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Tropical Cyclone Tornadoes: A Review of Knowledge in Research and Prediction

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ABSTRACT

The scientific documentation and investigation of tropical cyclone (TC) tornadoes has spanned portions of ten decades, but has been missing a documentary overview of topical knowledge accumulated to any given point in that time span. This review article summarizes the evolution of TC tornado-related literature from the perspectives of crucial historic tornadoes, climatology, distribution patterns, applied research into their environments, remote and environmental observations, forecasting practices, and numerical simulations at various scales. Discussion of the future of TC tornado research and prediction includes several testable hypotheses, along with potentially beneficial tools soon to be available to operational forecasters.

1. Introduction

Tropical cyclone (TC) tornadoes represent a relatively small subset of total U.S. tornado reports (about 6% from 1995–2009, from Edwards 2010). They deserve 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 convective storm type for tornadogenesis in TCs appears to be the supercell, particularly for significant events of at least F2/EF2 rating (Hales 1988; Grazulis 1993). From a framework of ingredients-based forecasting of severe local storms (e.g., Doswell 1987, Johns and Doswell 1992, Moller 2001), supercells in TCs share with their midlatitude counterparts the needed 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 differ somewhat from extratropical baroclinic perturbations in supporting tornadic supercell potential, not in the necessity of those basic ingredients inasmuch as in their relative magnitudes and spatial juxtaposition. Understanding such differences, as well as TC tornado climatology, can aid the diagnosis and prediction of TC tornado environments.

This review article summarizes the climatology, distributions and environments of TC tornadoes, using a chronological accumulation of findings used in research and forecasting. Section 2 follows the historic documentation of major TC tornado events in the U. S. and abroad, and the resultant concepts brought to understanding TC tornadoes. Section 3 describes various TC tornado climatologies that have been compiled and summarizes their contributions to our knowledge of TC tornado distributions. Section 4 offers an overview of the physical concepts related to TC tornadoes. Forecasting practices and operational concepts appear in section 5. Section 6 presents questions, challenges and testable hypotheses for future work in this area.

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2. Recognition and notable events

a. U.S. TC tornado milestones

American observations of tornadoes[1] spawned by TCs date at least as far back as 1811 and 1814, each at Charleston, SC (Tannehill 1944). The 1811 "dreadful visitation" killed one person, and the 1814 "fatal waterspout" moved off land before sinking a schooner in Charleston Harbor, drowning 25 sailors (Ludlum 1970). The latter may rank as the deadliest TC tornado in U.S. history. Even in the early 1900s, TC tornadoes were shown to affect areas hundreds of miles inland, in landlocked states. Henry (1924), in the commentary capacity of *Monthly Weather Review* Editor, briefly described a tornado at Hobbs, NM, on 19 September 1919, within the remains of a Texas coast hurricane.

Several especially noteworthy TC tornadoes have occurred in the U.S. since then, in the era of systematic tornado records commencing in the 1950s. On 30 September 1959, a tornado from the remains of Hurricane Gracie killed 11 people at Ivy, VA, ten of them in a poorly constructed bunkhouse (Grazulis 1993). Hurricane Carla spawned the first recorded violent (F4 damage, from Grazulis 1993) TC tornado, at Galveston, TX on 12 September 1961. This tornado, originally a waterspout[2] that moved ashore, injured 55 people and killed eight others, more than 25% of Texas fatalities from Carla. Just over three years later (3 October 1964), the second and last violent TC tornado on record struck Larose, LA from Hurricane Hilda, also rated F4 (Grazulis 1993), with 22 fatalities and 165 injuries.

Aside from the intensity of damage, the Galveston and Larose tornadoes also were noteworthy for their timing—either at night or well before peak diurnal surface heating (0915 and 1230 UTC respectively, UTC=LST+6 h), unlike typical diurnal trends for TC tornadoes described in the next section. The enhanced deadliness of nocturnal tornadoes in the American South has been tied to a "unique juxtaposition of both physical and social vulnerabilities" (Ashley 2007). In these two cases, included in Ashley's analysis of killer tornadoes for 1880–2005, the influence of nonmeteorological factors (i.e., nocturnal timing, sociological characteristics, lack of both warning and communication) on their comparatively high casualty tolls is uncertain. Still, the occurrence of such events during climatologically unfavorable hours after local midnight underscores the need to understand and predict the situational variability in tornado threat from storm to storm.

The remains of Hurricane David produced a rain-wrapped, F3 tornado with a fatality at Falls Church, VA, on 5 September 1979 (Hoadley 1981; Grazulis 1993). Occurring close to Washington, DC, this event politically motivated a change to the National Weather Service (NWS) policy on TC tornado watches. At the time, TCs were covered only by short-form tornado watches sent to aviators. Public watches were forbidden because of perceived TC-product overload and public confusion with hurricane bulletins (J. E. Hales and S. J. Weiss 2010, personal communications). The prevailing rationale resembled the reasoning of Pearson and Sadowski (1965) regarding forecaster hesitation to issue tornado warnings in hurricanes, in their words, "arguing that there was little more that the public could do about the tornado that they had not already done in preparing for the hurricane." Such thinking contradicted their own (and earlier) findings that tornadoes mainly hit outside the area of hurricane force winds for which hurricane preparations were performed. The demand for public TC tornado watches following the deadly Falls Church event led to the watches that since have been issued by the Storm Prediction Center (SPC) for TCs.

A pair of exceptionally damaging tornadoes struck south-central Texas in the remains of Hurricane Allen (1980): one rated F3 at San Marcos, the other an F2 in Austin that caused $50 million in damage on and near the former municipal airport. The San Marcos tornado is listed in the SPC tornado database as having the longest track of any TC tornado at 47 mi (76 km). Grazulis (1993), however, claimed that

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[1] During the 1800s, the words "hurricane," "tornado" and "cyclone" virtually were interchangeable in the common lexicon, based on assorted tornado descriptions in the popular press later reproduced by Ludlum (1970). To some extent, as such, their distinction has been left to post facto assessment of event descriptions.

[2] "Waterspout" and "tornado" are defined herein by the NWS classification, where a waterspout is a tornado over water that is not recorded in official tornado databases.

the event was a family of three to five tornadoes, with only about 20% of the damage path being continuous, and that it was the first TC tornado event to show conclusive evidence of multiple vortices. This conflict exemplifies the difficulty of obtaining accurate, precise and reliable information on even the most robust TC tornadoes. McCaul (1987) published striking photos of Alabama tornadoes with the inland remains of Hurricane Danny (1985). The images showed multiple-vortex structures and a separate funnel, along with pronounced wall clouds and other visual characteristics commonly observed in larger, deeper, nontropical tornadic supercells of the Plains states. The prolific Atlantic hurricane season of 2004, which yielded the largest single-TC tornado count (Ivan, Table 1 and Fig. 1), also included the first categorical SPC "moderate risk" convective outlook products (section 5) driven specifically by TC tornado probabilities, during Frances, Ivan and Jeanne.

Table 1: Top ten U.S. tornado producers among TCs, using SPC TCTOR (Edwards 2010) data and citations discussed in Section 3. Landfall intensity category is denoted by H for hurricane, TS for tropical storm. Given the ability to amend TCTOR, totals for storms from 1995 onward are subject to revision pending additional investigations.

TROPICAL CYCLONE	YEAR	TORNADO REPORTS
H Ivan[#]	2004	118
H Beulah	1967	115
H Frances	2004	103
H Rita	2005	98
H Katrina	2005	59
H Andrew*	1992	56
TS Fay	2008	50
H Gustav	2008	49
H Cindy	2005	48
H Georges	1998	48

* Second (Louisiana) landfall; no tornadoes were documented in the Florida phase.

[#] First (eastern U.S.) path; no tornadoes occurred with the second (Louisiana) landfall.

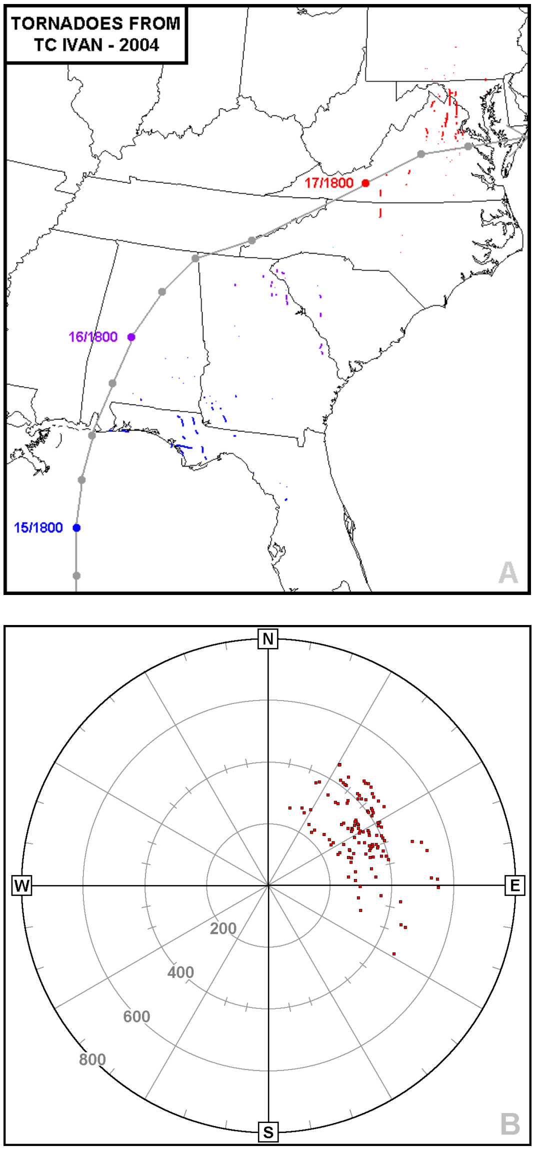

Figure 1: Three-day plot of tornadoes from Hurricane Ivan, 15–17 September 2004, as follows: a) Geographically by day. Large dots represent 6-hourly positions of the TC center from NHC best-track data, with each day's 18 UTC (midday local time) TC center position labeled. TC track is in gray. Correspondingly colored dots and paths represent tornadoes recorded in TCTOR for each convective day (1200 UTC same date through 1159 UTC the next). b) In bulk, polar-plotted with respect to north-relative azimuth (tick marks and full radials at 10° and 30° intervals respectively) and range (km as labeled) from center position, at the time of each tornado. Due to scaling effects, some tornado plots may obscure others on each panel. *Click images to enlarge.*

b. TC tornadoes worldwide

Tornado documentation from other parts of the globe has been more erratic and uncommon than in the U.S. Nonetheless, tornadoes are possible with TCs worldwide. On 11 August 1923, a typhoon produced a damaging tornado about 240 km north-northwest of its center at Peitaiho Beach, northeast of the major city of Tientsin (now Tianjin), China. The tornado formed about 1 km offshore over Bohai Bay and moved inland with "the usual freakish destruction of buildings" (Barbour 1924). Fujita et al. (1972) documented 68 tornadoes produced by Japanese typhoons from 1950–1971, five being rated F3. Occurring in a densely populated nation, the Japanese tornadoes caused at least 10 known deaths and 389 injuries. Suzuki et al. (2000) described one tornado each from three supercells in a 1990 typhoon, along with six other nontornadic supercells. Other studies of Japanese TC tornadoes include Mashiko et al. (2009), Niino et al. (1997) and Fujita et al. (1972).

Tornadoes from TCs may be common in Cuba, given the island's length (about 1140 km) and geographic position. Their documentation is sparse, however, with inconsistent, informal reporting via news services. For example, multiple tornadoes were reported in western Cuba with the outer fringes of Hurricane Wilma of 2005 (BBC, cited 2011), injuring at least seven people and destroying 20 houses. A supercell associated with Wilma, which eventually produced a spectacular waterspout near Key West, FL (Fig. 2), moved off Cuba and spawned an intervening waterspout sighted by Coast Guard rescue crews 50 mi (80 km) south of Key West (K. Kasper, personal communication).

Despite the inconsistent and often absent tornado data collection standards internationally (Brooks et al. 2003), the pertinent physical characteristics of TCs described in Section 4 are valid for China and Japan, and should apply everywhere TCs make landfall, especially in midlatitudes where the ambient westerly flow component aloft contributes to supportive wind profiles (McCaul 1991; Verbout et al. 2007). Favorable environmental shear profiles and TC-relative distribution patterns as described in section 3c would be mirrored in the Southern Hemisphere.

Only one Southern Hemispheric TC tornado has been documented as of this writing: 21 February 2011, in Karratha, Western Australia (Australian Bureau of Meteorology, 2011). An outer-band thunderstorm spawned the tornado, which damaged buildings in the town's central business district.

Figure 2: Supercell-spawned waterspout just offshore of Key West, FL about 12 h prior to the closest passage of Hurricane Wilma, 23 October 2005, in its northeastern sector. [Photo credit: Tim Chapman, *Miami Herald*; used by permission.]

3. Climatologies and distribution patterns

a. TC tornado climatologies

A TC tornado climatology is considered herein as any bulk documentation of tornadoes from multiple TCs and hurricane seasons. Furthermore, a climatology does not include single-storm analyses (e.g., Sadowski 1962; Orton 1970) or single-season compilations (e.g., the 1964 grouping in Pearson and Sadowski 1965). Table 2 summarizes known TC tornado climatologies as of this writing.

Climatologies generally have expanded in size with time as TC tornadoes have become better documented. The three Table 2 listings that contain ~10^3 tornado records include (and contain numerous events from) the era of the fully deployed eastern U.S. WSR-88D (Crum and Alberty 1993), from roughly 1995 onward. Such relatively large datasets now support sorting by specific storm characteristics, such as Florida only (Agee and Hendricks 2011), or Gulf-coast hurricanes (Moore and Dixon 2011). Most early datasets (prior to 1990) stated no specific thresholds or reproducible criteria for inclusion. Since then, selection criteria show considerable inconsistency across climatologies,

Table 2: Summary of TC tornado climatologies in the literature. Radius *r* is defined from TC center.

AUTHOR(S)	YEARS	EVENT COUNT	TC LEVELS	PLACE	INCLUSION CRITERIA
Tannehill (1944)	1811–1933	10	All	SC, FL	Unspecified
Malkin and Galway (1953)	1811–1952	22	All	U. S.	Unspecified
Wolford (1960)	1916–1957	84	All	U. S.	Unspecified
Smith (1965)	1955–1962	98	All	U. S.	"Within the cyclonic circulation"
Pearson and Sadowski (1965)	1955–1961, 1964	137	All	U. S.	Unspecified
Hill et al. (1966)	1955–1964	136	All	U. S.	"Subjectivity"
Fujita et al. (1972)	1950–1971	68	Typhoon	Japan	Unspecified
Novlan and Gray (1974)	1948–1972	373	All	U. S.	Unspecified
Gentry (1983)	1973–1981	120	All	U. S.	Unspecified, no records at r > 350 km
Weiss (1987)	1964–1983	397	All	U. S.	"Subjectively matched"
McCaul (1991)	1948–1986	626	All	U. S.	$r \leq$ 800 km
Verbout et al. (2007)	1954–2004	1089	All	U. S.	$r \leq$ 400 km, landfall ±2 days
Schultz and Cecil (2009)	1950–2007	1767	All	U. S.	$r \leq$ 750 km then "inspection" for 750 km $\geq r \geq$ 500 km
Belanger et al. (2009)*	1950-2008	1375	All	U. S.	Gulf landfalls, $r \leq$ 650 km, only during NHC advisories
Edwards 2010	1995–2010#	1163#	All	U. S.	Meteorological analysis, no max r
Agee and Hendricks (2011)	1979–2010@	300–334@	All	FL	Pre- and post-installation of WSR-88D system
Moore and Dixon (2011)	1950–2005	734	Hurricane at landfall	U. S.	Gulf landfalls, $r \leq$ 400 km, landfall ±1 day

[*] Available via supplemental FTP link in manuscript
[#] Climatology updated yearly, data complete through 2010 as of this revision
[@] 1994–1995 data listed, but omitted from analyses

the most common threshold being an arbitrary inclusion radius from TC center. One climatology (Edwards 2010), strictly covering the WSR-88D era, is updated yearly, is open to correction or amendment of entries, and is provided freely online for independent analysis.

TC tornado climatologies are influenced by the large number of reports with several exceptional cyclones (Table 1). The general increase in 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 reflection of the recent major increase in overall tornado reports, particularly those of the weakest (F0/EF0) damage category in the database. The nationwide increase in the number of 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, Doppler radar usage, greater media coverage, increasing population, enhanced real-time electronic communication, and the spread of video and photographic documentation. McCarthy (2003), Brooks et al. (2003), Verbout et al. (2006), and Doswell (2007) further discuss these factors. Figure 2 from Verbout et al. (2007) offers a pronounced illustration of the dominant contribution of the weakest (F0) events to the overall yearly tornado totals.

In any TC tornado climatology, historic F-scale ratings were prone to subjective judgment, since the entire U.S. tornado database is fraught with inaccuracies (e.g., Doswell and Burgess 1988). The increased precision and number of damage indicators and degrees of damage in the EF scale includes trees and other commonly rural targets. This presumably reduces the potential for undocumented TC tornadoes in less densely populated areas (Edwards et al. 2010), even though the rating and event-verification process remains considerably subjective.

On the other hand, distinguishing damage of some EF0 and EF1 TC tornadoes from that produced by the coincident passage of hurricane winds over the same areas may be challenging, whatever the density of damage indicators. Tornadic effects on damage indicators, along immediate coastal areas, also may be masked or obliterated by hydraulic damage (i.e., storm surge, battering waves, freshwater flooding) before, during or after the possible tornado. Furthermore, some weak or brief tornadoes 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.

Available surveys and climatologies indicate that TC tornadoes tend to be smaller, less damaging, and shorter-lived than nontropical tornadoes. This characteristic was recognized in damage survey analyses 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 (F4+/EF4+) rating, with no F5 or EF5 events on record. The 1950–2007 tornado-occurrence analysis of Schultz and Cecil (2009) yielded 81.1% weak (F0–F1), 13.8% strong (F2–F3), and «1% violent (F4, no F5) tornado ratings in TCs, compared to whole-U.S. tallies of 74.4%, 20.6%, and roughly 2%, respectively. In the 1995–2010 version of TCTOR, 93.2% had weak ratings, with 6.8% strong. Analysis of the 1995–2009 SPC TC tornado dataset (TCTOR, Edwards 2010) indicates that, for supercellular convective modes, significant (F2+/EF2+) events were slightly more common outside TCs (16% of all tornadoes) than in TCs (10%).

The decrease in proportion of strong TC tornadoes since 1995 indicates a secular influence associated with WSR-88D usage in warning and verification efforts. To test this notion further, the data from Schultz and Cecil (2009) have been broken down by periods corresponding to the eras before and after essentially full nationwide deployment of the WSR-88D network around 1995 (Fig. 3). More recent data from TCTOR (TC tornado database, Edwards 2010) also reveal an increase in the proportion of weak (EF0–EF1) tornadoes under the current warning and verification system.

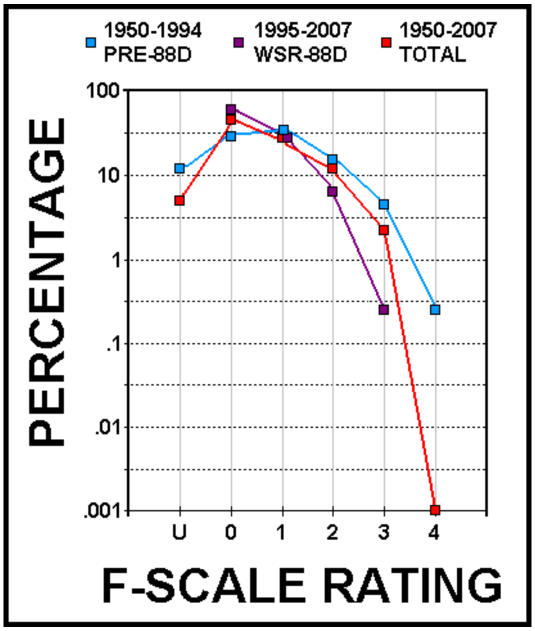

Figure 3. Logarithmically scaled line graph of tornado damage-rating distribution, as percentages of each period's total, for time bins preceding (blue) and during (purple) the WSR-88D era, and for the entire period (red). U represents unknown ratings and unrated events, collectively. From data supplied by Schultz and Cecil (2009). *Click image to enlarge.*

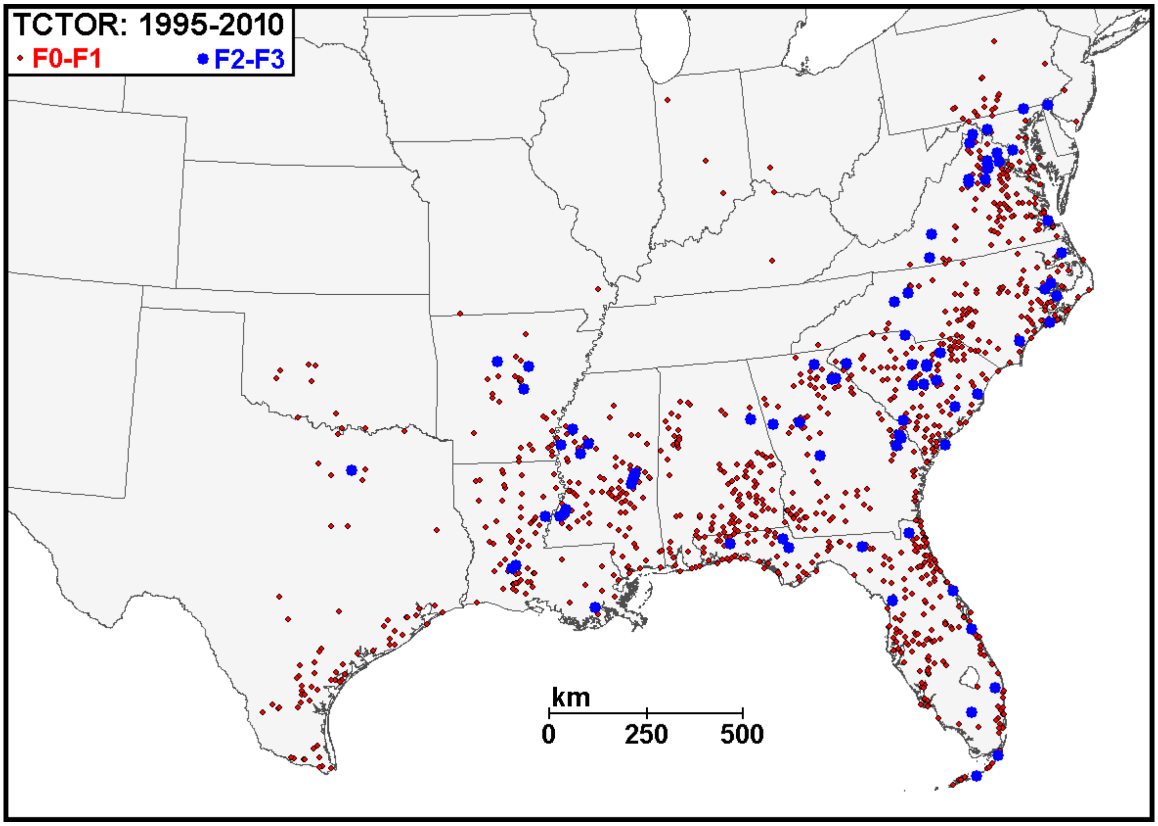

Figure 4: Map of initiation points of 1163 U.S. TC tornadoes, 1995–2010, from the SPC TCTOR data; damage rating bins as labeled. *Click image to enlarge.*

Schultz and Cecil (2009) data also contain a marked proportional increase in tornado numbers in the current era, with 999 events in the 13-y WSR-88D subset (77 y^{-1}), compared to just 768 in the preceding 45 y (17 y^{-1}). These results indicate a pronounced influence of the radar's usage on the U.S. TC tornado record. The Florida-specific study of Agee and Hendricks (2011) concludes that pre-WSR-88D TC tornadoes are "severely underestimated" there.

b. TC tornado event classifications

For total number of tornadoes produced by a single U.S. TC, Hurricane Ivan of 2004 holds the apparent record with 118[3], although it is possible that Beulah (1967), herein credited with 115 tornadoes, exceeded that total[4]. Ivan's tornado production followed a sharply defined, three-day cycle across a long (>1200 km) and wide (up to 500 km) swath of the eastern U.S. (Fig. 1a). Each day resulted in outbreaks of at least 20 tornadoes, matching the Curtis (2004) criteria—an unprecedented pattern of sustained tornado productivity from any known TC. When plotted relative to TC center position (Fig. 1b), Ivan's tornado production was more compact than Beulah's (cf. Fig. 4 in Orton 1970). By contrast, given Ivan's elongated geographic and

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[3] Verbout et al. (2007) claim 117 tornadoes for Ivan, while Belanger et al. (2009) count 122.

