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.

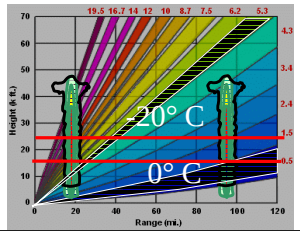
Part 1: Near range tornado signatures

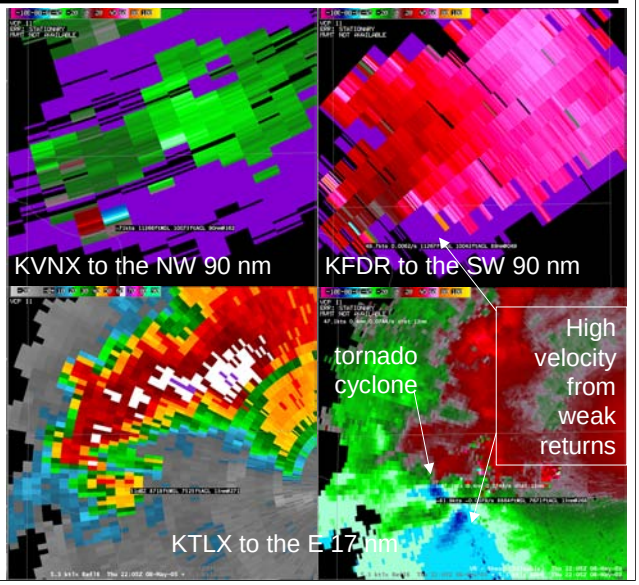
- TVS and mesocyclone appearance at close range
- Low-level convergence
- Hook echoes
- Debris

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.

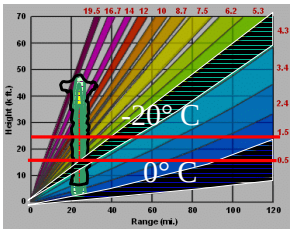
To start off, we show the appearance of this mesocyclone at approximately 10 kft AGL from two radars of different viewing angles but 90 nm away to that of KTLX, only 17 nm away just before the start of the tornado at 2205 UTC. To the northwest, KVNX lucks out and manages to sample the tornado cyclone 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.

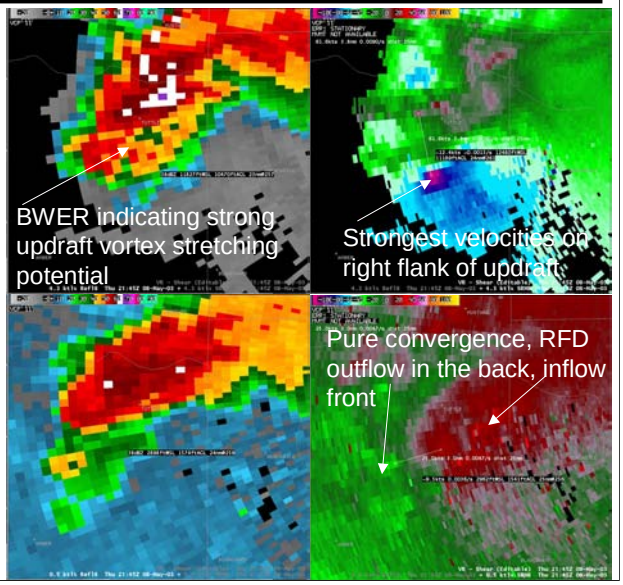
KTLX, 17 miles away, and with an elevation in the center of the 0.5° slices of the other radars, is close enough to resolve the low reflectivity, high velocity signature on the storms right flank. This is often visualized as rapid horizontal motion in the cloud bands to the right of the visual storm 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)





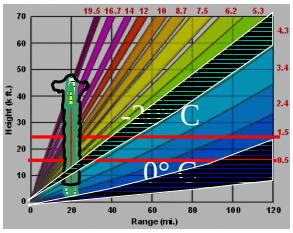
The environment on this day was very supportive of tornadoes, low LCLs, 0-1 km wind shear exceeding 25 kts, CAPE on the order of 4000 j/kg, no CIN and a strong dryline west. A PDS tornado watch is in effect and any supercell in the stage of development shown above is likely to have high tornado potential.

