Tropical Cyclone Tornadoes, 1950–2007

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ABSTRACT

An expanded “climatology” of U.S. tropical cyclone (TC) tornadoes covering the period 1950–2007 is presented. A major climatology published in 1991 included data on 626 TC tornadoes. Since then, almost 1200 more TC tornado records have been identified, with almost half of that number from the 2004–05 seasons alone. This work reexamines some findings from previous studies, using a substantially larger database. The new analyses strongly support distinctions between inner- and outer-region tornadoes, which were suggested in previous studies. Outer-region tornadoes (beyond 200 km from the TC center) have a stronger diurnal signal, commonly occurring during the afternoon. Inner-region tornadoes typically occur within ~12 h of TC landfall, with no strong preference for a particular time of day. They are disproportionately less damaging tornadoes, with more rated F0 than in the outer-region sample. In more general terms, the TC tornado database includes a smaller percentage of significant (≥F2) tornadoes (14%) than does the overall U.S. tornado database (22%). Most TC tornadoes (60%) occur within 100 km of the coast; this includes core-region tornadoes near the time of landfall as well as tornadoes from rainbands coming ashore far from the circulation center. The F0-rated tornadoes are slightly more common near the coast but compose a smaller percentage of the tornadoes inland. The threat often persists for 2–3 days after landfall and extends ~400 km inland and ~500 km from the TC center, although there is much case-to-case variability. This puts locations at risk that might otherwise avoid damage from the TC.

1. Introduction

Although tornadoes spawned by land-falling tropical cyclones (TC) have been reported as far back as 1773 (Sadowski 1962), there is still much to be learned about these dangerous phenomena. Their preferred area of occurrence in the United States tends to stretch inland about 400 km from the Gulf of Mexico and Atlantic Ocean coasts, south and west of Virginia. In 2005 alone, the TC tornado damage estimates totaled over $100 million. Two recent hurricane seasons have had a combined higher count of tornado reports (over 500) than many decadal counts since 1950, contributing to a renewed interest in the topic.

Multiple “climatologies” have been constructed over the years to document the times, locations, and environmental conditions under which TC tornadoes occur (Sadowski 1962; Smith 1965; Pearson and Sadowski 1965; Hill et al. 1966; Novlan and Gray 1974; Gentry 1983; McCaul 1991; Verbout et al. 2007). These have shown a strong preference for tornado occurrence in the right-front quadrant with respect to TC motion, or the northeast quadrant (there is often substantial overlap between these quadrants). There is a diurnal signal present in the data, with more of the tornadoes occurring during the afternoon. TCs are more likely to produce several tornadoes when recurving toward the north and northeast and interacting with troughs in the midlatitude westerlies (Weiss 1987; McCaul 1991; Verbout et al. 2007). McCaul (1991) also examined proximity soundings to quantify the magnitudes of severe-weather parameters, enabling comparisons with the more studied Great Plains–type tornadoes. The sounding parameters were consistent with an increased tornado threat in the right-front quadrant, due to increased veering of the vertical wind shear and increased helicity in that region.

The period covered by McCaul (1991) spanned 1948–86 and included 626 TC tornadoes. In the ensuing 21 yr, ~1200 TC-spawned tornado records have been identified. The following work is an effort to update and expand upon relationships examined in earlier research.
Using two standard datasets for TCs and tornadoes, a merged TC tornado database is assembled. Section 2 describes this merged database. Some basic relationships that are well known from previous studies but are reexamined because of the more extensive sample size are included in the first part of section 3. These include tornado location, time of day, range and azimuth from the TC center, and TC motion. These basic relationships lead to topics examined in the second part of section 3, in which distinctions emerge between tornadoes located near the TC center and those farther away and between tornadoes that occur near the time of TC landfall and those happening days later. These distinctions support the idea from previous studies that TC tornadoes can be separated into two radial regimes—the core region and the outer rainband. This is discussed in section 4 in the context of previous studies. Section 5 summarizes the results and draws conclusions.

2. Data and methods

a. Merged TC tornado database

The National Hurricane Center's (NHC) official record of tropical cyclone data for the North Atlantic basin, called Hurricane Data (HURDAT; see online at http://www.nhc.noaa.gov/pastall.shtml), is the best-track dataset (so named because it contains the best estimate of tropical cyclone location and intensity as determined in a postanalysis of all available data). Only TCs that originate in the North Atlantic Ocean are used in this study. In a similar way, the Storm Prediction Center has compiled a database of severe weather that includes the final "whole tornado" database for tornado reports in the United States [also called One Tornado (ONETOR; see online at http://www.spc.noaa.gov/wcm/#data] dating back to 1950, sorted by date and time of occurrence. This listing is a compilation of the county-based path segments from the National Climatic Data Center's Storm Data. It includes information concerning path-length, width, F scale, start and end location, fatalities, damage estimates, counties, and states affected by the tornado. By combining the two official datasets, it is possible to automate the process of identifying tornadoes associated with a tropical cyclone based on the distance from the tornado to the TC center and its time of occurrence.

