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OBJECTIVE ENVIRONMENTAL ANALYSES AND CONVECTIVE MODES FOR U.S. TROPICAL CYCLONE TORNADOES FROM 2003-2008

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1. INTRODUCTION and BACKGROUND

Tropical cyclone (TC) tornado prediction remains a substantial challenge, both on its own and compared to advances made in prognostically relevant understanding of midlatitude supercells in particular. An ingredients-based approach (e.g., Johns and Doswell 1992), used for supercell tornado environments in midlatitudes, likewise can be applied to TCs, focusing on moisture, instability, vertical shear and lift for that majority of TC tornado situations resulting from supercells. Being rich in low level moisture, the main factors influencing the occurrence of supercell tornadoes in TCs are the relative distribution and overlap of shear, instability (as indicated by buoyancy) and various forms of convective bands and boundaries as foci for convection.

a. Cyclone-scale influences

TC tornado occurrence tends to decrease inward toward the TC center from some loosely defined maximum density located generally outside the radius of gale winds. Outer-band TC tornadoes often are supercellular (e.g., Spratt et al. 1997)and occur in regimes generally rightward or eastward of the center's track (with some exceptions), characterized by strong lower-tropospheric vertical shear and favorable CAPE (McCaul 1991). Though inner-band TC tornadoes have occurred with many TCs, three important factors contribute to a lower frequency of occurrence of discrete supercells and TC tornadoes inward toward the eyewall of a mature hurricane, a trend documented in multiple climatologies from Hill et al. (1966) to Edwards (2010), especially near and before TC landfall. First, although a hurricane's winds increase with proximity to center, vertical shear tends to decrease (e.g., McCaul 1991, Molinari and Vollaro 2008). Second, as illustrated by McCaul (1991), buoyancy tends to diminish markedly from a TC's outer fringes inward toward center. Third, convective mode nearer to center tends toward the nonsupercell, with more continuous banding structures, greater coverage of relatively amorphous rain shields, and ultimately (in sufficiently well-developed storms) one or two eyewalls whose annular radii and degrees of closure may vary with time, and from storm to storm. The relatively dense precipitation patterns near center, concurrent with the presence of thicker deep-layer cloud cover associated with the storm's central dense overcast (CDO), restrict diurnal heating and its contribution to buoyancy, and render those reduced tornado trends that do exist in that region less dependent on time of day (e.g., Smith 1965).

b. Meso-β to convective-scale influences

Supercells within TCs tend to be smaller in vertical and horizontal extent than those of midlatitude systems, more similar to the dimensions of midlatitude "mini-supercells" (e.g., Kennedy et al. 1993, Burgess et al. 1995), and that term has occasionally been used in the TC setting (e.g., Suzuki et al. 2000). This spatial compression appears to be related, in part, to the warm-core nature of the TC, its resultant weak thermal lapse rates aloft and the resultant concentration of buoyancy in the lowest few kilometers AGL. This also corresponds quite well to the layer where vertical shear is maximized in the environment, along with peak perturbation pressure (non-hydrostatic) forcing on the storm scale (McCaul and Weisman 1996).

TC tornado environments typically are characterized by small convective inhibition (e.g., McCaul 1991), indicating only weak lift is necessary to produce deep convection in favorably buoyant areas. This lift is manifested often in the form of spiral convergence bands, and sometimes around in situ baroclinic boundaries away from the immediate TC center that have been associated with marked changes in tornado distribution of TCs (Edwards and Pietrycha 1996). Whether embedded in convective clusters or in bands, the tornado potential in supercells may increase upon, or soon following, their interaction with low level boundaries embedded in the TC envelope— such as fronts and wind shift lines, where backed winds and relatively maximized convective boundary-layer vertical and horizontal vorticity commonly are present. This phenomenon was well-documented with midlatitude supercells in VORTEX field observations (e.g., Markowski et al. 1998, Rasmussen et al. 2000), and has been applied to various forms of in situ and pre-existing boundaries in the landfalling TC environment (e.g., Rao et al. 2005, Edwards and Pietrycha 2006).

Discrete, tornadic supercells also may develop outside well-defined precipitation bands in the weakly capped free environment, 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 excellent

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examples of discrete supercells, with or without banded or clustered convection nearby, are found in many recent studies, e.g., Suzuki et al. (2000), Edwards et al. (2000), McCaul et al. (2004), and Schneider and Sharp (2007).

