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.

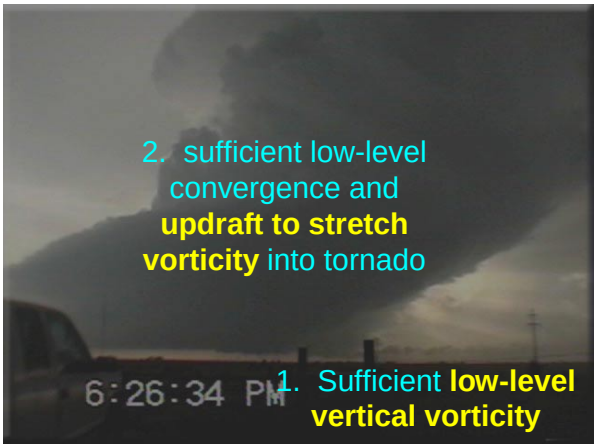
Storm scale signatures considered in tornado warnings

- 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.

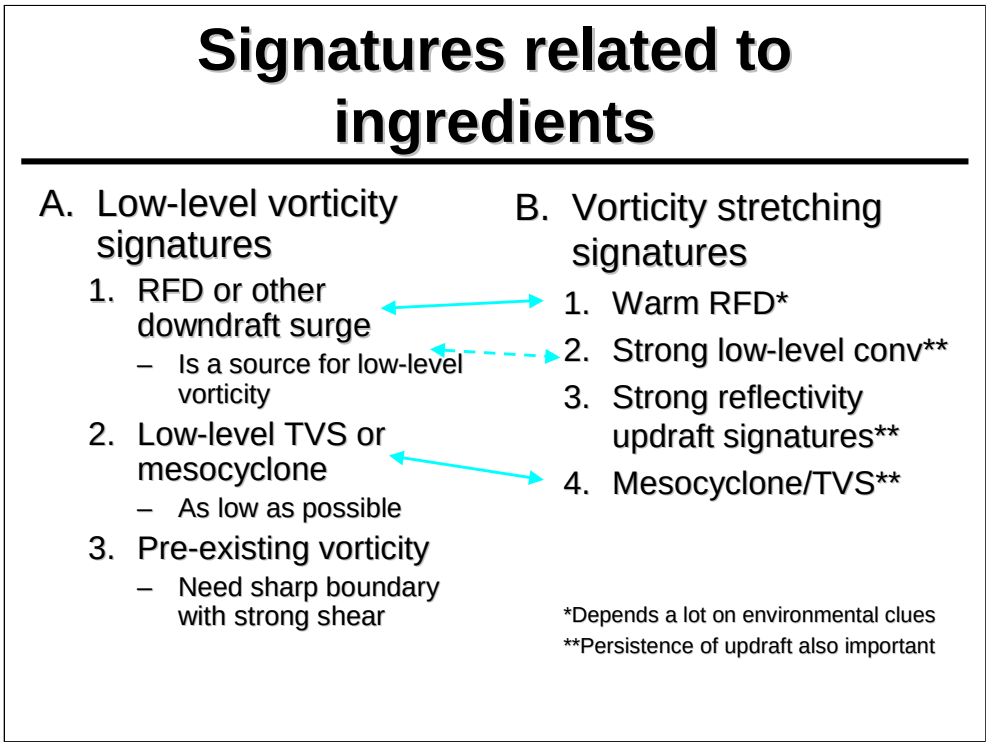
Tornado ingredients



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.