The HURDAT database provides the name, date, winds, pressure, and a location of each cyclone (at the center of circulation) at 6-hourly intervals. It begins at the tropical depression stage and extends into the extratropical stage while the storm can still be tracked as a distinct system. For each 6-hourly entry in HURDAT, a preliminary search is conducted of the ONETOR database to list any tornado occurring within 3 h of the entry. A corrected TC center position is then computed (by interpolation along its path by time) for each tornado identified. This step insures correct placement of each tornado within the TC structure. Any records meeting this first criterion are pared down using a 750-km limiting range between the TC center and the tornado location. This step is done to eliminate tornadoes that have occurred elsewhere in the United States yet are not related to the TC. The information associated with the HURDAT TC center point and all tornadoes (and associated information listed in ONETOR) meeting the two criteria are written to the Tornado Hurricane database (TORHUR). These two criteria identify around 1800 TC tornadoes in the continental United States.

With the data segmented this way, they can be further refined and sorted according to quantities derived from the TC and tornado locations. Information computed includes a direction and translational speed of the TC, a range and azimuth of the tornado relative to either TC motion or true north, and the tornado’s distance from the coast.¹ Landfall time of the TC center is also calculated by interpolating the 6-hourly best track to the point where it crosses the coast. For TCs making multiple landfalls (e.g., Florida followed by Louisiana), a tornado is assigned to the prior landfall time if the TC is over land, and to the subsequent landfall time if the TC is over water. The time of each tornado’s occurrence relative to the time of landfall is then computed and stored. In the case of a tornado being produced while a TC moves near the coastline yet does not make a U.S. landfall, no time from landfall information is computed, but the record is included in the dataset.

b. Sources of error and uncertainty

Significant questions exist concerning the accuracy of the official tornado record through the years. The number of tornadoes reported in the United States each year has increased from about 600 in the 1950s to about 1200 in the current decade, typically attributed to increased public awareness, the advent of Doppler radar, and increased vigilance by the National Weather Service (Verbout et al. 2006). It has been noted that tornado counts, especially of the lower F scales, may have been biased (negatively or positively) because of the unreliability (or absence) of spotter networks or because of

¹ A shape file of the U.S. coastline was generated using ArcGIS. Estuaries, inlets, etc., were smoothed using the shortest line connecting the sections of coastlines. The thick range lines shown in Fig. 1 show the coastline used.
multiple/inflated reports (Kelly et al. 1978; Doswell and Burgess 1988; Brooks and Doswell 2001; McCarthy 2003). Brooks and Doswell (2001) suggested that stronger tornadoes have been reported more consistently over time. Verbout et al. (2006) showed the number of tornado reports of F1 and greater has remained fairly consistent, suggesting the doubling of the tornado reports over the record is likely attributable to the increased reporting of F0 tornadoes.

Damage ratings for TC tornadoes can be complicated by the presence of additional damage from strong winds in or near the eyewall, storm surge, or flash flooding. Low cloud bases, heavy rain, and terrain hamper spotter networks that are an integral part of tornado detection. Terrain is especially a factor when TC landfall is in the southeastern United States, where line-of-sight visibility is obstructed by vegetation, buildings, and rolling terrain.

Keeping all of these factors in mind, it is plausible then to consider looking at only the tornadoes with higher damage ratings (≥F2). The hypothesis contends that the counts of higher F-scale ratings may be more reliable because of the amount of damage that must be present to be labeled with a higher damage rate. Because of the subjective aspects of the assignment of tornado damage ratings over the years (McCarthy 2003; Edwards 2003), it is not the authors’ intent to argue or verify this hypothesis but rather to see how the relationships vary if this restriction is placed on the dataset. During the study, efforts were made to look at both subsets to investigate whether/how the results differ. We also added a separate analysis of the F-scale counts for 1995–2000, because those damage assessments should be more representative of current standards and practices.

The distance of 750 km is used to limit the search range instead of the 800 km used by McCaul (1991). Either of these large ranges tends to result in most if not all associated TC tornadoes being listed for each system, at the expense of allowing a few unrelated events into the record. Reducing the limit to 750 km was done to help to reduce this error, eliminating 26 records that do not appear to be related to a TC. Comparisons with other studies (McCaul 1987; Grazulis 1993; Spratt et al. 1997; McCaul et al. 2004) were done to ensure consistency in the number of tornadoes assigned to individual TCs. Additional quality-control measures include inspection of any tornado event that occurred outside of 500 km from the center of the TC, those events that occurred more than 500 km from the coast (e.g., Wisconsin and Michigan), and tornadoes that occurred more than 3 days from landfall. These limitations were identified in previous climatological studies (Novlan and Gray 1974; Gentry 1983; McCaul 1991) as exceeding where the majority of TC tornadoes were known to occur. For cases meeting any of these criteria, we performed a cursory examination of available radar and surface data. This allowed us to eliminate 52 tornadoes that appeared to be unrelated to a TC.

