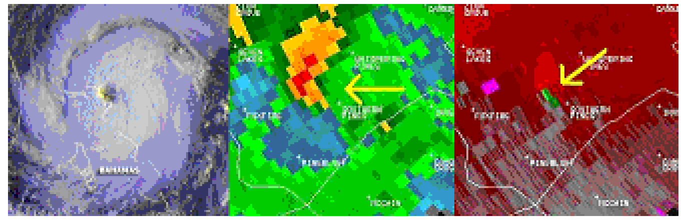
Notes on Tropical Cyclone Tornadoes across Central NC

July 2008



In recent years, a large number of significant Tropical Cyclones (TC's) have made landfall in the southeastern United States. The geography of North Carolina makes the state especially vulnerable to tropical cyclones as systems from both from the western Atlantic and the Gulf of Mexico can potentially impact the state. Various studies have shown that the majority of tropical cyclones produce at least one tornado. The unique nature of the tropical cyclone environment, when compared to the typical tornado environment, makes it a difficult forecast problem and one that requires a special approach by forecasters.

TC tornadoes are likely mini-supercells or shallow supercells (McCaul and Weisman 1996) which develop in an environment with strong lower-tropospheric vertical wind shear and limited instability. As a result, midlatitude conceptual models have shown limited success when applied to TC tornadoes. McCaul (1991) provided the conditions that are favorable for TC tornadoes; they are shown in the Tornado Threat Parameters table on the third page.

Synoptic Scale Features and Precursors

McCaul (1991) in a rigorous study of tornadoes associated with landfalling hurricanes over the period 1948 through 1986, found that:

- 59% of all hurricanes that made landfall over the U.S. produced at least one tornado. Some of these tornadoes were produced as many as five or more days after landfall.
- The vast majority of tornadoes occur in the right front quadrant (between 0 and 120 degrees) with respect to the motion of the tropical system.
- Shear and helicity parameters are maximized in the front and right quadrants with respect to the motion of the tropical system. With the system possessing very large storm-relative helicity (SRH) values.
- Many of the tornadoes associated with tropical systems occurred in environments with high moisture content but with relatively low CAPE (< 1000 J/kg). The TC tornado environment is typically conditionally unstable, with maximum buoyancy between 9,000 and 13,000 ft AGL (3 - 4 km level).
- Tropical systems moving faster than 35 mph show a reduced tendency to produce tornadoes. Most tornadoes were produced by systems moving between 7 and 20 mph.
- The strongest winds in the tropical cyclone tornado environments were in the 6,500 to 10,000 ft AGL (2 - 3 km level). Nearly all major tornado outbreaks had wind maxima at this level in excess of 30 kts (15 m/s). The level of wind maxima tended to roughly correspond to the level of maximum buoyancy.
- Shear values in the tropical cyclone tornado environments were typically around or in excess of 30 kts (15 m/s) in the 0 - 1 km layer, 40 kts (20 m/s) in the 0 - 3 km layer, and 50 kts (25 m/s) in the 0 - 6 km layer.

Curtis (2004) found a correlation between the entrainment of dry air into tropical cyclones and their subsequent tornado production. Some specifics that his study found include:

- The intrusion of dry air can substantially alter the thermodynamic structure of the tropical cyclone environment (with substantial enhancement of CAPE and surface-based instability) through increased solar surface heating and through the generation of potential instability due to drying aloft.
- Tornadogenesis appears to be enhanced when the favorable northeast (or right-front quadrant) of the storm coincides with a pronounced gradient in relative humidity, generally best reflected at the 700 or 500-hPa level.
- Curtis had three other findings regarding a composite of storms that had midlevel dry intrusions along with tornado outbreaks:
    - The composite storms had a lower average lifting condensation level (LCL) compared to non-tornadic storms. Other studies (McCaul and Cohen 2006) found that a lower LCL reduced the strength of the surface outflow, prevented outflow dominance and promoted storm persistence.
    - The composite storms were more moist in the layer from just above the surface through 900 hPa.
    - The composite storms were much drier at levels above 700 hPa.
- Curtis also found a strong diurnal signal in the distribution of tornadoes with 65% of the tornadoes occurring during the daylight hours. Schneider and Sharp (2007) found that nearly 90% of the cases in their study occurred during the daylight or early evening hours.

Other recent studies have highlighted the importance of baroclinic surface boundaries in tropical cyclone tornado production.

