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ARCHETYPES FOR SURFACE BAROCLINIC BOUNDARIES INFLUENCING TROPICAL CYCLONE TORNADO OCCURRENCE

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1. INTRODUCTION and BACKGROUND

The distribution of tornadoes within landfalling tropical cyclones (TCs) in the United States has been documented and examined since World War II, beginning with coarse estimations (e.g., Tannehill 1950, Malkin and Galway 1953, Sadowski 1962), and continuing with more refined climatological plots as tornadoes have become more thoroughly reported (e.g., Hill et al. 1966, Novlan and Gray 1974, Gentry 1983). Despite minor inconsistencies, these efforts progressively reinforced the notion that tornadoes tend to develop north through east of center, with the majority outside the radius of gale winds.

As TC tornado climatologies became more robust, forecasters and researchers investigated environments associated with the outer-northeastern quadrants which, in turn, further concentrated the understanding of the optimal TC tornado threat in space and time. The peak temporal window of tornado production during afternoon local time (e.g., Pearson and Sadowski 1965, Gentry 1983) was associated with diurnal maxima in surface heating and its influences on buoyancy, juxtaposed with favorable vertical shear profiles in the northeastern Cartesian quadrant (e.g., Novlan and Gray 1974), or alternatively, the right-front sector relative to system translation vector (McCaul 1991).

Those generalized studies are a precursor for the application to the TC environment of two crucial midlatitude concepts in analysis and forecasting:

1. The ingredients-based approach, already integrated into forecasting midlatitude severe local storms (Johns and Doswell 1992), flash flooding (Doswell et al. 1996) and winter storms (Wetzel and Martin 2001, with commentary by Schultz et al. 2002);
2. Surface mesoanalysis, a longstanding and important element of predicting tornadic supercell potential outside of TCs (i.e., Fujita et al. 1956, Magor 1958, Johns and Doswell 1992, Moller 2001).

Key ingredients for organized severe storms in midlatitudes – *moisture, instability, lift* and *vertical wind shear* – also are found to varying degrees in support of TC tornadoes. This is illustrated in the shear and CAPE composites of McCaul (1991), storm scale processes simulated by McCaul and Weisman (1996), favorable vertical shear profiles in the northeast quadrants of TCs as derived from dropwinsonde data (Bogner et al. 2000), and convective structure and mode considerations (i.e., the radar based studies by Spratt et al. 1997 and Rao et al. 2004). Also in common with midlatitude systems, those ingredients may be focused in the vicinity of thermodynamic inhomogeneities and associated with tornado occurrence, whether at the surface (e.g., Rao et al. 2000) or aloft (Curtis 2004).

Our aim is to blend those two fundamental concepts to benefit short-term, operational prediction, as applied to analyses of surface features that may influence environmental ingredients suitable for tornadic supercells. We illustrate four categories of association (Table 1) between baroclinic boundaries and TC tornado distribution, using idealized conceptual models based on actual mesoanalytic examples from recent storms. TC-embedded frontal boundaries may originate *a priori*, as in orographically influenced frontal zones and synoptic fronts, or *in situ*, as with areas of diurnal, differential diabatic heating.

2. BAROCLINIC ZONE CATEGORIES WITHIN TCs

2.1. *Buoyancy limiting*

Boundaries characterized by vertical shear favorable for supercells on both sides, but suitable buoyancy on only one, are termed “buoyancy limiting.” These fronts may be associated with pre-existing synoptic boundaries or *in situ* frontogenesis. In either event the relatively stable side is characterized by relatively cool air, imposing limits on surface-based buoyancy.

Although not explicitly categorized, the data presented by Suzuki et al. (2000) indicates such a boundary within the northeastern quadrant of a landfalling typhoon in Japan. The environment on the cool side of an orographically forced baroclinic zone appeared to be too stable to maintain tornado potential with mini-supercells that spawned three documented tornadoes along the front and in the warm sector.

