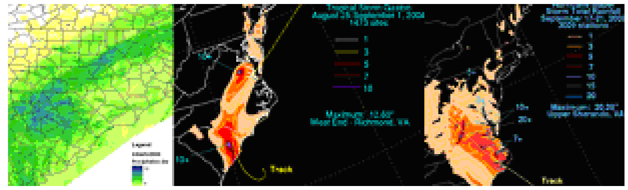
Notes on Tropical Cyclone Precipitation Distribution across central NC
July 2008



Tropical cyclones and their remnants pose a special forecast problem. These systems are capable of producing extremely heavy rainfall and often produce serious flooding and flash flooding. Rainfall rates up to 6 inches per hour are not uncommon and 43 inches of rain was reported in 24 hours when the remains of at Tropical Storm Claudette moved over Alvin, Texas. Flooding associated with the rainfall from tropical systems accounted for 292 deaths during the 1970-1999 period, which was 59% of the total deaths from tropical systems (Rappaport et al. 1999). These floods are why 63% of U.S. tropical cyclone deaths during that period occurred in inland counties. At least 23% of U.S. tropical cyclone deaths were associated with people who drown in, or attempted to abandon their cars and 78% of children killed by tropical cyclones drowned in freshwater floods.

Characteristics of Tropical Cyclone Rainfall from the Hydrometeorological Prediction Center

- Heaviest rain tends to fall left and downwind of the shear vector
- Diurnal variation in precipitation
  - Maxima ~ 0600-1500 UTC and 1800-0300 UTC
  - Minima ~ 0300-0600 UTC and 1500-1800 UTC
- Most of the rain in major Hurricanes occurs in the eye wall
- Most of the rain in Tropical Storms and Tropical Depressions occurs in the main inflow band/nearby boundaries
- Deep layered warm temperatures (warm cloud processes) lead to high precipitable water values
- High liquid water content around the storm's circulation leads to well organized convection
- Weaker storms tend to produce more widespread rains due to reduced organization
- For Tropical Cyclones
  - the dry side of the storm is to the west with the wet side to the east.
  - the Maximum rainfall falls within 50 miles of coast in 80% of cases
- For Tropical Cyclones in Transition
  - dry side of the storm is to the east with the wet side to the west.
  - rainfall max is often well removed from center, sometimes preceding the cyclone.
- Storms which drop most of the rain right of track are steered predominantly by shear or through a break in the subtropical ridge.
- Storms which drop most of their rain left of track recurve due to significant upper troughs in the westerlies. Rainfall streaks out well to the north of the system due to jet streaks moving around the upper trough and frontogenesis at the trough's leading edge.

Local Conceptual Models

Croke (2006) completed a study that looked at 28 tropical cyclones that made landfall or tracked along coastal North Carolina from1953 to 2004. The study included a precipitation analysis, climatological study, and some numerical simulations. She found that:

- The presence of the following features creates an environment favorable for enhanced precipitation:
  - negatively tilted upper trough over the Southern Plains.
  - strong upper-level divergence inland of the TC
  - strong inland moisture flux prior to landfall.
  - a wedge of cool air with a surface high pressure system centered over the northeast signals cold air damming.
  - formation of coastal front along Carolina coastline.

- The following are not necessarily dominant factors influencing rainfall:
  - maximum storm intensity or landfall intensity.
  - TC's translation speed.
  - distance from North Carolina.
  - The TC's landfall characteristics.

Cline (2003) described the distribution of rainfall relative to tropical cyclone tracks:

- Strong wind shear in the 850 – 300 hPa layer is typically the most dominating rainfall distribution factor. When wind shear (850 – 300 hPa layer) is strong (>= 30 knots at the latitudes of the Carolinas), it dominates the distribution of rainfall.
  - strong wind shear parallel (i.e., little or no cross track shear) to the tropical cyclone track typically spreads the rainfall well north in advance (by many hours and possibly days) of the TC's center.
  - strong cross track wind shear skews the rainfall distribution in the direction of the shear. For example, cross track shear left to right spreads and focus the maximum rainfall to the right of the track.
  - WFO RAH forecasters can evaluate the shear contribution relative to the projected tropical cyclone track in AWIPS using the "Tropical" procedure.
- Low level air mass boundaries are typically the second most dominating rainfall distribution factor, especially if the wind shear in the 850 to 300 hPa layer is not strong.
  - as a tropical cyclone tracks toward an existing low level surface boundary, the maximum rainfall will shift toward the boundary.
  - when the existing boundary is left (right) of an approaching tropical cyclone, the resulting rainfall will be skewed to the left (right) of the track.
- The translational speed of the tropical cyclone and orographic lift, are other factors contributing to the distribution of rainfall about a tropical cyclone.

