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Tropical Cyclone Tornadoes: History and State of Understanding

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Abstract

Tornadoes are a hazard from tropical cyclones (TCs) worldwide. Awareness of tornadoes spawned by tropical cyclones (TCs) dates back almost a century, with empirical and pattern-based awareness of their occurrence since the mid-1900s. At least rudimentary understanding of favorable environments within TCs began in the 1960s and has progressed to a modernized, ingredients-based approach. The characteristics of TC environments in which tornadoes tend to form sometimes are found in midlatitude settings away from TCs. The presentation will focus on these environments, which strongly resemble some midlatitude warm sectors in settings of strong low-level shear, high boundary-layer mositure content, and weak lower-middle tropospheric lapse rates.

1. Characteristics

Much of the information in this summary is from Edwards (2012) and references therein. Some of those references are cited again here for the reader's benefit in directly accessing source material; however, all are encouraged to peruse Edwards (2012) for much fuller coverage of this topic. After some background into the occurrence and climatology of TC tornadoes in this section, section 2 will focus on meteorological characteristics common to most TC tornado settings. Section 3 will conclude this article. See Edwards (2012) also for coverage of notable historic TC tornado events.

a. Climatologies

Although documented worldwide, tropical cyclone (TC) tornadoes are most commonly known to systems affecting the United States (U.S.), consisting of ≈6% of total tornado reports during the 1995–2009 time frame (Edwards 2010). Multiple TC tornado climatologies have been constructed since the 1960s, the largest and most recent being those of Schultz and Cecil (2009), Belanger et al. (2009) and Edwards (2010). See Table 2 in Edwards (2012) for a complete listing of TC tornado datasets and the different criteria for event inclusion in each listing. TC tornado reports have increased markedly in the era of full national Doppler radar deployment, consisting of roughly the mid-1990s onward, as documented by Verbout et al. (2007), Schultz and Cecil (2009) and Edwards (2012). The same sources attribute those changes to the increase in communications capabilities, video and still-photographic accessibility, growing media attention to tornadoes, and intensive National Weather Service (NWS) warning-verification efforts that followed the Doppler radar deployment.

A secular break in both the number and character (proportional weakness) of TC tornado records is well-documented with Doppler radar deployment, in the aforementioned literature. Because of that, and to support analyses of TC tornado data under relatively consistent, modern reporting and verification practices, Edwards (2010) built a database called TCTOR that starts in 1995 (Edwards 2010). Since that paper was written, the database has expanded to 1262 events, with great year-to-year variation (Fig. 1). TCTOR will continue to be updated and expanded yearly as each previous year's records are researched and constructed. Furthermore, TCTOR is a flexible, fluid dataset, subject to editing of any historic entries as new information arises. As such, precise specifics of the analyses presented herein may not be valid after additional data are considered in the future. General trends and maps should remain valid, however.

To summarize, TCTOR uses 1) subjective analysis of surface, upper-air and satellite characteristics of TCs and their inland remnents, and 2) the National Hurricane Center's TC dataset called HURDAT (Jarvinen et al. 1984; Landsea et al. 2008) to determine whether tornadoes in the broader Storm

Prediction Center (SPC) dataset (Schaefer and Edwards 1999) occurred in the circulation envelope of a tropical system, and to fix each of their center-relative positions. Climatological characteristics of TC tornado occurrence in the TCTOR record will be used herein unless otherwise specified.

b. Occurrence distributions

Although examples have occurred well inland during late-decay stages, most TC tornadoes occur within 500 km of the U.S. Gulf and Atlantic coasts (Fig. 2). Tornadoes are most common ~12 h prior to ~24 h following landfall (e.g., Schultz and Cecil 2009), but can occur much later, as with the third day of the diurnally cyclic, record-breaking tornado production from Hurricane Ivan (Fig. 1 in Edwards 2012). When TCs move inland from the Gulf of Mexico, tornado production may lessen until a brief cycle of rejuvenation near the Atlantic coast, as systems prepare to exit land and encounter more favorable oceanic air masses again (Edwards 1998). Tornadoes can occur anywhere in the circulation, but show a strong preference for the northern through southeastern sector (Fig. 3a), the greatest concentration being from about 45°–90° relative to center. As TC classifications become lower, tornado records tend to shift southward through the eastern semicircle (Fig. 3b–d). However, since tornadoes over the ocean are not in the SPC record, it is unknown how much of that shift is real, and how much of it is due to a greater sampling of the southeastern quadrant of TCs as they move inland and weaken. The same can be said for the dominance of weaker TCs (depressions and storms) in TC tornado numbers, since substantial portions of mature hurricanes tend to reside over the sea.