In the U.S., surface analyses and preliminary local storm reports indicate Tropical Storm (TS) Ernesto (2006) produced three tornadoes on the warm side of a frontal zone, near the North Carolina coast. A more pronounced example in the same region was Hurricane Floyd (1995, Fig. 1), which was featured in Pietrycha and Hannon (2002) and which is the idealized specimen used herein. Roughly 12 h before landfall, a baroclinic zone became increasingly well-defined along

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Table 1. Categorizations of baroclinic boundaries associated with TC tornado distributions.

EVENT CLASSIFICATION	GENERALIZED ENVIRONMENT SUMMARY	TORNADO DISTRIBUTION	CASE EXAMPLE
Buoyancy limiting	**Favorable shear on both sides, Favorable buoyancy on warm side**	**Within and warm side**	**Floyd -1999**
Shear limiting	**Favorable buoyancy on both sides, Favorable shear on cool side**	**Within and cool side**	**Earl-1998**
Buoyancy-shear overlapping	**Favorable buoyancy on warm side, Favorable shear on cool side, Overlap within baroclinic zone**	**Narrow corridor near front**	**Charley-2004**
Null	**Favorable buoyancy and/or shear missing or no overlap, or unfavorable convective mode**	**None, or singular outlier**	**Isabel-2003**

the North Carolina coastal plain, distinguishing a cooler air mass of midlatitude continental origin and the maritime tropical (mT) boundary layer characterizing the pre-landfall TC environment. The frontal zone strengthened with a sharper thermal gradient as the TC center approached. This was concurrent with a tightening pressure gradient and strengthening surface flow on both sides of the front.

The 18 documented tornadoes were spawned by supercells in Floyd's northeastern outer bands. Of these, 17 occurred within and east of the frontal zone, none more than 10 km into the cool side of the thermal gradient. The earliest tornado occurred east of where the front would form. The quasi-homogeneous, mT air mass preceded frontogenesis, then became characteristic of the mesoβ–scale environment of tornadic supercells after frontogenesis. Once the frontal zone formed, supercells moved northwestward to westward, producing tornadoes in the mT air mass containing surface-based buoyancy, based on sounding analyses by Pietrycha and Hannon (2002).

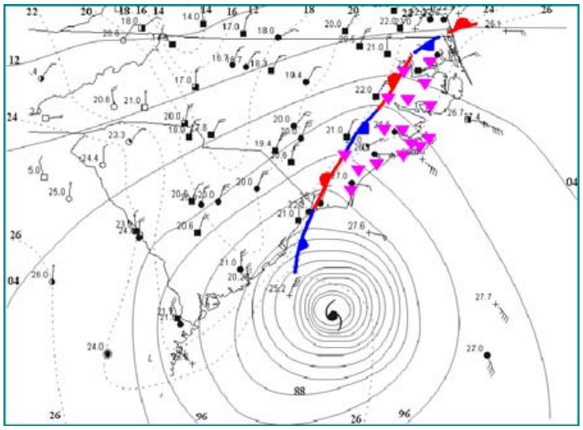

Figure 1. Conventional surface analysis for the landfall phase of Hurricane Floyd, 00 UTC, 16 September 1999 (adapted from Pietrycha and Hannon 2002). Isotherms are dashed in ^{O}C, isobars are solid every 4 hPa. Locations of tornado reports are plotted in magenta .

Although surface winds were strongly backed on the cool side of the front relative to the mT air (Fig. 1), tornado production abruptly ceased as supercells moved over the cooler boundary layer west of the front. This process is consistent with midlatitude cases characterized by supercells becoming elevated and losing tornado potential upon crossing over a relatively stable boundary (e.g., Doswell et al. 2002). The front moved little during the tornadic episode, its mean position being very close to that depicted for 00 UTC 16 September 1999 in Fig. 1.