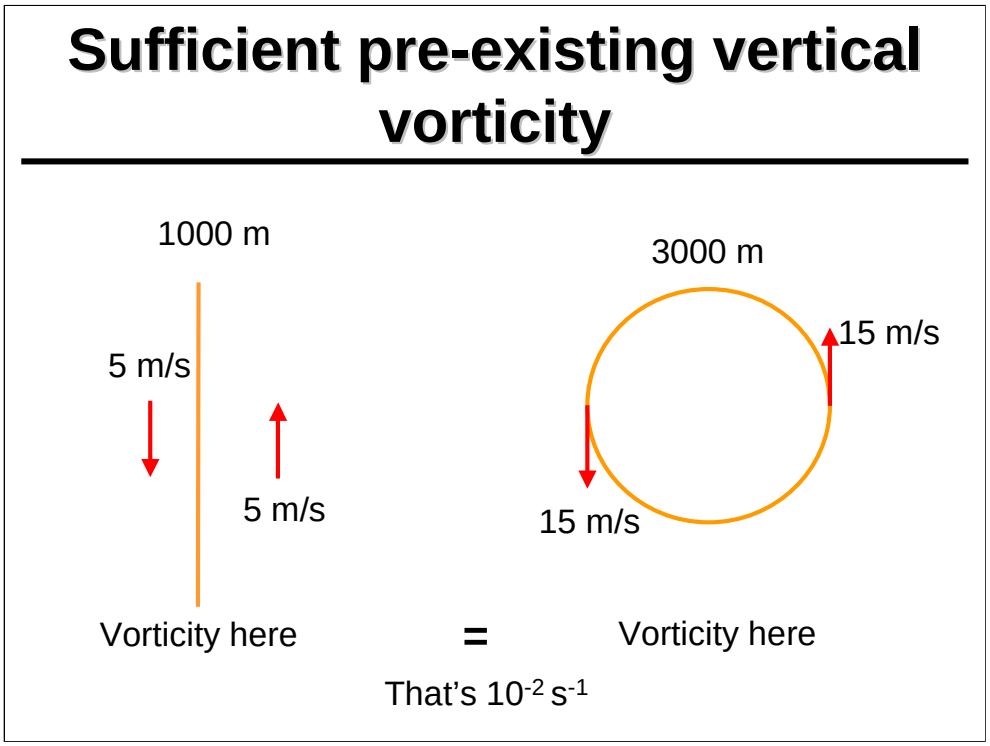
Low-level vorticity detection

- 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.

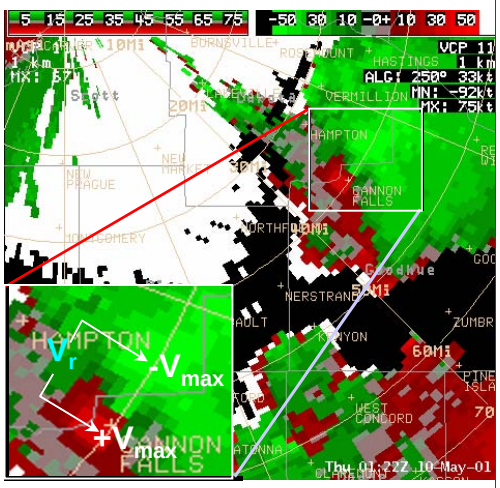
As a note, an RFD can generate vertical vorticity on short time scales (<5 minutes) and your opportunity to see it will be short lived. See the lesson on viewing tornadogenesis from close ranges.



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

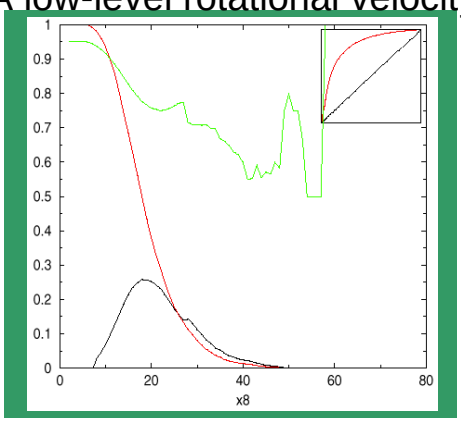
Thus vorticity = 2Vr (kts) / dist (nm) * 1000

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)



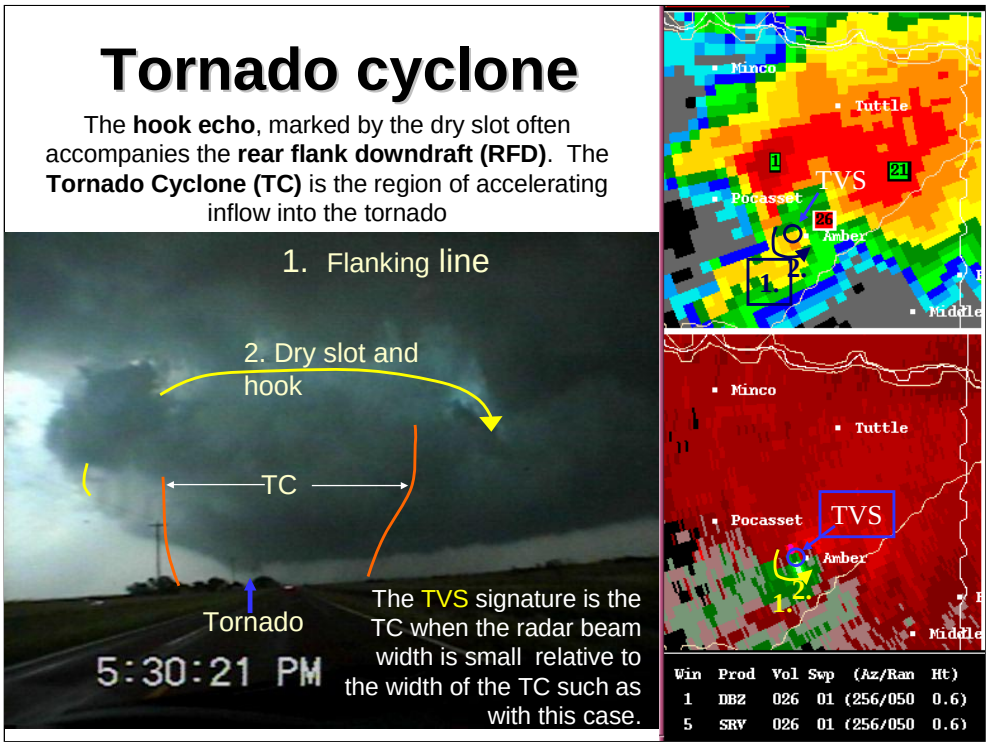
FAR = green line
POD = red line
HSS = black line

