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TROPICAL CYCLONE TORNADOES – A RESEARCH AND FORECASTING OVERVIEW. PART 1: CLIMATOLOGIES, DISTRIBUTION AND FORECAST CONCEPTS

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1. INTRODUCTION

Tropical cyclone (TC) tornadoes represent a relatively small subset of total tornado reports, but garner specialized attention in applied research and operational forecasting because of their distinctive origin within the envelope of either a landfalling or remnant TC. As with midlatitude weather systems, the predominant vehicle for tornadogenesis in TCs appears to be the supercell, particularly with regard to significant[1] events. From a framework of ingredients-based forecasting of severe local storms (e.g., Doswell 1987, Johns and Doswell 1992), supercells in TCs share with their midlatitude relatives the fundamental environmental elements of sufficient moisture, instability, lift and vertical wind shear. Many of the same processes – including those involving baroclinicity at various scales – appear to contribute to tornado production in both tropical and midlatitude supercells. TCs do diverge somewhat from extratropical perturbations in supporting tornadic supercell potential, not in the necessity of the aforementioned basic ingredients inasmuch as in their relative magnitudes and spatial juxtaposition.

Published literature documents various aspects of the history of significant tropical and midlatitude U.S. tornado occurrences (e.g., Grazulis 1993), applied research efforts related to forecasting nontropical tornadoes (e.g., Galway 1992, Doswell 2007), forecasting concepts and techniques for midlatitude tornado events (e.g., Johns and Doswell 1992), and climatological and analytic studies specifically covering TC tornadoes (numerous, to be cited subsequently as relevant). This extended abstract represents a preliminary subset of what will be a much more extensive formal article that will review all aspects of TC tornadoes, including historical events, climatologies, evolution of related literature and findings, physical concepts of supercell and tornado development specific to the TC environment, procedures and concepts of TC tornado prediction, and avenues for additional research. Herein is presented a somewhat chronological review of findings in the literature regarding the geospatial distribution of tornadoes – both within the TC environment and in a climatological sense. Next, current TC tornado forecasting practices are summarized. Finally, a brief overview is provided for those aspects of the remainder of the preliminary article that was not included in this conference preprint, for space considerations.

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[1] Significant tornadoes are defined (after Hales 1988 and Grazulis 1993) as those whose damage is rated >F2 (>EF2) on the Fujita (Enhanced Fujita) damage scale (e.g., Fujita 1971, LaDue and Ortega 2008).

2. CLIMATOLOGIES and DISTRIBUTION PATTERNS

a. Individual TCs and classifications

TC tornado climatologies are strongly influenced by the prolificacy of reports with several exceptional events (Table 1). The general increase in TC tornado reports, noted as long ago as Hill et al. (1966), and in the occurrence of "outbreaks" of 20 or more per TC (Curtis 2004) probably is a TC-specific reflection of the recent major increase in overall tornado reports, particularly those of the weakest (F0/EF0) damage category in the database. The nationwide boost in weak tornadoes over the past 2-3 decades is related to a tendency toward more intensive National Weather Service efforts in the storm spotting and warning verification realms, greater media coverage, increasing population and the spread of ready video and photographic documentation capabilities; see McCarthy (2003) and Brooks et al. (2003) for further discussion, and Fig. 2 from Verbout et al. (2007) for a vivid illustration.

It must be acknowledged that historic F-scale ratings were prone to considerable subjective judgment and that the tornado database at large is fraught with both known and potential inaccuracies (e.g., Doswell and Burgess 1988). The increased precision and number of damage indicators (DIs) and degrees of damage in the EF-scale (LaDue and Ortega 2008) presumably reduces the potential for missed tornadoes in less densely populated areas. On the other hand, distinguishing damage of some F0/EF0 and F1/EF1 TC tornadoes from that produced by the fortuitous passage of hurricane winds over the same areas may remain quite challenging, whatever the density of DIs. Tornadic effects on DIs along immediate coastal areas also may be masked or obliterated by hydraulic damage (i.e., storm surge and battering waves) occurring at any time before, during or after possible tornado occurrence. Furthermore, weak and brief tornadoes still may go unrecorded, especially at night and in remote, marshy, estuarine and/or heavily forested areas such as those over which many landfalling Gulf and Atlantic TCs pass. Still, available surveys and climatologies indicate that TC tornadoes tend to be weaker and shorter lived than their nontropical brethren, a characteristic recognized in damage survey analysis as early as the Fujita et al. (1972) survey of Japanese typhoon tornadoes and reinforced by the "F sum" analyses of McCaul (1991). Only two TC tornadoes to date, the aforementioned Galveston, TX and Larose, LA events, have been assigned a violent rating, with no F5 or EF5 ratings on record.