2.2 *Shear limiting*

Some tropical cyclone tornado distributions are limited to the warm side of a frontal zone, in cases where favorable buoyancy exists for deep convection on both sides. When supercells cross the front before tornadogenesis, these situations comprise TC analogs to the midlatitude storm-boundary interactions documented by Markowski et al. (1998) and Rasmussen et al. (2000). Since vertical shear profiles are favorable for tornadic supercells only on one side of the boundary, these are deemed "shear limiting" environments.

TS Earl (1998) yielded an outstanding example of this process (Fig. 2) with seven tornadoes during its pre-landfall phase. Discrete convection formed in the outer spiral bands, S of the northern member of a double structured surface warm front, but rotated weakly at most, with no tornadoes, until crossing the northern front into stronger low level shear. Seven tornadoes were documented north of that front. The associated thermal gradient had been reinforced diurnally by differential insolation between the cloudier, more precipitation filled areas of northern Florida and relatively clear sky in south Florida and the southeastern Gulf of Mexico. Despite cooling with northward extent, proximity sounding analysis (Edwards et al. 2000) revealed surface-based buoyancy on the cool side of the northern frontal branch. A gradual transition was evident toward a stable air mass at Tallahassee. Accordingly, tornadoes failed to occur that far north and were confined to within ~100 km of the front.

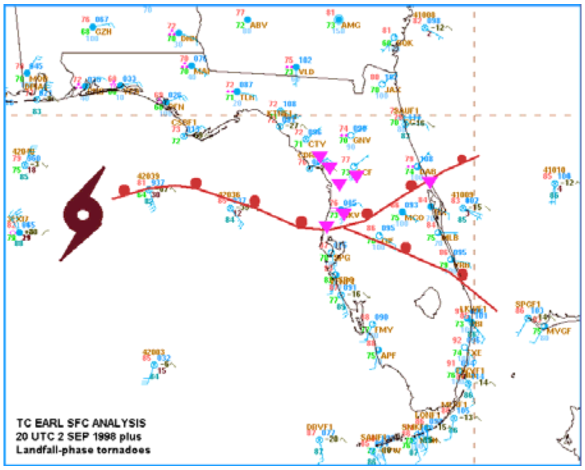

Figure 2. Surface data plot for 2 September 1998, 20 UTC (from Edwards et al. 2000). TC and warm front locations are affixed conventionally. Magenta triangles denote tornado reports that afternoon.

The cool side of the front also contained relatively backed low level winds and smaller dew point depressions, which in turn contributed to these factors favoring supercell tornado potential:

1. Enhanced storm-relative flow for tornadic supercells (based on Thompson 1998)
2. Enlarged low level shear values and hodographs (not shown) based on comparison of the 21 September 00 UTC soundings from Tampa (in the frontal zone, Edwards et al. 2000) and Miami (in the mT air mass);
3. Low lifted condensation levels (Rasmussen and Blanchard 1998, Thompson et al. 2003).

2.3. Buoyancy-shear overlapping

Another classification of tornado distribution associated with baroclinic boundaries in TCs is termed “buoyancy-shear overlapping.” This mode also is comparable to boundaries strongly influencing Great Plains supercells (Markowski et al. 1998), with a spatially narrow tornado distribution near the boundary. This regime contains favorable buoyancy on the warm side, suitable vertical shear on the other, and a distinct corridor of overlap optimizing supercellular tornado potential.

Hurricane Charley (13 August 2004) was an excellent example (Fig. 3). All 13 tornado reports (NCDC 2004) were within 60 km of a surface warm front moving slowly northward across the southern and central portion of the Florida peninsula; and most were slightly on the cool side of the front itself. The most robust tornado, however, occurred south of the front, producing F2 damage within a 68 km path length.

During the daylight hours, Charley turned northeastward across the eastern Gulf of Mexico and struck the southwest coast of the Florida peninsula (Fig. 3). After 12 UTC, as the air mass diabatically heated across southernmost mainland Florida, a baroclinic boundary developed in an area of pressure falls corresponding to a preexisting surface trough. This boundary moved northward through the daylight hours, remaining slightly to the right of the eventual track of Charley’s center.