In general, larger and more intense landfalling hurricanes tend to produce more tornadoes than smaller, weaker systems, mainly because of their tendency to spread favorable wind fields over broader inland areas during longer decay times. TC tornado production varies greatly from system to system; some produce none, while the remnants of major hurricanes Ivan (2004) and Beulah (1967) spawned over 115 tornadoes each. Moreso than midlatitude tornadoes, TC tornadoes tend to be weak—generally rated EF0 and EF1 by Enhanced Fujita (Edwards et al. 2013) techniques. This is apparent in Figs. 1 and 4 (more on convective modes is discussed in section 2). For TCTOR data updated through 2012, weak tornadoes accounted for 94% of the total, the balance being EF2–EF3. TC tornadoes tend to occur much more often during the day than at night (Fig. 5), though a slightly higher *proportion* of strong TC tornadoes has occurred at night. The only two violent (F4) TC tornadoes on record, occurring well prior to the TCTOR dataset, were after dark (Edwards 2012). TC tornadoes also tend to occur closer to center at night than during the day (not shown). Despite their presence in databases of reports, the actual existence of tornadoes in the eyewall itself is highly uncertain due to lack of any photo/video documentation, mobile-radar data or other evidence showing vertical continuity of surface vortices with the eyewall convection aloft (Edwards 2012).

2. Meteorological settings and forecast issues

Until about the last 10–15 y, TC tornado forecasting was a largely empirical endeavor, based in climatologies such as those above, and in the notion that most TCs do produce tornadoes in the U.S. However, some do not; and others tend to concentrate their tornado production in very sharply focused sectors (e.g., Hurricane Ivan in 2004; Fig. 1 in Edwards 2012). Tornado watches and tornado-based SPC outlooks for landfalling TCs formerly were virtually certain and large in area, yielding high probability of detection but high false-alarm rate. As scientific understanding of the role of specific ingredients in midlatitude tornadoes began to be translated to the specialized TC setting, forecasting has become more focused for both outlooks and watches. In fact, some TCs that affect the U.S. do not garner either watches or substantial outlook probabilities, because of a lack of 1) favorably juxtaposed ingredients and/or 2) foci for lift.

a. Ingredients for forecasting TC tornado potential

For tornado-forecasting purposes, being meso-α-scale convective process, hurricanes and weaker TCs all can be treated as a specific class of mesoscale convective systems. Ingredients-based reasoning justifies their climatologically favored sectors of tornado occurrence (Edwards 2012).

Figures 6 provides ingredients, and parameters dervived therefrom, for TC environents for comparison with non-TC tornado settings. Just as in midlatitude tornado prediction, ingredients-based forecasting principles (e.g., Johns and Doswell 1992) specify four necessary factors for tornadic supercells that, collectively, can explain much of their distribution in TCs:

- *MOISTURE:* Almost never a problem in mature hurricanes and seldom in post-landfall TCs in the U.S.—TCs tend to have precipitable water >2 in (5 cm), much higher than for most midlatitude tornado settings (Fig. 6c). Areas of drying aloft have been associated with tornado outbreaks in TCs (Curtis 2004); but this may be an incidental, indirect effect related to sunshine (below) instead of a direct causative ingredient.
- *INSTABILITY:* Lapse rates and CAPE are proxies for instability in the operational setting; each tends to be lower for TC tornadoes than midlatitude systems (Fig. 6), often reducing supercell size and depth compared to their Great Plains counterparts. In TC environments often characterized by only slightly larger than moist-adiabatic lapse rates, just a few degrees C of insolation-forced heating can boost CAPE by up to two orders of magnitude from <100 m^2 s^{-2} to near 1000 m^2 s^{-2}. Areas of CAPE can be produced or enhanced diurnally by diabatic surface heating beneath clear slots, likely accounting for much of the climatological difference in TC tornado production from night to day. Because cloud cover tends to decrease with distance from most TC centers, diurnal CAPE increases (McCaul 1991), contributing to the climatological preference for TC tornadoes in outer TC sectors. Baroclinic boundaries in TCs often serve as either overlapping areas for optimal instability and shear that focus TC tornado risk, or as buoyancy-limiting (Edwards and Pietrycha 2006) features that bind the risk away from cooler air masses. Examples are provided in the PowerPoint talk.
- *LIFT:* Supercells have been well-documented in spiral convergence bands accompanying TCs, as well as embedded in clusters and as discrete storms removed from other convection (E.g., Edwards et al. 2012a). Examples of these storm modes are given in the accompanying presentation. However, TC supercells tend to concentrate near convergence or confluence lines. Furthermore, baroclinic boundaries within TCs act as sources for lift, along with their thermodynamic effects discussed above.
- *VERTICAL SHEAR:* McCaul (1991), among others, described maximized deep-layer shear in those parts of TCs downwind (typically rightward of center) with respect to ambient midlatitude flow that influences their recurvature. Additionally, he and subsequent studies have showed a pronounced tendency for low-level hodographs to expand, with very strong 0–1-km AGL shear and storm-relative helicity, in the northeastern and eastern parts of TCs. This contributed to the predominance of tornadoes in those sectors, day or night, and juxtaposition with increased CAPE to boost diurnal risk. Baroclinic boundaries also can be shear-limiting (Edwards and Pietrycha 2006), where favorable shear and related tornado potential characterizes conditions on just one side of the boundary.

b. TC tornado prediction in practice

Given the above considerations, both SPC forecasters and local NWS warning meteorologists look for forecast and diagnosed zones within the TC envelope where these ingredients are likely to overlap. Automated, model-based mesoanalyses still often fail to resolve subtleties of the above ingredients and of boundaries within TCs (Edwards 2012), since they are designed for more baroclinic midlatitude systems with weaker presure gradients. As such, bulk parameters such as the significant tornado and sueprcell composite parameters, while appearing favorable, sometimes may not represent the environment adequately or discriminate from midlatitude settings well (Fig. 6b,e,f).

Relatively stronger shear but weaker CAPE in TCs offset each other in contributing to the lack of distinction between TC and midlatitude settings in diagnosing tornadic environments. However, midlatitude, non-TC processes that yield environments similar to TCs (weak lapse rates, marginal buoyancy, strong low-level shear) still can be highlighted by examining bulk diagnostic parameters, *as long as the forecaster understands the relative contribution of each ingredient to the resulting fields*[1].

While bulk parameters have diagnostic value, base observational data (temperature, moisture and wind) still offer the most important clues to changes in the TC environment that can influence tornadic threat. In the operational forecast setting, optimal diagnosis of the TC environment on the mesoscale still involves frequent hand analyses of thermal and kinematic characteristics, to detect crucial subtleties and their changes from hour to hour. Local NWS forecasters can track intensifying nonsupercellular convection, as well as supercells, into areas of more or less favorability in order to make more confident warning decisions. Similarly, time-trending of hand analyses and other diagnoses benefit SPC forecasters in the issuance of watches and mesoscale discussions for TCs.

c. SPC forecasting process for TC tornadoes

The presentation on SPC at this conference offers an overview of all forecast products issued by the center. This subsection will briefly discuss those forecasts as applied specifically to TCs. The accompanying PowerPoint show contains graphical examples of SPC forecasts in the TC tornado setting: outlooks, mesoscale discussions and watches, with watch status reports serving the same purpose as in midlatitudes.

Day-4–8 outlooks for TC tornado risk are unprecedented, because of: 1) the inherent uncertainty in National Hurricane Center (NHC) track and wind forecasts that far out, 2) mesoscale and subtle nature of TC tornado environments, and 3) the 30% probabilistic threshold for such outlooks, seldom met for TC tornadoes even on day-2 or day-1. Day-3 and day-2 slight risks can be assigned at 5% probability levels for TC tornadoes only, an exception to the prevailing 15% bulk-severe rules, since the dominant severe-weather offering in a TC is tornadoes.