There are cases in which previous work shows TC-spawned tornadoes in places where our analysis does not list any. This is a result of two mechanisms: the 6-hourly location information ends in the official TC record before the tornado occurs, or the tornado occurs farther than 750 km from the center. For the first, when the intensity of a TC decreases enough or it is no longer identifiable as a distinct system, NHC no longer tracks it. It is important to clarify that this does not mean that the system is no longer capable of producing severe weather. As an example, an in-depth study by McCaul and Grazulis (2008) found tornadoes associated with the remnants of Hurricane Andrew (1992) in Maryland, Delaware, and Pennsylvania. Our automated method does not include these tornadoes because the HURDAT track ended earlier in Tennessee. The second error was found to occur in Hurricane Gilbert (1988) for tornadoes occurring in Louisiana, Mississippi, Alabama, and Oklahoma. These four exceptional events occurred at a distance exceeding 750 km from the center of circulation yet are included in McCaul and Grazulis (2008). This, along with the uncertainty about the accuracy of reports or tornadoes that went unreported, makes it necessary to clarify between a count of records as used here and a count of tornadoes associated with a TC.

3. Results

Tropical cyclone tornadoes make up about 3.4% of the total number of tornado records since 1950. There have been almost 1200 tornado records added to the TC-spawned dataset since the McCaul (1991) study, nearly tripling its sample size. In addition, TC tornadoes have contributed approximately $1.4 billion² to the total amount of tornado damage done in the United States during the same time period. These damage values have not been adjusted for wealth or inflation (Brooks and Doswell 2001). Many aspects of the TC tornado climatology have been well established in previous studies. The locations, time of day, and TC motion characteristics associated with TC tornadoes are presented using current figures. This reevaluation primarily reinforces results from prior studies, although the more extensive sample size does afford more detail.

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² As computed by summation of the damage values (column 27; ONETOR) listed in the database.
a. Updates to the basic TC tornado climatology

1) Spatial distribution

Examining the geographical distribution of TC tornadoes has resulted in the generally accepted idea that occurrence is most likely within 200–400 km of the coast, with the coastal zone (within 50 km of the coast) incurring the largest percentage of hits (Fig. 1). Novlan and Gray (1974) and Gentry (1983) emphasized the importance of the water-to-land transition with increased frictional effects, resulting in decreased wind speed near the surface. This increases the shear in the vertical direction, a key component in the development of rotation on the convective scale. In addition, areas of increased convergence parallel to the coast can occur while the TC approaches, aiding in the rapid growth or intensification of supercellular storm structures. Recent work by Baker et al. (2009) and Eastin and Link (2009) with Hurricane Ivan (2004) shows evidence of supercellular structures capable of tornadic development well offshore. A combination of these mechanisms likely contributes to the large percentage of tornado events along the eastern U.S. coastline. Farther inland, stretching to the 400-km range line, clustering of tornadoes is apparent. This is typically due to a large number of tornadoes related to individual TC events. Some examples include a grouping located in south-central Texas that resulted from Hurricane Beulah (1967) or the clustering spread across northwestern Alabama that resulted from Hurricane Rita (2005).

Table 1 shows that ~94% of the TC-spawned tornado records occur within 400 km of the coast, 44% (800) of which occur within 50 km of the coast. Zooming in even further, 2 times as many tornadoes are located within the
The resultant distribution places 30% of the total TC tornado sample in the immediate coastal zone. The coastal resolution used in this analysis does not support any closer evaluation than 25 km. Note that this count is not limited to only the time or location that the TC center crosses the coast, as discussed in section 3b. As one examines farther inland, the number of records decreases rapidly with distance over the first 150 km. The percentages fall to about 5% or less (of the total) for each 50-km segment inland after 200 km.

All of the Gulf coast and Atlantic coast states from Virginia southward have experienced over 100 TC tornadoes each (Table 2). Although Florida leads the country with the most TC-spawned tornadoes by number, this classification of tornado only makes up 14% of the total tornado count for the state in the 58 yr reviewed. In contrast, Virginia’s TC tornado count makes up 23% of the state’s total record, the highest in the United States, followed by South Carolina with 22%. For the coastal states from Louisiana to Maryland, TC tornadoes account for ~10%–25% of each state’s total tornadoes reported.