Observed 12 and 00 UTC sounding data from Key West and Miami (south of the front) and from Jacksonville and Tampa (north of the front) were examined. So were numerous RUC model soundings, both in unaltered form and as modified in planar plots of shear and buoyancy parameters derived from the Storm Prediction Center’s objective mesoanalysis scheme (Bothwell et al. 2002). RUC soundings have been shown to be reliable proxies for observational soundings in assessing the proximity environments of midlatitude supercells (Thompson et al. 2003); however, their utility in the exceptionally intense kinematic gradients of mature hurricanes is yet to be tested in a systematic manner.

Based on the sounding series (not shown), the boundary layer became progressively less buoyant (i.e., ~1500 J kg^{-1} around Lake Okeechobee to <500 J kg^{-1} over west-central FL at 21 UTC) and more capped with northward extent through the front. Meanwhile, 0-1 km storm-relative helicity values ranged from 50-175 m^2 s^{-2} in the mT air to 200-300 m^2 s^{-2} in the cool air north of the front. The frontal zone comprised the overlap between most favorable low level shear and CAPE, also manifest in real time plots of derived parameters such as SPC Supercell Composite and Significant Tornado (as defined by Thompson et al. 2003).

2.4 Unfavorable baroclinic regime (null class)

Some TCs produce either no tornadoes or merely a singular, brief, weak outlier, despite the existence of thermal inhomogeneities at the surface. These storms comprise an effective null class, where either

1. Favorable buoyancy and shear are absent;
2. Buoyant and sheared environments do not overlap sufficiently to support tornadic supercells; or
3. Convective mode is unfavorable --- either too weak or too stratiform – lacking in discrete supercells which most strongly support tornadogenesis (i.e., Spratt et al. 1997).

Hurricane Isabel (18 Sep. 2003) exemplified the unfavorable situation where a surface front is present, but tornado production largely fails (Fig. 4). During the forenoon hours, as Isabel approached its landfall near Drum Inlet, North Carolina, a diffuse, broad baroclinic gradient was analyzed to its northwest, from southeastern Virginia southward over the eastern North Carolina coastal plain. Northerlies in a persistently rain-cooled inland air mass strengthened amidst the isallobaric response to the approaching hurricane, with diurnal surface warming east of the front. As Isabel made landfall during midday and penetrated inland through the afternoon, differential warming across the front became pronounced, sharpening the thermal gradient with which the core region of the hurricane began to interact. By 22 UTC the associated warm front was analyzed from Isabel’s core region westward over the Virginia/North Carolina border region, northeast across Virginia and east over southeastern Maryland.

