low-level shear. The 0-6 km shear is sufficient for some supercells, however.

Pre-existing vertical vorticity: a case

- 09 July 2003, ICT -Sharp boundary
- Vertical vorticity along boundary
- Slow boundary-relative storm motion
- No CIN and steep low level lapse rates

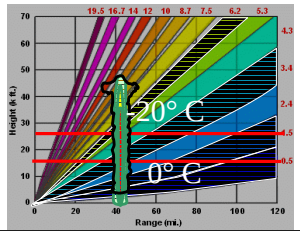


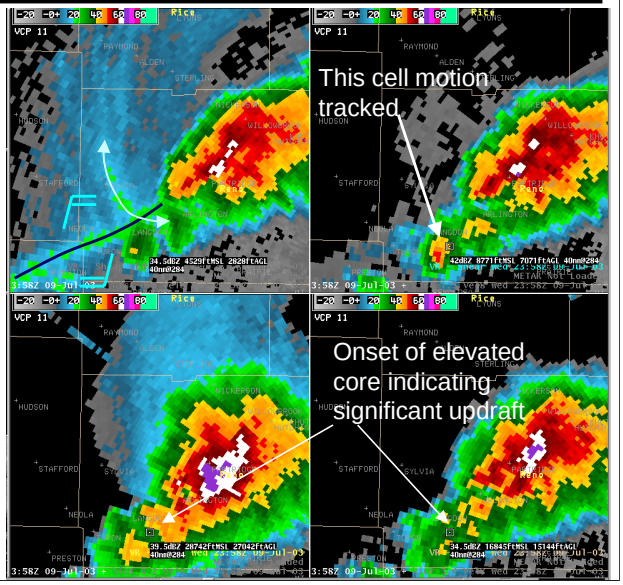
The cold front boundary can be seen dropping southeast. The winds on both sides of the boundary are angled roughly 45° to the orientation of the front. I took the peak winds observed on either side of the front and assumed that these winds continued right up to either side of the boundary. Vertical vorticity can be inferred by the streamline analysis across the boundary. If only satellite data were available, I would note that the boundary contained a thin line of enhanced cumulus and that its width was less than 4 nm. The actual boundary width was narrower than the width of the cumulus line as will be shown.

The slow boundary relative storm motion will also be shown by radar.

Pre-existing vertical vorticity: a case

- Storms moving with cold front
- Outflow boundary moving down front
- Rapid updraft growth on intersection



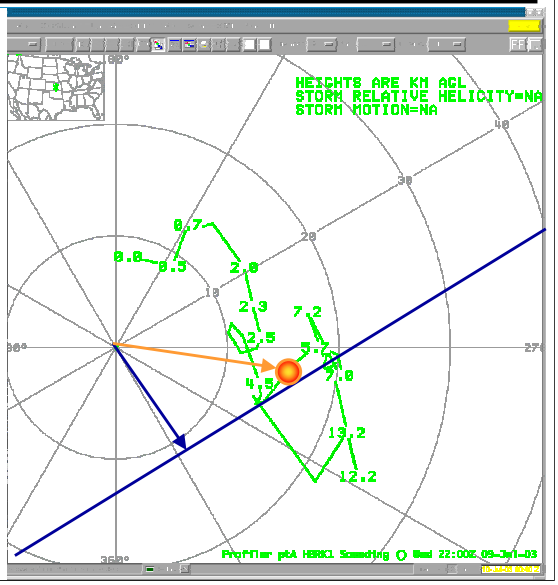


Progressing through this reflectivity loop, one can see the general motion of the cold front. Also noted, an outflow boundary from the storms was coursing down the front on both sides providing an intersection point. Rapid updraft growth was occurring along and just ahead of the outflow boundary as it moved southwest. The timing of the individual updrafts was important as they were the stretching mechanisms and sources for potential tornadogenesis.

I will use the young updraft marked in the upper-right panel to track as my storm motion. This is just the kind of cell that could be associated with a nonmesocyclonic tornado.

Pre-existing vertical vorticity: a case

- Cold front motion marked by the cyan arrow
- Initiating cell moving by yellow arrow
- Note small boundary-relative cell motion allowing for residence time of updraft over low-level vorticity source



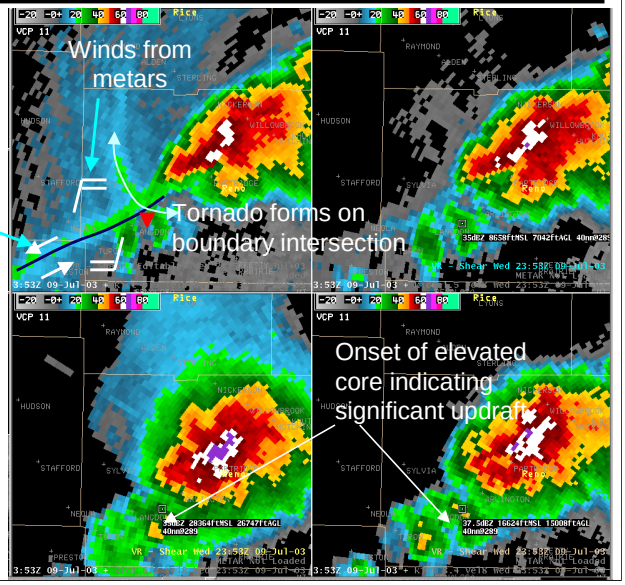
Plotting the motion of the cold front on a hodograph from a nearby profiler can be done by using the distance speed tool to track the boundary in a direction orthogonal to its orientation. I get a value roughly from 348° at 23 kts. The vector (in cyan) marks the frontal motion. I can actually plot the cold front axis, again, orthogonal to the frontal motion vector shown as the cyan line.

To show what the boundary-relative cell motion is, I take the observed cell motion, again using the distance speed tool, from the previous page, and I get roughly 281° at 31 kts (orange ball). Note that my storm motion lies almost on the front. This is favorable since I prefer to have an updraft reside over a low-level vorticity source for awhile. It may not take long, less than 15 minutes to stretch the vorticity into a tornado.

As an aside, I can visualize the wind at any level in a boundary-relative mode. The winds at 12 to 13 km are still ahead of the boundary, and thus, they are overtaking the boundary. Conversely, all winds below 4 km are behind the boundary, and therefore, are being overtaken by the boundary. The winds from 4 to 7 km are pretty close to the boundary axis, as drawn on the hodograph, and therefore, are able to keep up with the boundary. These are the winds that are probably steering young cells in this situation.

Pre-existing vertical vorticity: a case

- Winds are tangential to radar
- Take component of metar gusts along each side of the front = 13 kts
- Along-boundary wind shear across front by metars is 25 kts (14 m/s)
- Boundary width = 1-2 km
- Vorticity = $\Delta V/(\text{width}) \sim .01\ s^{-1}$



To further analyze what potential background vorticity there is, I first try to directly observe it with base velocity. Unfortunately, the northeast and southwest winds are mostly tangential to the radar and therefore, I cannot use something like the Vr shear tool.

Instead, I infer the larger scale winds seen in the metar data to come right up to either side of the front, at 45 ° angle to the frontal orientation (20kts). The white vectors represent the component of winds paralleling the front, and if I take 45 ° as the angle and calculate the front parallel component, I get roughly 13 kts. That corresponds to a shearing velocity difference of roughly 25 kts.

The boundary width I took from the width of the fineline, noting of course that the actual width may even be smaller. Still, I get a width of 1 to 2 km.

Calculating vorticity across that width is $\Delta V/(\text{width}) \sim .01\ s^{-1}$

That is easily mesocyclonic in strength for vorticity. Tornado cyclone scales need to magnify this vorticity by another factor of 10, tornado itself, a factor of 100. No problem. The outflow boundary intersection, and strong initiating updraft with slow boundary-relative storm motion is likely enough to do the job.

At the time of the image, a tornado was on the ground marked by the red triangle, right under one of the updrafts at the outflow boundary intersection point.

Summary

- Nonmesocyclonic tornadoes favored with
  - near zero CIN, steep lapse rates ground to cloud
  - Sharp boundary of 1 nm width or less
  - Prestorm vertical vorticity > .01s-1
    - vorticity sheet often rolls up into misocyclones
  - Superposition of strong developing updraft over low-level vertical vorticity
  - Often need a boost of vorticity and/or convergence from multiple boundary interaction
  - Prefers low boundary-relative cell motion

Nonmesocyclonic tornadoes are favored by:

near zero CIN, steep lapse rates ground to cloud

Sharp boundary of 1 nm width or less

Prestorm vertical vorticity > .01s-1

vorticity sheet often rolls up into misocyclones

Superposition of strong developing updraft over low-level vertical vorticity

Often need a boost of vorticity and/or convergence from multiple boundary interaction

Prefers low boundary-relative cell motion

None of this will give me an adequate false alarm or POD. These conditions can occur many times before there is a hit. But the increased awareness, and time to solicit for spotter reports may help in getting a warning out in time.

Storm Interrogation

AWOC Severe Track

IC3-III-G

Quasi-Linear Convective System tornadoes

Contributions from Ron Przybylinski

Welcome to the AWOC Severe Track

IC3-III-G

Quasi-Linear Convective System tornadoes

This lesson is 15 slides long and should take 15 minutes to complete.

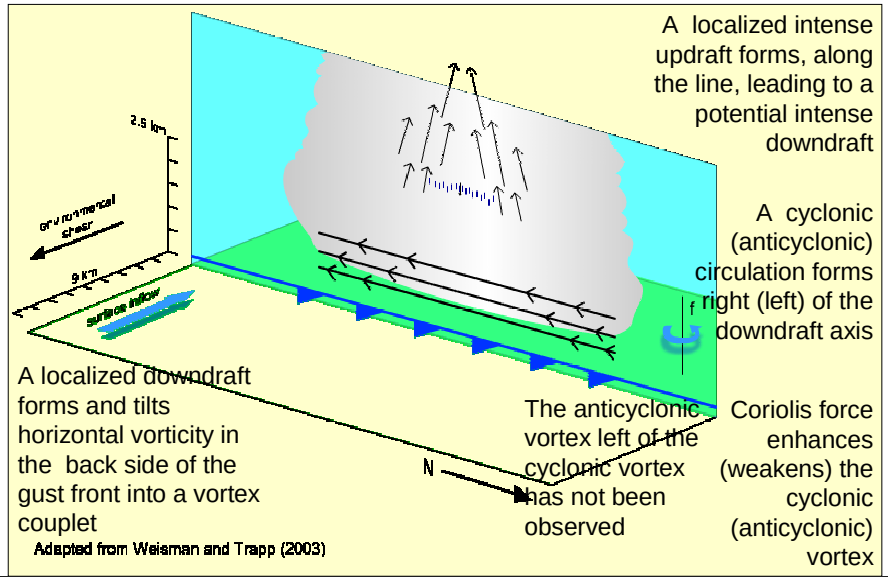
Much of this material has been adapted from Ron Przybylinski, the SOO at NWS, St. Louis, MO

Quasi Linear Squall Line (QLCS) tornadoes

- Objectives
  1. Recognize reflectivity/velocity precursor signatures to QLCS tornadoes
  2. Understand the importance of QLCS intersections with boundaries in regards to locating and timing the greatest tornado potential
  3. Understand the time-height evolution of a typical QLCS vortex
  4. What is the strength of of low-level rotation between tornadic and nontornadic vortices
  5. Familiarization with the theory of low-level QLCS vortex production by Trapp and Weisman (2003)

There are five objectives in this lesson. First, recognize the precursor signature in reflectivity and velocity most commonly observed with QLCS tornadoes. Second, learn how important QLCS intersections with boundaries are with regards to locating the greatest tornado threat. Third, learn the differences of the time-height evolution of a typical QLCS vortex and that of an isolated storm. Finally, this lesson will familiarize yourself with a theory of QLCS low-level vortex formation proposed by Trapp and Weisman (2003).

Theory for QLCS low-level vortices



According to Trapp and Weisman (2003),

1. A localized intense updraft forms, along the line, leading to a potential intense downdraft
2. A localized downdraft forms and tilts horizontal vorticity in the immediate back side of the gust front into a vortex couplet
3. A cyclonic (anticyclonic) circulation forms right (left) of the downdraft axis, when facing in the direction of QLCS motion
4. The Coriolis force enhances (weakens) the cyclonic (anticyclonic) vortex

This theory is based on numerical modeling results and a careful circulation budget analysis where the contributing terms to the vorticity equation were analyzed around the perimeter of both the anticyclonic and cyclonic vortices. To date, no one has observed a vortex couplet with an anticyclonic component to the left of the cyclonic component following QLCS motion. Therefore, it is likely some revision may need to be done to this theory.

This mechanism for vortex formation is not the same as that for the larger midlevel vortex commonly called Mesoscale Convective Vortex (MCV).

Low-level Boundaries

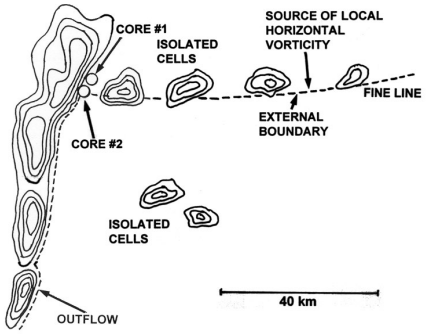
- A common occurrence with QLCS tornado events:
  - a ***low-level boundary*** from earlier convection or
  - an ***old quasi-stationary frontal boundary***
- Boundaries found to be ***orthogonal*** to the approaching convective line.
- **16** of the **21** MCSs we studied appeared to be directly influenced by either a low-level or elevated boundary

Research both at WFO DVN (Ray Wolf), and WFO LSX (Ron Przybylinski) found a majority of QLCS tornado events to be associated with some external boundary. Most of these boundaries were oriented mostly orthogonal to the QLCS axis. Of the 21 MCS (also QLCS) events that Pryzbylinski studied, 16 of them were influenced by a low-level, or elevated boundary.

These results are very similar to those of project VORTEX concerning more isolated convection.

(QLCS) tornado favored regions

- QLCS vortices are favored near and just on the cool side of boundary intersections.
  - Similar results to project VORTEX concerning isolated tornadic cells
  - This is the region of enhanced 0-1 km shear
  - Enhanced lifting occurs at the intersection point
  - This occurs prior to any bowing of the line

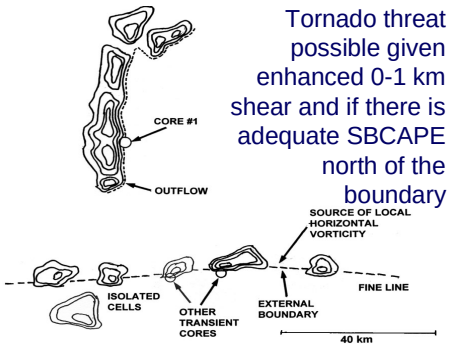


QLCS vortices appear to form near the intersection and just on the cool side of an external boundary. As with more isolated supercells, the enhanced low-level shear on the cool side of the boundary appears to enhance the probabilities of low-level vortex formation. However, it is not known if the same processes that generate low-level mesocyclones operate here. Another mechanism could be related to enhanced updraft and lifting promoting more intense cells near the boundary intersection with the QLCS.

Remember that you typically see vortex formation preceding the bowing of the QLCS segment near the boundary.

(QLCS) tornado favored regions

- QLCS vortices can occur well poleward of an external boundary if:
  - There is sufficient SBCAPE
  - Low SBCIN
  - Be careful about situations where severe winds can occur under the frontal inversion



Tornado threat possible given enhanced 0-1 km shear and if there is adequate SBCAPE north of the boundary

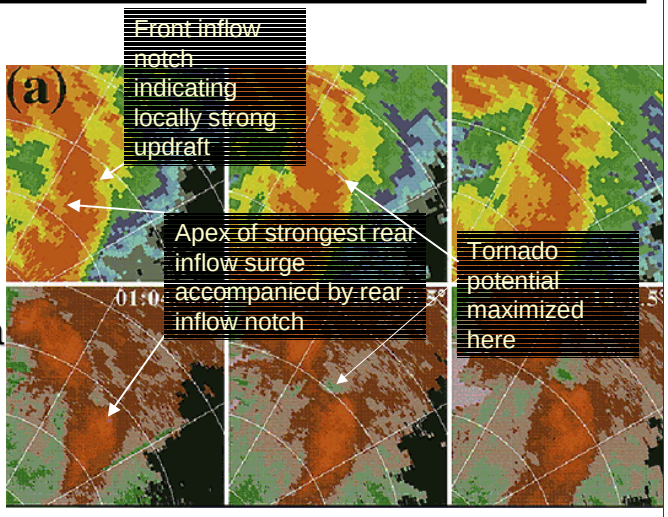
If the airmass north of a stationary front or outflow boundary is characterized by adequate SBCAPE and low SBCIN, QLCS vortices can form well poleward of the boundary.

Often the boundary may be difficult to detect after dark once solar heating diminishes. The only indication of the boundary may be from convective cells forming along a line, from METAR data, and vertical wind profiles. Some of these boundaries may be elevated. Either way, the fact that convective cells can develop along the boundary ahead of the QLCS should give you an indication that enhanced updraft is likely at the point where the QLCS intersects the boundary.

In some cases, the downdrafts and vortices may form in deceptively deep stable layers. Be aware of that fact.

Vertical vorticity signature along gust front of a squall line

- Low-level vortex formation behind leading edge, at or north of the apex
- A local maxima in vertical vorticity phases with strong updraft signature

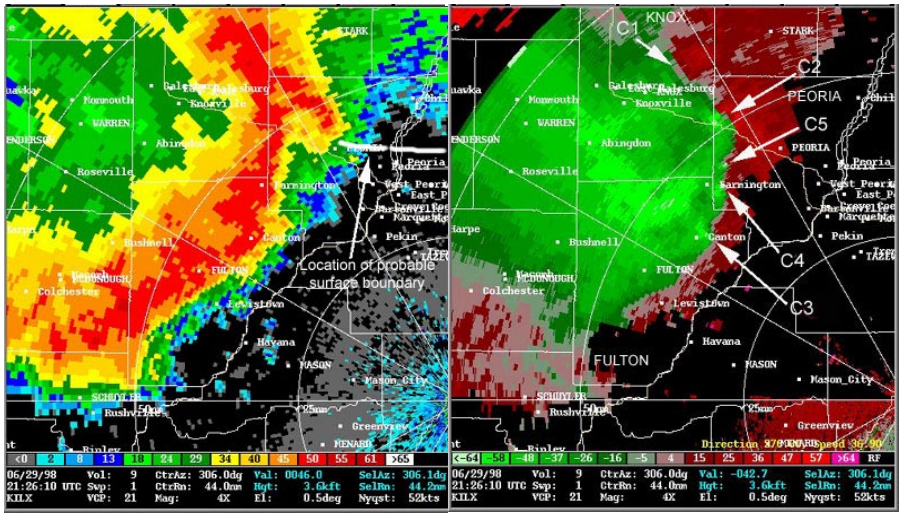


Provided that the updraft can keep up with the outflow surge (often needing strong deep layer shear), the left side and apex of the surge will contain a strong likelihood of tornado formation.

Vortex formation usually begins at low-levels and then builds up with time.

It is not known where the contributions to low-level vertical vorticity originate.

Vertical vorticity along a large bow echo: 29 June 1998



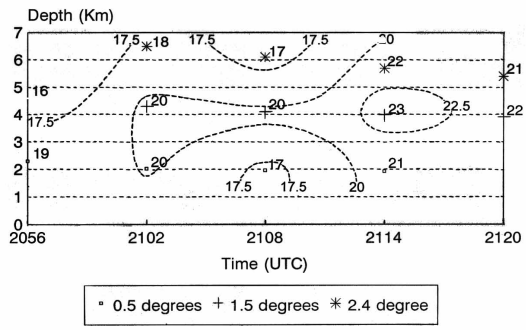
Adapted from Pryzbylinski (2002)

2103 UTC 29 June 1998 reflectivity (0.5°)(left); storm-relative velocity (right) from Lincoln IL (KILX). Convective towers extending southeast from the northern end of the large line reflects the location of an old outflow boundary. Circulation cores #1 and #2 formed at this intersection.

2126 UTC 29 June 1998 reflectivity (0.5°) slice (left); storm-relative velocity right). Circ #2 intensified rapidly since 2103 UTC and became tornadic (F1 damage). Core #3 became tornadic only during the very early stages of its lifetime. Core #4 became tornadic after 2135 UTC.

Time height comparisons

- Core #1 V_r reaches 20 m/s (40 kts)
- Note this core descends (the other 20%)
- No tornado reported



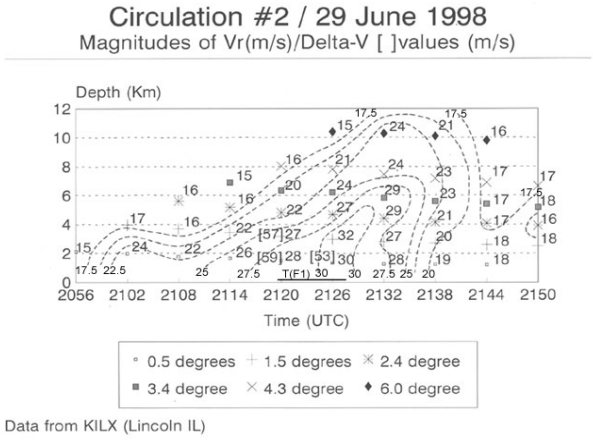
Data from KILX (Lincoln IL)

Core #1 Exhibited weaker rotation and lower overall depth compared to Core #2 that will be shown next. Maximum Vr reached 40 kts.

Note that this core descends with time, which is in the minority of observed QLCS vortex time height tendencies. Pryzbylinski (personal communication), has noted that many first cores descend over time, with none so far observed being tornadic.

Time height comparisons

- Core #2 was more intense V_r=30 m/s (60 kts)
- Nondescending V_r with time indicates low-level vorticity becoming stretched upward

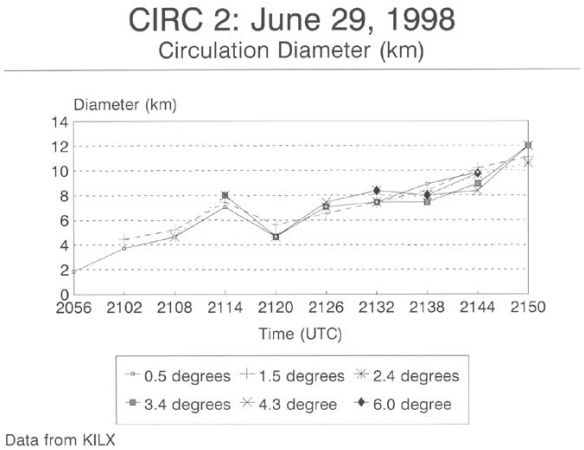


Core #2 Exhibits upscale growth non-descending characteristics) with strongest rotation detected within the lowest 3 km.
Vr reaches 60 kts as a peak intensity.

A Tornado produced **F1** damage between 2120 and 2126 UTC just before Core #2 reached its greatest depth.

Time height comparisons

- Core #2 showed collapse in diameter during tornadogenesis at 2120 UTC



A time plot of the core diameter of Core #2 shows a collapsing phase at tornadogenesis time at 2120 UTC. Collapsing core diameters of circulations have been found to frequently occur with tornadic supercells and other QLCS tornado events.

Mesocyclone strength: isolated vs linear convection

- Comparison of circulation characteristics between Przyblynski et al. 2001 data set and Burgess et al. (1982) data set.
- Larger mesocyclone diameters in linear systems than with isolated cell mesocyclones
- Weaker V_r with linear systems

	Rot Vel (m/s)	Diameter (km)	Height (km)
Squall Line (Low)	19.0	7.2	
Trad Super-cell (Low)	23.0	5.4	
Squall Line	18.8	7.4	7.6
Trad Supercell	25.0	6.0	9.2

L = surface to 8200 ft.

A comparison between QLCS and isolated supercell vortex characteristics show that QLCS vortices tend to have stronger maximum Vr values. However QLCS vortices tended to be wider. The top two rows in the table refer to the low-level values of Vr and core diameter while the highest values of each are labeled in the lowest two rows.

Summary

- QLCS tornadoes favored
  - In regions with strong 0-1km shear, 0-3 km (≥ 15 m/s), 0-5 km (≥ 18 m/s) shear, similar to supercell tornado parameter space
  - At or left of intersections with
    - quasi-stationary fronts
    - outflow boundaries
- QLCS vortices may develop from the tilting of horizontal vortex lines within the cold pool and then enhanced by the coriolis force

QLCS tornadoes are favored in regions of strong 0-1 km shear and 0-6 km shear, a very similar setup to that of more isolated mesocyclonic tornadoes. As with isolated mesocyclonic tornadoes, QLCS tornadoes tend to be favored at and just north of a boundary external to the QLCS event.

QLCS vortices may develop from the downward tilting of horizontal vortex lines within the cold pool and then enhanced by the coriolis force. The coriolis force seems to act fairly quickly, within an hour, to enhance the cyclonic vortex and weaken the anticyclonic vortex to its north. Again, this theory has yet to have observational support since there has been no anticyclonic vortex observed immediately left of the cyclonic one.

Summary (contd)

- QLCS tornado signatures
  - Near front inflow notch
  - In region of strong vertical vorticity along boundary
    - especially a low-level vortex
  - At or north of the initial bowing apex
- QLCS vortex time trends
  - mostly nondescending
  - typically larger and shallower than supercell mesocyclones
  - weaker rotational velocities than supercell mesos

QLCS tornadoes appear to be associated with a front inflow reflectivity notch in a region of strong low-level vertical vorticity just left of a region of a convex bow in the gust front. Look for a rear inflow notch to the right of the front inflow notch and behind the convex curve of the gust front as another indication that tornadogenesis probabilities increase.

QLCS vortices tend to be nondescending in nature. They are larger in diameter than traditional supercell mesocyclones but have weaker rotational velocities.

Resources in QLCS systems

- http://www.crh.noaa.gov/lsx/science.php

Storm Interrogation

AWOC Severe Track
ICSvr 3-IV-A

FFG Modification

Presenter: Bob Davis, NWSFO Pittsburgh

Flash Flood Index

FF=

diFF = ABR - FFG

- ABR and FFG both in inches
- Determining Flash Flood Severity within Flash Flood Monitoring and Prediction (FFMP)

•FFMP determines Flash flood severity in the difference column

•This can also be called a Flash flood index of potential flash flood severity

Flash Flood Index Values

- FF0 ABR = FFG
- FF1 ABR = FFG + 1.00 inches
- FF2 ABR = FFG + 2.00 inches
- FF3 ABR = FFG + 3.00 inches
- FF4 ABR = FFG + 4.00 inches
- FF5 ABR = FFG + 5.00 inches, etc

FF index gives potential severity of the flash flooding, and is a measure of how much assitional rainfall exceeding FFG occurs. FF1 is basically nuisance flooding, low lying areas, basements. FF2 is more severe, perhaps some water rescues, light damage. FF3 is severe flash flooding, significant damage, very high threat to life and property. FF4 and FF5 are catastrophic flash flooding, like Fort Collins, Johnstown, etc.

Flash Flood Guidance

$$FFG = TR + SM$$

- TR is the threshold runoff, a constant for each watershed, and a climatic average runoff needed to bring streams to bank full.
- SM is the amount of ABR needed to initiate runoff based on soil moisture content.

To know DIFF is valid you need:

1. Rainfall estimates good
2. FFG valid

- There are 2 components to FFG, TR and SM. FFG depends on these two factors added togther.

FFG Assumptions

- FFG is ABR over specific intervals (1, 3 hours) needed to initiate flooding on streams.
- Assumes stream at low flow level: TR
- Assumes no rainfall since data cutoff: SM
- Assume soil moisture computation for Mean Areal Precipitation area (MAP) from RFC model run is representative of the small basin's soil moisture state: SM

•If the stream is not at low flow conditions then FFG is too high and TR needs to be adjusted down

•RFC models are run at 12 Z and 0Z, if additional rainfall occurs after these times, SM will not incorporate it and FFG will be too high and SM needs to be adjusted down

•Soil moisture may not be well represented during the RFC model run

Places to Automatically Reduce FFG

- Highly urbanized watersheds
- Basins with steep terrain
- Basins with impervious soil, such as burn scars or bedrock soil.
- Watersheds with a high percentage of strip mined area.

FFMP allows you to change FFG for specific watersheds at any time that overides the RFC guidance for those watersheds. The potential basins you may want to consider lowering FFG are listed on the slide..

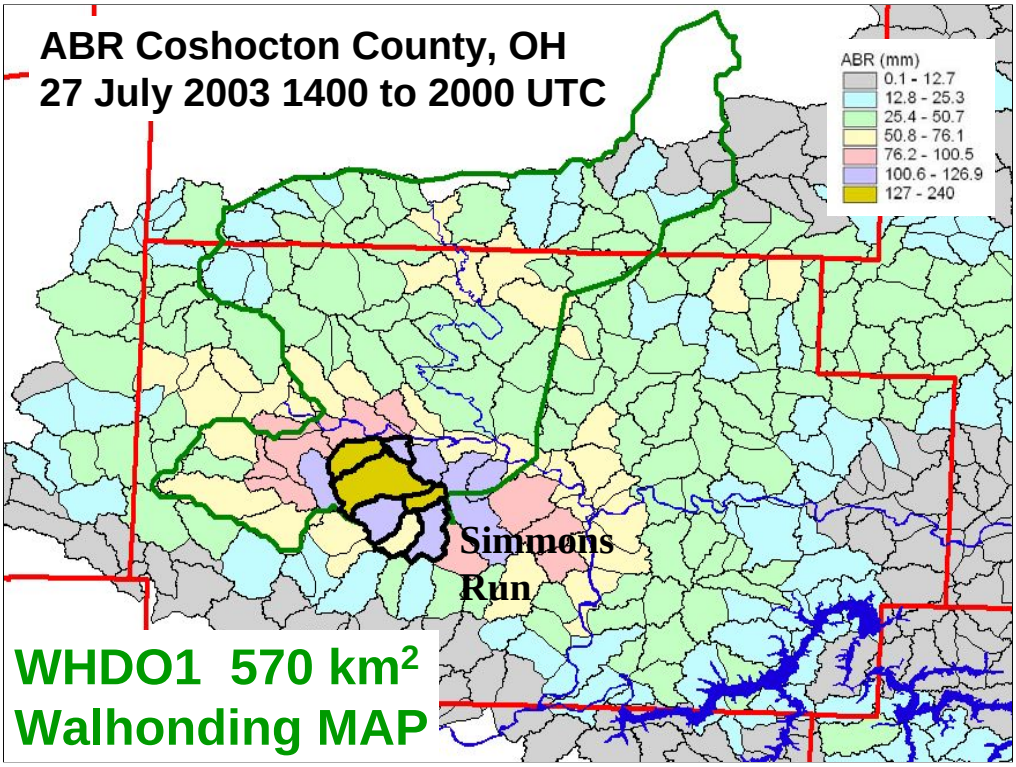
•Many offices already set urban watershed FFG to 1in/hr

FFG Reduction Example

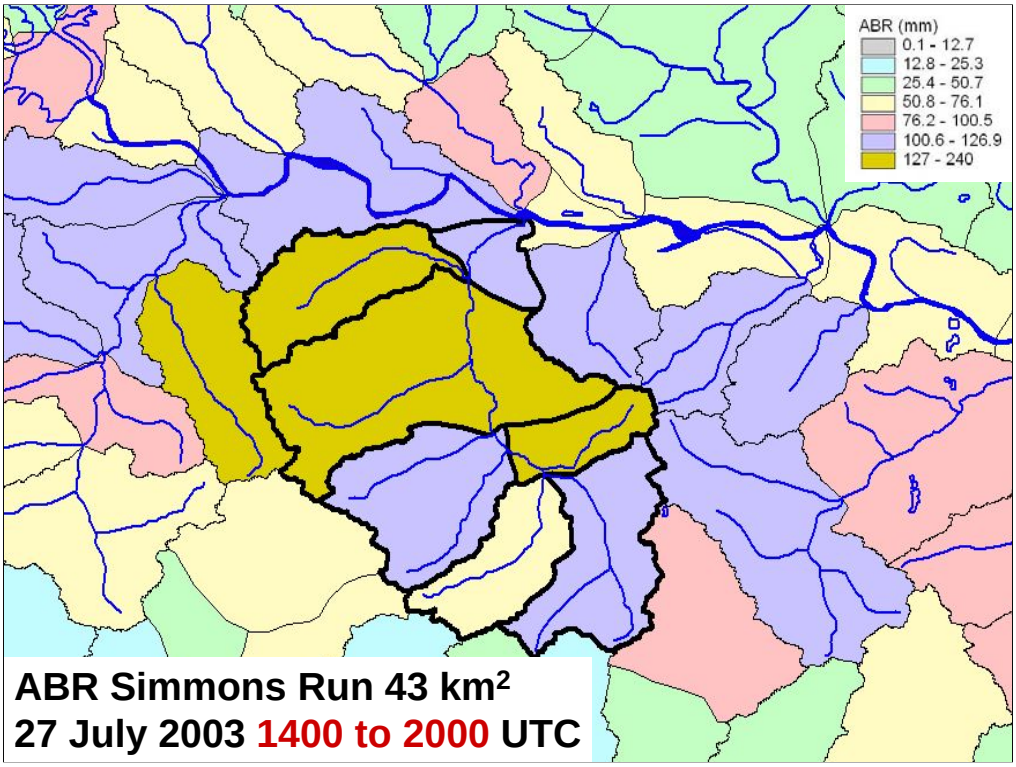
Simmons Run Flash Flood near Warsaw, OH

- **27 August 2003**
- **Coshocton County, OH**

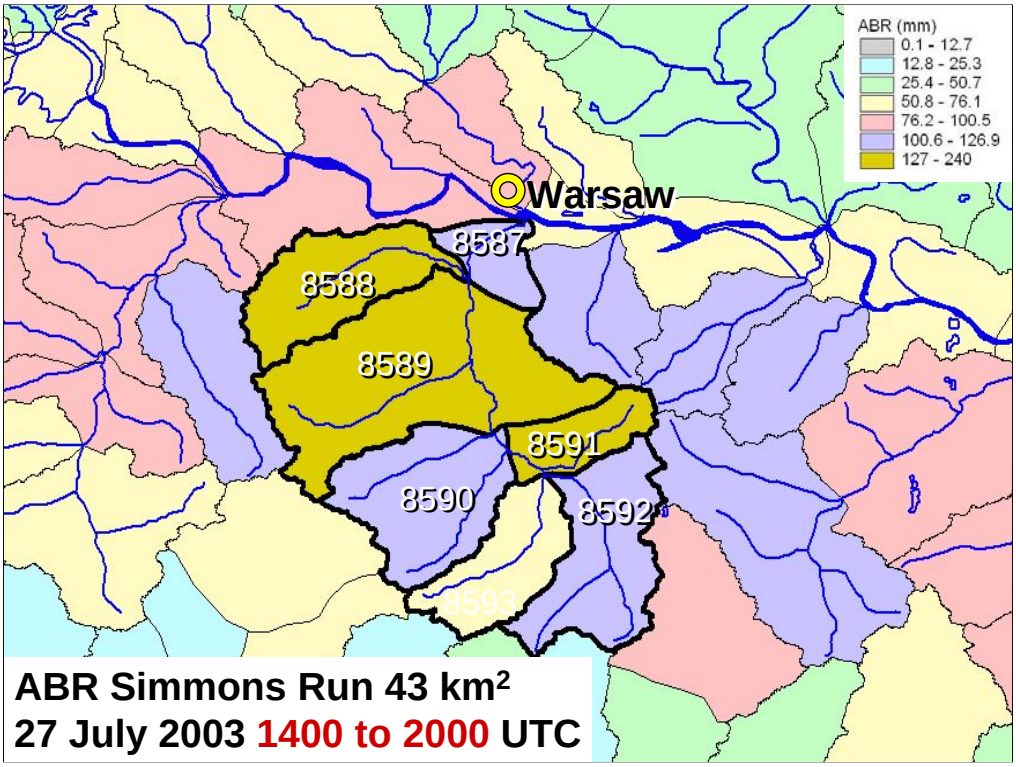
Case study to show how FFG modification factor may be applied.



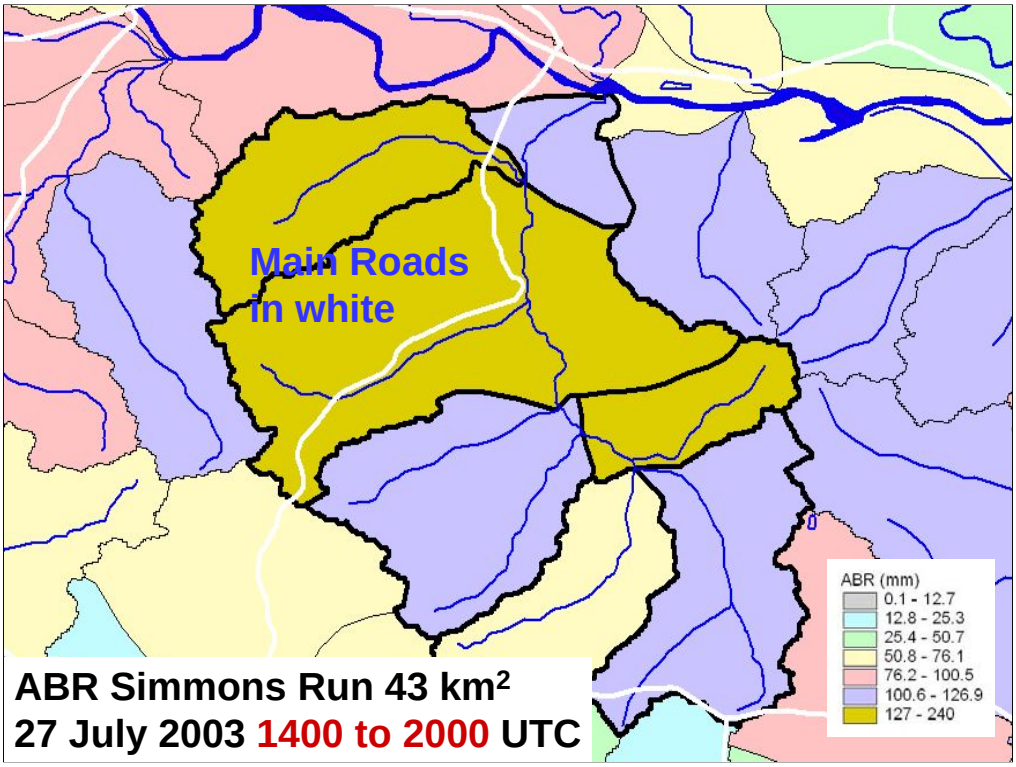
ABR 6 hour rainfall as it would appear in FFMP



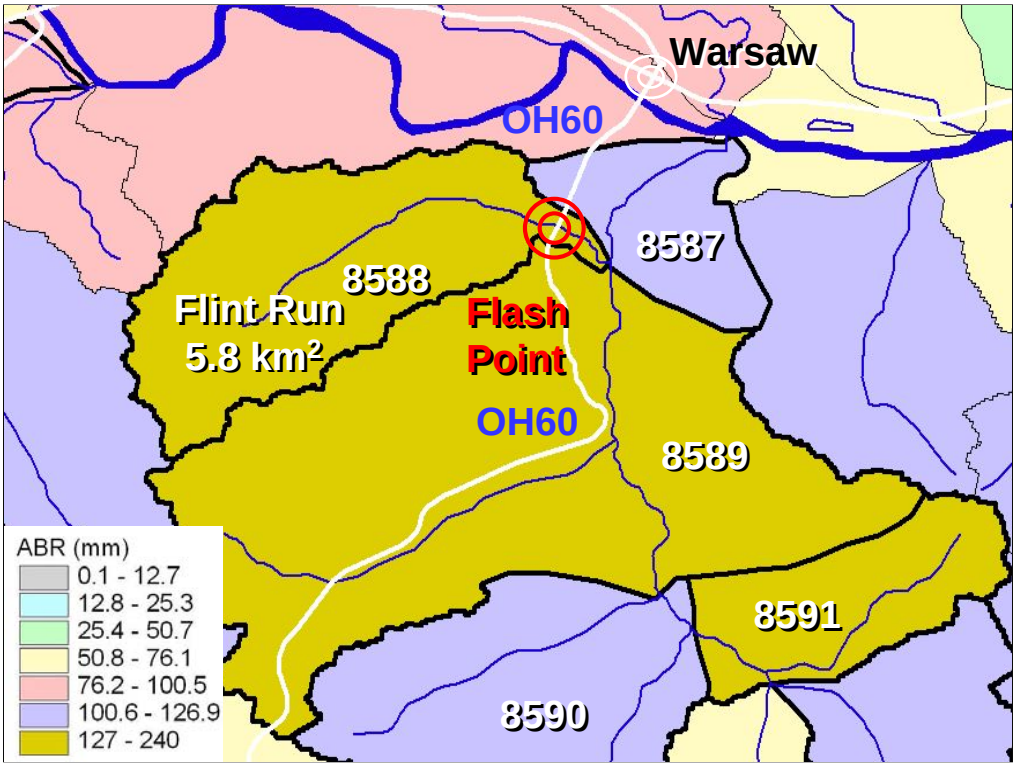
Zoomed into Simmons Run Water shed, 7 different segments flowing into the Walhonding river



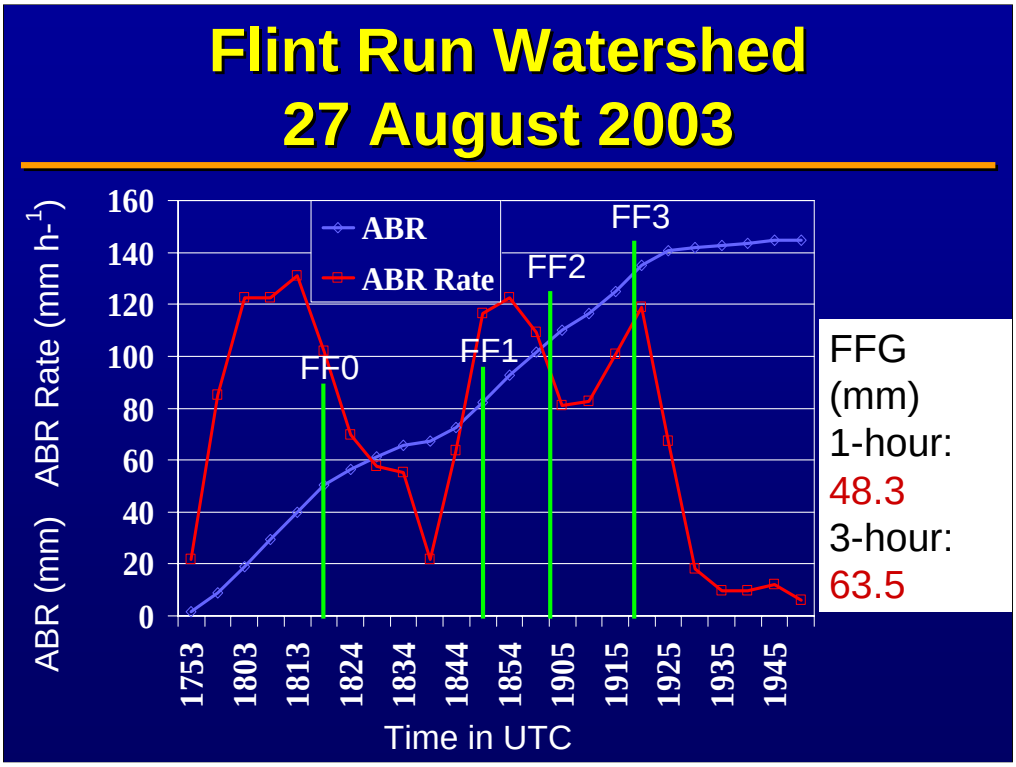
Each watershed segments would show up as a separate entry in FFMP threat table. Heavy rainfall concentrated in 3 small watersheds, with about 5 inches in 2-3 hours.