[4] Several totals for Beulah appear in the literature, the most commonly cited being 115 (Orton 1970), 141 (Novlan and Gray 1974) and 113 (McCaul 1991). Verbout et al. (2007) claim 117, 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 useful for its stated exclusion of damaging nontornadic winds (i.e., downbursts). Though admitting that "the actual number of tornadoes cannot be ascertained at present," that study excluded duplicated reports and "others that do not indicate clearly the storm to be tornadic in character." With some reservation, Orton's 115 total is used herein because of his study's thoroughness and multi-source approach.

temporal tornado distribution, Beulah remains the most densely concentrated of the largest TC tornado producers in a ground-relative sense (Orton's Fig. 1). The most productive hurricane season for tornadoes on record was 2004, with 317, followed by 2005, with 238. Five of the top ten tornadic TCs (Table 1) struck the U.S. in just those two years.

The most productive tornadic TCs, by almost any of the widely varying definitions for a tropical 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. Table 1 supports this notion. Nonetheless, the TS tornado threat should not be neglected. TS tornado outbreaks have occurred, including 50 from Fay in 2008 (Table 1). TS Beryl (1994) yielded 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 1970–1980.

c. U.S. TC tornado distribution

Climatological examinations of TC tornado reports indicate the greatest concentrations exist over coastal states from Virginia through Florida and westward to Texas, within 500 km of the coast (Fig. 4 herein; Hill et al. 1966; Novlan and Gray 1974; Gentry 1983; Schultz and Cecil 2009). TC tornado reports also diminish sharply northeastward from the Delmarva Peninsula through the Mid-Atlantic region into New England.

Hurricanes Beulah over Texas (1967) and Audrey over Alabama (1957) caused two dense clusters within distributions mapped by Novlan and Gray (1974). Tornadoes generally become less common with time as a TC moves inland (e.g, Fig. 15 in McCaul 1991). 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 largest daily tornado yield was on the third day after landfall. McCaul (1991) attributed lengthy time spans of inland TC tornado production to an increase in vertical shear after landfall, despite the decrease in surface winds. Furthermore, Edwards (1998a) documented several TCs that exhibited two periods of tornado production: near landfall and where the recurving TC approached the Atlantic coast. Such "exit-phase" tornado production shows that neither the inland weakening of a TC, nor an observed lull of many hours in tornado production, should be interpreted as a sign of permanently declined tornado yield. During such apparent lulls, the operational forecasting approach still should involve careful examination of the expected buoyancy and shear environments within the TC, in keeping with concepts presented in Section 4.

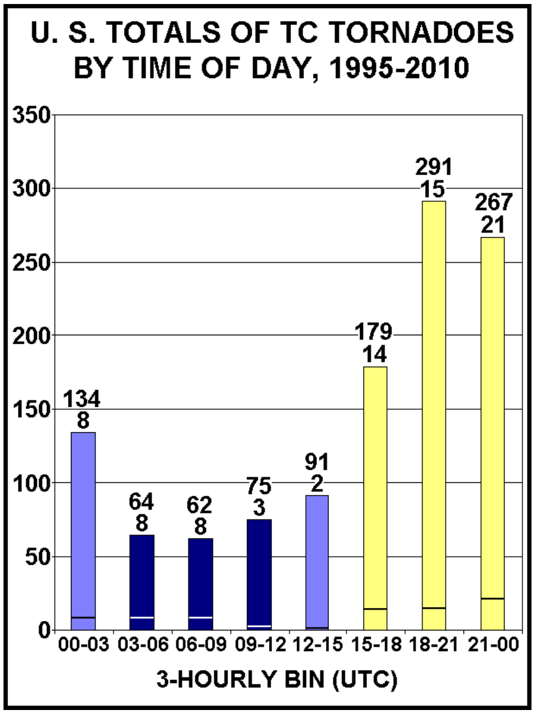

Figure 5: Time bins of 1995–2010 TCTOR events, starting with local evening period (0000–0300 UTC) on the Gulf and Atlantic coasts. Yellow bars denote peak periods and correspond to late morning through afternoon during TC season. Each bar is divided by weak (EF0–EF1, top) and strong (EF2–EF3, bottom) ratings. Top and bottom bar labels represent counts of total and strong tornadoes, respectively.

TC tornadoes often have occurred at night, especially in association with the TC landfall phase (Weiss 1987). Still, pronounced diurnal cycles exist in many events, concurrent with periods of 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 detect the diurnal peak. However, later studies with larger sample sizes have shown the diurnal peak in TC tornadoes. These include McCaul (1991), with 57% of tornadoes between 0900–1800 local sun time (corresponding roughly to 1400–2300 UTC in the southeastern U.S.), indicating the lesser influence of diabatically enhanced buoyancy in the more densely clouded portions of TCs. Schultz and Cecil (2009) concurred, showing a pronounced diurnal (early-mid afternoon) peak in TC tornado activity. Their data show a larger proportion of night tornadoes in TCs than in the U.S. as a whole and less day–night variation in tornado numbers within 200 km of TC centers.

Similar diurnal and nocturnal tornado distributions have continued in the WSR-88D era (e.g., Fig. 5). In TCTOR, the greatest numbers of strong tornadoes occurred within the daylight time bins. The largest proportions of strong tornadoes (11%) for a given time bin, however, were in the local overnight hours between 0300–0800 UTC. Well before the TCTOR era, the aforementioned violent tornadoes of Hurricanes Carla and Hilda also were nocturnal.

d. Tornado distribution relative to TC center

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 decrease in tornado-occurrence density from the gale sector inward toward the center. Polar plots of 1995–2010 TCTOR events (Fig. 6) indicate that the highest concentrations of tornadoes occurred 100–500 km from center. Figure 6 also shows a clockwise shift in tornado distribution relative to center for less intense TCs. That shift is associated with the greater overwater (and therefore report-deprived) coverage of the southern or rear portions of mature hurricanes, relative to the more commonly inland envelopes of weaker systems.

Mean and median radii of TCTOR events increased during daytime, along with an outward shift in tornado distribution by radial bins (Fig. 7). The median radius also was 214 km in the late local evening from 0300–0600 UTC, but 348 km during local late afternoon from 2100–0000 UTC (not shown). Such changes may reflect the daytime tendency for higher CAPE in the outer parts of the TC envelope, whereas CAPE is less variable from day to night near center (section 4b). The 79 strong (EF2–EF3) tornadoes averaged only 2.1 km farther from center (327.5 km) than the mean radial distance of 1084 weak tornadoes; however, no strong tornadoes were recorded <41 km from any TC center.

Generally, the greatest concentration of tornadoes occurs in the right-front (motion-relative) or northeast (pole-relative) quadrant. Smith (1965) plotted about half (51%) of the 1955–1962 tornadoes in the right-front quadrant, with considerable scatter into others. Pearson and Sadowski (1965) found similar distributions from 1955–1964—not surprising, since they used 98 events from Smith’s data. Japanese typhoon tornadoes (Fujita et al. 1972) also occurred mainly in the right-front quadrant. That quadrant essentially was collocated with the northeastern sector, because Japanese TCs translate with a strong northward component. More recently, McCaul’s (1991) environmental climatology also was based on a cyclone-relative framework, with the right-front quadrant a preferred location for tornado occurrence. Still, a great amount of scatter was evident, particularly toward the motion-relative rear (e.g., Fig. 11 in McCaul 1991).

In the earth-relative framework, Hill et al. (1966), Novlan and Gray (1974) and Weiss (1987) showed a strong preference for tornadoes in the northeast quadrant of the TC circulation. Comparing both methods for 1973–1980, Gentry (1983, his Figs. 1 and 2) illustrated a somewhat tighter distribution of tornadoes relative to true north than relative to TC motion. For Hurricane Beulah (1967), Figs. 3 and 4 in Orton (1970) shows a well-defined preference for the sector between 350° and 60° north-relative; though the lack of tornado reports in eastern and southeastern azimuths >60° may be attributed to the water in that portion of outer envelope. Beulah’s sharp southwestward turn after landfall (Fig. 1 in Verbout et al. 2007) abruptly resulted in the presence of numerous tornadoes over its left rear (cyclone-motion relative) quadrant, but in the same geographic area as before, suggesting that a shift in translational TC motion did not change the physical environment supporting tornadic supercells.

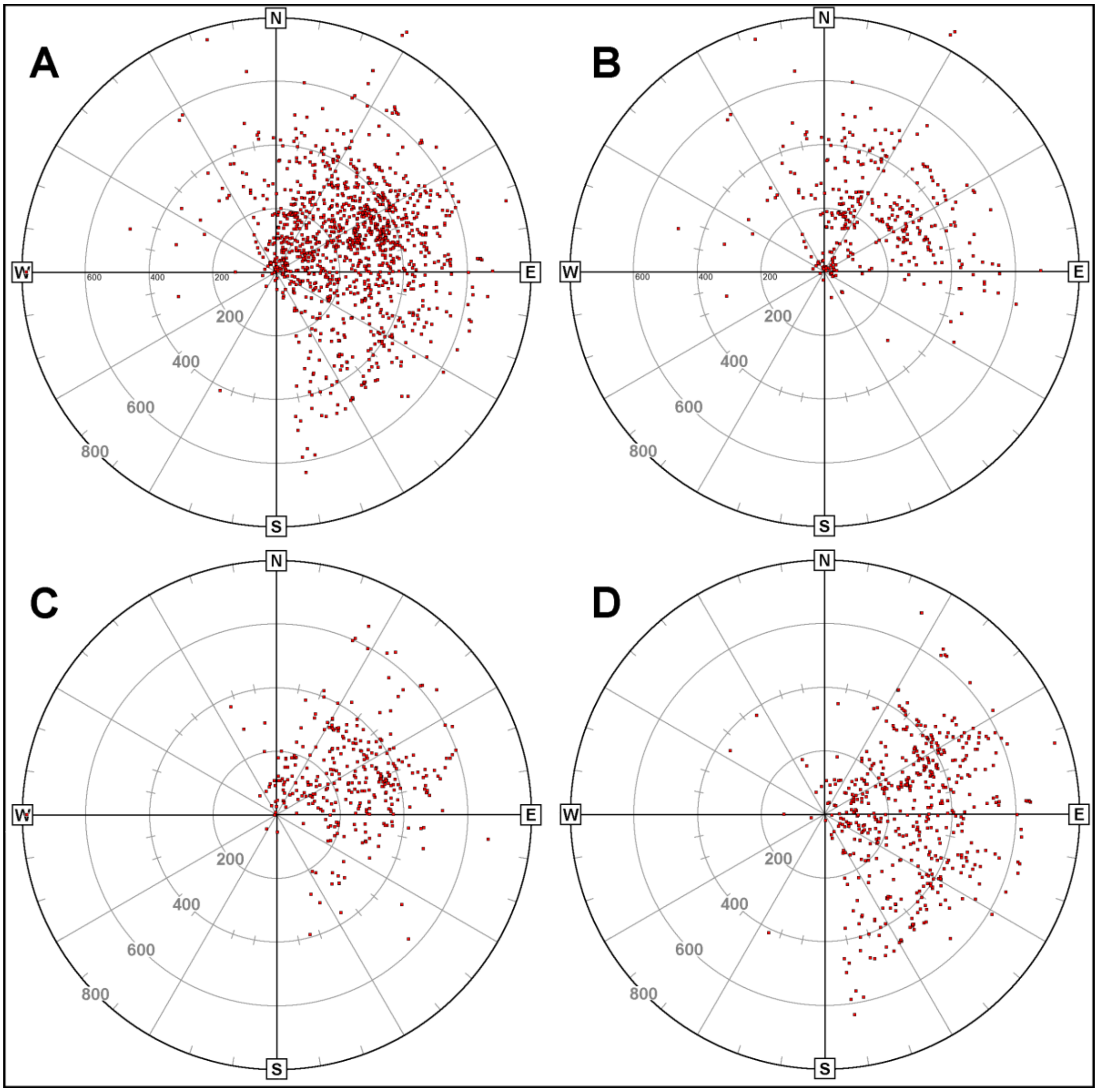

Figure 6: TC center-relative plots of 1995–2010 TCTOR records: a) all TCs, b) hurricanes, c) tropical storms, and d) tropical depressions, remnant lows and TC remnants. Events plotted with respect to north-relative azimuth (tick marks and full radials at 10º and 30º intervals respectively) and range (km as labeled) from center position, at the time of each tornado. Reference frame is with respect to north (up). Due to scaling effects, some tornadoes may obscure others on each panel. *Click image to enlarge.*

Both north-based and cyclone motion-relative frames of reference are used commonly in operational and research applications, sometimes almost interchangeably. However, important distinctions may exist for any TC translating appreciably off a northward bearing, as indicated by Fig. 8. Which frame of reference is more meaningful, more of the time? Polar plots of 1767 probable TC tornadoes by Schultz and Cecil (2009) indicate no obvious distinction between north-relative and TC motion-relative distributions. Their graphics for both frames of reference similarly show considerable and dense distributive scatter from the traditionally preferred northeast (right front) quadrant rearward across most of the southeast (right rear) quadrant, and leftward into a small adjoining part of the northwest (left front) quadrant.

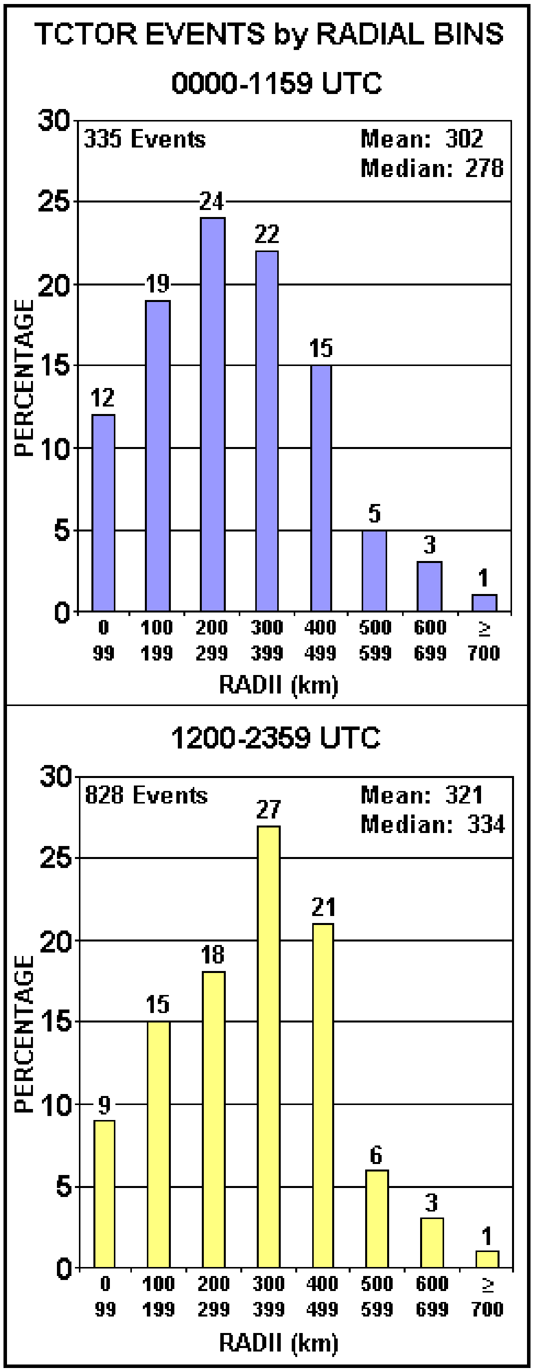

Figure 7: Percentage of 1995–2010 TCTOR reports in radial bins (km, as labeled) from TC center, for 12-h periods beginning at 0000 UTC (blue, top) and 1200 UTC (yellow, bottom). Percentages are labeled above each bar and may not equal 100 due to rounding. The 0000–1159 UTC period includes local nighttime, and the 1200–2359 UTC period is diurnal. Sample sizes and mean and median radii are given for each time period.

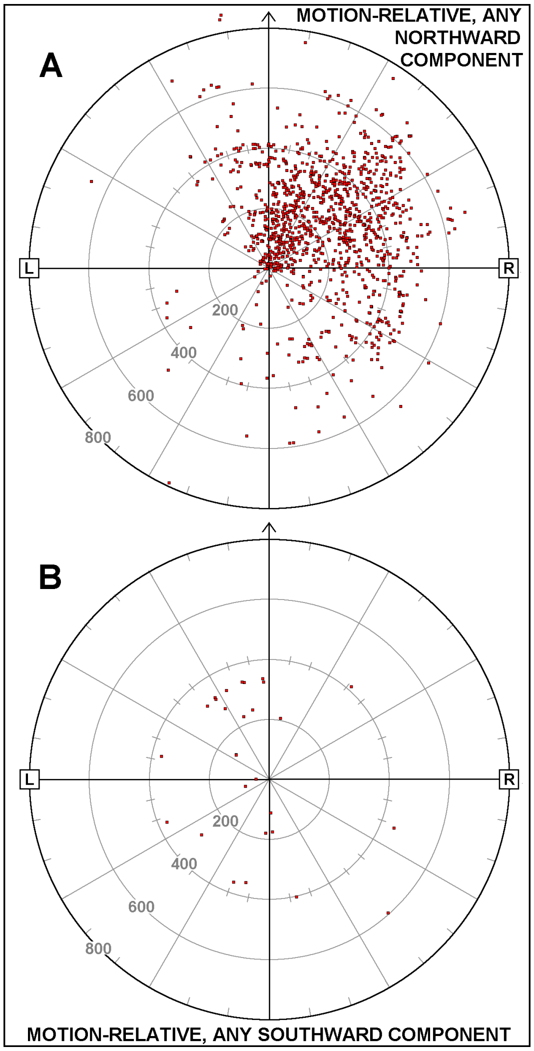

Figure 8: 1995–2010 TCTOR reports with respect to TC centers at tornado time, for translational TC motion toward any component of a) north, and b) south. Conventions as in Fig. 1b, except for right (R), left (L), and an arrow designating direction of TC translation. *Click image to enlarge.*

More recently, however, analysis of 1163 TCTOR events from 1995–2010 (cf. Figs. 6a and 7) indicates that tornado distribution relative to poleward coordinates is slightly less scattered toward the left (west) and rear than for the translation-relative framework. Also, because the "right front" and northeastern sectors usually overlap to a great extent anyway, much of any distinction between the two frames of reference may be obscured by large sample sizes of the databases as a whole. When segregating TCs translating with any *southward* component, a relatively small sample reveals a clear maximum in the *left* semicircle (Fig. 8b). Both Schultz and Cecil (2009) and the TCTOR data (not shown) show the greatest concentration—approximately 80% of TC tornadoes—within the sector from 350º–120º relative to center. Again, events southeast of center, in both datasets, may be underrepresented due to that sector of most hurricanes lying over water.

Given such broad azimuthal scatter within large sample sizes, it appears that strict quadrant-based definitions of preferred sectors should be discouraged. Rather, the favored area of TCs for tornadoes in the Northern Hemisphere should be viewed as a loosely defined *sector*, not a rigidly delineated *quadrant.* That relatively dense sector is north-northwest, through northeast, to southeast of center. In the Southern Hemisphere, assuming the physical processes are spatially mirrored as with other weather systems, this translates to a favored sector south-southwest through southeast and northeast of center.

By contrast, Molinari and Vollaro (2008) used a shear-relative framework for evaluating convective cell-relative helicity (and by extension, supercell risk). 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 for forecasting tornadic supercells. Helicity has been used alone and in bulk parameters (e.g., Thompson et al. 2003; 2007) as a statistically robust diagnostic indicator of favorable supercell environments.

The Molinari and Vollaro (2008) analysis was performed in the environment of a single TC (Bonnie of 1998), using data from maritime dropsonde deployments, based on assumed cell motions derived from midlatitude supercell algorithms[5] because of the lack of radar data. Their largest helicity values were located in the downshear-left quadrant of Bonnie, analogous to the directional northeast and cyclone-relative right-front quadrants discussed above, and also with some scatter into adjacent radial sectors. Molinari and Vollaro (2010) found similar results in extending their analyses to eight TCs in the Convection and Moisture Experiments (CAMEX). One concern with a shear-relative framework is that it is unclear where to sample the shear vector, given the horizontal dimension of a TC (10^2–10^3 km in diameter) and the potential variability of ambient flow across that scale. Another concern is how to define (or sample) the *appropriate* large-scale environmental shear in an operational setting.