The placement of discrete supercells, versus those embedded in convective bands, may affect their tornado potential via thunderstorm-scale processes. This was one of the motivators for determination of convective modes herein. Numerical simulations have indicated weak cold pools with discrete supercells in the TC environment (McCaul and Weisman 1996), related largely to the characteristically high moisture content of the lower troposphere and resultant lack of evaporationally aided θe deficit in the near-surface downdraft. McCaul and Weisman proposed this as a possible reason for the relative weakness of TC tornadoes compared to those arising in baroclinic perturbations of midlatitudes. Their simulations, however, did not involve environmental inhomogeneities in thermal or kinematic fields, such as the boundary situations described above, where tornado potential may be enhanced. Such inhomogeneities likely are not always resolvable using routinely available operational datasets. Despite their apparent weakness or absence in small, discrete TC supercells, convectively-generated 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 12 K θe deficits in the subcloud layer of spiral bands, indicating the existence of such processes.

The plausibility of 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). Among counterbalancing factors are restrictions imposed on supercell development and longevity by cell mergers and absorptions into somewhat more stable precipitation areas, each of which may be quite common in such close quarters. A related lack of discrete cells with inward extent toward the eyewall has been well documented (e.g., Barnes et al. 1983), and also has been related to diminishing CAPE inward toward TC center (McCaul 1991). These issues compel the question: to what extent can such small-scale cooling processes, potentially impacting tornado potential in the TC envelope, be resolved by operationally utilized objective analyses? This was another motivator for this investigation.

Midtropospheric drying has shown a pronounced collocation with clusters of TC tornadoes, especially outbreaks of 20 or more (Curtis 2004). At least part of this association may be related to the tendency for less cloud cover within such dry slots, and accompanying zones of stronger and more prolonged surface insolation. Such a process was implied by Baker et al. (2009) for the landfall-phase tornado episodes with Hurricane Ivan. Relatively cloud-free areas near the storm's periphery may enable sufficient diabatic surface heating needed to substantially magnify CAPE in a sounding, given ambient thermal lapse rates that are only slightly above moist adiabatic through most of the troposphere (e.g., the composite sounding profile of McCaul 1991). Meanwhile, drying aloft also has been implicated in aforementioned cold pool generation in outer bands (e.g., Barnes et al. 1983, Powell 1990b). Resulting differential heating between the band axis and any relatively cloud deprived slot outside the inward edge of a rainband may generate thermal boundaries suitable for supercell maintenance as described above, and may contribute to tornado occurrence such as has been documented in the inward side of inner and outer bands (e.g., McCaul 1987; Rao et al. 2005).

This study presents some preliminary analytic results for the near-convective environments and storm modes for TC tornado events during 2003-2008, and as such, may be taken as a Part II for Edwards (2008). For clarity, "storm" will refer to those convective elements, on horizontal scales of 10^0-10^1 km, specifically responsible for tornadoes. This term is used instead of "cell" since (as shown herein) some tornadic modes are not discretely cellular. "TC" will be used to refer to the tropical cyclone at large.

2. DATA and METHODS

TC tornado data comes from the 1995-2009 "TCTOR" database (Edwards 2010, this volume). Because TCTOR for 2010 is not finalized as of this writing, and no TC tornadoes were recorded in the conterminous U.S. during 2009, our analysis period stops at the end of 2008. The three most prolific TC-tornado seasons in the entire TCTOR dataset—2004, 2005 and 2008—fall within the subset analyzed in this study.

The number of tornado events examined (664) actually is less than that contained in the 2003-2008 temporal subset of TCTOR (762), because of the spatial/temporal gridding and filtering technique detailed in Smith et al. (2010, this volume). For this purpose, a tornado event (hereafter "tornado") constitutes the tornado report that was assigned the maximum F Scale rating in each 40 km grid square, for the analysis hour containing the report (e.g., a 2055 UTC tornado is assigned a 2000 UTC environment). These spatial and temporal bounds were chosen for comparison and analyses of environmental parameters with convective modes associated specifically with TC tornadoes, similar to analyses performed for a larger dataset of tornadic and nontornadic significant severe storm environments by Thompson et al. (2010, this volume).