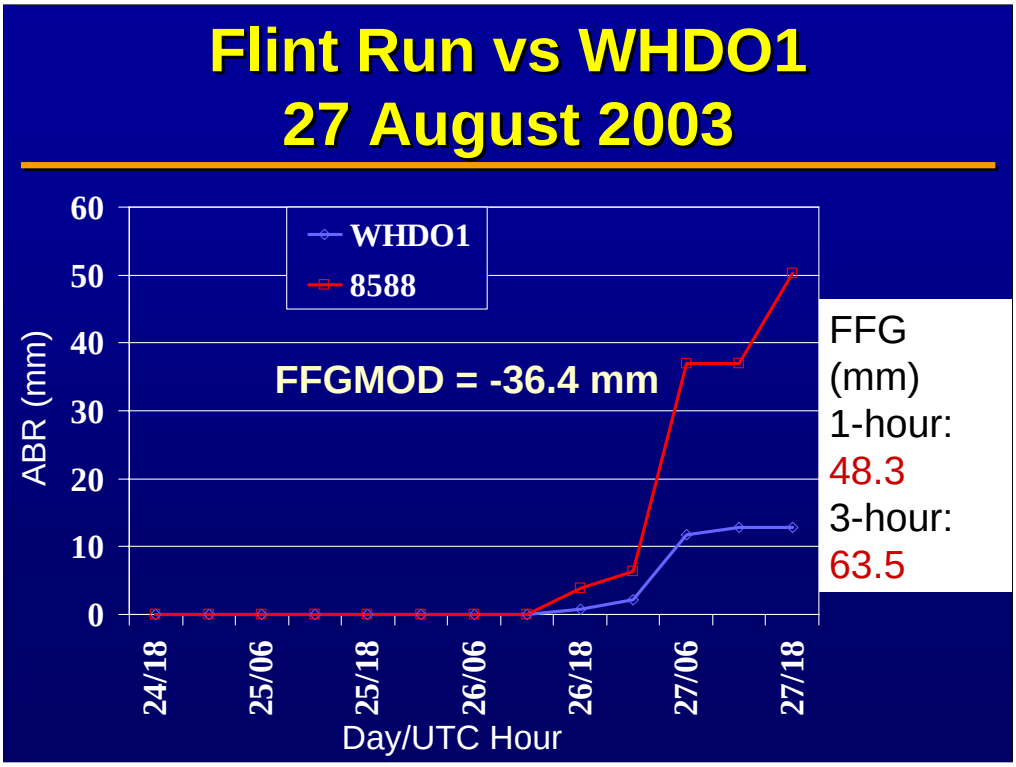
Main roads added showing where the highways would intersect the creeks, indicating areas of flash points were bridges could be washed out



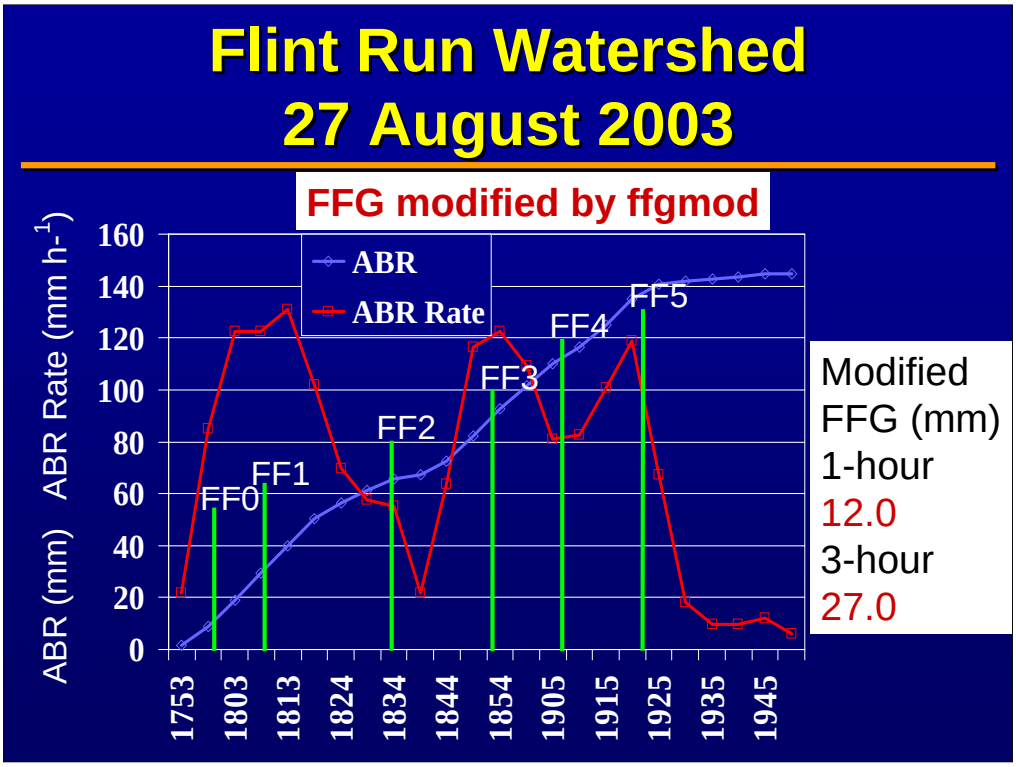
Zooming in on the 3 smaller tributaries with the heaviest rain: Flint Run contains one of the flash points where OH60 crosses the creek. The bridge was washed out at this point.



Graph showing accumulated rainfall for Flint run, 18-20 Z. Most of the rain did fall in about 2 hours. Green lines show when the flash flood index was exceeded.



FFG modification can be computed from the 6 hour rainfall amounts as observed in the watershed by FFMP (red line), and blue line is the computation of the Mean Areal Precipitation area from the RFC model run. Notice the difference in the two. This difference, since negative, is how much FFG should be reduced to get a better representation of FFG, and this difference is the FFGMOD factor.



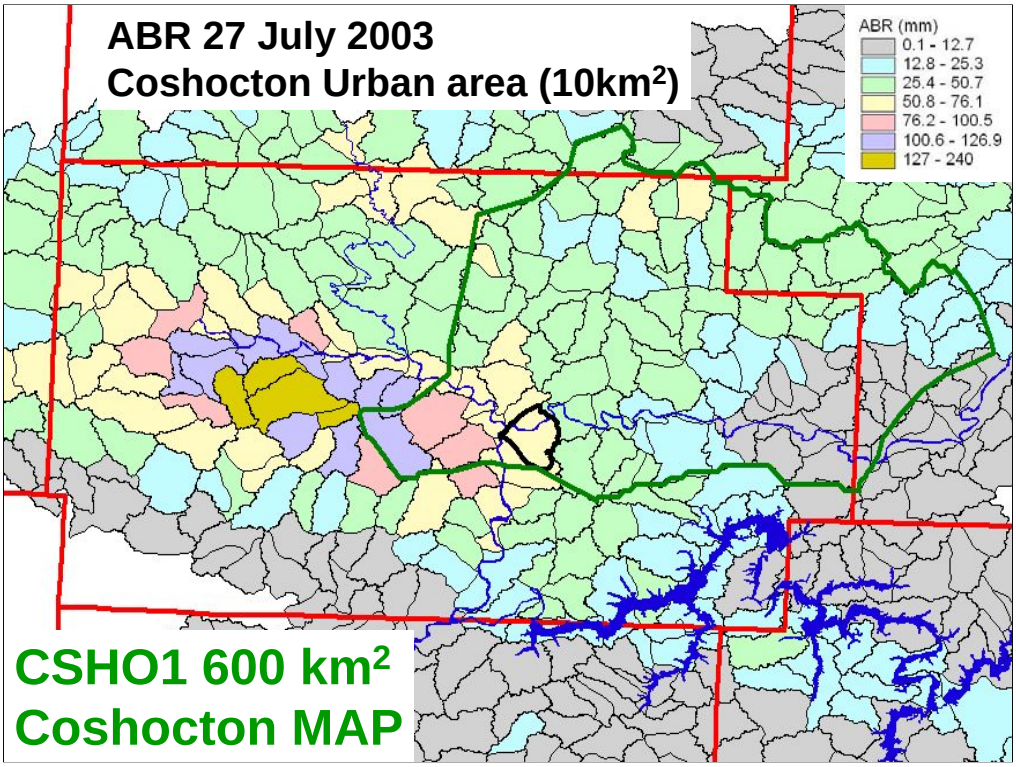
The impace of subtracting off the FFGMOD factore. Now FFG is 12.0 for 1-hour. FF0 state is reached 20 minutes earlier, FF1 is a half hour earlier, adding significant lead time to a Flash Flood warning. In addition to the added lead time, the magnitude of the flooding is better represented with FF5 as opposed to FF3. FF5 flooding was what had happened in reality.

Reduce FFG in Urban Areas Example

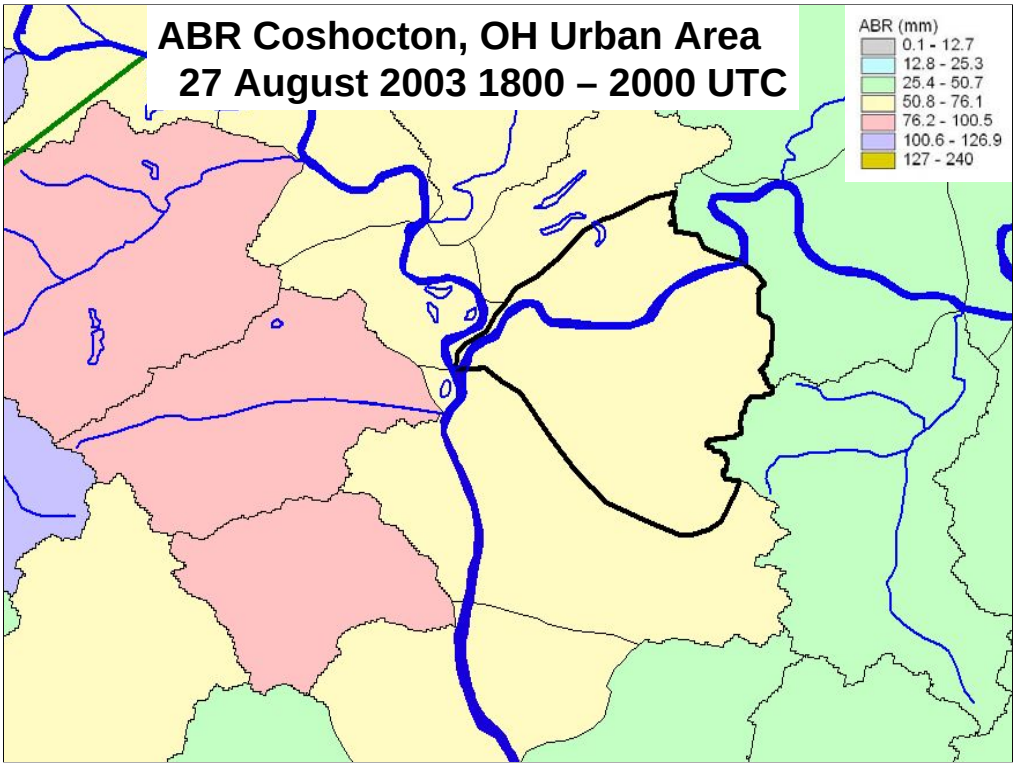
Coshocton, OH Flash Flood
Reduce FFG in urban areas

- **27 August 2003**
- **Coshocton County, OH**

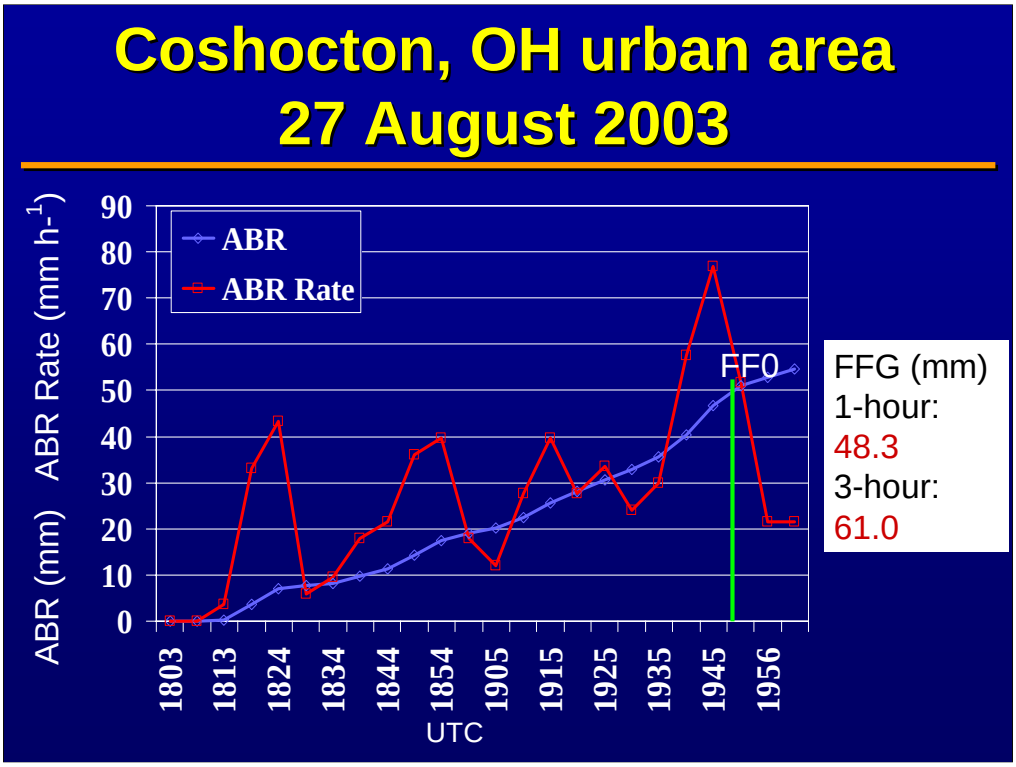
Flint Run was rural, this case study will look at a reduction of FFG within an urban area.



6 hours ABR for Coshocton County area, but this time the black area is the city of Coshocton. The area of the Coshocton MAP area is much larger than the city of Coshocton itself.



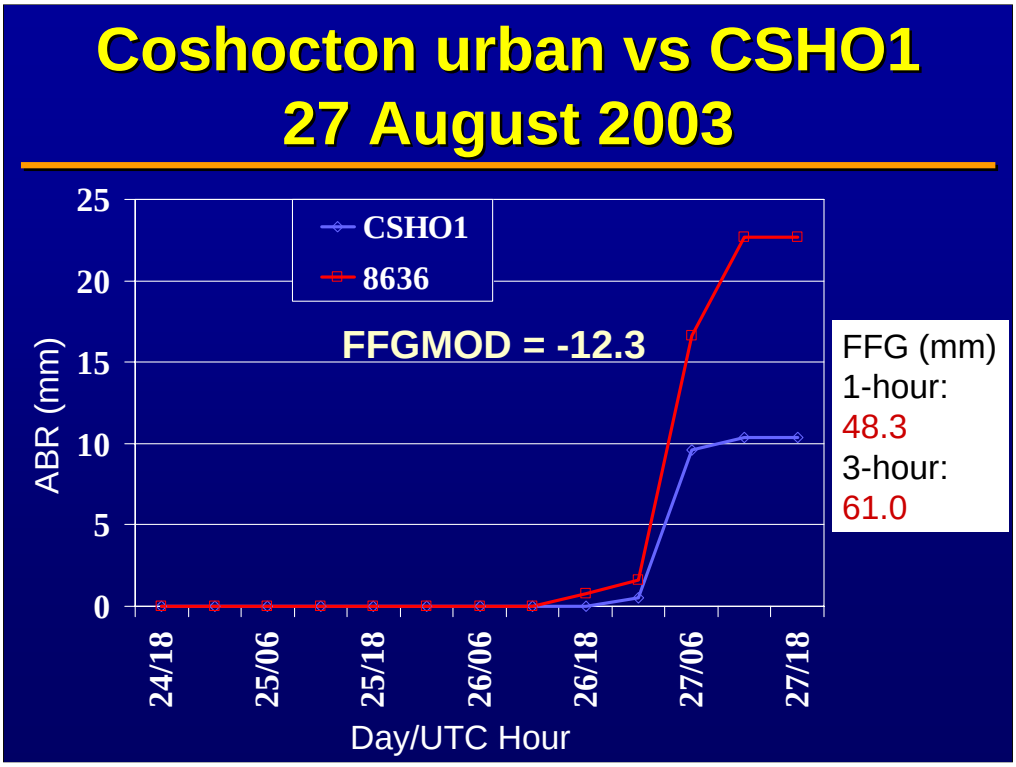
Zoomed in on ABR plot for Coshocton. 2-3 inches have fallen over the city of Coshocton in 2 hours.



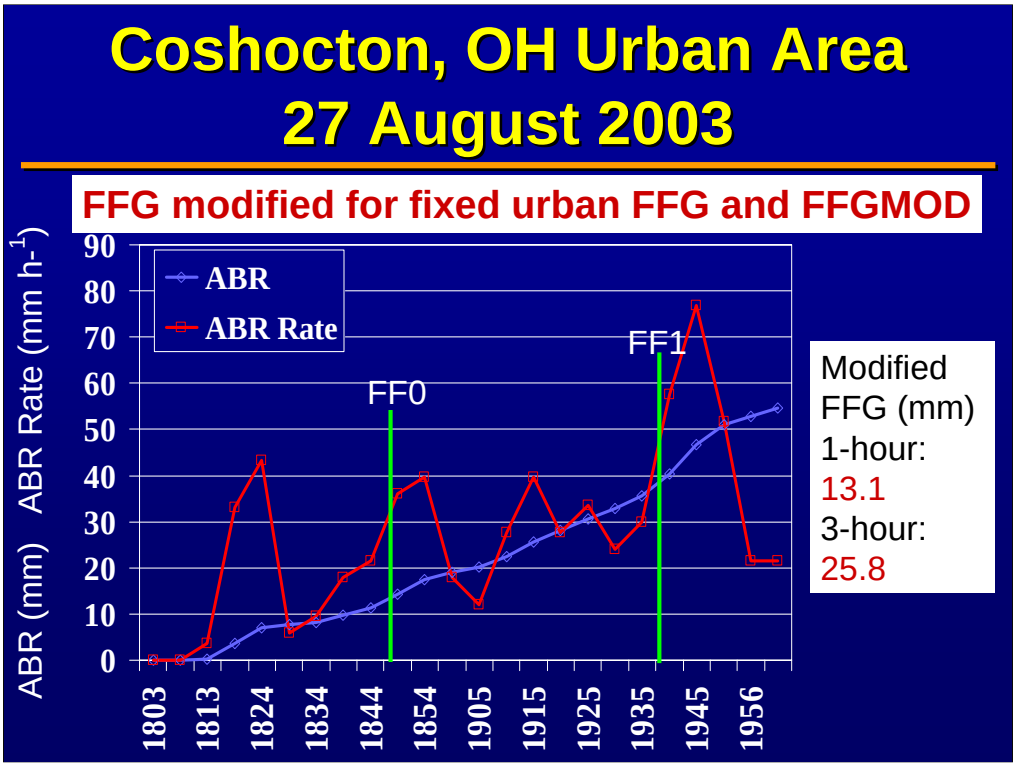
FFG, ABR and ABR Rate for the Coshocton urban area, AMBER basin 8636, in Coshocton

County, OH on 27 August 2003 from 1803 – 2001 UTC.

Barely reach FFG from RFC, and barely exceeded Flash flood guidance



FFGMOD plot, showing the differecne between the RFC Rainfall for the Coshocton MAP area and the actual rainfall in the city of Coshocton over the time period listed above. The difference is –12.3 mm, and thus FFG needed to be reduced by 12.3 mm per hour. For PBZ's urban areas, they use 1 in/hr for all urban areas, so the 12.3 is subtracted off the 1 in/hr FFG, making it even lower.



FFG modified for urban area and from subtracting off FFGMOD factor. The graph is now the modified ABR and ABR Rate for the Coshocton urban area, AMBER basin 8636, in Coshocton

County, OH on 27 August 2003 from 1803 – 2001 UTC.

FF0 reached much earlier, FF1 also achieve. There was significant urban flooding in Coshocton, and PBZ forecasters were able to detect the flooding earlier and get a sense of the magnitude of the flooding because they properly adjusted FFG.

Summary

- Reducing FFG for predefined basin conditions can improve FFMP detection capability and increase warning lead time.
- The use of FFGMOD factor for rainfall since data cutoff may aid in the updating of FFG between RFC issuance times.
- The use of FFGMOD may aid in the update of soil moisture conditions in small basins.

•This is especially true in highly urbanized areas

•FFGMOD may replace the “ratio” column in the FFMP threat table

Storm Interrogation

AWOC Severe Track
ICSvr 3-IV-B

Effective Use of FFMP

Thanks to Matt Kelsch for helpful input and for reviewing this material.

Effective Use of FFMP

Objectives:

- Understand how to best use FFMP
- Understand the radar limitations for rainfall estimation that directly affect FFMP and thus flash flood detection

FFMP

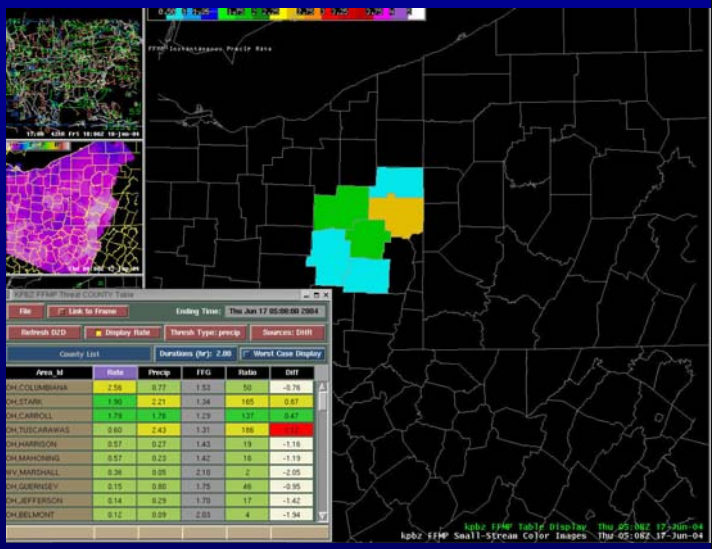
- Should have basins customized to very small scales already, and have the basics of FFMP well handled

- Refresher FFMP Presentation

If you haven't customized your basins already, its extremely important to do so as soon as possible. Because this is an AWOC presentation, the FFMP basics are not covered here but a link to FFMP basics is provided above.

FFMP: ABR Rate

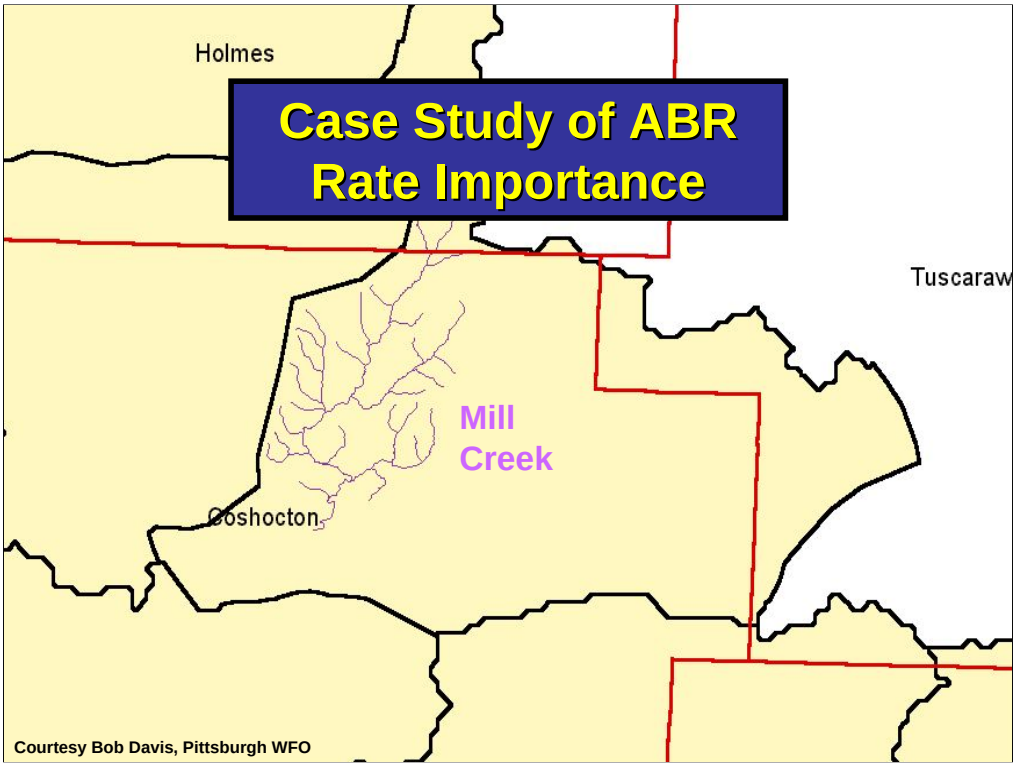
- Closely monitor ABR *rate* to assess flash flooding risk



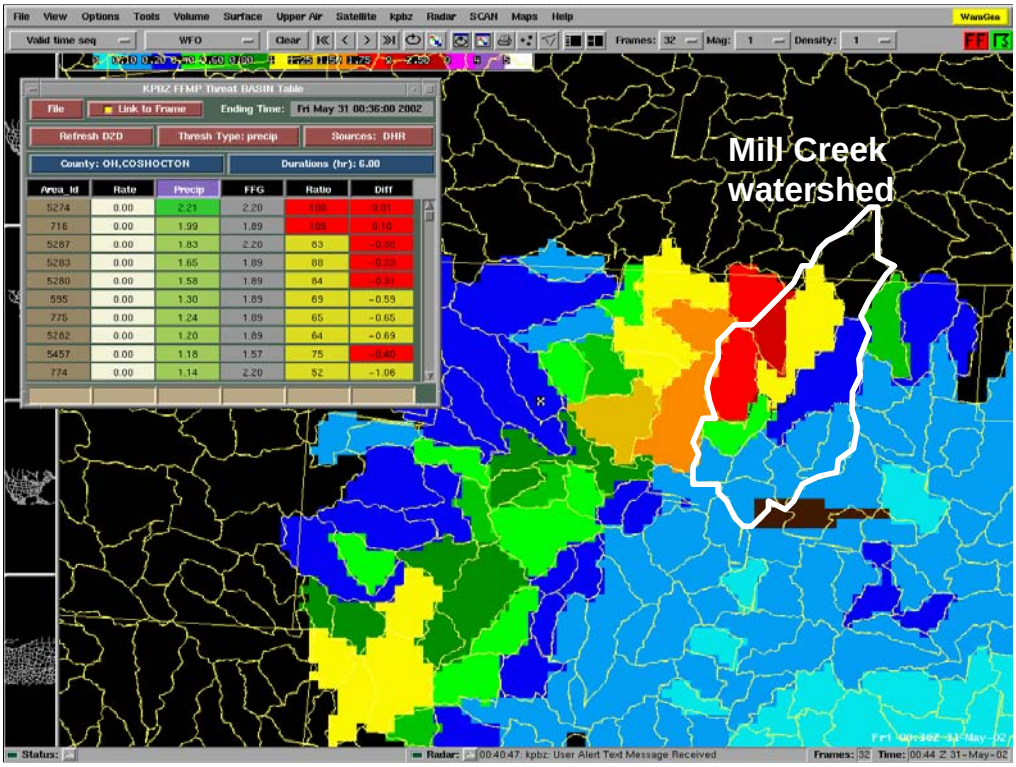
Rate MUST exceed 1-hr FFG to have any chance for flash flooding (provided FFG is accurate). Look for persistence of high ABR rates, especially for greater than 30 min. Monitoring rate gives you the best chance for significant lead time since rate shows a heightened flash flood threat well before any other parameter.

FFMP: ABR Rate Persistence

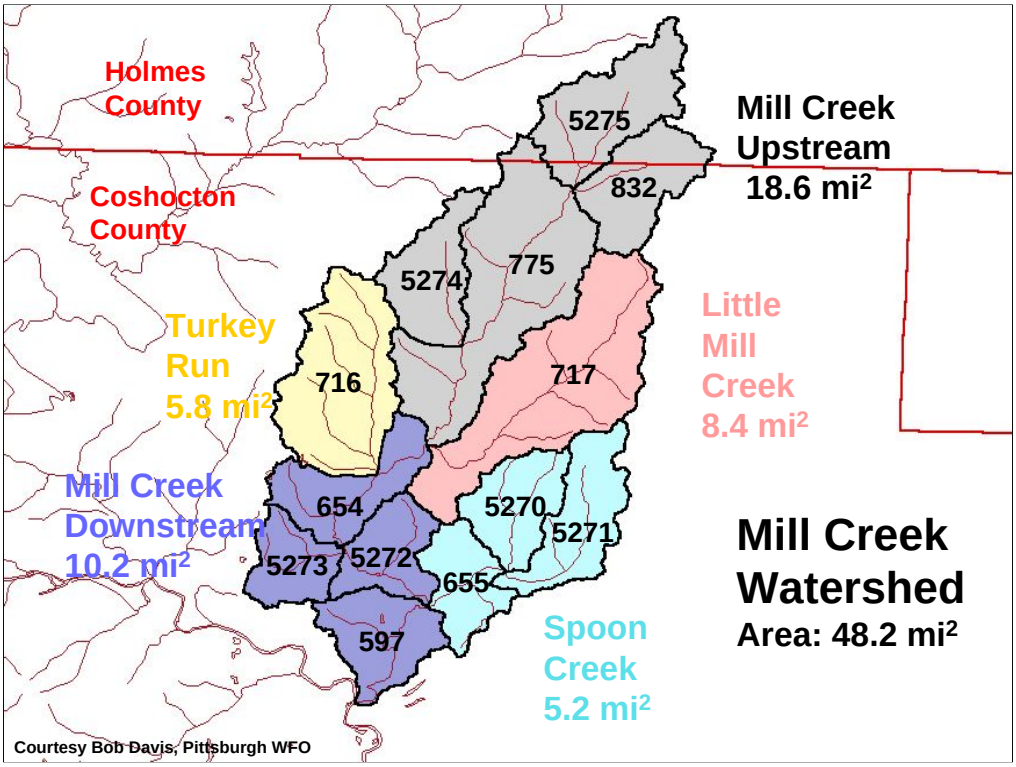
- When monitoring Rate, look for "rainfall bursts" of 3 or more volume scans with 1-5 in/hr rates
  - These bursts can be significant, and seldom last longer than 90 minutes
  - Focus on radar data to see if rainrates likely to continue



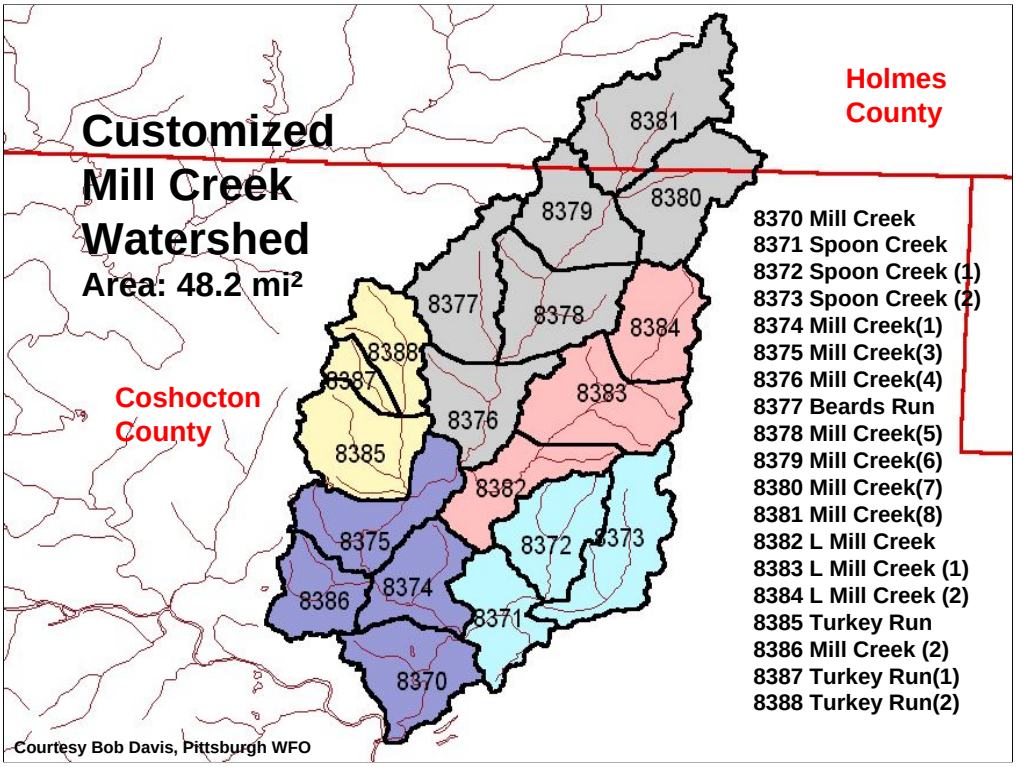
Mill Creek watershed in Ohio

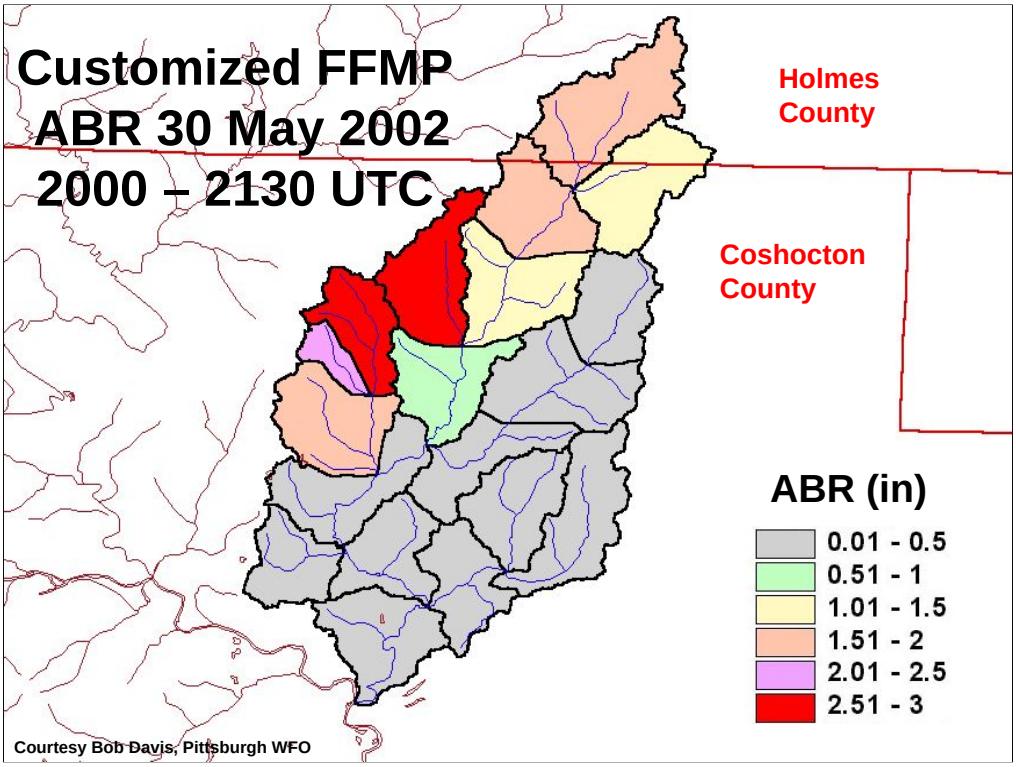


May 31, 2002 FFMP image from 00:44 UTC showing the Mill Creek Watershed with the smaller, customized basins.

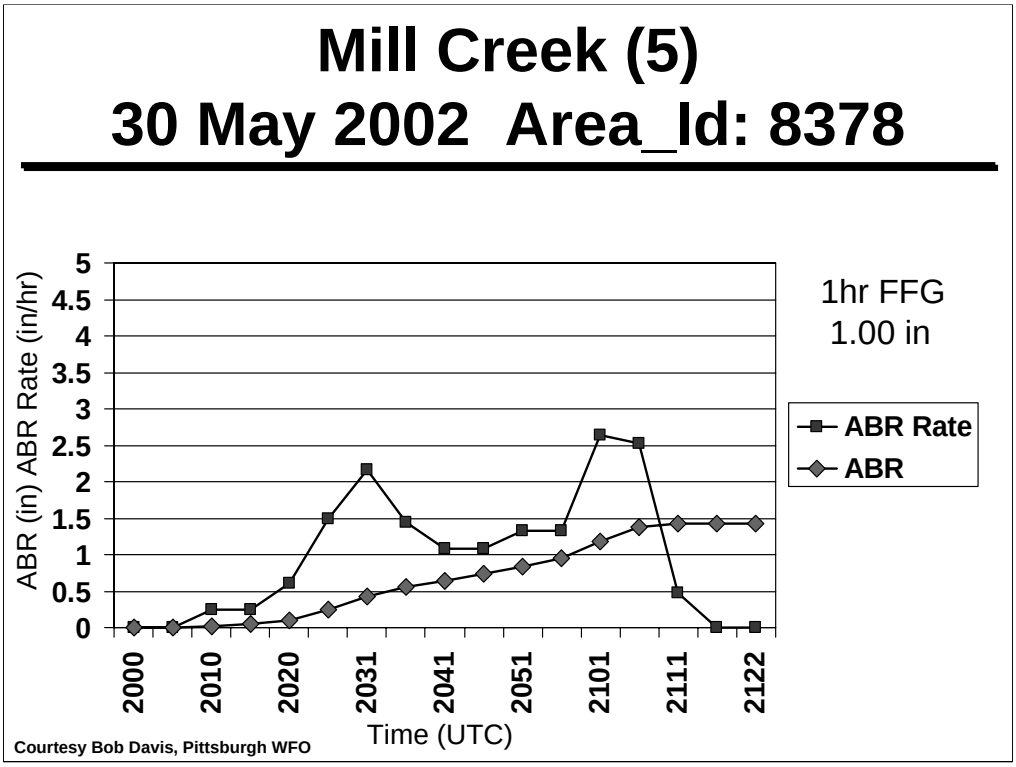


This is the customized basins within the Mill Creek Watershed.

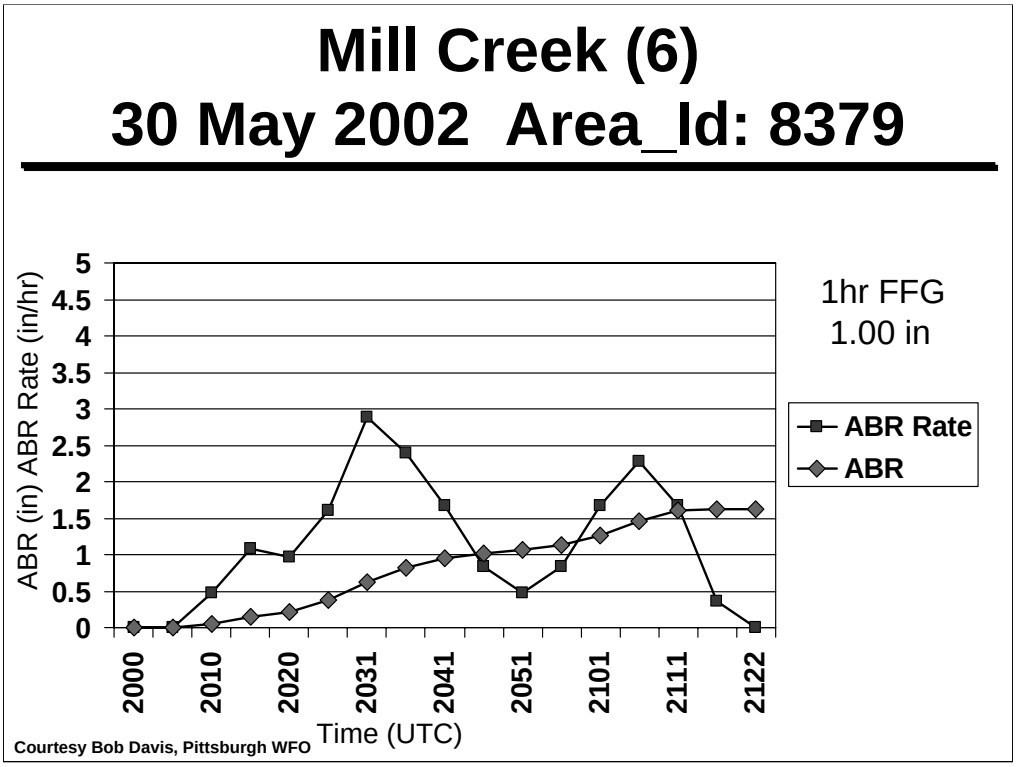

Customized
Mill Creek
Watershed
Area: 48.2 mi²
Holmes
County
Coshocton
County
8381
8380
8379
8377
8378
8384
8388
8387
8383
8376
8385
8382
8375
8372
8373
8374
8386
8371
8370
8370 Mill Creek
8371 Spoon Creek
8372 Spoon Creek (1)
8373 Spoon Creek (2)
8374 Mill Creek(1)
8375 Mill Creek(3)
8376 Mill Creek(4)
8377 Beards Run
8378 Mill Creek(5)
8379 Mill Creek(6)
8380 Mill Creek(7)
8381 Mill Creek(8)
8382 L Mill Creek
8383 L Mill Creek (1)
8384 L Mill Creek (2)
8385 Turkey Run
8386 Mill Creek (2)
8387 Turkey Run(1)
8388 Turkey Run(2)
Courtesy Bob Davis, Pittsburgh WFO



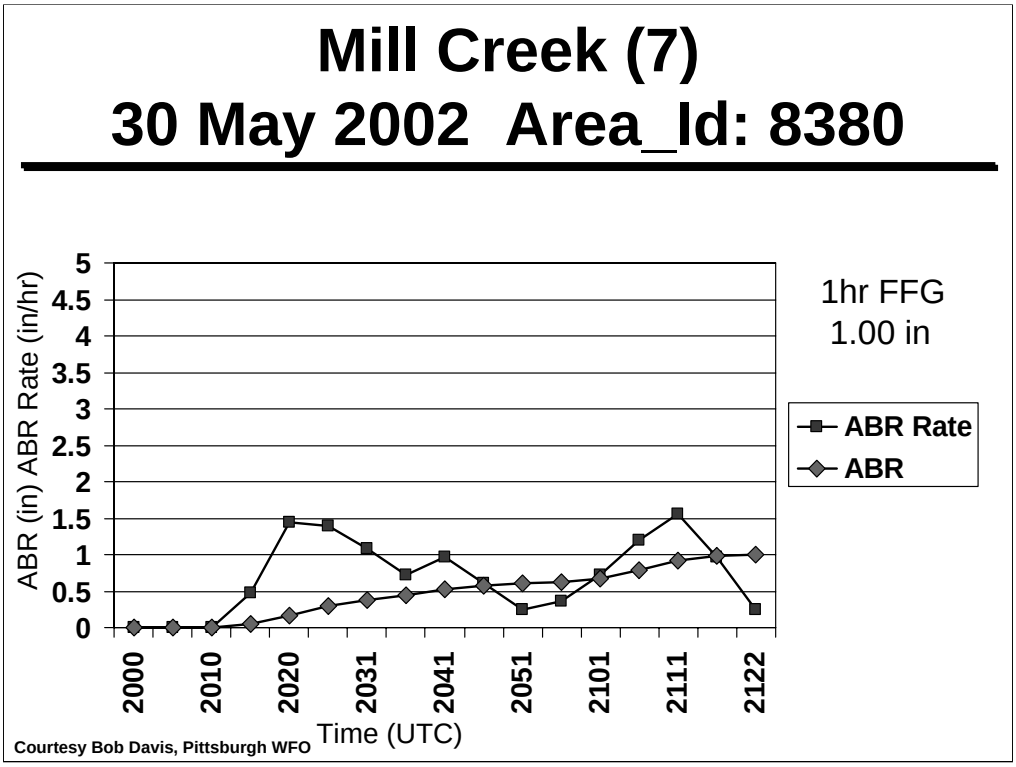
This is 90 minute ABR for the Mill Creek Bain, showing that 3 smaller basins, 2 of Turkey Run and the other Mill Creek (5) are significant 90 minute ABR



Notice the two “bursts” of heavy rainfall in this ABR plot from 2000-2122 UTC. 1 hour FFG was just 1 inch.

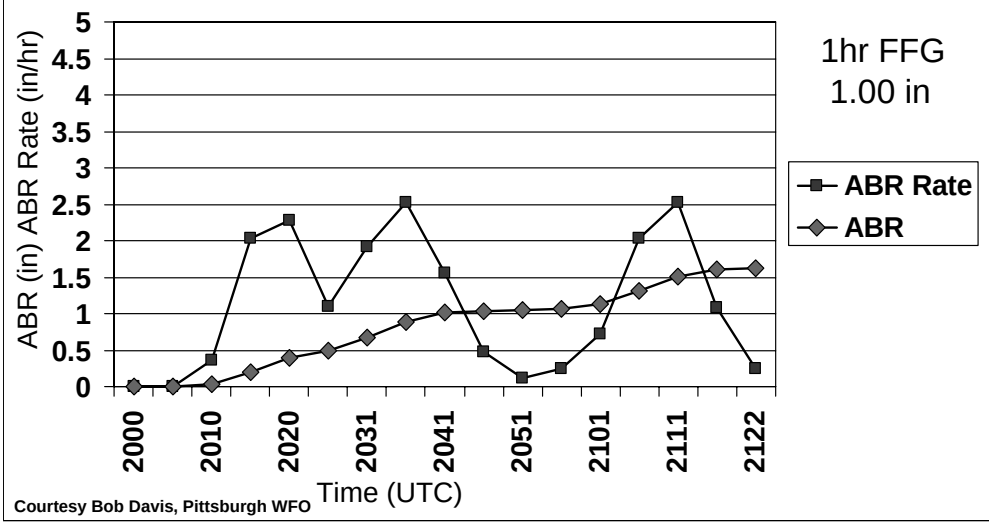


Two bursts, just as the other basin.