Gonski (2006) in an informal look at the numerous tropical systems that impacted central North Carolina in 2003 through 2005 found that:

- The heaviest rainfall was generally focused near the 150 mile corridor of the tropical cyclone center track unless there was significant shear or a low level boundary.
- The heaviest rainfall was generally focused near the 150 mile corridor of the tropical cyclone center track unless there was significant shear or a low level boundary.
- A system approaching from the southwest typically has the corridor of heaviest rainfall skewed to the left of the track
- A system from the southeast typically has the corridor of heaviest rainfall just to the right of the track
- The heaviest rainfall favored the side of the tropical cyclone with the greatest upper level (250-200 hPa) divergence
- The heaviest rainfall was enhanced by surface boundaries or low level troughs
- The heaviest rainfall was influenced by topography
- The rain pattern appeared to distort in the direction of the 850-300 hPa bulk shear when shear exceeded 30 kts (15 m/s). Along-track shear stretched the precipitation shield well ahead of the system while cross-track shear tended to distort the precipitation shield to the right of the track.

Chen et. al. (2006) studied the relationship between the structure of TC rainfall and the environmental flow by computing the rainfall asymmetry relative to the vertical wind shear. They used the Tropical Rainfall Measuring Mission Microwave Imager (TRMM) rainfall estimates over the six oceanic basins across the world.

- Vertical wind shear and storm motion were two of the most important factors contributing to rainfall asymmetries in tropical cyclones (TC's).
- The environmental vertical wind shear is defined as the difference between the mean wind vectors of the 200 and 850 hPa levels over an outer region extending 200–800 km around the storm center.
- The rainfall asymmetry increases with shear strength and decreases with storm intensity.
- Vertical wind shear is a dominant factor for the rainfall asymmetry when shear is strong while TC translation speed becomes an important factor in the low shear environment.

DeLuca, Bosart, and Keyser (2004) in a study of the distribution of precipitation over the Northeast accompanying landfalling and transitioning tropical cyclones found that:

- Diabatically induced upper-level ridging ahead of the topical system can reconfigure the upper level jet maximum and upper divergence along with the implied thermally direct circulation.
- Ridging in upper-levels extends to lower-levels and increases the geopotential height gradient and can enhance the low level jet.
- Impacts of the low-level jet:
    - proper orientation can result in a prolonged coastal front with maximum precipitation occurring on the cool side of the boundary
    - transports high theta-e air well in advance of the cyclone

Klein, Bosart, Keyser, and Vallee in a study of the mesoscale precipitation structures accompanying landfalling and transitioning tropical cyclones in the Northeast found that:

- The development of an upper-level downstream ridge and jet…
  - occurred in nearly every case
  - placed Northeast in equatorward entrance region of jet
  - amplified lower-level jet and positive theta-e advection
- Enhanced precipitation as the TC interacts with a pre-existing mesoscale boundary or coastal front…
  - found in almost every case
  - heavy precipitation region located along and in cold sector of coastal front
  - stronger theta-e gradient when interacting with a upstream midlatitude trough during extratropical transition (ET)
- Interaction between downstream jet and upstream trough is critical for determining LOT versus ROT precipitation distribution.
- TC's large circulation induced an influx of tropical air over a distinct mesoscale boundary.
- Heaviest precipitation occurred over areas where strong surface frontogenesis, Qs and Qn forcing for ascent were present.

Atallah, et. al. (2007) completed a study investigating precipitation distribution associated with landfalling tropical cyclones over the eastern United States.

- Results indicate that a left of track precipitation distribution (e.g. Floyd 1999) is characteristic of TC's undergoing extratropical transition (ET). In these cases, a positively tilted mid-latitude trough approaches the TC from the northwest, shifting precipitation to the north-northwest of the TC. PV redistribution through diabatic heating leads to enhanced ridging over and downstream of the TC, resulting in an increase in the cyclonic advection of vorticity by the thermal wind over the transitioning TC.
- A right of track precipitation distribution is characteristic of TC's interacting with a downstream ridge (e.g. David 1979). When the downstream ridge amplifies in response to TC-induced diabatic heating ahead of a weak mid-latitude trough, the PV gradient between the TC and the downstream ridge is accentuated, producing a region of enhanced positive PV advection (and cyclonic vorticity advection by the thermal wind) over the TC. The diabatic enhancement of the downstream ridge is instrumental in the redistribution of precipitation about the transitioning TC's in both cases and poses a significant forecast challenge.

Extratropical Transition (ET)

Extratropical transition is a gradual process in which a tropical cyclone loses tropical characteristics and becomes more extratropical in nature. During extratropical transition, the cyclone begins to tilt back into the colder airmass with height, and the cyclone's primary energy source converts from the release of latent heat from condensation to baroclinic processes. The low pressure system eventually loses its warm core structure and becomes a cold-core system.

The precipitation associated with an ET event can be substantial and result in severe flooding. They are often associated with interactions of decaying tropical cyclones with the baroclinic environment in the midlatitudes. Extratropical transition poses an especially challenging quantitative precipitation forecasting (QPF) problem. Successful QPF requires an accurate prediction of the track, intensity, and structural changes of storms undergoing ET. Changes in the structure of a system as it evolves from a tropical to an extratropical cyclone during ET necessitate changes in forecast strategies

When a tropical cyclone begins to interact with the midlatitude baroclinic environment, the characteristics of the cyclone change dramatically:

- In satellite imagery, the inner core of the tropical cyclone loses its symmetric appearance and gradually takes on the appearance of an extratropical cyclone. In addition, a decrease in deep convection, the disappearance of the high-cloud canopy of a tropical cyclone, the exposure of the low-level circulation center, and the appearance of a comma-shaped cloud pattern or frontal structure (Merrill 1993).
- The nearly symmetric wind and precipitation distribution around the circulation center of the tropical cyclone evolve to a broad asymmetric distribution over a larger area.
- The expanding cloud field associated with a poleward-moving tropical cyclone includes large amounts of high clouds due to the tropical cyclone outflow into the midlatitude westerlies, areas of significant precipitation are often embedded in the large cloud shield.