The counts of all U.S. tornado and TC tornado records are segmented by the F scale in Table 3. From earlier climatologies (Novlan and Gray 1974; McCaul 1991; McCaul and Cohen 2002), TC tornadoes are typically weaker than those that occur in the Great Plains region. For the 58-yr dataset in Table 3, TC tornadoes have a larger number of F0 reports (49%) as compared with all U.S. tornadoes (42%). The F1-rated numbers share a
similar percentage of each dataset, whereas only 2% of TC tornadoes are rated F3 or stronger as compared with 6% of the full U.S. tornado database.

Questions arose concerning a regional bias or seasonality related to the parent storm associated with the tornado event. Brooks et al. (2003) and Trapp et al. (2005) have shown variation in the daily tornado threat with respect to location and month of occurrence. The coastal regions of the United States (primarily the Southeast) represent the largest region affected by TC tornadoes (Fig. 1) with a monthly distribution spread between May and November (not shown). To evaluate this possible bias, the 58-yr dataset for all U.S. tornadoes was limited to the regions typically associated with landfalling TCs (the area defined by the 400-km-range ring depicted in Fig. 1) and restricted to the months from May to November. Again, there is a slightly larger percentage of F0-rated tornadoes associated with TCs (7% difference) when compared with the limited U.S. tornado record. In addition, a smaller proportion of the TC tornadoes (<14%) are rated significant (≥F2) than for the adjusted U.S. dataset (~19%). In both cases, the TC tornado distribution shows a larger fraction of less-damaging-tornado reports than the U.S. record.

The lower portion of Table 3 shows the breakdown of tornado records by damage rating for 1995–2007. An examination of recent years may be more relevant to current standards. Improvements in detection, reporting, and damage assessment may change the F-scale distribution as discussed in section 2b. In all categories, the number of F0-rated tornadoes has increased, in agreement with Verbout et al. (2006). Most differences between the TC tornado counts and the U.S. counts (in either category) are small. The major difference is a near absence of F3-and-greater TC tornadoes (3 out of 1000) as compared with F3 and greater making up ~2% of the remaining databases since 1995.

2) AZIMUTHAL DISTRIBUTION

It has become somewhat common knowledge from prior studies that TC tornadoes are typically clustered in the right-front quadrant with respect to TC motion or the northeast quadrant in a fixed reference frame (Smith 1965; Hill et al. 1966; Novlan and Gray 1974; Gentry 1983; McCaul 1991). Figure 2 suggests that it is more appropriate to speak of a preferred sector or region instead of a preferred quadrant. Over 90% of tornadoes take place between 340° and 120°, relative to TC motion (over 80% in north-relative coordinates). There is a rightward shift with increasing distance from the center (Fig. 2c). Inside a 200-km radius, the mean tornado location is ~32° to the right of the storm motion vector (~52° to the right of true north). Between 200 and 400 km, the mean is ~50° to the right of storm motion (~60°), and beyond 400 km it is ~65° to the right of storm motion (~68°). Although arguments have been made in the literature in favor of both motion-relative and earth-relative reference frames, it is not clear from Fig. 2 that either one more tightly constrains the TC tornado spatial distribution. In the north-relative reference frame (Figs. 2b,d), the mean tornado location shifts slightly from northeast at small radii from the TC center to east–northeast at large radii. Both reference frames have preferred sectors but also have outliers from individual cases. As an example, Hurricane Audrey (1957) produced 14 outlier tornadoes in the south–southeast region (north relative) and Hurricane Beulah (1967) produced over 30 tornadoes in the rear to left-rear region (storm relative).

3) TIME OF DAY

Pearson and Sadowski (1965), Smith (1965), and McCaul (1991) all presented work depicting the tornado counts as a function of time of day. In McCaul’s (1991) 626-tornado sample, the peak occurrence was between 1500 and 1800 LST. With a threefold larger sample size, it is now practical to examine this on a finer time scale. The peak for all U.S. tornadoes is in late afternoon from 1600 to 1800 LST (Fig. 3, black bars), as compared with mid- to late afternoon (1400–1700 LST) for TC tornadoes (Fig. 3, gray bars).

For the amplitude of change over the day, the full U.S. tornado record showed the sharpest increase of a factor of ~12 from morning to afternoon as compared with about a fourfold increase in the TC tornado record. Again limiting the U.S. dataset to within 400 km of the coast and to May–November results in an amplitude of a factor of ~7. This suggests that TC tornadoes are a bit less dependent on daytime heating (buoyant forcing) than tornadoes are in general. This is reasonable, because extensive cloud cover and rain-cooled air limit daytime heating over much of the region affected by a TC.

Figure 4 considers more-damaging TC tornadoes separately, because they would seem to be less likely to suffer from a reporting bias (e.g., a potential lack of reporting overnight). The phase and amplitude of the histograms for ≥F2 TC tornadoes are very similar to those for all TC tornadoes, adding confidence to the result. A possible diurnal relationship to the time of landfall of the parent TC was investigated and was found to offer no distinct signal.