For total tornado yield in a U.S. TC, Hurricane Ivan (2004) appears to reign with 118 in the SPC listings[2]; although it is possible that Beulah (1967), herein credited with 115 tornadoes, exceeded that total[3]. Ivan's tornado production followed a distinctive three-day cycle across a long (>1200 km) and wide (up to 500 km) swath of the eastern U.S. (Fig. 1), each day resulting in outbreaks of at least 20 tornadoes by the Curtis (2004) criteria -- an unmatched pattern of sustained tornado productivity from a TC. Such widespread spatial and temporal distribution in Ivan, however, keeps Beulah (mapped in Orton 1970) as the most densely concentrated of the largest TC tornado producers. An effort to tabulate and map TC tornadoes for the full WSR-88 deployment era (1995 onward) yields a preliminary count of 300 for 2004, making it the most productive hurricane season for tornadoes on record. Three of the top ten tornado producing TCs (Table 1) struck the U.S. that year.

The most profusely tornadic TCs, by almost any of the widely varying definitions for a topical tornado "outbreak" (e.g., McCaul 1991, Curtis 2004, Verbout et al. 2007), are of hurricane intensity at landfall, as opposed to those of tropical storm (TS) classification. Nonetheless, the TS tornado threat should not be neglected. TS tornado outbreaks have occurred, including that of Beryl (1994), which resulted in 37 reports, some of which arose from long-lived, cyclic supercells (McCaul et al. 2004). Gentry (1983) found tornado reports from 62% of landfalling TSs during the 1970-1980 period.

b. U. S. spatial and temporal distribution

Climatological examinations of TC tornado reports indicate the greatest concentrations exist over coastal states from Virginia through Florida and westward to Texas, within approximately 161 km (100 nm) nm of the coast. TC tornado records diminish dramatically northeastward from the Delmarva Peninsula through the Mid-Atlantic region into New England, as well as everywhere more than 483 km (300 nm) inland from the Gulf and Atlantic coasts (e.g., Novlan and Gray 1974, Gentry 1983). Hurricanes Beulah in Texas (1967) and Audrey (1957) caused two pronounced, dense clusters within distributions mapped by Novlan and Gray (1974).

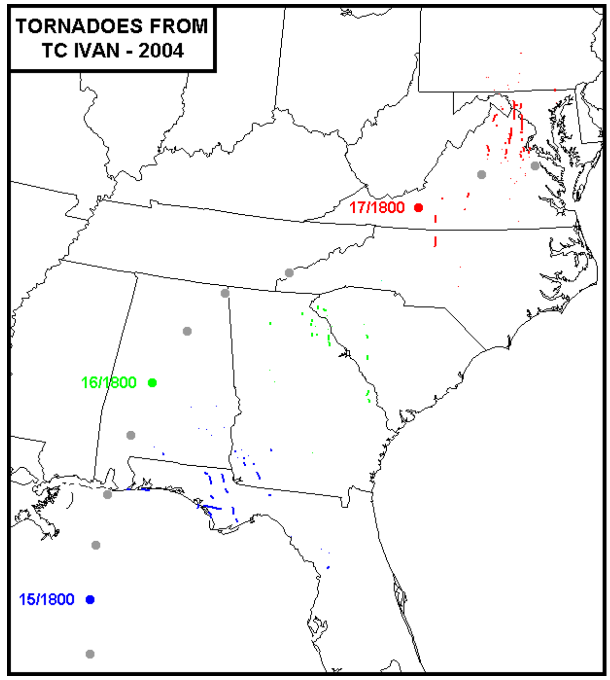

Figure 1. Three day cycle of tornadoes resulting from Hurricane Ivan (15-17 Sep 2004). Large dots represent six hourly positions of the TC center from NHC best track data, with each day's 18 UTC center fix colored. Correspondingly colored dots and paths represent tornadoes recorded in the SPC database for each convective day (1200 UTC same date through 1159 UTC the next). Due to scaling effects, some tornado plots may be overlaid or blended on this map.