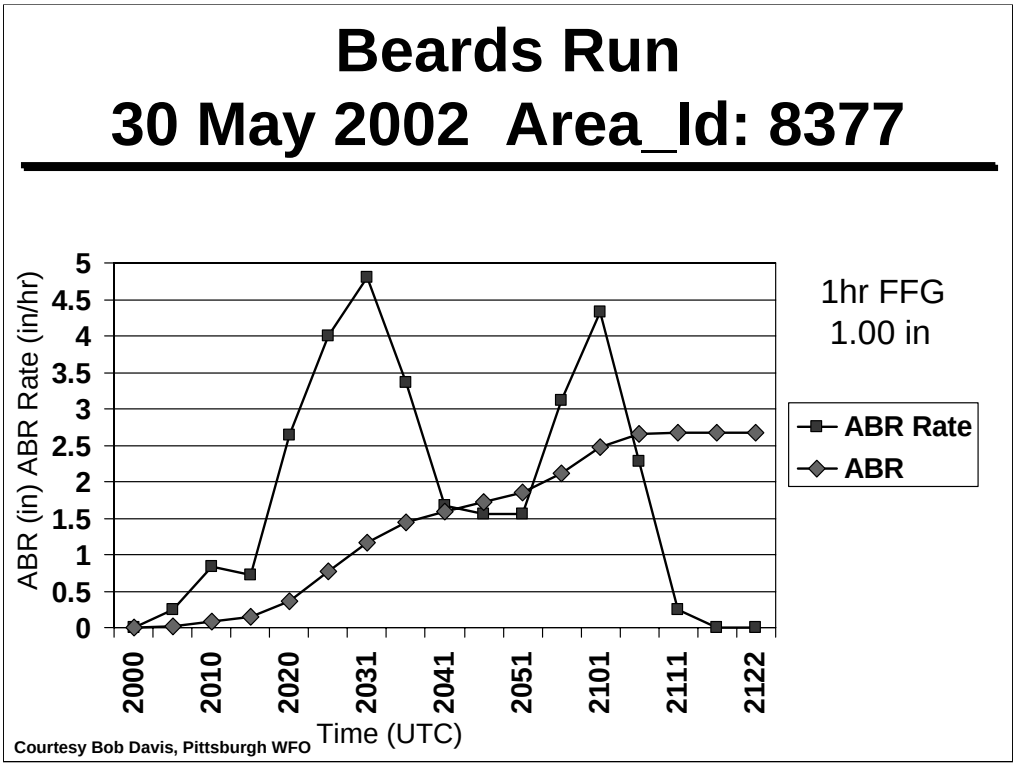


Mill Creek (7) had two bursts, but the intensity of those bursts were much less than the other basins, such as Mill Creek (5)

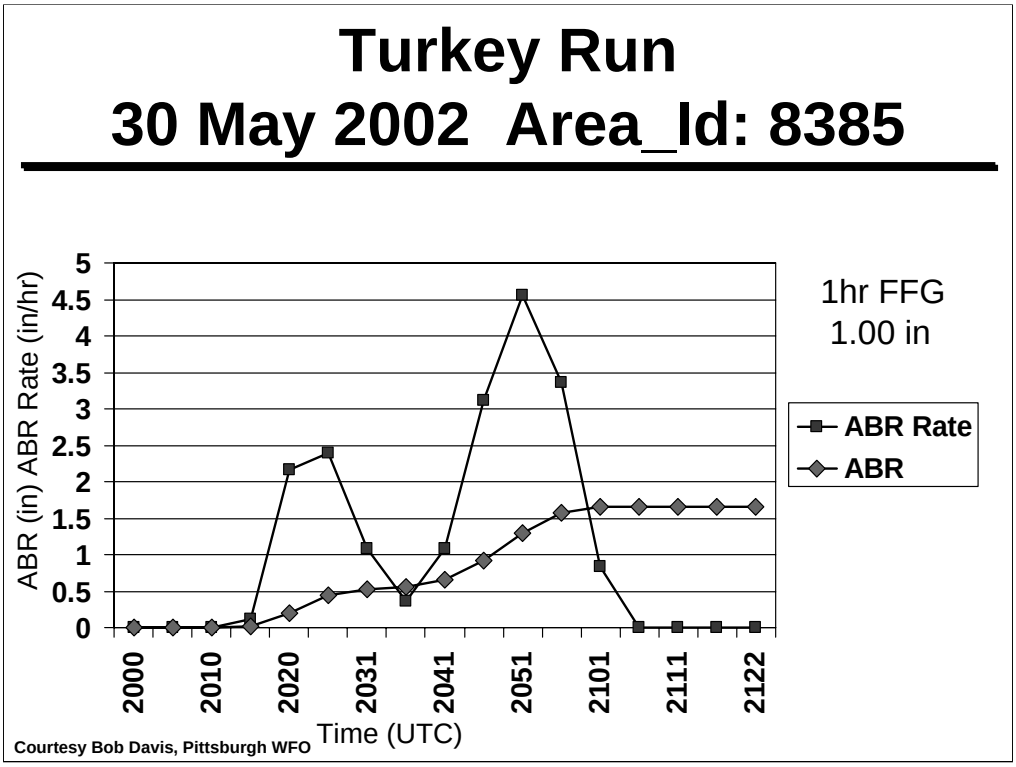
Mill Creek(8)
30 May 2002 Area_Id: 8381



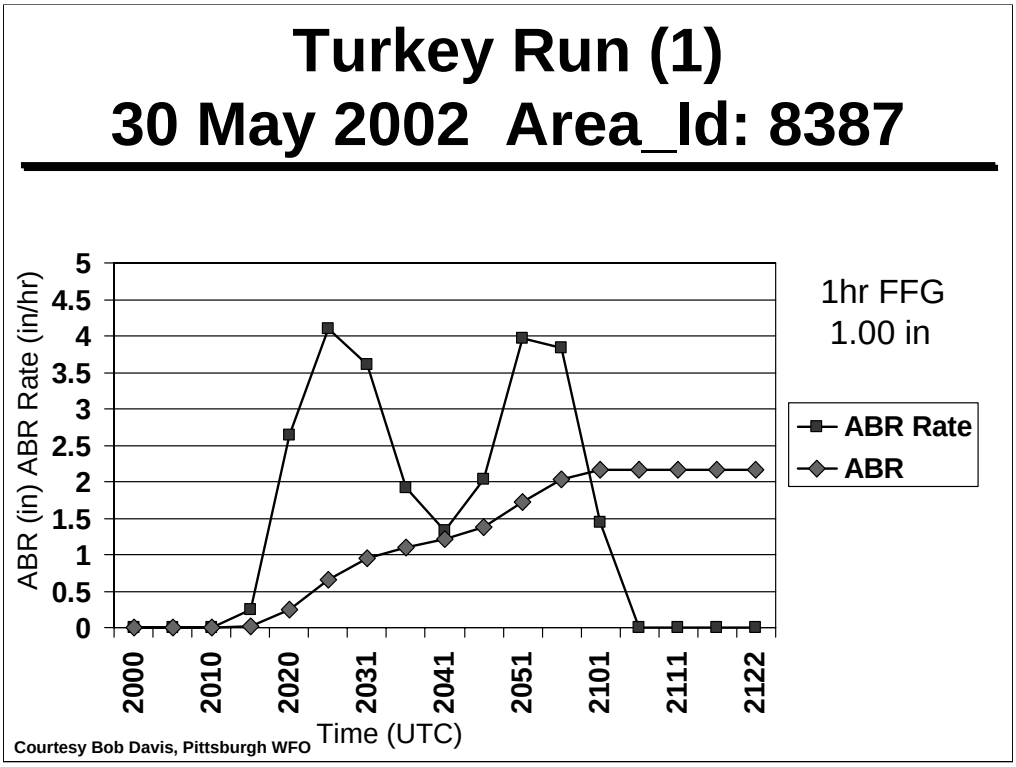
Courtesy Bob Davis, Pittsburgh WFO



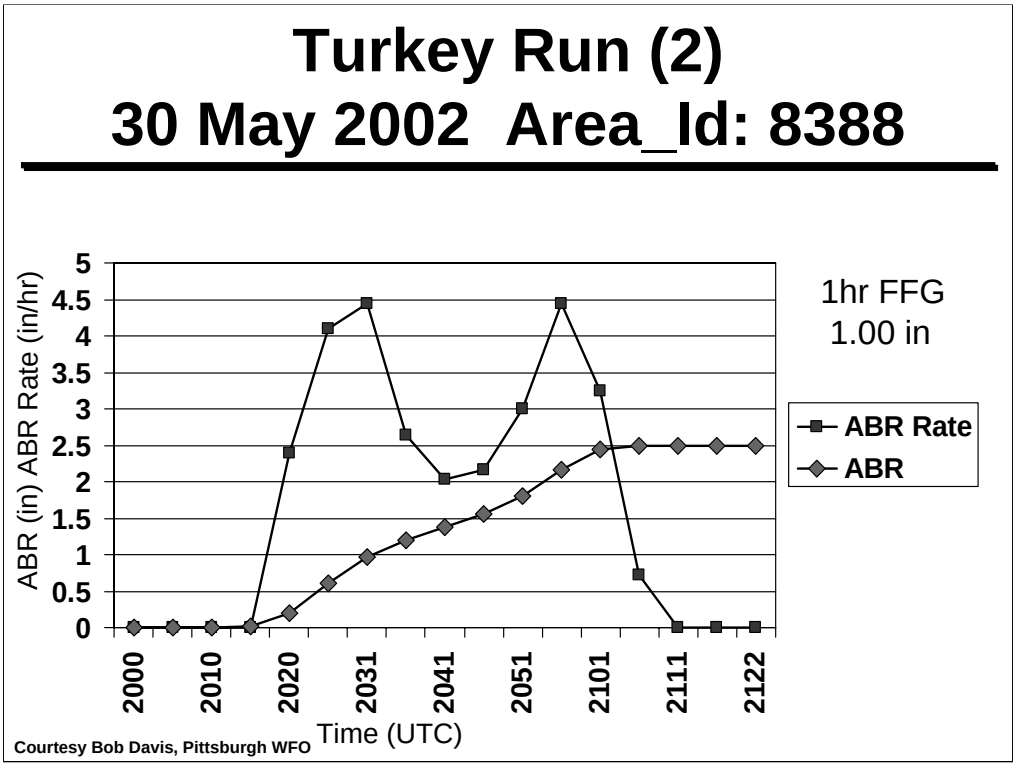
Beards Run had 2 very significant rainfall bursts, with 3 and 4 consecutive volume scans over 2 inches/hour rates.



This also shows 2 significant rainfall bursts, with the second burst of 3 volume scans over 3 in/hr.



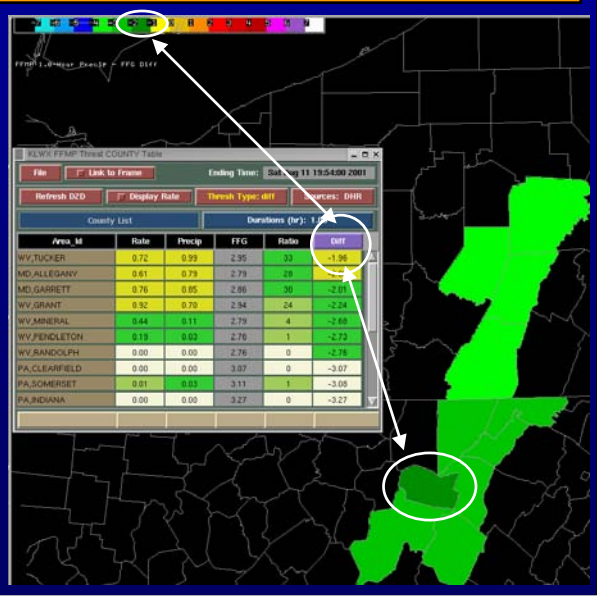
2 significant bursts.



Essentially the same as other Turkey run plots. The magnitude of the bursts made all the difference to the magnitude of the flash flooding, with the most significant flash flooding occurring in basins that had the intense bursts.

FFMP: DIFF vs Ratio

- The DIFF column far more important than RATIO
- Direct measurement of required rainfall to produce flooding, also magnitude of flooding



The DIFF column allows you to assess the flooding magnitude as this is the FF index number, with minor flash flooding at DIFF=1inch, serious flash flooding at DIFF=3 inches, and so on. It give you an idea of how much additional rainfall is required to reach FFG so you can closely monitor Rate and Accumulated precip.

WSR-88D Rainfall Estimation Limitations

- FFMP depends on 88D rainfall estimation: Any limitations in rainfall estimation are thus limitations of FFMP

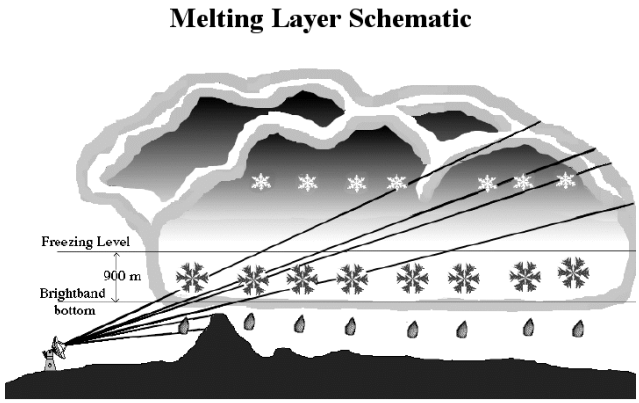
- Focus on errors significant to FFMP that may be overlooked

Rainfall Estimation Limitations for FFMP

- Brightband Contamination

→ Overestimate rainfall

→ But rare to affect convective flash flooding events

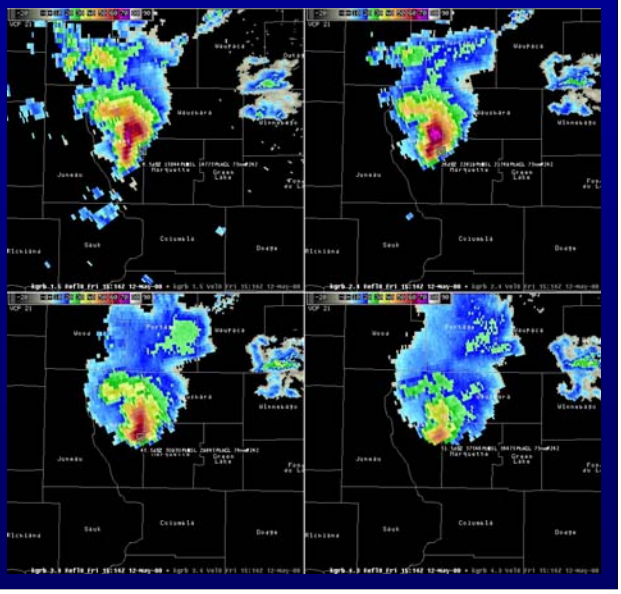


More difficult to identify bright band on FFMP than on precipitation products

Brightbanding occurs when frozen precip melts on it's way to the surface, becoming highly reflective and thus increasing reflectivity at a certain height above the radar level. This can lead to overestimation of rainfall amounts, which in turn affects the inputs into FFMP.

Rainfall Estimation Limitations for FFMP

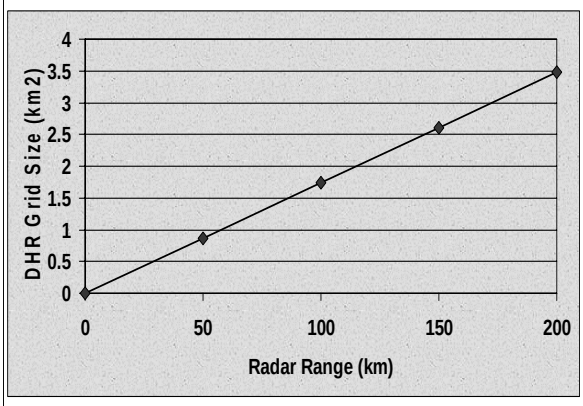
- Hail Contamination
  → can significantly overestimate rainfall, especially for high-end hailstorms like the one on the right



This can become a problem, especially with supercellular convection that has significant hail cores. However, often times hail contamination is not a problem. Comparing amounts to rain gage totals helps in this area.

Rainfall Estimation Limitations for FFMP

- Distance from Radar

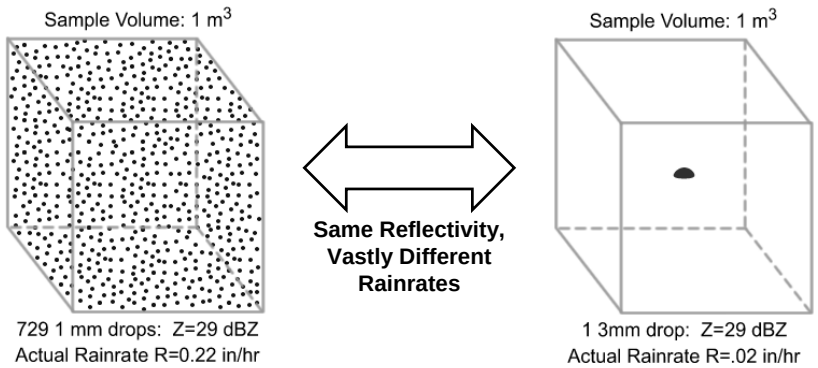


- Basin may include
  - Several 1 km (.54nm) x 1 degree bins
  - One 1 km (.54nm) x 1 degree bin
- Height of reflectivity used for calculation may be
  - Hundreds of feet
  - Over 10,000 feet

With height of beam above terrain, evaporation and advection of precipitation can both contribute to inaccurate rainfall tallies the further away from the radar the precipitation is.

Rainfall Estimation Limitations for FFMP

- Inaccurate Z/R relationship due to estimation of drop size distributions



Rainrate is dependent on the contributions from each drop within a radar volume, and diameter is raised to the 6th power. For rainrate, dependence is of the 3rd power of drop size diameter, hence the great potential for discrepencies. FFMP depends on the chose Z-R relationship. If that relationship is unrepresentative of the prevailing drop size distributions within the flash flood producing storms, then rainfall estimates will be inaccurate and FFMP will not be as effective.

Summary

- FFMP is by far the best tool for flash flood detection
- FFMP *RATE* and *DIFF* products should be closely monitored
- Limitations of radar rainfall estimation affect FFMP greatly, especially hail contamination, distance from radar, and Z/R relationships

Storm Interrogation

AWOC Severe Track
ICSvr 3-IV-C
Radar Rainfall Estimation

Thanks to Matt Kelsch for helpful input and for reviewing this material.

Radar Rainfall Estimation

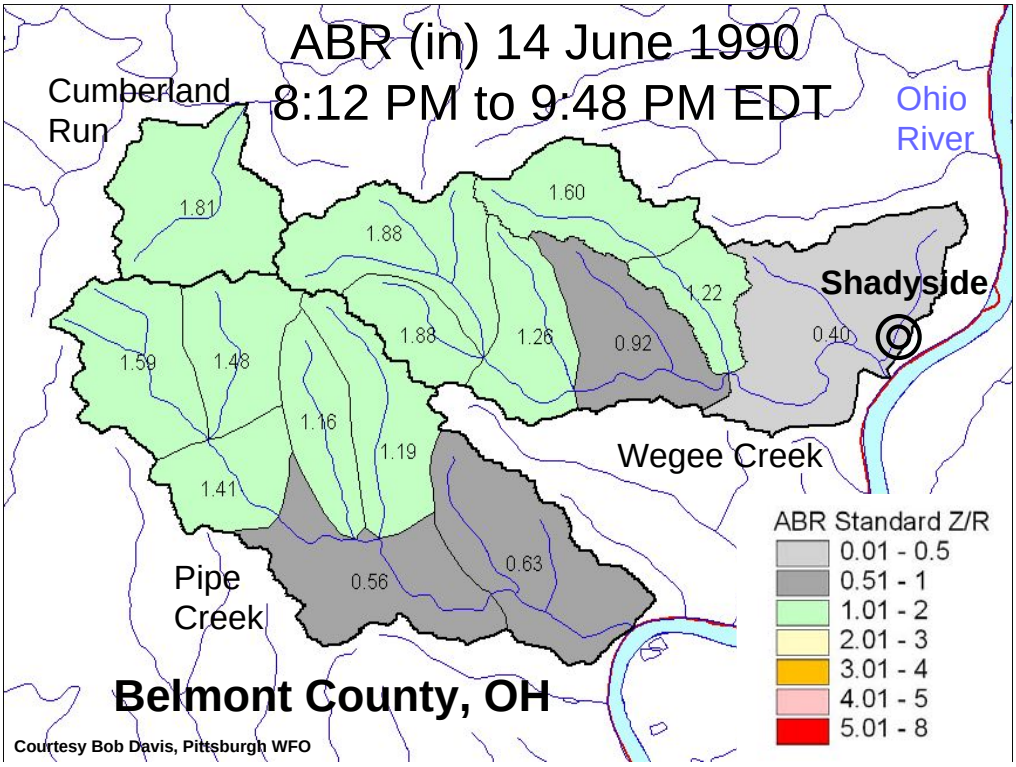
Objectives:

- Understand how inaccurate Z/R relationships at the RPG can result in a missed flash flood detection
- Know how to anticipate warm rain processes

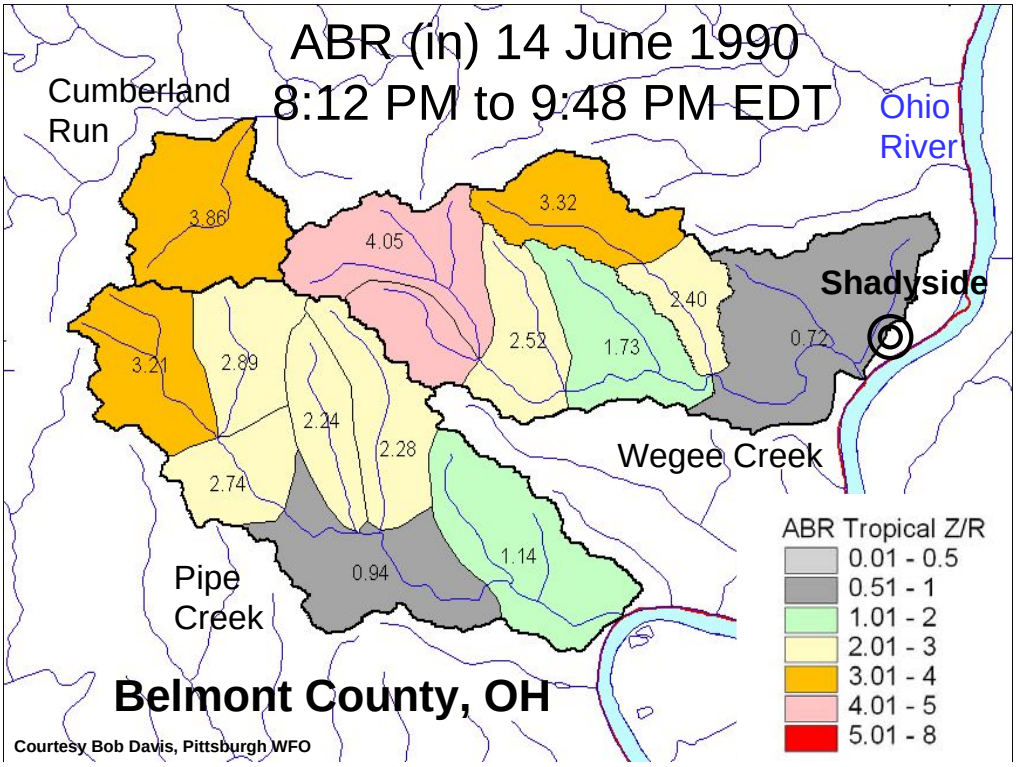
Z/R Relationship

- The standard Z/R relationship ($300R^{1.4}$) may underestimate precipitation by 50% in warm rain process-dominated storms (Davis 2004)
- Failure to switch to a tropical Z/R can lead to a failure to detect a flash flood: Shadyside Ohio

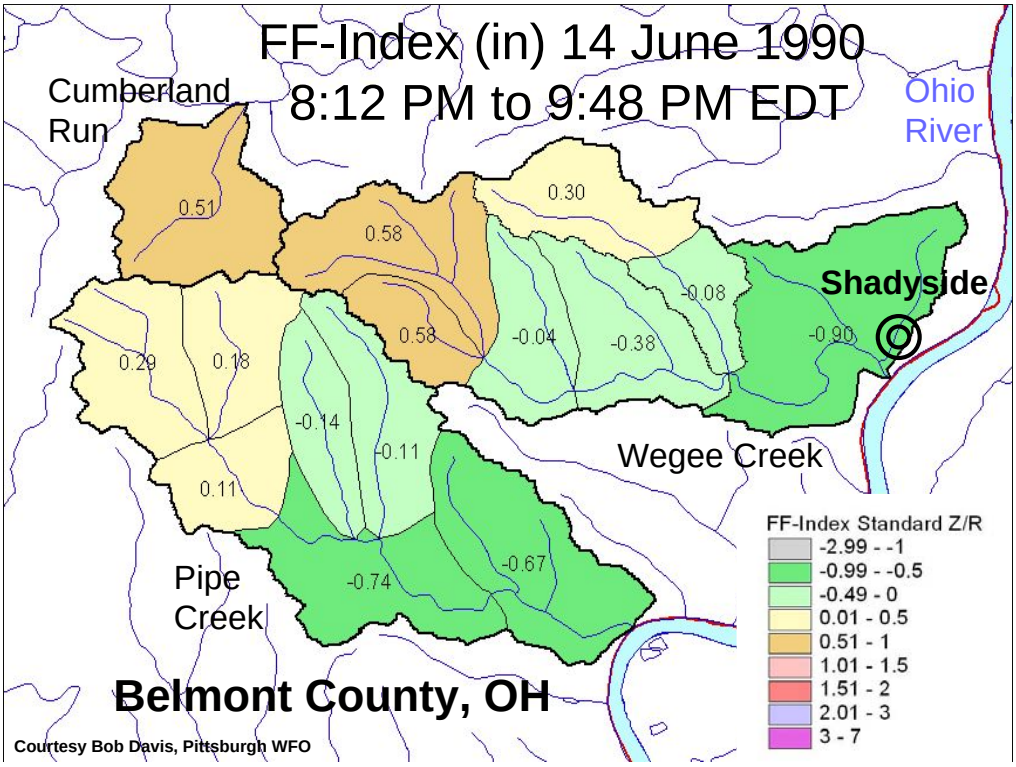
Knowing when to switch to a tropical Z-R is not a clear cut decision since there is no way to measure drop size distributions in convective storms. However, there are several clues to pick up on in the data that will help determine whether warm rain processes are dominant. We'll discuss those now.



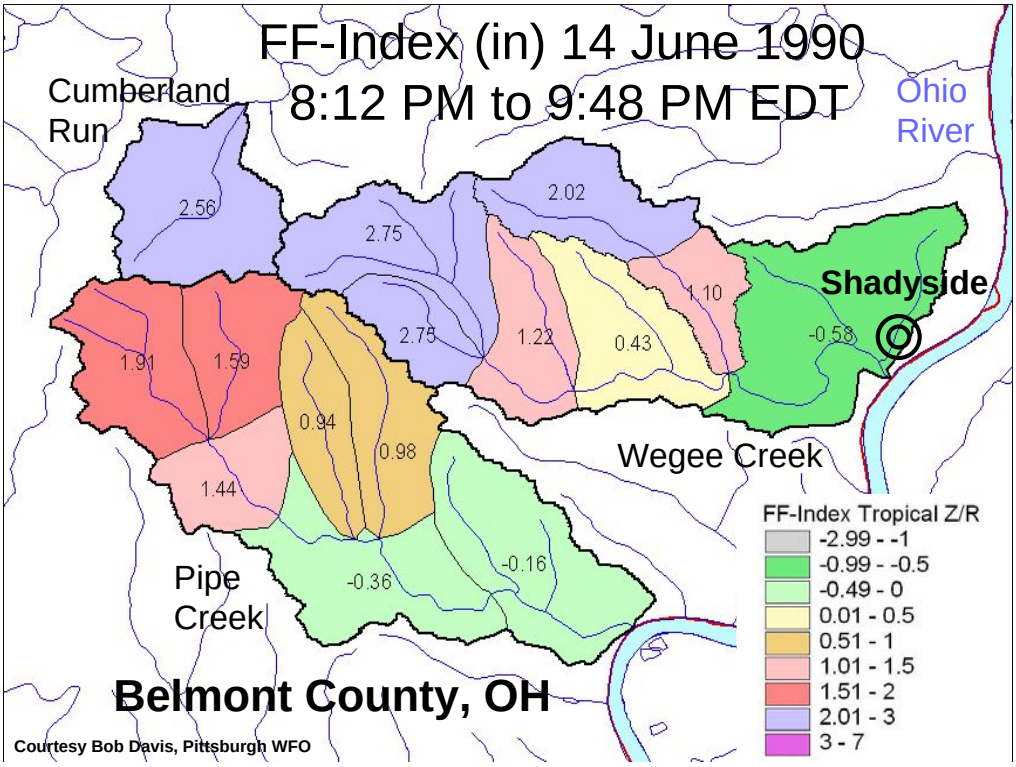
Shadyside Ohio ~90min ABR using the standard Z/R relationship



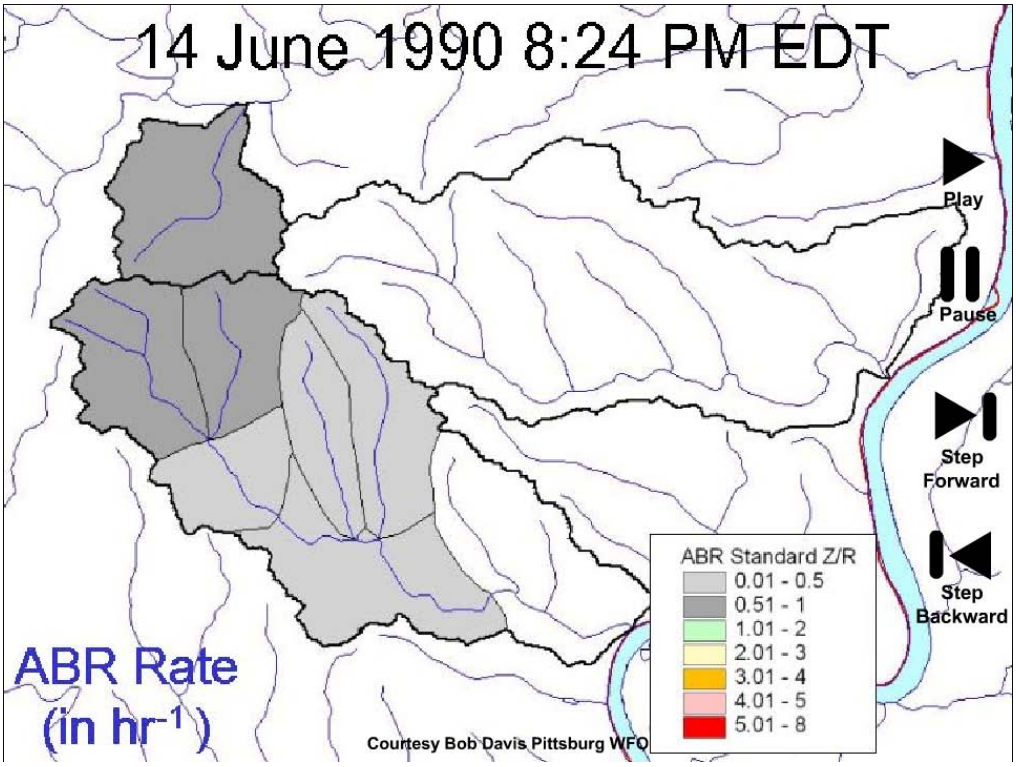
Shadyside Ohio ~90min ABR using the tropical Z/R relationship. Amounts are over twice as much in many instances.



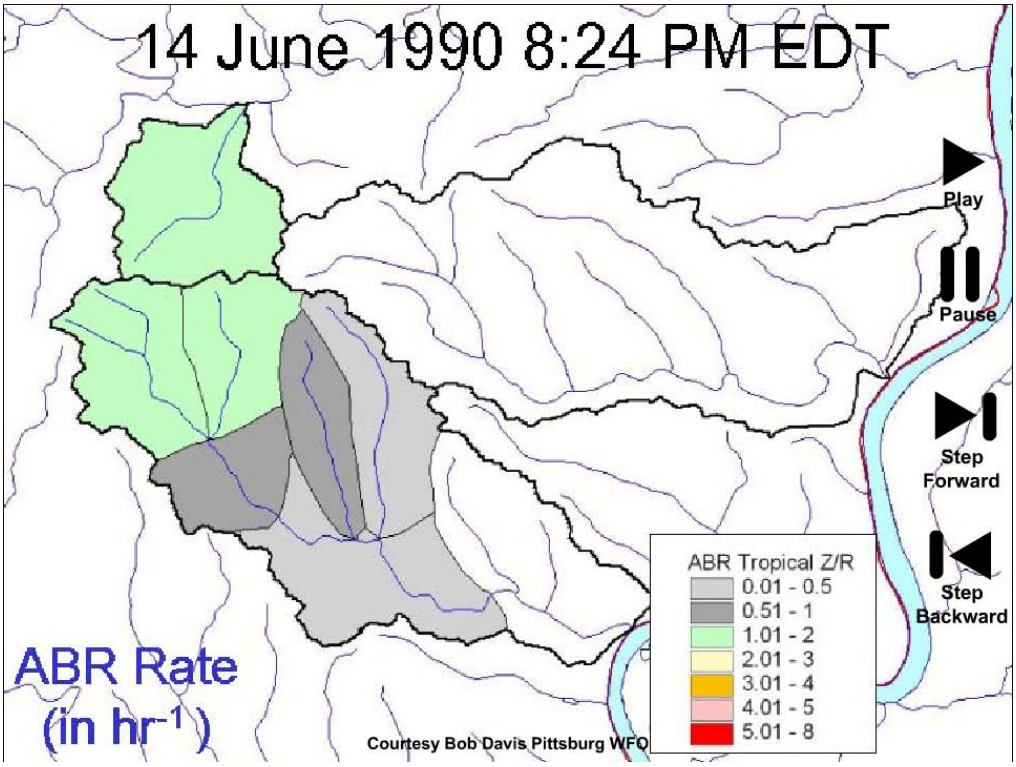
Flash flood index for the same basins, using the standard Z/R



Flash Flood index using tropical Z/R, over 2 in many sports and approaching FF3.



These loops display the large differences in rainfall rate and FFI over the ~90 minute time period. The rain that fell was from warm rain process-dominated storms and the rainfall totals matched the totals with the tropical Z/R relationship. The Standard Z/R did not detect a flash flood, while the tropical Z/R had more accurate rainfall totals and thus caught the magnitude of the flash flooding in Shadyside.



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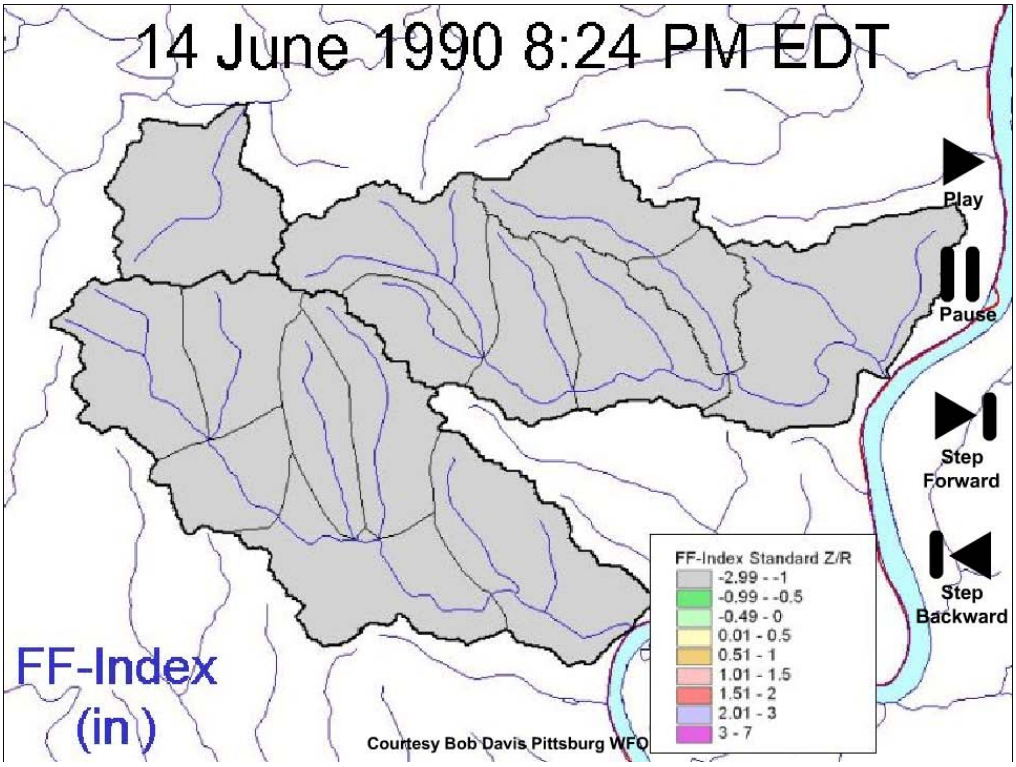

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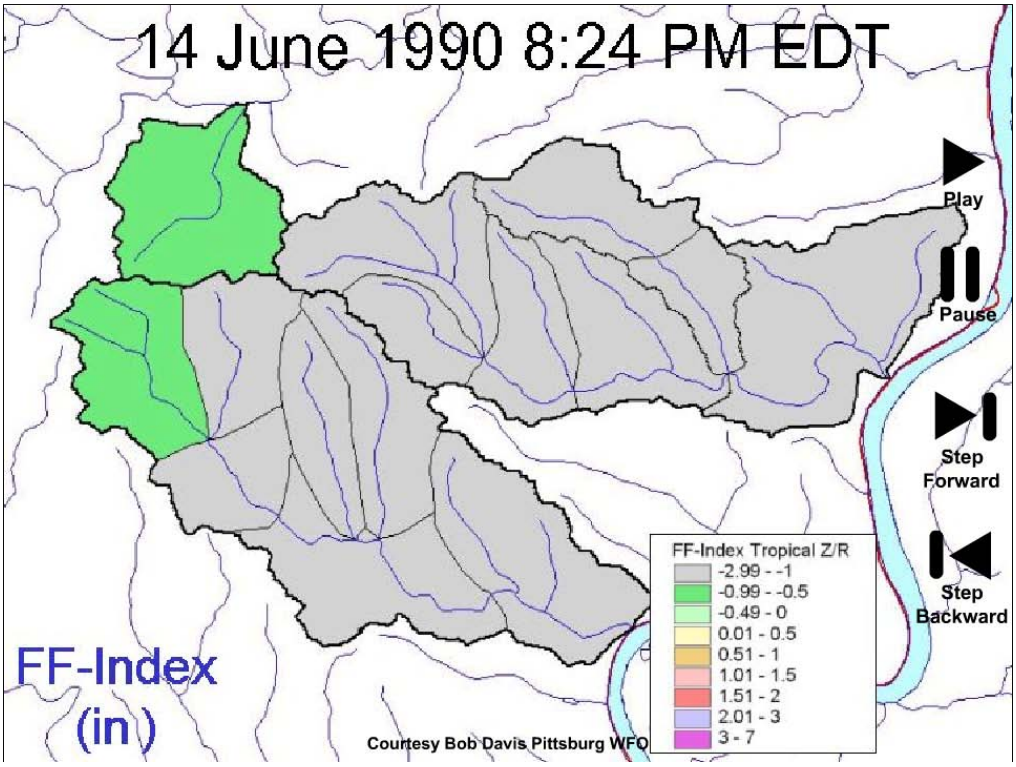

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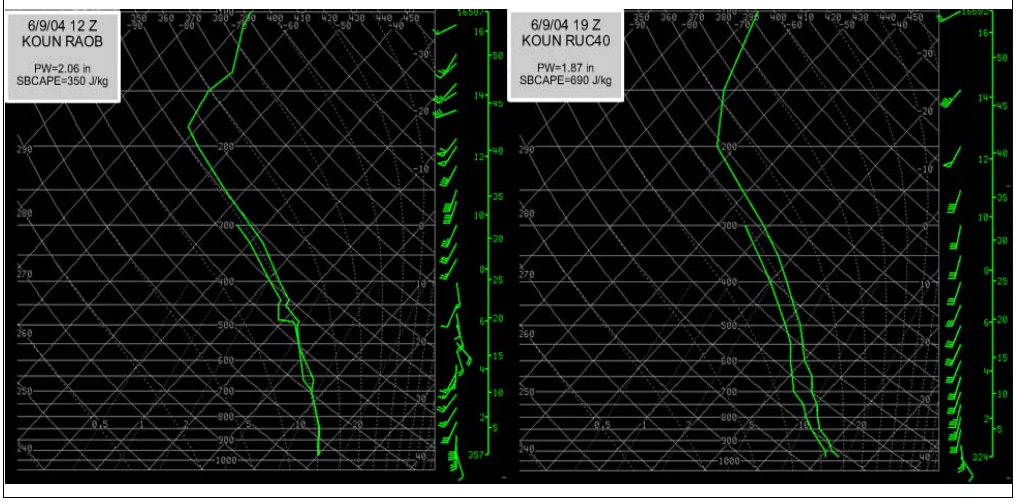
Anticipating Dominant Warm Rain Process Convection

- The sooner you can key in on warm rain process dominated convection, the quicker you can switch to tropical Z/R and help detect flash flood-producing rain
- Environmental assessment is most important, then supplement with real-time data signatures

Environmental assessment is most important if you are going to catch the warm rain processes quickly. There are several environmental clues to key in on when determining whether a certain storm is going to display warm rain process characteristics.

Anticipating Dominant Warm Rain Process Convection

- Assess the environment



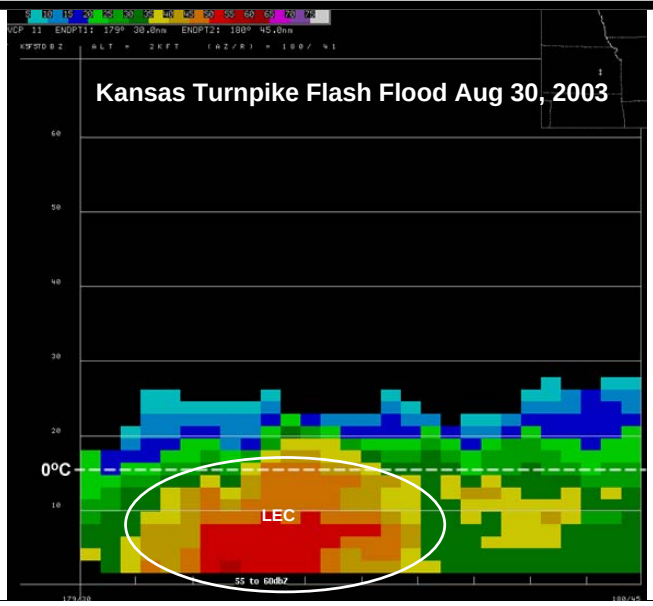
These two soundings have characteristics of a warm rain process environment: Very high PW, especially relative to climatology, little to no CIN, thin CAPE and the CAPE shouldn't be very high (1000 J/kg or less is all that is required), absence of dry air at any level, low wind shear, very deep warm cloud depth. You can look at real-time data to assess whether storms are feeding off the moisture rich environment and becoming warm rain dominant. This environment could certainly be characterized as tropical even hours before any rainfall occurs, preparing the forecaster for the possibility of switching to tropical Z/R.

Warm Rain Processes Real-Time Data Signatures

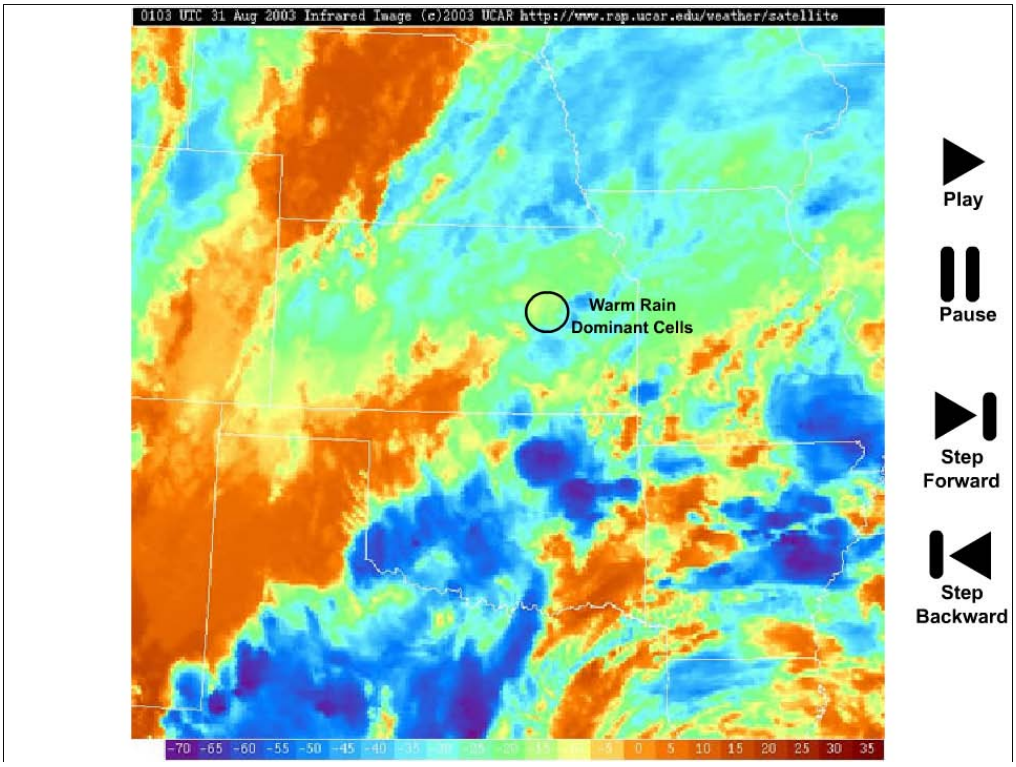
- Look for reflectivity structures, satellite, and lightning data
  - IR Satellite: Cloud tops “warm”
  - High reflectivity concentrated below the in-cloud freezing level (low echo centroid)
  - Lack of significant lightning

3 methods of helping to determine whether a certain batch of convection is dominated by warm rain processes. Reflectivity is certainly the most useful to determine this.