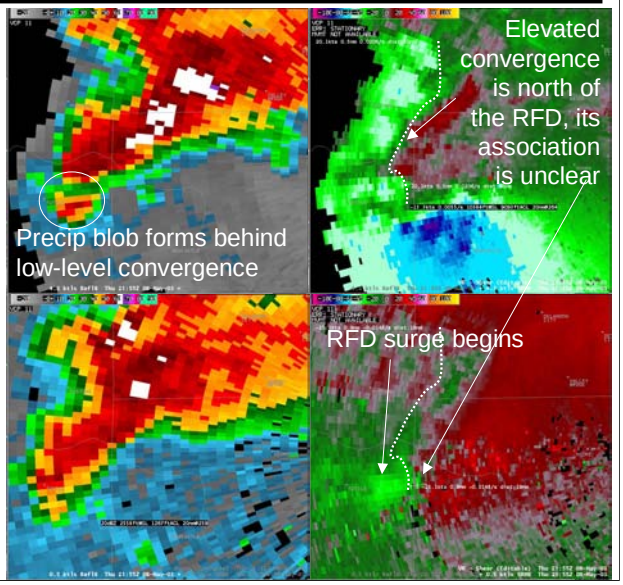
We'll take a walk through of common signatures at near range leading up to the tornado. We'll start at 2145 UTC, about 20 minutes before tornado time. Two slices are displayed, the lowest slice at 1 kft AGL, and the other at 11 kft AGL. As the storm approaches the radar, I will change elevations to keep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

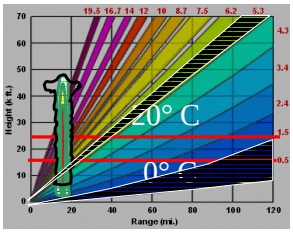


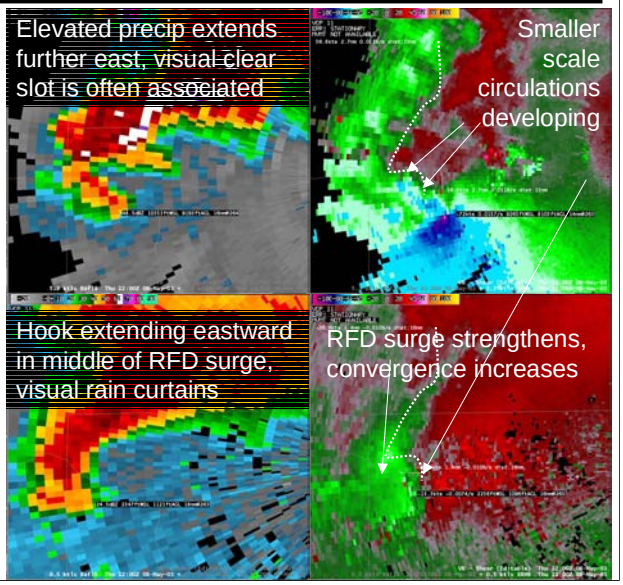


At 2155 UTC, 5 minutes later, the low-level velocity shows the RFD outflow surge may indeed be underway. Convergence at its nose ramps up considerably. But note there is no rotation. Above the RFD surge, note the inbounds and midlevel convergence increases a little behind the low-level convergence (accounting 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)