The environmental-analysis time frame began in 2003, using the same database as Schneider and Dean (2008). In short, an objectively analyzed field of surface observations, using hourly Rapid Update Cycle (RUC, after Benjamin et al. 2004) analysis as a first guess, is combined with 40-km gridded RUC model data aloft in an identical manner to that used in creating the SPC hourly Mesoscale Analyses (Bothwell et al. 2002). This provides hourly three-dimensional fields from which numerous parameters

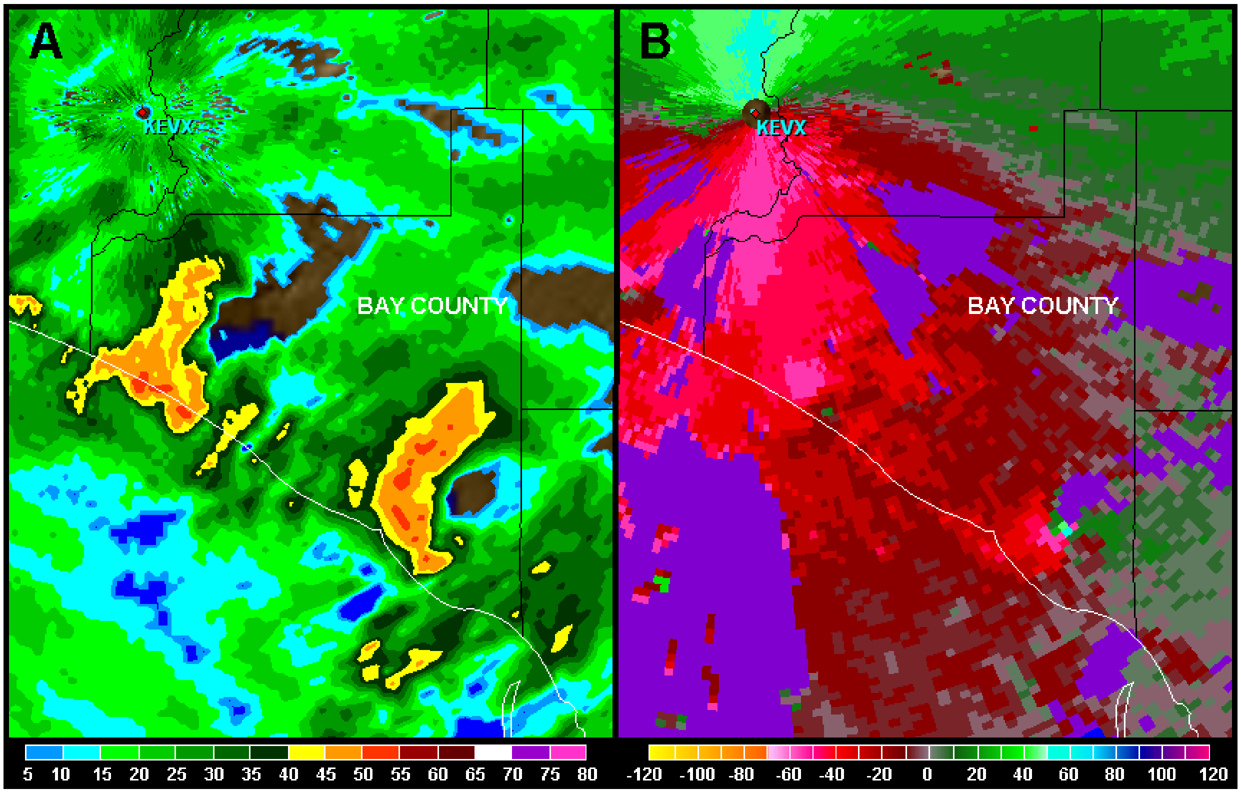

Figure 1. Radar imagery at 0.5° beam tilt from Eglin Air Force Base (KEVX) WSR-88D, 0352 UTC 15 September 2004, of a discrete, tornadic supercell in southeastern Bay County FL: **a)** reflectivity, scale at bottom in dBZ; **b)** storm-relative motion, scale at bottom in kt. Two associated, F1-rated tornadoes, 3 min apart, killed two people and injured eight others. North is up; mesocyclone was located ~65 km southeast of KEVX at sampling time. This was Storm A mapped in Fig. 1 of Baker et al. 2009.