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.



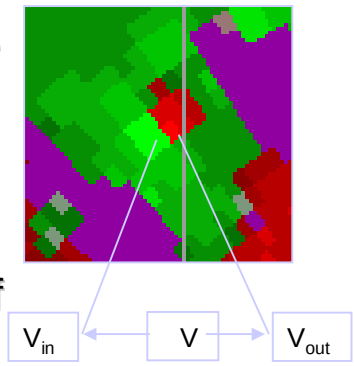
In order to generate vertical vorticity at ground level, a downdraft must bring and tilt elevated horizontal vorticity towards the vertical. The formation of the RFD usually indicates that the mesocyclone is developing downdraft within it, causing a bifurcation in the original simple rotational structure 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

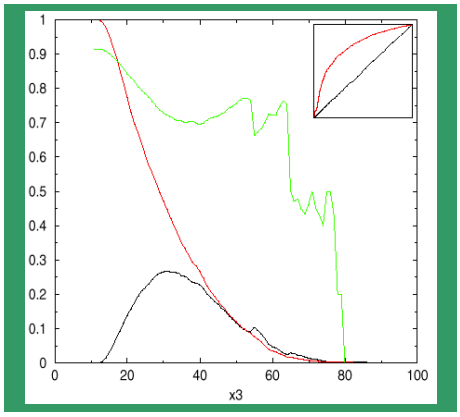
- Tornado Vortex Signature (TVS) strength is partly estimated by measuring the velocity difference, V, for each elevation slice
  - $V = |V_{in}| + |V_{out}|$
- A TVS is not definable beyond about 60 nm, thus if one exists, it is primarily a low-level feature



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

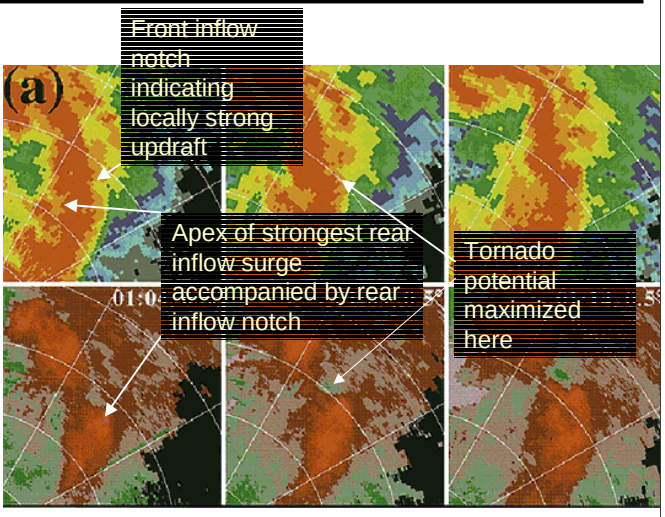
Inset = POD vs FAR

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.

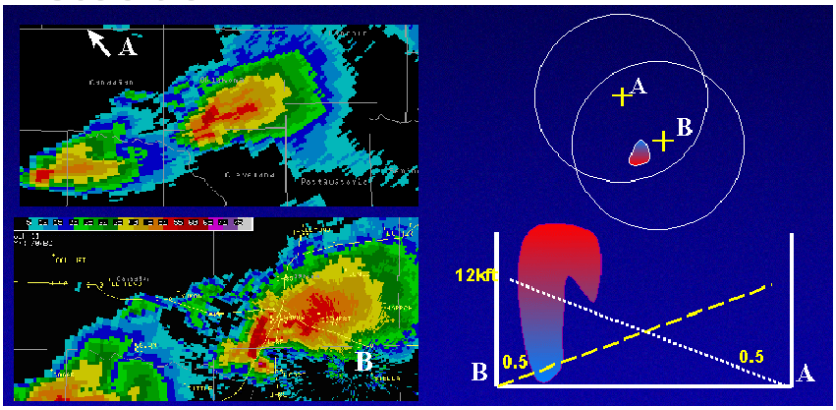
Strong Updraft Signatures

- 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.