At day-1, the SPC outlooks explicitly provide hail, wind and tornado probabilities. Severe hail is exceedingly rare in TCs. Damaging wind typically falls in the domain of the NHC product suite for TC watches and warnings. However, outer-fringe thunderstorms can be severe well beyond ambient flow magnitudes; those sometimes are covered by SPC 5% wind outlooks and local severe-thunderstorm warnings. The primary TC hazard covered in day-1 outlooks is tornadoes, which still compel categorical outlooks at ≥5% gridded probabilistic threat levels. Please refer to the SPC presentation and mansucript for more details on probabilistic and categorical outlook relationships.

During the day-1 time frame, SPC coordinates tornado-related hazard wording in NHC forecasts with NHC specialists via a dedicated hotline that also includes local NWS offices in affected areas. SPC also collaborates tornado watches with local NWS offices, not just in TC settings but in all cases. Slow-moving TCs typically yield the longest-lasting tornado watches, at ~9–12 h. Mesoscale discussions offer meteorological insight into the tornado threat—from the time the favorable sector approaches land to the last vestiges of inland decay, when shear and/or instability finally weaken enough to make tornado risk negligible. When issued prior to watches, mesoscale discussions also provide probabilities of watch issuance; during watches they update the threat areas and magnitudes as they change with the TC evolution.

3. Concluding remarks and future considerations

While still quite challenging, the prediction of TC tornadoes had become more precise and specific, apace with a deeper understanding of the physical processes involved in distinguising parts of TCs most favorable for supercells. Although numerical models designed for midlatitude, baroclinic systems may become unreliable in the TC setting, diagnostics derived from them have some utility for TC tornado forecasting (Edwards et al. 2012a). As these and other explicitly convection-allowing

[1] Doswell and Schultz (2006) offer an enlightening and critical discussion on the use and abuse of indices and parameters in the forecasting process.

models become more precise, they will be tested against convective characteristics in actual TCs and evaluated for use in forecasting both supercell and nonsupercell processes associated with tornadoes.

In particular, SPC plans to take a high-resolution inner nest of the Hurricane Weather Research and Forecasting (HWRF) model (Zhang et al. 2010), designed to replicate and predict TC structure, and test it for both convective and environmental characteristics relevate to tornadic supercells. Some TC tornadoes are not produced by supercells (Edwards et al. 2012b); and HWRF may offer some utility for those settings as well. Currently, there is too little difference apparent in supercell and nonsupercell TC tornado environments to make operationally useful distinctions; often, both modes occur in what appears to be the same environment (Edwards et al. 2012b). SPC also intends to disaggregate temporal forecasts of severe weather over the next few years, so that time bins within day-1 will have their own tornado forecasts. This effort will extend to TCs.