Although tornadoes generally diminish with time as a TC moves inland, associated primarily with weakening of the meso-α scale wind fields and of low-level vertical shear, some pronounced exceptions include TS Beryl (1994), which produced 31 (84%) of its tornadoes on the second and third days combined after landfall (Vescio et al. 1996), and Hurricane Ivan (Fig. 1), whose third day yielded the largest number of tornadoes. Furthermore, Edwards (1998a) documented several TCs that exhibited distinct temporal phases of tornado activity peaking once near landfall and again near their exit back into the Atlantic, with relative minima in between. Such cycling of tornado production in post-landfall TCs shows that, for forecasting purposes, neither the characteristic inland weakening of the system as a whole, nor even an observed lull of many hours in tornado activity, should be construed necessarily as an indicator of nontornadic future performance. Instead, the forecasting approach should involve careful examination of the expected buoyancy and shear environments within the system, in keeping with physical concepts to be presented in the formal draft.

Although TC tornadoes often have occurred at night, pronounced diurnal cycles exist in many events, concurrent with periods of relatively maximized buoyancy that result from the daily surface diabatic heating period. A few early examinations, such as Dunn (1951) and Malkin and Galway (1953) did not ascertain such a trend, with no particular temporal window preferred. However, numerous other studies, with larger sample sizes, since have shown the diurnal preference for TC tornadoes. These include Smith

[2] Verbout et al. (2007) claim 117 tornadoes for Ivan, matching their count for Beulah.

[3] Several different totals for Beulah appear in the literature, the most cited being 115 (Orton 1970), 141 (Novlan and Gray 1974) and 113 (McCaul 1991). Verbout et al. (2007) claim 117 tornadoes, citing Orton (1970), even though the latter tallied two fewer. Grazulis (1993) wisely contended that the true total never may be known, and that the Orton tally was the most robust for its exclusion of damaging nontornadic winds (i.e., downbursts). While Orton admitted that "the actual number of tornadoes cannot be ascertained at present," that study specifically excluded duplicated reports and "others that do not indicate clearly the storm to be tornadic in character." With some reservation, the 115 total is used herein because of the thoroughness and multi-source forensic approach taken by Orton.

(1965), with 82% of TC tornadoes in years 1955-1962 occurring between 0900-2100 UTC; and McCaul (1991), with 57% of tornadoes between 0900-1800 local sun time (corresponding roughly to 1400-2300 UTC in the southeastern U.S.). Tornadoes documented by Smith (1965) were less dependent upon diurnal cycle with inward distance toward a TC center, indicating the lesser influence of diabatically enhanced buoyancy in the more densely clouded portions of TCs.

The TC buoyancy and shear environment has been shown to be favorable for supercells offshore, as derived from the dropsonde readings (Bogner et al. 2000). Supercells have been observed remotely over water through land-based radar (e.g., Spratt et al. 1997, Rao et al. 2005). Operational experience indicates that it is common for supercells to develop offshore, then move inland, producing tornadoes on or very near shoreline. The violent Galveston tornado from Carla (1961) moved onshore from the Gulf of Mexico (Grazulis 1993), with an unknown prior duration over water. How productive are supercells for offshore tornadoes (a.k.a. waterspouts)? Although reports of tornadoes originating offshore are much more improbable in the TC environment due to lack of observers, they have been noted (e.g., Barbour 1924, Spratt et al. 1997), and actual supercellular waterspouts could be quite common. If so, they present some risk to shipping and crude oil extraction interests offshore, in addition to the TC-scale damaging wind and hydraulic impacts.

c. Intra-cyclone distribution

Climatologically, relatively early studies (e.g., Pearson and Sadowski 1965) noted the predominance of TC tornado distribution within the envelope of gale (34-47 kt or 17-24 m s-1) winds and in outer rainbands (e.g., Hill et al. 1966), and a marked decrease in aggregate tornado occurrence density with proximity to center from the gale force sector of TCs.