- McCaul et. al. (2004) described the importance of a low-level boundary in the tornado outbreak associated with the remnants of Tropical Storm Beryl in South Carolina, where most of the tornadoes occurred near or just northwest of a boundary, in slightly cooler surface air, with backed surface winds.
- Pietrycha and Hannon (2002) found that 16 of the 18 tornadoes associated with Hurricane Floyd developed immediately along and/or within the warm side of the coastal front that developed and moved onshore ahead of the storm.
- Edwards and Pietrycha (2006) emphasized the importance of surface boundaries in TC tornadoes. Such boundaries involve horizontal gradients of both CAPE and vertical wind shear, so it is unclear which effect predominates, or whether the boundaries are important for another reason.

Locklear (2008) in a study of severe weather and tornadoes across WFO Raleigh's (RAH) CWA during the period of 1950 to 2005 found that:

- Tropical cyclones that produce tornadoes in the WFO Raleigh CWA can make landfall anywhere along the Gulf Coast, the Southeast, or on the North Carolina coast.
- Of the 284 tornadoes that were reported, 48 tornadoes (17%) were associated with tropical systems or their remnants. Almost all (96%) were classified as weak (F0-F1) tornadoes.
- The active tropical season of 2004 (Charley, Frances, Gaston, Ivan and Jeanne) accounted for 10% of all of the tornadoes reported in the RAH CWA from 1950 to 2005.

Tornado Threat Parameters
Parameters that can be used to determine if a tropical cyclone environment poses a low or high threat of tornadoes. Adapted from McCaul (1991)

Parameter	Low Threat	High Threat
Location with respect to storm center	120 - 359 deg	1 - 120 deg
Lifted Index	> - 1	< -1
CAPE	< 500 J/kg	> 500 J/kg
0 to 3 km shear	< 39 kts (20 m/s)	> 39 kts (20 m/s)
SRH	< 100 m^2/s^2	>100 m^2/s^2
BRN	< 10 or > 50	10 to 50
850 hPa wind speed	< 30 kts (15 m/s)	> 30 kts (15 m/s)
Storm motion	< 10 mph or > 30 mph	10 to 30 mph
Axis of low level convergence over area	NO	YES

Other factors to consider:
LCL height
Surface dew point depression
Existence of a mid level dry intrusion and its location

A Difficult Radar Interrogation Issue

Schneider and Sharp (2007) summarized many of the issues which make tropical cyclone tornadoes such a difficult warning issue.

- Given the smaller dimensions and lower rotational velocities of mesocyclones in the tropical cyclone environment, the techniques that are used to warn for non–tropical cyclone tornadoes may not apply in the tropical cyclone environment. Thresholds of rotational velocity would have to be lowered, and reflectivity signatures would be more subtle.
- Radar sampling limitations may lead to lower radial velocity values.
- Reduced radar resolution due to the smaller storm dimensions also contribute to lower apparent radial velocity values, especially at far distances from the radar.
- Most of the tornadic storms in the study had shallow rotation, often observed only in the lowest one or two radar elevation angles, and usually extended no higher than 15,000 ft AGL (4.5 km).
- A deep, persistent mesocyclone often did not precede tornado touchdown. Most of the tornadoes were very short lived with rotational signatures often lasting only two to four volume scans (about 10 – 20 minutes).
- In this study, there were only a few long-lived supercells that produced multiple tornadoes. These long-lived supercells were the exception rather than the rule.

Local Warning Strategies

Of the 15 tornado events across central North Carolina studied in 2004 by Schneider and Sharp (2007), only 3 showed rotation at or above the 1.5 degree elevation angle before touchdown. But 14 of the 15 tornado events showed a feature called the Velocity Enhancement Signature (VES):

- The VES signature appears as a small area of enhanced radial velocity of 30 kts (15 m/s) or greater. It was observed between 7,000 and 14,000 ft AGL (2 - 4 km).
- In this study, the average lead time from the first appearance of a VES to the first tornado touchdown was 27 minutes.
- When a VES was observed along with a hook and a low-level rotation signature, these features were vertically collocated; the VES was directly above the reflectivity hook and the low-level rotation.
- Three precursors were found to give good lead time for tornado touchdowns:
    1. a near gate-to-gate mesocyclone rotational velocity of 20 kts (10 m/s) or greater
    2. a hook or appendage signature in the reflectivity data
    3. the presence of a VES of 30 kts (15 m/s) or greater between 7,000 and 14,000 ft AGL (2 - 4 km).