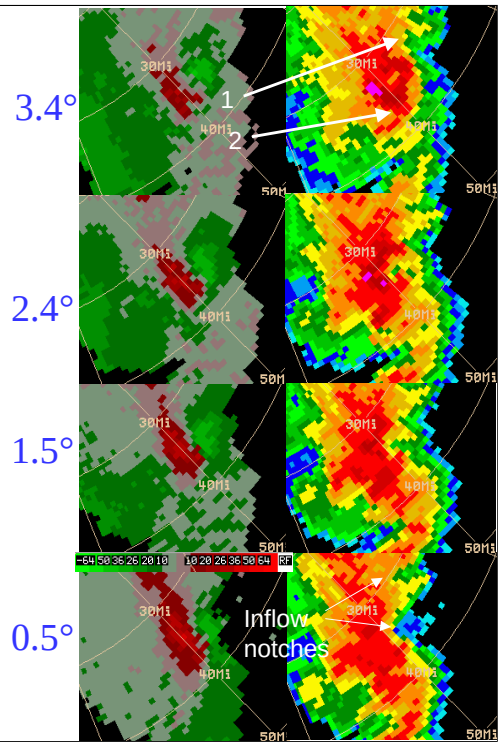
Note that this shape can be detected even from relatively far away. This gradient often marks one side of the WER. The locally concave feature is one of the most common amongst storms with intense updrafts.

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.

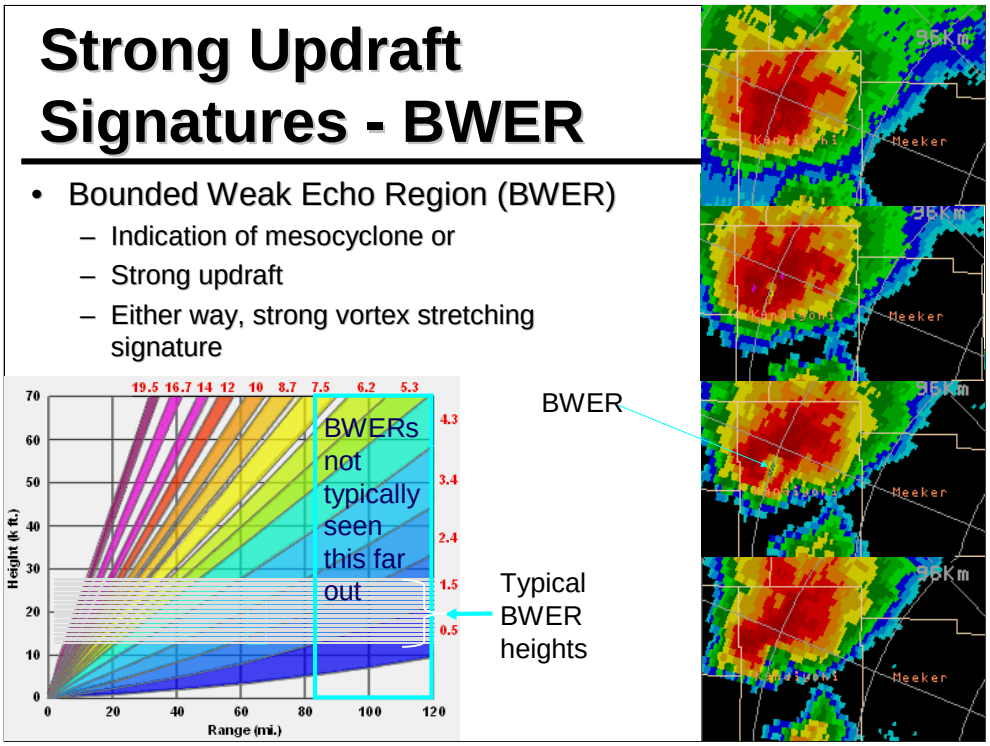
Strong Updraft Signatures – inflow notch

- 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.