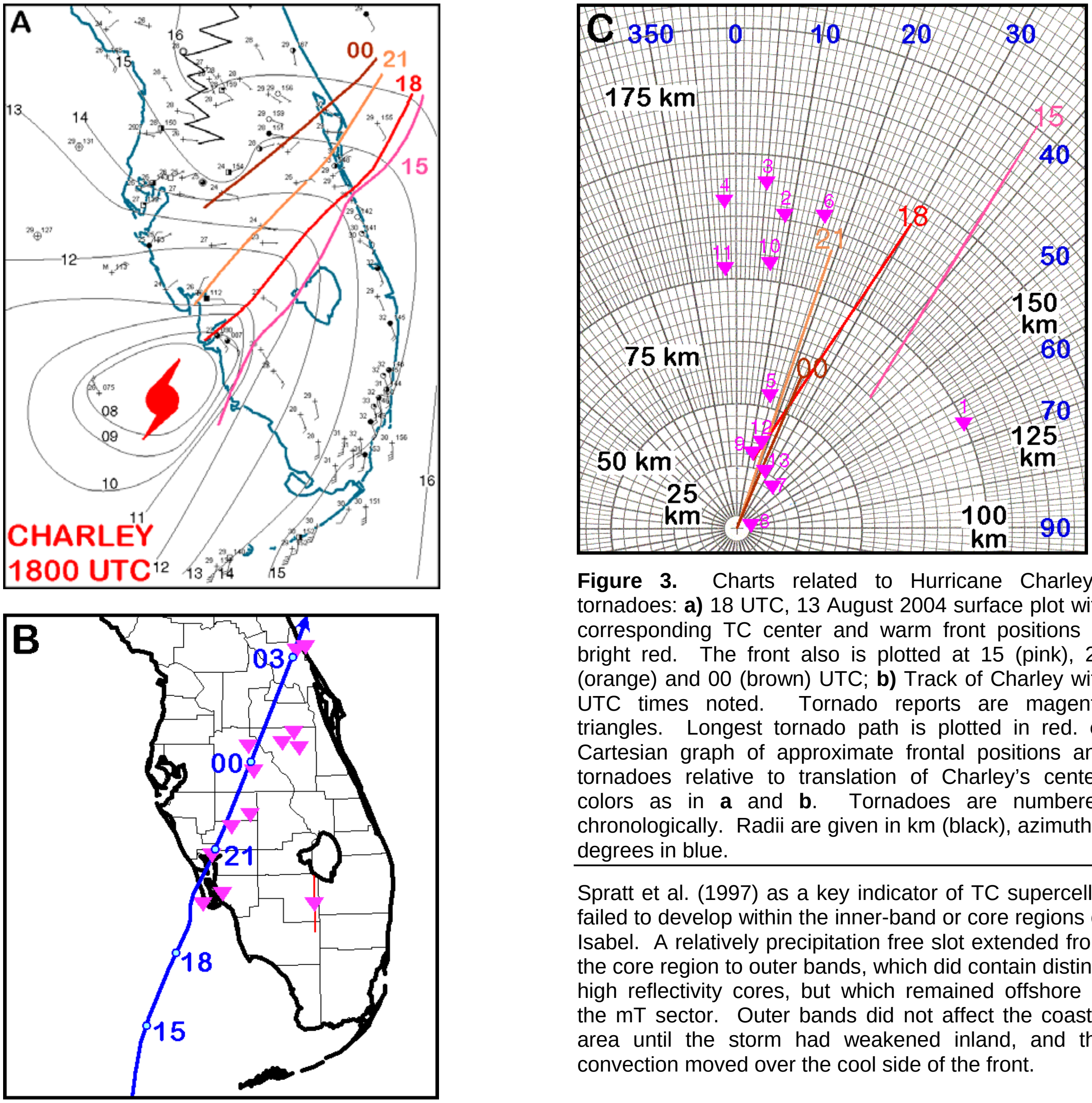

Figure 3. Charts related to Hurricane Charley's tornadoes: **a)** 18 UTC, 13 August 2004 surface plot with corresponding TC center and warm front positions in bright red. The front also is plotted at 15 (pink), 21 (orange) and 00 (brown) UTC; **b)** Track of Charley with UTC times noted. Tornado reports are magenta triangles. Longest tornado path is plotted in red. **c)** Cartesian graph of approximate frontal positions and tornadoes relative to translation of Charley's center, colors as in **a** and **b**. Tornadoes are numbered chronologically. Radii are given in km (black), azimuthal degrees in blue.

Isabel deformed the baroclinic zone into a pronounced S-shape (Fig. 4).

Observed soundings from 19/00 UTC (not shown) sampled favorable shear but too much stability for surface-based supercells northwest of the front at Washington DC, and favorable buoyancy and shear just southeast of the front at Wallops Island VA. Within the mT environment, only one brief and questionable tornado was reported in an inner band, in Norfolk VA, at 18/22 UTC. Despite occurring in a city, the tornado produced no evident damage (NCDC, 2003), and was rated F0 based on a visual sighting by law enforcement that apparently was not independently corroborated.

Examination of composite reflectivity imagery for the event indicates that unfavorable convective mode was a major contributor to the absence of tornadoes. Discrete and persistent cores of high reflectivities, identified by Spratt et al. (1997) as a key indicator of TC supercells, failed to develop within the inner-band or core regions of Isabel. A relatively precipitation free slot extended from the core region to outer bands, which did contain distinct high reflectivity cores, but which remained offshore in the mT sector. Outer bands did not affect the coastal area until the storm had weakened inland, and the convection moved over the cool side of the front.