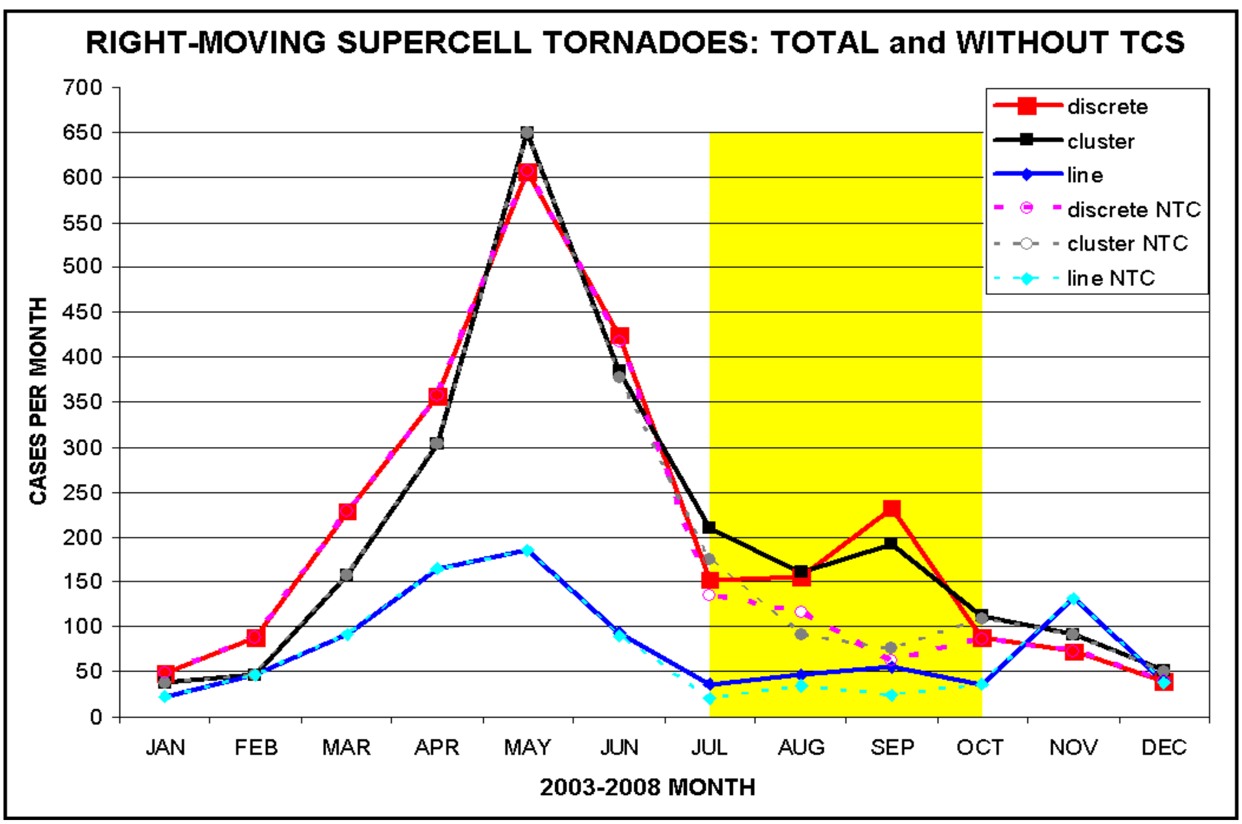

Figure 2. Monthly graph of tornadic supercells, cumulatively for 2003-2008, in three modes: discrete, embedded in a cluster, and embedded in a line. Solid curves denote all supercells (from Smith et al. 2010); dashed curves are non tropical-cyclone (NTC) events. Yellow shading brackets the period during which TC tornadoes occurred.

can be derived that are common to sounding analysis of the moist-convective environment.