4. Environmental concepts

An ingredients-based approach (e.g., Johns and Doswell 1992), used for assessing and forecasting environments favorable for supercellular tornadoes in the midlatitudes, likewise is applied to TCs, focusing on moisture, instability, vertical shear and lift. Given the inherent abundance of low-level moisture, the main factors influencing the occurrence of tornadoes in TCs are the relative distribution and overlap of shear, instability (as indicated by positive buoyancy) and boundaries or other sources for convective initiation.

a. Synoptic-scale TC environment

The U.S. Gulf and Atlantic coasts reside in subtropical and higher latitudes within which midlatitude weather systems influence TC motion and structure. TCs there tend to encounter ambient westerlies, which favorably enhance internal vertical wind profiles to levels favorable for supercell development (McCaul 1991; Verbout et al. 2007; Molinari and Vollaro 2010). Such TCs also tend to recurve (Fig. 6 in Verbout et al. 2007), because of encountering midlatitude westerlies influenced by baroclinic perturbations. Composite synoptic patterns for Texas TCs (Verbout et al. 2007) revealed: 1) that their most prolific tornado yields occurred with a mean 500-hPa trough in the north-central U.S., related to closer proximity of the TC to the polar

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[5] Common supercell motion utilities, such as Bunkers et al. (2000) and its Ramsay and Doswell (2005) adjustment, were developed using large sample sizes of deeper, midlatitude supercells. Those assumptions have not been tested systematically in multiple TCs, where curvature and magnitude of ambient low- and mid-tropospheric winds can be much stronger. Molinari and Vollaro (2008) did determine, for one storm, that the planar pattern and existence of large helicity was insensitive to cell-motion estimate. Eastin and Link (2009) found that observed supercell motions in Hurricane Ivan were 15–20° less deviant rightward than for the Ramsay and Doswell (2005) technique.

jet, and 2) greater 500-hPa geopotential height anomalies and stronger height gradients accompanying TCs with relatively high tornado counts. These factors together suggest that TCs with tornado outbreaks possess greater deep-layer shear.

b. TC-scale influences on tornado potential

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; Baker et al. 2009). Both land-based (e.g., Spratt et al. 1997; Rao et al. 2005) and airborne (Eastin and Link 2009) radars have detected supercells over water. Operational experience indicates that it is common for supercells to develop offshore, and then move inland, with tornadogenesis occurring either inland or over water prior to moving ashore. Other supercells may weaken and dissipate upon reaching more thermodynamically stable land areas, making operational tornado watch and warning decisions more challenging (section 5 further discusses forecasting issues). How productive are supercells for offshore tornadoes (waterspouts)? A few TC tornadoes have been documented to move ashore (e.g., Barbour 1924; Spratt et al. 1997), and actual supercellular waterspouts could be quite common. If so, they pose a threat to shipping as well as fixed structures (e.g., wind turbines and oil platforms) offshore. The violent Galveston, TX tornado from Carla (1961) moved onshore from the Gulf of Mexico (Grazulis 1993), with an unknown prior duration over water.

Tornado environments are better documented for inland supercells, whether or not the TC center itself has made landfall. Though inner-band TC tornadoes have occurred with many TCs, three important factors contribute to a lower probability of discrete supercells and tornadoes inward toward the eyewall of a mature hurricane, especially near and before TC landfall. First, although such a hurricane's *winds* increase inward toward the radius of maximum wind, outside the eye, vertical *shear* generally tends to decrease (e.g., McCaul 1991; Molinari and Vollaro 2008). Limited dropsonde sampling, however, indicates that boundary-layer shear actually may increase for surface winds >60 m s^{-1} (Franklin et al. 2003). Second, Edwards et al. (2012) indicates that convective mode nearer to center tends toward nonsupercellular, with more continuous banding structures, eyewall(s) in hurricanes, and greater coverage of nonconvective rain shields. Third, and perhaps most importantly, McCaul (1991) documented a well-defined CAPE decline from a TC's outer fringes inward toward center. The relatively dense and/or conterminous precipitation patterns near the center of weaker TCs without eyes, concurrent with the presence of thicker deep-layer cloud cover associated with the storm's central dense overcast, restrict diurnal heating and its contribution to buoyancy. Accordingly, tornadoes closer to TC centers tend to be smaller, weaker-rated, and less related to time of day. Despite the diurnal tornado peak (e.g., Fig. 5), conditions within the TC can remain at least marginally favorable throughout the night.

c. Meso-β to convective scale characteristics

1) Convective-scale properties

Supercells within TCs tend to be smaller in vertical and horizontal extent than those of midlatitude systems, akin to the dimensions of midlatitude "mini-supercells" (e.g., Kennedy et al. 1993; Burgess et al. 1995). Occasionally, that term has been applied to convective storms in the TC setting (e.g., Suzuki et al. 2000). The small nature of TC supercells and their weaker apparent rotational characteristics make algorithmic radar detection more difficult than for midlatitude supercells (Spratt et al. 1997), emphasizing the importance of base radar moments in the TC supercell setting. The compact supercell scale in TCs appears to be related to the warm-core environment with weak thermal lapse rates aloft, and the resultant concentration of buoyancy in the lowest few kilometers AGL. That layer corresponds to vertical maxima in both vertical shear and perturbation-pressure forcing on the storm scale (McCaul and Weisman 1996), each affecting convective-scale persistence and morphology.

Supercells in TCs can last for just a few radar volume scans, or several hours. McCaul et al. (2004) documented several cyclic, tornadic supercells with the remnants of TS Beryl (1994), including one storm that was identifiable on radar for 11 h and intermittently tornadic for over 6 h, rivaling the lifespans of some Great Plains and Midwestern tornadic storms. Such persistent tornado potential in some TCs is a contributing factor to the relatively long duration of SPC tornado watches for TCs in general

(Edwards 1998b). Section 4d has more discussion on factors related to tornadoes after landfall.

Storm-scale processes, such as in situ cold pool generation, likely will not be evident in an operational setting except through fortuitous dropsonde deployments in the near-offshore area for supercells approaching the coast. The chances of such sampling being performed regularly, and having the data transmitted to the forecaster in sufficient time to influence the warning decision, appear very low for now. Still, the relative position of a supercell within a convective band may provide clues as to its likelihood for interaction with baroclinic zones generated within the band and aligned parallel to its axis. This is especially important near the inner edge of a band, where cyclonic vorticity and convergence also are maximized (Powell 1990a). Supercell development and longevity can be limited by the presence of somewhat more stable precipitation areas, which become more common nearer to the TC center. A related lack of discrete cells with inward extent toward the eyewall has been documented (e.g., Barnes et al. 1983), and has been related to diminishing CAPE in the TC core area (McCaul 1991).

2) Influences of boundaries and storm modes

TC tornado environments typically contain weak convective inhibition (e.g., McCaul 1991). As such, only weak lift is needed for deep convection in favorably buoyant areas. Such lift occurs in spiral bands, and sometimes with baroclinic boundaries that have been associated with spatial gradients in TC tornado distribution (Edwards and Pietrycha 2006; Green et al. 2011). Such boundaries may be at least partly continental in nature and originate before TC arrival (e.g., Knupp et al. 2006), produced by precipitation processes over water (e.g, Barnes et al. 1983), or outflow over land (Bosart and Dean 1991).

Whether convective mode is discrete, clustered or embedded in bands (Edwards et al. 2012), the tornado potential may increase as TC supercells interact with boundaries. Such features may include fronts and wind-shift lines, where backed surface flow and related enhancements to low-level helicity commonly are present. In midlatitudes, this process was well-documented in field observations (e.g., Markowski et al. 1998; Rasmussen et al. 2000), and has been applied to various forms of boundaries in the landfalling TC environment (e.g., Rao et al. 2005; Edwards and Pietrycha 2006; Green et al. 2011). Boundary-layer rolls have been observed in TCs by mobile radar (Wurman and Winslow 1998), but the influences of accompanying horizontal vortices on longevity or internal dynamics of TC supercells remains unknown.

Discrete, long-lived tornadic supercells also may develop outside well-defined precipitation bands, whether supported by diurnal heating over land or (especially near shore) the relatively high surface θ_e characteristic of the maritime tropical air mass at night. Several examples of such supercells, with or without banded or clustered convection nearby, are found in many recent studies, such as Suzuki et al. (2000), Edwards et al. (2000), McCaul et al. (2004), and Schneider and Sharp (2007).

Supercell mode (e.g., discrete vs. embedded in bands) also may affect their tornado potential via convective-scale processes. Idealized numerical simulations have indicated weak cold pools with discrete TC supercells (McCaul and Weisman 1996). Weak cold pools are related largely to the characteristically high moisture content of the lower troposphere in TCs. Resultant high humidity causes a lack of evaporation in the near-surface downdraft, minimizing the θ_e deficit. McCaul and Weisman proposed this process as a possible reason for the relative weakness of TC tornadoes compared to those with midlatitude supercells. Their simulations, however, did not involve environmental inhomogeneities in thermal or kinematic fields, such as the boundary situations described previously, where tornado potential may be enhanced. In that regard, midlatitude observations (e.g., Markowski 2002) have documented strong to violent tornadoes in regimes of warm storm-scale downdrafts. This appears to contradict the findings of McCaul and Weisman (1996) when applied to the TC supercell setting, where warm downdrafts occur but significant tornadoes are relatively uncommon.

Despite the apparent weakness or absence of thermal gradients in small, discrete TC supercells, cold pools from training spiral-band convection can create and reinforce such gradients[6]. Barnes et al. (1983) documented 12-K θ_e deficits in the subcloud layer of spiral bands, related to a combination of weak evaporative cooling and sensible heat loss to precipitation cascades in cooler regions aloft. Buoy data analyses in Cione et al. (2000), showed an increased sea–air thermal difference with the passage of strong convective bands (their Fig. 5a) outside the relatively homogeneous hurricane inner-core region. Eastin et al. (2012) documented cold pools with long-lived, quasi-linear convective modes in outer rainbands of TC Hanna (1988), related to the presence of cross-band vertical shear and midlevel dryness. The relationship of cold pools in such modes to nonsupercell TC tornadoes (Edwards et al. 2012) remains unknown.

3) Midtropospheric dryness

Midtropospheric drying is often collocated with clusters of TC tornadoes, especially outbreaks of 20 or more (Curtis 2004). The Curtis dataset was not detrended to account for report inflation, and processes offshore were not necessarily sampled in the land-based soundings. Further, it is unclear whether the association represents a physical process or manifests some other common influence (e.g., interaction with midlatitude troughs and recurvature, per Verbout et al. 2007). Relatively cloud-free areas under midlevel dry slots can support the few degrees C of diabatic surface heating needed to magnify CAPE substantially, amidst nearly moist-adiabatic environmental lapse rates (e.g., the composite sounding of McCaul 1991). Meanwhile, drying aloft also has been implicated in cold-pool generation in outer bands (e.g., Barnes et al. 1983; Powell 1990b; Eastin et al. 2012). Resulting differential heating between the band axis and a relatively cloud-free slot adjacent to the band's inner edge may yield thermal boundaries suitable for supercell maintenance. In turn, such boundaries may contribute to the tornadoes documented in the inward side of inner and outer bands (e.g., McCaul 1987; Rao et al. 2005).

4) Lightning indications of supercells

The outer regions of a TC that are preferred for supercell development also contain a climatologically defined maximum in cloud-to-ground (CG) lightning distribution (e.g., Molinari et al. 1999), roughly outside a 200-km radius from center. This CG lightning maximum relates to: 1) the differential vertical thermal structure of the hurricane along a radius, with heights of isotherms rising inward toward center, and 2) deepening buoyant layers with outward extent from center. Over outer portions of the TC, the latter results in CAPE that extends into thermal layers conducive to separation and redistribution of electric charge. Superimposed upon (and probably contributing to) those thermally influenced factors is that lightning production can be enhanced with supercells in the TC environment because of stronger and deeper updrafts (McCaul et al. 2004), especially in inland-decay modes or the outer reaches of more mature, near-coastal TCs.

Lightning may be a useful indicator of TC supercells—and in turn, tornado risk, given that most TC tornadoes occur in supercells (e.g., Edwards 2012). CG lightning rates maximize with tornadic supercells over land, relative to other convection in a TC environment (e.g., McCaul 1987), even though some tornadic TC supercells produce few or no CG strokes. McCaul et al. (2004) also showed that, similar to Great Plains supercells, lightning occurrence can diminish just before or during tornadic phases. Lightning-trending is a useful indicator of tornado potential in the TC setting, suggesting supercells when other data are absent. Further studies are needed to demonstrate lightning more convincingly as a supercell indicator, but the early work shows promise.

d. Tornadoes in the eyewall environment?

Eyewall tornadoes appear in climatologies of tornado reports (e.g., Fig. 1 from Gentry 1983; Figs. 1a and 11 from McCaul 1991), but remain elusive in terms of verifiable observations. As such, there are concerns about their existence. No video or photographs exist of eyewall tornadoes. There also is a lack of conclusive indirect evidence, such as land-based or mobile-radar sensing of columnar, tornado-strength vortices that are continuous from ground level into the eyewall.

Eyewall tornadoes could be inferred from patterns of relatively intense damage in narrow corridors (Wakimoto and Black 1994); however, other potential sources would need to be ruled

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[6] Powell (1990a,b) provided an overview of the dynamics, motion and morphology of outer hurricane rainbands.

out. Damaging ground-level vortices in the inner eyewall of Hurricane Andrew, apparently resulting from horizontal shear processes, were documented by Fujita (1993), who *specifically avoided referring to them as tornadoes*. Instead, Fujita incorporated a hitherto unused term, "mini-swirls." Were these "mini-swirls", one of which was deemed a "possible small tornado" by Wakimoto and Black (1994), vertically continuous with the convection above? Did they connect to any helically symmetric columnar vortices (after Emanuel 1984) that may have existed in the regime of strong cyclonic horizontal shear on the inside edge of Andrew's atypically intense and convective eyewall (Powell and Houston 1996)? If so, and if established as part of the convective updraft process of the eyewall, they may be classified as tornadoes. Damage from supercell tornadoes and "mini-swirls" may be similar, and the difference may seem semantic to those affected. Nonetheless, correct classification of damaging eyewall vortices still is important for physical understanding and accurate climatological classification of the *processes* involved.

Alternatively, do some swaths of enhanced eyewall damage result from convective downbursts, as speculated by Powell and Houston (1996) for one such event in Andrew? Downburst areas in the eyewall would have a high aspect ratio because of their superimposition upon extreme ambient flow.

Such concerns, along with existing observations and models of non-discretely convective eyewall structure, argue for more investigation on eyewall tornadoes. In the meantime, 1) any statement of certainty on eyewall tornadoes remains premature, and 2) nonsupercellular processes probably are responsible for eyewall tornadoes, if they occur. High-resolution, aerial Doppler radar sampling between the sea surface and the convective plume, and/or observations by mobile Doppler units deployed amidst an inland eyewall, may provide important clues about processes in the eyewall that yield tornado reports.

Otherwise, direct documentation from the ground may remain elusive for several reasons, including: 1) the difficulty and safety risk of visual and photographic documentation under extreme conditions of wind and rain, 2) the likelihood that such tornadoes would translate very rapidly past any observer and would be small and ephemeral, and 3) the difficulty of distinguishing damage due to weak eyewall tornadoes from that produced by embedded downbursts or severe, nontornadic eddies (Fujita 1993). In conclusion, given the lack of evidence for them, the eyewall environment's closest approximation to current consensus definition of a tornado (AMS 2000) has not been verified.

e. Tornado environments in the inland TC

The peak time period for TC tornadoes is from ~12 h prior to ~24 h after landfall (e.g., Schultz and Cecil 2009). Tornado production also is common >24 h after landfall—sometimes yielding a majority of a TC's total tornado count (e.g., Ivan in 2004 and Beryl in 1994). As the TC moves inland in the midlatitudes, its wind profiles tend to weaken nonuniformly in the vertical. In other words, inland TC winds weaken faster at the surface than aloft because of frictional effects (Gentry 1983), with directional backing. In addition, ambient middle-upper tropospheric wind profiles often strengthen with time and with poleward extent from the TC center and downstream from midlatitude troughs that compel recurvature of the TC (McCaul 1991, Verbout et al. 2007). Overall, both processes can help to maintain favorable vertical *shear* despite slower wind *speeds*. As such, shear may remain suitable for tornadic supercells for days, particularly near any lower tropospheric boundaries that may back the near-surface flow. An example of such a regime was analyzed by McCaul et al. (2004), associated with the inland weakening phase of TS Beryl (1994).

Meanwhile, diurnal diabatic heating of the land surface from insolation, especially beneath cloud breaks, increases buoyancy and contributes to a more pronounced diurnal character of tornado distribution. An extreme example of diurnal tornado cycles inland is Hurricane Ivan (Fig. 1). Ivan followed a post-landfall course roughly similar to Beryl, another prolific tornado-producer, although Ivan was a much larger and stronger cyclone upon landfall.

5. Current state of TC tornado prediction

TC tornado forecasting follows an approach resembling the generalized "forecast funnel" (Snellman 1982), where risk is focused more narrowly in time and space as landfall approaches. This process begins with initial NHC track forecast up to five days out, follows through specific tornado discussion in SPC and NHC products, and culminates with storm-specific tornado warnings and statements from local NWS offices.

a. Operational practices—outlook to warning to verification

Official tornado forecasts are provided by the NWS in this order: 1) SPC general severe weather outlooks 2–8 days out, 2) coordinated statements by NHC concurrent with day-1 SPC convective outlooks (e.g., Fig. 9), 3) SPC mesoscale discussions and tornado watches 1–12 h in advance (e.g., Fig. 10), and 4) local NWS tornado warnings. NHC predicts track, intensity and surface wind radii for TCs, as well as other factors unrelated to tornado threat (e.g., storm surge); Rappaport et al. (2009) describes NHC's function and structure.

SPC outlooks communicate a threat for severe weather up to eight days in advance, though explicit tornado probabilities are not introduced until day-1. Outlooks use probabilistically derived categorical risk areas focused on land areas just rightward or east of NHC forecast tracks. Clients involved with NWS, private meteorology, media, homeland security and emergency management use these outlooks for hazard-mitigation planning.

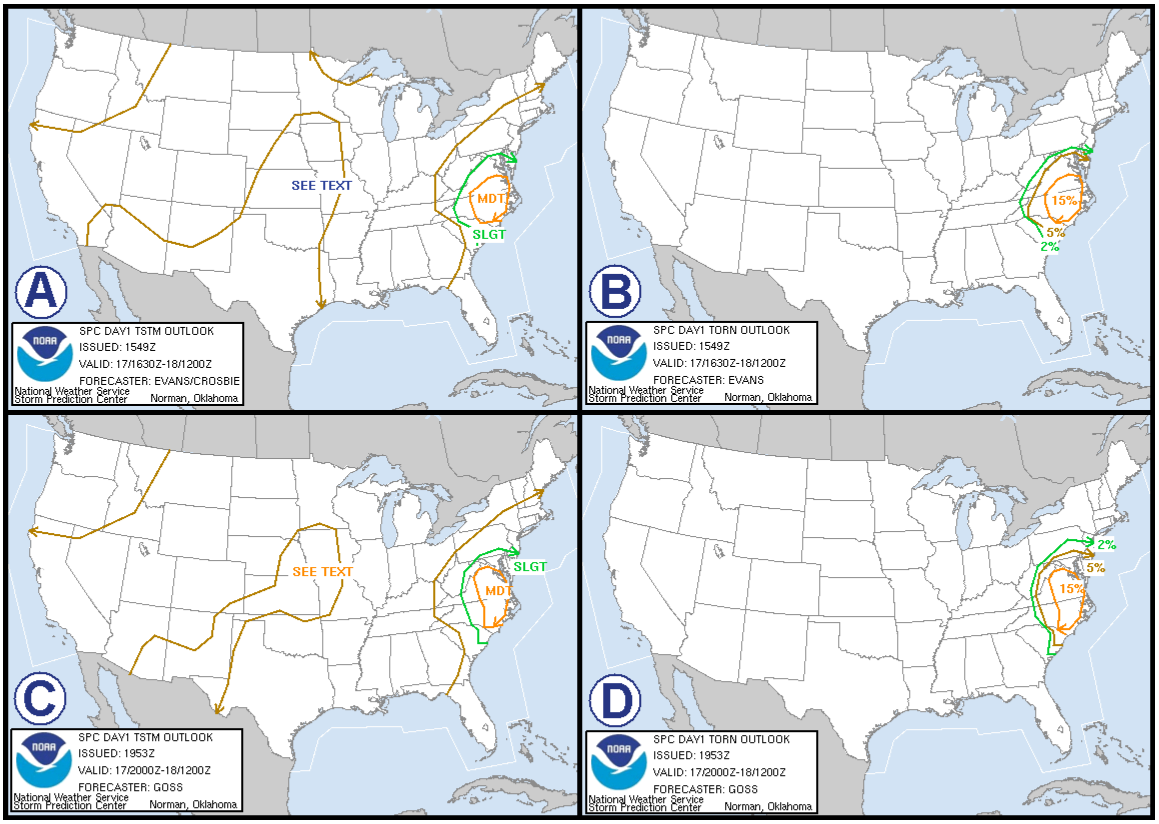


Figure 9. Graphical SPC day-1 convective outlooks issued 17 September 2004, valid until 1200 UTC the following day: a) Categorical convective potential, issued 1549 UTC. Unlabeled brown line represented general thunderstorm forecast; b) Corresponding tornado probabilities within 40 km radius of any point as of 1549 UTC; c) as in (a) but for 1953 UTC; d) as in (b) except for 1953 UTC. *Click image to enlarge.*