3. SUMMARY and DISCUSSION

An ingredients-based approach examines lift, instability, vertical shear and moisture for predicting tornadic supercells. In the moisture-rich TC environment, the approach concentrates on foci of shear, lift and instability. Instability (as evident in thermal lapse rate) often is weak in the landfalling TC environment, leaving surface heating or a favorable, ambient mT sector as an important element to develop and sustain buoyancy. Vertical shear, optimized east through north of the TC center, may be further focused by surface kinematic adjustments associated with frontal zones.

This work illustrates associations of tornadoes and three general regimes associated with baroclinic zones inside the TC envelope (Table 1). Tornado distribution may congregate on the buoyant side of fronts where favorable shear exists on both sides; the more strongly

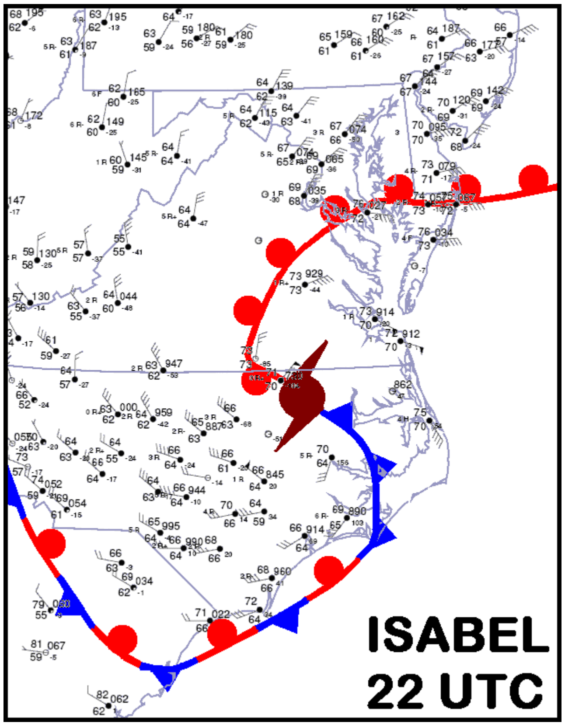

Figure 4. Surface data plot for 18 September 2003, 22 UTC. TC and fronts (derived from hand analyses of the thermal field) are labeled conventionally.

sheared side where CAPE is sufficient on both; and in an overlap near the front, outside of which favorable buoyancy and shear are insufficiently juxtaposed.

A fourth example concerns the existence of a frontal zone, with a lack of tornadoes that is associated with unfavorable CAPE, shear and/or convective mode on both sides of the boundary. This class may be the most difficult to forecast given the variety of tornadic possibilities in TC-frontal situations as exemplified above, the mesoanalytic uncertainties imposed by insufficiently dense observational data (discussed and illustrated by Sanders and Doswell 1995), and the "asymmetric penalty function" (e.g., Thompson et al. 2003) in operational tornado prediction, which encourages high thresholds for probability of detection concurrent with a de-emphasis on low false alarm rate.

Future expansion of this effort will involve systematic examination of numerous TCs to determine presence and character of any embedded fronts and associated CAPE and shear patterns, as well as tornado distributions relative to them.

Although outside the specific scope of this study, it must be noted that tornadic TCs sometimes lack robust surface baroclinicity. The environments of such storms may be favorable for tornadoes over a broad area without apparent presence or necessity of boundaries. Given supercells, such situations can yield large tornado outbreaks, in part because of the *lack of* baroclinic restrictions to shear and/or instability. This class of profusely tornadic TCs may be considered a tropical analog to widespread midlatitude outbreaks, where tornadic supercells are common throughout the warm, moist, favorably sheared and weakly capped sector of the cyclone -- sometimes without significant baroclinic forcing (e.g., the 3 May 1999 event, as documented in Thompson and Edwards 2000). One recent example is Katrina's Gulf landfall in 2005, with at least 45 tornado reports (NCDC 2005) over Alabama, Mississippi and the Florida panhandle, and Georgia tornadoes over 500 km from the hurricane's center –all in the absence of surface fronts.