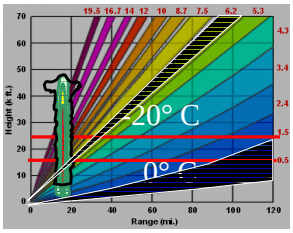


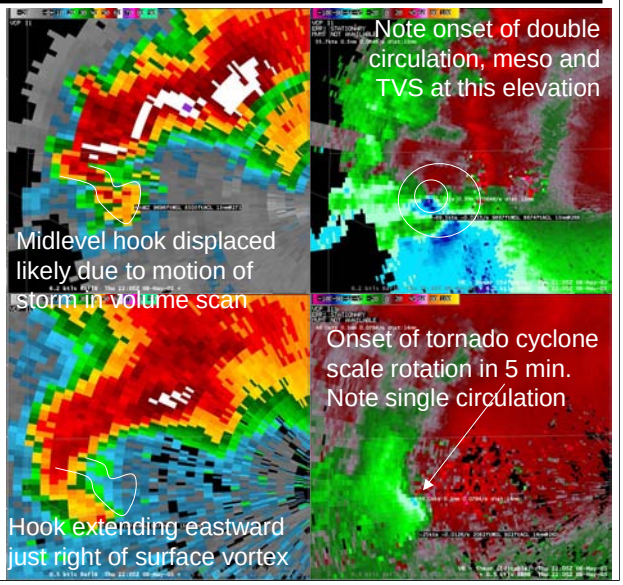


At 2200 UTC, the elevated precipitation blob connects with the low-levels to form the beginning of a hook echo. The part of the hook about to curl to the east lies in the middle to south part of the RFD surge. Strong convergence begins to broaden north to south just ahead of the hook echo. Note that 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)



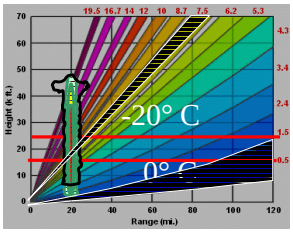


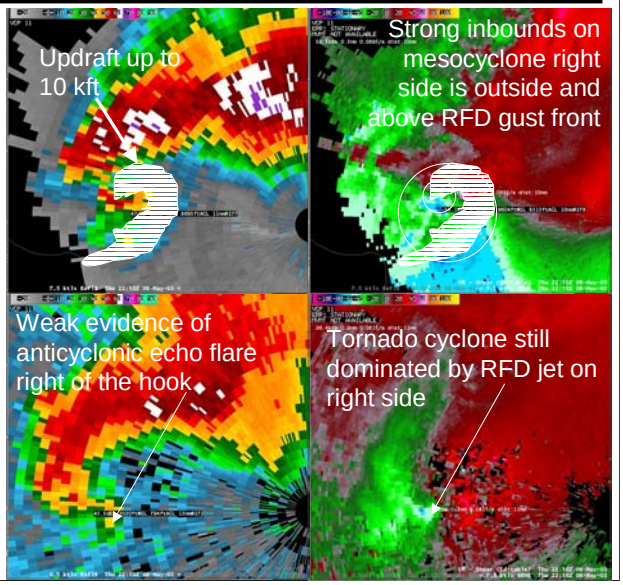
At 2205 UTC, the southern of the two circulations at 8.7 kft AGL consolidates and links with the rapid onset of circulation at the lowest level. This is tornadogenesis underway. The hook echo extends further east embedded on the strengthening RFD surge, now right of the circulation, now a tornado cyclone.

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)



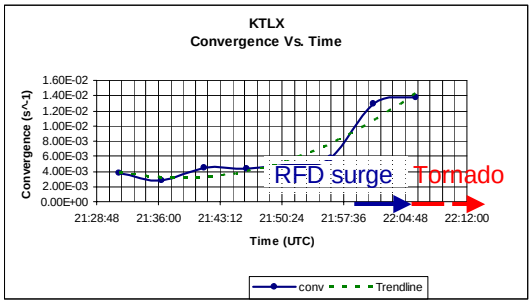


The tornado cyclone is still dominated by an RFD jet on its right side. At 8.7 kft AGL, note that the tornado cyclone (inner circle) still has the maximum inbound/outbound velocities away from the center. A TVS is present after noting the gate-to-gate shear of adequate magnitude. Some tornado cyclones 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

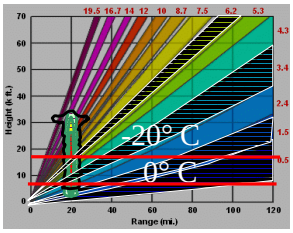
- WSR-88D shows increase in low-level convergence exceeding .01 s^{-1} prior to tornadogenesis
- Eastward RFD surge apparent at the same time