Warm Rain Processes
Radar Signatures

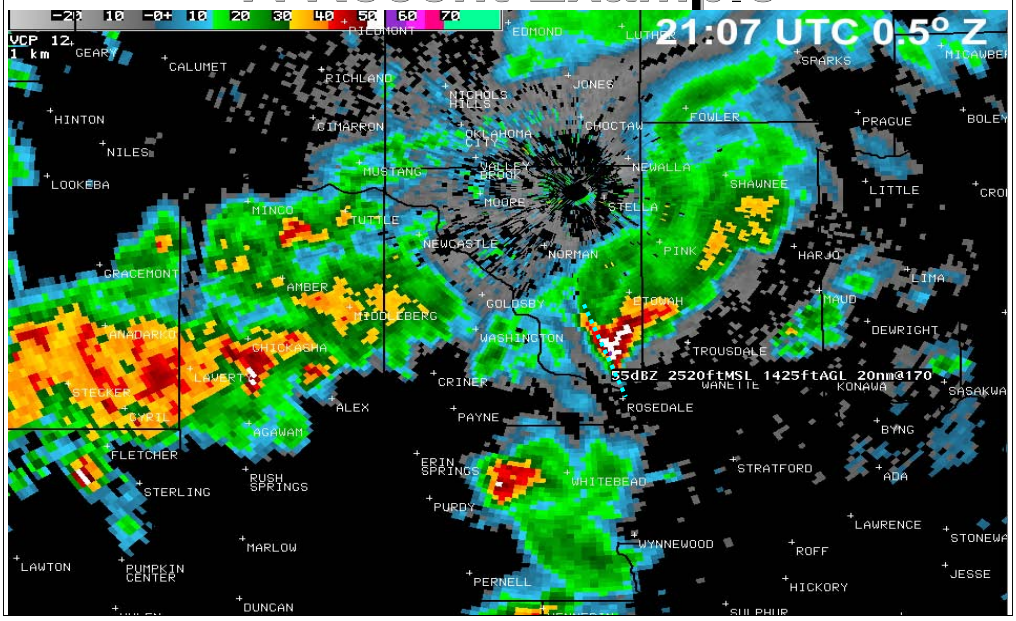


This is an example of a Low Echo Centroid (LEC) radar siganture. Maximum reflectivity is confined to the lowest tilts, and typically most of it is warmer than 0°C. One can assume that since nearly all the reflectivity is warmer than freezing, that it is all liquid and thus collision/coalesence is dominated the precipitation process. Tropical Z/R would be required anytime the environment and an LEC signature is sighted. There was no lightning with this storm, futher evidence that the dominant mode of precipitation formation was warm rain.



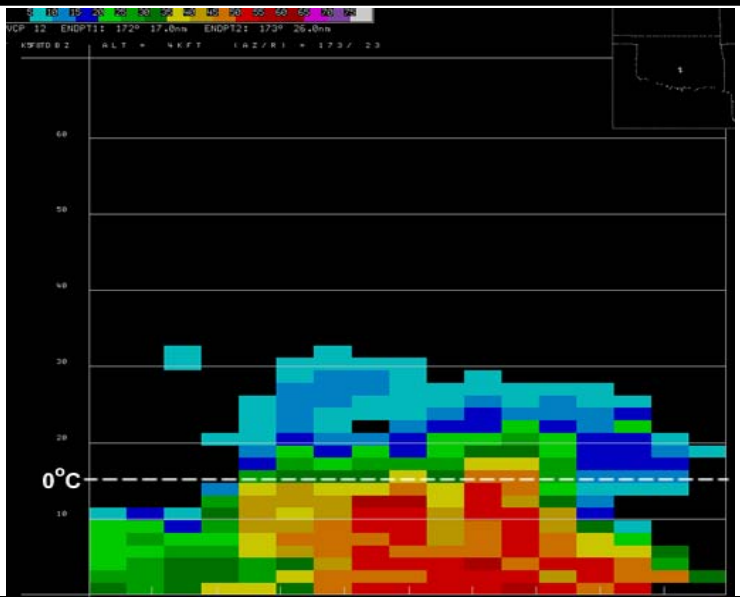
This satellite loop shows the "uneventful" appearance of warm-rain process dominant convective cells. You cannot discern their features from satellite other than to see that they are very innocent looking on IR satellite. Visible satellite would likewise appear to be innocent-looking, with a lack of any crisp cloud tops, nothing overshooting, certainly no enhanced-V signatures.

Warm Rain Processes
A Recent Example



You've already seen the environment for this day with the 2 soundings a couple of slides ago. So there is a large batch of precip to the southwest of the radar, and 2 cells to the south, both exhibiting moderate rotation in the lowest levels and hook echoes from time to time. 55-60 dBZ exists, but how can you be sure there is warm rain in there? Cut a cross section through the core (which is the turquoise dotted line) to find the following:

Cross Section through Warm-Rain Supercell



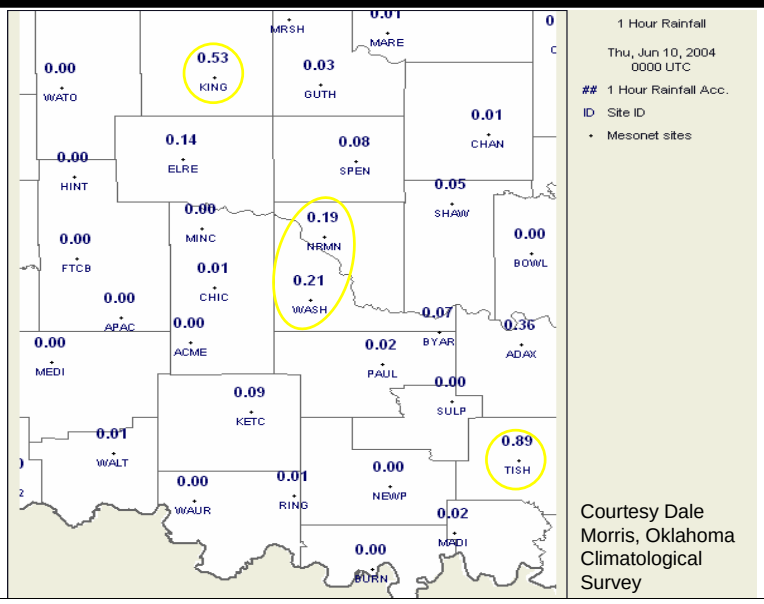
This is an example of a warm-rain process and LEC signature on a supercell storm. Not only were tornadoes a threat, but flash flooding as well because of intense rainrates. Fortunately, the storm moved NE at 25 mph and significant flooding did not occur. WDTB Instructor Jim Ladue was on this storm, verifying the complete lack of lightning and hail within this storm.

Rain Gage Comparison

- When available, compare rain gage to radar rainfall amounts
  - when comparing gage rainfall amounts to radar, remember that they measure different things

Radar measures an “average” rainfall amounts across a large 2.2 nm squure grid. A rain gage measures rainfall amounts at a point location, which can vary widely over small distances. With this in mind, rain gages are still very useful to determine the bias in the radar estimate. Spotter reports of rainfall are very useful in many instances.

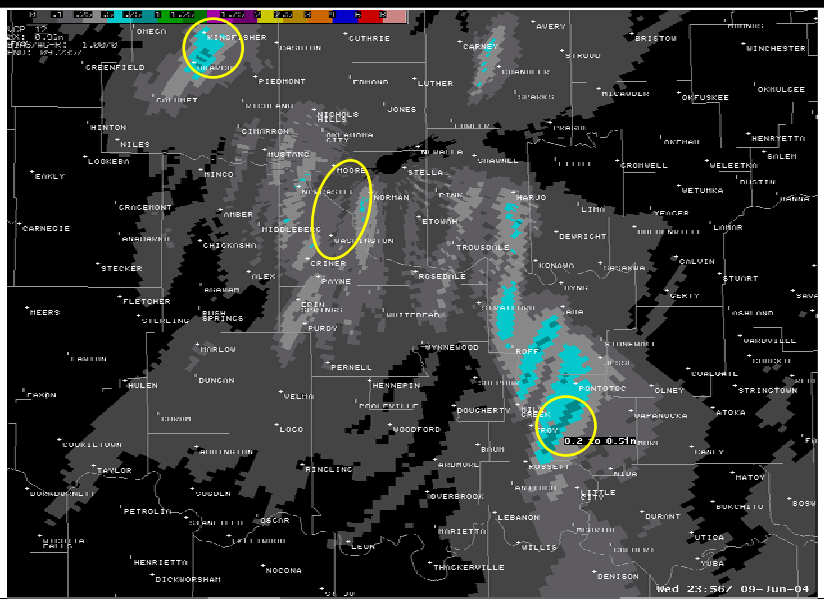
Rain Gage Comparison: Back to Example



Courtesy Dale Morris, Oklahoma Climatological Survey

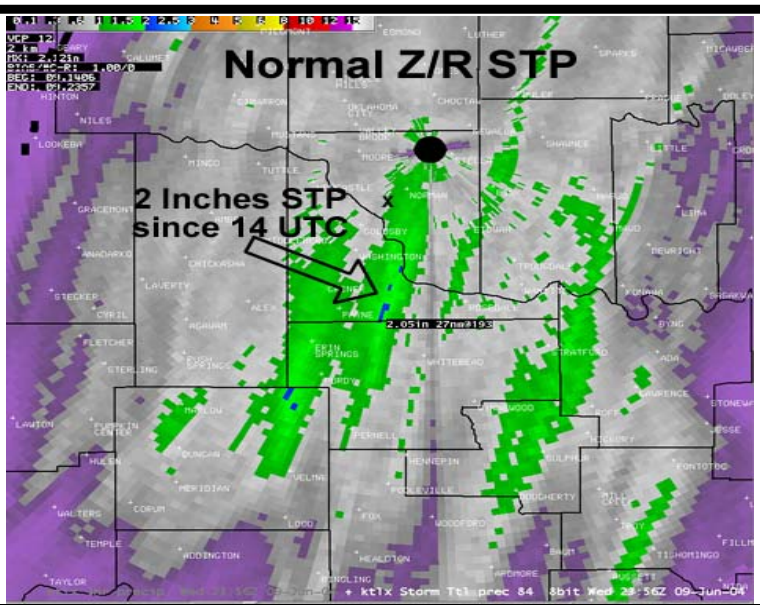
Here is an example of comparing radar estimated rainfall with a mesonet of rain gages using the Oklahoma Mesonet and the "warm rain process dominated supercell" we've been looking at. Checking to see if rainfall is accurate can be tough, even with a mesonet as can be seen in this example. Focus on the one hour precip accumulation at the 4 gages outlined in yellow.

Rain Gage Comparison: Back to Example



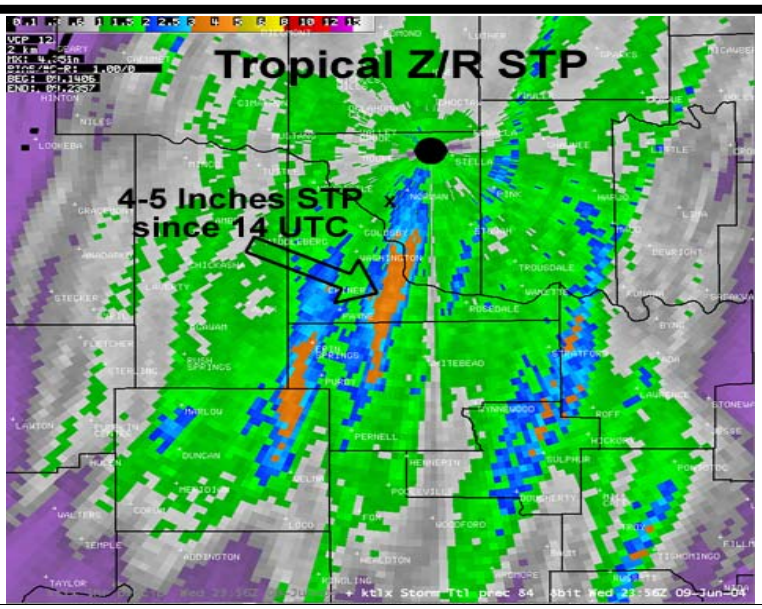
The southern most maxima is closest to being directly over a gage, and even with a mesonet it is tough to compare to radar because the gages simply aren't underneath the strongest rainfall, as is especially evident in the center oval, the the maximum rainfall southeast of either the Washington or the Norman mesonet gage. Rainfall at the southern oval is underestimated by 50%, this is using the standard Z/R, and in this event warm rain processes appeared to be dominant.

Switching Z/R can make a Difference



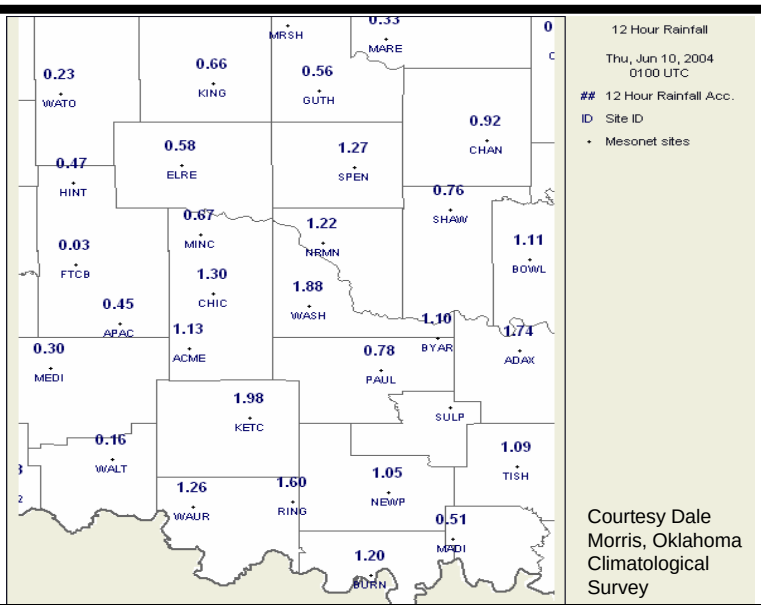
This is STP beginning at about 14 UTC using the normal 300R^1.4 convective Z/R. The X is the location of WDTB member Paul Schlatter's rain gage.

Switching Z/R can make a Difference



WDTB employee Paul Schlatter had 2.4 inches at point X in the image over roughly the same time period, clearly showing that normal convective Z/R underestimated rainfall amounts by 50%. He stood outside during the heavy showers, and reported low visibility, moderate rain with extremely heavy amounts of smaller drops, no lightning (NDLN verifies this). T/Td was 74/73 throughout the heaviest showers. Switching to tropical Z/R certainly would have resulted in accurate rainfall estimates on this day as this image implies.

Switching Z/R can make a Difference



Courtesy Dale Morris, Oklahoma Climatological Survey

Here are the storm totals over the same time period as the previous 2 images. Unfortunately, no gages exist in the axis of heaviest rainfall, but the gages even over the lighter rainfall amounts were much more accurate with the tropical Z/R than the standard Z/R.

Z/R Relationship Caveats

- Rarely a clear cut decision to switch to tropical Z/R
- Not all storms are created equally: Certainly true of DSDs within storms and across the radar umbrella
- Significant overestimate in storms that are not warm rain process-dominated

There is so much uncertainty inherent in the process and within microphyhsical aspects of convective storms that switching to a tropical Z/R in the interior portions of the U.S. is rarely an easy decision.

Both Fort Collins and the KS turnpike flash floods had other storms within the radar umbrella that were not warm rain process-dominated storms. Thus, if one were to switch to a tropical Z/R, those storms that were not warm rain process dominated would have a significant overestimate in rainfall totals and rates. Even warm rain process dominated storms may not have DSDs that are close to the ones used in the tropical Z/R, meaning even when you switch to tropical Z/R for a warm rain-process dominated storm, rainfall amounts and rates may still be inaccurate due to uncertainly in the actual DSD.

Summary

- Radar rainfall estimation contains many important sources of errors that affect FFMP

- Failing to quickly and properly anticipate warm rain processes and then switch to tropical Z/R can result in failure to detect a flash flood

Storm Interrogation

AWOC Severe Track

ICSvr 3-V-A

Three Body Scatter Spike

With Guest Commentary from Les Lemon

Three Body Scatter Spike (Hail Spike)

Objective:

- Understand what causes a three body scatter spike, what it signifies, and how it may contaminate velocity data

Three Body Scatter Spike (Hail Spike)

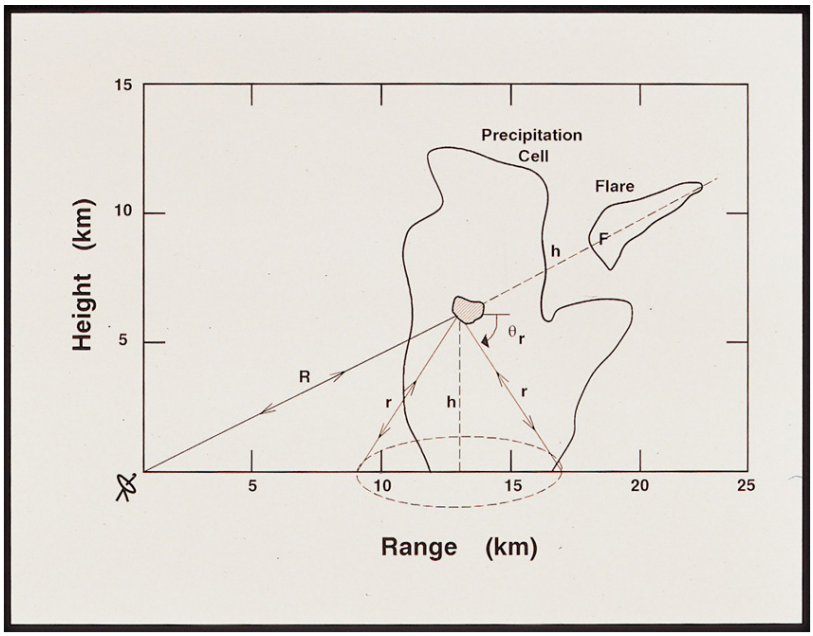
- A feature, like many others, that is not all-inclusive: If the signature is in the data, it is a guarantee of large hail, but with many severe hail storms it is not visible
  - Can be masked by “real” reflectivity behind the main core

Hail Spike

- If visible, it is the most robust indicator of severe hail

Step by step process

1. radar pulse from radar to hail core
2. strongly reflecting large, wet hydrometeors are encountered, and scatter the signal in all directions, including downward
3. The trees, earth, and vegetation reflect the energy diffusely
4. reflected energy illuminates the hail core once more
5. the reflected energy from the ground has been found to drop off as r^{-3} (r is the distance the energy travels from the ground to the hail core)
6. for a second time, the large, wet hydrometeors scatter the energy, but this time a significant amount of the ground reflected energy is backscattered and received by the radar
7. the radar “sees” this entire event as occurring along the same radial, and due to the longer traversed paths of the triple reflected signals, the spike appears at a range downradial from the hail core
8. The hail spike begins down the radial at a distance exactly equal to the height of the hail core above the ground
9. Note that each successive range gate along the hail spike will have progressively lower reflectivities because of the r-3 decrease of power with distance from the scatterers
10. 1st gate of the hail spike will have maximum reflectivities



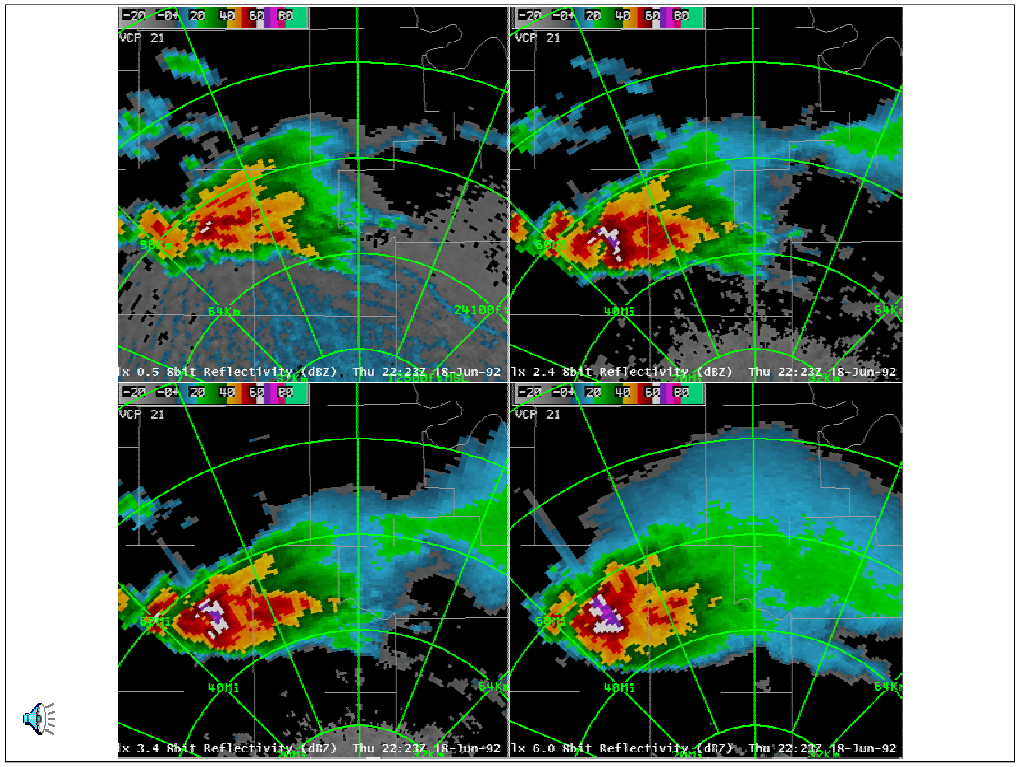
You get a range of possible reflection regions from the ground back to the hail stone, such that a “cone” of possible reflection areas are possible. This is precisely why the flare extends for various lengths down radial, as the reflection along dotted line h is both quickest and strongest (again, returned power falls off as R^3). Power returned from the edges of the cone takes longer and is weaker, thus the flare extends further downradial and decreases intenstity the further down radial you look.

Hail Spike

- position of hail spike along the radial is proportional to core altitude above the surface
  - → Precisely why it is seen primarily at higher tilts
- strength of hail spike proportional to: hail size, concentration, wetness, and vertical extent of core
- must be no precipitation behind core along radial

•The factors affecting the strength of the hail spike is important to comprehend. Extremely wet hail, in very high quantities, even though it could be “small”, can produce a hail spike.

•Most storms with large hail or large quantities of small hail likely produce hail spikes, it’s just that typically the precipitation core is too broad or there are other storms down radial such that the hail spike is not visible.



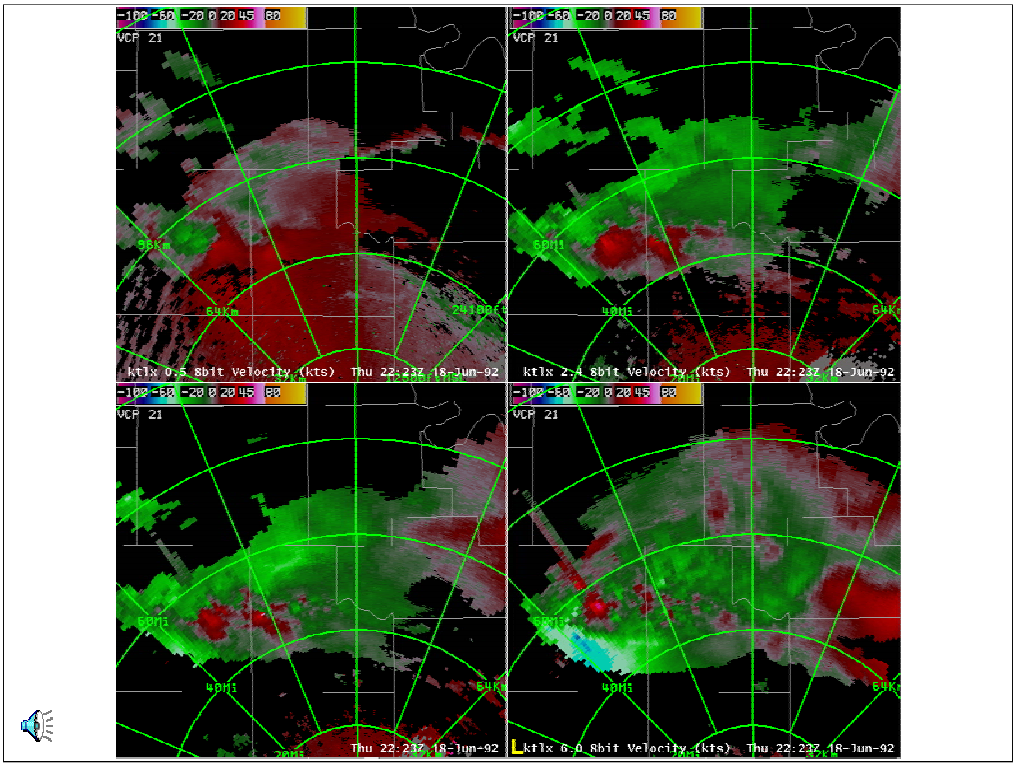
4 panel reflectivity.

•Hail spike shows up on tilts 2.4 degrees and above, but not at 0.5 degrees

•TBSS begins at a range from the radar that is the range to the hail core plus the twice the height above the ground the beam hits the core.

•AT 0.5 degrees the core is closest to the ground, and thus the TBSS begins very near the back side of the hail core, and the reflectivities are so low in the hail spike that the actual reflectivities from the northwest portion of the storm “drown” them out

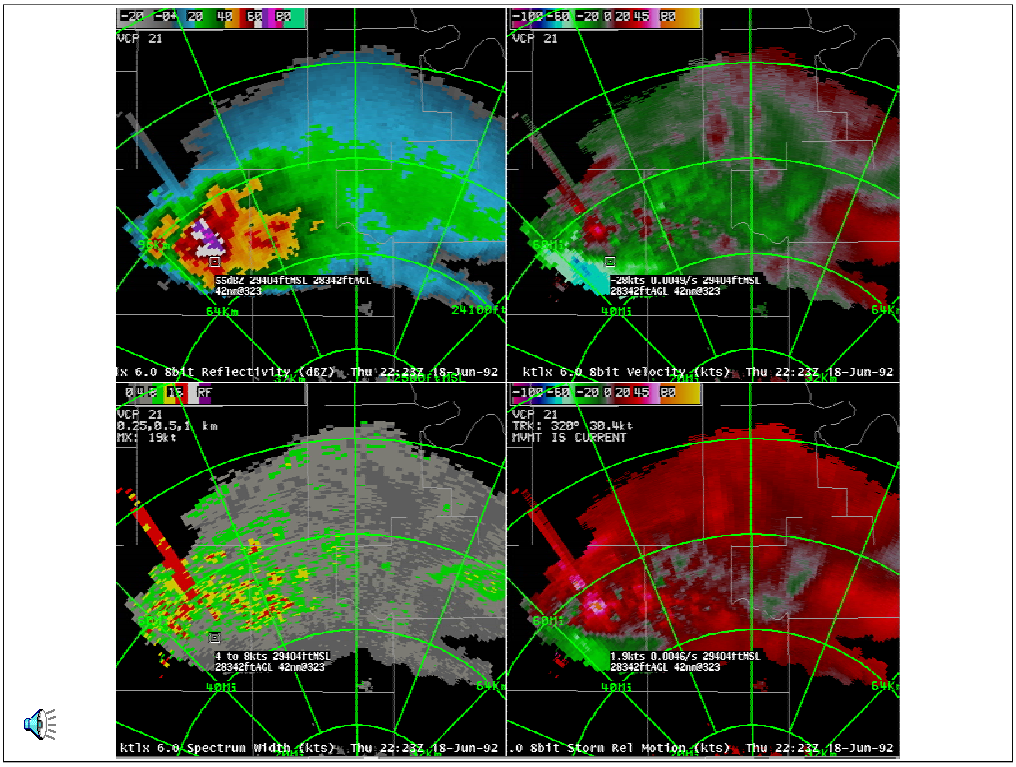
•Rapid hail stone growth occurs aloft in mid-levels, in wet growth making them highly reflective, and at 6 degrees the core is hit at 33 kft, thus the TBSS is much longer and extends a long distance down radial behind the core.



4 panel velocity: Velocities are low in the TBSS

•At each range gate you are combining both horizontal and vertical air motions, and hail is normally falling relative to the ground

•Thus, velocities are low negative velocities within the TBSS, but you are combining returns at each range gate withint TBSS from multiple areas within the hail core, both horizontal and vertical motions. Velocities themselves are meaningless, but generally low and negative.



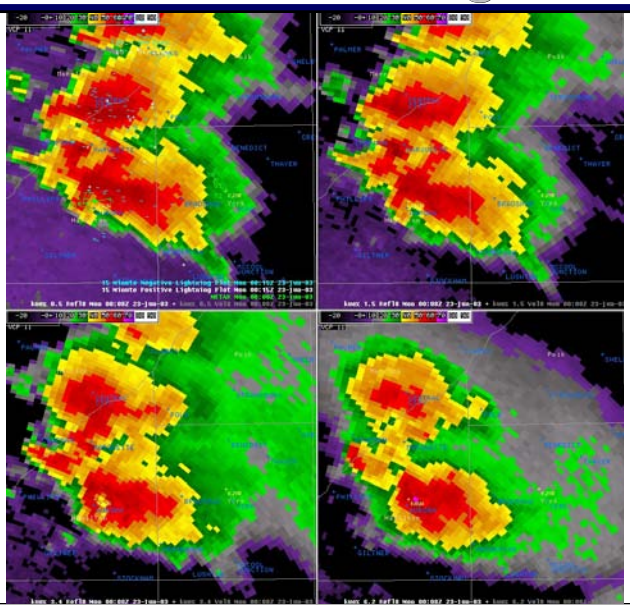
6 degree Z (top left), V (top right), SW (lower left), and SRM (lower right)

•Horizontal region in Velocity away from radar in the hail region itself that is outbound, then another region further down radial of the core that is also outbound: this is created by the TBSS, velocity contamination and is an unfortunate result of TBSS

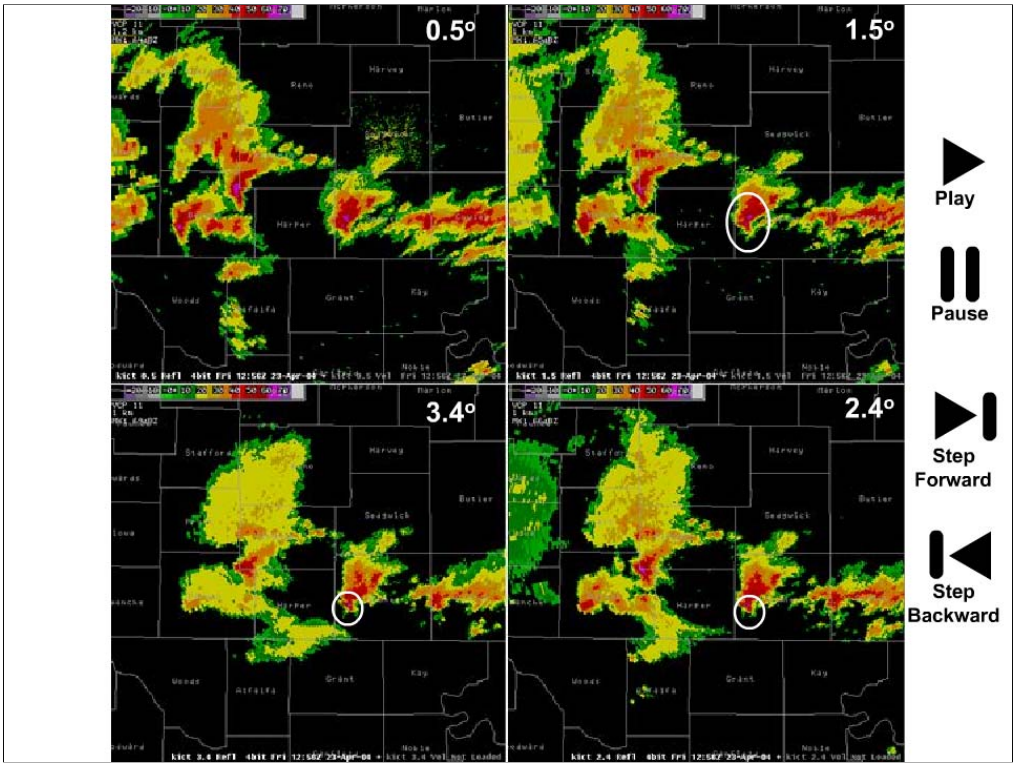
•SW has very high values within the TBSS: each location along the TBSS is a combination of several different motions both horizontally and vertically from multiple locations within the hail core. The spectrum is very broad as as result and is very near white noise along the TBSS. SW can help identify TBSSs.

•TBSS means you have a serious core, but just because you don't see it doesn't mean the storm cannot produce very large hail. It is a "sufficient condition" for knowing large hail exists in the storm, but it not a "necessary condition". TBSS is not an algorithm, if you see it, you should be completely confident that large hail is occurring with the storm.

June 22, 2003 Aurora: Record Breaking Hail

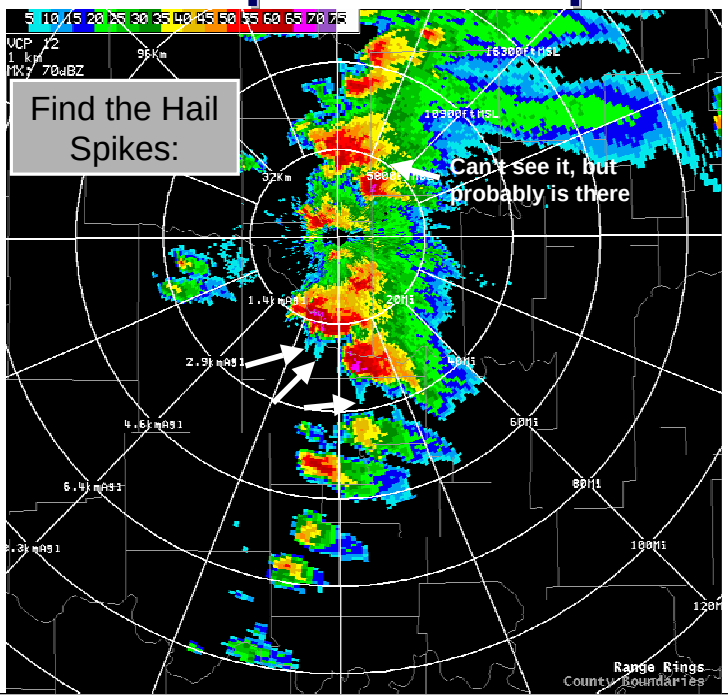


No hail spike with this storm at any time, although technically it would be very hard to see.



Examine this loop of reflectivity from morning supercell. The hail spikes are very small, and could be mistaken for an appendage on the southern flanks of the storm. Always investigate velocity (and SW if available) and zoom far in on any potential hail spikes to verify their presence.

Hail Spike Example

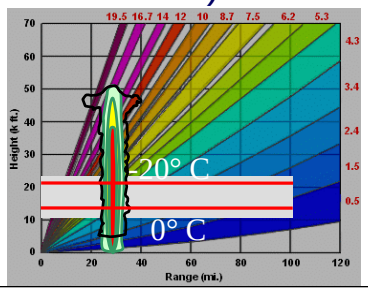


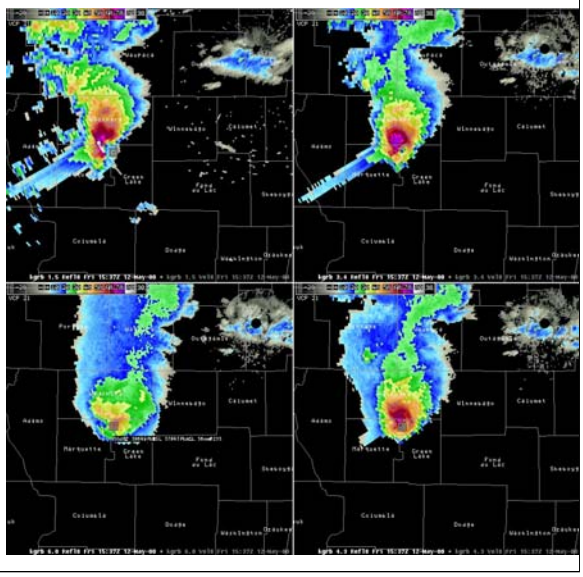
It is your job to find the hail spike in this image. Golfball to baseball hail was reported with these storms, although around this time just 1-1.5 inch hail falling out of any one storm. The storm entering Logan county "should" have a hail spike but the spike is obscured due to echoes all around behind the main core. I would point this out.

Hail Spike: Summary

- "storms producing the artifact, will or are now, *with absolute certainty*, producing very large hail"

(Lemon 1998)





Another important point Lemon brings up in his paper is the additional threat of severe winds. With large hail and/or large quantities of wet hail, downburst potential is very high due to precipitation drag, and thus storms with hail spikes ALSO are likely to contain severe damaging winds, as is the case with this storm.

Storm Interrogation

AWOC Severe Track

ICSvr 3-V-B

VIL and VIL Density

VIL and VIL Density

Objectives:

- Understand how VIL is calculated
- Recognize that VIL and VIL density are not good indicators of severe hail

VIL: Calculations

- Reflectivity values at consecutive tilts are input into (h is height in meters between the 2 grid boxes):

$$3.44\times10^{-6}\left(\frac{Z_{low}+Z_{above}}{2}\right)^{4/7}\Delta h$$

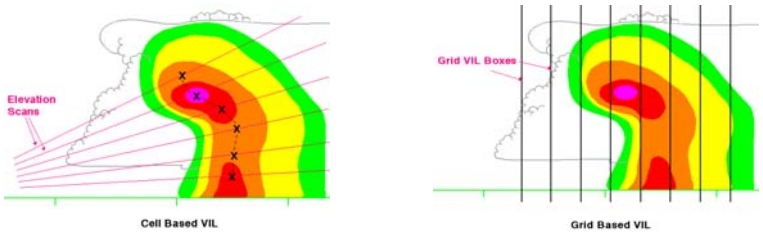
- 2 ways to sum up each of the above values throughout the depth of the echo returns:
  1. Cell based & 2. Grid based

•VIL is vertically integrated liquid.

•It was intended to “throw out” the contributions from ice, so warning sirens should be going off right off the bat for it’s usefulness for hail.

•VIL is calculated from the above equation.

VIL: Grid and Cell based



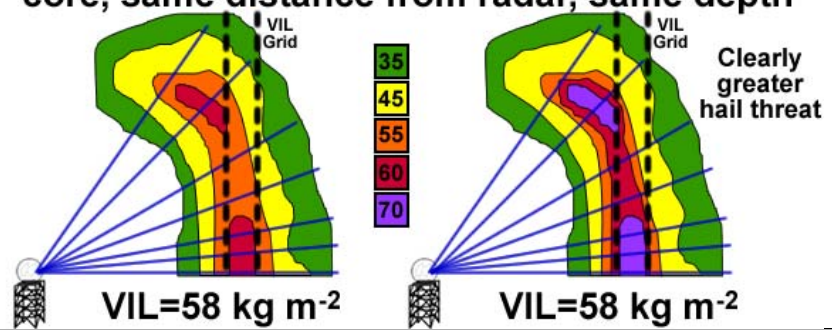
- Cell based (listed in SCAN tables): each vertical integration is done between cell centroids
- Grid based (what you can view in D2D): vertically stacked 2.2 x 2.2 nm boxes

Cell based VIL will have higher values than grid-based VIL as a result. Centroids will have higher reflectivity values. Cell based VIL depends on the accuracy of the SCIT algorithm. Grid Based VIL fails with fast moving storms or storms that are strongly tilted.

VIL: Calculations

- Caveat: In order to "filter out" hail as was originally the design, all reflectivity values greater than 56 dBZ are truncated to 56 dBZ
- Lower cap of 18 dBZ as well

2 Storms, idential shape and size of 55 dBZ core, same distance from radar, same depth



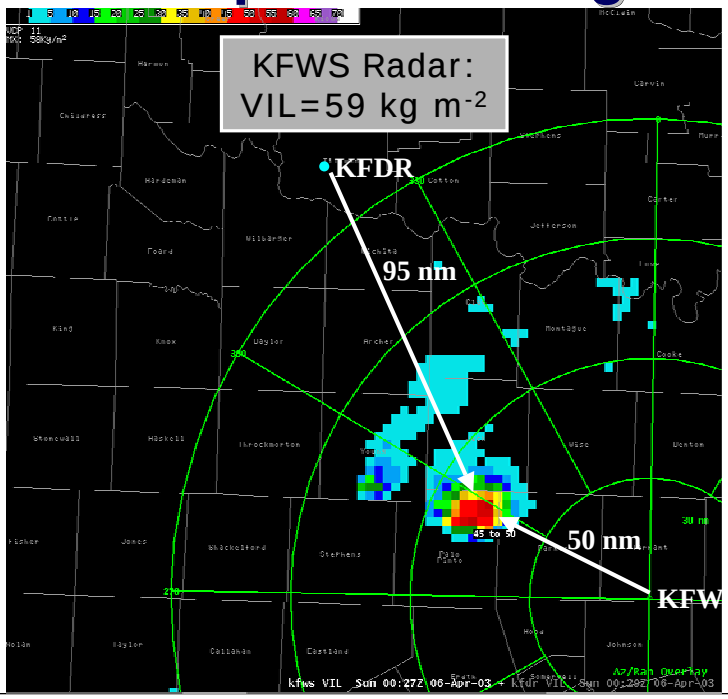
The problem of truncation becomes clear in this hypothetical storm. Both storms have identical extents of 55 dBZ, thus due to truncation their VILs are identical as well, even though the storm on the right is clearly more severe with several large areas of 70 dBZ.

VIL (legacy product)

- Cannot discriminate between severe and non-severe hail
  - Threshold of 50 kg m^{-2} has been shown to have nearly perfect POD of all hail larger than 2 inches in diameter, but FAR very high as well
- Problems: Highly dependent on environment, storm type, distance from radar

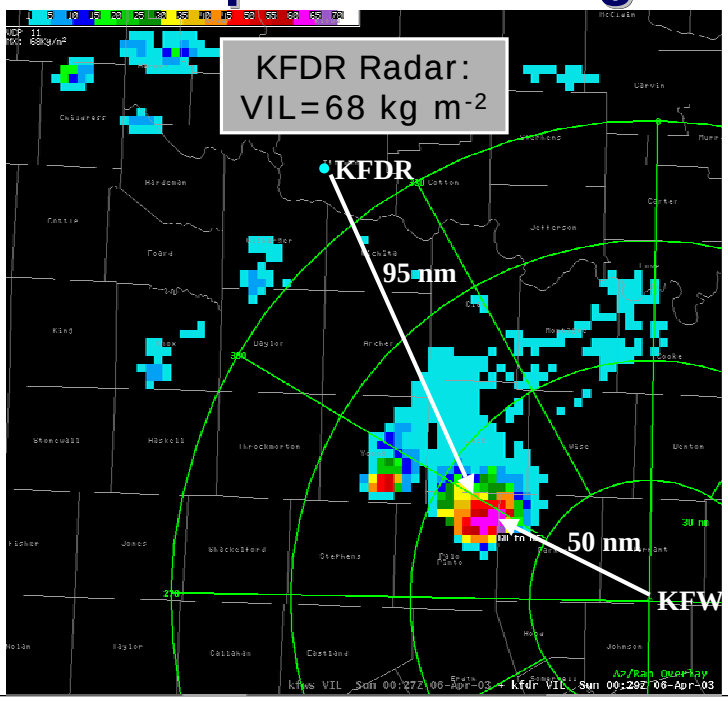
All thresholds only apply to the old “low res” VIL product. The new, high res VIL product is computed completely differently and new thresholds will have to be established. As will be shown shortly, 8-bit VIL values are much higher than the old 4-bit because they are not truncated at any upper limit.