Most landfalling TCs, however, are not monolithic, homogenized entities with equal tornado potential everywhere in the climatologically favored sectors, and should not be treated as such in operational forecasting. Instead, the TC is a *fluid mesoscale process* – often characterized by important and evident variations in its structure. For tornado prediction, these complexities may be identified and understood in many of the same ways as midlatitude systems. To this end, fronts have been shown to merge with and even to develop within the TC envelope. Fronts sometimes may be associated with relatively abrupt bounds of tornado potential that are quite strongly analogous to the role of mesoscale and synoptic boundaries in midlatitude cyclones.

Detailed and frequent surface mesoanalysis – especially by hand, but also utilizing automated objective analysis tools – is critical to improved diagnosis of a tornado-favoring environment within the broader TC envelope. Temporal continuity of such careful analysis is important to ascertain subregimes in the TC that are, or may soon become, (un)favorable for the development and maintenance of tornadic supercells. Forecasters should devote as much attention to mesoanalysis for TCs as for midlatitude cyclones, in order to refine the optimal tornado threat areas, and specifically, to judge where and when supercells may transition toward a higher or lower tornadic probability. The goals are to promote:

1) Lower false-alarm rate and higher probability of detection for tornado watches and warnings, including les "dead area" for watches (Edwards 1998). [County-based watches, being more precise, favor this approach much more than their former definition by coarse parallelogram.]
2) Provide a more robust basis to refrain from unnecessary (i.e., tornado free) watches and warnings when mesoscale conditions are relatively unfavorable, and
3) More precisely refine the threats in shorter-term SPC outlooks and mesoscale discussions.

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REFERENCES

Bogner, P. B., G. M. Barnes, and J. L. Franklin, 2000: Conditional instability and shear for six hurricanes over the Atlantic Ocean. *Wea. Forecasting*, **15**, 192–207.

Bothwell, P. D., J. A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., J117–J120.

Curtis, L., 2004: Midlevel dry intrusions as a factor in tornado outbreaks associated with landfalling tropical cyclones from the Atlantic and Gulf of Mexico. *Wea. Forecasting*, **19**: 411-427.

Doswell, C.A., III, H.E. Brooks, and R.A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**: 560-581.

_____, D.V. Baker and C.A. Liles, 2002: Recognition of negative mesoscale factors for severe-weather potential: A case study. *Wea. Forecasting*, **17**, 937-954.

Edwards, R., 1998: Storm Prediction Center forecast support for landfalling tropical cyclones. Preprints, *23rd Conf. On Hurricanes and Tropical Meteorology*, Dallas, Amer. Meteor. Soc., 53-56.

_____, G.V. Rao, and J.W. Scheck, 2000: Examination of tornadic supercells in Tropical Cyclone Earl (1998) using conventional and WSR-88D data suites. Preprints, *20th Conf. on Severe Local Storms*, Orlando, FL, Amer. Meteor. Soc., 97–100.

Fujita, T.T., H. Hewstein, and M.Tepper, 1956: Mesoanalysis: An important scale in the analysis of weather data. U.S. Weather Bureau Res. Paper no. 39., Washington DC, 83 pp.

Gentry, R.C., 1983: Genesis of tornadoes associated with hurricanes. *Mon Wea. Rev*., **111**, 1793-1805.

Hill, E.L., W. Malkin and W.A. Schulz, Jr., 1966: Tornadoes associated with cyclones of tropical origin -- practical features. *J. Appl. Meteor*., **5**, 745-763.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588-612.

Magor, B. W., 1958: A meso-low associated with a severe storm. *Mon. Wea. Rev.*, **86**, 81–90.