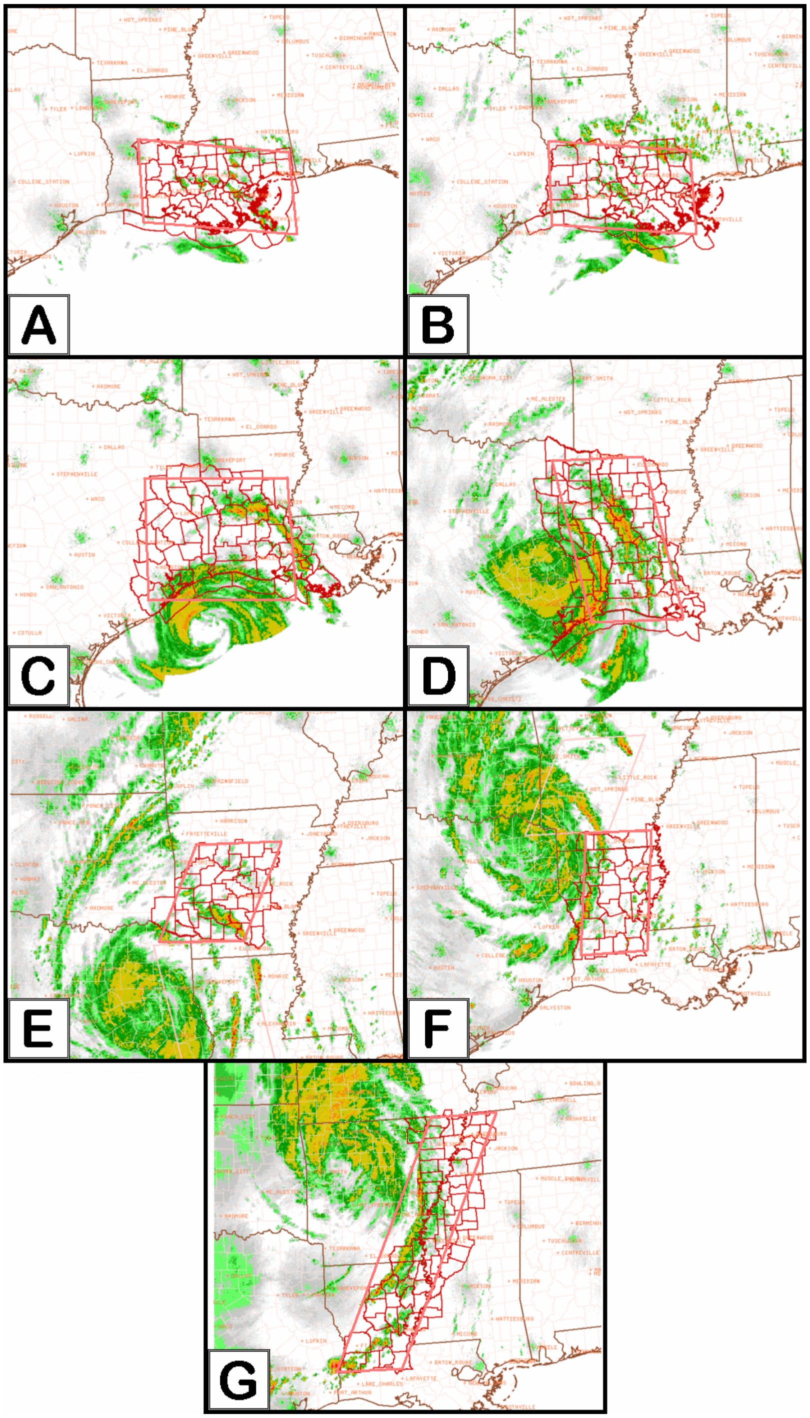


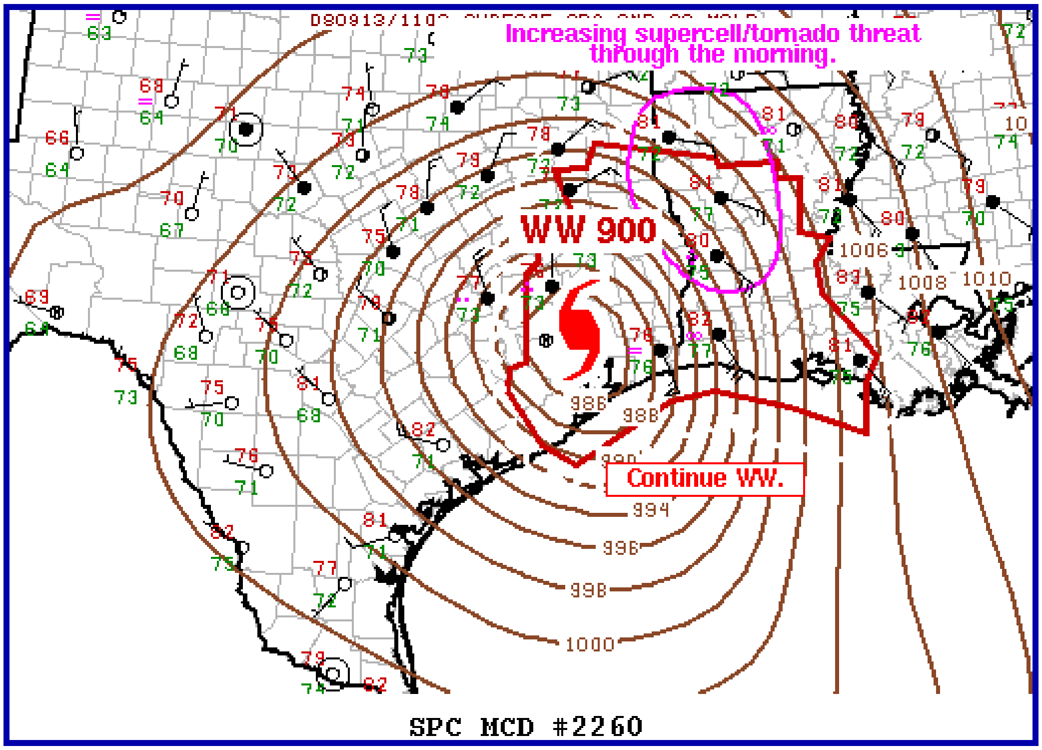
Figure 10. Chronological sequence of graphical SPC tornado watches for Hurricane Ike of 2008. Red outlines are valid counties and marine zones for each watch. Juxtaposed parallelograms represent *approximate* watch area for aviation purposes (i.e., traditional parallelogram). Each map background is at identical scale and centered on the watch centroid. Underlying radar image represents regional composite radar reflectivity snapshot available at these watch issuance times: a) 0850 UTC 12 September, b) 1745 UTC 12 September, c) 0055 UTC 13 September, d) 1440 UTC 13 September, e) 1910 UTC 13 September, f) 0000 UTC 14 September, and g) 0655 UTC 14 September. *Click image to enlarge.*

Table 3. SPC forecast products as applied to TC tornado situations, as of 2012. 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.

Typically, NHC and SPC forecasters begin to coordinate the tornado threat as a small part of scheduled conference calls via the "Hurricane Hotline", a self-contained telephone system that also includes affected local NWS forecast offices, NWS regions, military interests and the Department of Homeland Security. Discussion of the TC tornado threat on the hotline occurs within 6–12 h before the outer fringe of the TC's circulation begins to affect land. Edwards (1998b) discussed the SPC forecast process for TC tornado threats near landfall time. Table 3 summarizes the current SPC suite of forecast products as specifically applied to threats of TC tornadoes. NWS offices also mention the tornado threat in text products known as "hurricane local statements", as well as in graphical hazard maps of their jurisdictions produced for Internet display.

The SPC outlook process includes the inland remnants of TCs, as long as they have tornado risk. Inland decay of TC surface wind structure, as forecast by NHC, incorporates a supplemental decay version of the Statistical Hurricane Intensity Prediction Scheme (SHIPS, after DeMaria et al. 2005), called D-SHIPS. Included in D-SHIPS are concepts from the empirical Kaplan and DeMaria (1995) model assuming an exponential inland decay rate proportional to both the TC's strength (in terms of maximum sustained wind speed) at landfall and the time since landfall, as well as a modified decay model (DeMaria et al. 2006) emphasizing the influence



MESOSCALE DISCUSSION 2260
NWS STORM PREDICTION CENTER NORMAN OK
0701 AM CDT SAT SEP 13 2008

AREAS AFFECTED...ERN TX / WRN AND CNTRL LA

CONCERNING...TORNADO WATCH 900...

VALID 131201Z - 131400Z

THE SEVERE WEATHER THREAT FOR TORNADO WATCH 900 CONTINUES.

THE POTENTIAL FOR SUPERCELLS CAPABLE OF TORNADOES WILL GRADUALLY INCREASE THROUGH THE MORNING WITHIN FAVORABLE NERN QUADRANT OF HURRICANE IKE. WITH TIME...THIS THREAT WILL DEVELOP TO THE N OF WW 900...REQUIRING A NEW WW.

AS OF 1140Z...THE CENTER OF IKE WAS LOCATED APPROXIMATELY 35 SE UTS WITH A WOBBLY NWD MOTION OF AROUND 20 KT. EPISODIC RAINBANDS COMPOSED OF MULTIPLE SUPERCELLS HAVE EVOLVED OVER THE PAST SIX HOURS WITHIN ERN SEMICIRCLE OF HURRICANE OVER SWRN INTO W-CNTRL LA. THIS AREA IS JUST OUTSIDE THE ENVELOPE OF STRONGEST SURFACE WINDS WHERE LOW-LEVEL BULK SHEAR IS BEING MAXIMIZED. AIR MASS WITHIN THIS ZONE OF STRONGER SHEAR REMAINS QUITE MOIST WITH DEWPOINTS IN THE MID 70S RESULTING IN SUFFICIENT BUOYANCY /REF. 12Z LCH SOUNDING/ TO SUPPORT STORM ORGANIZATION/ROTATION.

EXPECT THE SUPERCELL/TORNADO THREAT TO INCREASE BY MID TO LATE MORNING NWD INTO PORTIONS OF E-CNTRL/NERN TX AND NRN LA AS THESTRONGLY SHEARED BOUNDARY LAYER BEGINS TO WARM/DESTABILIZE.

..MEAD.. 09/13/2008

Figure 11. Graphic and textual SPC MCD issued 1201 UTC, 13 September 2008, for tornado threat of Hurricane Ike. Graphic contains a conventional surface plot, SPC tornado watch outline (red), approximate TC center location at issuance time, objectively analyzed isobars, and magenta outline of the nowcast threat compelling the next watch issuance. Operational MCD graphic format varies by situation from this example.

of small, narrow landmasses such as Cuba and Florida. D-SHIPS is used in predicting both maximum wind values near the TC center and the horizontal wind radii. The latter is more directly pertinent to prognosis of low-level vertical shear supporting supercell potential.

NHC heavily incorporates D-SHIPS into inland wind forecasts for decaying TCs. In turn, SPC uses those NHC products in its own forecasts covering tornado risk (Table 3). Other input to SPC tornado outlooks include analyses of surface and upper air observations, satellite image animations, automated diagnostics, forecast fields from operational NWP models, model forecast soundings, and coordination as needed with affected local NWS offices via chats and conference calls.

As public bulletins, SPC watches serve the general public, emergency managers and storm spotters, in addition to aforementioned audiences. The watch serves to heighten awareness of the tornado threat and often initiates contingency plans in the user community (e.g., activation of spotter networks, increased staffing in emergency operations centers, etc.). For detailed mesometeorological analysis, however, 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 diagnostic and short-term forecasting insights in a technical text product that covers a 30-min to 3-h period. MCDs are accompanied by both a text headline and a graphic that describe the threat area (Fig. 11).

Since nationwide deployment of the WSR-88D network largely was completed (about 1995), Doppler radar has become the primary tool for operational tornado warning issuance by local NWS offices. This is especially true for TCs, which are characterized by heavy rain, low cloud bases, fast cell translation, unconventional direction of motion (often from the east or southeast near the Gulf and Atlantic coasts), and brevity of most tornadoes. Those circumstances make the best practices for storm spotting (Doswell et al. 1999) extraordinarily difficult in TCs, the striking photographic examples in Fig. 2 and in McCaul (1987) notwithstanding.

Spratt et al. (1997) provided early examples of the utility of Doppler radar for TC tornado indication, mainly at close ranges where the lowest beam elevations best sample the relatively compact mesocirculations of most TC supercells. They also emphasized the difficulty of algorithm-based mesocyclone and tornado detection in TCs, given the shallower and more subtle nature of cell-scale rotation compared to midlatitude supercells. Tornado warnings are issued 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 that presents unique challenges for dissemination and interpretation of warnings (Ferree and White 2008). A combination of radar interrogation and environmental analysis typically is used in the operational warning environment. SPC MCDs contribute to environmental situational awareness at the local warning desk, especially in coastal landfall situations when a variety of TC-specific products and duty responsibilities adds to workload. Local NWS offices also issue severe weather statements in text format, as updates within the valid warning timeframes.

Under current practices, each warning is verified by the same NWS office issuing the warning. Any resulting tornado reports are relayed in segmented form, by county, to the National Climatic Data Center (NCDC) for processing into a national report collective. Final warning verification is done on these data by a branch of NWS headquarters. SPC then analyzes segmented NCDC reports for those that may have crossed county or state lines, effectively “stitching together” all conterminous county path segments. The result is a final, whole-tornado tally that is used in verification of SPC products (Schaefer and Edwards 1999).

Explicit documentation of TC tornadoes, however, has been an inconsistent endeavor, performed at various times by local NWS offices (for tornado events in an office’s jurisdiction), articles in NCDC *Storm Data* featuring the most noteworthy TCs, NHC’s post mortem TC reports of each system’s meteorological evolution and societal impacts, and/or the Annual Summaries of Atlantic-basin TC activity in *Monthly Weather*

Review. In each case, event-reporting practices have varied over time. The TCTOR effort is underway at SPC to tabulate and map known TC tornado occurrences in a consistent manner (Edwards 2010), as discussed in Section 3.

b. Basic forecast techniques and practices

For TC tornadoes, forecasting has evolved away from largely empirical approaches using simple climatology and pattern recognition. For example, SPC tornado watches from the 1970s–1990s often lasted ~12 h, covering at least the rightward half of the projected TC envelope during valid time, plus lateral room to cover track-error uncertainties. Today, watches target specific areas of a TC indicated as most favorable by diagnostic and short-term model tools. The TC now is treated more as a highly variable and evolving mesoscale convective system (MCS) instead of a largely monolithic and slowly evolving entity. As such, an ingredients-based tornado forecasting approach is advocated and increasingly practiced. This concept concentrates on the identification and juxtaposition of specific foci for instability, lift and shear within the moist surface environment, along with ambient upper air influences such as areas of differential drying (Curtis 2004). The TC tornado forecast process necessarily begins with the most thorough possible diagnostic understanding of the unique environment and character of each TC at any given time, before any prognostic guidance is involved.

Objectively analyzed mesoanalysis fields can be useful tools in diagnosing TC tornado environments (below); and overall operational understanding has improved regarding factors favorable for supercells as outlined above. Sometimes, however, the TC supercell environment remains poorly sampled and depicted by automated analyses and numerical model guidance. The Rapid Update Cycle (RUC; Benjamin et al. 2004), for example, was not designed to address either the extreme pressure gradients and wind intensities or the ocean-land wind transition of a hurricane. Surface data used to adjust the RUC profiles also could be compromised in landfalling hurricanes by power failures of the Automated Surface Observing System (Brennan 2010, personal communication). The Rapid Refresh (RR) model (Benjamin et al. 2007) replaced the RUC operationally on 1 May 2012. Though using similar physics as the RUC, its performance in the operational TC setting is yet to be determined.

The apparent influence of various forms of meso-β and smaller scale boundaries and convective bands on supercellular tornado potential in TCs emphasizes the need for very careful and detailed manual analysis of the TC environment for outlook, watch and warning purposes. Such analyses are especially important at the surface where data are most dense spatially and temporally, in order to deduce: 1) areas of relatively maximized tornado 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 for TC tornado forecasters, using conventionally plotted data and including a minimum of:

- thermal analyses at 1° C interval for subtle baroclinic boundaries,
- streamlines, for highlighting areas of backed flow and kinematic boundaries such as confluent zones, and
- isallobars at 1 hPa h^{-1} increments—conventionally plotted as 2-h MSL pressure changes—for assessing pressure-change fields that may influence winds.

This fundamental surface analysis approach should be integrated with observed upper-air data from available rawinsondes, dropsondes, airplane soundings, wind profilers and radar-based velocity azimuth display (VAD) winds to obtain a three-dimensional assessment of the TC environment. Power loss at surface stations can impair both manual and objective analyses, heightening the importance of other observational tools in maintaining continuity of situational awareness.

Upper-air data from non-rawinsonde sources can be plotted on conterminous upper-air charts for finer-scale analysis. Curtis (2004) demonstrated the potential value in sounding examination and planar 700- and 500-hPa analyses, in order to identify the location, strength, orientation, and time 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), in combination with surface data and relatively cloud-free slots in satellite imagery, 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[7].

On the nowcast time frame, automated hourly mesoanalyses and derived fields such as those provided by SPC (Bothwell et al. 2002) also may be useful for assessing general trends. Objective diagnostic tools often are used to assess the environments favorable for supercell tornadoes over land areas. Such analyses have proved operationally beneficial for diagnosing some TC tornado environments (Edwards et al. 2012), despite the aforementioned RUC and surface-data limitations. Useful fields include CAPE and cell-relative helicity, as well as bulk indices that have shown skill in midlatitude situations.

Two such indices, the supercell composite and significant tornado parameters (SCP and STP respectively; Thompson et al. 2003), are being tested in TC tornado settings (Edwards et al. 2012). At least partly because of the spatial overlap of gridded parameter spaces for weak (EF0–EF1) and strong (EF2–EF3) tornadoes in the outer portions of the TC circulation, all but the upper 10% of the SCP distribution also overlaps greatly for those classes. The high decile of the SCP distribution shows some preference for strong tornadoes. Edwards et al. (2012) also found strong overlap on all but the lowest 10% of STP distribution for strong vs. weak TC tornadoes (i.e., the STP distribution reaches lower for weak tornadoes, but not higher for strong ones). More recent variables using effective parcels tied to storm depth (Thompson et al. 2007), would be computed over vertically compressed sampling columns for most TC tornado situations. Results in Edwards et al. (2012) also indicate some discrimination between supercell and nonsupercell TC tornado environments using effective bulk shear.

Great care should be exercised, however, to avoid *overreliance* on such mesoanalysis tools, in consideration of 1) the potentially poor spatial resolution of input observational data, and 2) the uncertain reliability of the RUC and RR for TCs. Hurricane core regions, in particular, contain extreme isobaric gradients and subtle baroclinicity. The RUC, which will be the base model for archived SPC mesoanalyses, did not demonstrate representativeness in that setting, and lacked a means to initialize TC intensity and location correctly (Manikin and Pondeca 2009). Given those concerns, there is no guarantee that RUC- and RR-based parameters will work consistently well in TCs. Automated mesoanalyses also are intended as diagnostic and not prognostic products. Further precautions and appropriate uses of diagnostic parameters in severe-storms forecasting are discussed by Doswell and Schultz (2006).

On the warning scale, TC tornado prediction can be challenged by limited time for environmental assessment, heightened workloads, and a lack of active spotters offering ground truth in the TC. The tornado threat may be more difficult to convey when public, media and emergency personnel are too focused on the cyclone itself to consider the tornado hazard. Warning efforts also can be complicated by ambiguous and uncertain radar signatures.

Tornado warnings typically depend on Doppler-radar indications of strengthening storm-scale circulations. This is conditional on cells being close enough to the radar site for adequate sampling of the lowest few kilometers AGL—the layer with the bulk of TC supercells' mesocyclones. McCaul et al. (2004) recommended measuring angular momentum instead of rotational shear, due to the former's greater independence from range. Magnitudes of horizontal shear and rotational velocity, however, are more readily available in the operational setting and can indicate a tornadic mesocyclone. Caution must be used when applying automated, midlatitude supercellular tools such as the WSR-88D Mesocyclone Detection Algorithm (Stumpf et al. 1998) to the TC setting because of the TC supercells' shallowness and horizontal smallness, their rapid evolution, and often weaker rotational velocity (e.g., McCaul et al. 2004, Rao et al. 2005, Schneider and Sharp 2007).

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[7] Caution: the efficacy of GPS PW readings has not been evaluated systematically with respect to the often extreme wind and precipitation fields of TCs, nor tested specifically in TC dry slots for utility, given that most PW is located beneath the 700-hPa level.

Although storm-relative velocity can be a very useful radar tool, it is important for the warning forecaster to understand potential inaccuracies of the automated storm-motion vector in TC situations. Reliability of algorithms using storm motion and reflectivity-echo centroids may be compromised by poor resolution—particularly at a distance and in inner-band supercells—as well as by cyclonically curving cell paths. The aforementioned lack of TC-specific testing of midlatitude supercell motion algorithms (footnote 5) also imparts additional uncertainty. These factors can influence not only projected storm paths, but 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.

Such diagnostic pitfalls need to be considered quickly in the short-fuse warning decision setting. This is the case not only for risk assessment of imminent tornadogenesis, but also for delineating a storm-based warning polygon that captures the most probable path through the warning duration, with minimal false alarm area. Accurate TC tornado warnings strongly depend on careful interrogation of low-elevation base radar data to identify persistent reflectivity maxima associated with strengthening velocity couplets and/or anomalies of spectrum width (Spratt et al. 1997; Spoden et al. 2012). Radar interrogation alone offers the warning forecaster an incomplete understanding without situational awareness provided by an ingredients-based examination of the near-storm environment.

Difficulty remains in detecting tornadic cells at long ranges from the radar, where the beam overshoots the low-level mesocyclone and/or beam width becomes too large to resolve circulations in mini-supercells. The possibility of supercells then must be inferred from such clues as: persistent, standout cores of high reflectivity (at long-range); small areas or spots of relatively cold cloud tops in infrared satellite imagery over environmentally favored sectors; overshooting tops in visible satellite wavelengths; and/or continuity of cloud-to-ground (CG) lightning production at relatively high flash rates, indicating the location of intense updrafts (Molinari et al. 1999). Animations of any of those tools also may indicate cell motions to the right with regard to surrounding echoes or bands, which would indicate a possible supercell.

6. Future of TC tornado research and forecasting

The landfalling and inland TC may be recognized as a form of MCS of tropical origin. Given their embedded inhomogeneities, the tornadic TC contains definable processes resulting in environments favorable for tornadic supercells. As such, ample avenues remain for additional research into TC tornado environments and occurrence.

a. TCs lacking tornadoes

One of the greatest challenges in TC tornado prediction is distinguishing between tornadic and nontornadic events, from the cyclone scale down to the thunderstorm scale. Some TCs produce no known tornadoes even when the climatologically favorable sector described in section 3d moves overland. One such case was Hurricane Kate of 1985 (Case 1986). Hurricane Isabel (2003) effectively was a null event, having produced a single, brief, and questionable tornado report (W. Sammler, 2006, personal communication). Isabel's environment contained a baroclinic boundary (Edwards and Pietrycha 2006), but lacked favorable ingredients otherwise (e.g., at least marginal buoyancy and supercellular convective mode).