Example: VIL Range



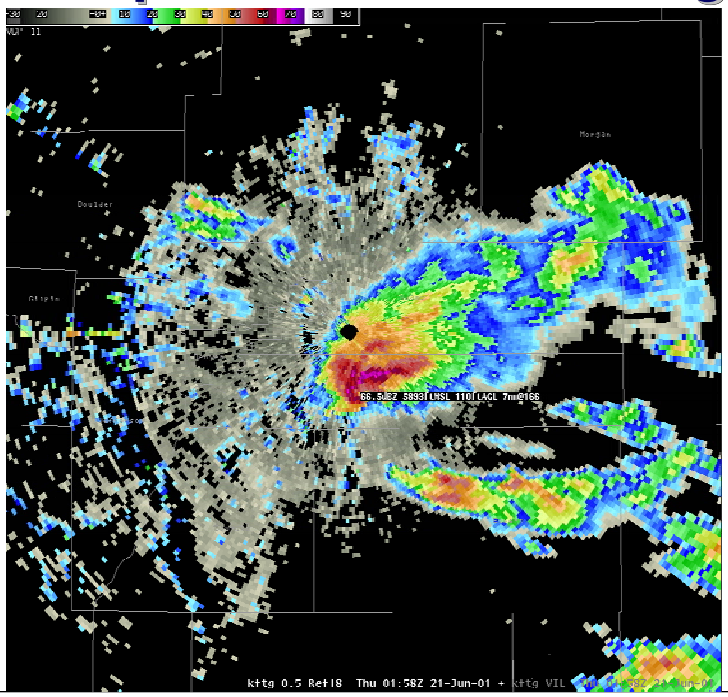
This and the following image displays the problems of VIL with range. In this particular case the storm was close enough to KFWS to get a better VIL measurement, but that will not always be the case across the country, as just 80 nm from a radar can really hurt the derivation of VIL. It should also be noted that storms very close to the radar will also have very unrepresentative VIL values. Baseball hail was falling out of the storm in Palo Pinto County. This particular supercell had a history of softball hail as well.

Example: VIL Range



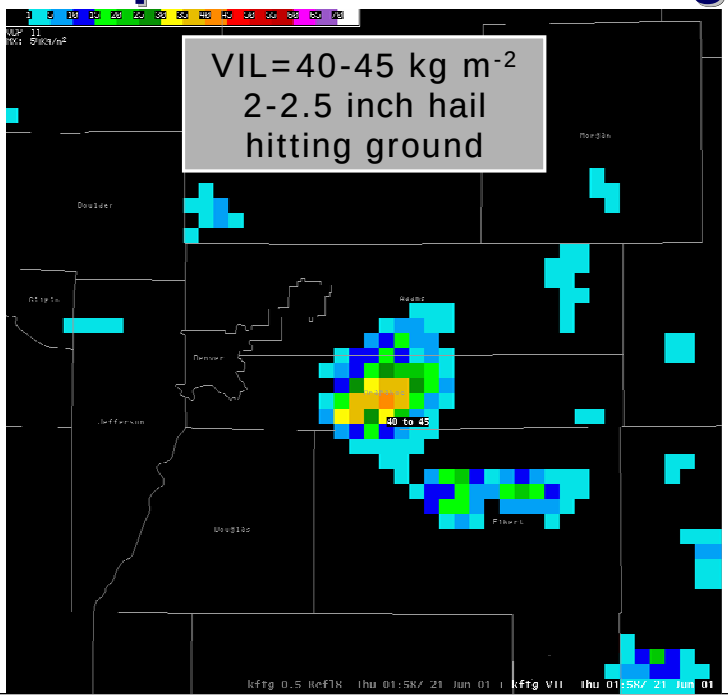
Here is Frederick radar at almost twice the distance to the storm as Ft. Worth, with much higher VIL values. That is typical of storms far from radar, as VIL is typically overestimated.

Example: VIL Close Range



This and the following radar image are taken just a few minutes after KFTG radome got pelted with 2.25 inch hail. 2 inch hail is pounding central Arapahoe County and Watkins right now.

Example: VIL Close Range

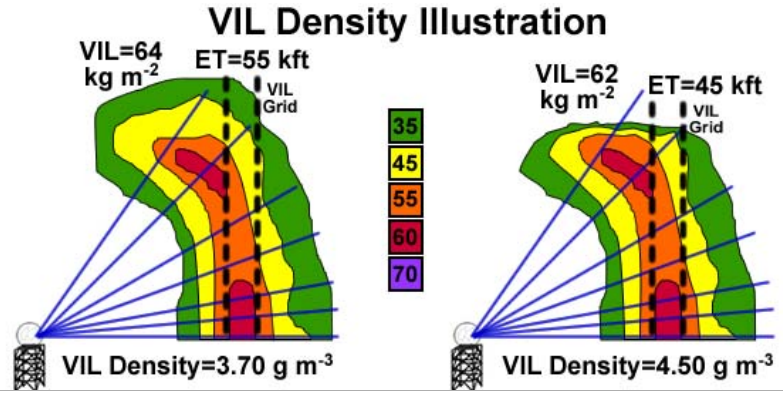


The storm is so close to the radar VIL is useless, with just 40-45 max indicated in spite of 70 dBZ at 100 feet off the ground. Any storm closer than 20-30 nm of the radar is going to have VILs that are lower than reality.

VIL Density

VIL Density= (VIL/Echo Tops) x 3280

- As VIL density increases, the hail cores tend to be deeper and more intense in the context of the storm. Unless:



•Remember that the echo tops product is capped at 18 dBZ

•3280 is the metric conversion from the kft echo top product

•In this hypothetical case, the reflectivity is packed near storm top, leading to a much higher VIL density. However, which storm is really more severe? Though VILs are nearly the same, the storm on the left extends much higher into the atmosphere, and thus at this time would pose a greater threat.

VIL Density Chart

Echo Top (kft)														
	70	0.70	0.94	1.16	1.40	1.64	1.87	2.10	2.34	2.57	2.81	3.04	3.27	3.51
	65	0.75	1.01	1.26	1.51	1.76	2.02	2.27	2.52	2.78	3.02	3.27	3.52	3.78
	60	0.82	1.09	1.36	1.64	1.91	2.18	2.45	2.73	3.00	3.27	3.55	3.81	4.09
	55	0.89	1.19	1.49	1.79	2.08	2.38	2.67	2.98	3.27	3.57	3.86	4.17	4.46
	50	0.98	1.31	1.64	1.96	2.29	2.62	2.95	3.27	3.60	3.93	4.26	4.58	
	45	1.09	1.45	1.81	2.18	2.55	2.91	3.27	3.64	4.00	4.36	4.73		
	40	1.23	1.63	2.04	2.45	2.86	3.27	3.68	4.09	4.50	4.91			
	35	1.41	1.87	2.34	2.80	3.27	3.73	4.21	4.67	5.14				
	30	1.64	2.18	2.73	3.27	3.82	4.36	4.91	5.46					
	25	1.96	2.62	3.27	3.93	4.58	5.23	5.89						
	20	2.45	3.27	4.09	4.90	5.72	6.54							
	15	3.27	4.43	5.46	6.55	7.64								
		15	20	25	30	35	40	45	50	55	60	65	70	75

VIL (g/kg)

1. VIL Density ≥ 3.5 has a 90% POD.
2. VIL Density ≥ 3.27 is a minimum threshold for 3/4 inch hail and works best for fast moving storms.
3. VIL Density ≥ 3.9 works best for slow moving vertically stacked storms.
4. In general, the greater the VIL Density the larger the hail size.

The thresholds listed above do a decent job for hail warning decision making with deep, moist, continental convection, especially when combined with reflectivity structure and heights of the strongest reflectivity in relation to the freezing, -20ºC, and EL. Again, with the advent of the new high res VIL product, this chart will have to be modified.

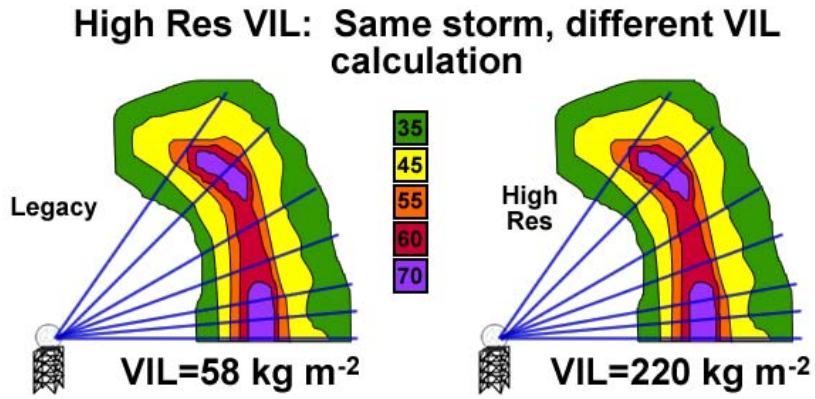
VIL Density

- Still depends on usefulness of VIL itself
- Edwards & Thompson (1998) found VIL Density unreliable because:
  1. Imprecision of ET product
  2. Differences in hail climatology
  3. Regional variances of the WSR-88D SWP algorithm

VIL denstiy depends on VIL, which all by itself is not a good way to determine the hail threat of a storm. Edwards and Thompson did an extensive study of over 400 hail events all across the country, and found both VIL and VIL density unreliable for severe hail detection and interrogation

High Res VIL

- No studies yet with warning thresholds, but calculation different than the legacy VIL
  - No upper or lower reflectivity truncation



Looking at the new 8-bit VIL product with hypothetical storms, two identical storms, 2 very different VIL values because of the lack of truncation in the new 8-bit product. The values you see displayed on D2D use the same color scale and values as the 4-bit legacy VIL product and **caps the values at 80 kg/m2**, so you aren't likely to see these types of values displayed graphically in D2D. The problem that arises is that most deep convective storms will have about 80 kg/m2 VIL, so this product isn't useful at all for hail threat diagnosis.

VIL / VIL Density Summary

- These products are not very useful in the context of hail detection when compared to base data and the HDA
- Understand VIL/VIL density limitations: distance to radar, environment, resolution, storm motion
- VIL of the Day? No way

VIL of the day struggles in that VIL is still used with it's many drawbacks, and then add to the fact that different environments can and typically do exist within the same radar umbrella on the same day, different storm structure can result in different hail threats even with similar VILs on the same day.

Investigate On Your Own

- Check out how VIL works for yourself:

  Click Here

  – Or enter into any browser window:
  http://wdtb.noaa.gov/courses/awoc/ICSvr3/jobsheet.html

This link takes you to the HDA/VIL jobsheet exercise. It's very informative.

Storm Interrogation

AWOC Severe Track

ICSvr 3-V-C

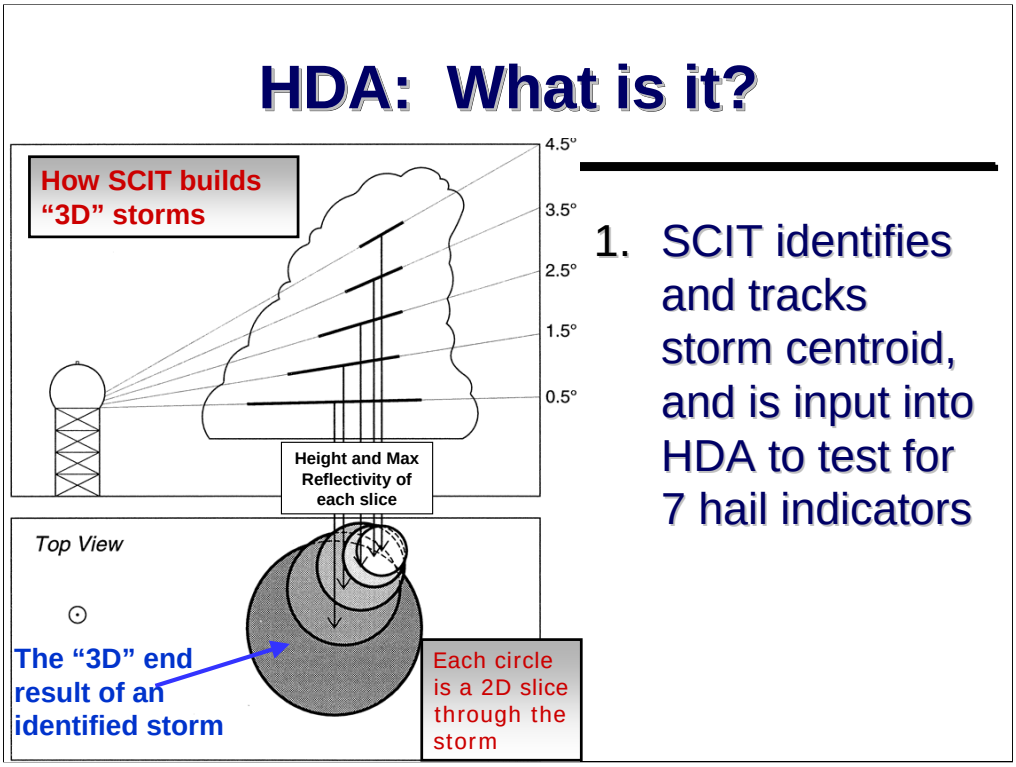
The Hail Diagnosis Algorithm (HDA)

NSSL is recommending a change in the name of the “D” in HDA, from Detection to Diagnosis, since single polarized radar can’t really “detect” hail in a storm, it can only be inferred or “diagnosed”

The HDA

Objectives:

- Understand how the HDA produces severe hail probabilities and sizes
- Know how to best utilize the HDA, including ways to improve upon it



SCIT looks at the height and maximum reflectivity for each slice (top portion of the figure), stacks these regions of maximum reflectivity, giving a 3D depiction of an identificed storm (bottom portion). This 3D depiction is input into the HDA

HDA: 2. Severe Hail Index

- 2 Weighting functions to determine severity of hail *aloft* (SHI):
  1. *Reflectivity* weighted, adaptable with upper and lower defaults set at 40 and 50 dBZ
  2. *Location* of reflectivity weighted, with ORPG HCI 0°C and –20°C height inputs

- SHI=severe hail index.
- Cell based rather than grid based, much better computationally with fewer data artifacts
- Upper and lower defaults delineate what is taken to be hail and what is taken to be rain. For example with the defaults, anything less than 40 dBZ is taken to be rain, while anything greater than 50 dBZ is taken to be hail (all of this assumes temperatures above the environmental freezing level). Values in between are weighted in a linear fashion from near 0 at 40 to near 1 at 50 dBZ.
- The other weighting function looks at the location of the reflectivity. Anything located below freezing the function is set to 0. Anything above –20°C and a max weight of 1 is given, thus any reflectivity that fits the first threshold is given full weight if above –20°C. In between 0 and –20oC it is again a linear weighting function with near 0 at 0oC and nearly 1 near –20°C.
- Thus, using the default settings, 50 dBZ at –20°C is given the maximum weighting possible, and anything below 40 dBZ or 0oC is given no weight at all in the SHI

HDA: 3. POSH

- Uses empirical probability formula with SHI and "warning threshold" (WT) selection model

  -- WT incorporates the height of the hail core MSL relative to the ORPG 0°C and –20°C input heights

POSH=Probability of Severe Hail. POSH has many different threshold values with which to warn/not warn, they are not worth mentioning. Every office may have a different threshold that they like to use.

HDA: 4. MEHS

- Maximum expected hail size (MEHS) employs an empirical formula with SHI the only input
- Tends to overpredict at smaller hail sizes (melting not accounted for and verification efficiency issues)
- Again, can be used as a consistency check and to assist in wording of your SVR/TOR

Most of the algorithms output depends on the accuracy of SHI

Newer versions of the HDA (EHDA) will incorporate melting using a variety of RUC inputs

Verification efficiency issues would be related to population density, undereporting of smaller but still severe hail, spotter quality, etc.

One of the biggest problems with FAR is that the largest hail within a storm is typically not reported because the area in which these fall are often extremely small even within the context of the hail shaft as a whole

HDA Usage

- Works best in the Central/Southern Plains and for significant hail events

- Useful to compare to base data as a consistency check
- POD generally greater than 80% for 1.00 inch hail in a nationwide study, although FAR also quite high
  - verification efficiency due to population density, Witt et al., 2000
  - POD over 90% for 2.00 inch hail

HDA is especially useful if you want to have a high POD and don't care too much about FAR even if it isn't the fault of the HDA, which is actually an okay thing concerning hail.

How to “beat” HDA

- Anytime SCIT misidentifies the vertical structure of a storm (strongly tilted)
- Knowledge of storm structure (meso, divergence, convergence, etc.)
- HDA needs a full volume scan of data before computing statistics
- When thermo. Environment characteristics change quickly or vary widely across radar umbrella

The HDA does not directly handle melting, which we showed in Severe IC1 that smaller sizes are highly affected by melting. Thus in areas with very moist environments HDA will overpredict sizes and POSH

•You can write a warning and send it out after viewing the bottom 2 radar scans in the time it takes the HDA to produce statistics from that volume scan

•Of course, with VCP 12 that time is decreased to about 4 minutes now.

•Knowing that a storm has rotation (HDA can’t account for that), BWER, other supercell characteristics is useful, especially in the early going before the hail cores really develop

Investigate On Your Own

- Check out how the HDA works for yourself:

  Click Here

  – Or enter into any browser window:
  http://wdtb.noaa.gov/courses/awoc/ICSvr3/jobsheet.html

This link takes you to the HDA/VIL jobsheet exercise. It's very informative.

Storm Interrogation

AWOC Severe Track

ICSvr 3-V-D

Hailstorm Characteristics

Hailstorm Characteristics

Objective:

- Recognize the following radar signatures of severe hailstorms and understand the limitations of the data.
  - Reflectivity height
  - Convergence/Divergence
  - Storm structure

Large Hail

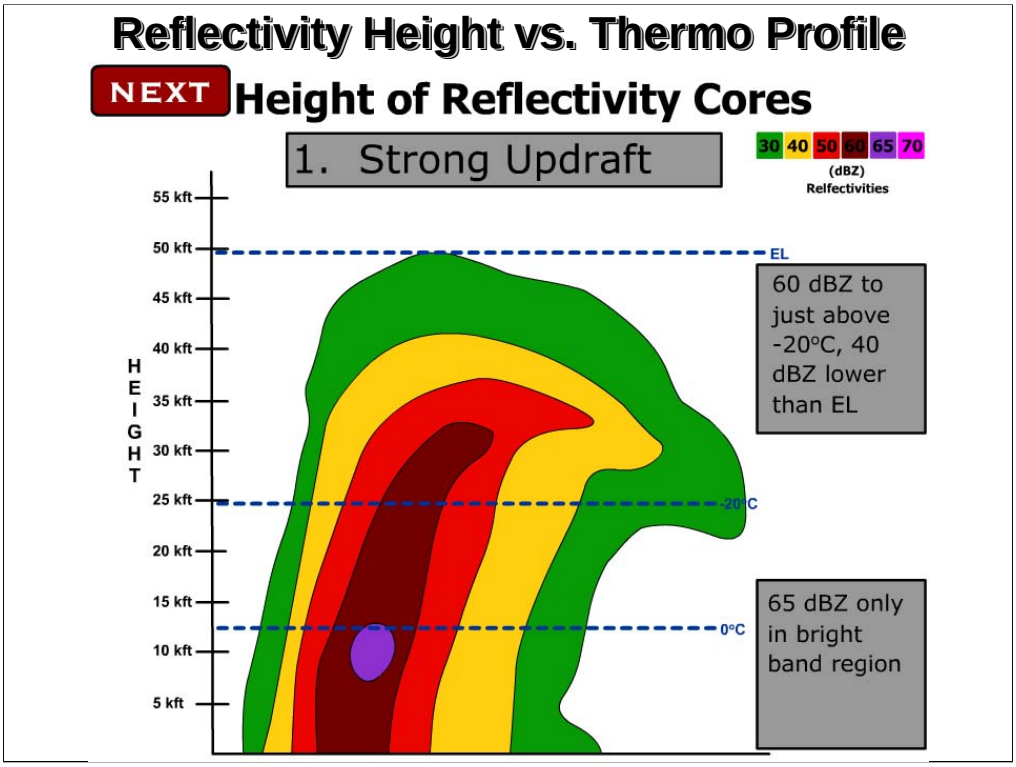
- WSR-88Ds very rarely directly observe the presence of large hail
  - We rely on storm structure and inferred hail signals to diagnose a particular storm's hail threat
  - HDA to see if we are missing something

Hail Considerations

- Updraft strength (covered in other lessons)
  - Height of strong reflectivity in relation to 0ºC, -20ºC, EL
  - Storm top radial divergence, low level radial convergence
- Updraft persistence
- Supercellular storm structure
- Derived products: HDA best of these

These are the 4 areas to examine for the severe hail threat.

•Updraft strength was covered in an earlier lesson, but with regards to hail, it is important how high above the freezing level, -20, and EL strong reflectivities extend. Velocity signatures for updraft strength with regards to hail include radial divergence in the upper levels and convergence in the lower levels.

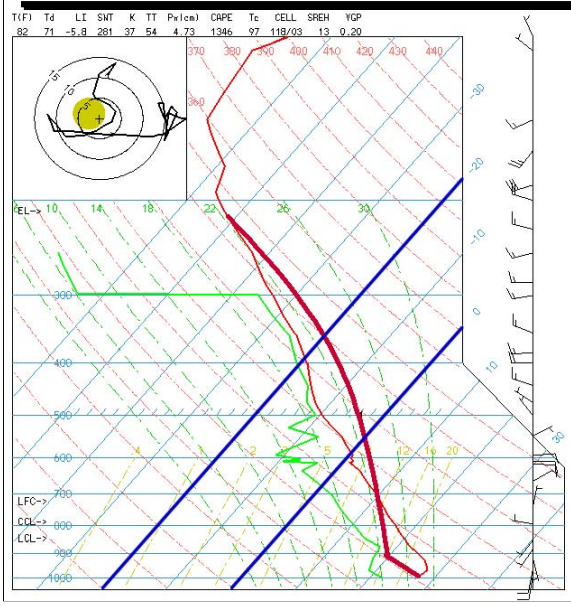


If used properly, can be the most reliable since it depends only on base data. Higher Z aloft had to be transported by some mechanism: That mechanism is a stronger updraft. The greater the Z aloft above the –20°C, the greater the hail threat. This assumes accurate knowledge and representation of the NSE thermodynamic profiles. 65 dBZ is particularly important in that studies have shown that nearly all storms that have > 65 dBZ above the 0°C go on or are in the process of producing severe hail OR winds. One of the problems with this technique, and as it turns out, with any hail forecasting technique, is that the lead times widely vary. Sometimes the strong cores develop aloft simultaneously with severe hail at the ground, sometimes there can be as much as 30 minutes lead time from strong core development aloft and severe hail at the ground. Dual-pol radar should help out here.

Reflectivity Height

- A recent study (Gerard 1998) of 39 convective events (64 storms total) in CLE and JAN: 96% of storms with 65 dBZ height above FRZ were severe (wind or hail or both)
  - 30% of the storms with 65 dBZ max heights below FRZ were severe
- Waiting for 65 dBZ also a bad idea since storm could already be severe before 65 dBZ core develops

Example



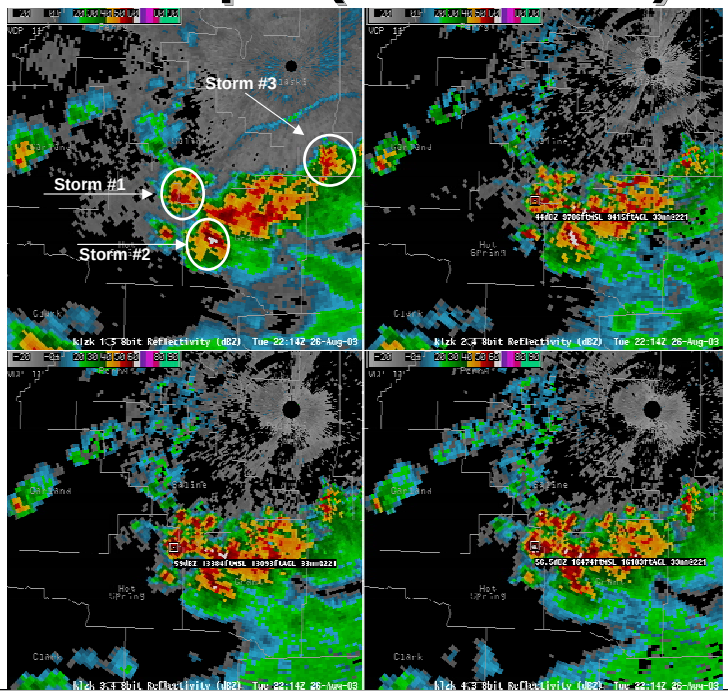
- FRZ = 15.3 kft
- WBZ = 13.0 kft
- EL ~ 42 kft
- LCL = 5.3 kft
- -20°C = 27 kft (surface parcel)
- No rotation potential

This is an example of hail production potential good for single cell with a pulse mode of convection. Looking at this sounding, several things stand out concerning the hail threat:

•Decent CAPE profile, plenty of low level moisture, cloud bases well below freezing for liquid drop production for embryos, lots of CIN, very little wind shear through any layer

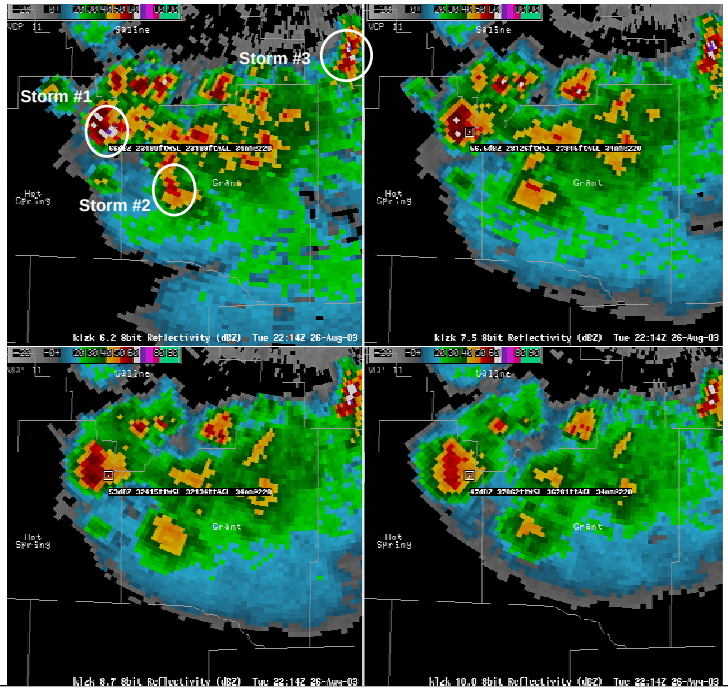
•Melting potential in this sounding appears **very high**: very high WBZ, FRZ, VERY moist in the low levels, fairly warm in the low levels. But remember what you learned in IC severe 1 Lesson 5 Hail, if you have large hail aloft, the large hail will still make it to the surface fairly large. The next slides are radar images from this day.

Example (Lower tilts)



Focus on the three storms circled in the upper left panel. Storm 3 is very close to the radar.

Example (Upper tilts)



•Storm one has a strong core aloft, with well over 50 dBZ to 37 kft (lower right), 43 dBZ at 50 kft (not shown), and 65 dBZ near the –20C level, and is in the mature phase. Golfball hail was indeed reported with storm #1 15 minutes from this image and the HDA had a good handle on it with a max size of 2.00 inch hail, POSH 70%.

•Storm 2 is just as deep at storm #1, but the core right around the –20C level is weaker as it had descended during the previous scans, as this storm is in the decaying stage. Just one volume scan ago this storm looked just like storm 1 looks now, with 67 dBZ at –20C. Golfball hail is falling right now out of this storm, and the HDA has 1.5 inch hail max with 60% POSH.

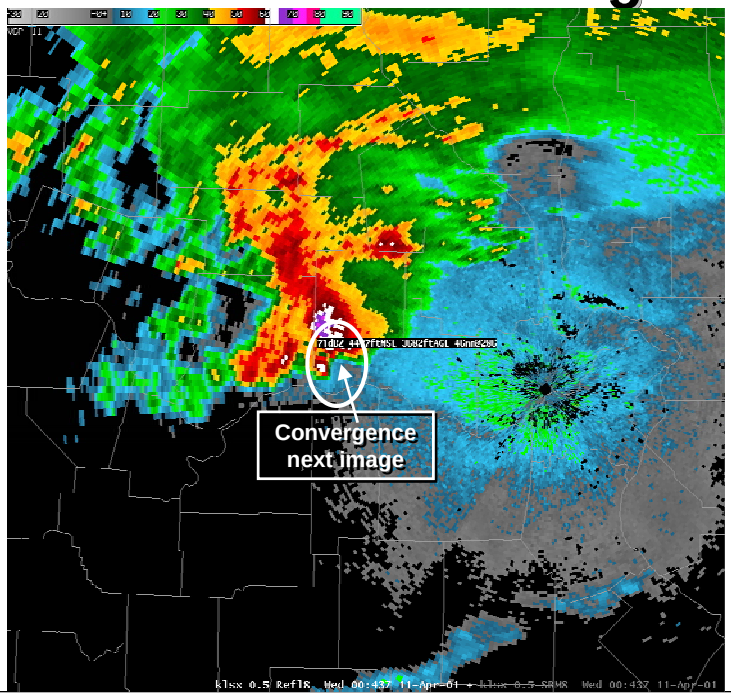
•Storm 3 has 40 dBZ to 40 kft (not shown) at the highest available tilt. This storm is not as deep out there although the max reflectivities (60-65 dBZ) are below the 0C level. Like storm 2, this is in the decaying stage. HDA has 1.00 inches right now, with a POSH of 40%. No hail was reported with this storm, although that could be due to the core being over rural Pulaski County.

Moral of this example?: shows that even in a warm, moist, summertime environment large hail is still possible if the large hail signature is there (deep cores, high Z around –20C). Severe hail can and will reach the surface.

Updraft Signatures: Velocity

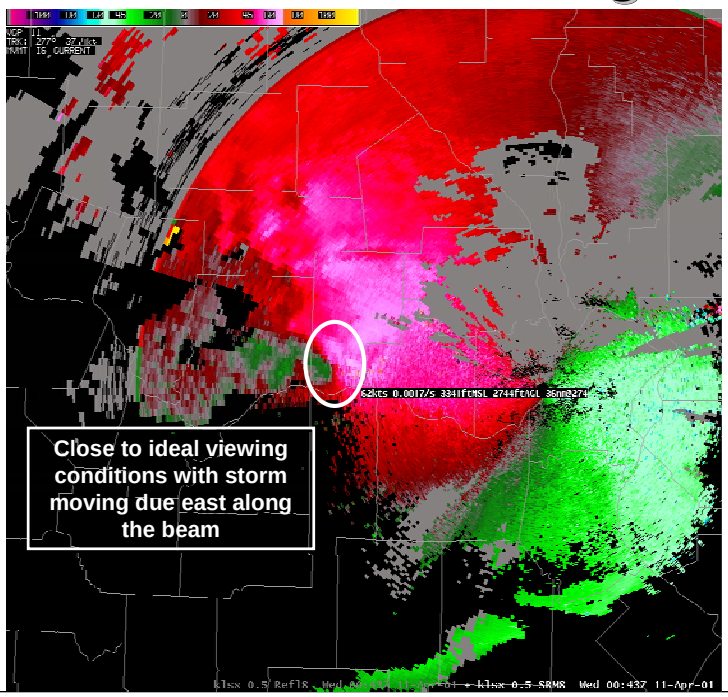
- Refer to updraft strength section in IC Severe 3-II (lessons 5-9)
- Problematic: due to viewing angle, dealiasing, range folding, range from radar, etc.
- Seeing either signature should only validate what you may already know: the updraft is very strong and the hail threat is enhanced

Ex: Low Level Convergence



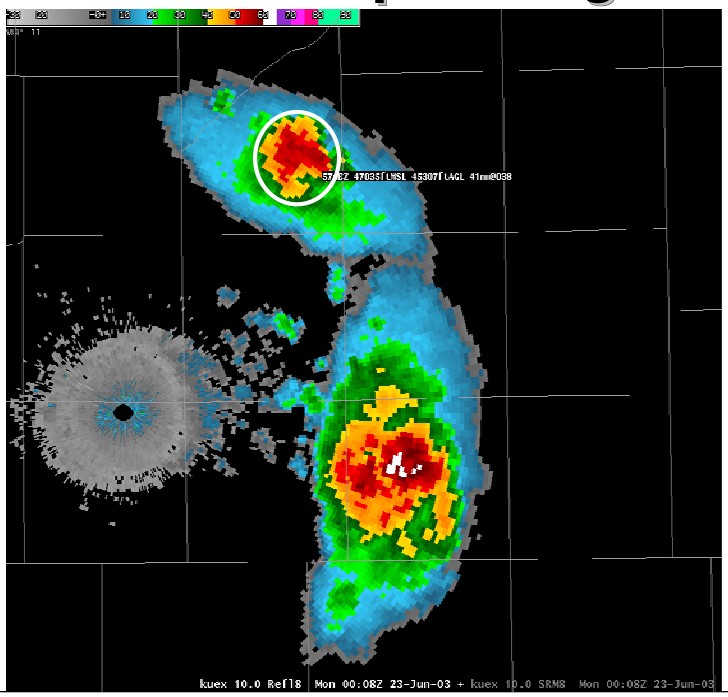
This is the hybrid multi-supercell hailstorm monster that hit KC to Columbia to St. Louis, all within a 5-6 hour period. This first image is of 0.5 degree reflectivity that should be used to compare to the next image, SRM to see placement of low level convergence.

Ex: Low Level Convergence



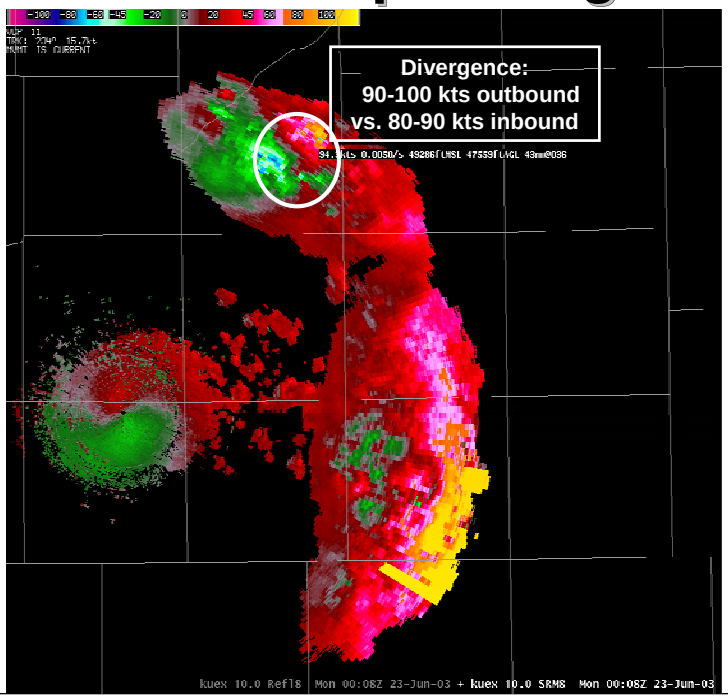
The circle is in the identical position from the previous image. It had a DCZ.

Ex: Storm Top Divergence



This reflectivity image is near the top of the BWER and near the storm top as well. Not related to the issue of storm top divergence, but this is just about the highest occurrence of 55-65 dBZ I have seen (45-50 dBZ to 56 kft with these 2 supercells as well).

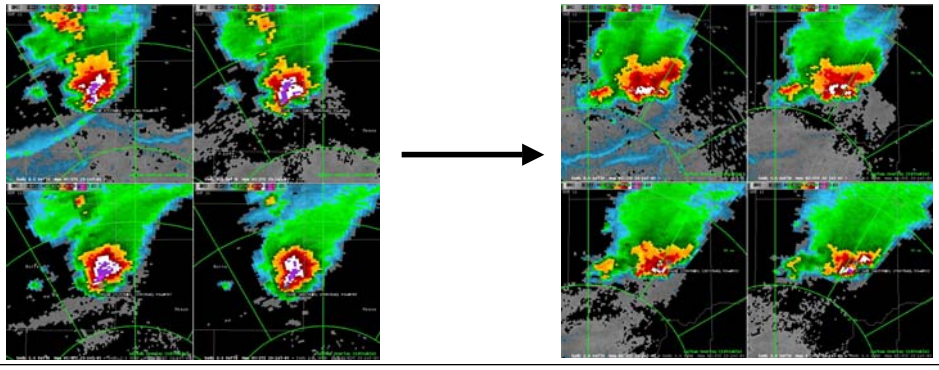
Ex: Storm Top Divergence



There are some dealiasing problems with the southern supercell. You aren't likely to see divergence of this magnitude on any storm, this is just about as strong as it gets.

Updraft Persistence: Considerations

- Investigate the longevity of the updraft signatures
- The consideration lies in the fact that updraft signatures that last longer than ~20 minutes could allow for longer residence time, more recycling, etc.



There have been no studies showing the importance of having a persistent updraft. In theory, a persistent updraft could have sufficient time to have multiple recycling trajectories across and through the updraft, leading to a greater chance of severe hail.

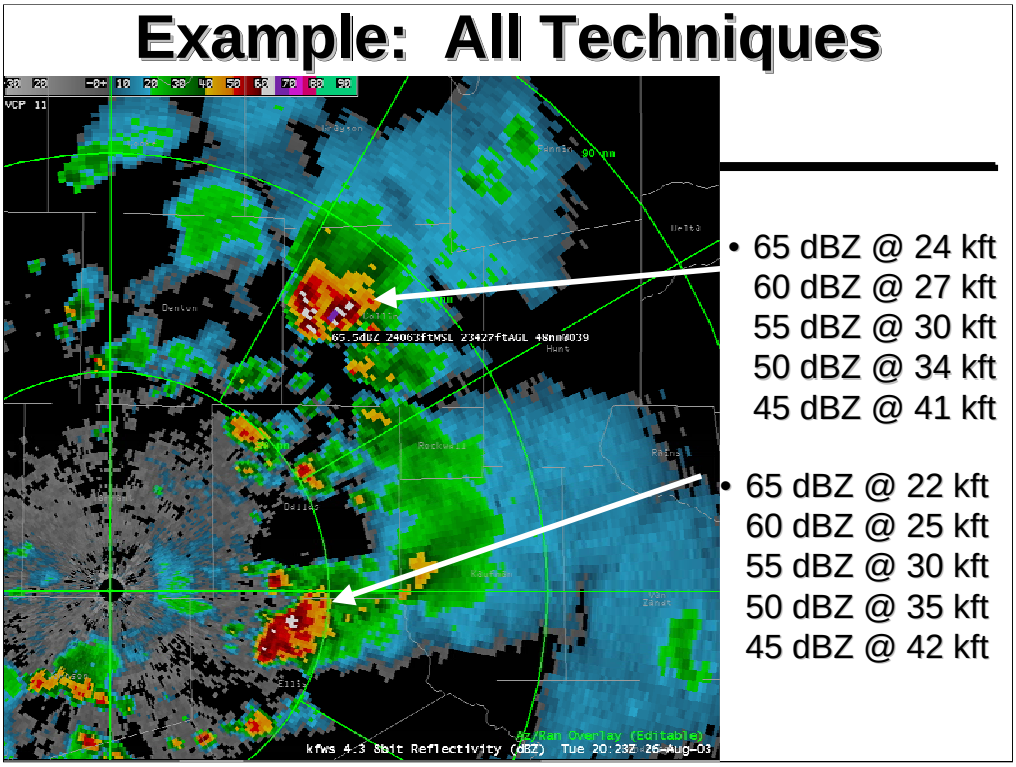
Storm Structure

- WER, BWER, mid-level mesocyclone, inflow notch, low level strong reflectivity gradients: all good indicators of the potential for strong updrafts and thus severe hail
  - As long as supercells are not low-topped (examine the reflectivity above -20°C level), any storm with supercellular structure has the capability to produce severe hail

Most of these signatures indicate supercellular structure, which is responsible for the majority of truly giant hail.

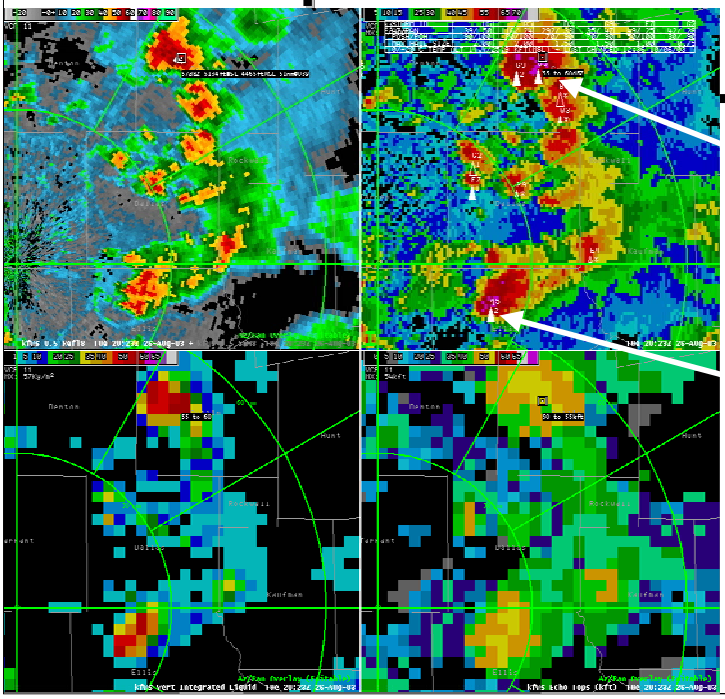
Storm Structure

- Even subtle supercell characteristics (i.e. weak rotation in mid-levels) can make a huge difference in hail size
  - See the next example:



Same day as 1st example in AR, this one near DFW. This area had similar environments with 0ºC level at 14.5 kft and –20ºC at 26.5 kft, very little vertical wind shear. We are looking at pulse storms in Colllin and Ellis Counties that have fired along a westward moving gust front. This environment should be good for VIL since storm movement is less than 10 knots. The 4.3 degree slice hits the Collin County storm right around the –20ºC level, while in Ellis County it is at around +3ºC. Heights of the respective reflectivity levels are given above for each storm. The Ellis County storm has a 45 knot shear gate to gate mesocyclone at 15 kft, while the Collin County storm has no rotation at all.

Example: All Techniques



- HDA: 2 in
  VIL: 55-60
  VIL/ET: 3.5
  No rotation
- HDA: 2 in
  VIL: 55-60
  VIL/ET: 3.7
  some rotation

POSH 90% on storm in Collin County (north storm), 80% in southern storm, certainly enough to warn on for hail alone in either storm

Event Summary

- Collin County (north storm) had no hail but damaging winds
- Ellis County (south storm) had 0.88 inch hail reports

→ Subtle differences can make a difference (like the presence of weak rotation), but there are many storm scale aspects concerning hail we cannot measure with our current instrumentation

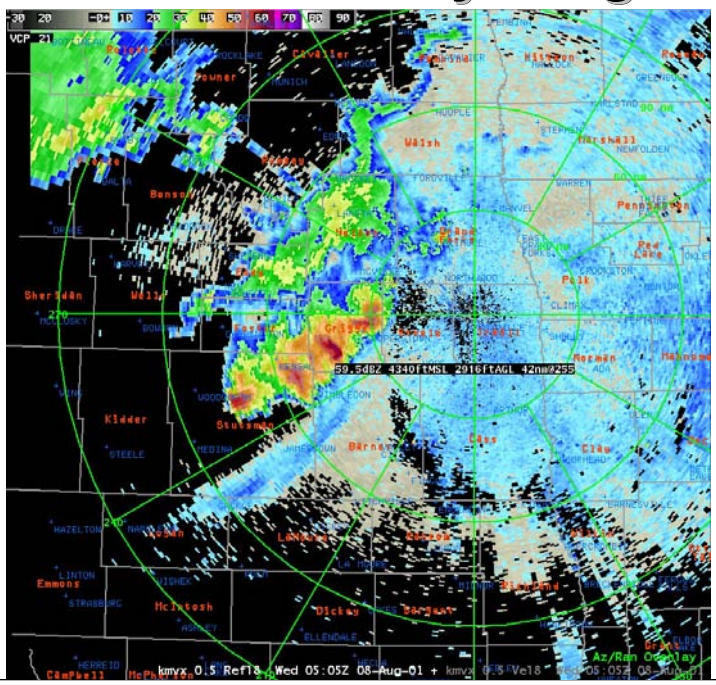
The Collin County storm “should have” had hail reported but did not. It is possible decent hail fell and went unreported despite the fact that the core fell over a highly populated area.

Multicell/MCS Considerations

- Same interrogation strategies apply: height of reflectivity in relation to –20, 0°C heights, erectness of updraft, rotation in mid-levels, then consistency checks with HDA
- Linear systems tend to have larger hail earlier in their lifecycles, especially before convective line becomes solid

Derechos and bow echoes may be enormous wind producers, but they can still produce very large hail and need to be monitored as such. Once systems become linear updrafts are far more tilted, forward speed increases, and residence time within the updraft is dramatically decreased, all leading to smaller hail sizes. Embedded rotation can mitigate these effects however, by further increasing residence time.

Multicell: Early Stage



Golfball to baseball hail out of this developing derecho at this time (midnight local). Had very high Z aloft in a very high CAPE environment and some mid-level rotation. Once the storm organized into a linear system with raging surface winds, the hail was never larger than 1.00 inch.