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FIGURES

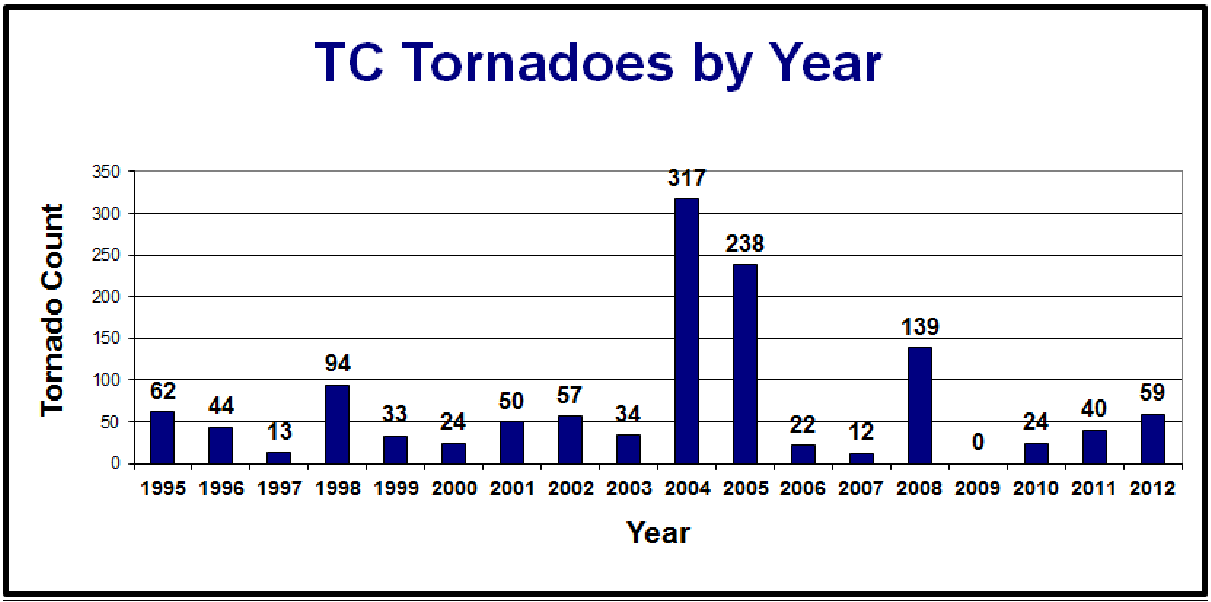


Figure 1: U.S. counts of TC tornadoes, 1995–2012, totalling 1262 reports in the TCTOR database described by Edwards (2010).