Examining 1955-1962 TC tornadoes, Smith (1965) plotted 51% in the right-front quadrant of the systems relative to their motion, but with considerable scatter into each of the other sectors. Pearson and Sadowski (1965) illustrated similar distributions of tornado reports relative to storm heading for 1955-1964 TCs. For Japanese typhoon tornadoes during 1950-1971, Fujita et al. (1972) also indicated a preference for the right-front quadrant, which in most cases was strongly collocated with the Cartesian northeast quadrant given the strong meridional component of Japanese typhoons' translation. More recently, McCaul's (1991) extensive environmental climatology also was based on a cyclone-relative framework, with the right front quadrant a preferred tornado concentration. Still, a great amount of scatter was evident, particularly toward the motion-relative rear (e.g., Fig. 11 in McCaul 1991).

By contrast, Hill et al. (1966), Novlan and Gray (1974) and Weiss (1987) showed a strong preference for tornadoes in the Cartesian northeast quadrant of the TC circulation. In comparing both methods, Gentry (1983, Figs. 1 and 2) illustrated a somewhat tighter distribution of tornadoes relative to true north than relative to storm motion, for the period 1973-1980. For the singular but profusely tornadic case of Beulah (1967), Figs. 3 and 4 in Orton (1970) shows a strong preference for the sector between 350° and 60° Cartesian; though the lack of tornado reports in eastern and southeastern azimuths >60° may be attributed to the absence of land in that portion of outer envelope. Beulah's sharp southwestward turn after landfall abruptly resulted in the onset of numerous tornadoes over its left rear (cyclone-relative) quadrant, but in the same Cartesian sector as before, suggesting that a shift in translational TC motion did not change the physical environment supporting tornadic supercells.

Both Cartesian and cyclone motion-relative frames of reference commonly are used in operational and research application, sometimes almost interchangeably. However, important distinctions may exist for any TC translating appreciably off a northward bearing, as illustrated spectacularly by Beulah. Which is more correct, more of the time? While a consensus of available climatologies suggests a preference for the Cartesian northeast versus TC-relative right-front quadrant, and while there is considerable distributional dispersion rearward (southeastward) from right-front (northeast) quadrants, specific comparisons of one framework to the other are needed, akin to Gentry's, but using more modern and robust TC tornado data to better assess this issue.

To complicate the matter further, but perhaps in a more physically meaningful way, Molinari and Vollaro (2008) used a shear-relative framework for evaluating cell-relative helicity. Streamwise vorticity (Davies-Jones 1984) has been shown to contribute to thunderstorm-scale rotation (e.g., Davies-Jones et al. 1990), and is quantified in the form of storm-relative (or for this purpose cell-relative, to distinguish from the TC frame of reference) helicity as applied to forecasting tornadic supercells. Helicity, in its various sampling iterations, has been used alone and in blended parameters (e.g., Thompson et al. 2003, 2007) as a statistically robust indicator of favorable supercell environments. The Molinari and Vollaro analysis was performed in the environment of a single TC (Bonnie of 1998), as derived from maritime dropsonde deployments, using cell motions assumed from midlatitude supercell algorithms because of the lack of radar data. Their largest helicity computations came from the downshear-left quadrant of Bonnie, analogous to the Cartesian northeast and cyclone-relative right-front quadrants. One concern with a shear-relative framework is where to sample the shear vector for use as a benchmark, given the horizontal dimension of a TC (102-103 km) and the potential variability of ambient flow across that scale. This method also needs testing on multiple storms to assess its potential predictive merit in a more robust way.

3. CURRENT STATE of TC TORNADO PREDICTION

a. Operational procedures – outlook to warning to verification

Tornado forecasting services in the public arena are provided by the NWS, first via the SPC through outlooks up to eight days out, then in coordinated statements by NHC concurrent with day-1 SPC outlooks, followed by SPC tornado watches and local NWS tornado warnings. Typically, NHC and SPC forecasters begin to coordinate the tornado threat as part of a dedicated conference call that also includes affected local NWS forecast offices, NWS regions, military interests and the Department of Homeland Security, within 6-12 h before the outer fringes of the TC's circulation envelope begin to affect land. Edwards (1998b) discussed the SPC forecast process for TC tornado threats near landfall time, though SPC has changed guidelines and timelines for some outlook, mesoscale and watch products since. Table 1 summarizes the current SPC suite of forecast products as specifically applied to threats of TC tornadoes.