At the start of an ET event, heavy precipitation becomes embedded in the large cloud shield associated with the tropical cyclone outflow that extends poleward from the tropical cyclone center (Bosart and Dean 1991). As ET proceeds, the distribution of heavy precipitation begins to resemble that of an extratropical cyclone with the heaviest precipitation to the left of track. The change in the distribution of precipitation can be related to the large-scale forcing of ascent due to the interaction of the tropical cyclone with an upstream trough and/or with a low-level baroclinic zone

Storms undergoing a transition to extratropical typically have their heaviest rain to the west or left of track (LOT) along the 700 hPa low track near an area of enhanced frontogenesis.

Cold-air damming to the east of the Appalachians can lead to enhanced precipitation during an ET event (Atallah and Bosart 2003) with other orogaphic effects capable of enhancing the precipitation during an ET event considerably.

Synoptic Scale Features and Precursors

In an informal study based on the work of Croke (2006) that examined synoptic and mesoscale features that enhanced precipitation associated with landfalling tropical cyclones in North Carolina, Hartfield (2006) compiled signals of heavy rain events relative to the time of landfall:

48-hours prior to landfall

- Positively tilted upper-tropospheric trough across the Southern Plains that is becoming more neutral or negatively tilted
- Increasing 925-850 hPa moisture flux, moisture flux vectors and convergence to drive moisture westward.

36-hours prior to landfall

- Increasing magnitude of 925-850 hPa moisture flux vectors, directed onshore.
- 250-500 mb PV, examine high values (>.5 PVU) across the Southern Plains.

24-hours prior to landfall

- Increasing 250-500 hPa PV values across the Southeast with a strengthening negatively tilted trough of PV that can interact with the TC.
- Look for signs of surface ridge building south and bringing cool air into inland North Carolina.
- A north-northeasterly flow across the Ohio River Valley and Central Appalachians with initial signs of frontogenesis
- High 925-850 hPa moisture flux values across the Southeast.

12-hours prior to landfall

- Well defined trough at 250-500 hPa beginning to interact with the TC.
- Significant pool of cool air at the surface.
- Increasing 925-850 hPa moisture flux across the Southeast.
- Strong frontogenesis along coastal NC and into Va.
- Strong onshore winds.

References

Atallah, E., L. F. Bosart, and A. Aiyyer, 2007: Precipitation distribution associated with landfalling tropical cyclones over the eastern United States. Mon. Wea. Rev.,**135**, 2185–2206.

Atallah, E. H., and L. F. Bosart, 2003: The extratropical transition and precipitation distribution of Hurricane Floyd (1999). Mon. Wea. Rev., **131**, 1063–1081.

Chen, S.S., J.A. Knaff, and F.D. Marks, 2006: Effects of Vertical Wind Shear and Storm Motion on Tropical Cyclone Rainfall Asymmetries Deduced from TRMM. *Mon. Wea. Rev.,***134**, 3190–3208.

Cline, J. W. (2003) Recent tropical cyclones affecting North Carolina, unpublished thesis (M.S.), University of Miami.

Croke, M.S. (2006) Examining Planetary, Synoptic and Mesoscale Features that Enhance Precipitation Associated with Landfalling Tropical Cyclones in North Carolina, unpublished thesis (M.S.), North Carolina State University.

DeLuca, D. P., L. F. Bosart, and D. Keyser, 2004: The distribution of precipitation over the Northeast accompanying landfalling and transitioning tropical cyclones. 20th Conference on Weather Analysis and Forecasting, Seattle, WA., Amer. Meteor. Soc.

Gonski, 2006: Tropical Cyclone Precipitation Distribution of Storms Impacting the Carolinas from 2003-2005. Local NWS Raleigh Seminar.

Hart, R. E., J. L. Evans and C. Evans., 2006: Synoptic Composites of the Extratropical Transition Life Cycle of North Atlantic Tropical Cyclones: Factors Determining Posttransition Evolution. Mon. Wea. Rev., **134**, 553-578.

Hart, R. E., 2003: A cyclone phase space derived from thermal wind and thermal asymmetry. Mon. Wea. Rev., 131, 546-564.

Hartfield, 2006: Tropical Cyclone Precipitation Distribution with Land Falling North Carolina Storms. Local NWS Raleigh Seminar.

Rappaport, E.N., M. Fuchs, and M. Lorentson, 1999: The threat to life in inland areas of the United States from Atlantic tropical cyclones. Preprints, 23rd Conf. on Hurricanes and Tropical Meteorology, Dallas, TX., Amer. Meteor. Soc.