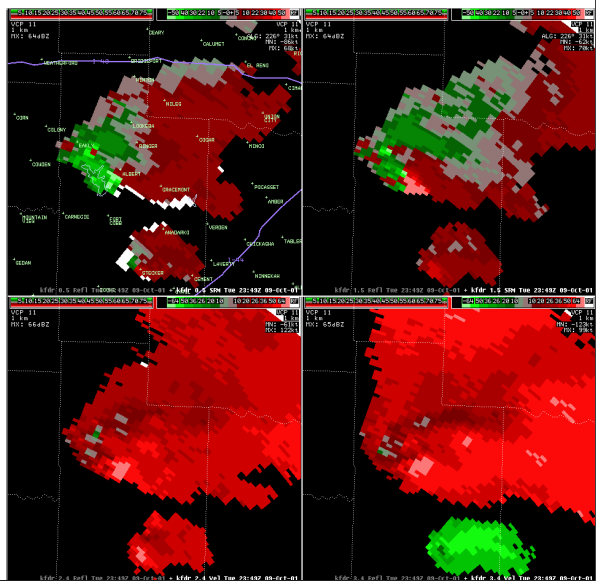


The BWER, as noted by the TWG study, when colocated with a mesocyclone and TVS increase the odds of a tornado being associated with the two rotational signatures.

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.

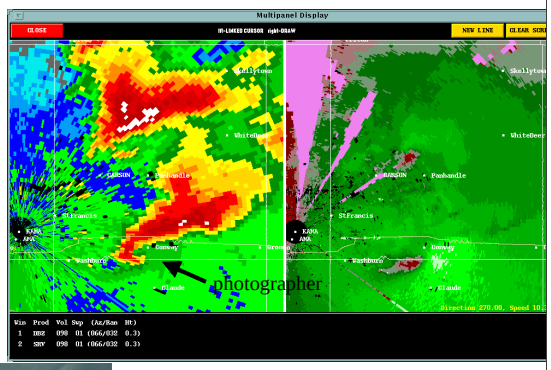


Midlevel mesocyclones provide a updraft forcing as a strong upward directed nonhydrostatic pressure gradient forcing forms beneath significant rotation aloft. The mesocyclone aloft may also have other relationships to providing for the tornado ingredients that we do not know of yet.

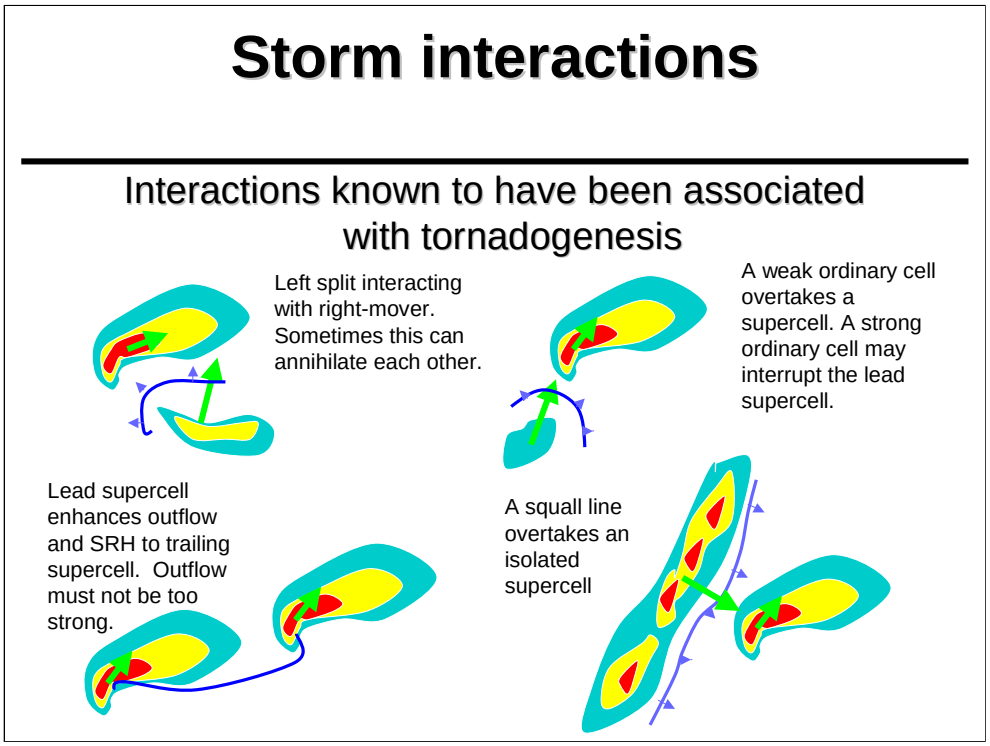
Remember that a mesocyclone also contains part downdraft during its mature phase. Most of the upward directed nonhydrostatic pressure forcing occurs in the updraft flank of the midlevel mesocyclone, usually on the right and front sides, perhaps extending beyond the visual cloud boundary.

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.