Outlooks serve notice of a general threat on the scale of days, using probabilistically driven categorical risk areas skewed strongly to land areas just rightward or northeast of NHC forecast tracks, and are utilized by NWS, private meteorologists, media, homeland security and emergency management interests for hazard planning purposes. As public bulletins, SPC watches serve the entire gamut of weather interests – i.e., general public, in addition to aforementioned audiences. Meteorologically, the most critical SPC product within the TC tornado environment is the mesoscale convective discussion (MCD), which is issued on an unscheduled, situationally driven basis as the hazard evolves. MCDs for TC tornado situations contain scientifically rooted insights in a technical textual narration, covering the hazard and how it should change within a 30 min to 3 h time period. MCDs are accompanied by both a text headline and a graphic that describe the threat area.

Table 1. SPC forecast products as applied to TC tornado situations. All times UTC. A convective day is defined as 24 hours in length, beginning at 1200 UTC. Changes in UTC product deadlines between Daylight Savings Time (DST) and Standard Time (ST) are specified.

SPC PRODUCTS	**VALID PERIOD**	**TIME(S) ISSUED**	**TC TORNADO USAGE**
Day 4-8 Severe Outlook	Fourth through eighth future convective day	0900 for DST, 0830 for ST	Very rare because of TC track/intensity uncertainties and 30% minimum total-severe probability threshold (at 80 km grid resolution).
Day-3 Severe Outlook	Third future convective day	0730 for DST, 0830 for ST	Uncommon because of TC track and intensity uncertainties. Categorical slight risk invoked at 5% total-severe probabilistic threshold *only if valid entirely for tornadoes*.
Day-2 Convective Outlook	Second future convective day	0600 for DST, 0700 for ST	Variable, more common for mature, major hurricanes with relatively low track/intensity uncertainties per NHC guidance. Categorical slight (SLGT) risk invoked at 5% total-severe probabilistic threshold *only if valid entirely for tornadoes*.
Initial Day-1 Convective Outlook	Upcoming convective day	0600	Tornado-specific probabilities of 2% (Subcategorical "See Text" label); 5 or 10% (Categorical "Slight" risk); 15% ("Moderate"); 30%, 45% or 60% ("High")
Later Day-1 Convective Outlooks	Ongoing convective day	1300, 1630, 2000, 0100	Same as for initial day-1 outlook.
Mesoscale Discussion	30 min to 3 h	As needed, before and during watches	Text discussion of tornado threat and watch potential, graphic areal outline
Tornado Watch	Up to 12 h	As needed	Aviation and public watch products, affected county listing, whole-watch tornado probability
Watch Status Report	Up to 1 h	20-40 min past each hour during watches	Lists counties remaining in threat area covered by associated watch

Since deployment of the WSR-88D network largely was completed (c. 1995), Doppler radar has become the standard and primary tool for operational warnings in all tornado prone environments. This is hardly truer than in the TC, where the abundance of rain, low cloud bases, fast translation, unconventional (often from east or southeast near the Gulf and Atlantic coasts) direction of motion, and ephemeral nature of most tornadoes, make the best practices for storm spotting (see Doswell et al. 1999) extraordinarily difficult. Spratt et al. (1997) provided excellent early examples of the utility of Doppler radar in this setting, particularly at close ranges where the lowest beam elevations best may sample the relatively shallow and narrow mesocirculations typically characterizing TC supercells.

Tornado warnings are drawn for "storm-based" polygonal corridors (Ferree et al. 2006) that typically cover a fan-shaped area along and some distance either side of the projected path of a potentially tornadic TC supercell, for up to 1 h. Given the typically small size, fast motion and close proximity of some TC supercells, multiple warning polygons could cover the same county at the same time, a situation which presents unique challenges for dissemination and interpretation of warnings (Ferree and White 2008). A combination of environmental analysis and radar interrogation typically is used in the operational warning environment, with a considerable contribution to environmental situational awareness provided by SPC mesoscale discussions given the time constraints inherent to local warning operations, especially in coastal TC situations when a variety of TC-specific products and duty responsibilities adds to workload.