More specifically focused study on the environmental setting of such null events should improve understanding of tornado potential. Better discrimination of null TC tornado events would reduce false alarm ratio and false alarm area in forecasts of all scales. The perfectly verifying retrospective forecast ("hindcast") for a storm like Kate would be no outlook probabilities, watches or warnings for tornadoes. Reality, however, offers real-time meteorological uncertainties, along with nonmeteorological influences such as the "asymmetric penalty function" for missed events (Doswell 2004). As such, the null TC-tornado forecast may remain even less common than the tornado-free TC, until we have greater physical understanding of the internal and environmental differences between tornadic and nontornadic TC supercells.

b. Boundaries within tornadic TCs

One promising area for real-time mesoanalysis of TC tornado potential is in diagnosis of influential boundaries. For both landfall and inland phases of TCs, Edwards and

Pietrycha (2006) suggest four distinct classes of baroclinic boundaries influencing TC tornado potential:

- Buoyancy limiting: supportive vertical shear on both sides, but sufficient CAPE on one side;
- Shear limiting: CAPE on both sides, but favorable shear on one side;
- Buoyancy-shear overlapping: CAPE on one side, favorable shear on the other, with an overlapping corridor of tornado potential along and near the boundary;
- Null: tornadoes absent on either side of a boundary, with no apparent juxtaposition of favorable CAPE and shear.

Analysis of additional cases in each class is planned to expand sample sizes.

c. Tornadic vs. nontornadic supercells

On the storm scale, Spratt et al. (1997) discussed the difficulty of distinguishing tornadic and nontornadic TC supercells, along with tornadic and nontornadic phases of the same supercell, using radar information available in the short-fuse warning setting. In examining a marginal TC tornado event (Frances in 1998) that produced six weak (F0–F1 damage) tornadoes, Rao et al. (2005) described the lack of apparent differences in the environments of weaker, brief, mesocyclones compared to their stronger and more persistent counterparts. Those studies, along with Edwards et al. (2012) show that tornadic and nontornadic supercells can occur in close proximity in space and time within a TC, and in the same parameter space of objective environmental analyses.

d. TC supercell and tornado observation

As with midlatitude supercells, much understanding remains to be gained between tornadic and nontornadic supercell environments, and in verification of TC tornado occurrences. Distinguishing TC tornado settings of supercellular and nonsupercellular origin (Edwards et al. 2012) also remains challenging.

In both areas (supercell vs. nonsupercell, tornadic vs. nontornadic) lie some of the value of continued in situ observation of TCs. More focused sampling of TC supercell environments can be done via:

- GPS dropsondes over water (Hock and Franklin 1999);
- Deployment of portable fixed stations (e.g., “StickNets” after Weiss and Schroeder 2008) and mobile mesonets (Straka et al. 1996) inland;
- Portable Doppler radar interrogation from land (e.g., Wurman and Winslow 1998, French et al. 2009) and air, and
- Near-coastal development of more densely populated networks of fixed radar platforms, either as an extension of or similar to the Collaborative Adaptive Sensing of the Atmosphere program (Brotzge et al. 2010).

Tropical cyclone tornadoes and their environments would form a viable basis for a field program analogous to Verification of the Origin of Rotation in Tornadoes (Rasmussen et al. 1994). Such a project, likewise rooted in testable hypotheses and heavily observational in scope, specifically would target multiple landfalling and inland TCs. Such hypotheses may include:

- Mesocyclone intensity and tornado production each increase as supercells encounter baroclinic zones in the TC envelope;
- Differences in production of tornadoes among TC supercells in seemingly close proximity is related to storm-scale processes;
- As around midlatitude supercells, the TC environment is far from homogeneous with respect to helicity, with great variations observable across tens of kilometers;
- More TC tornadoes may occur per unit area than have been documented, thereby boosting the proportion of tornadic supercells detected by radar and leading to recalibration of operational vortex-detection algorithms;
- Any eyewall tornadoes that may occur, and related nonsupercellular processes, can be documented through close-range, targeted, mobile-radar interrogation;
- Other nonsupercell TC tornadoes may be associated with shear instabilities along convectively active convergence lines, as with their midlatitude counterparts (Wakimoto and Wilson 1989);

- Although more subtle than in midlatitudes, θ_e deficits in the rear-flank downdraft region of TC supercells still can contribute to re-ingestion of baroclinically generated vorticity by the tornadic mesocyclone;
- Damage signatures can be differentiated from the prevailing TC-related destruction to identify tornado hits consistently, in close association with fixed- and mobile-radar indications.

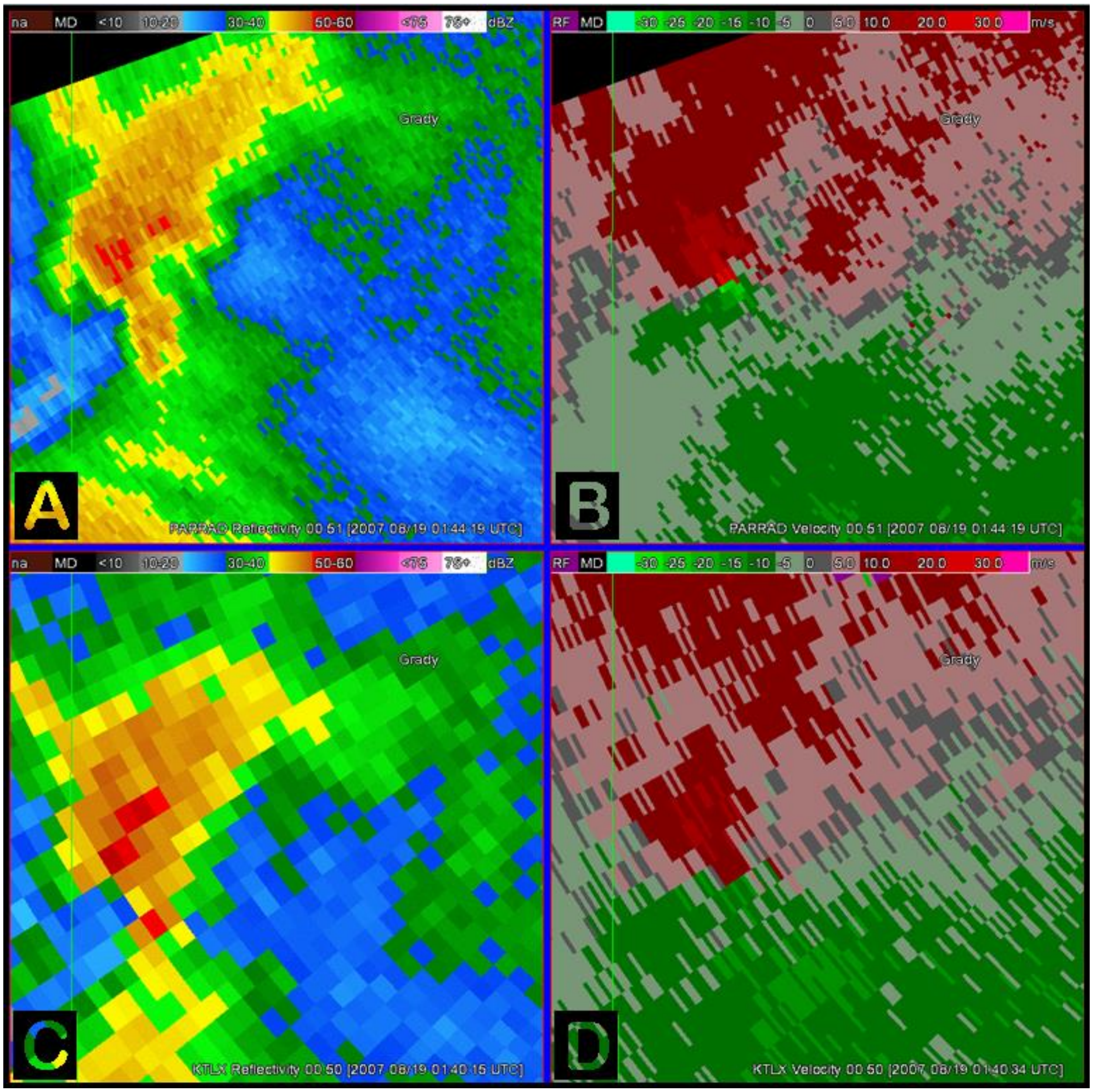

Figure 12. Geographically synchronized radar display comparison for a tornado-warned, inland TC supercell showing the Norman, OK phased array radar (PAR) unit (top) and Twin Lakes (Oklahoma City) WSR-88D (bottom): a) PAR 0.5º elevation base reflectivity at 0144 UTC 19 August 2007; b) as in (a) except base velocity; c) as in (a) except WSR-88D, 0140 UTC; d) as in (c) except base velocity. Reflectivity (left, dB*Z*) and velocity (right, m s^{-1}) values as given in accompanying color scales. Radar location is off the upper right portion of each panel. Times are not simultaneous, but instead represent last WSR-88D imagery available at the time of the PAR update. Radar imagery provided by P. Heinselman, NSSL. *Click image to download synchronized animation (MS PowerPoint) that includes the above images.*

e. Numerical-modeling approaches

Numerical simulations of the TC supercell environment may provide operationally beneficial insights. This will require substantial advances in data assimilation, and initialization of convection-allowing models and improvements in model physics, before usage in operational forecasting. Newer configurations of the multiply-nested Hurricane Weather Research and Forecast (HWRF) model system that include convection-allowing scales in the inner nest (Zhang et al. 2010) are being developed and tested, and examination of explicit TC supercell prediction will be one focus of attention.

Another major challenge in TC tornado research and prediction is in the unclear relationship between supercellular occurrence and inland decay of the mesoscale TC structure. In particular, how does the rate of inland weakening aloft, versus at the surface, effect evolution of low-level vertical wind shear? Improvements to D-SHIPS and its successors, as well as advancements in explicit NWP modeling of inland filling of TCs (e.g., Vickery 2005) ostensibly could extend to forecasting inland TC supercell potential. In turn, their TC decay prognoses could be incorporated into operational guidance packages and forecast sounding generators commonly used by SPC and local NWS forecasters. This realm presents ample opportunities for further research.

Related investigation could include nested numerical simulation of the meso-α scale TC decay process down to the 1–10-km scale of supercells themselves. Methods can include 1) explicitly modeling the supercells or 2) using as proxies the fields of low-level, supercell-scale horizontal vorticity, as with more modernized counterparts to the nested MM5-based simulations of tornadic supercell environments performed by Gallagher (2002) and Rao et al. (2003). Nested, high-resolution simulations also may work better to assess the relative influences of wind decay at the surface and aloft on environmental shear—both in Eulerian (e.g., measures of ambient bulk shear) and Lagrangian (e.g., storm-relative hodograph) frameworks.

f. Radar tools

To distinguish tornadic storms better in forecast operations, there is some promise in dual-polarization appearances of low cross-correlation coefficient commonly found with tornadic debris (Rhyzhkov et al. 2005). For operational training purposes, those signatures have been identified with supercell tornadoes in Hurricane Irene of 2011 (WDTB 2011). As dual-polarization capabilities spread to more radars in the southern and eastern U.S., a large sample of cases may be built for examining the utility of dual-polarization algorithms to TC-tornado diagnosis.

Although apparently uncommon, the inland reintensification of TCs has been documented in association with tornadoes. One recent case involved the remains of TS Erin over Oklahoma (e.g., Arndt et al. 2009; Monteverdi and Edwards 2010). Erin also fortuitously passed across the coverage domain of the National Weather Radar Testbed’s phased-array radar (e.g., Heinselman et al. 2008). Phased-array capabilities include greatly increased volumetric sampling rate (e.g., Fig. 12 and accompanying animation). This promises benefits both to timeliness and precision of warnings for TC tornadoes, and to understanding of short-fuse changes in mini-supercell morphology during both tornadic and nontornadic modes. Preliminary examination by Holt and Kloesel (2009) indicated these advantages using a 43-s phased-array scanning strategy, depicting the rapid strengthening of one of Erin’s tornadic mini-supercells during three minutes prior to tornadogenesis.

7. Conclusion

Early case documentations, distributional studies, and various empirical efforts to understand TC tornadoes largely were tied to occurrence climatology. Physical understanding and predictability each have improved a great deal since the 1970s.

The TC now may be regarded as a spiral MCS that is changeable, evolving and internally heterogeneous in many respects. Great variability in tornado potential exists not only between TCs, but within the same storm on time scales ranging from days to minutes, and spatial scales as small as kilometers. As has occurred with midlatitude tornadic supercells, forecasting of TC tornadoes relies increasingly on an ingredients-based methodology, dependent in turn upon progressively higher resolution diagnostic tools and prognostic guidance.

Amidst the longstanding recognition that some TCs produce few or no tornadoes, climatologically favored areas are interrogated for more precisely located foci of shear, lift and instability, such as: areas of drying aloft, surface boundaries and convective bands, and relative weaknesses in convective inhibition. Each of those foci arises from specific physical causes that may be poorly understood in origin. Improving the understanding of those factors should enable more accurate and precise forecasts on all time scales.

Targeted research is underway or planned on the climatology of boundaries in TCs versus tornado occurrence, aiming toward better understanding of the physical influence of meso- to storm-scale baroclinicity on supercells in TCs, as well as toward explicit differentiation of the TC tornado environment from that of midlatitude systems in the national storm-environment database described by Schneider and Dean (2008). Other areas for hypothesis testing may include: multi-scale analysis and numerical modeling of exceptional outbreaks; analysis of essentially null tornado producers; differentiation of tornadic and nontornadic TC supercells in both observational and modeling work; environmental distinctions between nonsupercell TC tornadoes and their supercell counterparts, examining the relationship of inland TC decay to tornado potential; and four-dimensional data collection through field observations of TC supercells inland and over water.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Michael J. Brennan):

Initial Review:

Recommendation: Accept with major revisions.

General comments: This manuscript provides a review of several aspects of tornadoes associated with tropical cyclones, including the impact of the events, their climatological distribution, a summary of the current state of operational forecasting and warning of these events, and possible directions for future research. Overall the manuscript is well organized in terms of the content discussed and order of presentation; however the readability of the manuscript is very poor due to problems with writing style and sentence structure. These issues need to be improved substantially to allow the reader to absorb the material that the author is trying to convey. For example, in many places I found myself lost in run-on sentences with too many parenthetical expressions, commas, and modifying clauses that made it difficult to discern the main point of the statement. I encourage the author to carefully edit the entire manuscript for readability and clarity, which should also result in a reduction in the length of the manuscript. I will provide a few examples of where this could be done in the major comments section.

Thank you. Reviewer C (who also is the manuscript editor) provided an extraordinarily thorough assessment of just such instances throughout the paper. As a result of his efforts and your suggestions, a great deal of rewording—including the cleavage of numerous sentences and paragraphs—has been performed. I hope you find this draft more palatable, in that way and others.

Please note that incorporation of assorted clarifications and added discussion, made at your request and that of other reviewers, has resulted in net lengthening of the manuscript. This seems to counterbalance the elimination/compression of excessively verbose text I have performed otherwise. Still, the verbiage now should be more efficient, even if the word count is larger.

I did have to reorganize several areas to address concerns of other reviewers; so your re-examination (per your request below) will be most welcome.

Beside the stylistic aspects mentioned above, most of my comments are relatively minor and should be easy to address. However, I would like to review the revised manuscript again to ensure that the readability is improved to the point that it is ready for publication.

Substantive comments:

1. Here are a couple of examples of improvements that could be made to the writing style throughout the manuscript. At the bottom of the left side of page 22, a sentence reads:

While automated mesoanalyses may prove beneficial on a case-by-case basis in diagnoses of internal boundaries and of favorable TC tornado environments in general, systematic testing of basic and composite diagnostic variables, including those provided in SPC hourly mesoscale diagnostics, should be performed across multiple TC environments to assess the consistency and strength of their utility.

This could be modified to say:

Automated mesoanalyses may prove beneficial in case-by-case diagnoses of internal boundaries and favorable TC-tornado environments. However, the utility of these variables, including SPC mesoscale diagnostics, need to be evaluated across a wide variety of TC-tornado environments.

Thanks. That's a good suggestion. However, I ended up removing that paragraph, in response to another reviewer's declaration of it as "banal."

On the right side of page 12, two sentences read:

Despite their apparent weakness or absence in small, discrete TC supercells, thermal inhomogeneities may be created and reinforced in a collective sense by cold pools of nearly continuous, training convection in spiral bands. Barnes et al. (1983) documented 12º K θ_e deficits in the subcloud layer of spiral bands, indicating some combination of weak evaporative cooling (TC boundary layers not necessarily being characterized by RH of 100%), and sensible heat loss to precipitation cascades generated in cooler regions aloft. The plausibility of such cooling processes with bands was reinforced by the buoy data analyses of Cione et al. (2000), who documented: 1) increased sea-air thermal deficit outside the relatively thermally homogeneous (horizontally, as well as air-sea) inner core region of hurricanes, and 2) thermal deficits with passage of strong convective bands (e.g., their Fig. 5a).

These could be modified to say:

Despite the apparent weakness or absence of thermal gradients in small, discrete TC supercells, cold pools from training spiral-band convection can create and reinforce such gradients. Barnes et al. (1983) documented 12 K θ_e deficits in the subcloud layer of spiral bands due to a combination of weak evaporative cooling and sensible heat loss to precipitation cascades in cooler regions aloft. The plausibility of these cooling processes was reinforced by the buoy data analyses of Cione et al. (2000), which found an increased sea-air thermal deficit with the passage of strong convective bands (their Fig. 5a) outside the relatively homogeneous hurricane inner-core region.

Thanks. I've done so. Also, please note the addition of text thereafter regarding the Eastin et al. (2012) paper on outer-band cold pools. That paper has been published during my revision process, and is quite pertinent here.

Left side of page 21:

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 strengthening couplets of velocity, and/or persistent or increasing anomalies of spectrum width—in context of diagnostic situational awareness (i.e., a thorough, ingredients-based understanding of the near-storm environment).

Could be modified to say:

Accurate TC tornado warnings strongly depend on careful interrogation of low-elevation base radar data to identify persistent reflectivity maxima associated with strengthening velocity couplets and/or anomalies of spectrum width and situational awareness provided by an ingredients-based understanding of the near-storm environment.

Thanks. I've also added to your suggested text a citation on spectrum width, an EJSSM paper that has been accepted and is in final editing stages. It will be published well before this paper.

2. The discussion of TC tornado related products and operational practices in section 5 a little SPC-centric. There could be more discussion of the challenges faced by WFOs trying to issue tornado warnings on such short-lived phenomena that are often difficult to detect. The importance of the information conveyed in the warnings themselves, follow-up severe weather statements, and reports of damage or ground truth should be discussed. Additional discussion could focus on the difficulty in conveying the tornado threat when the public, media, and emergency response community may be already focused on the larger-scale "direct" TC impacts or not tuned in at all since "direct" TC impacts are not expected in their area.

Excellent points. I've added some brief discussion of these items.

3. Page 1, first sentence of section 1: Add reference for the statement about the proportion of all U.S. tornadoes that are associated with TCs.

Done.

4. Page 4, first paragraph of section 3: The deployment of the Doppler radar network warrants mention here as one of the reasons that the number of weak tornado reports has increased.

Done. That's certainly a contributor I didn't intend to overlook. Also, as part of reorganization suggested by Reviewer C, the paragraph has been moved down and a list of tornado climatologies created to illustrate expanded discussion thereon in this section.

5. Figure 1, caption: Replace "center fix" with "center position" and add "TC" between "from" and "center position".

Done.

6. Figure 3, caption: Reword first sentence to say "Distribution of U.S. tornadoes analyzed using data from Schultz and Cecil (2009) sorted by a)…" and strike "Ratings per color legends" since this is already obvious.

I omitted the legend redundancy in the caption for the new, smaller and simplified version of Fig. 3, which has been redone completely on a log-scale following another reviewer's suggestion.

7. Figure 3, panel b: Is the 0.001% value for F4 tornadoes? This is not clear since you cannot see the color of the small pie slice for that value.

Yes. The logarithmic scale of the new version makes that value quite visible now.

8. Figure 6, caption: Replace "post-classification TCs" with "TC remnants".

Done.

9. Page 9, left column, 3rd paragraph: Why is there a slight preference for the Cartesian framework? This is stated, but the next sentence says the two frameworks are basically the same.

In bulk, there's little difference, because the two frameworks typically have great overlap in tornado numbers. However, from the TCTOR and included HURDAT data, I found that the difference (slight preference for "Cartesian") is related to a southward TC translation component. This is illustrated in Fig. 7 in the form of the relatively small sample of left-side tornadoes. As noted in the text, Beulah (1967) also had numerous tornadoes in the left semicircle during its southwestward translation, further illustrating the concept.

Also, for full disclosure, I reworded "Cartesian" throughout, as a descriptor for that framework, at the behest of another reviewer who was unfamiliar with such usage.

10. [Former] Figure 8, caption: Replace "Background Images" with "Satellite images".

Figure 8 was removed at the request of another reviewer. If it reappears after further discussion with him, I will follow your suggestion.

11. Page 11, right column, first paragraph: The sentence about double eyewall structure doesn't seem to fit in with the rest of the discussion here. Either delete it or add material explaining why it is relevant.

In the interest of much-needed brevity, I removed that sentence and just mentioned "eyewall(s)" in the previous sentence as another example of nonsupercellular TC structures.

12. Page 11, right column, second paragraph: Much of this material seems out of place. The cyclical supercell discussion doesn't have much to do with the TC-scale tornado influences being discussed in this section. I would move the first sentence of this paragraph to the end of the previous paragraph and delete the rest.

Yes, I see how it seems out of place. Upon further review, the bulk of that paragraph belongs better with the section covering meso-β and storm-scale characteristics. I have shifted that initial sentence as you suggested.

13. Page 11, right column, first paragraph of subsection b: Several run-on sentences here that make this very difficult to read.

I'll admit there were some lengthy sentences—not necessarily technical run-ons by definition, but still needing more efficient expression. I have made several sentences shorter now. Paragraphs also have been cleft here and elsewhere, mainly per Reviewer C.

14. Page 12, left column, end of first paragraph: Have the boundary-layer rolls been observed in the TC environment?

Yes…see Wurman and Winslow (1998) as cited.

15. Page 13, lightning paragraph: I'm not sure this paragraph carries its weight for inclusion here. It seems that all the lightning is in the outer rainbands, regardless of whether tornadoes occur there or not. I'm especially puzzled by the final sentence that says "lightning is a useful but fallible indicator of tornado potential in the TC setting". How is it useful since it doesn't seem to discriminate between tornado-producing and non-tornado producing supercells in the TC environment?

The point was more that lightning indicates supercells, which are responsible for most TC tornadoes. I tried to clarify and reorganize the wording of this discussion, in response to your concerns and those of another reviewer. That paragraph also was rather long; so I split it at the most seemingly appropriate place (where the introduction/overview concepts of lightning in TCs transition specifically to lightning with supercells).