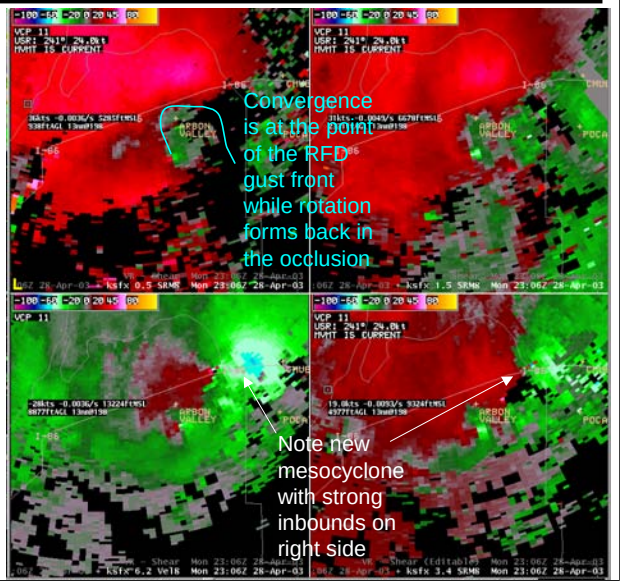


The RFD surge in combination with increasing storm-relative low-level inflow increases convergence rapidly just before tornadogenesis. Low-level convergence values rise above .01 s^{-1} across a one km baseline. There is perhaps a 1 to 10 minute leadtime before tornadogenesis in this case.

Another example of low-level convergence

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

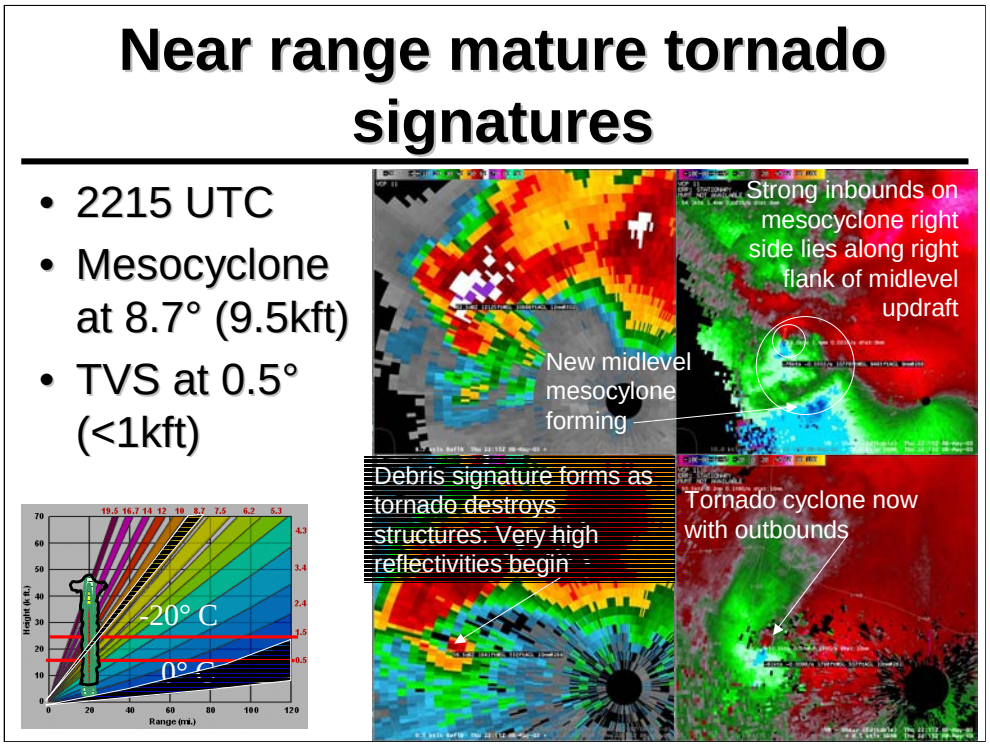




A close range tornadogenesis event occurred just south of Pocatello, ID on 28 April 2003. This time, the radar was left of the storm track, whereas on 08 May 2003, the radar was to its right. The different viewing angle precludes viewing the full strength of the RFD surge; it is directed more to the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

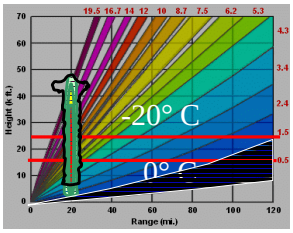
The RFD shows strong connection to the downdraft and outflow from the forward flank region of the storm's core.