Under current practices, each warning is verified by the same local NWS office issuing it. Any resulting tornado reports are relayed in segmented form, by county, to the National Climatic Data Center (NCDC) for processing into a national collective. Final warning verification is done by NWS on this data. SPC then filters segmented NCDC reports for those that may have crossed county or state lines, effectively stitching together all conterminous county path segments to create a final, whole-tornado tally that is used in verification of SPC products. More details on the "final" SPC severe storm database are available from Schaefer and Edwards (1999). These verification and collection practices are common to all tornado reports nationwide.

Explicit parsing of TC tornadoes, however, has been a fortuitous endeavor, performed at various times by local NWS offices (for tornado events in an office's jurisdiction), NCDC *Storm Data* feature articles on the most noteworthy TCs, and/or NHC's post mortem "storm wallets" that collect and summarize each system's assorted impacts. In each case, event reporting practices have varied over time. An effort is underway at SPC to tabulate and map known TC tornado occurrences in a consistent manner, with the results to be presented in the future formal version of Section 2.

b. Basic forecast techniques and practices

For TC tornadoes, just as with those in midlatitudes, forecasting has evolved away from purely empirical approaches based on simple climatology and pattern recognition, e.g., away from essentially automatic issuance of long-lasting tornado watches for the entire core and northeast quadrant, plus sometimes vast "wiggle room" accounting for spatial uncertainties, for all TCs. Now, an ingredients-based forecasting approach is advocated, concentrating on the appearance and juxtaposition of specific foci for instability, lift and shear within the moist surface environment, along with ambient upper air influences on such foci, such as areas of differential drying (Curtis 2004). The TC tornado forecast process necessarily begins with thorough diagnostic understanding of the unique environment and character of each TC at any given time, before any prognostic guidance is involved.

Despite the growing abundance of automated diagnosis and predictive tools for mesoscale forecasting, and improved understanding of factors favorable for supercells, the TC supercell environment remains poorly sampled and depicted in many cases by automated analyses and numerical guidance. The apparent influence of various forms of meso-β and smaller scale boundaries and bands on supercellular tornado potential in TCs emphasizes the need for very careful, precise and detailed subjective analysis of the TC environment for outlook, watch and warning purposes, especially at the surface where data is most dense spatially and temporally, in order to deduce: 1) areas of relatively maximized potential in a purely diagnostic sense, and 2) temporal trends in influential features and fields.

Based on aforementioned diagnostic studies and operational experience, manual surface analyses are recommended, using conventionally plotted data and including a minimum of thermal analyses at ≤1° C interval (for thermal boundaries), streamlines (for highlighting areas of backed flow and kinematic boundaries such as confluent zones), and both positive and negative isallobars at 1 hPa h^{-1} increments (conventionally plotted as 2 h pressure changes), for assessing pressure change fields that may influence winds in the nowcast term.

This critical and fundamental diagnosis tool should be integrated with observed upper air data from available rawinsondes, dropsondes, airplane soundings, wind profilers and radar-based velocity azimuth display (VAD) winds. Where near synoptic (six hourly) balloon launch times characteristic of landfalling TC situations, upper air data from the other sources can be plotted on or otherwise integrated with resulting upper air charts for finer scale analysis. Curtis (2004) demonstrated the potential value in sounding examination and planar 700 and 500 hPa upper air analyses, for ascertainment of the location, strength, geometry and tendencies of areas of drying aloft associated with the largest TC tornado outbreaks. Where usefully located, GPS based precipitable water (PW) retrievals (Duan et al. 1996) may indicate the presence of substantial drying aloft in the time and space between rawinsonde and dropsonde deployments, provided the TC has not rendered GPS sensing equipment unreliable or inoperable[4]. The other mandatory-level upper air charts, analyzed on a situationally flexible basis for base-variable thermodynamic and kinematic factors influencing moisture, instability, lift and shear within the TC, can indicate other important meso-α to synoptic scale effects on the TC and its supercell and tornado potential. Examples of such analyses will be provided in the formal version of this manuscript.