4) TROPICAL CYCLONE SPEED AND DIRECTION

Vertical wind shear profiles are more favorable for tornadoes in the right-front (northeast) region while
being further enhanced when the tropical cyclone interacts with the midlatitude westerlies (e.g., McCaul 1991; Verbout et al. 2006). This adds to the westerly shear and the upper-level forcing. Weiss (1987) found the forward translational speed of a TC was associated with tornado production. Verbout et al. (2007) showed that the occurrence of a large number of TC tornadoes (sometimes termed an outbreak, depending on how it is defined) is more likely with TCs that are recurving ahead of a midlatitude trough approaching from the northwest. Examination of the TC environment is beyond the scope of this study. Instead, this relationship between TC recurvature and tornado occurrence is manifested in most of the tornadoes occurring while TCs are moving toward the north or northeast (Fig. 5). These headings are more common for TCs in general in the
U.S. region, but even more so when considering TCs that are spawning tornadoes. With the TC database in 6-hourly intervals, ~15% of the time periods with translational TC headings between 340° and 80° have tornadoes (dashed line with squares in Fig. 5). For most other headings, ~5%–10% of the time periods have tornadoes. In a similar way, ~15%–25% of the time periods with TC forward speed of at least 5 m s⁻¹ have associated tornadoes (Fig. 6). There is a spike in the number of tornado occurrences at TC forward speeds of 5 m s⁻¹, because the faster forward speeds are less common for TCs in general.

5) TIME FROM LANDFALL

From a statistical standpoint, the majority of TC tornadoes begin occurring 1–2 days ahead of landfall (as the TC approaches or parallels the coast, with rainbands penetrating inland), although a few TC tornadoes have occurred as early as 4 days before landfall (e.g., Hurricane Georges in 1998). They continue to occur through 2–3 days after landfall (McCaul 1991), with some slow-moving, persistent TCs producing tornadoes into days 4 and 5. Of course, there is tremendous case-to-case variability in this regard, with some TCs moving too fast or dissipating too quickly to spawn tornadoes over multiple days. In some cases the favorable conditions for tornadoes only coexist for a brief period (which could be before, during, or after landfall). In the composite, there is a rapid increase in tornado counts in the last 12 h while a TC approaches its landfall (Figs. 7a,b). A majority of tornadoes occurs between 12 h before and 24 h after landfall. About 84% of the tornado record occurs from about 12 h before to 48 h after landfall, with the threat continuing out to 72 h. More-damaging tornadoes (≥F2) have a broad distribution with a relative peak at 350 km from the center of the TC and tend to occur after landfall rather than before (Fig. 7b). There are distinct spikes at landfall in the counts of tornadoes in the 0–100- and 100–200-km bins (Fig. 7a), whereas the other range bins have a broader distribution, with relative peaks in later time bins.

b. Bimodal segmentation

Weiss (1987), Gentry (1983), and McCaul (1991) discussed a bimodal signal that occurs with respect to range from the center of the TC outward. In McCaul (1991), the data showed a distinct peak from 200 to 400 km with a “shoulder” located approximately inside the 160-km range. In the current data, the maximum falls between 250 and 500 km with a shoulder inside 250 km for the F0
distribution (Fig. 8) and located inside the 200-km range for the higher damage ratings. Molinari et al. (1999) used the radius outside of 200 km to describe the outer rainband region in terms of lightning activity. For this study, the area described as “core region” is defined to be within 200 km of the center while the “outer rainband” classification describes tornadoes that occur outside the 200-km limit. For individual cases, smaller or larger distances might be preferable for this distinction.

McCaul (1991) noted that these core tornadoes are more prominent on the day of landfall, with the threat in the outer regions sometimes persisting for a few days. This is also seen in the in 1950–2007 dataset (Figs. 7a,b), with 62% of core-region tornadoes occurring in the 12 h bracketing landfall. There is a broad peak of tornado occurrence in the outer region from 12 h prior through 24 h after landfall, with a gradual decline thereafter.

To illustrate this better, the relationships between tornado F scale and time from landfall are considered separately for the inner and outer regions (Figs. 9a,b). Tornadoes within 200 km of the center occur mostly near the time of landfall and tend to be relatively weak, mostly F0 and F1 (over 80% of subtotal), supporting the findings in McCaul (1991). It is important to note here that this type of TC tornado only makes up one-quarter of the entire dataset so that the numbers are arguably small overall.