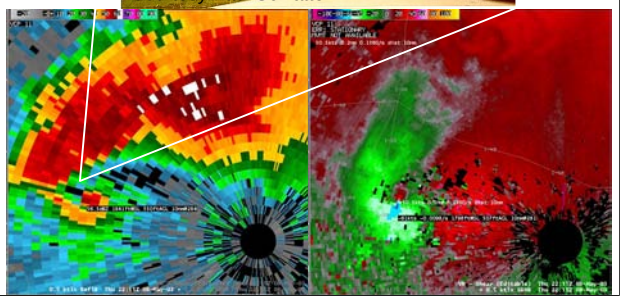
The tornado cyclone and larger mesocyclone still appear as separate circulations at 10 kft AGL. Note, however that on the right flank of the midlevel mesocyclone, a separate area of enhanced inbounds increase in strength that indicates the development of localized updraft rotation and the beginnings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

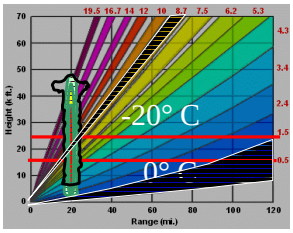


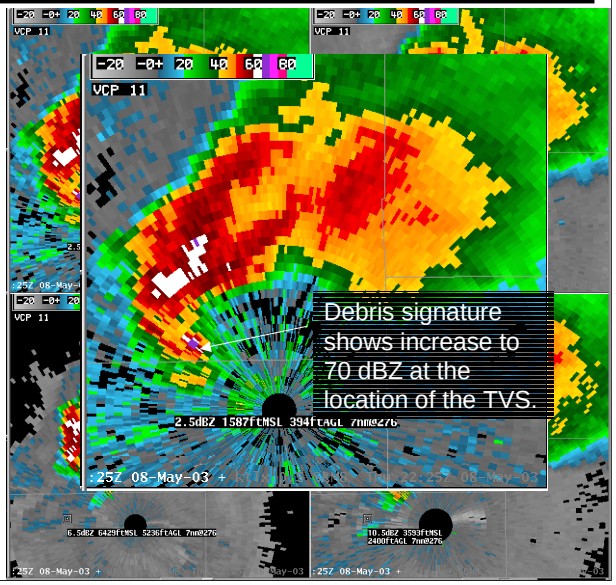


As observed from the ground to the northwest, and a couple minutes before the radar image, the tornado is beginning to loft debris several hundred feet into the air. At 16 miles range, large debris at this altitude is enough to be detected by the radar. Again, the debris needs to be large to present 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



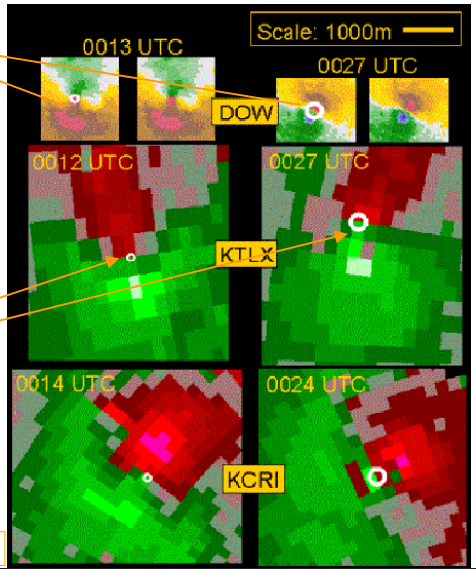


At 2225 UTC, the tornado impacted the General Motors plant in Southeast Oklahoma City resulting in a significant upward surge in debris.

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.