16. Page 14, first paragraph of subsection d: This paragraph should be re-worked to improve readability.

I have tried. This also is subsection "e" now, for tracking purposes.

17. Page 16, right column, end of main paragraph: run-on sentence.

The paragraph has been broken and rewritten.

18. Figure 9, caption: Times in final line should be 1953 UTC.

Fixed…good catch.

19. Page 19, right column: You could expand on why the automated analyses and NWP guidance perform poorly, discussing, among other issues, difficulty properly analyzing and modeling the TC inner core, a lack of reliable wind data in the TC inner core over land due to ASOS power failures, the difficulty in parameterizing the boundary layer in the TC wind environment, particularly over the ocean and in the transition from ocean to land environments.

I have rewritten this discussion some (breaking the paragraph up to make room for additional brief discussion), but am not sure how necessary it is to wander too far off into that potential tangent and, in doing so, lengthen this already large manuscript even further. Thanks for the reminder about the ASOS-failure problem. Do you have a citable reference for that? Otherwise I'll cite you as a personal communication; as I know we have talked about this at a conference.

20. Page 20, left column, end of first paragraph: Run-on sentence and over-use of parenthetical statements here, since the information inside the parentheses is at least as important as the other material being discussed. Please re-work this sentence.

Done. A more reader-friendly bulleted format now is employed, sans parentheses.

21. Page 20, left column, first paragraph: This is another place to mention the loss of surface data in the TC environment due to power outages at ASOS sites, as this lack of surface data can hinder both objective and subjective surface analyses.

Good point. I inserted a sentence about that, and also, broke that paragraph in two given its additional verbiage volume (in keeping with the general comments of Reviewer C).

22. Page 20, left column, start of second paragraph: The first two sentences of this paragraph are very difficult to read, please re-work these.

Done. Those are shorter now. I also had some spurious words that inexcusably appeared mid-paragraph; those have been expunged.

23. Page 20, right column, first paragraph: There are several comma splices and at least one run-on sentence here.

That paragraph has been rewritten.

24. Page 21, left column, final sentence: How does one know the lightning is "anomalously intense"? It this known by examining flash rate? Would the background value be computed from elsewhere in the TC circulation? Please clarify.

Yes, flash rate...wording was changed to "relatively high flash rates".

25. Figure 12, caption: Replace "Background imagery" with "Radar imagery".

Done.

26. Page 22, right column, middle of main paragraph: Run-on sentence beginning with "In those areas…".

That paragraph has been gutted and reorganized in response to another reviewer's suggestions.

27. Page 22, right column, bottom of main paragraph: awkward wording when discussing VORTEX field program, please reword.

Removed/condensed much of that wording [and] tied it to testable hypotheses per suggestion of another reviewer.

28. Page 23, right column, final sentence of first paragraph is confusing, please clarify.

That paragraph as a whole probably was unnecessary and too tangential to the prevailing discussion. It has been removed.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General Comments: The author has substantially revised the manuscript and addressed most of my prior comments. After reading the revised manuscript I'm pleased to see that the readability and clarity of the manuscript have been greatly improved, and I commend the author for undertaking substantial revisions to reach this point. I still however, did notice a few portions of the manuscript where the organization and clarity could be further improved, and these areas have been outlined below. I also have numerous technical comments listed below as well. If these remaining issues are addressed to the satisfaction of the editor, I will not need to review the manuscript again.

Thank you. Countless minor revisions also were made in this round at the request of the other two remaining reviewers. Collectively and individually, your suggestions have benefited the paper greatly.

1. As noted above, there are still several areas where some of the previous readability and wording issues persist in the manuscript. I encourage the author to provide at least one more careful read of the manuscript and look for areas where wording can be shortened and simplified.

Done. The net length hasn't changed much, though, thanks to adding more clarifications in several locations at the request of the reviewers, as well as one more figure (now Fig. 7).

2. Page 8–9, carryover sentence: I see mixed messages in this sentence. At the beginning the wording states that there is a diurnal preference for TC tornadoes, then citing the McCaul (1991) study that supports it but then pointing out the lesser influence of diabatically enhanced buoyancy in the inner portion of the TC circulation. I think this just needs to be reworded for clarity.

Done. I can see how that sentence was too long and awkwardly phrased. I've broken it up and removed and reorganized wording for clarity.

3. Page 11, right column middle of the page: The discussion of the southward moving TC distribution should note that it's for a very small sample.

Done…good suggestion.

4. Page 12, right column, end of subsection a): What is the polar jet in closer proximity to? The TC? Please clarify.

Yes. Now that is stated specifically.

Also, an adjective for the anomalies would be "greater" rather than "larger".

Changed accordingly.

5. Section 4d remains very difficult to read and is poorly organized. I realize this is a difficult subject area given the uncertainty about the phenomena in question, but I think this section could be shortened substantially with a simple up front statement summarizing the uncertainty associated with eyewall tornadoes. The second paragraph in the section regarding the uncertainty in radar observations could be better connected to the discussion in the first paragraph, which also mentions radar. The discussion of the "mini-swirls" in the 4th paragraph is also difficult to follow, in particular the final sentence. In the 5th paragraph radar is again being discussed, which could be folded back into the first paragraph. Perhaps the final paragraph on laboratory and satellite studies discussing the low- to mid-level vortices in the eyewall could be eliminated, since it doesn't really discuss eyewall tornadoes specifically.

Thanks for the additional input. I've removed potentially redundant verbiage in this section, and reorganized the paragraphs a little more so that they fit better thematically, with breaks at seemingly more *appropriate places. I broke up that long sentence on mini-swirls into two, and further clarified its meaning. At your suggestion, I also expunged the entire discussion of low-middle level mesovortices in the eyewall, along with the Kossin et al. and Montgomery et al. references cited. I see how that discussion could be considered too tangential, as you allude.*

6. Page 25, final sentence that carries over to page 26: This is quite long and difficult to read—please reword and clarify.

Done…yes, that was a big sentence indeed. I removed the last half of the sentence altogether and more precisely worded the start ("Nested, high-resolution simulations…") for clarity and specificity.

[Minor comments omitted...]

REVIEWER B (Matthew D. Eastin):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Summary: This manuscript is a well written and well researched review of tropical cyclone (TC) tornadoes with an emphasis on current forecasting practices and limitations. The article presents a thorough review of the TC tornado climatology and the ingredients-based approach to forecasting such events. The manuscript is well organized and is effectively motivated by previous observational and theoretical studies. The review of previous work and ongoing practices at SPC are generally well explained. However, the manuscript would benefit from greater discussion regarding: a) the spatial and temporal distribution of the more intense F2-F3 TC tornadoes, b) non-supercell tornadoes, and c) specific environmental parameters (derived from soundings or surface observations) and decision criteria used at SPC to issue tornado watches. Recommendations on how to remedy these deficiencies and other minor concerns are outlined below. Overall, a revised manuscript will provide a comprehensive review of our current understanding of supercell and tornado prediction in the TC environment. Thus, after my concerns are addressed, this review article should be acceptable for publication in the *Electronic Journal of Severe Storms Meteorology*, and I look forward to referencing this article in the future.

Thanks for the good words, and for your attentive and insightful review. Because of recommendations of other reviewers, I have performed a great deal of rewording and reorganization within the same basic skeleton. Given the major nature of the changes, I will appreciate your second review as well. Your general recommendations above are addressed as they arise in the following comments.

Comments and Recommendations:

1. Page 2—second paragraph and Figure 5: While the diurnal distribution of deaths may be related, in part, to social factors, the diurnal distribution of tornado intensity cannot.

You're right. Do you think this is a point that needs to be made specifically, and if so, where (either here or in the climatology section)?

The Galveston and Larose tornadoes were noted as being the most intense tornadoes in the TCTOR database, but they occurred well away from the diurnal heating maximum. It may be worth presenting and discussing the diurnal distribution of >F2 tornado in conjunction with all tornadoes and/or F0–F1 tornadoes. One might suspect that the more violent tornadoes exhibit a stronger diurnal cycle.

Actually, both of those tornadoes were rated by Grazulis, and long predate TCTOR, which starts in 1995. Your request is well-taken, though…and TCTOR documentation (Edwards 2010) can offer the breakdown you're seeking for the period since 1995. One way to do this is to add a labeled divider to each bar in the Fig. 5 bar graph, below which EF2–3 tornadoes are segregated. I've also added the actual counts for each *category. That should accomplish your request here within the efficiency of an existing figure. Will this work for you? Finally, I've re-analyzed TCTOR, updated this figure, updated the polar plots in Figs. 6–7, and replotted the map in Fig. 4, all for tornado data through 2010 (which wasn't available at time of submission), for consistency. Final 2011 national tornado data hasn't been received at SPC at the time of this response.*

2. Page 2—fourth paragraph: Regarding the Grazulis (1993) report on the San Marcos tornado, the context is a little misleading (or at least confusing). Was the cell undergoing cyclic tornado formation (i.e., producing three to five unique tornadoes over a 47-mi path)? Or, was there a single tornado with evidence of multiple vortices (or suction vortices) at a given single time? Please clarify, as these are distinct events.

Those specific aren't known; and Grazulis only described the event as a tornado "family"—implying cyclic processes. Given what we know now about long-lived, tornadic supercells in either the tropical or midlatitude setting, I could speculate with confidence that the Allen/San Marcos event was cyclic on the storm scale. Without any evidence other than hearsay to support that speculation, however, it's not a statement I feel scientifically justified to make in this paper.

3. Page 4—first column: Your global tornado discussion focuses on the Northern Hemisphere, with only a casual nod to the Southern Hemisphere. At a minimum, I recommend searching the Australian Bureau of Meteorology tropical cyclone report archives to provide some evidence as to the existence and frequency of TC tornadoes in the Southern Hemisphere.

Good suggestion. I had done so during an early draft of the submission and come up empty, with none of their tornadoes prior to 2011 clearly related to a TC. Since then, however, their 2011 reports document a damaging tornado associated with TC Carlos in Karratha. I've inserted mention of that event. Alas, given that event's singularity, and the sparsely populated nature of much of northern Australia, there's nothing much that I can say about TC tornado climatology there except what we don't know. The rest of the Southern Hemisphere is as devoid of TC tornado documentation as can be.

4. Section 3b, pages 6–7, and Figure 4: Given that F2–F3 tornadoes pose a greater threat to society (despite being fewer in number) than the weaker tornadoes, your discussion of the spatial and temporal distribution might be expanded to specifically address the most intense tornadoes observed in the TC environment. For example, Fig. 4 suggests the majority of F2–F3 tornadoes occur >50 km from the coastline (and thus occur more than one day after landfall). This seems like a potentially important component of the TC climatology for forecasters.

Strong tornadoes are sprinkled throughout the spatial and temporal distribution from the perspectives of coastline and landfall time. Distance >50 km from the coast isn't a foolproof indicator of distance in time from landfall, as: 1) some nearshore tornadoes in the Carolinas occurred in the exit phase of Gulf-coast TCs; and 2) some of the other nearshore tornadoes occurred either before landfall or >24 h later as well (from trailing bands).

5. Section 3c, pages 8–11: Much of this discussion focuses on the *azimuthal* distribution of TC tornadoes relative to either true north, TC motion, of the deep-layer shear vector. While these differences are important, one could argue that the *radial* distribution is equally important (yet only the first two sentences of the first paragraph are dedicated to it). I recommend expanding your discussion to review the radial distribution as a function of TC intensity, tornado intensity, time from landfall, and time of day. Schultz and Cecil (2009) provide some insight on each of these topics.

These are good points. While the purpose of the paper isn't to rehash the Edwards (2010) TCTOR analyses, nor re-analyze the updated TCTOR in detail, your questions here and above touch on some areas not explored in that other work. I have summarized some of the radial information you requested in relevant parts of the various subsections of Section 3. Also, I've added some discussion on the trends in tornado numbers and rating since WSR-88D deployment, both from TCTOR and Schultz and Cecil, at the request of Reviewer D.

6. Section 4, pages 11–13: Much of your discussion focuses on the environmental and physical processes related to *supercell-spawned* tornadoes. However, it is well-recognized that many TC tornadoes (particularly in the TC core) are spawned by nonsupercell convection. I recommend providing a brief overview of the important physical processes associated with mid-latitude non-supercell tornadoes (e.g., Lee and Wilhelmson 1997a,b). Then, this could then be enhanced by the TC-specific caveat that high-Rossby number (>1) convection in the TC core is believed to be inherently different than the low-Rossby number (<1) convection found in typical mid-latitude tornadic cases, as described by Willoughby et al. (1984), Montgomery and Kallenbach (1987), and Rozoff et al. (2006). In particular, the TC core contains strong horizontal shear in the tangential flow that can quickly shear apart (or axisymmetrize) coherent convective entities, making long-lived supercells less common and spiral rainbands more common.

Personally, based on mounting evidence, I agree with you re: nonsupercell TC tornadoes, and some more discussion on these has been added. Another reviewer was very skeptical about the existence of nonsupercellular TC tornadoes, but given the storm-mode classifications of Edwards et al. (2012) and their precursory AMS conference paper (available on the SPC Publications website), the evidence seems to be leaning toward your position here.

7. Page 11—first paragraph of section 4a: It is important to recognize that the *deep-layer* (0–6-km) vertical shear decreases as one moves closes to the TC center; the low-level (0–1-km) shear may actually increase due to combined effects of increased friction and limited vertical momentum flux (see Franklin et al. 2003).

Thanks. I inserted this exception with the Franklin et al. citation, as well as mentioning their own caveat about limited sample size at the surface wind speeds (>60 m s^{-1}) where this effect appeared (i.e., the wind adjustment factor from top of boundary layer to surface increased again above its relative min in the 40–60 m s^{-1} range).

8. Pages 13–14, Section 4c: First, Wakimoto and Black (1994) showed convincing evidence of an eyewall tornado that caused a narrow path of intense damage during Hurricane Andrew's (1992) landfall in south Florida (see their Fig. 5). Second, much of your discussion in this subsection seems to question the validity of eyewall tornado reports, yet your Figs. 6–7 clearly show a number of "official" tornadoes reported (and apparently verified) within 50 km of the TC center (or in the TC eyewall region). Please clarify this apparent contradiction.

This section has been rewritten and reorganized somewhat in effort to clarify this, including the difference between reported (the official data) and observationally corroborated eyewall tornadoes. Wakimoto and Black is a good citation to use and I have added that, along with mentioning their indefinite language (e.g., "possible small tornado"). An important caveat to the Wakimoto and Black damage assessment is that there was no way for them to determine whether the apparent vortex responsible for the tornado-like damage had physical, vertical continuity with the convection in the eyewall (which would constitute confirming evidence), or was merely a shear eddy embedded in the intense angular flow of the inner east eyewall (as Fujita alluded with his "mini-swirl" descriptions of the same processes in the same eyewall).

9. Page 20, second column: Throughout much of this section you seem to avoid providing any specific forecast parameters (e.g., CAPE, LCL, SRH, BRN, SCP, STP, etc.) or their threshold values for which SPC forecasters use to issue TC tornado watches. Given that the TC environment is inherently different than the mid-latitude supercell environment, please provide some discussion as to how your forecast process and decision criteria are different. In particular, Baker et al. (2009) demonstrated that the SPC and STP showed promise in distinguishing tornadic TCs from non-tornadic TCs, despite their development from mid-latitude cases.

True, Baker et al's work, as well as Edwards et al. (2012, in Round-1 revisions for WAF as of this writing) show some promise for a few such diagnostic parameters. However, there are some good reasons not to offer thresholds of derived parameters for forecasting purposes. Indeed, SPC forecasters have no threshold values of anything when it comes to issuance of tornado watches. I wish it were that easy! ☺ *Instead, the process is situationally dependent, even from TC to TC, with automated diagnoses being just* *one among many tools in the forecaster's toolbox. Personally, I rely far more on hand analyses of surface and upper-air charts in TC situations (discussed in the paper also) than on objectively analyzed fields. Other reasons to tread lightly on the topic of derived indices (as I have here) include: 1) limited testing of their value in TC situations in published research (notwithstanding the Baker and Edwards et al. results, each of which was mentioned briefly), and 2) Doswell and Schultz' (2006) strong admonitions regarding overdependence on multi-parameter diagnostic indices in the forecast process. One of the authors of the latter paper also is a reviewer of this one (D. Schultz); and another reviewer (L. Schultz) supported the cautionary statements about use of automated parameters as well.*

10. Page 21, second full paragraph: Spratt et al. (1997) advocated the use of enhanced spectral width values to identify the small circulations associated with miniature supercells at greater range from the radar. This is worth mentioning here.

I agree, and have included the Spratt et al. citation in the place where spectrum width is mentioned. I also have cited a new EJSSM manuscript on operational uses of spectrum width.

11. Page 23, paragraph addressing VHTs: It may be worth mentioning the distinct structural differences between supercells and VHTs that are already documented in the literature. In particular, the seminal paper on supercell structure by Lemon and Doswell (1979) identified the forward-flank downdraft (FFD) and rear-flank downdraft (RFD) as defining components, yet the seminal paper on VHTs (Hendricks et al. 2004) does not include any downdrafts as defining components - only an intense rotating updraft. Given that current theory regarding supercell tornadogenesis relies on the RFD to provide either barotropic or baroclinic sources of near-surface horizontal vorticity (see Markowski and Richardson 2010), this distinction seems important and should be included.

Another reviewer (who also is the manuscript editor) suggested removing the VHT discussion as too tangential to the paper. After further consideration, I've done that.

References:

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting,* **18,** 32–44.

Lee, B. D, and R. B. Wilhelmson, 1997a: The numerical simulation of non-supercell tornadogenesis. Part I: Initiation and evolution of pretornadic misocyclone circulations along a dry outflow boundary. *J. Atmos. Sci.,* **54,** 32–60.

Lee, B. D, and R. B. Wilhelmson, 1997b: The numerical simulation of non-supercell tornadogenesis. Part II: Evolution of a family of tornadoes along a weak outflow boundary. *J. Atmos. Sci.,* **54,** 2387–2415.

Lemon, L. R., and C. A. Doswell III, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.,* **107,** 1184–1197.

Markowski, P. M., and Y. P. Richardson, 2010*: Mesoscale Meteorology in Midlatitudes*. John Wiley and Sons, 430 pp.

Montgomery, M. T., and R. J. Kallenbach, 1997: A theory for vortex Rossby waves and its application to spiral bands and intensity changes in hurricanes. *Q. J. R. Meteorol. Soc.*, **123**, 435–465.

Rozoff, C. M., W. H. Schubert, B. D. McNoldy, J. P. Kossin, 2006: Rapid filamentation zones in intense tropical cyclones. *J. Atmos. Sci.,* **63**, 325–340.

Wakimoto, R. M., and P. G. Black, 1994: Damage survey of Hurricane Andrew and its relationship to the eyewall. Bull. *Amer. Meteor. Soc*., **75**, 189–200.

Willoughby, H. E., F. D. Marks, and R. J. Feinberg, 1984: Stationary and moving convective bands in hurricanes. *J. Atmos. Sci.,* **41,** 3189–3211.

Second review:

Recommendation: Accept with minor revisions.

Summary: The manuscript provides a review of tropical cyclone (TC) tornadoes with an emphasis on current forecasting practices. The article presents a thorough review of the TC tornado climatology (the addition of Table 2 is most welcome) and the ingredients-based approach to forecasting such events. As before, the manuscript is well organized and is effectively motivated by previous observational and theoretical studies. The author has satisfactorily addressed all of my concerns from the first review, but a few additional concerns require some clarification. Recommendations on how to remedy these minor concerns are outlined below. Overall, a revised manuscript will provide a comprehensive review of our current understanding of supercell and tornado prediction in the TC environment. Thus, after my concerns are address, this review article should be acceptable for publication in the *Electronic Journal of Severe Storms Meteorology*, and I look forward to referencing this article in the future.

Thanks for the compliments, and for your labors in this round of review. Your suggestions and those of the other remaining reviewer certainly have improved the paper still further. I greatly appreciate your willingness to do so, both for this article and for this journal.

[Minor comments omitted...]

REVIEWER C (David M. Schultz):

Initial Review:

Reviewer recommendation: Accept with major revisions.

Substantive comments: Clearly a labor of love by the author, this review article summarizes much of the available research on tropical cyclone tornadoes and offers insight into the forecasting process. The author has a long history in research and operations on TC tornadoes, so is certainly appropriate to serve as author of such a paper. As someone who has dabbled in this topic, I learned quite a bit of new information about the topic, so I appreciated that.

Thank you for those words, and most of all for your thorough, attentive and very intensive review. I cannot imagine having had a more rigorous review of this paper in any other journal. Though it resulted in a very time-consuming revision process, it was time well spent for the sake of improving the manuscript. The vast majority of your suggestions were followed and very much appreciated. In the minority of instances where your suggestions were unclear, debatable or not followed, I have noted such.

Nevertheless, I had to force myself to read through until the end of the manuscript, having lost patience with it about ten pages in. As I detail below, there are good reasons for why I struggled with this paper. Making it publishable will require major revisions at all levels of the writing/editing funnel (*Eloquent Science*, p. 63). Consequently, that model will serve as how I will structure this review.

I. Organization

Let's consider the organization of this article.

1. Introduction
2. Recognition and notable events
    a. US TC tornado milestones
    b. TC tornadoes worldwide
3. Climatologies and distribution patterns
    a. Tornado classifications and TC events
    b. US spatial and temporal distribution

  - c. Intra-cyclone distribution
- 4. Environmental and physical concepts
  - a. TC-scale influences
  - b. Meso-beta to convective scale influences
  - c. Tornadoes in the eyewall?
  - d. Tornado environments in the inland TC
- 5. Current state of TC tornado prediction
  - a. Operational procedures—outlook to warning to verification
  - b. Basic forecast techniques and practices
- 6. Future of TC tornado research and forecasting
- 7. Summary and future work

After reorganization based on your (below) and other reviewers' requests, the revision is outlined as follows:

- *1. Introduction*
- *2. Recognition and notable events*
  - *a. U. S. TC tornado milestones*
  - *b. TC tornadoes worldwide*
- *3. Climatologies and distribution patterns*
  - *a. TC tornado climatologies*
  - *b. Tornado events and TC classifications*
  - *c. U. S. TC tornado distribution*
  - *d. Tornado distribution relative to TC center*
- *4. Environmental concepts*
  - *a. Synoptic-scale TC environment*
  - *b. TC-scale influences on tornado potential*
  - *c. Meso-beta to convective scale characteristics*
  - *d. Tornadoes in the eyewall environment?*
  - *e. Tornado environments in the inland TC*
- *5. Current state of TC tornado prediction*
  - *a. Operational procedures—outlook to warning to verification*
  - *b. Basic forecast techniques and practices*
- *6. Future of TC tornado research and forecasting*
- *7. Conclusion*

At the upper-outline level, that doesn't look too different; but a large number of changes were made on the text level. Material has been moved around, deleted, shorted and introduced; indeed, it almost is a whole new paper despite the stuff I did keep, and the superficial similarities to the first draft. The two subsections of section 5 still are rather long; and I'm open to breaking them down further for organization's sake, if you and/or other reviewers desire.