At larger radii (beyond 200 km) from the TC center (Fig. 9b), there is less dependence on the time since landfall, with the distribution of each of the intensities

![Figure 7](image1.png)  
**Fig. 7.** (a) The 1950–2007 TC tornado counts as a function of time from landfall (12-h bins) and distance from the TC center (km). (b) The TC tornado counts as a function of time from landfall (12-h bins) and damage rating.

![Figure 8](image2.png)  
**Fig. 8.** The 1950–2007 TC tornado F scale as a function of range from the TC center (km).
being fairly well spread between the 12-h blocks. Although outer-region F0-rated tornadoes slowly decrease after their broad peak near the time of landfall (from 12 h before through 24 h after), the counts of the stronger tornadoes peak slightly later. The F1 counts in the outer region reach their maximum in the 12–24-h block and slowly decrease through 48 h, whereas $F_2$ tornadoes have a broader peak 12–36 h after landfall. This analysis supports the idea of two distinct radial modes of TC tornadoes. A specific look at the distribution of tornadoes outside of 200 km (Fig. 9b) shows that the major threat for more-damaging tornadoes extends through 2 days after landfall, with some occurring even later.

When considering the core- and outer-region tornadoes separately, it is seen that the diurnal signal is almost entirely a result of afternoon tornadoes in the outer regions (Fig. 10). Core-region tornado numbers remain fairly consistent throughout the day, with about a two-fold increase from overnight to afternoon. In the outer-rainband mode, the presence of a diurnal effect is similar to the climatological distribution shown in Fig. 4 with over a fivefold increase from overnight to afternoon. The TCs that produced a tornado were checked for a preference in the TC time of landfall. There was no obvious influence, ruling out the possibility of a preferred TC landfall time contributing to a preferred tornado diurnal distribution.

This result further delineates the subtle differences between the two radial modes of TC tornadoes. Because there is little observational evidence of the inner-region tornado regime, more study is required to understand fully the specific structure of the cells that produce these tornadoes as well as to verify this hypothesis. The similarities between the diurnal distribution of the outer mode of TC tornadoes and the general U.S. diurnal distribution highlight the similarities these cells have to the more typical non-TC tornadoes.

The finding that stronger tornadoes tend to be in the outer regions and continue to occur more than a day after landfall leads to the question of whether they are found farther inland than most TC tornadoes. The difference in the damage rating as a function of distance from the coast is small. As seen in Fig. 1 and Table 1, the overall number of TC tornadoes decreases rapidly over the first 100 km inland. This is also true for each damage rating (Fig. 11), but there is a slight preference for F0-rated tornadoes near the coast in comparison with farther inland. It is obvious that the core-region tornadoes near the time of landfall are near the coast, and it would be tempting to conclude that most tornadoes within 100 km of the coast fit that description. In fact, only about one-third of the tornadoes located near the coast (the 0–100-km-range bin) are designated as core-region tornadoes. Nearly half of the coastal zone tornadoes occur more than 12 h from landfall (not shown). These tornado events within 100 km of the coast are therefore a combination of the inner-region tornadoes and more distant tornadoes related to outer rainbands coming ashore.
4. Discussion

The analyses presented up to this point indicate distinct statistical differences between the two hypothesized radial modes of TC tornadoes. Most case studies in the literature focus on tornadoes in the outer region. In this section, we discuss some of the previous studies in the context of those results presented in section 3.

McCaul and Weisman (1996) identified subtle yet important differences in the understanding of how a cell in a landfalling TC environment could produce severe weather (including a tornado) despite its comparatively smaller magnitudes of CAPE (when compared with Great Plains cells where it is a major factor) and overall smaller size (heights of 5–7 km rather than 12–17 km). In their numerical simulations of TC cells, they found that the total contribution of the dynamically associated, upward pressure-gradient terms made up 75%–85% of the total contribution to updraft development. The buoyant forcing, dictated by the thermodynamic profile, was found to contribute only a small portion to the updraft intensity. This finding led to the hypothesis containing that small amounts of CAPE had a greater effect on the intensity of the updraft if the bulk of the quantity was collocated with the pressure-gradient maximum, typically about 700 hPa. This was later simulated and better established in McCaul and Weisman (2001).

Using this framework, McCaul and Weisman (2001) defined the “CAPE starved” environment as that in which, if all other parameters were held constant, bulk CAPE must be increased for the full intensity of the storm to be maximized. This type of storm also would be associated with a low bulk Richardson number (BRN). The opposite relationship exists for a “shear starved” environment. The hodograph trace radius would have to be increased, indicative of a high BRN number, for the storm potential to be maximized. This distinction is important when describing the supercell environment, especially in the moist, strongly sheared low-level environment of a landfalling TC.