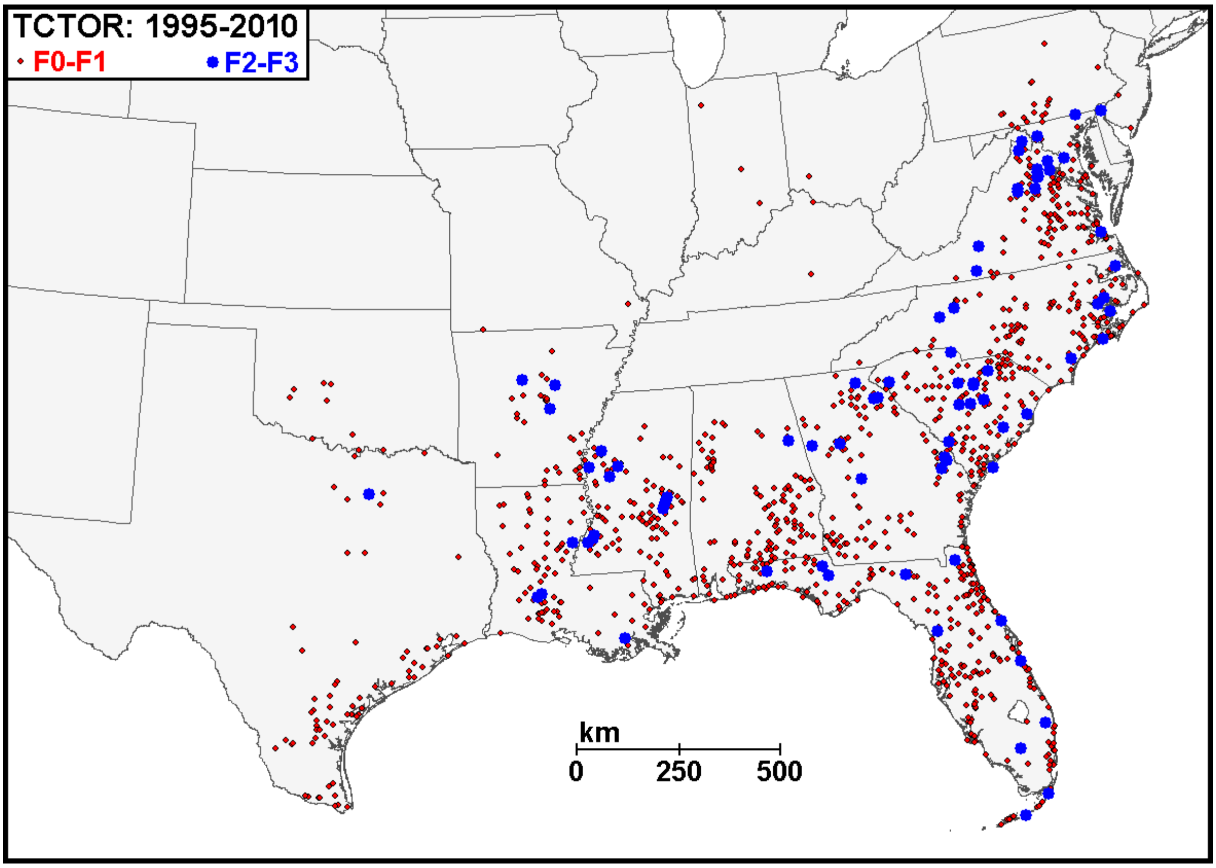


Figure 1: Geographic distribution of U.S. TC tornado records from the 1995–2010 subset of TCTOR (Edwards 2010), by