Summary:
Large Hail Radar Interpretation

- At long range from the radar certain updraft characteristics may not be well resolved
- Understand data limitations, especially far from radar and/or with fast moving systems
- Usage of velocity signatures depend on range from radar and on viewing angle

Storm Interrogation

AWOC Severe Track

IC3-VII-A

Hybrid/wet microburst detection

Welcome to the

AWOC Severe Track

IC3-VII-A

Hybrid/wet microburst detection

This session is 20 slides long and may take 20 to 25 minutes to complete.

Hybrid/wet microburst detection

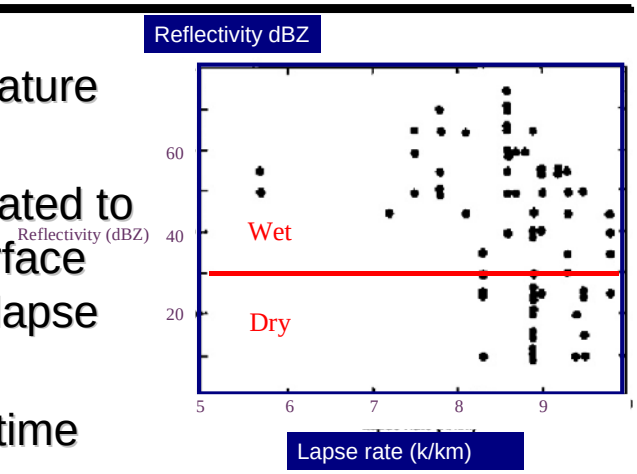
- Objective
  - Determine which microburst precursor signatures give
    - The most lead time
    - The highest probability of detection
- Motivation
  - Need to limit initial missed detections

The one objective of this lesson is to show which stormscale precursor signatures give you the most lead time and the highest probability of detection of wet and hybrid microbursts. The motivation for this session is to limit missed detections of the first microburst producing storm of the day and then increase the leadtime of all following microburst events.

We will limit ourselves to mostly stormscale signatures within the context of the environmental sounding.

Environmental consideration

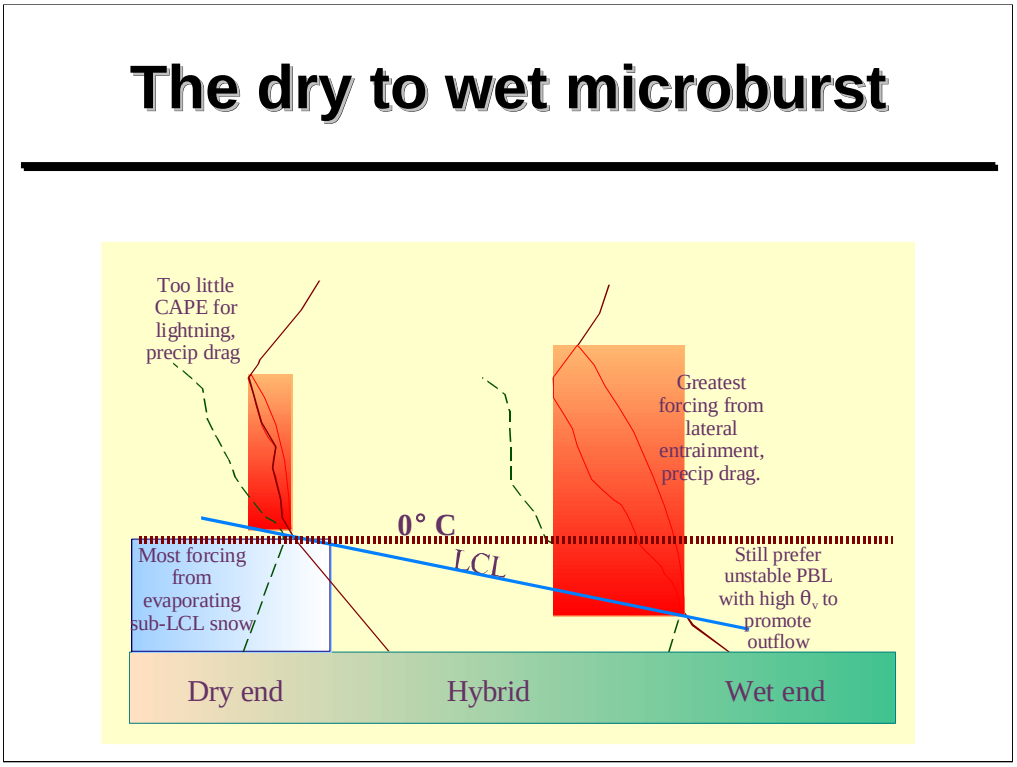
- Environmental precursor signature
- Microburst occurrence related to near storm surface to cloud base lapse rate
- Greatest lead time



Wet microbursts imply significant precipitation (>.01") associated. Srivastava (1985)

The first step in improving leadtime is recognizing the favorable microburst environment.

Srivastava 1985 plotted the surface to cloud base lapse rates versus the microburst reflectivity at 500m AGL for a population of low shear pulse storm microburst events. He found that no microburst events occurred with a lapse rate less than 5.5° K/km and most microbursts prefer greater than 7° K/km. Note that dry microbursts (microbursts with almost no surface precipitation) require a nearly dry adiabatic layer. All these microbursts were sampled during the JAWS project which took place east of Denver.



Microburst environments range the full spectrum with one end being dry, the other being wet.

Dry end microburst environments carry very little CAPE (< 500 j/kg), and extremely deep, mixed boundary layers

with LCLs near the freezing level and greater than 13000 ‘ AGL. In this case, both temperature and height coordinates

are important. Height coordinates are important because the higher the LCL, the more room for an accelerating downdraft

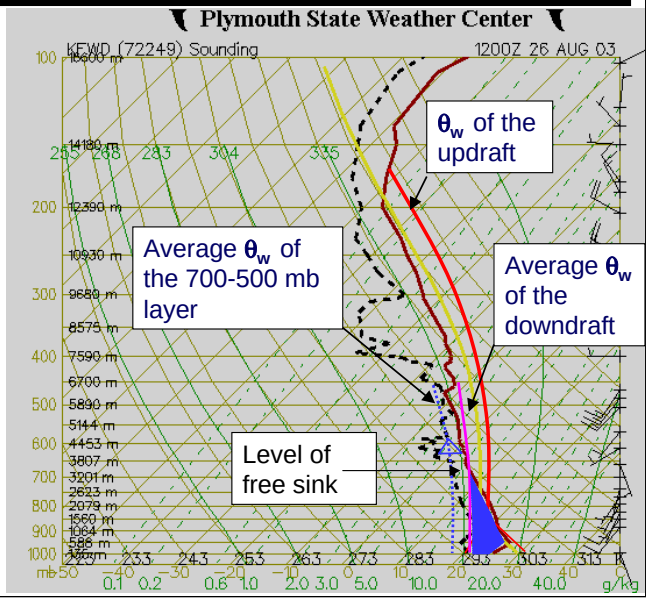
there is to reach severe speeds, DCAPE is larger. Temperature coordinates of the LCL are important only whether the LCL is higher or lower than the freezing level. If the LCL is higher, frozen hydrometeors become exposed to the subcloud air and you suddenly can add the latent heat of melting liquid to evaporation and increase the negative buoyancy of the downdraft. The downdraft forcing is almost entirely below the LCL and there is no significant precipitation loading. Maximum storm reflectivities are less than 35 dBZ in many cases.

Wet end microbursts feature significant CAPE and low LCL heights. These events feature large DCAPEs when midlevel dry air is present to act as a source of evaporational cooling when precipitation becomes mixes with the environmental air. The high CAPEs create intense reflectivities, and therefore, significant precipitation loading potential. Precipitation loading when reflectivities exceed 60 dBZ become as important as evaporational cooling. Look for wet microburst environments when there is a large θe difference between the surface-baesd updraft parcel, and the midlevels (3-6 km AGL). If you expect storms with 60 dBZ cores, precipitation loading becomes a big factor to consider. Most downdraft forcing occurs by lateral dry air entrainment in the midlevels, and very little comes from below the surface-based LCL. Surface based convection is highly favored for microbursts since you don’t want significant surface-based CIN.

Many environments favoring microbursts may have a little bit of both dry and wet microburst characteristics. Environments where significant CAPE resides above high LCLs (above

Wet microburst case 1

- The orange parcel is the best estimate for the afternoon Θ_w.
- Blue dotted parcel is the average Θ_w of the 700-500 mb environment
- Purple parcel is the best guess downdraft Θ_w
- Blue shaded area is the estimated DCAPE area



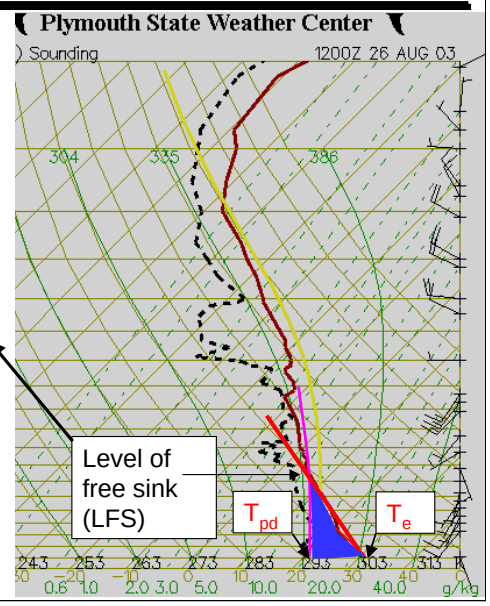
On 26 August 2003, the Dallas area is in the middle of a fairly active summertime convective period. You've probably seen this case presented before in the hail storm interrogation and in the sessions on locating pulse storm updrafts. The morning sounding modified for the afternoon temperature/dewpoint combination shows significant CAPE but somewhat marginal source of dry air, except for a layer that is typically too high to consider as a downdraft initiation level (400 mb). This sounding is not a classic high end microburst environment. We should have

Let's calculate what shape the DCAPE may look like. We'll assume that the downdraft air will have a mix of temperature and dewpoint between the updraft air parcel and the environment. As long as that's a safe assumption, we can visualize DCAPE as following:

1. First, we find a representative θ_w for the environment around the midlevels, say about 630 mb. The θ_w can be found at midlevels by launching the environmental air parcel using the temperature and dewpoint at that level and raising it to its LCL. Note the little blue triangle, the left vertex being the dewpoint at 630 mb, the right vertex being the temperature, the top vertex being the LCL. The point at the LCL is the θ_w at that level. I highlighted that θ_w as a dotted blue curve.
2. Then I launch the surface-based, or mixed layer parcel from the ground up and call it the updraft θ_w visualized as the solid red curve.
3. The mixed layer downdraft parcel should be somewhere in the middle, and I chose the magenta θ_w curve as the curve the downdraft will follow.
4. The negatively buoyant area for the downdraft is anywhere the downdraft temperature is lower than the environment. Note that there is a small layer just below my downdraft initiation level where the downdraft air is positively buoyant, and then it reaches the Level of Free Sink (LFS) where the downdraft is unobstructed from accelerating. The LFS is exactly analogous to the LFC for updrafts.

Wet microburst case 1

- Estimating DCAPE
- Find these
  - Surface environment temperature (T_e)
  - Expected downdraft surface temp (T_{pd})
  - Depth of negatively buoyant air ΔZ (LFS to sfc)
- DCAPE ≅ ½ $g((T_e-T_{pd})/T_e)\ \Delta Z$ (LFS to sfc))
- DCAPE ≅ ½ 9.81((304-297/304)3300m
- DCAPE ≅ 372 m^2/s^2
- Maximum W ≅ $(2*DCAPE)^{1/2}$ ≅ $(2*372)^{1/2}$ ≅ 27 m/s
- Downdrafts almost never realize the theoretical DCAPE because they are unsaturated



The DCAPE can actually be estimated by taking the afternoon surface temperature minus your theoretical temperature of the downdraft at the surface, dividing it by the environmental surface temperature and multiplying by the depth of the layer from the surface to the LFS (meters), multiply again by gravity (9.81) and divide by 2 since we're calculating the area of a triangle, not a parallelogram.

DCAPE =1/2 $g((T_e - T_{pd})/ T_e)\Delta Z$

I estimate the environmental T_e to be 304 K, The downdraft T_{pd} is about 297 K, ΔZ is the distance from the LFS down to the surface and I will put in 3300 m. Entering in those numbers, I get this:

DCAPE=1/2[9.81((304-297)/304)3300] ≅ 372 m^2/s^2

If an updraft has a hard time realizing all of its theoretical CAPE, a downdraft will practically never realize its full DCAPE. In order for my theoretical T_{pd} to be fully realized, my downdraft would have to be saturated. In other words, saturated descent would be required for my downdraft to follow the downdraft θ_w all the way to the surface. Observations show that downdrafts are almost never saturated. Therefore, we have to be realistic and perhaps cut the DCAPE by a factor of 2. But let's use the 384 m^2/s^2 to compare with later cases.

As an additional task, we can take the DCAPE and estimate the maximum potential downdraft velocity from evaporational cooling mechanisms.

Maximum W=$(2DCAPE)^{1/2}$ = $(2*372)^{1/2}$ = 27 m/s

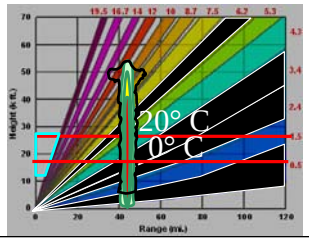
But if only half the theoretical DCAPE is realized, then Maximum W = $(2*186)^{1/2}$ = 19 m/s

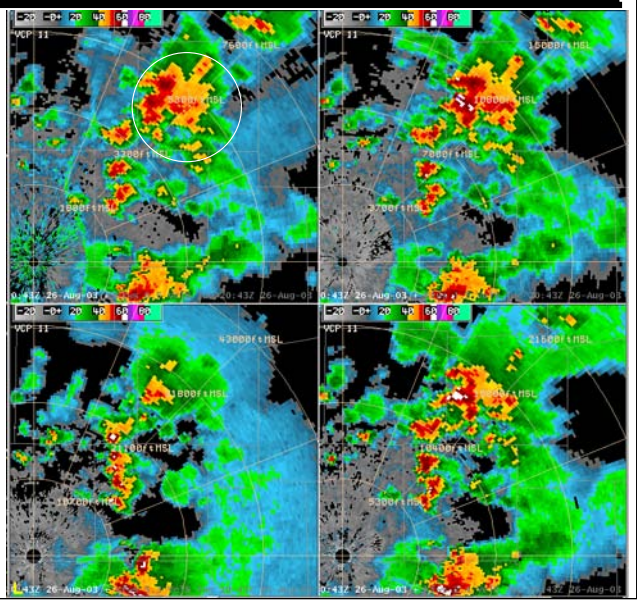
This downdraft strength is not likely to be very severe. However, we haven't considered:

- The precipitation loading factor to overall downdraft intensity. This will add further downward forcing to the evaporational cooling for which we calculated DCAPE.
- Potential changes in the environment

Example 1: FWS 26 Aug 2003

- Low shear multicell initiating on colliding boundaries

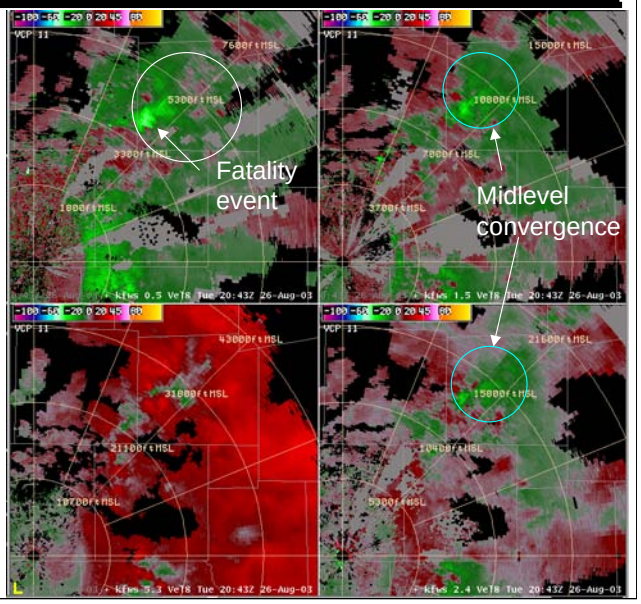


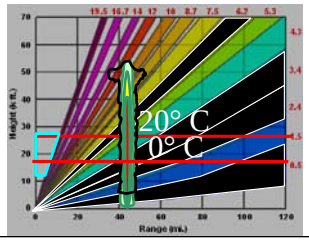


The multicell storm in question is inside the white circle. You may notice that the multicell is propagating down an outflow boundary merger with new cells forming on the southwest side of the complex. Strong reflectivities > 60 dBZ extend up to 21 kft in the storm just prior to 2043 UTC, the last frame of the loop.

Example 1: FWS 26 Aug 2003

- Well defined midlevel convergence forms

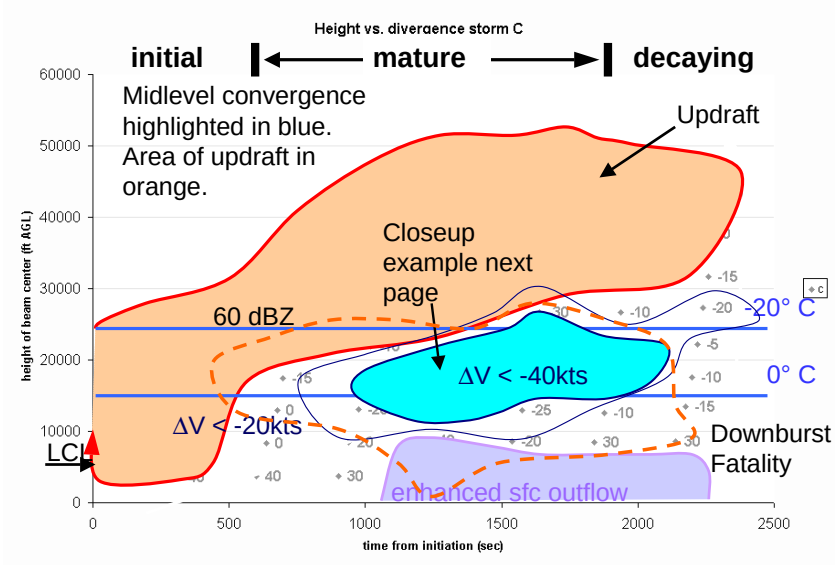




Note in the 4 panel velocity loop, the onset of strong midlevel convergence at 9000' AGL to above 15800' AGL just prior to the strong inbounds seen in the lowest slice (upper left). Weak midlevel convergence exists before with greater lead time to the surface downburst.

The strong winds at the surface were likely in existence for some time before it impacted the home construction site where the fatality existed.

Example 3 time-height velocity



I sampled the maximum reflectivity for each level of the storm, using new cells if they developed so close to the older ones that they were all one contiguous heavy reflectivity area.

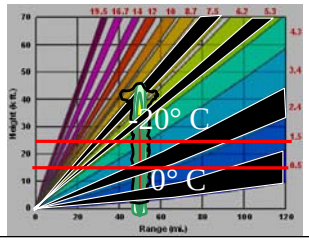
The first time height plot is of reflectivity.

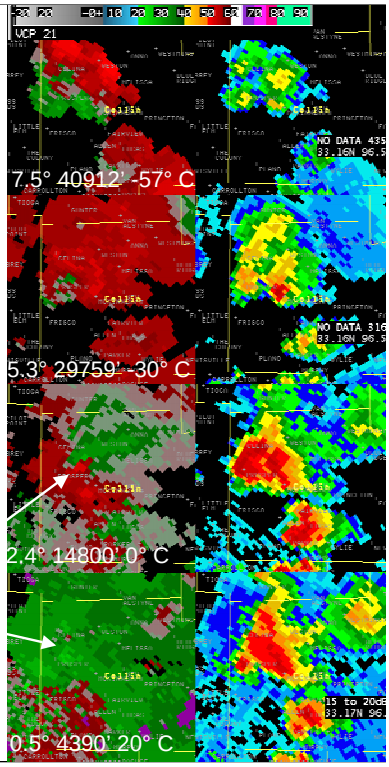
The next time height plot is the maximum velocity difference found within the bounds of the heavy reflectivity core. At the lowest slice (5000' AGL), there was strong convergence, mostly ahead of the precipitation core while divergence was found inside the core. I chose the divergence. At midlevels, I found strong negative velocity differences (convergence) in the core while divergence existed to some extent on either side. Midlevel convergence patterns are often complicated, sometimes the convergence axis being on the core edge. Perhaps that is not unexpected because of the complex nature of the cores themselves, and therefore, downdraft forcing mechanisms. The downdraft initiates, and the midlevel convergence follows.

Note that the midlevel convergence followed 5 – 10 minutes after the onset of > 60 dBZ reflectivities in the 0 to -20° C layer. Strong midlevel convergence < -40 kts appeared only 5 minutes before the onset of strong inbounds and divergence in the 0.5° elevation slice (4500' AGL). It was to be another 15 minutes before the fatality event. Several downburst surges probably occurred in this time span.

midlevel convergence

- Midlevel convergence is well detected here
- Damaging winds are quite possible here though the first report is 20 minutes later





This example shows very well the midlevel convergence at 14.8 kft AGL and near the freezing level right within the intense reflectivity core. Updraft is likely above this level but the midlevel convergence is likely a response to the downdraft already underway and beginning to show up as a divergence field at the surface. At this distance, the divergence at 4390' is nowhere nearly as strong as it would be had the radar sampled the lowest few hundred feet above ground.

Example 1: 26 Aug 2003

Precursor signatures in order of occurrence

Strong, large initial core, 55 dBZ 20 to 25 kft AGL (0 to –20 C) level:	leadtime = 10 – 15 min
Descent of high reflectivity's (>50 dBZ) to the surface:	leadtime = 5-10 min
Onset of midlevel 30kt convergence 12 – 20 kft AGL (0 to –10 C) level:	leadtime = 0-5 minutes

In this example, the 55 dBZ then 60 dBZ core appeared in the layer where we would expect initial downdraft formation, somewhere near the freezing level and just above. Downdraft forcing is likely occuring at lower levels too. Anywhere with midlevel convergence in reflectivity core, downdraft forcing is possible. The best leadtime is the onset of the strong core aloft, followed by the weak midlevel convergence, and finally, strong convergence (ΔV<-30 kts).

Example 1: 26 August 2003

- Large area of midlevel convergence in this large multicell event.
  - High magnitude convergence
  - Above the LCL suggesting lateral dry air entrainment and precipitation drag
- Best leadtime is earlier with strong elevated reflectivity after initiation

This event also had a large area of midlevel convergence. The convergence was strong and above the LCL suggesting that wet microburst processes were occurring, that is lateral dry air entrainment and precipitation drag.

Waiting till the onset of strong midlevel convergence before considering a warning will not give you any leadtime. But there will probably be a pretty low probability of a false alarm.

Example 2: 19 Aug 2003 LSV

- 19 Aug 2003
- Large CAPE implies big precip loading
- Larger DCAPE than with FWD
  - 1009 m^2/s^2
- Both combine to increase threat of downbursts

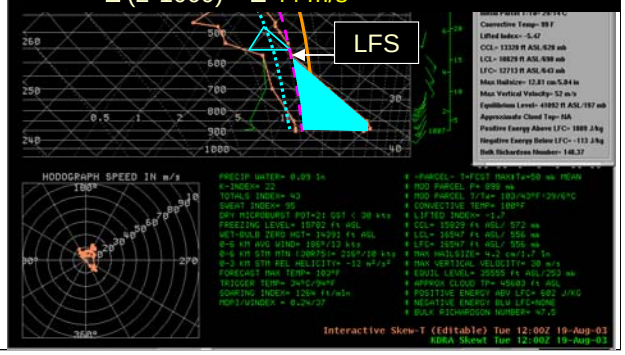
•DCAPE ≅ ½ $g((T_e-T_{pd})/T_e)\ \Delta Z$ (LFS to sfc)\

•DCAPE ≅ ½ 9.81((311-295/311)4000m

•DCAPE ≅ 1009 m^2/s^2

•Maximum W ≅ $(2*DCAPE)^{1/2}$

•≅ $(2*1009)^{1/2}$ ≅ 44 m/s



Now we go to the 19 August Las Vegas storm of 2003. All sorts of severe weather occurred on this day, including high winds.

Low-level monsoon moisture entered into the valley after this sounding was taken allowing for high CAPEs. The hot surface temperatures made sure that the LCL was high and that plenty of negative buoyancy would be available below.

1. Following the same method of visualizing the potential DCAPE area, launching a midlevel air parcel (note the cyan triangle) helps to

estimate the midlevel θ_w. Remember that there is a lot of flexibility as to what midlevel parcel height to choose for the θ_w.

2. Next, choosing a representative parcel at the surface gives us the updraft parcel θ_w in the orange curve.

3. Then the magenta dashed line represents an average of the two θw curves and that becomes our downdraft θ_w.

4. The DCAPE area occupies everywhere the downdraft θ_w is colder than the environmental temperature,

I estimate the surface environmental temperature Te to be 311 K, The downdraft surface temperature is about 295 K, the starting point of my downdraft is 4000 meters above ground.

Entering in those numbers, I get this:

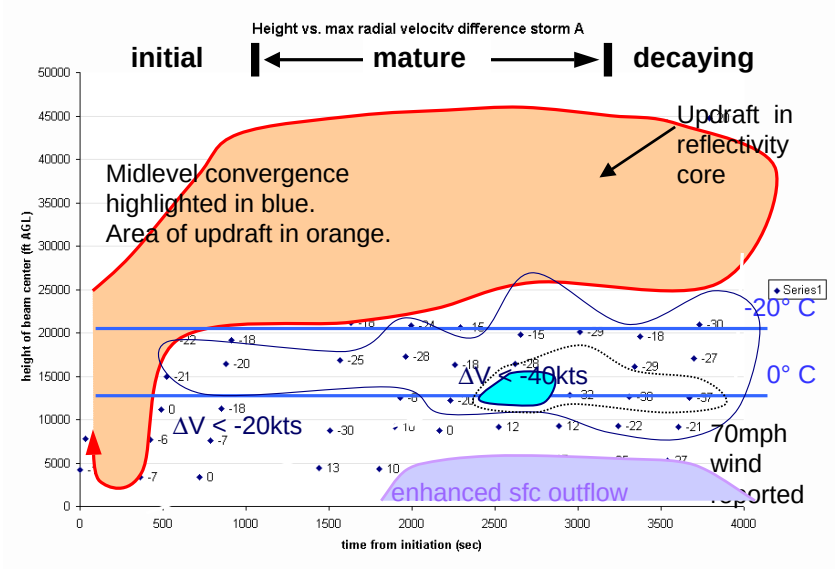
DCAPE ≅ 9.81((311-295)/311)4000/2 ≅ 1009 m^2/s^2

This value is larger than the Dallas event. Add big CAPE precipitation loading potential and the downburst potential is quite high.

Maximum theoretical W = $(2*DCAPE)^{1/2}$ = 44 m/s

Again, this is likely overestimating the potential some but the purpose here is to show the numbers are larger than for the Dallas microburst event.

LSV storm time-height reflectivity/velocity



I was still able to find several gates with < -40 kts of midlevel velocity difference. But for the most part, the midlevel convergence was narrow and fairly weak. The updraft appeared strong on radar throughout this event, with two main cells making sure some strong updraft was always present. Enhanced low-level divergence appeared about 15 minutes before the 70 mph wind was reported. Strong winds were likely occuring well before the wind report.

Example 2: 19 Aug 2003

Precursor signatures in order of occurrence

Strong, large initial core, 55 dBZ 20 to 25 kft AGL (0 to –20 C) level:	leadtime = >15 min
Descent of high reflectivity's (>50 dBZ) to the surface:	leadtime = 15 min
Onset of midlevel 30kt convergence 12 – 20 kft AGL (0 to –10 C) level:	leadtime = 0 minutes

The best leadtime was the onset of a large initial core > 55 dBZ above 20 kft AGL.

The descent of the high reflectivity core would give you about 15 minutes leadtime

The onset of –30 kt velocity difference at 12 – 20 kft would have given you nearly 0 leadtime to the onset of low-level divergence.

Example 2 summ: 19 August 2003 – Las Vegas

- Midlevel convergence is actually weaker except for one volume slice – no leadtime
  - Inflow into midlevel convergence may have been mostly tangential
- But larger DCAPE and stronger reflectivity core than Ft. Worth event suggests bigger potential for damaging downburst

This may be speculative but the axis of inflow into the downdraft at midlevels was possibly oriented in a way that prevented the radar from detecting it. Note that the long axis of the core is down radial. If the axis of convergence followed a similar orientation, then the inflow into the downdraft could be mostly tangential and hard to detect.

The strength of the core above the freezing level in conjunction with the environment should give you an idea that strong downburst would be likely once that core descended to ground.

Example 3: 12 Nov 2003 LAX

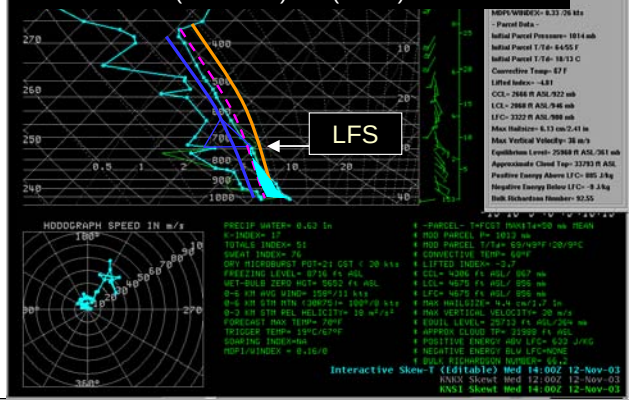
- Smaller CAPE, but high buoyancy (orange parcel)
- Small DCAPE (cyan shaded region)

DCAPE ≅ ½ $g((T_e-T_{pd})/T_e)\ \Delta Z_{\text{(LFS to sfc)}}$

DCAPE ≅ ½ 9.81((289-285/289)2400m

DCAPE ≅ 162 m^2/s^2

Maximum W ≅ $(2*DCAPE)^{1/2}$ ≅ $(2*162)^{1/2}$ ≅ 18 m/s



Contrast the Las Vegas and Dallas events with a cool season, low topped event. There is actually a fair amount of dry air and low θ_w air in the midlevels. CAPE is low only because the equilibrium level is low. Buoyancy or CAPE density is high relative to the total CAPE.

Putting the numbers in,

DCAPE ≅ ½ $g((T_e-T_{pd})/T_e)\ \Delta Z_{\text{(LFS to sfc)}}$

DCAPE ≅ ½ 9.81((289-285/289)2400m

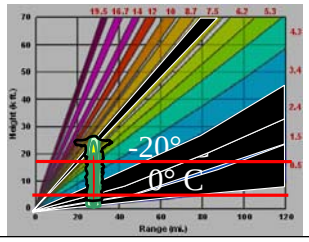
DCAPE ≅ 162 m^2/s^2

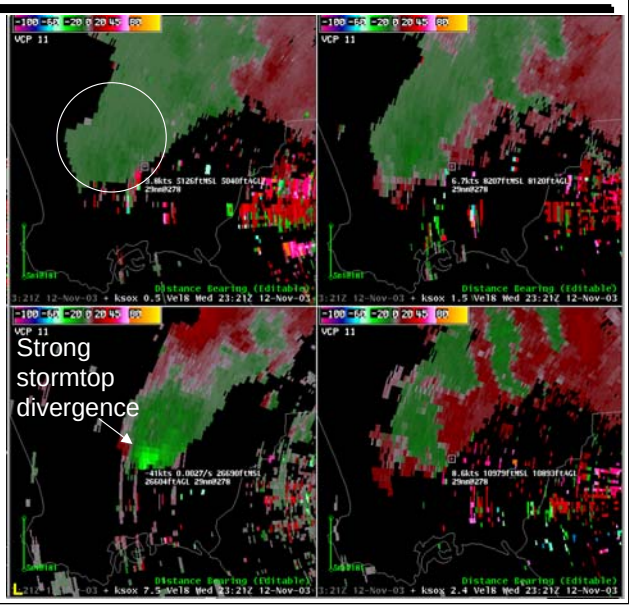
Maximum W ≅ $(2*DCAPE)^{1/2}$ ≅ $(2*162)^{1/2}$ ≅ 18 m/s

These numbers are small compared to the other two cases. Unless there is an exception, or precipitation loading is a big factor, or other downdraft forcing mechanisms are at work (e.g., Rear Flank Downdraft), then we don't expect severe downdrafts in this environment.

Example 3: 12 Nov 2003 LAX

- Midlevel convergence (ΔV) peaks at -30 kts at 2.4° (10 kft, -4° C)





This cell does have a midlevel convergence axis and a downdraft is being generated. The differential velocity across the convergence is weak, perhaps 25 to 30 kts. Reflectivities are high and precipitation could be a factor. However, several parameters work against a severe downdraft in this case:

1. Depth of the negative buoyancy is small and DCAPE is small
2. Weak midlevel convergence supports the idea that downdraft may not be strong.
3. Precipitation loading is there but the depth of its forcing is small too.
4. Lack of very strong horizontal environmental flow means no vertical mixing of horizontal momentum.

The last point is something not typically considered, however weak shear pulse convection can occur in strong wind environments. They do produce severe surface winds without strong downdrafts.

Example 3: summ 12 Nov 2003

- CAPE = 800 j/kg, DCAPE much smaller than first two cases
- > 60 dBZ core implying precipitation loading is significant but depth is small
- Midlevel convergence –30 kts compared to –54 kts for FTW case and –40 kts LSV case
  - Likely well sampled midlevel convergence based on orientation of its axis
- No severe wind reports

No severe winds were reported with the Los Angeles hail storm. The midlevel convergence appears well sampled with the axis perpendicular to the radials. But the values were weaker than for the other two cases. The depth of the convection was smaller too resulting in less room for downward acceleration of air to achieve high velocities. There was no other downdraft forcing besides precipitation loading and that is even limited by the shallow depth of the high reflectivities. This is the kind of environment and storm structure in which severe winds are not expected. No severe wind reports have been received from this storm as far as I'm aware.

Summary: Hybrid/Wet downbursts

Precursor signatures

Signature	FAR	leadtime
1 Large enough CAPE to produce significant precipitation loading	high	Day 1
2 Significant DCAPE – evaporational cooling	high	Day 1
3 Strong initiation with high reflectivities (see updraft strength sessions)	med	15 min
4 Descent of high reflectivity core	med	5-10 min
5 Onset of midlevel convergence	med	0-10 min
6 Midlevel convergence (ΔV) > 50 kts	low	0 - 5 min

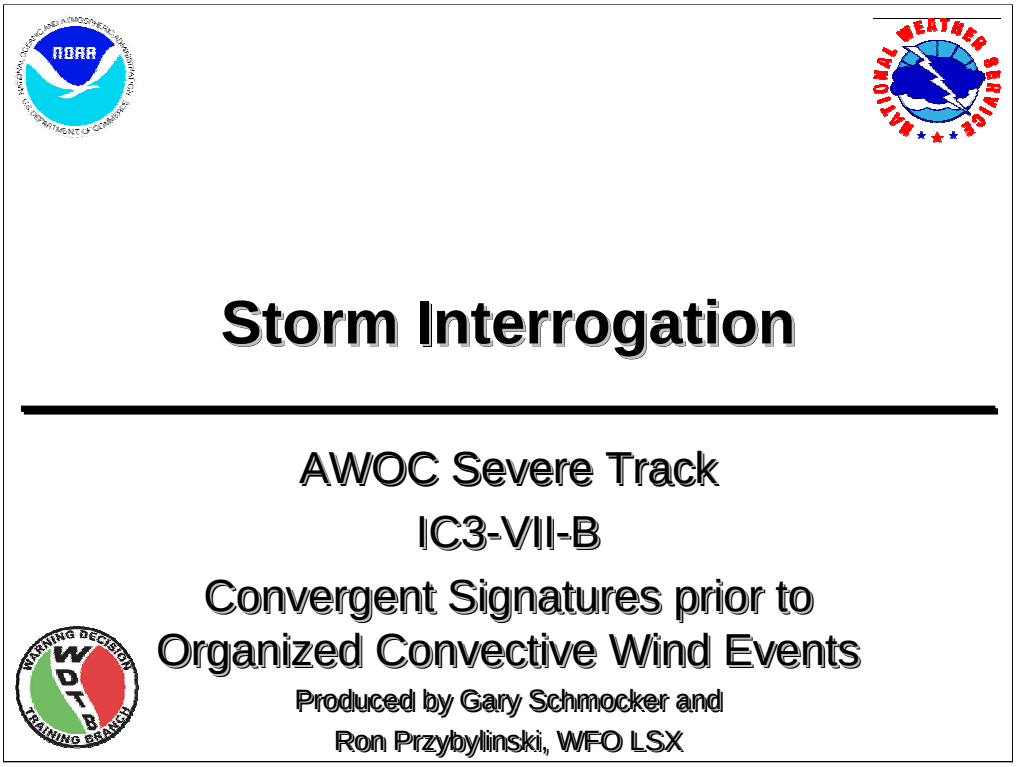
In summary, I present a table of microburst precursor signatures ordered with respect to the lead time each one offers.

The environment makes up for the most lead time but individual storm behavior precludes using the environment as a sole warning tool for every storm and thus the FAR is potentially high.

The best set of parameters to view in conjunction with the environment is to watch for the storms with rapid initiation capable of sending high reflectivities to greater altitudes than other adjacent storm. The descent of the high reflectivity core results in lower lead time but is usually when a warning is sent out since the descending core occurs rather rapidly. It is usually when the reflectivity core descends that the onset of midlevel convergence occurs. Don't wait for the midlevel convergence to reach some large value since large values of midlevel convergence and the period of strongest outflow occur nearly simultaneously.

In this session, I have not mentioned situations of weak shear convection embedded in strong horizontal winds. There have been many events where even weak showers have been able to initiate downdrafts bringing the high horizontal winds to the surface.

I encourage the use of DCAPE more than other parameters, because it accounts for downdraft forcing by lateral and sub cloud base dry air entrainment for a wider variety of situations. The method shown in this lesson is something that can be applied relatively quickly on the day of an expected event. There are some caveats to its use. Note that it assumes a constant lapse rate of environmental temperature from the surface to the level of free sink. In many cases, the bumps and wiggles in the vertical temperature profile tend to cancel each other out. Sometimes they don't. DCAPE is best applied for isolated convection either in weak or significant vertical wind shear. DCAPE becomes less relevant when you are faced with an organized multicell cold pool or in situations of weak convection embedded in strong horizontal winds.



Welcome to the AWOC Severe Track

IC3-VII-B

Convergent Signatures prior to Organized Convective Wind Events

The content of this lesson has been produced by Gary Schmocker of NWS WFO St. Louis, MO

The lesson is about 8 slides long and should take 10 minutes to complete.

Convergent Signatures in Multicell Convective Lines

- Objectives
  - Identify velocity precursors which will lead to improved warning lead time for damaging wind events in multicell convective lines
  - Show the limitations of the precursor velocity signatures

Objectives

Identify velocity precursors which will lead to improved warning lead time to damaging wind events in multicell convective lines

Show the limitations of the precursor velocity signatures

Convergent Signatures in Multicell Convective Wind Events

- Przybylinski et al. 1995 noted strong Mid-Altitude Radial Convergence (MARC) along the forward flank of convective lines before they began to “bow out”

- When the intensifying MCS is upstream
  - strong outbounds indicate updraft
  - strong inbound velocities indicate downdrafts & origins of the mesoscale RIJ

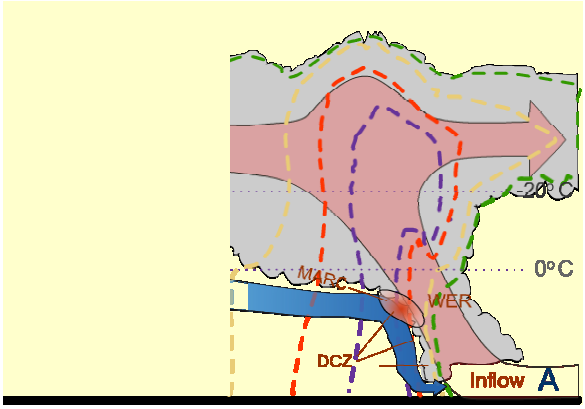
Przybylinski et al. 1995 noted strong Mid-Altitude Radial Convergence (MARC) along the forward flank of convective lines before they began to “bow out”.

We are using the WSR-88D to survey a component of the squall line’s sloping updraft/downdraft currents along the forward flank of the MCS during the intensifying stage.
The region of strong outbound velocities signifies a component of the storm’s updraft current and FTR flow (with respect to approaching storm west or upstream of radar)

The region of strong inbound velocities represent the component of the storm’s downdraft current or early stages of the mesoscale Rear Inflow Jet (RIJ).

MARC signature in a mature MCS

- Persistent localized strong radial convergence
- In larger background of convergence
- In forward flank of intense convective line echoes



The MARC signature represents the convergence of two air streams, the developing Rear Inflow Jet (RIJ) and the leading convective updraft.

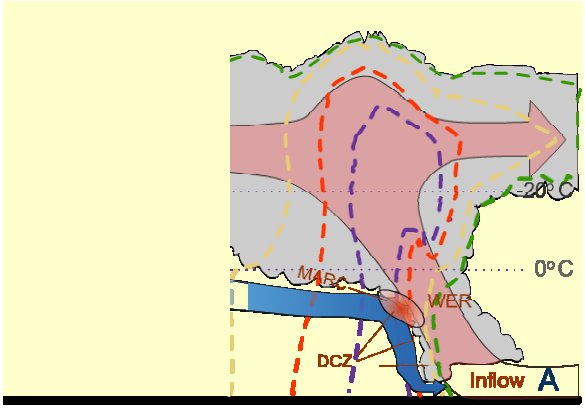
The RIJ in a severe Mesoscale Convective System (MCS) forms on the upshear side immediately behind the tall convective towers and develops rearward with time.

The MARC manifests itself as a persistent localized zone of radial convergence as viewed by radar. It is typically embedded in a longer region of background convergence and resides in the forward flank of the intense convective line echoes.

MARC signature in a mature MCS (contd)

- Length < 15 km
- Width < 7 km
- Nearly gate to gate strong velocity gradient

  $\Delta V \geq 25$ m/s increases potential for severe surface wind



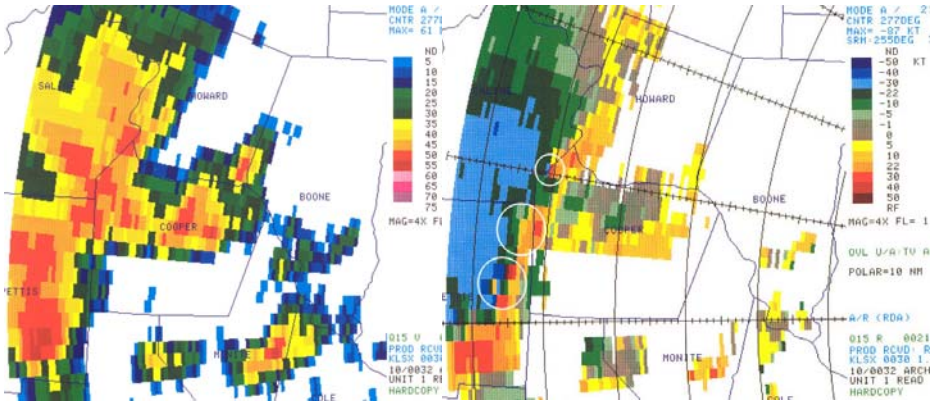
Actual convergence ranges from .0056 to .025 s^{-1} within a 7 km baseline

The length of a typical MARC signature is approximately less than 15 km long by 7 km or less wide. There can be nearly gate to gate radial velocity differences that can exceed 25 m/s (50 kt). If you detect 25 m/s or more of velocity difference, expect an increased threat of severe surface winds.

You can calculate actual convergence, either by using the Vr shear tool, or by visual inspection by taking the near gate to gate radial velocity difference and dividing by the distance of the baseline. You should see values ranging up to .025 s^{-1} or more for severe MARC signatures. These convergence values were taken within a 7 km baseline. Remember that you want to pick a consistent baseline if you use the Vr shear tool.

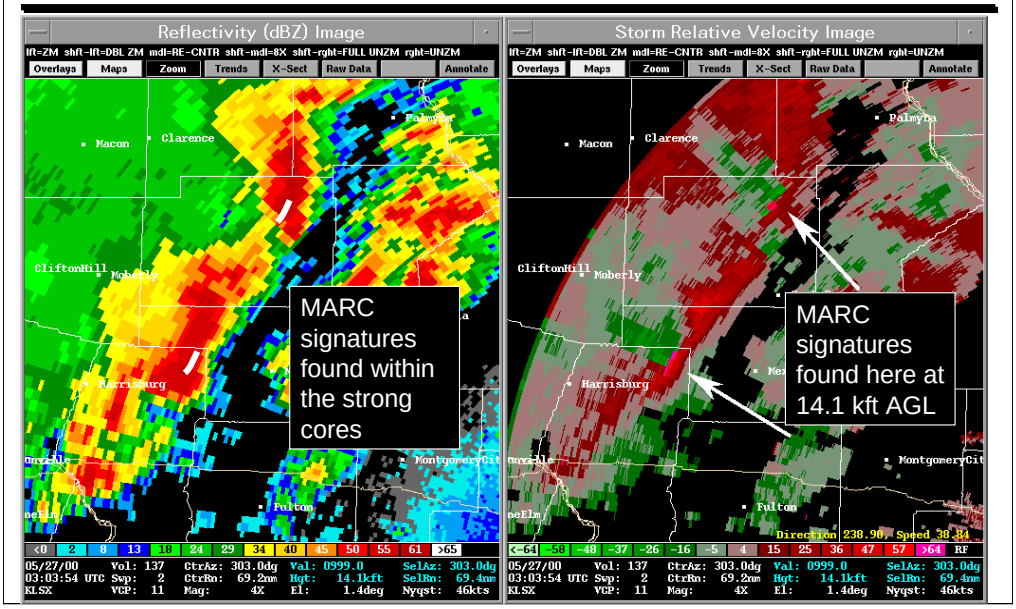
An example MARC

- White circles indicate three enhanced convergent signatures embedded in longer region of convergence



This example shows three MARC signatures, each one roughly in a localized enhanced reflectivity core, and about 15 kft AGL. Note that the velocity difference in these MARCs exceed 50 kts. All three MARCs are embedded in a contiguous convergent zone along the axis of the convective line.