  None of these signatures should be used by themselves. All three should be considered in conjunction with storm environment data, other radar data, and radar sampling limitations.

In addition, a review of TC Tornadoes across central North Carolina in 2004 found:

- All tornadoes had a gate-to-gate velocity couplet at some point before touchdown, although the couplet may have only been visible on neighboring radars.
- All tornadoes had at least 15 kts (8 m/s) of rotational velocity, most had 20 kts (10 m/s) or greater.
- Cells with 25 kts (13 m/s) or more of rotational velocity had a tornado every time.
- Nearly every hook signature was accompanied by a tornado but not every tornado had a hook.

Recommended Tropical Cyclone Warning Criteria
Adjust thresholds downward for cells at greater distances from the radar

- Gate-to-gate rotational velocity of 15 kts -
  Minimum threshold for most TC tornadoes. Storm requires close vigilance, if a contributing factor is present, issue a TOR

- Gate-to-gate rotational velocity of 15 kts -
  If a VES of 30 kts or greater exists between 7,000 and 14,000 ft AGL, issue a TOR

- Gate-to-gate rotational velocity of 20 kts -
  Issue a TOR, may provide 15 to 20 minutes of lead time

- Gate-to-gate rotational velocity of 20 kts and a hook signature -
  Issue a TOR immediately, may provide 15 minutes of lead time

Best Practices - Storm Scale Features and Warning Techniques/Tools at RAH

- Recent studies at RAH suggest that Tropical Cyclone Tornadoes (TC Tors) were often bottom-up developers with rotation evident in the lowest elevation angles. The rapid development requires a quick warning decision and considerable radar vigilance as critical signatures might exist for only 2 to 4 radar scans.
- Know the environment and ensure that the storm coordinator or someone outside the immediate warning process is looking at the bigger picture – look for boundaries, axis of deep moisture and convergence. Use all of the appropriate tools available including…
  - Manual surface analysis, SPC Mesoanalysis Page and mesonet data in AWIPS
  - Local wind profilers,VWP Plotting tool, VWP hodograph in D2D
  - Look for boundaries in radar, satellite, and surface data (areas where helicity is potentially enhanced and surface dew point spread is narrower.
  - Monitor water vapor imagery for dry air intrusion potential.
- Designate at least one staff member to monitor the radar exclusively for the tornado threat. Rotate staff members through this position to maintain some freshness.
- If multiple bands of convection are moving across the CWA then sectorize the warning operations with forecasters assigned to follow the convective bands and not a fixed geographical area.
- Use VCP 212 to provide the greatest frequency of volume scans with the least range folding. Know how to change the PRF's or change VCP's to move range folding areas.
- With the rapid development of TC Tors there will likely be no evidence of a descending mesocyclone. Any gate-to-gate rotation in the lowest elevation angles warrants quick attention. Note that at further distances from the RDA the rotation will likely be more diffuse and not as apparent; be more liberal with TOR's here.
- Use reflectivity to track and screen the strongest cells which are the ones most likely to produce a tornado. Reflectivity signatures such as hooks and appendages will be much more subtle but they also warrant quick attention. (example: the Harnett County Tornado of 8/29/2004)
- Use SRM data in Warngen in lieu of reflectivity data to locate the circulation center, set the storm motion, and to issue the TOR.
- Use the Distance Speed Tool or the Warngen motion to set storm motion. The RPG will have problems defining a storm motion with individual storm cells rotating around a circulation center. Set the storm motion for your storm of interest.
- Use neighboring radars and TDWR's at TCLT and TRDU to see rotation in lower portions of the storm. Submit an RMR for super resolution and 8-bit data from neighboring radars.
- Storm history is very important. Bands of thunderstorms moving into the CWA that have a history of producing tornadoes require a more liberal approach to issuing of TOR's. These same cells are also typically far away from an RDA which also requires a more generous approach. (example: Scotland/Hoke County tornadoes in 2004)
- Watch for broad scale rotation that becomes better defined and tightens from one scan to the next. A quick generation of the gate-to-gate circulation is possible.
- Monitor LSR's and radar data while the system of outside of the RAH CWA. The Gibson Ridge Radar software allows the viewing of RDA's, elevation angles, and super resolution radar data that may not be available for a variety of reason including bandwidth.
- Use the recommended tropical cyclone tornado warning criteria.
- Note that super resolution radar data should provide significantly more reflectivity detail and some improvement in velocity detail. The current warning criteria was based on legacy radar data and thresholds may need to be adjusted.

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