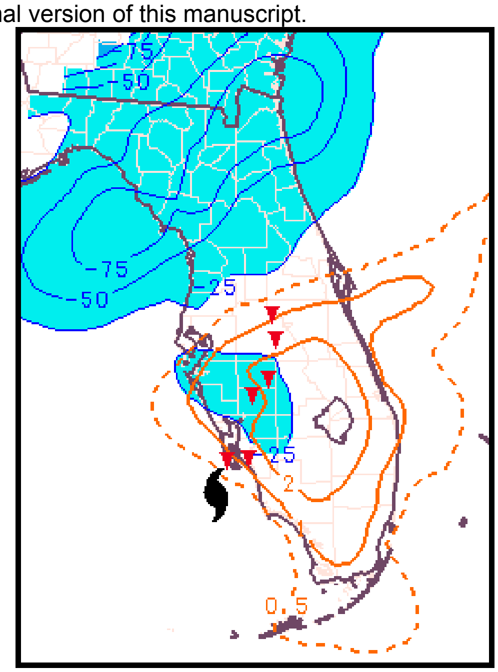

Figure 2. Analysis of significant tornado parameter (orange) and mixed layer convective inhibition ($J\ kg^{-1}$, blue) for 1800 UTC 13 August 2004. Hurricane symbol marks 1800 UTC NHC center fix for Charley. Triangles represent tornado reports during 1600-2000 UTC.

On the nowcast time frame, automated mesoanalyses and derived fields such as those at SPC (Bothwell et al. 2002) also may be useful for assessing general trends. Great care should be exercised, however, to avoid overreliance on such mesoanalyses in consideration of: 1) the potentially poor spatial resolution of input observational data at needed scales, and 2) the uncertain reliability of the Rapid Update Cycle (RUC, see Benjamin et al. 2004) model amidst the often extreme isobaric but subtle thermal gradients of most TCs, particularly prior to their substantial inland decay. Composite variables such as supercell composite and significant tornado parameters (Thompson et al. 2003), which have shown robust statistical associations with supercells and tornadoes in midlatitude weather systems, have not been tested systematically in TC environments, whether landfalling or decayed. Neither have more recent variables using effective parcels tied to storm depth (Thompson et al. 2007), which would operate through vertically compressed sampling columns for most TC tornado situations. Given those concerns, there is no guarantee that such parameters will work consistently well in TCs, despite preliminary anecdotal evidence of their utility in some individual events (e.g., Fig. 2). See Doswell and Schultz (2006) for a thorough discussion of the proper use of diagnostic variables as severe weather forecast parameters.

On the warning scale, TC tornado prediction depends strongly on Doppler radar indications of strengthening storm-scale mesocirculations, where convection is sufficiently close to the radar site for adequate sampling of the lowest few km AGL, the layer in which the bulk of TC supercells' mesocyclones reside. Although McCaul et al. (2004) recommend measuring angular momentum instead of rotational shear due to the former's greater independence from range, the magnitudes of rotational velocity and horizontal shear are more readily available parameters in the operational setting and may provide useful indications that a mesocyclone is imminently tornadic. Caution must be used when applying automated, midlatitude supercellular algorithms to the TC setting because of the compressed spatial dimensions, rapid evolution, and weaker rotational velocity magnitudes commonly evident in the latter's tornadic supercells (e.g., McCaul et al. 2004, Rao et al. 2005, Schneider and Sharp 2007).

While storm-relative velocity can be a very useful radar tool, it is important for the warning forecaster to ask, "How good is the storm motion being used?" Reliability of algorithms utilizing storm motion and reflectivity centroids may be compromised by poor resolution – particularly at distance and in nebulous and/or inner-band supercells – as well as by cyclonically curving translational paths. These factors, along with the lack of TC-specific testing of midlatitude supercell motion algorithms, can impart troublesome uncertainty not only to projected storm paths, but in other computations (e.g., storm-relative helicity derived from VAD wind profiles) used for assessing the near-term TC supercell and tornado threat over small areas.