At landfall, the inner-TC-region surface winds slow because of the frictional effects induced by the water-to-land transition (Gentry 1983), potentially increasing the already strong low-level vertical wind shear in the area (as described in Spratt et al. 1997). This frictional slowing also creates convergence immediately inland from the coast, which favors increased vertical motion and the stretching of vorticity. This is the case for onshore flow both in the inner region and associated with the outer rainbands. Following the ingredients-based approach, moisture is abundant in the TC environment. The locally maximized convergence near the coast may aid in tilting horizontal vorticity into the vertical plane, leading to low-level mesocyclogenesis. Although there may not be large amounts of instability in this area (as evidenced by the low values of CAPE at smaller radii while the TC is offshore; Bogner et al. 2000), McCaul and Weisman (2001) showed that small amounts of CAPE maximized at the lower levels would be sufficient to aid in updraft development. Because of the greater shear magnitudes already present near the center of the TC during landfall (Bogner et al. 2000), the regions near the coast should be strongly favored for inner-region tornadoes. This appears to be the case as 75% of the core-region tornadoes occur within 100 km of the coast, as compared with only 55% of the outer-region tornadoes. When inner-region winds are no longer much stronger than those in outer regions, the number of core-region tornadoes rapidly decreases. This could explain the high number of core-region tornadoes being maximized within 12 h of landfall.

When looking outward into the outer rainband area, Bogner et al. (2000), Baker et al. (2009), and Molinari and Vollaro (2008) have shown the offshore TC environment can support the potential for rotating convection. Spratt et al. (1997), Baker et al. (2009), and Eastin and Link (2009) showed radar evidence of the development of supercells offshore that went on to produce a tornado shortly after moving onshore. In Hurricane Ivan (2008), long-lived cells were tracked from about 150 km offshore until moving onshore, producing a tornado soon after. Baker et al. (2009) found rapid increases in storm intensity and updraft rotation occurred as the supercells themselves made landfall. A magnitude of 0–1-km shear was 50% greater over land, with a corresponding increase in the 0–1-km storm relative helicity, highlighting the probable role of enhanced surface friction over land on the wind profile.

The results presented in Fig. 10 suggest outer-rainband-region tornadoes are more sensitive to afternoon heating. McCaul (1987), Vescio et al. (1996), and Curtis (2004) hypothesized that dry air, ingested at midlevels, would act to influence the structure of the storm (e.g., eroding cloud cover and steepening lapse rates). Where dry slots are accompanied by clearing skies, insolation can act to warm and destabilize the afternoon boundary layer. It also can lead to baroclinic boundaries induced by differential heating. Either of these effects could increase the afternoon tornado threat. The tornado outbreaks associated with dry-air intrusions in case studies discussed in Curtis (2004) tended to be concentrated in the afternoon and in the outer regions, consistent with the statistical results of this study.

An association between outer-region TC tornadoes and formation along boundaries has been shown
observationally in a few studies. In Curtis (2004), 11 of 13 outbreak cases (those producing more than 20 tornadoes each) were shown to be associated with a pronounced gradient of relative humidity caused by the intrusion of dry air at the 700–500-hPa levels. McCaul et al. (2004) found some of Tropical Storm Beryl's (1994) tornadoes formed along a weak coastal frontlike boundary that was moving across the area, coincident with the TC's outer rainbands. Spratt et al. (1997) speculated that the interactions between incipient boundaries and the TC outer rainbands may provide local vertical motion and vorticity enhancements. The presence of a boundary related to the dry intrusion or weak frontallike boundaries (Knupp et al. 2006) in the environment could act to aid the mesocyclogenesis or mesocyclone intensification process (Markowski et al. 1998).

Edwards and Pietrycha (2006) described four categories of baroclinic boundaries as they relate to TC tornado distributions, primarily in the outer regions of the TC, based on mesoanalyses of TC events. The categories are buoyancy-limiting, shear-limiting, buoyancy-shear overlapping, and null classifications. The first describes a boundary with favorable shear on both sides but in which suitable buoyancy conditions only exist on one. The other side is dominated by relatively cool, stable air that acts to limit the surface-based buoyancy. Shear-limiting describes the opposite case in which buoyancy exists on both sides of the boundary while only one side of the boundary has favorable shear conditions. The overlapping class is most comparable to boundaries that influence Great Plains supercells. Here, the favorable buoyancy is located on the warm side with vertical shear on the other, causing an area, or corridor, of overlap near the boundary itself. The last classification covers events in which environmental conditions may appear to be broadly favorable for tornadoes yet the production is limited to few if any tornadoes because the suitable conditions are not juxtaposed.

The strong vertical shear and storm relative helicity in the core region before landfall reported by Bogner et al. (2000) are consistent with the generation of inner-region tornadoes in the strong wind field near the time of landfall, as seen in our statistical results. Tornadoes in the outer region seem to have more dependence on a boost from daytime heating (Fig. 10) and/or interactions with boundaries or dry intrusions in the observational studies cited.