MARC example 27 May 2000



Another example here shows two MARC signatures in eastern Missouri on 27 May 2000. The radar beam is 14 kft AGL and in a good elevation to see this signature. Each MARC shows nearly 50 kts of gate-to-gate velocity differences with increasing range, a sign of intense convergence. Also note that each MARC signature is embedded in the most intense cores in this display.

In some ways, it appears that the MARC signature in an MCS (or a Quasi Linear Convective System, QLCS), is similar in appearance to mid-level convergent signatures found in single cell pulse convection. Both of them occur in intense midlevel cores and are precursor signatures to severe surface winds. The difference lies in the fact that the MARC signatures in an organized event are embedded along a sloping interface between a long-lasting updraft sheet and the rear inflow associated with the RIJ and cold pool. This sloping interface is able to keep its configuration over a long period of time, much longer than the time it takes for individual air parcels to traverse its length, on either side. The pulse storm midlevel convergence and downdraft result in a spreading outflow, quickly resulting in the demise of the original cell.

Here, the MARC signature often marks the genesis of a bow echo, and in fact, the localized downburst activity helps to initiate the bow echo. Many times the worst wind damage may occur before a bow echo has formed.

Summary: MARC signature

1. Look for $\Delta V \geq 25$ m/s in a small region (typically 15 by 7 km) embedded in larger scale convergence
2. Usually prior to formation of bows, line end vortices, low-level vortices within intense, deep reflectivity core
3. Found at midlevels of 4 – 5 km (13-16.5 kft)
4. Difficult to discern when line is parallel to the radials

To summarize, look for velocity differences > 25 m/s in a small region, typically 15 by 7 km and embedded in a larger convergent region at midlevels

The MARC signatures occur prior to the formation of bows, line-end vortices and low-level vortices within the intense deep reflectivity core.

Look to the midlevels, approximately 4 – 5 km AG for the MARC signature.

One final note, if the radials of your radar are roughly parallel to the line axis, you will have a difficult time detecting the MARC signature since most of the air flow is tangential and not radial.

Summary: MARC signature (contd)

5. Environment favors these events in regions where surface-based CIN is not large
   - Downdrafts have increasing difficulty penetrating to the surface if cool, stable layer exceeds 2 km
   - Damaging wind potential thus mitigated in areas deep in the cool side of a polar front or ourflow boundary

Finally, the environment in which a MARC signature leads to severe surface winds, the optimal situation for severe surface winds in the vicinity of a MARC is one in which the pre-storm CIN is low and there is no shallow stable layer. However, there are a minority of events where severe winds have been observed in elevated MCSs where the stable layer can reach 2 km, even a bit more.

Storm Interrogation

AWOC Severe Track

IC 3-VII-C

Extreme Non-tornadic Wind Damage Events

Presentation by Dan Miller,
NWSFO Norman

Extreme Non-Tornadic Wind Damage Events

XDW – e<u>X</u>treme <u>D</u>amaging <u>W</u>ind

Characterized by one or more of:

- Widespread forest blowdowns
- Observed damage of ≥ high-end F1 intensity
- Peak measured wind gusts ≥ 80kt

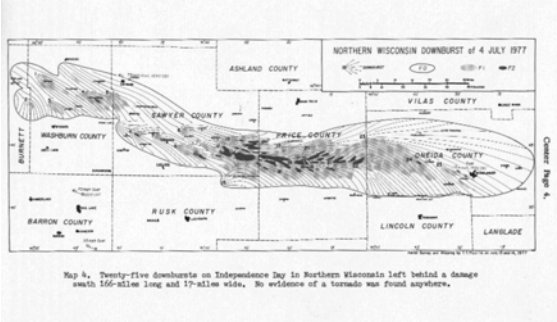
A Detailed Look at Extreme Wind Damage in Derecho Events
D.J. Miller and R.H. Johns, 2000 SLS Conference

Observations of the 27 May 2001 High-End Derecho Event in Oklahoma
D.J. Miller, D.L. Andra, J.S. Evans and R.H. Johns, 2002 SLS Conference

Study of Extreme Non-Tornadic Wind Damage Events, or XDW events, began about 5 years ago and was motivated initially by a simple desire to document an event on 1 July 1997 in central Minnesota. After looking at that event in detail, and with level 2 WSR-88D data, it became apparent that the conceptual model of high-end non-tornadic wind events needed scrutiny, because many of these events do not fit well into the bow echo conceptual model very well when high resolution radar data is examined. The initial phase of the study was focused on derecho producing MCSs that resulted in exceptionally severe non-tornadic winds and/or wind damage. It should be emphasized that considerable effort was made to distinguish these events from "ordinary" derecho events, in that these events are a sub-set of derecho events, characterized by widespread forest blowdowns or wind damage areas that include observed damage of high-end F1 or greater intensity and/or peak measured wind gusts roughly 80 knots or greater. Two SLS conference papers has been published to date on this topic, and those publications are listed at the bottom of this slide. Additional motivation for study of similar events was generated by examination of the 1 July 1997 case, which is summarized on the next slide.

Motivation For Study

4 July 1977 – Northern Wisconsin



Damage path 17 miles wide and 166 miles long MN/WI - widespread F1 and embedded F2 damage

30-31 May 1998

Spencer SD Tornadic Supercell

Deaths: 6
Injuries: 150
Damage: ~ $20,000,000

Overnight Derecho Event – MN to NY

Deaths: 6
Injuries: 209
Damage: ~ $291,000,000

Additional motivations for further study are numerous. First, these events are the non-tornadic equivalent to tornado outbreaks, and although a qualitative study has not been done to date, it is quite likely that a disproportionate amount of the injuries, deaths, and damage from non-tornadic winds each year are due to XDW events. Second, many XDW events produce widespread damage areas that include considerable areas of equivalent F1 damage, and some include quite sizeable areas of F2 equivalent damage. The figure at the top of this slide (from one of Dr. Fujita's publications) is an extreme example from 4 July 1977. The damage path is 166 miles long, and up to 17 miles wide, extending across parts of 6 counties in northern Wisconsin, and includes widespread F1 damage (in the dark gray shading), and considerable areas of F2 damage (in the black shading.) Winds in this event were estimated at 100-120 mph winds with gusts up to 135 mph. One eyewitness account from this event stated that the intense wind continued for 20 minutes and was accompanied by large hail. Third, many XDW events produce just as much, if not more, dollars in damages than tornadoes, and injury/deaths can be comparable. For example, a major severe weather outbreak occurred on 30-31 May 1998 from the northern plains states eastward into much of the Great Lakes region. An F4 tornado struck the tiny town of Spencer, SD during the afternoon of the 30th, killing 6, injuring 150, causing $20 million in damage, and destroying over half of the town. Consequently, media converged on the town and provided several days of coverage. 6 years later, many remember the Spencer, SD tornado. However, what most DO NOT remember about this event is the very intense derecho event occurred during the overnight hours following the Spencer, SD tornado. This XDW event from the evening of the 30th, through the morning of the 31st, affected areas from central Minnesota, eastward across Wisconsin, Lake Michigan, Lower Michigan, extreme northern Ohio, Lake Erie, and far western New York State, resulting in 6 fatalities, 209 injuries, and $291 million in damage. The winds also resulted in a 4 foot seiche on Lake Michigan, that was the primary factor in the sinking of a ship in port on the eastern shore of the lake. It is only a matter of time before an event like this affects a major metro area, perhaps during rush hour, that could result in event greater loss of life and property. There is much improvement that can be done with respect to forecasting and warning for these events, and increased situation awareness to these events is the primary goal of this module.

Extreme Non-Tornadic Wind Damage Events

Pakwash Forest Blowdown Event
18 July 1991 - Northwest Ontario, Canada

To drive home the point, this slide shows a now somewhat-famous video taken during an XDW event in the Pakwash forest of northwest Ontario, Canada on 18 July 1991. Incidentally, this video was taken on the edge of a large forest blowdown area. Damage in the center of the blowdown path was described as considerably more severe than at the location where the video was taken. The entire video is about 15 minute long, and shows three separate pulses of extreme winds, within a period of sustained winds ~50-60 mph. There was no hail in this video, but in some XDW events, particularly ones that involve supercells, the intense wind can be accompanied by golfball to baseball size hail. As an interesting aside, note the time stamp on the video (which is accurate) – 1051 AM CDT.

What Convective Elements Are Associated with XDW Events?

Non-Supercell (Serial or Progressive Bow Echo)

15 July 1995 – Upstate New York
30-31 May 1998 – Minnesota to New York

Hybrid (Line Mesovortex/Supercell structure)

30-31 May 1998 – Minnesota to New York
4 July 1999 – Northern Minnesota
22 July 2003 – Western Tennessee (Memphis event)
4 March 2004 – Texas/Oklahoma

Supercell (MCS with embedded supercells)

3-4 May 1989 Texas/Oklahoma
1 July 1997 – Central Minnesota
29 June 1998 – Central Iowa
27 May 2001 – Oklahoma
26 August 2002 – Western Kansas

In investigating XDW events, it quickly became obvious that the best way to look at them was to define an XDW event, and then work backward to the radar data and 4-D storm structure evolution. So, what storm-scale convective elements are associated with XDW events? Many (most?) of these events are produced by forward propagating MCSs, and therefore are, by definition, part of a derecho event. As one might expect according to the widely held conceptual model (from Johns and Hirt, 1987, and many other papers) some events are produced by serial or progressive bow echoes. However, some of the forward propagating MCSs involved exhibit very complex 4-D reflectivity/velocity structure evolution, and involve cirulations on the storm-scale. For the purpose of this presentation, we will focus on the MCSs that contain embedded supercell storm structures. A summary of events that have been studied in full or in part are listed on the slide.

27 May 2001 - Oklahoma

SBCAPE 4874 j/kg

MLCAPE 3279 j/kg

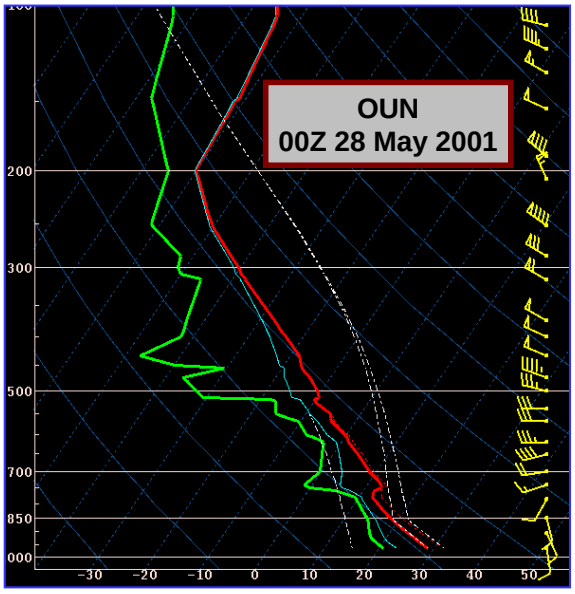
CIN 0 j/kg

LI -11

WBZ 11653 ft

700-500 LR 7.6 deg/km

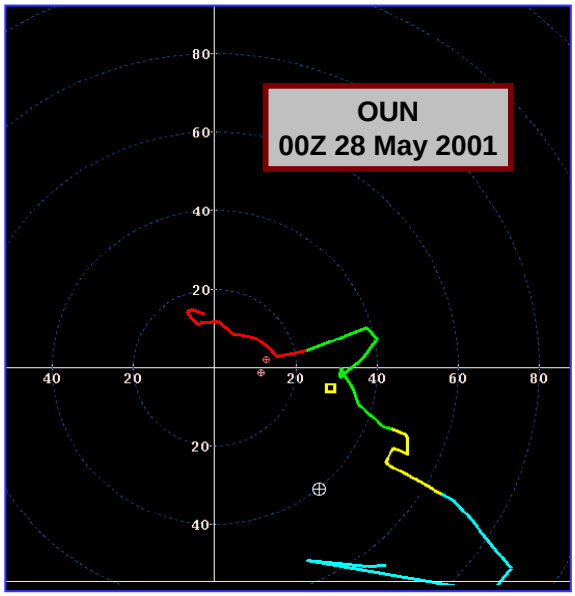
LCL 858 mb



The first case example we will look at occurred on 27 May 2001 in Oklahoma. This slide and the next provide a brief overview of the larger-scale environment that supported this MCS. The thermodynamic profile was characterized by very strong instability (surface-based CAPE approaching 5000 j/kg), and rich tropical moisture in the low levels (surface dewpoints in the low 70s F.) Also of note is the relatively low LCL height at 858 mb, which is roughly 2,500 meters agl.

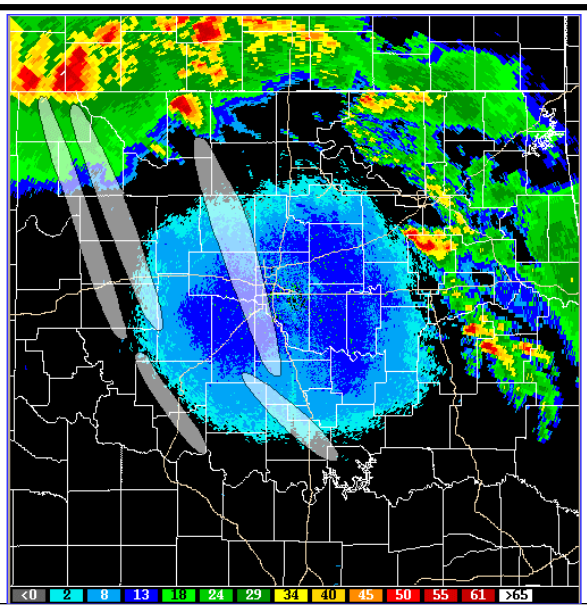
27 May 2001 - Oklahoma

Sfc-6km shear	30 m/s
Sfc-3km SRH	264m^2/s^2
BRN	47
BRN Shear	67m^2/s^2
LFC-EL wind	280/30kt
Storm motion	320/40kt



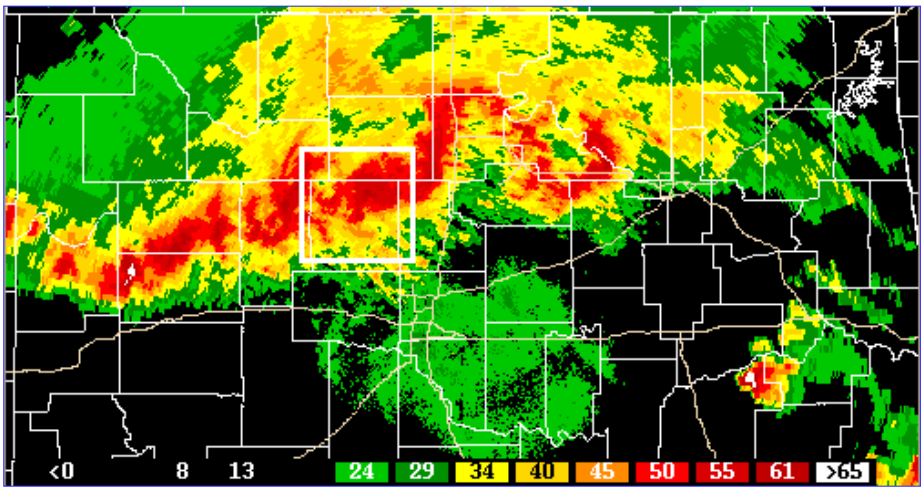
The wind shear profile, when viewed in combination with the thermodynamic profile as seen on the previous slide, reveals an environment that would easily support supercell thunderstorms, with surface to 6 km wind shear of 60 kts (30 m/s), and BRN shear of 67 m^2/s^2.

27 May 2001– Oklahoma



This XDW event was produced by a forward propagating MCS that evolved from several discrete supercells over southwest Kansas. The annotated areas on the radar loop are corridors of XDW that were produced by this MCS (corridors were derived from a combination of Oklahoma mesonet peak winds, damage reports, and damage surveys conducted by local emergency managers.) Radar data viewed at this scale, suggests that this was a rapidly moving and large-scale bow echo. However, if one studies the loop carefully, individual storm elements can be identified, that coincide with the corridors of XDW. These elements are supercells embedded within the MCSs, and we will examine the storm structure in detail on the next several slides.

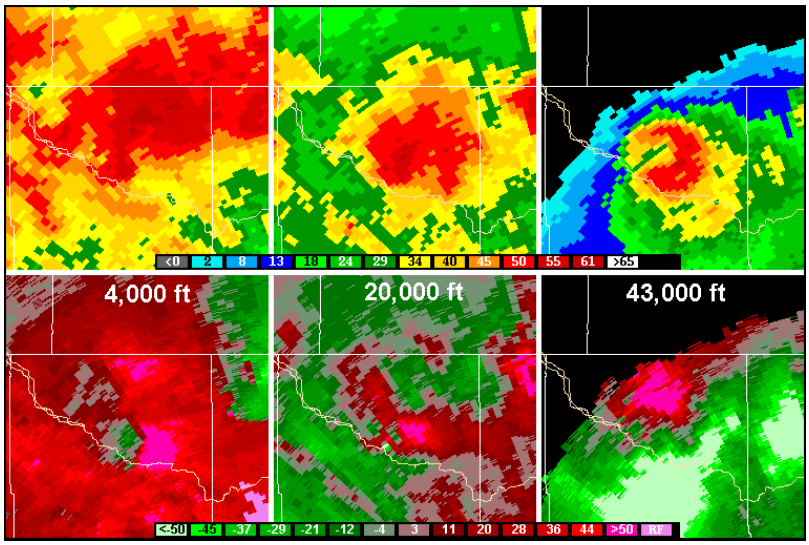
State-Scale Radar Data



0210 UTC

The image on this slide is a state-scale reflectivity image from the central Oklahoma Twin Lakes WSR-88D (KTLX) at 0210 UTC 28 May 2001. Again, viewed at this scale, the MCS at first glance appears to be a large-scale bow echo. However, on the next slide we will zoom in on the area within the white square.

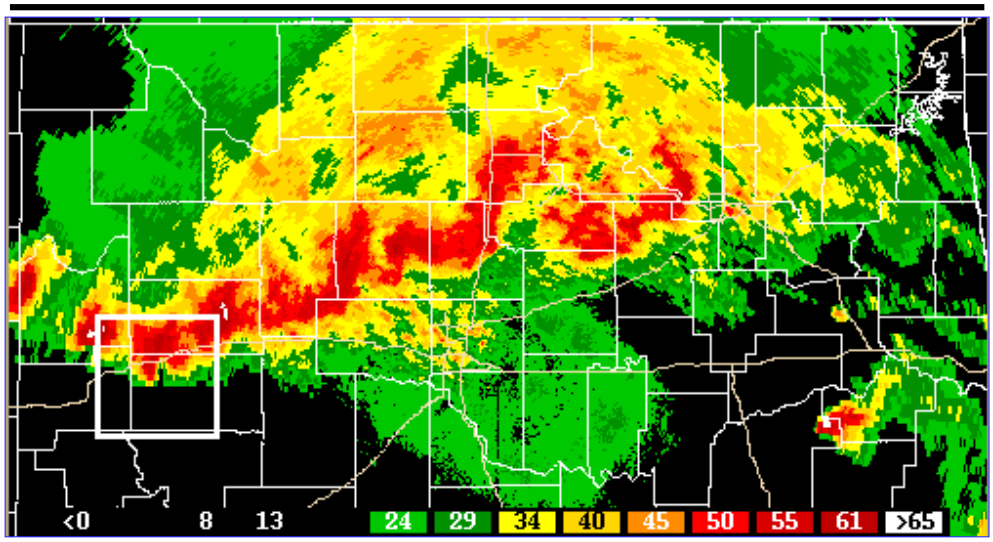
Volumetric Radar Data



AZ/RAN – 326º/51 nm

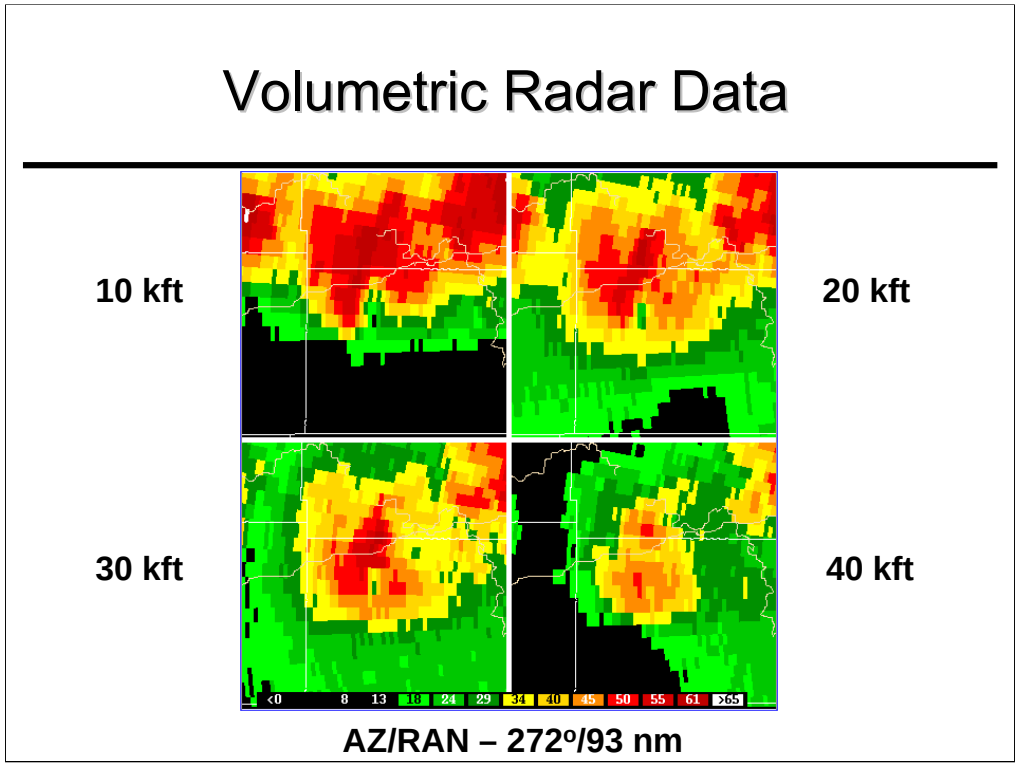
Here is the volumetric reflectivity/velocity data from the white box on the previous slide at 0210 UTC. Reflectivity (top) and velocity (bottom) data are shown at roughly 4,000 ft agl (left), 20,000 ft agl (center) and 43,000 ft agl (right), which should provide a representative view of the storm at low, mid and high levels, respectively. The reflectivity core is strong and very deep, with 55+ dBz echo evident up to at least 43,000 ft, with significant mid and upper level overhang to the inflow (south) side of the storm. A rather large and high reflectivity hook echo is also evident in the low levels. Velocity data at low levels clearly indicates a cyclonically convergent mesocyclone that is displaced slightly to the lower reflectivities on the inflow flank. In the mid levels, a strong mesocyclone is evident (although there are velocity dealiasing errors in the radial inflow velocities), that is co-located with the high reflectivity core. At high levels, strong anti-cyclonic divergence is indicated near the storm summit. The combination of these reflectivity and velocity signatures is exceptionally consistent with the conceptual model of radar-observed supercell storm structure, and indicates a mature (likely Hp-type) supercell embedded within the MCS. The location just on the upshear flank of the low-level mesocyclone was directly associated with a long-tracked XDW corridor.

Volumetric Radar Data



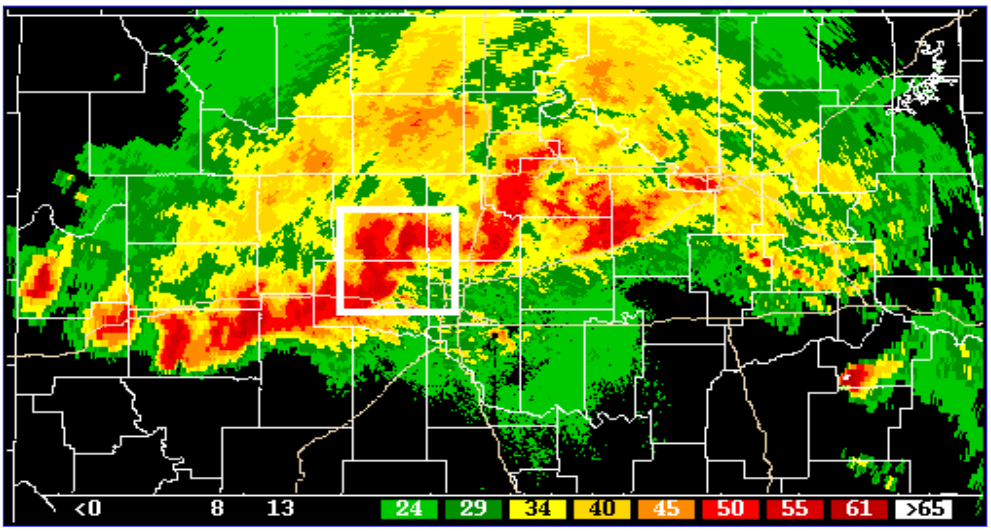
0230 UTC

At 0230 UTC, we will zoom in and examine an area farther to the west in the quasi-linear MCS. On the next slide, we will look at volumetric reflectivity data from the area highlighted in the white box.



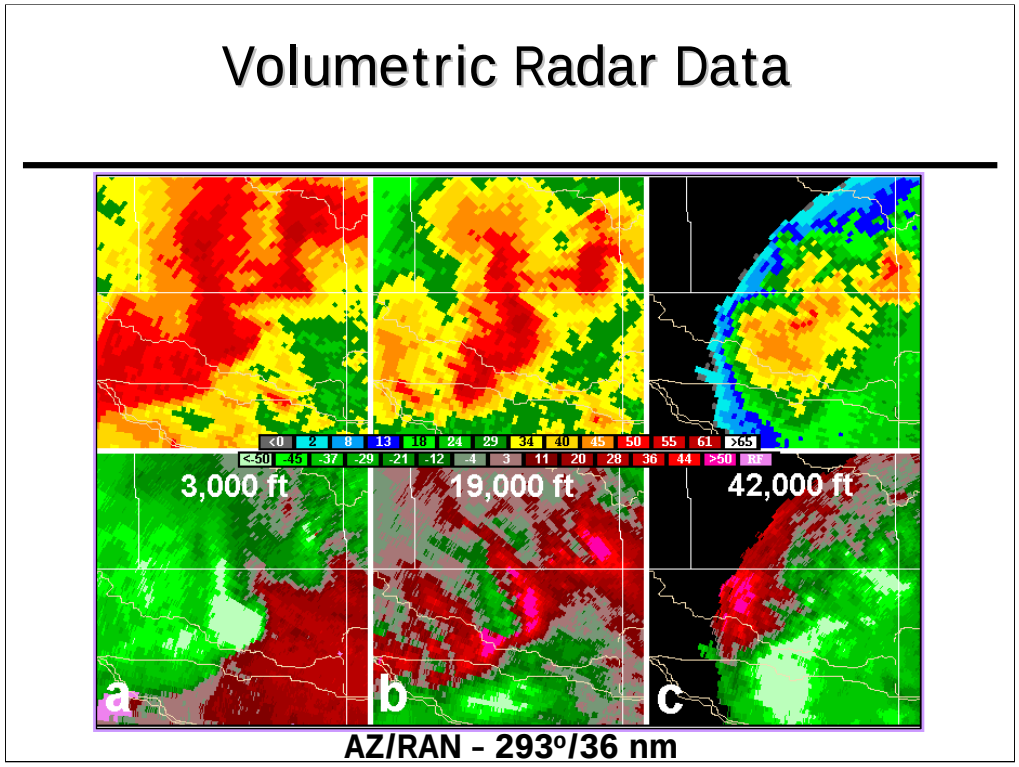
Radial velocity data at this location was range-folded. However, the volumetric reflectivity data reveals a lot. We are somewhat limited in sampling the lower levels of the storm at a range of 93 miles, but at 10,000 ft agl, an notch on the inflow side and a well-defined hook echo are clearly evident. At 20,000 and 30,000 ft agl, a very well-defined bounded weak echo region is present, with the storm summit and highest reflectivities at 40,000 ft agl displaced to the inflow side, directly above the inflow notch at low levels. This feature was present for over 30 minutes, and again is clear evidence of a mature, intense and long-lived supercell updraft. This embedded supercell was responsible for another long corridor of XDW over western Oklahoma.

Volumetric Radar Data

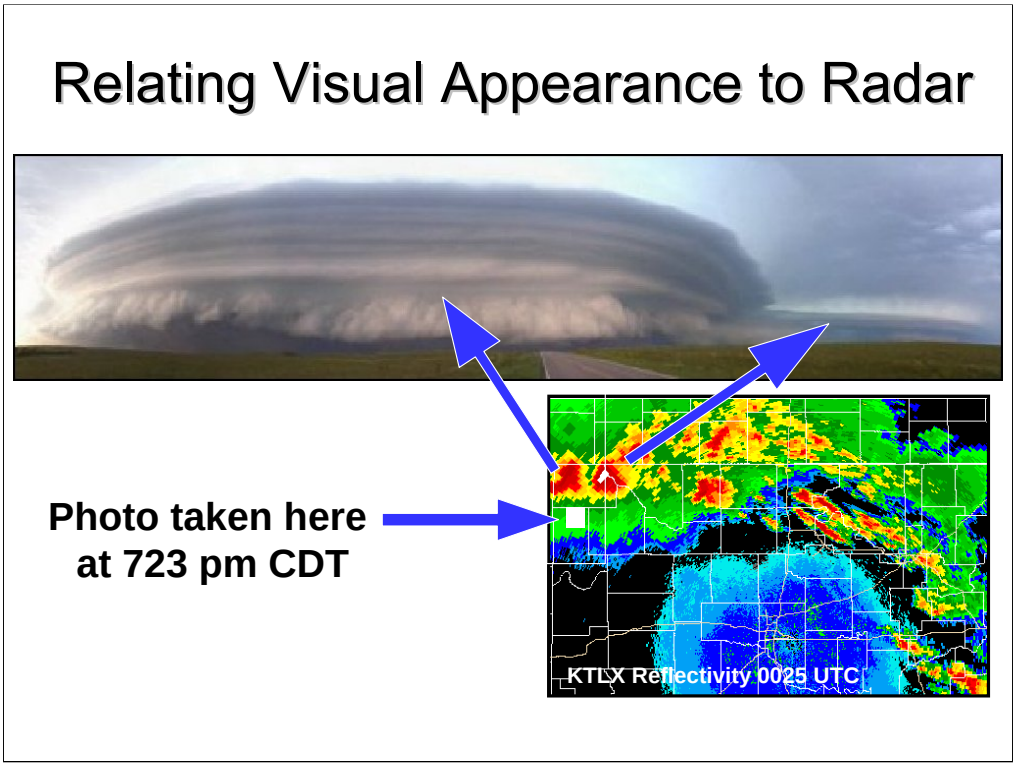


0249 UTC

Finally, at 0249 UTC, we will zoom in and examine a storm in the MCS immediately to the west of the storm we examined in slides 8 and 9. On the next slide, we will look at volumetric reflectivity data from the area highlighted in the white box.

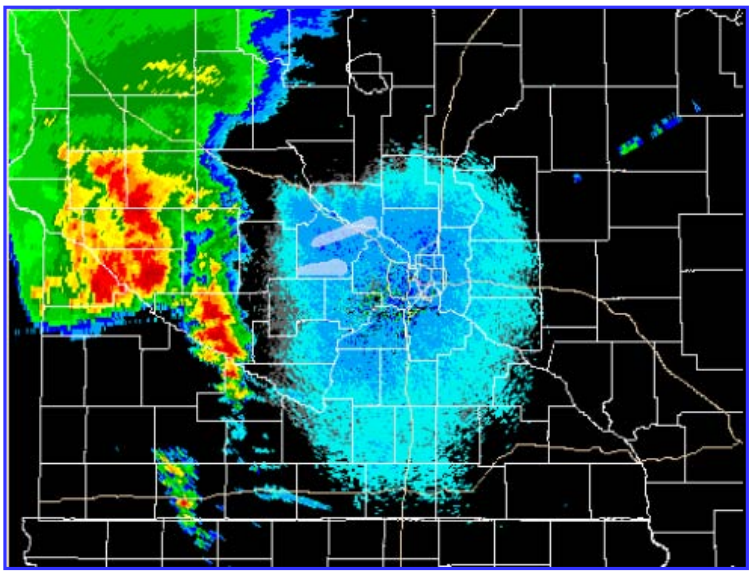


This slide shows volumetric reflectivity/velocity data from the third storm embedded within the MCS at 0249 UTC. This storm was located immediately to the west of the storm that we looked at in slides 8 and 9 at 0210 UTC. Again, reflectivity (top) and velocity (bottom) data are shown at roughly 3,000 ft agl (left), 19,000 ft agl (center) and 42,000 ft agl (right). Very similar signatures are evident. The reflectivity core is strong and very deep, (although the highest reflectivities are a bit more shallow than the 0210 UTC storm we looked at) with 50+ dBz echo evident at 42,000 ft, with significant mid and upper level overhang to the inflow (southeast) side of the storm. A rather large and high reflectivity hook echo is once again clearly evident at 3,000 ft agl. Velocity data at low levels clearly indicates a strong and unbalanced cyclonically convergent mesocyclone coincident with the low level reflectivity hook. The velocity image at 3,000 ft agl above is radial base velocity, and raw data sampling revealed nearly 100 kt inbound velocities at 3,000 ft agl. In mid levels, a mesocyclone is evident, co-located with the high reflectivity core. At high levels, strong anti-cyclonic divergence is indicated near the storm summit. Again, clear indication of a mature (HP-type) supercell embedded within the MCS. As with the other two storms we have looked at, locations just on the upshear flank of the low-level mesocyclone (underneath the location of strong inbound radial velocities) experienced XDW. This storm was responsible for considerable F2 structural damage in the city of El Reno, including taking the roof off of a hospital and city hall.

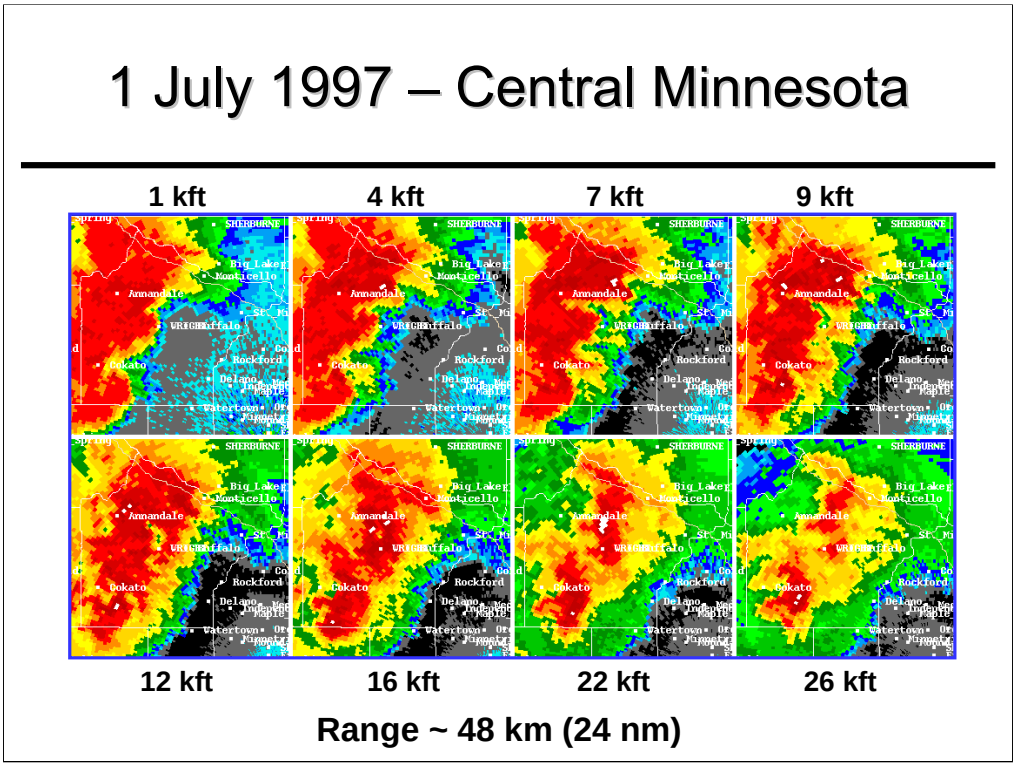


Here is a photograph of the storm complex as it appeared in northwest Oklahoma, just before 730 PM local time (0030 UTC.) At this time, the MCS was still in the process of transitioning from discrete supercells, to a quasi-linear MCS with embedded supercells, but a common gust front and strong surface cold pool had already become established. The photo shows two distinct HP type supercell storms, linked by a common gust front. For comparison, the location of the photo is annotated on the lowest cut reflectivity image in the lower right, with the two arrows pointing to the two storms from their respective radar echoes.

1 July 1997 – Central Minnesota



It is also useful to provide an example from another part of the country. This is a 0.5 degree reflectivity loop of the 1 July 1997 MCS that produced an XDW event. The XDW areas are annotated in white on top of the radar loop. Much as in the Oklahoma case we just looked at, the MCS is quasi-linear, and at state-scale appears much as a large-scale bow echo.



This slide is an enlarged view of the volumetric radar data, zoomed in on Wright County, Minnesota at the time two corridors of XDW were in progress. Nearly identical volumetric reflectivity and velocity signatures are again clearly apparent, with the location of the XDW events placed just on the upshear flank of the low level mesocyclone, coincident with the precipitation filled rear-flank downdraft portion of the HP supercell.

Ground-Relative Wind Production Mechanisms

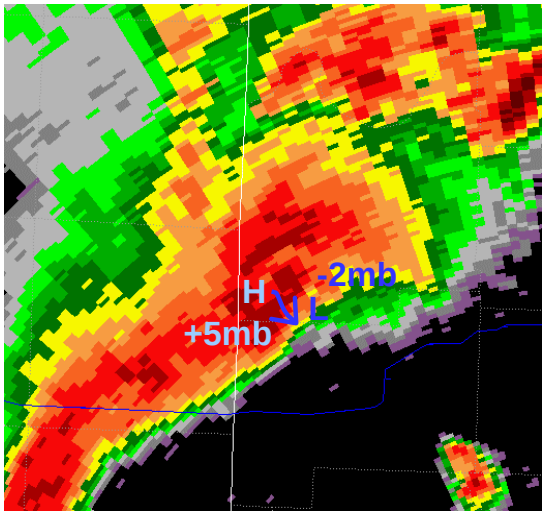
Superposition of

1) Exceptionally strong storm-scale isallobaric accelerations
2) Maximum ground-relative winds within the mesocyclone circulation
3) Precipitation loading and
4) Column cooling due to melting hail

→ Overall message is that warning forecasters need to be keenly aware of an enhanced potential for wind damage (possibly high-end) when circulations are present

So, why do XDW events seem to have a favored storm-relative location of occurrence? Primarily because of the juxtaposition of exceptionally strong storm-scale isallobaric wind accelerations near the surface, the ground relative winds in the near-surface mesocyclone circulation, and precipitation loading and column cooling from hail melt. The primary point is that these events appear to be much more complicated than a simple "downburst," with a significant contribution to the extreme ground-relative wind speeds coming from storm-scale dynamic forcing.

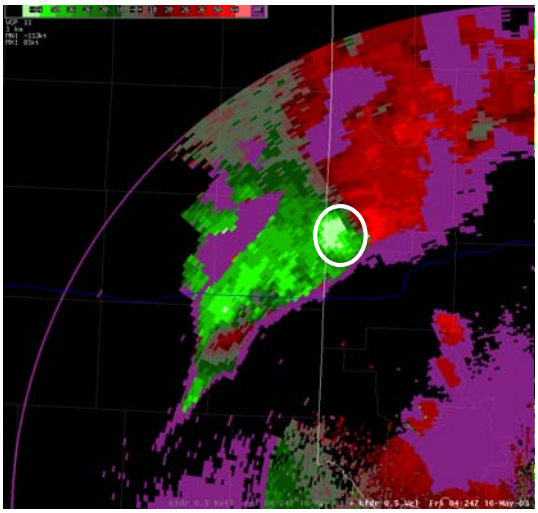
Ground-Relative Wind Production Mechanisms



Much more than a simple ‘downburst’

Meteograms from several XDW events indicate that a 5-10 mb pressure perturbation exists between the low under the updraft, and the high underneath the downdraft and cold precipitation core, and radar data suggests that separation of these storm-scale features was generally on the order of 5 to 10 miles. Most of the MCSs examined had forward propagation speeds of greater than 35 kts, and it follows that a very intense storm-scale isallobaric wind acceleration is likely a very strong contributor to the intense wind speeds.

Ground-Relative Wind Production Mechanisms



Most likely area for XDW is on up-shear flank of low-level mesocyclone and in the precip-filled RFD area

This annotated velocity image simply shows where this area of the storm is located in the velocity imagery.

Unique? Characteristics of XDW Events

1) Quite long in duration at any one location along the path (10-20 minutes - or longer in extreme supercell/mesovortex events vs. a few minutes or less for bow echoes)
2) Very tight damage gradients along the periphery of XDW area
3) Supercell events have a much higher probability of being accompanied by large hail (> 4cm)

Much more research needs to be done, including obtaining data from new cases as they occur, to ascertain whether these XDW characteristics are generally the case with all XDW events. However, these characteristics were common in most cases examined thus far.

Operational Considerations

- Supercells *within* a derecho producing MCS can be associated with an enhanced threat for XDW
- In *many* high-end derecho events - the most extreme damage is associated with supercells/mesovotices
- Supercell/Mesovortex XDW events *may* have somewhat different characteristics than “traditional” Bow Echo XDW events
- Events often move/evolve rapidly → timely flow of accurate information becomes *very* challenging
- Even high resolution surface mesonetwork observations may not be dense enough to completely capture storm-scale extreme wind events

The bullets presented here generally need little additional explanation. All are important things to remember when working an XDW event operationally. AWIPS and other operational procedures should be optimized to maintain maximum situation awareness during the event.

Forecasting 6-24 Hours

- Almost all of these events have tornado watches
  - → *many* have PDS tornado watches
- Significant overlap of atmospheric conditions between XDW events and tornado outbreak days
- Event type/evolution seems to be highly dependent on convective mode

A few brief comments about forecasting these events. It should be emphasized that a qualitative study of environmental parameters has not been completed yet, primarily because the dataset is still too small for results to be statistically significant. With addition of additional cases as they occur, hopefully the dataset will reach a critical mass soon. With that said, there are a few general points about forecasting these events that can be stated from anecdotal and observational evidence. First, the fact that most of these events occur in tornado watches, and many in PDS tornado watches, seems to suggest that there is a significant overlap in the large-scale environmental conditions that support both XDW events and significant tornado events (strong instability, strong surface-6 km shear, strong surface-1 km shear, low LCL/LFC heights, etc.) It seems as though event type is highly dependent on convective mode (discrete supercells vs. MCS development.)

Tips for AWIPS D2D Display

- All tilts (especially enhanced all tilts for those offices that have it), in combination with judiciously constructed 4-panel displays from multiple radars, is exceptionally useful in seeing the 4-D storm structure evolution
- Remember to keep at least one radar panel paired with base velocity – 8bit products will allow much better sampling of near-ground radial winds
- Possible to be fairly confident about specifics of enhanced wind damage area in warnings/statements and graphical products

Here are a few tips for AWIPS procedures and conveying information to users in warnings, statements and graphical products.

Storm Interrogation

AWOC – Severe Track

IC3

Storm Interrogation Overview

IC Severe 3 Acknowledgements

- Dan Bikos, John Weaver, and Dan Lindsay, CIRA
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- Greg Smith, Colorado River Basin RFC
- Greg Stumpf, CIMMS/NSSL
- Pete Wolf, WFO ICT
- Ray Wolf, WFO DVN

In alphabetical order, we'd like to thank all these meteorologists and scientists for providing data, input and reviews, and in some cases, entire lessons.