In general, it's not a bad organization on the section level. Section 1 is short and allows the reader to get right into the topic. Brilliant.

Thank you very much. I have reworded the end to be more specific to the ideas presented in each subsequent section, as suggested in the minor comments.

Section 2 provides additional background information and some context for the topic. It's not how I would have done it, but it works well given the ability of the author to story-tell and to weave interesting historical tidbits into the narrative.

Thank you.

1. Section 3, however, is where many of the problems of the manuscript are epitomized.

a. Section and subsection titles are vague and do not clearly indicate to me what is contained within each one.

See next reply.

b. Moreover, what I felt was missing in this section didn't hit me until much later in the paper. At some point, you started discussing the different years that different climatologies were performed over. What would have been useful early in the paper in this section was a clear subsection laying out all the previous climatologies of TC tornadoes and summarize their characteristics in a table (e.g., which years of data were used, whether TCs or only hurricanes, criteria for inclusion, number of tornadoes in dataset). Including a new subsection here would be a great service to the community, provide all the introductory information for these climatologies early in the paper so that you can discuss them later in the paper with the confidence that the reader knows the characteristics of each study, and allow you to discuss strengths and weaknesses of different approaches by each of the authors and the implications for the resulting science.

Great idea. Per your request, a new subsection now appears early—namely at the start of section 3. This includes a new summary table of TC tornado climatologies, which is an excellent suggestion by the reviewer. Subsequent subsection titles also have been renamed and moved as appropriate, to better reflect content.

2. Section 4 isn't any better.

a. There is some organization to this section that suggests that a range from large-scale to small-scale is going to be discussed, with inland TC environments being discussed at the end. But, I didn't see the environment of the TC discussed. Verbout et al. (2007) discusses some of this.

Thanks for reminding me. To better focus that organizational tree, I've added a short subsection "a" to discuss the synoptic environment of the TC, within which that citation is included. This has enriched the discussion, for which I am grateful. (Of course, for tracking purposes, each succeeding subsection now is one letter greater.)

b. How do "eyewall tornadoes" fit into the "environment"?

The eyewall is a well-defined feature in the core environment of a mature hurricane.

c. What are "physical concepts"?

That adjective probably isn't needed, so I flushed it.

3. Section 5.

a. How are operational procedures different from forecast techniques and forecast practices? Again, the terminology you've chosen does not provide clarity.

Procedures and techniques are just two sometimes overlapping subsets of operational practices—since not everything a forecaster does is pure, rigid procedure, nor the strict execution of a defined technique. I've changed the wording some there, especially in using the umbrella term "practices" in the subsection title to convey this distinction better.

b. Also, I don't feel like I have a clear picture of how the forecast process works. The author assumes the reader knows about the outlook, watch, warning and verification system. A better introduction is needed.

Section 5 has been reorganized some, with what I hope is satisfactorily concise and numbered rewording of the first part.

c. Rather than showing snapshots of products from several different storms, perhaps following a single event through the whole cycle would make more sense to the reader and tell a more compelling story.

I see the merit in that, and indeed considered it early in the manuscript-development process. However, upon attempting to go down that path, I couldn't find an ideal single TC event where either 1) all the most representative products from all sources were available, start to finish, or 2) some examples available from a single-event chain weren't obsolete or inferior in quality to examples from other cases. Hence, I played the diversity card and went with good examples from multiple events.

d. p. 21, left column, first full paragraph and other material. These seem more like challenges than basic forecasting techniques, which is what the title of the section promised.

Accounting for those challenges is more of a practice than a technique, per se.

4. I didn't see the organization within section 6.

a. Should it parallel the structure of the preceding parts of the paper? Is some internal structure needed with subsection headings? It reads like a laundry list of ideas, not a coherent narrative. Too many vagaries and banalities.

Section 6 has been reorganized and reworded to add more specifics, condense/remove those areas you highlighted in red as "banal", and offer some testable hypotheses per your requests below.

b. Conclude section 6 with a list of your testable hypotheses and unresolved questions. Perhaps a sidebar. Otherwise, this crucial information is embedded throughout the paper at various points and is hard to identify. This list would benefit your writing, too, by helping you to focus on testable hypotheses rather than vague banalities for more data and better models and improved understanding.

See above. Right now, I've bulleted the testable hypotheses, since they fit with the preceding text discussion; however, if you think a sidebar of some sort would work better, I'm open to that possibility as well. If that's preferable, I would ask for your aid in developing one that would be editorially acceptable, since: 1) EJSSM has not had any up to this point; and 2) it would set a precedent of sorts for sidebar use in the future.

5. Section 7 is only two paragraphs long. It is not a summary of the entire paper; it concludes the paper. I would re-title section 7 as "Conclusion".

That section has been re-titled as suggested. Perhaps the rewording (in the form of questions and hypotheses) that I have done to address your in-document coloring shall help with the comment below.

Or, rewrite the section to be a proper summary. The second paragraph is full of platitudes and wish lists. I would delete it. Or, provide testable hypotheses instead.

I wouldn't trivialize those ideas as "platitudes and wish lists"; instead they are suggestions for future research and exploration. This is a common practice in published manuscripts of all sorts, including reviews. How is it invalid here? Beyond the wording changes already performed, I'm open to suggestions for improvement, of course, but contend that the basic idea of suggesting avenues of further exploration is worthwhile.

Thus, here is a partial list of what needs to be done to improve the organization and the heading titles.

6. Last paragraph of the introduction needs a more clear layout of the article and what is being discussed in each section (use section numbers explicitly). As written now, the text starting with "This review article summarizes..." vaguely winds through the paper, providing no specifics about where the reader can find specific information. Given the length of this 30-page review, the reader should receive more guidance about the structure of this manuscript.

It has been reworded to be more specific.

7. Section and subsection titles need to be more clearly written, so that their meaning is unquestionable. The subsections of section 3 are not parallel structure. "Physical concepts" and "distribution patterns" are vague. "Future work" could be viewed to be redundant with "Future of TC..."

Several subsection titles have been reworded for specificity.

8. Rethinking the organization of material within sections should be considered. Nothing is said about large-scale environments in section 4. The present section 4c does not seem relevant to this section.

A relatively short section has been added (new 4a) on synoptic-scale environments.

II. Paragraphs

This list is not comprehensive, but is representative of the types of problems that I am encountering. Major problems at the paragraph level include:

1. Paragraphs are too long and some contain multiple themes. Each paragraph should have one theme (chapter 8 of Eloquent Science, see especially p. 65). I have indicated in the text where some paragraphs can be broken up into two. The author should seek out other excessively long paragraphs and break them up(section 8.4 of Eloquent Science).

Thank you. I have bifurcated several lengthy paragraphs at your behest and that of other reviewers. I also have made the great majority of wording changes suggested by you in your in-document comments, except as noted or where rendered moot by elimination.

2. The topic of some paragraphs does not follow the topic of the previous paragraph. Themes sometimes come out of nowhere, rather than being a result of a logical progression from the previous topic. Improved transition is needed between paragraphs, providing coherence (section 8.3 of *Eloquent Science*).

I have tried to do this more often, including incorporation of specific suggestions you've made in the document, as well as moving a few paragraphs to better-fitting places within the same section or subsection.

3. Paragraphs often are poorly organized within, lacking coherence (section 8.2 of *Eloquent Science*). Also, material is presented later that supports previous statements. Rearrange the order of the sentences so that it reads more clearly (section 7.3 of Eloquent Science).

Suggestions for in situ rewording and rearrangement of paragraphs have been incorporated.

4. Content that is clearly irrelevant (or not sufficiently worked into the topic to show why it IS relevant) should be deleted: stuff on GPS, phased-array radar, D-SHIPS, lightning should be considered for possible deletion. If not, then they need to be integrated better into the text.

I have tried to integrate them better. These are all relevant to the current or future TC tornado-forecasting process in various ways; but apparently I did an insufficient job of expressing how. I hope rewording and reorganization of those portions of Section 5 has mollified your concerns. Our NHC-based reviewer had no problems with the D-SHIPS discussion; but I did reword it somewhat to make the operational connection clearer. Maybe we can ask him if there is anything else I should mention (or not mention) about it. Otherwise, see responses to the minor comments (in-document) as well.

III. Sentences

Major issues at the sentence level include the following:

1. I find the text incredibly verbose. Verbosity makes the paper longer than it needs to be, and it reduces the reader's comprehension. There were points in the paper where I just went "huh?" because I didn't understand what was trying to be communicated. Look for green highlighting in the annotated manuscript.

Thank you for being specific with the points of contention via your incorporation of thematically colored textual highlighting, both for this problem and for those in your review points below. I have attempted to clarify the language in most of those cases—sometimes resulting in more words, sometimes fewer. In a few instances, I have asked (in the in situ comments) for suggestions and/or clarifications from the reviewer. Please note that incorporation of assorted clarifications and added discussion, made at your request and that of other reviewers, has resulted in net lengthening of the manuscript (in case anyone might bean-count for pure word volume). This offsets the elimination/compression of superlatives, highlighted "banalities" and excessively verbose phrases. Still, the wording now is more efficient.

2. The author uses excessive banalities: statements that are so obvious as to go unstated or that are not particularly meaningful or that lack testable hypotheses. Being more precise in your writing will help (section 10.2 of *Eloquent Science*). I have highlighted some of these statements in red in the annotated manuscript.

Thanks. See previous reply.

3. Too many unproven or uncited speculations were included in the manuscript. I have highlighted these in magenta in the annotated manuscript.

See previous reply. Thanks also for the additional citation suggestions.

IV. Words, Punctuation, Grammar, Etc.

1. The author loves unnecessary superlatives, such as "strong/strongly". Such words do not help convey the magnitude of the problem. Take out these words and see if the sentence is improved. In most cases, the sentence is improved (section 10.2.5 in *Eloquent Science*). I have highlighted these words in cyan in the annotated manuscript.

Thank you. That was helpful. I have addressed those, removing most.

2. The author seems to be mostly consistent with the use of the word "tornado" throughout the manuscript, yet, there are a few times when the word "waterspout" is used.

a. Why? Are waterspouts not tornadoes in these contexts?

Physically, yes, but not in historical recordkeeping (and by extension climatological analysis rooted therein)—hence, the need to differentiate.

b. Whatever the explanation, the author should state the definition of tornado and waterspout used in this manuscript. He should also discuss the issues with the classification more generally (just a few sentences early in the paper), so that readers from other countries understand that in the U.S. waterspouts are not tornadoes. When waterspouts come onshore, are they tornadoes?

Yes, as with the Carla tornado in Galveston. I have noted this in the place where that tornado first is mentioned in the paper.

c. What are the implications for not identifying waterspouts as tornadoes in the datasets for these TCs? In other words, what issues are there with a landfalling TC that only produces tornadoes over the water, hence are not counted in the database? Is such a TC that produces 10 tornadoes over water any different than a TC that produces 10 tornadoes over the land?

Only in how the vortices are (or in the case of waterspouts, are not) recorded in the database. Whether *they* should be *recorded as tornadoes is another issue altogether, a general-policy matter applying to* all *waterspouts (TC or not) that is outside the scope of discussion in this paper.*

d. Therefore, are waterspouts part of your climatology or not? You need to be excruciatingly clear on these points in your manuscript.

A footnote (sorry!) has been added in Section 2 defining waterspout vs. tornado in the context of this manuscript. I hope it's simply clear, and not "excruciating"! ☺

3. Technical and copyediting needs work, especially because I am going to be the one likely serving as copyeditor. ;-) This is just a partial list of things that need to be checked. The author should be responsible for fixing the rest.

Except where noted specifically in the in situ replies or below, all of the editing problems below have been addressed. I hope I didn't introduce any new ones of an onerous nature in reorganizational revision.

a. Some references are not in proper format. Are you sure that the citations are correct? Some are grammatically incorrect, suggesting to me that they were not copied correctly.

There were a few lingering formatting problems in the references that I have fixed. Also, one "grammatically incorrect" reference title actually appeared that way in the cited paper, and was left as-is (see notation in document).

b. Hyphens and dashes are not used consistently.

Though I tried to be extremely diligent about this before submission, some did escape my eyes and those of internal reviewers. Thanks for pointing them out in the document.

c. The serial comma is not used, which I thought was EJSSM style.

EJSSM has used the serial comma in lists of four or more, following manuals of style such as AP and Chicago.

d. Semicolons should be used instead of commas in between lists of references.

Fixed.

e. The abbreviations i.e. and e.g. should only be used inside parentheses.

Done.

f. Spell out numbers less than ten, except when used in situations where numerical values would be preferred (e.g., with units) (*Eloquent Science*, section 10.3.2).

Done. Thanks for pointing out specific instances.

4. p. 22, Do not use the parenthetical words to indicate the opposite. This is confusing to the reader (amid a paragraph that is nearly all unintelligible).
http://eloquentscience.com/2010/11/a-heretical-parenthetical-thought/

The entire paragraph has been condensed and reorganized for clarity and conciseness, and to ameliorate this parenthetical heresy.

5. You use the word "see" when it is often unnecessary, as in before references. Not needed.

Fixed. I didn't see that I had used "see" so much. Where you saw "see", now you don't see "see", you *see? ☺*

6. You use the word "while" (implying simultaneity) when "whereas" or "although" would be more appropriate.

I word-searched "while" and substituted your suggested alternates as appropriate.

7. Personal communications require a year after the name.

Done.

8. You use the word "trends" for more than just changes over time. This is confusing. Reword throughout the manuscript.

Done. "Trends" still appears when specifically discussing temporal tendencies.

9. p. 3, what is an "accessory tornado"? I am not familiar with that term.

"Separate" is a more appropriate adjective and now is used instead.

10. What is the difference between ~ and a squiggly equals sign? Just say the meaning in words, not symbols, for total clarity: "about".

The symbol "~" stands for "on the order of" whereas "≈" is "approximately." I did juxtapose these erroneously in at least one instance. Although it expands the text in an already voluminous manuscript, I have substituted the full word for each symbol.

11. Spell out "DI" throughout the manuscript. It is not used frequently enough to warrant its introduction, and I had a hard-time remembering what it stood for.

Done.

12. "Tornado activity" is vague. Is it tornado occurrence? Tornado frequency? Tornado start locations? Be precise

Done. "Tornado production" is more appropriate in the context.

13. Some words are not the best, most precise words in their present context. I have marked them in the annotated manuscript; in many cases, I have suggested a better word.

Thank you. Such specific suggestions are very helpful and appreciated, especially those areas you shaded in blue as "superlatives".

V. Figures and Tables

1. Tables 1 and 2: What is the meaning of the red and blue colors? Not stated in the caption. I suggest if you're trying to be aesthetic, then color the background into a light yellow and use sans serif fonts. Do not alternate colors in such a simple table. It is clear what lines are which.

Your idea has been incorporated in tables old and new, improving their appearance.

2. Figure 1: The light green is unreadable. Choose a different color. Connect the dots of the path; otherwise, it is difficult to see the path of the storm.

Done.

3. Figure 3 needs a lot of help. In panel (a), how do you explain that nearly 3/4 of the pie chart is occupied by 999 events and 1/4 is occupied by nearly as many (768 events)? This panel can be deleted and replaced with a single sentence in the text. The figure adds nothing. Panels (b)–(d) are not easy to compare. Use the linear–log graphic technique that Brooks and Doswell (2001) used to compare tornado F-scale distributions in different countries, different regions within the U.S., and different time periods. Doing so, you'll be able to compare all three pie charts on one line graph much more simply.

Those are all good ideas. Thank you. Panel A has been replaced with a sentence in the text as recommended, the numbers double-checked and verified (the pie didn't weight them correctly). In looking through Brooks and Doswell (2001), their first logarithmic scale related to CPI and wealth (their Fig. 1), and had nothing to do with differing F-scale ratings in different nations. That figure's specific scaling doesn't mate very well with data of this sort anyway. However, the form of log-scaled ordinates used in their Figs. 3 and 4 ("Fatalities/Damage") seem to work well; though the data there doesn't match your description.

That confusion aside, I agree that pies (b)–(d) can be translated to one logarithmically scaled line graph, and have constructed such. I also corrected a hitherto undetected transcription error with the 1950–94 EF-U bin where the pie slice was the correct size, but wore the wrong label. The correct percentage (11.5%) now appears on the log-scaled plot.

Following the replacement text for the former panel A, I also have added brief text mentioning the closely related but geographically limited results of Agee and Hendricks (2011), a new J. Climate *paper that has appeared since your initial review was performed. Their analysis reinforces the notion that the WSR-88D represents a profound secular influence on TC tornado climatology.*

4. Figure 4 should be two-columns wide for better clarity.

Done.

5. Figure 6 caption: Spell out the characteristics of Fig. 1b. Readers don't want to flip back many pages to find out what they are looking at. Also, Figure 6 is a polar plot, not a Cartesian plot.

Caption reworded accordingly with correct verbiage.

6. Figure 8: I have a hard time supporting this figure. Delete this figure.

The intent of the figure was to illustrate, graphically for the sake of conceptualization, climatologically favored sectors as they are known in the northern hemisphere and as they would be in the Southern Hemisphere (mirror image of kinematic regime). However, given your concerns below, and some space-saving benefit, it has been expunged for now.

a. First, the sector in panel (a) exists entirely over land and excludes any water, so I have no idea if tornadoes were present outside this sector, but just over water. Coincidence?

b. Second, panel (b) has no verification. This is unacceptable presenting hypothetical situations and saying that this is the sector where tornadoes would exist, if we knew where they were.

We are inescapably handcuffed in both instances by simple absence of observational information—especially in the Southern Hemisphere, yielding an abject dearth of "verification". Analogous work (i.e., "Here's where it should be…") is presented in the discipline of subatomic particle physics with suspected (but not tangibly documented) entities such as the Higgs boson. This is the case despite the published existence of "Higgsless models" that assume no such particle. [References available offline if you're curious, or you can crank up Google.] By contrast, there is no specifically "tornadoless" TC model for the Southern Hemisphere, nor any reason other than lack of systematic observing ability to insinuate that we can't understand where they should occur in the TC envelope.

Other than the sign of the Coriolis parameter, the physics of the atmosphere doesn't change on the other side of the equator. So…mirror the cyclone. That yields the analogously favored SH sector. Could it be presented merely as hypothetical, pending ground truth that may not arrive for decades, if ever? As for whether SH TC tornadoes occur at all: Need we be less confident in the existence of SH TC tornadoes than physicists are for that utterly hypothetical elementary particle? How is such an approach "unacceptable" here but acceptable in that science? Are they guilty of a line of fallacy that somehow isn't one there, but is one here? With considerable reluctance, I'll acknowledge the validity of your *argument sufficiently to dump the figure for now, but wouldn't mind bringing it back if you can see enough merit in* mine.

7. Figure 10: The domain keeps jumping around, especially for panels (a), (b), and (c), which could have the same map domain, and (d), (e), (f), and (g), which could have the same domain. Also, enlarge the text in the titles of each panel.

As we discussed via e-mail (and I'm pretty sure you found acceptable after that exchange), the domain of each panel is intended to follow the storm at fixed-width resolution, for ease of comparison. Moreover, a statically centered geographic background, forced onto this large cyclone with a curving path, would necessitate scalar compression of the background at the risk of legibility. I'd like to give the reader enough credit to understand what's going on here, especially if explained succinctly in the caption (as now is the case). Will this suffice? Also, the text in each panel wasn't crucial to the presentation (the times being provided in the caption) and was removed to minimize clutter.

8. All figures: Use lower case "(a)", "(b)", etc. in the figures. Do not use upper case letters or letters enclosed in circles. Be consistent with the figure captions, which use lower case in parentheses.

This convention isn't set in stone, in rule or practice, either in EJSSM or AMS journals. It seems to be a matter of personal preference as much as anything. I have ensured that the labels are quite legible, and internally consistent in each figure.

9. Figure 11 should be entirely in one column.

The figure already is. Do you mean the figure and caption? The figure is sufficiently tall in its column that "spillover" from the previous page precluded the figure+caption combination from being shoehorned into a single column, while maintaining legibility.

10. Clicking on the link in Figure 12 to get the animation didn't work for me.

I apologize for the glitch. The site mirroring apparently didn't finish for some reason when you performed the operation. It seems to be working now. The link goes to a PPT file which can be downloaded, saved or opened immediately, depending on your preferences. In either event, it contains the desired animation of phased-array versus WSR-88D for a TC supercell.

VI. Other Issues

1. I am really disappointed that the author provided only four cursory citations to Verbout et al. (2007). This paper took an entirely different approach to examining TC tornadoes, albeit focusing on outbreaks and hurricanes instead of individual tornadoes and TC in general. We determined some characteristics that distinguish hurricanes with outbreaks from hurricanes without outbreaks, determined regional variations in tornado production, and suggested a mechanism by which recurvature could produce enough wind shear for supercells. Yet, none of these conclusions are discussed within this manuscript. It really hurts to see statements like "One of the greatest challenges in TC tornado prediction is distinguishing between tornadic and nontornadic events." Yet, Verbout et al. examined that. Our nonoutbreak cases had 5 or less tornadoes associated with them, whereas the outbreak cases had at least 12 tornadoes in them. Verbout et al. also showed that there was no seasonal preference for outbreak hurricanes. This article deserves citation in other places in the manuscript, as well. Why was it so blatantly omitted?

There was neither deliberate omission nor desire to neglect that excellent paper lead-authored by Verbout *and co-authored by this reviewer. It certainly is pertinent in many ways. I have added several more as noted in your in situ commentary. This includes an entirely new subsection (4a) heavily dependent on that study, per an exchange of ours below.*

2. In places, the paper reads as if it were written for an insider, not for a general meteorological audience. Facts and stories are thrown out to the reader, and it is not clear why they are. The naive reader then wonders what information was missed. Instead, the author should fully explain the details or omit them if they are not relevant. I have tried to indicate some locations in the annotated manuscript where this occurs. Nevertheless, the entire manuscript needs to be perused, looking specifically at content that needs to be explained for the general reader.

Thank you for your embedded notations to this effect; I have attempted to address them duly.