5. Summary and conclusions

An updated climatology based on almost 1800 tropical cyclone tornadoes for the period of 1950–2007 is consistent with many earlier findings. The vastly larger sample size allows for a reexamination of some of those findings and reveals additional aspects of a distinction between tornadoes near the TC core and those in the outer regions. The most straightforward results are found in the first half of section 3 and in general have been described in prior climatologies. The greatest frequency of TC tornadoes is along the coastline, with numbers decreasing rapidly over the first 150 km inland. Seventy-nine percent are within 200 km of the coast, and TC tornadoes account for ~10%–25% of all tornado records for each of the coastal states from Louisiana to Maryland. Other than a preference for F0 tornadoes near the coast, there is no strong relationship between TC tornado rating and distance inland. In general, significant (≥F2) tornadoes are less common with TCs (<14% of TC tornadoes) than with non-TC tornado events (<20% of U.S. tornadoes). Since 1995, only ~7% of TC tornadoes and ~10% of U.S. tornadoes have received ≥F2 ratings.

The right-front (northeast) region of the TC produces the largest number of tornadoes (as in previous studies), with 80% occurring between 350° and 120° relative to the TC motion vector (81% in the same sector relative to Cartesian north). The peak in mid- to late afternoon (1400–1700 LST) for TC tornadoes is slightly earlier than that reported by McCaul (1991) (1500–1800 LST) and slightly earlier than the peak in the overall U.S. tornado distribution (1600–1800 LST). The amplitude of the diurnal signal for TC tornadoes is smaller (a factor of 4 increase from overnight to afternoon) than for other tornadoes (a factor of 12 increase for the entire U.S. database, and about a factor of 6–7 increase for the region and months most associated with TC tornadoes). Tornadoes are most common when TCs are moving northward or northeastward at 5 m s⁻¹ or faster (consistent with recurvature and interaction with the westernlies), showing general agreement with Verbout et al. (2007).

New information was found concerning the bimodal distribution of TC tornadoes noted by Gentry (1983), Weiss (1987), and McCaul (1991)—in particular, with regard to tornado distribution by F scale and the diurnal cycle. Tornadoes near the center of the TC and/or near the time of TC landfall are disproportionately less damaging (more F0s) than those occurring farther away or later. Inner-region tornadoes (defined here as those within 200 km of the center) compose 26% of the population. Only 10% of these are significant tornadoes (≥F2), as compared with 15% of those in the outer regions. The core-region tornadoes occur mostly near the time of landfall, with 75% from 12 h before to 24 h after landfall. Slightly over half of the outer-region tornadoes...
occur during the same time period; the outer region also poses a tornadic threat in the days preceding and following landfall. A vast majority (94%) of tornadoes occur within 48 h of landfall. The core region has a slight afternoon maximum of tornado occurrence, but the amplitude of this diurnal signal is much greater in the outer region.

Based on these composite results, there are distinct ways to characterize the tornado threat in landfalling TCs. Tornadoes near the TC center mostly occur within a day of landfall and, for the most part, are relatively weak. Farther from the TC center (mostly 200–500 km away), tornadoes are a threat, especially during the afternoon as the TC nears the coast and for another afternoon or two during and after landfall. The threat is typically maximized where surface heating and destabilization can occur (e.g., clear slots associated with dry-air intrusions) and veering vertical shear profiles are maximized (the right-front sector with respect to TC motion, or the northeastward sector). Of course this is strongly dependent on a particular TC’s track, forward speed, and environmental conditions. The TC is more likely to have some significant tornadoes in this outer region than near the core, although they are less likely than in the general U.S. tornado population. These outer-region tornadoes have the potential to be the primary hazard in locations that are spared from the main TC wind, coastal storm surge, and inland flooding hazards. They can also be a hazard along the TC track well ahead of the storm, before residents expect the main TC impacts (Spratt et al. 1997; McCaul et al. 2004).

This analysis reveals common attributes of the location, timing, and damage potential of TC tornadoes, but individual cases must be considered in the context of their environmental conditions and interactions. Some TCs spawn few if any tornadoes; others spawn over 100. Interactions with large-scale troughs, dry-air intrusions, low-level boundaries, available thermodynamic instability, and so on contribute to the large variability among cases. Our findings could factor into the situational awareness when a tornado watch or mesoscale discussion is considered with a tropical cyclone. In the inner regions (<200 km from the center of circulation), vigilance is warranted—in particular, near the coast—regardless of time of day. In the outer regions, the coastline continues to be vulnerable, with greater vigilance warranted in the daytime hours. The threat in the outer regions can extend far inland and can include an increased threat of more damaging tornadoes. In all, these suggestions are meant to supplement, but certainly not to replace, careful consideration of the synoptic and mesoscale environment.

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REFERENCES