damage rating, as labeled.

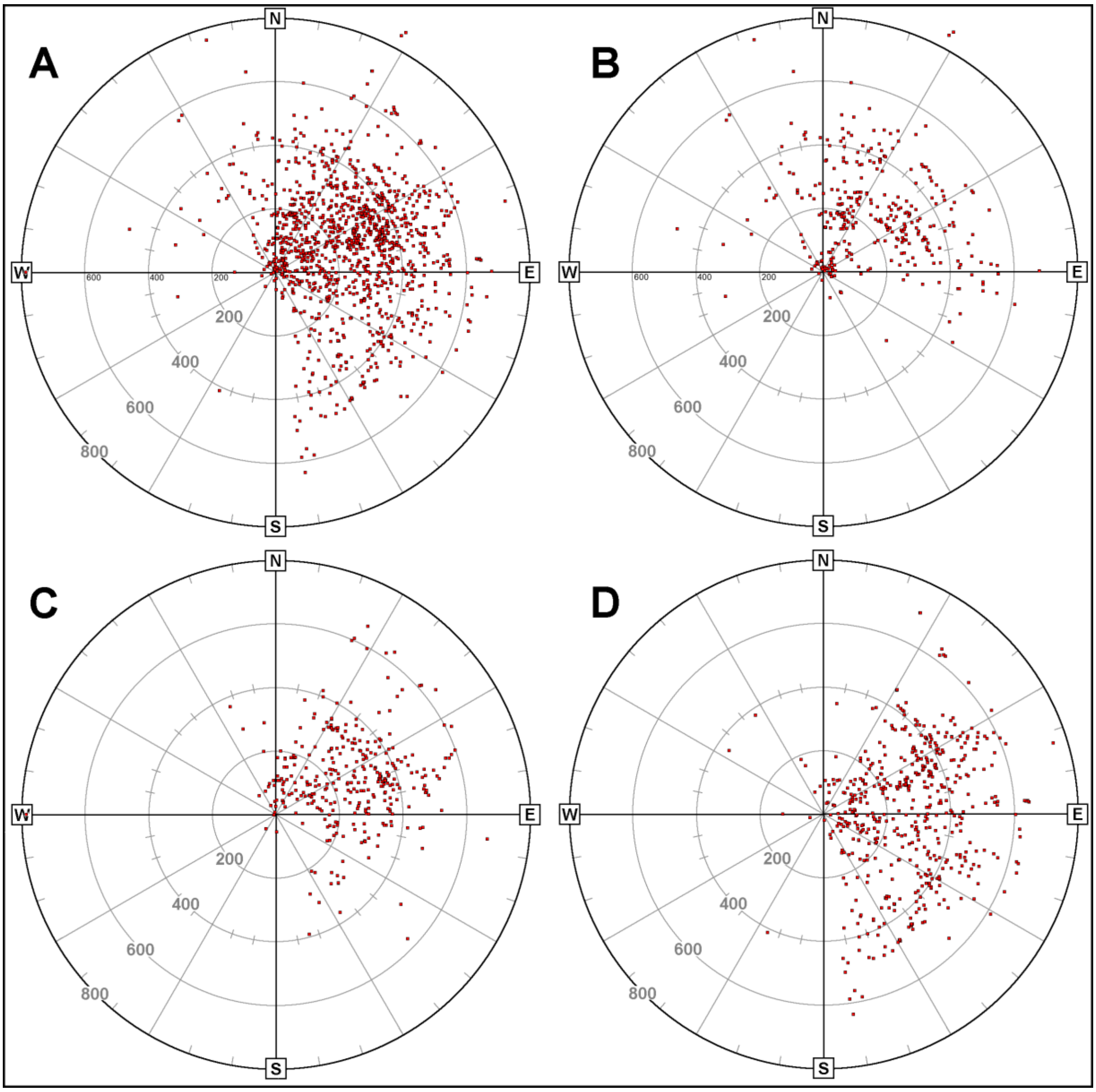
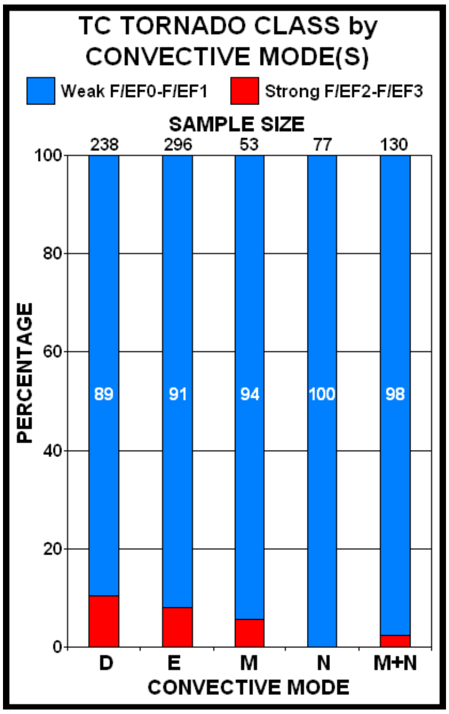
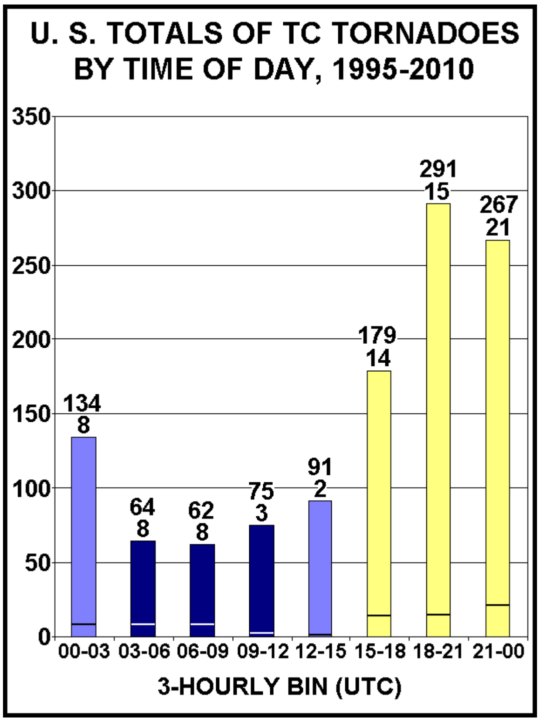