Accounting for such diagnostic pitfalls quickly, in the short-fuse warning decision setting, is critical not only for deduction of the threat of imminent tornadogenesis, but also for assigning a storm-based warning polygon that captures the most probable path through the warning duration, with minimal false alarm area. Accurate TC tornado warnings, therefore, depend strongly on careful interrogation and interpretation of low-elevation base data – e.g., for enhanced and persistent reflectivity maxima associated with tightening couplets of velocity, and/or persistent or increasing anomalies of spectrum width – in context of diagnostic situational awareness (i.e., thorough analytic understanding of the presence and character of ingredients-based foci in the near storm environment).

Difficulty remains detecting TC supercells at long ranges, where the beam overshoots the low level mesocyclone and/or beam width becomes too great to resolve mesocyclones, as well as in all areas devoid of radar coverage. Supercells then must be inferred from clues such as persistent, standout cores of high reflectivity (for long-range or reflectivity-only radar coverage), small areas or spots of relatively cold cloud tops in infrared satellite imagery over environmentally favored sectors, overshooting tops in visible satellite

[4] The efficacy of GPS PW readings has not been evaluated systematically with respect to the often extreme wind and precipitation fields of TCs.

wavelengths, and/or continuity of anomalously intense cloud-to-ground (CG) lightning production. Animations of any of those tools also may indicate rightward deviance of cell motion with regard to surrounding echoes or bands, which itself would constitute a strong indicator of potential supercell character.

4. SUMMARY of ADDITIONAL WORK

Despite its relative youth, the physical understanding and predictability of TC tornado environments has made considerable advances since the early case documentations, distributional climatologies and empirical efforts. As has occurred with midlatitude tornadic supercells, forecasting of TC tornadoes relies increasingly on an ingredients-based methodology dependent upon increasingly higher resolution diagnostic tools and prognostic guidance, with considerable improvement left to be made. Amidst recognition that some TCs fail to produce tornadoes, mainly related to unfavorable convective mode and/or lack of instability, climatologically favored areas are interrogated for more precisely located foci of shear, lift and instability, as areas of drying aloft, various forms of surface boundaries and bands, and relative weaknesses in convective inhibition, each of which arises from specific physical causes that range from poorly- to well-understood in origin. Improving the knowledge base for the development and nature of those foci likewise should translate to more accurate and precise forecasts, on times scales from outlooks to warnings.

This manuscript presents a preliminary review of advances the climatological understanding of tornado patterns and distribution within TCs, as well as the state of current forecasting practices, and recommendations for diagnostic situational awareness in the operational environment. The formal version of this review article will include some additional discussion and illustrations on these topics.

In addition, a chronological overview from the early 1800s will be presented, covering many of the most influential TC tornado events, with regard to their direct impacts (e.g., human casualties and exceptional damage), and/or their major influences on changes in research and forecasting emphases.

Several decades of research advances in physical understanding of supercell environments and tornadogenesis will be applied to the TC setting, from the framework of an ingredients-based approach (moisture, instability, lift, vertical shear). Being richly endowed with low level moisture, the main factors influencing the occurrence of tornadoes in TCs are the relative distribution and juxtaposition of shear, instability (as indicated by buoyancy) and boundaries or other sources for convective initiation. These influences will be presented on the TC, meso-β, and supercell scales, both near shore and well inland, along with a discussion on the ill-defined physical concept of eyewall tornadoes (i.e., are they real?).

The formally submitted version of this manuscript also will contain more updated developments in the field of diagnosing and predicting TC tornado environments. This presumption is based on further interrogation of presentations at this conference, feedback and interactions herein, and the anticipated acceptance in at least two formal journals of a few unpublished manuscripts that the author either is reviewing, or knows to be in review by others, as of this writing.

In addition, TC tornado reports will be tallied and mapped for the fully deployed WSR-88D era of NWS severe storm verification practices (1995 at least through 2007), so trends in their occurrence and relative frequency of their damage ratings can be analyzed using “apples to apples” comparison within a common framework of tornado data acquisition. Several additional figures and tables will be added to illustrate such data, and to exemplify diagnosis and forecasting concepts described above. Radial distribution of those modern-era TC tornado reports will be plotted with respect to both Cartesian and cyclone-relative frameworks, in order to assess the relative merits of each in a climatological sense. Updated parsing of exit tornadoes (from Edwards 1998a) also is planned.

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