Layout of IC Severe 3

- 6 Topics with 26 lessons to choose from, NO Exam
- Your training facilitator will require you to take at least six based on what could most benefit you and your WFO
- The 6 Topics Are:

1. ICSvr-I: Updraft Location (Lessons 1-4)
2. ICSvr-II: Updraft Strength (Lessons 5-9)
3. ICSvr-III: Tornado Warning Guidance (Lessons 10-16)
4. ICSvr-IV: Flash Flood Warning Guidance (Lessons 17-19)
5. ICSvr-V: Large Hail Signatures (Lessons 20-23)
6. ICSvr-VI: Damaging Wind Signatures (Lessons 24-26)

You can take as many lessons as you desire: your facilitator will only require a minimum of 6.

IC Severe 3 Performance Objective

- The participant will demonstrate selection of products and proper procedures for effective data analysis in completing storm interrogation strategies for tornadoes, hail, flash flooding, and severe straight line winds.

Lesson 1: Weakly sheared updraft location

- Objective:
  - Determine where to look for severe pulse storm updraft signatures based on the stage in its lifecycle.

This module shows several examples of where the updraft is most likely to be located depending on where in the storm is in its lifecycle.

Not only clues in reflectivity and velocity can help us discriminate between updraft and downdraft within the mid- to upper-level of a convective

cell but also at the source level of initiation, a level which is often overlooked during the cell's initial stages.

Lesson 1 Summary: Pulse storm updraft location

- Reflectivity
  - Updraft is colocated with cores at these locations
    - Under and within new elevate cores
    - Within the top of strong growing echoes (e.g., top of the 55 dBZ echo)
    - In growing strong echoes at temperatures < -10° C
  - Updraft is not colocated with these cores
    - descending high reflectivity cores
    - High reflectivity cores (growing or not) at temperatures > -10° C

Summarizing, Reflectivity

Updraft is colocated with cores at these locations

Under and within new elevate cores

Within the top of strong growing echoes (e.g., top of the 55 dBZ echo)

In growing strong echoes at temperatures < -10° C (this height rises though, in the late lifecycle of a pulse storm)

Updraft is not colocated with these cores

descending high reflectivity cores

High reflectivity cores (growing or not) at temperatures > -10° C

Lesson 1 Summary: Pulse storm updraft location

- Velocity
  - Updraft is located
    - Above the zone of maximum low-level convergence in a developing storm
      - Low-level convergence difficult to spot without gustfronts
    - Between the maximum midlevel convergence and anvil-level divergence in a mature storm
    - From the low-level gustfront convergence sloped to the core's periphery at midlevels for a mature storm

Velocity

Updraft is located (Remember this is most likely located)

Above the zone of maximum low-level convergence in a developing storm

Low-level convergence difficult to spot without gustfronts

Between the maximum midlevel convergence and anvil-level divergence in a mature storm

From the low-level gustfront convergence sloped to the core's periphery at midlevels for a mature storm

For all of these pieces of evidence, none of them are direct measurements of vertical velocity. Also, as a cold pool

spreads out from its axis upon the core reaching the ground, updrafts may grow on a preferred flank of the parent cell,

resulting in a sloped updraft appearance. It is too simplistic really to show a time height diagram of maximum reflectivity and

convergence and say specifically that the entire core is either updraft or downdraft. The flanks of a midlevel core can certainly

be occupied by updraft while its center, downdraft. This is certainly true during the mature stages of a cell. Within the core, what

I can say is that it is likely the core is dominated by either updraft or downdraft.

Lesson 2: Sheared storm updraft shape and location

- Objective: Determine where and what shape the updraft is in a sheared convective cell
  - Specifically, locate the part of the Weak Echo Region occupied by updraft
  - How to determine if a WER exists in fast moving storm

This module builds on the one in which we determine the location of updrafts in pulse storms. Locating the updraft in sheared storms is something that is frequently done by warning forecasters. In this session, we show a methodology that may help your skills in discriminating the updraft size and shape at different altitudes. In addition, we discuss what a real echo overhang and underlying weak echo region is from that which is artificially generated by the volume scan with a moving storm.

Then we show a case emphasizing where in a weak echo region may lie the main updraft of a sheared cell.

Lesson 2 Summary: Sheared storm Updraft location

- Low-levels
  - Facing low-level SR flow side
  - Tight reflectivity gradient
  - Concave shape reflectivity gradient
  - Enhanced velocity convergence
  - WER
- High levels
  - Intense echo overhang (>45 dBZ)
  - On inflow side to mesocyclone
  - Storm summit divergence and echo center
  - BWER core
  - Low spectrum width

To summarize, the updraft location in a sheared storm is more likely than not to tilt with height. Therefore, look for reflectivity and velocity signatures at both low and high altitudes to gain a better understanding of the nature of particular storm's tilt.

At low-levels, you want to look for the updraft on the side roughly facing the low-level storm-relative inflow where there is a tight reflectivity gradient, preferably in a concave shape. You should see enhanced velocity convergence if your lower slices are below 4 to 5000 feet AGL. This area may lie in a weak echo region capped by intense reflectivity overhang. Recall that the echo overhang is not entirely occupied by low-level updraft. But the coincidence of more pieces of evidence at any point, does lead to higher confidence that the echo overhang is updraft.

At higher levels, the intense echo overhang, below an upper-level reflectivity maxima, under the region of strongest storm summit divergence gives you most of what you need to call the area an updraft. Your confidence increases if this area is in a BWER overlaid by high reflectivities, and in the vicinity of a mesocyclone. Remember that mature mesocyclones are partiall occupied by rear flank downdraft, even at high altitudes.

Lesson 3: The nature of the WER

- Objective:
  - Understand the characteristics of a WER
    - Specifically, determine the relationship between the WER and the updraft shape and location
- Motivation: The WER is a critical feature for
  - Determining updraft location
  - Estimating updraft severity

The Weak Echo Region is a storm signature commonly used to assess the severity of and to locate a convective updraft. But exploring the nature of the WER is the objective to be satisfied in this lesson. And specifically, what is the updraft shape and location with respect to the WER?

Lesson 3: WER Summary

- In moderate to strong shear, the WER is partly due to
  - intense storm summit divergence
  - And the updraft itself
- More is needed to locate the updraft in sheared convection

Jim: In moderate to strong shear, the WER is partly due to strong storm summit divergence advecting hydrometeors horizontally into the anvil canopy, and it is partly due to the updraft suspending hydrometeors above the ground. However, in order to locate the updraft itself, we have to do more than solely identifying the WER location. Other sessions in storm interrogation focus more detail on updraft location.

Lesson 4: Sheared storm updraft location via satellite

- Objective
  - As a compliment to, or without radar data, use satellite data to locate an updraft to deep, moist convection in a sheared environment
    - Be able to use satellite data during the day or night

This lesson looks at how to interpret storm top brightness temperature information from GOES to locate the storm top in an environment with significant vertical wind shear. This process may seem straightforward if there is a unique relationship between storm height and brightness temperature. However, that is often not the case. We will look at how you can locate a storm top even if cloud height and brightness temperature are not colocated.

Lesson 4 Summary: Sheared updraft detection by satellite

- Positive lapse rate above EL
  - Updraft summit height and IR brightness temperature well related
- Negative lapse rate above EL (inversion)
  - Updraft summit height and IR brightness temperature may **not** be well related
- Small overshooting tops will be poorly resolved by 4km GOES IR
- Parallax correction needed

When there are positive lapse rates above the EL, there is good agreement between updraft summit height and IR Tb.

When the lapse rates become negative (inversion), the Tb minimum gets displaced upwind. In some cases, there might not be a Tb minimum.

Small overshooting tops are likely to be unresolved by satellite and therefore, you need to look at the upwind side of the anvil relative to the storm-relative anvil layer flow.

Lesson 5: Upper-level Z core height and intensity

- Objective
  - Provide guidance on assessing the potential for an updraft to produce severe weather based on the height and intensity of the upper-level reflectivity core

The primary objective of this lesson is to provide you guidance on assessing whether an updraft may lead to severe weather based on the height and intensity of the upper-level reflectivity core.

Much of the guidance will be based on the same principles on which the Hail Detection Algorithm or HDA, is based. I believe you will find this useful since this technique uses the height and intensity of the reflectivity core above the 0° and -20° C levels, and therefore helps to account for widely varying severe weather scenarios.

As a companion to this lesson, we have provided you a tool in which you can enter in your own reflectivity values, the heights of those values, the 0° and -20° C heights, and the height of your radar so that you can use this tool to help determine how to apply this lesson to real world examples in your CWA.

Lesson 5: Summary

- Updraft intensity likely stronger as the height of 50, 55 dBZ core increases.
  - Warning performance (CSI) peaks at a certain altitude
  - That altitude depends on your thermal profile
- Presence of > 60 dBZ above the freezing level give strong likelihood of some type of severe
- Use the HDA worksheet to account for
  - different thermal profiles
  - Storm updraft dominant phase

To summarize, we've seen strong evidence of how strong the relationship between severe weather likelihood and the height of the upper level reflectivity core can be. We've also seen a case where a strongly initiating storm results in a large hail indication as a function of its intense upper-level reflectivity core and yet VIL density understates the storms intensity. Conversely, we've seen a storm with a high hail signal but where the reflectivity profile falls off in the sub -20° C air resulting in a low VIL density, and perhaps correctly.

In either case, a strong updraft should contain strong reflectivities, and those reflectivities should extend well into the sub -20° C air and close to the equilibrium level.

Lesson 5: Summary cont'd

- Updraft intensity that governs potential for severe
  - Hail size through lofting larger hailstones
  - For severe winds, precipitation loading
- Updraft intensity not the only factor
  - Hail size also a function of updraft width, trajectory paths
  - Severe microbursts a function of DCAPE even more than CAPE

Updraft intensity increases the odds of severe weather as it is capable of lofting larger hailstones, and increasing downdraft intensity through heavy precipitation loading.

Remember that updrafts evolve through time and looking at storm trends to discern when the maximum updraft intensity is the most important consideration. Also note that hail takes time to grow, and in the process traverse through complicated 4 dimensional paths, something that the HDA or these techniques do not consider. And remember that downdraft and outflow intensity is not solely a function of updraft intensity.

Lesson 6: Updraft strength– Low-level convergence

- Objective
  - Understand the contribution of low-level convergence to CAPE on updraft intensity

At the end of this presentation, you should understand the contribution of low-level convergence to CAPE on updraft intensity

You may not be able to provide specific values on how strong an updraft is likely to be, but you will have gained an appreciation in how updraft strength can be significantly enhanced beyond what the theoretical CAPE can provide in certain situations.

Lesson 6 Summary: Pulse storm updraft

- Convergence adds vertical velocity to the peak updraft expected from buoyancy alone
- Convergence depth and magnitude modulate the strength of the updraft
- Caveats
  - Updraft must reside over convergence to realize its vertical velocity
  - That means boundary-relative storm motion needs to be small

To summarize this event, the boundary collision may have added up to 8 kts of vertical velocity to the base of the convective updrafts. In addition, large plumes of moisture have been advected upward to produce a much stronger base for buoyancy to continue the initiation process. The result was a more intense set of thunderstorm updrafts than the initial storms that created the original cold pool boundaries in the first place.

There are some caveats to everything. First, the convective layer steering flow must be such as to minimize boundary-relative storm motion in order to generate the strongest, deepest updraft possible. Deep layer shear should be optimally balanced with the motion of the gust front to generate a deep overturning convective current. In this event, shear is not a consideration in the environment, storm motion was small, and the updraft generated by the boundary collision was likely upright and deep.

Lesson 6 Summary: Strong shear severe storm

- Updraft strength profile is maximized due to
  - Strong convergence (ΔV>50 kts over a few km)
  - Deep convergence (>3 km or 10 kft)
  - Low boundary-relative storm motion
    - Storm matching cold pool speed

Summarizing, this boundary moving at 50kts resulted in some incredible convergence, especially considering that the ground-relative low-level inflow was out of the southeast. This convergence was also deep (3 km) and the matching vertical velocity was calculated at 30 m/s at 3 km. The convective layer storm motion allowed the deep updraft to maintain its footing close to the vertical velocity generated by the convergence zone and the result was a deep overturning updraft capable of generating all the features associated with a high end severe squall line including tornadoes, severe low-level winds and excessive rainfall rates. Very severe hail was not something found in this event for many reasons. One of them may be that squall line updrafts tend to flatten out at lower altitudes than for more isolated modes of convection in similar environments.

Lesson 7: Severe updraft structural signatures

- Objective: Understand how the following signatures are an indication of, or contribute to severe updrafts in convection
  - WERs
  - BWERs
  - Stormscale velocity

This session adds onto the session on the height of reflectivity profiles. For sheared storms, however, signatures appear that are unique to this class of convection. The objective in this lesson is to understand the signatures in reflectivity and velocity that indicate a severe updraft is in progress. Again, what is meant by severe updraft is one that is often accompanied by large hail, severe straight line winds. As a performance objective, you should understand how Weak Echo Regions, Bounded Weak Echo Regions and stormscale velocity patterns contribute to recognizing a severe storm.

Lesson 7 Summary: Severe updraft signatures

- severe updraft signatures common to all storms in order of most severe first
  - BWER
  - WER
  - Intense reflectivity core, and deep relative to the –20° C level
  - Storm top displaced over WER
  - Deep convergence zone

Summary: Severe Updraft Signatures

The most severe updraft signatures tend to have these features common, even for linear systems.

- BWER
- WER
- Deep, intense reflectivity cores * *Severe linear updrafts tend to have somewhat shallower cores than discrete severe updrafts
- A storm top displaced over the WER
- A deep convergence zone** **This is a weak requirement as many discrete severe updrafts may not exhibit this. For example, classic or Low Precipitation (LP) supercells mostly fail to show any deep convergence and yet have extremelyi ntense updrafts.

Lesson 8: Estimating updraft intensity with satellite: part 1

- Objective
  - Use satellite data to qualitatively estimate updraft strength in the absence of radar data based on
    - Cloud top growth rates determined from temperature and the D2D cloud height estimation tool
    - Temperature and height of the storm equilibrium level

As a motivation for this lesson, there have been times when offices are stripped of radar data for various reasons. Satellite data can provide a useful backup, or as a tool of confirmation.

The objective of this lesson is to qualitatively estimate updraft strength from satellite based on two major parameters that you have the capability to evaluate

1. The cloud top growth rate in terms of time trends of cloud top temperature and height.
2. Temperature and height of the storm Equilibrium Level (EL)

Both of these parameters, you can evaluate for yourself using the D2D cloud height estimation tool.

We will discuss this more later in this lesson.

Lesson 8: cloud top cooling rates

- The peak cloud top cooling and ascent rate for the storm should be used
- Different criteria before and after storm produces an anvil

Storm B went on to produce 70 mph winds and 1” hail. No reports came in for Storm A, although I caution that storm A originated over relatively unpopulated territory and there may have been unreported severe weather at the surface.

Note that we used the peak cooling rates prior and after anvilgenesis for the lifetime of a particular single or multicell event.

Remember that cooling rates pre- and post-anvil are distinct and should be treated separately.

Lesson 8: cloud top cooling rates (contd)

- Cooling rates are dependent on image temporal frequency
  - Faster scans usually result in higher growth rates
  - Really need 30 second scanning to capture individual updraft growth spurts
- Best to make relative comparisons
- Another technique next

There are real problems using this technique, the worst of them is the uncertain image time interval. Cooling rates can be more a function of image frequency than anything real. A good check

The optimal frequency should be 30 seconds, which the GOES satellites have done under research operations.

Probably the best way to assess cooling rate is to compare cooling rates between storms in a similar environment.

The next satellite-based updraft intensity technique may help a bit to account for image frequency problems.

Lesson 8: Anvil T_{eql}

- Strengths –
  - Allows you to approximate the theta-E the updraft is realizing.
  - Relative strengths between storms
- Limitations
  - Required anvil exposure to undisturbed environment
    - Storm complexes push the equilibrium level higher
  - T_{eql} and height ambiguity in isothermal layers and inversions at the equilibrium level

To summarize, assessing the satellite based EL temperature can give you clues as to the θ_e in the updraft column, and therefore how well the storm is utilizing the θ_e found in its environment. Use this technique to assess relative updraft strengths between adjacent storms. But be careful. The storm anvil should be exposed to undisturbed environment free of pre-existing anvils. Equilibrium temperatures may also lose their relation to anvil height where isothermal layers or inversions exist across the EL.

Lesson 9: Estimating updraft intensity with satellite: part 2

- Objective
  - Utilize the following satellite signatures to assist radar in estimating updraft strength and severe storm potential
    - overshooting top characteristics,
    - presence of an enhanced-V,
    - anvil shape vs. storm-relative anvil-layer flow,
    - and anvil top temperatures.

This objective uses a case to highlight how the following signatures can be used to assist radar in estimating updraft strength and severe storm potential. We will mention:

•Overshooting top characteristics,

•enhanced-V signatures,

•anvil shape vs. storm-relative anvil-layer flow,

•and Anvil top temperatures.

We will also look at the radar presentation of this storm and some near storm environmental information.

Lesson 10 TWG: mesocyclones

- Objectives
  - Interpret mesocyclones and how they fit into providing the necessary tornado ingredients given radar sampling limitations
  - Know how the overall tornado warning skill scores may be related to mesocyclone strengths
  - Understand the impacts of radar sampling on mesocyclone strength and strength trends

The main objectives center primarily on how mesocyclones fit into satisfying the ingredients for tornadogenesis, what the most effective parameter is, and how effective it is at discriminating tornadic from nontornadic mesocyclones, and how sampling affects its strength and when to know If a trend in rotational velocity is real.

Lesson 10 Summary: Mesocyclone sampling

- Radar observed mesocyclone rotational velocity decreases as range of a constant intensity mesocyclone increases
- Uncertainty of trends in rotational velocity increases with increasing range
- However, the best warning performance using thresholds of rotational velocity seem to peak at 51-100km (30-65 mi) range.

In summary, radar observed mesocyclonic V_r decreases with range.

Uncertainty in V_r trends increases with range as the angular separation becomes more important.

Tornado discrimination potential of low-level V_r represented by the Heidke Skill Score, HSS peaks at 51 to 100 km in range.

It is important to know what is a real change in mesocyclone strength trend and what is a spurious artifcact of radar sampling.

Remember though that the mesocyclone diameter also can change with time and this fact will influence further what a real trend may be. Meoscyclones often contract prior to and during tornado time. The impact on sampling may result in the appearance of a mesocyclone weakening or going through more volatile trends during this contraction. Be mindful of this when it does happen.

Level 11: Storm scale signatures considered in tornado warnings

- Objectives
  - This lesson is intended to be an overview of common storm scale signatures associated with tornadogenesis. In particular:
    1. Discuss the ingredients for tornadogenesis
    2. Determine the range of low-level velocity difference that leads to good tornado discrimination in a TVS signature

This is intended to be a review of tornado precursor signatures for the most part. As a first objective this lesson presents the signatures and how they relate to the ingredients for tornadogenesis. In some contexts, the storm scale signatures we can detect are directly related to the ingredients for tornadogenesis. In other contexts, the role of these same signatures in contributing to the ingredients for tornadogenesis are still in the realm of the unknown.

As a second objective, this lesson covers the range of low-level velocity difference that lead to good tornado discrimination in a TVS signature based on the Tornado Warning Guidance (TWG) project conducted by the National Severe Storms Laboratory (NSSL) in 2001 and 2002. The results for the TVS velocity attributes were also extended to mesocyclone signatures, and near storm environment parameters. This lesson also mentions the ability of mesocyclone rotational velocity to discriminate tornadic from nontornadic storms. However, another lesson in IC3 delves into mesocyclone signatures and sampling in more detail.

Lesson 11: Storm scale signatures considered in tornado warnings

- Objectives (cont'd)
  3. Determining the relationship between the TVS and the tornado cyclone
  4. Recognize signatures conducive to vortex stretching
  5. Recognize common storm interactions observed with tornadogenesis in the past
  6. Understand what is not known in the relationships between the storm scale signatures in this lesson and ingredients for tornadogenesis

This talk also covers the relationship between the TVS signature and the tornado cyclone, and recognizes the signatures conducive to vortex stretching (e.g., updraft signatures). I devote some discussion to a topic of growing interest amongst researchers: the role interstorm interactions have on tornadogenesis.

Finally, we will discuss what we do not know about storm scale and near storm environmental signatures in regards to how the contribute to the tornado ingredients at the end of the lesson.

Lesson 11: Strong Updraft Signatures

- Strong signals favoring low-level vortex stretching
  i. Locally sharp concave reflectivity gradient facing the inflow
  ii. Inflow notch
  iii. Mesocyclone
  iv. WER
  v. BWER
  vi. Low-level velocity convergence and accelerated low-level inflow

A lot of the same signatures from which the presence of low-level vorticity can be inferred can also infer the presence of strong updrafts. In addition, there are other velocity and reflectivity signatures to infer strong updraft forcing and vortex stretching potential.

Lesson 11 Summary: Tornado signatures

- Storm scale
  - Interstorm interactions
  - Relationship between radar observed signatures and tornado ingredients
    - Mesocyclone
    - TVS
    - BWER
- Near storm environment
  (Covered in storm interrogation, IC2)
  - Low-level (0-1 km) shear
  - Deep layer shear
  - Pre-existing vertical vorticity
  - CAPE
  - CIN
  - Boundary layer humidity

To summarize, we discussed the relationship between radar observed signatures and the two tornado ingredients: low-level vorticity supply and vortex stretching potential. We also discussed the interstorm interactions and the most commonly observed ones related to initiating tornadoes.

Keep in mind that we did not cover the near storm environment and the relation between the most common parameters and tornado ingredients, except for the presence of low-level vertical vorticity.

Lesson 12: Stormscale enhancement to SRH

- Objective
  - Determine the likelihood that a storm is enhancing low-level SRH in its inflow
- Motivation
  - Some storms enhance SRH more than others from the base state environment

The objective of this lesson is to provide you considerations on how a potentially tornadic supercell may enhance Storm-Relative Helicities (SRH) in its stormscale environment. These considerations are based on results from recent project VORTEX experiments and other studies.

It is important to know which storms enhance SRH more than others due to factors that you cannot detect on the mesoscales.

Some storms may modify their local environment more than others and it is important to determine which ones may do so.

Lesson 12 Summary: Low-level SRH enhancement

- Close to radar, can detect
  - Forward flank outflow boundaries in velocity
  - Storm-induced inflow acceleration in velocity
- Far from the radar, must infer
  - FFD boundary right of the reflectivity core
  - Adequately high dewpoint depressions
- Anvil baroclinicity
  - Anvil must extend ahead of anticipated storm motion
  - Adequate solar heating right of anvil edge

Low-level SRH enhancement can be detected close to the radar in the form of forward flank outflow boundaries, and storm-induced inflow acceleration.

Far from the radar, your information content goes down and the need for inference and intuition go up. FFD boundaries are most likely to become prominent when supercells produce long forward flank cores and there are adequately high dewpoint depressions in the boundary layer.

Another, less tested consideration, is the anvil baroclinicity. Look for this where the anvil extends ahead of the anticipated storm motion and there is solar insolation outside the anvil shadow.

Lesson 13: Part 1--Near range tornadogenesis signatures

- Objectives
  - Recognize how tornado precursor signatures such as the mesocyclone and TVS appear in ranges less than 50 km
  - Interpret favorable signatures indicating a likely tornado that can only be detected at close ranges

The appearances of the classic mesocyclone and TVS are quite different when these features become large relative to the beam width. As we will see, the TVS may not represent the entire tornado cyclone, but perhaps an increasingly small part of it. The mesocyclone may not even look like a coherent rotational structure when smaller velocity structures within can be resolved.

On the other hand, it is these close ranges where radar data becomes by far the most useful tool because of the extreme detail it can portray.

There are two objectives in Part 1:

1. Recognize how tornado precursor signatures such as the mesocyclone and TVS appear in ranges less than 50 km
2. Interpret tornado signatures that can only be detected at close ranges.

Lesson 13 Summary: Close range rotation signatures

- More complexity of rotation
  - TVS is the detection of the tornado cyclone
  - Mesocyclone scale shows less symmetry
    - strongest velocities are located at midlevels on the right flank of the updraft for cyclonically rotating mesocyclones
    - Difficult to discern mesocyclone rotation at low-levels

To summarize, close range rotation signatures are more complex in scales.

At close ranges, the TVS is the manifestation of the tornado cyclone.

The mesocyclone does not appear as symmetric as before, with most of the strong velocities displaced to the right side of the updraft for cyclonically rotating storms. At low-levels, the mesocyclone may not appear at all.

Lesson 13 Summary: Close range tornadogenesis signatures

- Lowest level velocity signatures
  - RFD surge
  - strong convergence under higher level rotation and other updraft signatures
  - Increase in convergence with time
  - Rotation onset at tornado time
- hook echo
  - Rapid extension associated with RFD surge
  - Perhaps an elevated descent of reflectivity core into back side
  - Occasionally an anticyclonically shaped flare south of the hook

Remember that these signatures apply best to mesocyclone induced tornadoes.

Tornadogenesis signatures appear at low-levels as the RFD begins to develop. Convergence increases dramatically at low-levels and should appear under a midlevel mesocyclone and other strong updraft signatures. Only immediately before tornado formation is there any appearance of a tornado cyclone at low-levels. The convergence signature gives you on the order of 5 to 10 minutes of lead time. The onset of an intense tornado cyclone may only appear within a minute of tornadogenesis.

The hook echo may appear to extend in length and definition as the RFD develops. More recent research work has suggested that a descending ‘blob’ of reflectivity on the back side of the storm may contribute to RFD genesis.

As the RFD matures and begins to develop low-level rotation, an anticyclonic flare echo may be detected right of the main hook echo. Anticyclonic tornadoes are most likely if this anticyclonic flare coincides with the gust front underneath strong updraft.

Lesson 13 Summary: Close range mature tornado signatures

- Lowest level velocity signatures
  - TVS likely, sometimes not visible as a gate to gate signature – too close for a TVS
  - RFD gust front with other vortices along interface
- Reflectivity
  - Debris appears as a ball of very high reflectivity

Close range radar signatures of a mature tornado include good sampling of the tornado cyclone. Sometimes, the sampling is such that no gate to gate TVS strength signature appears in the tornado cyclone. The RFD gust front appears well defined, and there may be other vortices appearing along its interface.

If the tornado is ejecting large debris (e.g., tree branches, building parts), a reflectivity debris ball may appear as a small region of very high reflectivities extending upward several thousand feet or more.

Lesson 14: Part 2--Near range TDWR tornadogenesis signatures

- Objectives
  - Familiarize yourself with the applications and weaknesses of using Terminal Doppler Weather Radar (TDWR) for analyzing close range tornadogenesis signatures
  - Be familiar with the characteristics of the TDWR

As objectives, you should familiarize yourself with the applications and weaknesses of using the TDWR for analyzing close range tornadogenesis signatures. The same applications and weaknesses should apply to the interrogation of many meteorological features.

This lesson will also help you become more familiar with the characteristics of the TDWR.

At this point, development is underway to send TDWR data to WFOs on an operational basis. Thus for any site that has a TDWR in your CWA, this lesson will have more relevance to you.

Lesson 14: Summarizing TDWR vs. WSR-88D in near range tornadoes

- WSR-88D
  - Poorer resolution
  - Good unambiguous velocities
  - Poor temporal frequency
  - Low attenuation
  - Good coverage
  - Poor siting on mountain tops
  - NWS control
- TDWR
  - Better resolution
  - Poor unambiguous velocities
  - Good temporal frequency
  - High attenuation
  - Poor coverage (20 cities)
  - None sited on mountain tops
  - FAA control

The TDWR offers you excellent resolution and temporal frequency. However, given other factors favoring the WSR-88D, the TDWR will serve as an enhancement to the current network, and certainly not a replacement. Note the strengths of each radar are colored in yellow. The WSR-88D's advantages lie in its coverage, high

It is not known at this time how the TDWR data will be made operational to the NWS forecasters. Work will need to be done that will be defined during the course of AWOC delivery. As the details are worked out on delivering the data to the field, WDTB will provide more training on the use of TDWR data.

Lesson 15: Nonmesocyclonic tornadoes

- Objectives
  1. Given the example, show the conditions where pre-existing vertical vorticity is a significant tornado ingredient
  2. Determine the timing of greatest tornado threat given the superposition of
     - vertical vorticity and prestorm misocyclones
     - incipient updrafts
     - boundary intersections and/or collisions

The objectives of this lesson are two fold:

1. Show where pre-existing vorticity should be a significant tornado ingredient. This goes far beyond the analysis that is often shown in the SPC mesoanalysis web page using an objective analysis. Here, we go to the boundary scale using radar data, make some assumptions as to the nature of the wind field right up to the edge of either side of the boundary, then use the boundary width as a baseline from which to make an estimate of the background vorticity supply. This is probably as close as we can get to estimating what is really out there. However, note that boundary widths seem to decrease every time a newer higher resolution dataset becomes available.
2. Determine the timing of the greatest tornado threat given the superposition of vertical vorticity, perhaps prestorm misocyclones, incipient storm updrafts, and boundary intersections and/or collisions. Again, anticipating nonmesocyclonic tornadogenesis is very difficult when no significant rotational signatures appear on radar in advance of the event. Timing the convergence the tornado ingredients, vertical vorticity, vertical vortex stretching potential, based on what is detected by radar may help, along with spotter data, to provide some lead time.

Lesson 15 Summary

- Nonmesocyclonic tornadoes favored with
  - near zero CIN, steep lapse rates ground to cloud
  - Sharp boundary of 1 nm width or less
  - Prestorm vertical vorticity > .01s-1
    - vorticity sheet often rolls up into misocyclones
  - Superposition of strong developing updraft over low-level vertical vorticity
  - Often need a boost of vorticity and/or convergence from multiple boundary interaction
  - Prefers low boundary-relative cell motion

Nonmesocyclonic tornadoes are favored by:

near zero CIN, steep lapse rates ground to cloud

Sharp boundary of 1 nm width or less

Prestorm vertical vorticity > .01s-1

vorticity sheet often rolls up into misocyclones

Superposition of strong developing updraft over low-level vertical vorticity

Often need a boost of vorticity and/or convergence from multiple boundary interaction

Prefers low boundary-relative cell motion

None of this will give me an adequate false alarm or POD. These conditions can occur many times before there is a hit. But the increased awareness, and time to solicit for spotter reports may help in getting a warning out in time.

Lesson 16: Quasi Linear Squall Line (QLCS) tornadoes

- Objectives
  1. Recognize reflectivity/velocity precursor signatures to QLCS tornadoes
  2. Understand the importance of QLCS intersections with boundaries in regards to locating and timing the greatest tornado potential
  3. Understand the time-height evolution of a typical QLCS vortex
  4. What is the strength of of low-level rotation between tornadic and nontornadic vortices
  5. Familiarization with the theory of low-level QLCS vortex production by Trapp and Weisman (2003)

There are five objectives in this lesson. First, recognize the precursor signature in reflectivity and velocity most commonly observed with QLCS tornadoes. Second, learn how important QLCS intersections with boundaries are with regards to locating the greatest tornado threat. Third, learn the differences of the time-height evolution of a typical QLCS vortex and that of an isolated storm. Finally, this lesson will familiarize yourself with a theory of QLCS low-level vortex formation proposed by Trapp and Weisman (2003).

Lesson 16 Summary

- QLCS tornadoes favored
  - In regions with strong 0-1km shear, 0-3 km (≥ 15 m/s), 0-5 km (≥ 18 m/s) shear, similar to supercell tornado parameter space
  - At or left of intersections with
    - quasi-stationary fronts
    - outflow boundaries
- QLCS vortices may develop from the tilting of horizontal vortex lines within the cold pool and then enhanced by the coriolis force

QLCS tornadoes are favored in regions of strong 0-1 km shear and 0-6 km shear, a very similar setup to that of more isolated mesocyclonic tornadoes. As with isolated mesocyclonic tornadoes, QLCS tornadoes tend to be favored at and just north of a boundary external to the QLCS event.

QLCS vortices may develop from the downward tilting of horizontal vortex lines within the cold pool and then enhanced by the coriolis force. The coriolis force seems to act fairly quickly, within an hour, to enhance the cyclonic vortex and weaken the anticyclonic vortex to its north. Again, this theory has yet to have observational support since there has been no anticyclonic vortex observed immediately left of the cyclonic one.

Lesson 16 Summary (contd)

- QLCS tornado signatures
  - Near front inflow notch
  - In region of strong vertical vorticity along boundary
    - especially a low-level vortex
  - At or north of the initial bowing apex
- QLCS vortex time trends
  - mostly nondescending
  - typically larger and shallower than supercell mesocyclones
  - weaker rotational velocities than supercell mesos

QLCS tornadoes appear to be associated with a front inflow reflectivity notch in a region of strong low-level vertical vorticity just left of a region of a convex bow in the gust front. Look for a rear inflow notch to the right of the front inflow notch and behind the convex curve of the gust front as another indication that tornadogenesis probabilities increase.

QLCS vortices tend to be nondescending in nature. They are larger in diameter than traditional supercell mesocyclones but have weaker rotational velocities.

Lesson 17: FFG Modification

Objective:

- Understand the drawbacks of FFG, and recognize regions and times when modifying FFG would be very beneficial to detecting flash flooding

Bob Davis, forecaster at WFO Pittsburgh, presents this lesson on modifying FFG to better represent more accurate hydrological conditions

Lesson 17: Summary

- Reducing FFG for predefined basin conditions can improve FFMP detection capability and increase warning lead time.
- The use of FFGMOD factor for rainfall since data cutoff may aid in the updating of FFG between RFC issuance times.
- The use of FFGMOD may aid in the update of soil moisture conditions in small basins.

•This is especially true in highly urbanized areas

•FFGMOD may replace the “ratio” column in the FFMP threat table

Lesson 18: Effective Use of FFMP

Objectives:

- Understand how to best use FFMP, including Rate and Diff products
- Understand the radar limitations for rainfall estimation that directly affect FFMP and thus flash flood detection

Lesson 18 Summary

- FFMP is by far the best tool for flash flood detection
- FFMP *RATE* and *DIFF* products should be closely monitored
- Limitations of radar rainfall estimation affect FFMP greatly, especially hail contamination, distance from radar, and Z/R relationships

Lesson 19: Radar Rainfall Estimation

Objectives:

- Understand how inaccurate Z/R relationships can result in a missed flash flood detection
- Know how to anticipate warm rain processes

Lesson 19 Summary

- Radar rainfall estimation has errors that affect FFMP
- Failing to quickly and properly anticipate warm rain processes and then switch to tropical Z/R can result in failure to detect a flash flood

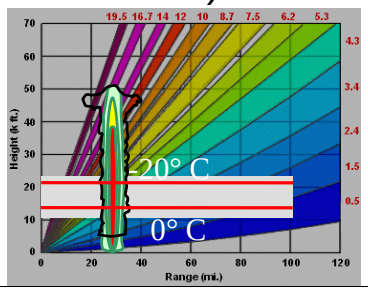
Lesson 20: Three Body Scatter Spike (Hail Spike)

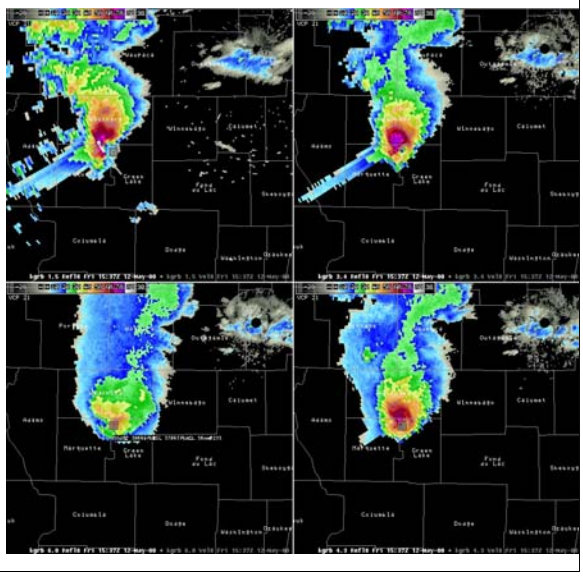
Objective:

- Understand what causes a three body scatter spike, what it signifies, and how it may contaminate velocity data

Lesson 20 Summary

- "storms producing the artifact, will or are now, *with absolute certainty*, producing very large hail" (Lemon 1998)





Another important point Lemon brings up in his paper is the additional threat of severe winds. With large hail and/or large quantities of wet hail, downburst potential is very high due to precipitation drag, and thus storms with hail spikes ALSO are likely to contain severe damaging winds, as is the case with this storm.

Lesson 21: VIL and VIL Density

Objective:

- Understand how VIL is calculated
- Recognize that VIL and VIL density are not good indicators of severe hail

Lesson 21: VIL / VIL Density Summary

- These products are not very useful in the context of hail detection when compared to base data and the HDA
- Understand VIL/VIL density limitations: distance to radar, environment, resolution, storm motion
- VIL of the Day? No way

VIL of the day struggles in that VIL is still used with it's many drawbacks, and then add to the fact that different environments can and typically do exist within the same radar umbrella on the same day

Lesson 22: The HDA

Objectives:

- Understand how the HDA produces severe hail probabilities and sizes
- Know how to best utilize the HDA, including ways to improve upon it

SCIT looks at the height and maximum reflectivity for each slice (top portion of the figure), stacks these regions of maximum reflectivity, giving a 3D depiction of an identificed storm (bottom portion). This 3D depiction is input into the HDA

Lesson 22: How to “beat” HDA

- Anytime SCIT misidentifies the vertical structure of a storm (strongly tilted)
- Knowledge of storm structure (meso, divergence, convergence, etc.)
- HDA needs a full volume scan of data before computing statistics
- When thermo. Environment characteristics change quickly or vary widely across radar umbrella

The HDA does not directly handle melting, which we showed in Severe IC1 that smaller sizes are highly affected by melting. Thus in areas with very moist environments HDA will overpredict sizes and POSH

•You can write a warning and send it out after viewing the bottom 2 radar scans in the time it takes the HDA to produce statistics from that volume scan

•Of course, with VCP 12 that time is decreased to about 4 minutes now.

•Knowing that a storm has rotation (HDA can’t account for that), BWER, other supercell characteristics is useful, especially in the early going before the hail cores really develop

Lesson 23: Hailstorm Characteristics

Objective:

- Recognize the following radar signatures of severe hailstorms and understand the limitations of the data.
  - Reflectivity height
  - Convergence/Divergence
  - Storm structure

Lesson 23 Summary: Large Hail Radar Interpretation

- At long range from the radar certain updraft characteristics may not be well resolved
- Understand data limitations, especially far from radar and/or with fast moving systems
- Usage of velocity signatures depend on range from radar and on viewing angle

Lesson 24: Hybrid/wet microburst detection

- Objective
  - Determine which microburst precursor signatures give
    - The most lead time
    - The highest probability of detection
- Motivation
  - Need to limit initial missed detections

The one objective of this lesson is to show which stormscale precursor signatures give you the most lead time and the highest probability of detection of wet and hybrid microbursts. The motivation for this session is to limit missed detections of the first microburst producing storm of the day and then increase the leadtime of all following microburst events.

We will limit ourselves to mostly stormscale signatures within the context of the environmental sounding.

Lesson 24 Summary: Hybrid/Wet downbursts

Precursor signatures

Signature	FAR	leadtime
1 Large enough CAPE to produce significant precipitation loading	high	Day 1
2 Significant DCAPE – evaporational cooling	high	Day 1
3 Strong initiation with high reflectivities (see updraft strength sessions)	med	15 min
4 Descent of high reflectivity core	med	5-10 min
5 Onset of midlevel convergence	med	0-10 min
6 Midlevel convergence (ΔV) > 50 kts	low	0 - 5 min

In summary, I present a table of microburst precursor signatures ordered with respect to the lead time each one offers.

The environment makes up for the most lead time but individual storm behavior precludes using the environment as a sole warning tool for every storm and thus the FAR is potentially high.

The best set of parameters to view in conjunction with the environment is to watch for the storms with rapid initiation capable of sending high reflectivities to greater altitudes than other adjacent storm. The descent of the high reflectivity core results in lower lead time but is usually when a warning is sent out since the descending core occurs rather rapidly. It is usually when the reflectivity core descends that the onset of midlevel convergence occurs. Don't wait for the midlevel convergence to reach some large value since large values of midlevel convergence and the period of strongest outflow occur nearly simultaneously.

In this session, I have not mentioned situations of weak shear convection embedded in strong horizontal winds. There have been many events where even weak showers have been able to initiate downdrafts bringing the high horizontal winds to the surface.

I encourage the use of DCAPE more than other parameters, because it accounts for downdraft forcing by lateral and sub cloud base dry air entrainment for a wider variety of situations. The method shown in this lesson is something that can be applied relatively quickly on the day of an

Lesson 25: MARC Signatures

- Objective
  - Be able to identify MARC signatures in radar data, and understand the characteristics of a signature associated with an impending severe wind event

The learning objective for this lesson.

Lesson 25 Summary: MARC signature

1. Look for $\Delta V \geq 25$ m/s in a small region (typically 15 by 7 km) embedded in larger scale convergence
2. Usually prior to formation of bows, line end vortices, low-level vortices within intense, deep reflectivity core
3. Found at midlevels of 4 – 5 km (13-16.5 kft)
4. Difficult to discern when line is parallel to the radials

To summarize, look for velocity differences > 25 m/s in a small region, typically 15 by 7 km and embedded in a larger convergent region at midlevels

The MARC signatures occur prior to the formation of bows, line-end vortices and low-level vortices within the intense deep reflectivity core.

Look to the midlevels, approximately 4 – 5 km AG for the MARC signature.

One final note, if the radials of your radar are roughly parallel to the line axis, you will have a difficult time detecting the MARC signature since most of the air flow is tangential and not radial.

Lesson 25 Summary: MARC signature (contd)

5. Environment favors these events in regions where surface-based CIN is not large
   - Downdrafts have increasing difficulty penetrating to the surface if cool, stable layer exceeds 2 km
   - Damaging wind potential thus mitigated in areas deep in the cool side of a polar front or ourflow boundary

Finally, the environment in which the MARC signature is embedded. The optimal situation for severe surface winds in the vicinity of a MARC is one in which the pre-storm CIN is low and there is no shallow layer. However, damaging winds have been observed in elevated MCSs where the stable layer can reach 2 km, even a bit more. Do not be surprised when a seemingly deep stable layer is insufficient to prevent damaging surface winds in an organized system. These kinds of events are not understood as well as we would like them to be. However, the probability of such an occurrence is still low.

Lesson 26: Extreme Non-Tornadic Wind Damage Events

- Objective
  - Identify characteristics of extreme non-tornadic wind events, and understand how to best observe and forecast their occurrence

The learning objective for this lesson.

Lesson 26: Unique? Characteristics of XDW Events

1) Quite long in duration at any one location along the path (10-20 minutes - or longer in extreme supercell/mesovortex events vs. a few minutes or less for bow echoes)
2) Very tight damage gradients along the periphery of XDW area
3) Supercell events have a much higher probability of being accompanied by large hail (> 4cm)

Much more research needs to be done, including obtaining data from new cases as they occur, to ascertain whether these XDW characteristics are generally the case with all XDW events. However, these characteristics were common in most cases examined thus far.

Lesson 26: Operational Considerations

- Supercells *within* a derecho producing MCS can be associated with an enhanced threat for XDW
- In *many* high-end derecho events - the most extreme damage is associated with supercells/mesovotices
- Supercell/Mesovortex XDW events *may* have somewhat different characteristics than “traditional” Bow Echo XDW events
- Events often move/evolve rapidly → timely flow of accurate information becomes *very* challenging
- Even high resolution surface mesonetwork observations may not be dense enough to completely capture storm-scale extreme wind events

The bullets presented here generally need little additional explanation. All are important things to remember when working an XDW event operationally. AWIPS and other operational procedures should be optimized to maintain maximum situation awareness during the event.

Lesson selection strategies

- Two – Part 1,2 lessons
  - ICSvr3-II-D and ICSvr3-II-E
    - Satellite detection of severe storms
  - ICSvr3-III-D and ICSvr3-III-E
    - Close range detection of tornadic storms
  - Suggest that both be taken
  - Part 2 lessons have part 1 as a prerequisite
  - Taking part 1 and 2 counts as two of the minimum of six lessons required for IC Svr 3

If you or your student picks either ICSvr3-II-D and/or ICSvr3-III-D, remind them that these are part 1 of a 2 part lesson, namely ICSvr3-II-E and ICSvr3-III-E. I encourage them to view both lessons. I consider the part 1 lessons to be prerequisites of the part 2 lessons because the part 2 versions contain extensions of the material in part 1 but not the introductions or the explanations. If a student wants to view a part 2 lesson, have them add the part 1. The students will be credited for taking 2 of the minimum of 6 lessons in IC Svr 3.

Lesson Selection Strategies

- Six lessons from six topics
  - Would cover one lesson from
    - updraft strength,
    - updraft location,
    - tornado,
    - flood,
    - wind and
    - hail interrogation
  - For a broad exposure to all topics
  - or

If you wanted a student to cover all storm interrogation topics here, one lesson from each topic will do the job. This would satisfy an environment where all convective and flash flood warning events are possible.

Lesson Selection Strategies

- For offices with high flash flood threat
  - Have the student concentrate on
    - updraft strength,
    - flood,
    - wind and
    - hail interrogation
  - For a broad exposure to all topics
  - or

If you wanted a student to cover all storm interrogation topics here, one lesson from each topic will do the job. This would satisfy an environment where all convective and flash flood warning events are possible.