Figure 3: Center-relative position of 1995–2010 TCTOR events (red) from a Cartesian frame of reference for a) all TCs, b) hurricanes, c) tropical storms, and d) tropical depressions and post-classified remnant circulations. Range rings are in km as labeled, with the origin representing TC center. Radials are every 30° with respect to north (directions labeled). Small tick marks at 400-km radius represent 10° azimuthal intervals. From Edwards (2012).



<u>Figure 4:</u> TC tornado events sorted by weak and strong EF scale ratings within specific convective modes as adapted from Edwards et al. (2012): D stands for discrete supercell; E is supercells embedded in lines or clusters; M is marginal (very weak, sub-criteria) supercells, N is nonsupercellular convection.



<u>Figure 5:</u> 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 U.S. 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. From Edwards (2012).

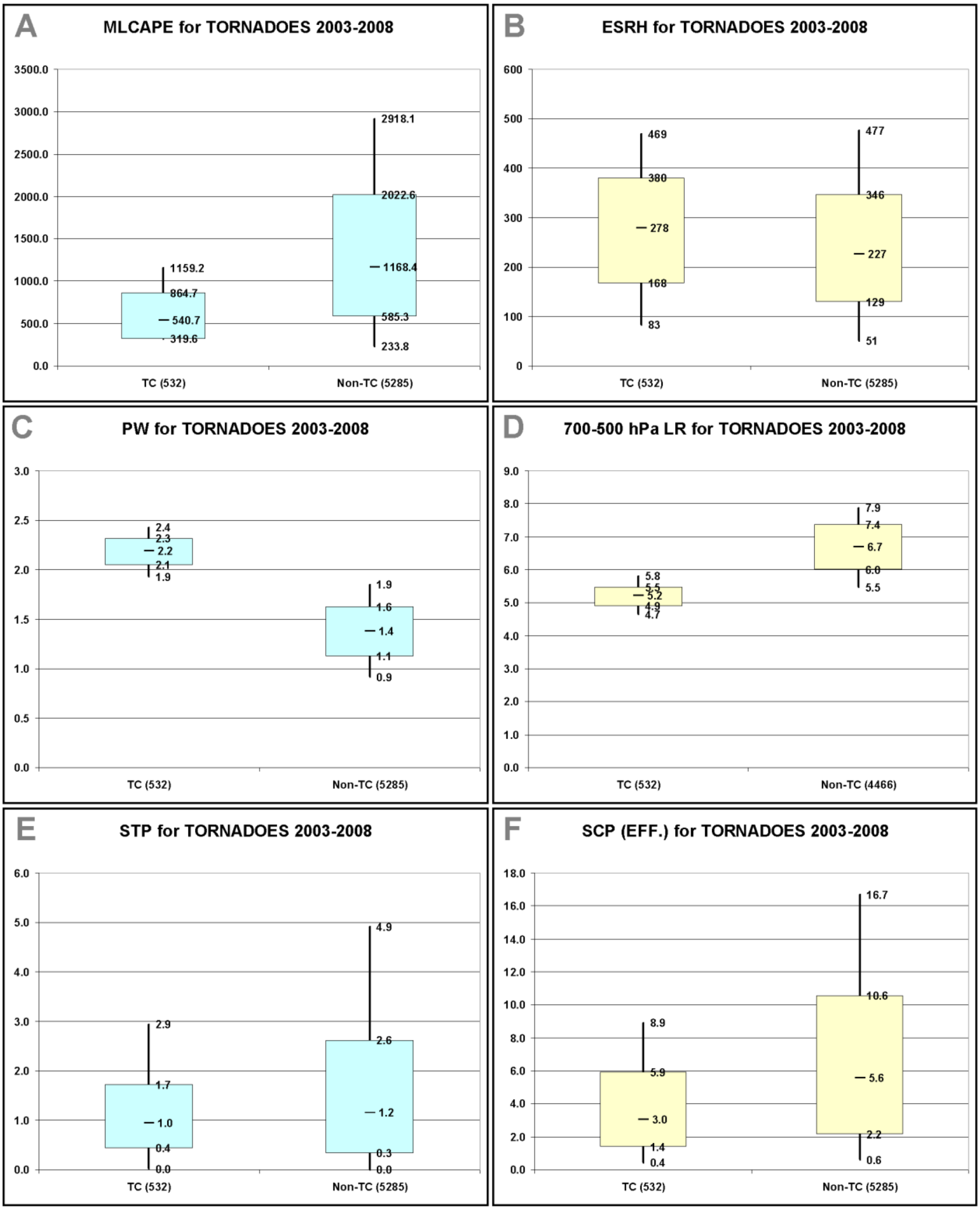


Figure 6: Box-and-whiskers diagrams of the following for TC (left) and non-TC (right) tornado environments during the 2003–2008 time frame: a) 100-mb mixed-layer (ML) CAPE, $m^2 s^{-2}$; b) effective (Thompson et al. 2007) storm-relative helicity, $m^2 s^{-2}$; c) preciptable water (in); d) 700–500 hPa lapse rates, °C km^{-1}; significant tornado parameter (Thompson et al. 2003), unitless; and f) supercell composite parameter (Thompson et al. 2003), unitless. Boxes represent 25th-75th percentiles; whiskers extend to 10th and 90th percentiles. From Edwards et al. (2012).