3. Some material is duplicated in the manuscript. For example, we seem to be reminded frequently that Beulah was a huge tornado producer. Is this necessary every time the storm is discussed?

Yes, since that's Beulah's only relevance to the discussion. However, your implication that Beulah shows up too much is well-taken, and I have removed one arguably unnecessary set of verbiage where it is mentioned. See specific comments.

4. The author is very clearly biased against eyewall tornadoes. However, a better approach would be to state the issues, present the evidence for and the evidence against, then let the reader decide based on the evidence presented. This is a situation where it is best to be agnostic first, then argue for your gut feeling as the text progresses. You report, we decide.

Good point. The main problem here isn't evidence of eyewall tornadoes, but lack of it. The glaring dearth of corroborating evidence for them is an issue that (to my surprise) hasn't been raised in any literature to date. If we had video, photos or dual-DoW sampling (for example), almost none of this discussion would be needed. In the process of reviewing climatological literature on TC tornadoes during the past few years, it became clear quickly and consistently that eyewall tornadoes essentially are an unverified phenomenon. As such, the question, "Is it real?" is quite legitimate at this point in time, pending better documentation. This issue stood out on its own quite well, without any preconceived slant on my part. It is a duty to the science, as a review author on the subject of TC tornadoes, to report a lack of evidence of a subset of TC tornado reports that has appeared unquestioned but without robust documentation in climatologies. That's the report. The reader then can "decide" what the implications are.

I already had done what you ask: "state the issue" early, followed by "presenting the evidence" (in this case, specific supporting manifestations of the lack *of evidence). Still, to make this section less polemic in tone and more concise, I have reorganized it somewhat, removed superfluous verbiage as noted by your beneficial in-document coloring scheme (thanks!), and removed some other text as noted in the specific responses. I hope that will suffice and welcome any further ideas for improvement.*

5. The title could be reconsidered.

a. I think "understanding" hurts the title as the word is weak relative to the other much stronger words.

Fair criticism…I substituted the stronger word "knowledge".

b. Also, how will the journal indicate that this is a review article? Is this the first one published? Maybe the logo at the top should have a "Review" included?

The title contains the words, "A Review…", which should be extraordinarily difficult to interpret as anything but a review. Furthermore, there is a "Review" section available in the OJS into which this manuscript specifically was submitted. Once published, the word "Review" should appear before the title in the listings for the paper, as did "History and Biography" before Lewis' paper on Bob Johns. The manuscript editor should be able to make sure the paper is appropriately classified in the system.

6. The abstract seems like an afterthought; it is weak and incomplete. More specifics from the paper are needed to fill it out and make it truly informative (Eloquent Science, section 4.4).

Thanks for pointing this out. In hindsight, I can see how you were right. My original abstract was overly ambiguous, non-descriptive rubbish. I have rewritten it considerably to summarize the paper's motivation, purpose and objectives better, specifically list covered themes, and summarize the contents, in roughly the same relatively short space as before (for conciseness).

7. p. 22: You mentioned Spratt et al. (1997) and the difficulty of distinguishing tornadic and nontornadic TC supercells, but how close is this to the problem of distinguishing tornadic from nontornadic supercells (non-TC)? Why is this problem unique to TCs or not? Could relating these two issues help provide testable hypotheses to this section, rather than a laundry list of things you'd like to see done?

Yes. Thanks for the suggestion. I have reworded the last part of the original paragraph (that you highlighted in red). I also have broken up that original paragraph, suspecting it was one of those onerously lengthy ones that motivated your general comments above on that matter. Several testable hypotheses now are specifically offered in the reorganized Section 6, in response to your requests here and elsewhere in the review.

8. p. 10, "strict quadrant-based [missing word] should be discouraged." But that doesn't stop you from generalizing just a few sentences later: "should be viewed as a loosely defined sector, not a rigidly delineated quadrant". Whether the sector is 90 degrees or 130 degrees is pretty immaterial, isn't it? What is your FAR and POD for such a forecasting scheme? Please provide quantitative evidence in support of your argument, rather than forecasters' rules of thumb and empirical relationships.

I think you missed the point, perhaps because I may not have made it clearly. There is no "forecast scheme" and therefore no POD or FAR. Instead I am arguing against the traditional practice of rigidly targeting "right front" and "NE" quadrants based not on forecasting verification (which doesn't exist for specific TC sectors, per se), but instead its colloquial appearance in forecasting discussions, which counters what we find from patterns of actual tornado occurrence (e.g., Fig. 7).

9. p. 11, "inherent abundance of low-level moisture": How confident are you that all TC environments as they approach landfall and possible tornado production have an adequate moisture supply? Could dry continental air be entrained into the circulation around the TC?

Of course—especially above the surface, as shown by Curtis (2004). This is why I used the "low-level" caveat. My examination of surface maps for TCTOR compilation shows dew points commonly in the upper 60s to middle 70s ºF (upper teens to mid 20s ºC) in all tornadic TCs approaching landfall.

10. p. 18: The author says that forecasters are getting away from largely empirical approaches, but Figure 8 smacks of this. How do you explain advocating an empirical approach while arguing for a more scientific forecasting approach? I have a similar concern about D-SHIPS, which is a statistical tool.

The former Figure 8 is gone now (per earlier request). As for D-SHIPS, its predictions of inland wind decay are used by NHC, whatever its limitations. For the sake of internal NWS consistency, SPC is supposed to follow NHC forecast guidance in describing the predicted path and intensity of the TC. As such, D-SHIPS should be described in this paper. That said, your in-document comment about it perhaps being more appropriately discussed in Section 5 is on the mark; and I have moved it there.

11. Throughout the manuscript, the author seems to have multiple opinions about diagnostic composite tools. In one place, he indicates that they are no replacement for manual surface mesoanalyses. In another, he says that they are "robust statistical associations", but gives short shrift to the paper critical of such approaches (Doswell and Schultz 2006). Which is it? More discussion of the pros and cons are needed.

As noted in the in-document comments, I didn't intend to offer mixed messages on the use of automated diagnoses. I apologize if that's the impression you got. Admittedly, expressing gray areas isn't my strong *suit; yet that's exactly where this issue stands. It's not an "Are they or are they not?" question. Instead, I am trying to portray their operational role in TC tornado environments as conditionally useful tools, situationally dependent, with caveats. I have changed the wording in related portions of Section 5, attempting to express that better. This includes a short new paragraph with explicit discussion of STP and SCP, as requested by another reviewer. Your and Doswell's astute EJSSM discussion on indices and parameters remains referenced as well, as it should be in any formal paper that discusses these topics.*

12. All the footnotes are distracting. Are they all needed? I view footnotes as the inability of the author to integrate the text clearly together (Eloquent Science, p. 86). If they absolutely must be used, then the font size needs to be smaller.

Although one footnote was added to address a separate review comment regarding waterspouts, the net number of footnotes indeed is less than before. As for font size, EJSSM has been using the same as prevailing text; however, if you want to make an exception here, I'm willing.

13. The author provides no justification that the FAR and POD of TC tornadoes is any better or worse than those of regular supercell tornadoes. Without that information, it is hard to justify the required expenditures into a VORTEX for TC tornadoes. In other words, if supercells are supercells no matter where they occur and TC tornadoes are largely a product of supercells, why focus on TC tornadoes specifically when a general study on supercells will resolve your questions, regardless of the environment (midlatitude or tropical)?

Much of that discussion has been reworded or removed. No explicit accounting of POD or FAR is known for TC versus non-TC tornado forecasts yet, at any scale. Also, focusing only on supercells doesn't address nonsupercell TC tornadoes and the eyewall-tornado issue.

14. p. 2, At first, the tornado is referred to as the Falls Church tornado, then it is referred to as the Washington, DC, area event. The readers may not know that Falls Church is a suburb of DC and be confused. I was initially. Be consistent. If the fact that the tornado occurred near the politicians and this was responsible for political progress, you might wish to be more explicit about this point in the text.

I reworded the beginning and end of that paragraph to be more specific.

15. p. 4, I am concerned about the statement that TCs everywhere are the same. Although not unreasonable, do you have enough (or any) evidence to support this?

See specific comment in the annotated version.

16. p. 4, Although Verbout et al. (2007) does discuss this point, it is made more forcefully in Verbout et al. (2006). I would cite that paper here instead of, or in addition to, Verbout et al. (2007).

Verbout, S. M., H. E. Brooks, L. M. Leslie, and D. M. Schultz, 2006: Evolution of the U.S. tornado database: 1954–2004. *Wea. Forecasting,* **21,** 86–93.

Done.

17. p. 4, it seems a bold statement to claim that better damage indicators reduces the potential for missed tornadoes in sparsely populated areas.

I meant "more", more than "better". The EF scale has introduced 27 additional DIs over the original F scale, many of then common to rural areas as discussed in that citation and others. I can add more EF scale citation(s) that include such concepts if you wish.

18. I don't understand why you keep calling it a Cartesian sector. You need a more clear explanation of the difference between the storm-relative and earth-relative frameworks first. Then, you can elaborate on the relative strengths and weaknesses of these approaches. Otherwise, putting this question at the end doesn't

help the reader understand what the point of being dragged through all this material is.

I've seen "Cartesian" used as a synonym for the north-relative frame of reference in the literature; but to resolve your concern for clarity's sake, I've replaced the term throughout with "north-relative", "poleward", "directional" or other non-"Cartesian" verbiage as appropriate.

19. Although Curtis' study is valuable, I don't think you are critical enough of its limitations.

That's a fair criticism, which I have tried to address…

a. For example, dry descent stabilizes the air. So, if the dry air is important to the tornadoes, how do you explain the increased stability?

Dry air isn't necessarily descending; it could have advected into the system from its source region of subsidence outside the TC.

b. The dry air may only be a signature of other processes, like the arrival of the trough and recurvature noted in Verbout et al. (2007). Therefore, the association of dry air with TC tornado outbreaks may not be the real physical explanation.

I agree.

c. His dataset was not detrended to account for the increase in tornado reports over time (Verbout et al. 2007, p. 260).

True.

d. His analysis was based on observed sounding data, which may have been problematic offshore.

I agree.

These points (a-d) all are valid, and I've added mention of them in that discussion. Thanks.

20. p. 13, I can't believe I am reading this paragraph. Where the CG lightning occurs is related to the supercell development? The ingredients for CG lightning are different from those responsible for supercells. Why would you expect a relationship between CG lightning and supercells, especially in TCs?

I can believe you read the paragraph, but can't believe it wasn't understandable. I thought I explained it, but maybe I need to do so differently. I've reworded this part somewhat: "CG lightning rates have been found to maximize with tornadic supercells over land, relative to other convection in a TC environment (e.g., McCaul 1987), even though some tornadic TC supercells produce few or no CG strokes."

The cited references also touch upon the physical meaning that summarized in bullets 1 and 2 of the second sentence of that paragraph. I'm wide open to any other suggestions as to how to state this discussion better.

21. D-SHIPS: It is not clear how you go from the 2D wind profile to a forecast of vertical wind shear for supercells. From what I understand, D-SHIPS tells you something about how the vortex decays. How is that related to supercell potential or TC tornadogenesis? It is not clear from the text (at least that I can see). For example, Verbout et al. (2007) showed that outbreaks were more likely to occur in intense landfalling hurricanes than weaker hurricanes. Yet that result is not stated anywhere.

See above reply regarding the operational purpose of D-SHIPS and the revised text in the paper. I hope the connection is clearer now.

VII. Annotated Manuscript

In the annotated manuscript, I've indicated words and phrases that I think are verbose in yellow, phrases and sentences that are vague or where I went "huh?" in green, and unnecessary superlatives in blue. Purple areas are unsubstantiated claims, speculation, or statements requiring citations. Banalities are highlighted in red. Gray shading means grammar or syntax isn't followed.

I have adhered to the great majority of those relatively minor comments and recommendations, and changed wording on colored highlights, unless otherwise indicated by specifically noting any questions, confusion or disagreement regarding any of them. Those responses are provided in situ, per an attached MS Word file.

I had one strong sense of conflict in addressing your review, namely between some statements you reddened to classify them as "banal" and, as you wrote above, "content that needs to be explained to the general reader". This is the reader who is not so familiar with concepts that you might see as obvious or trite (banal). That conflict meant that I had to balance your unique expertise and insight versus that of the broader spectrum of readers, many of whom who might not occupy your plane of understanding of the subject matter. As such, some of what you subjectively classified as "banalities" were kept, but reworded in effort for more clarity. In those cases, it's a compromise.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comments: The author has made considerable improvements in the manuscript. The one big problem remains the presentation: concision, clarity, and precision are lacking in many locations. The manuscript could be easily improved. I have made some suggestions in the attached annotated manuscript, but it is not the reviewer's responsibility to fix all the problems in such manuscripts. I do not wish to review the manuscript again.

I appreciate and respect your additional suggestions. As I did with your deep and extensive collection of constructive in-document comments during the first round, I have attended to each one in the marked-up Word file, followed great majority of your suggestions, documented the changes made, and noted/justified the few instances where I didn't follow a recommendation. Your suggestion for a new figure (Fig. 7) was astute. You found numerous instances of unclear or imprecise verbiage that all the prior eyes somehow missed, and that (as you noted above) were easily correctable. For that I am grateful. Thank you for your work here.

REVIEWER D (Lori A. Schultz):

Initial Review:

Reviewer recommendation: Accept with major revisions.

General comments: The paper provides a nice overview of TC tornadoes both from a historical understanding, what the science has investigated, the results and how those results can and will affect where scientists and forecasters should go next to improve our overall ability to forecast this type of event. It was nice to see the "ingredients based approach" applied to the TC tornado prediction problem, with highlighted caveats where the TC environment differs from more traditional forecasting methods. The warnings about using automated indicator algorithms that have not been fully tested on the TC tornado were well stated.

The paper appears to bring together 3–4 conference papers that have been presented over the last few years to produce one cohesive, peer-reviewed paper. The sections providing a "state of science" and not just a history of severe events were especially appreciated as the sheer amount of literature covering many specific aspects were presented in such a manner as to help draw a complete picture of the TC tornado environment. For those looking to learn, especially operational forecasters, these sections provide a clear concise tool to start the process with, allowing them to branch out into the specific areas of interest without missing important details that may have been covered in another piece of work not necessarily directly related to TC tornadoes. I have concerns that some of the presented statements are not discussed enough in this particular paper, and the supplied references are from unrefereed conference preprints written by the author. Although not fundamentally against the use of conference preprints as a reference for some types of work, in the cases described below, I have questions. My recommendation is for the paper to be accepted with major revision.

Thank you for the good words, on all counts, and for your thoughtful review and ideas for improvement.

Substantive comments:

SPC TC tornado database: The statement was made pointing out that the use of empirically defined forecasting methods built by looking at historical databases has served well up to a point, but more clearly defined methods are needed to take the science to the next logical step. The assembly of a TC tornado database, restricted to the time period of the WSR-88D era, allows for a more detailed study of the tornado events using updated methodologies developed by people somewhat more well-versed in the phenomenon. That being said, I do not believe that the submitted article gives enough information concerning the assembly of this database. Although a conference paper (written by the author) is referenced in the article numerous times and there is good information to be found there, that work is the basis for many of the statements and analyses presented in this article.

The explanation of the SPC TCTOR database as shown in Section 2 of the author's conference paper should be included in this paper as it defines an integral part of how this database and subsequent analysis differs from previous database work. In the particular case of the choice to include tornadoes that occurred after NHC tracking guidance further underlines the need for discussion on what criteria were used to pick tornadoes included in the database. Highlighting the "individual-assembled manual techniques" used in the assembly would also be an important factor to include, as it would allow the reader to understand how to use the data as well as allow for reproducibility. The included example of the varying numbers of tornados associated with strong tropical systems such as Beulah and Ivan highlight this point.

It could be argued that this particular methodology and database could make for its own-refereed paper due to its importance and future affect on subsequent TC tornado studies. The database is an important step, and owing to the author's visibility and ability to maintain it in the future, publishing the work in a more formal manner is something to consider. If this is the path chosen, I recommend the work come out in parallel or before this review article.

Thanks for the comment. In response to your concerns about the lack of more information on TCTOR, and another reviewer's about climatologies as a whole, I have reworded and reorganized Section 3 in a major way. It now specifically includes a new, opening subsection on TC tornado climatologies, with a new table listing and comparing the various datasets, including TCTOR and yours with Cecil. I also have provided a little more summary information on and from TCTOR in several places in the paper. Having done so, however, it's probably beyond the more broad-brushing aim of this paper to exhaustively regurgitate the detailed specifics of TCTOR found in Edwards (2010). That exercise also would make this already big paper (which has grown slightly, thanks to assorted reviewers' suggestions) into something perhaps onerously monstrous in size. Your encouragement to write a formal documentation of TCTOR on the side is well-taken, and if I were to do so at this juncture, it probably should be as a supplementary "note".

Page 7: Section 3b: Consider using additional subtitles to denote the different areas of climatologically and distribution patterns discussed. Under (b.) U.S. spatial and temporal distribution, a discussion concerning the buoyancy and shear environment is included.

After reading your review and others, it was apparent to me that this section needed intensive revision overall. Two other reviewers hammered that need hard, and justifiably so in retrospect. You and they have helped in this regard, beyond measure. As a result, this section has been reorganized considerably, with blocks of text removed, reshuffled, moved to more relevant subsections, and rewritten in several areas. See what you think of the "new and improved" subsection (now 3c).

Page 11 TC Scale influence: Three factors are listed that contribute to a lower probability of discrete supercells and tornadoes inward toward the eyewall. The information appears to come from the author's conference paper, "Objective environmental analyses and convective modes for U.S. tropical cyclone tornadoes from 2003–2008". The three reasons stated are in the first section of this preprint. First, it is my opinion that aesthetically, the wording in the conference paper is better stated then what is presented in the review paper (I guess this is not an official recommendation, just an observation). But in reading the rest of the paper, I did not see the analysis that showed that "the convective mode nearer to the center tends towards the nonsupercell". I suspect that the analysis was done and discussed at the conference and may have been referenced on/in the poster/presentation, which would make it difficult for a reader later on to evaluate.

The confusion over modal analysis may have resulted from my wording the modal trends specifically that way in a formal submission version (in second-round revision for Wea. Forecasting *as of this writing) versus the conference paper. I apologize for any confusion or ambiguity there, and have changed the citation to the formally submitted version.*

This is another example of where more information from the author's conference paper needs to be addressed in either this article, or presented in its entirety in its own paper. The conference preprint references other preprints (by different authors, presented at the 25th Severe Local Storms conference) where comparisons were made to similar work being done on the nationwide totals of tornadic supercells. The impression I had from reading the preprints is that is new work. Looks like great new work, but as such, it needs to be put out there for people to evaluate, play with, learn from, as well as express their opinions on. I do not believe enough information is given in this review article to support the statement.

Thanks. The preprint did represent new work, which has been translated/expanded into a formal paper unto itself—the aforementioned WAF submission. Since you brought up the midlatitude material, the TC tornado paper is Part III of a large project, the first two parts being contemporaneous examinations of midlatitude supercell environments and modes involving mainly Thompson, Smith and Dean. Again, your concern legitimately deals with the issue of how much of a preprint (or now, another formal paper in review for another journal) to regurgitate here. Given the already large page-count of this EJSSM review article, I'm loath to cram too much more into it from here on, unless the manuscript editor (who also is Reviewer C) deems it necessary. Still, I'll be happy to supply you or any of the other reviewers with the latest revision of the WAF submission(s), if you wish.

Section 4, page 11, part B: The section gives a concise, well-supported, well-explained synopsis of the TC storm environment pertinent to an operational forecaster or a topic-novice researcher. The sections does a great job bringing together the sum of the scientific studies, how they related to both the topic and to each other to paint a clearer picture of what is known and understood about the TC tornado environment. It also lends itself to a clear standard of how the TC environment differs from some of the traditional storm environments most have knowledge of, an important concept to a forecaster faced with preparing for, predicting, and warning on this type of event. Well done!

Thank you. Based on commentary by Reviewer C, I added some more information on midtropospheric drying and lightning, and reworded/regrouped this section a little. I also added two citations to very relevant studies that have been published since submission: Green at al. (2011) and Eastin et al. 2012. I hope you still find it well done!

Another aesthetic point; consider the use of sub headings in this section to allow for a "quick reference" style. Discussion concerning the elements of the environment, type of supercell, the cold pool, boundaries, mid-tropospheric drying and lightning are all hot topics. Subheadings would make them easier to find in the text quickly.

His section has been reconfigured. In the process of doing so, I've accommodated your very helpful suggestion to use tertiary subsections. Thanks…it helped in the process of performing reorganizations requested by Reviewer C.

Page 13, Tornadoes in the eyewall: First let me state that I do not disagree with the inclusion of this section. As the passage leans towards discussing existence and possible ways to confirm/deny that damage originally designated as originating from a tornado, it may be better placed elsewhere. Although portions of the text could stay where it is, some of the discussion may be better suited to Section 6.

I see your point, and have reconfigured some of the text in this subsection after the suggestions of Reviewers A and D. Even then, it was rather awkward to attempt splitting the eyewall discussion between two sections, given its thematic continuity. I ended up keeping the eyewall theme all in one subsection, albeit with revisions.

Page 17, Figure 10: The caption not being collocated with the imagery was bothersome. I didn't actually see the caption at all, mistaking it for part of the text for what was the caption on Figure 11. As this is not likely the finally format, this may not be an issue, but just in case, an option would be to locate the caption on the facing page to the figure rather than the next page, where the reader must flip back and forth to read the description.

Most journals do this with a large, full-page, vertically aligned figure, at least when the figure itself is not fractured across two pages. I agree that it's less than ideal, so for now, I shrank the displayed figure so that the caption could fit on one page beneath. Another possibility is breaking the figure in two and putting a "Fig. 10 Continued…" notation on the page after the break (as with the Appendix figures in the PDF of this EJSSM paper). A third alternative may be to lay the figure out sideways on one page with caption underneath, and then flip the page 90°, as has been done with tables in this EJSSM paper's PDF. I'll leave this up to the manuscript and layout editors and will roll with whatever they recommend.

Page 21, Paragraph starting with "While storm-relative velocity..": The first sentence reads awkwardly. I think if you drop the 'is' at the end of the sentence (4th word from the end), it reads better. In the very next sentence, "particularly at a distance", the 'a' was missing. Lastly, in the third sentence, there is a reference to footnote 5, I believe it is footnote 6, which discusses the use of algorithms that use supercellular motion assumptions, that fits the passage.

Thanks. I have made each of the fixes that you suggested, as well as some other minor changes at the behest of Reviewer C. You were right about the footnote citation; but due to the elimination of an earlier footnote, the same wording now is correct.