Malkin, W., and J.G. Galway, 1953: Tornadoes associated with hurricanes. *Mon. Wea. Rev*., **81**, 299-303.

Markowski, P.M., E.N. Rasmussen, and J.M. Straka, 1998: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting*, **13**, 852-859.

McCaul, E.W., Jr., 1991: Buoyancy and shear characteristics of hurricane-tornado environments. *Mon Wea. Rev*., **119**, 1954-1978.

_____ and M.L. Weisman, 1996: Simulations of shallow supercell storms in landfalling hurricane environments. *Mon. Wea. Rev*., **124**, 408-429.

Moller, A. R., 2001: Severe local storms forecasting. *Severe Convective Storms, Meteor. Monogr*., No. 50, Amer. Meteor. Soc., 433–480.

National Climatic Data Center (NCDC), 2003: *Storm Data*, **45**, no. 9, W. Angel, Ed., 122 pp.

_____, 2004: *Storm Data*, **46**, no. 8, W. Angel, Ed., 316 pp.

_____, 2005: *Storm Data*, **47**, no. 8, W. Angel, Ed., 358 pp.

Novlan, D.J., and W.M. Gray, 1974: Hurricane-spawned tornadoes. *Mon. Wea. Rev*., **102**, 476-488.

Pearson, A.D., and A.F. Sadowski, 1965: Hurricane-induced tornadoes and their distribution. *Mon. Wea. Rev*., **93**, 453-459.

Pietrycha, A.E., and C.D. Hannon, 2002: Tornado distribution associated with Hurricane Floyd 1999. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 619–622.

Rao, G.V., R. Edwards, and J.W. Scheck, 2000: Case studies of tornadoes associated with tropical cyclones based on conventional and WSR-88D data. Preprints, *24th Conf. on Hurricanes and Tropical Meteor.*, Fort Lauderdale, FL., Amer. Meteor. Soc., 306–307.

_____, J.W. Scheck, R. Edwards, and J.T. Schaefer, 2004: Structures of mesocirculations producing tornadoes associated with Tropical Cyclone Frances (1998). *Pure Appl. Geophys*., **162**, 1627-1641.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148–1164.

_____, and co-authors, 2000: The association of significant Tornadoes with a baroclinic boundary on 2 June 1995. *Mon. Wea. Rev*., **128**, 174-191.

Sadowski, A., 1962: Tornadoes associated with Hurricane Carla, 1961. *Mon. Wea. Rev*., **90**, 514-516.

Sanders, F., and C.A. Doswell III, 1995: A case for detailed surface analysis. *Bull. Amer. Meteor. Soc*., **76**, 505-521.

Schultz, D.M., J.V. Cortinas Jr., and C.A. Doswell III, 2002: Comments on ``An operational ingredients-based methodology for forecasting midlatitude winter season precipitation." *Wea. Forecasting*, **17**, 160-167.

Spratt, S.M., and co-authors, 1997: A WSR-88D assessment of tropical cyclone outer rainband tornadoes. *Wea. Forecasting*, **12**, 479-501.

Suzuki, O., H. Niino, H. Ohno, and H. Nirasawa, 2000: Tornado-producing mini-supercells associated with Typhoon 9019. *Mon. Wea. Rev*., **128**, 1868-1882.

Tannehill, I.R., 1950: *Hurricanes: Their Nature and History*, 7th Ed., Princeton University Press, 220 pp.

Thompson, R. L., 1998: Eta model storm-relative winds associated with tornadic and nontornadic supercells. *Wea. Forecasting*, **13**, 125-137.

_____, and R. Edwards, 2000: An overview of environmental conditions and forecast implications of the 3 May 1999 tornado outbreak. *Wea. Forecasting*, **15**, 682-699.

_____, R. Edwards, J.A. Hart, K.L. Elmore and P. M. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243-1261.

Wetzel, S. W., and J. E. Martin, 2001: An operational ingredients-based methodology for forecasting midlatitude winter season precipitation. *Wea. Forecasting*, **16**, 156-167.