Radar data for this era were interrogated as described in Smith et al. (2010, this volume), in order to assign a convective mode to each tornadic event. In the absence of consistent, unambiguous and reproducible prior definitions, modal designation was necessarily subjective, but followed guidelines. Ten tornadic storm modes appeared in TCs, with the name and sample size of each event in bold:

- **Discrete right-moving supercell (RM):** Cells accompanied by deep, persistent mesocyclones[2] generally characterized by ≥20 kt (10 m s^{-1})rotational velocity at most ranges, and distinct from surrounding echoes at ≥35 dBZ; **238 events (36%)**.
- **Quasi-linear convective system (QLCS):** Contains 35 dBZ reflectivities for a length ≥100 km at ≥3/1 aspect ratio; non-supercellular; **16 events (2%)**.
- **Cluster:** As with QLCS, but with an aspect ratio <3/1; non-supercellular. Included disorganized and/or amorphous reflectivity patterns; **24 events (4%)**.
- **Supercell in line:** Meets velocity and continuity guidelines for supercells but is embedded in a QLCS; **64 events (10%)**.
- **Supercell in cluster:** Meets supercell velocity and continuity guidelines but is embedded in a cluster; **232 events (35%)**.
- **Discrete nonsupercell:** Lacks horizontal rotation, or rotational characteristics are too weak and transient to classify even as "marginal" (below); **12 events (2%)**.
- **Marginal discrete supercell:** Shows at least brief, weak rotational characteristics but not fulfilling supercellular guidelines; **17 events (3%)**.
- **Marginal supercell in cluster**; **29 events (4%)**.
- **Marginal supercell in line**; **7 events (1%)**.
- **Cell in cluster**, non-supercellular; **25 events (4%)**.

The three unambiguously supercellular categories (discrete, in-line, in-cluster) were analyzed separately and as a subgroup for this study. Within the supercellular categories, mesocyclones further were classified as weak, moderate or strong, following a subjective 3-bin ranking of range-dependent horizontal rotational velocity guidelines offered by Stumpf et al. (1998) and related nomograms (e.g., Andra 1997). A radar example of the discrete, tornadic TC supercell category is shown in Fig. 1; others are exhibited in the conference poster.

Nonsupercell TC (NSTC) tornadoes likewise were examined both in terms of their mode classification (e.g., clustered, linear, marginal-supercell) and as a second subgroup. Nonsupercell tornadoes have been studied formally for over two decades (e.g., Wakimoto and Wilson 1989), but not including those within TCs. Continuous spiral bands or segments of bands are treated as QLCSs if they meet the above criteria. Although tornadic bow echoes were a mode investigated in Smith et al. (2010), and have been documented in TCs in years outside this study (e.g., the "Iron Bend" storm documented by Spratt et al. 1997), no bow echoes were identified in association with TC tornadoes in our sample.

3. ANALYSES and PRELIMINARY FINDINGS

a. Error sources in tornado data

As with the national tornado database, close examination of TCTOR reports revealed a small number of apparent errors in time and/or location. By far, the primary source of such errors was the time of reports compared to radar signatures (or lack thereof). Where the location appeared accurate, but the apparently responsible echo (e.g., cell or mesocyclone) passed over the location earlier or later than the tornado report time, we adjusted the time to match the echo passage, as in Smith et al. (2010). This was done in 43 TC cases (6.5% of total TC events), with an average absolute error of 46 min, and extremes of 2 and 210 min. The most common time-error integer was 60 min, occurring in 14 cases—i. e., 33% of all documented time errors were displaced by precisely one hour. This indicates incorrect entering of an adjacent time zone, or erroneous transposition of daylight with standard time, in report logging. In a few instances, it was not obvious which cell or echo among multiple possibilities was responsible for the report, and a guess had to be made. Three cases required a change in a listing for report location (county and/or latitude/longitude entry), and one for UTC date. A few other cases had radar presentations so nebulous or uncertain that a time or place adjustment could not be made. Those time and/or location errors that were obvious and can be adjusted with confidence will be submitted for revision in the nationwide ONETOR and TCTOR databases (see Edwards 2010 for more details on the TCTOR record).

Other possible but not quantifiable sources for error include:

- Reports of tornadoes that actually were other phenomena, e.g. gusts in gradient flow, wet microbursts, or damaging horizontal-shear vortices in the eyewall's inner rim occurring without documented vertical continuity into the convective plume;
- Tornadoes that were sufficiently weak to go unreported amidst ambient hurricane damage; and
- Tornadoes that occurred in areas too remote or unpopulated to be witnessed or to cause noticeable damage.

b. General results

Compared with non-TC findings of Smith et al. (2010, this volume) and Thompson et al. (2010, this volume), TCs heavily influenced the nationwide totals of tornadic supercells during the peak months of the Atlantic hurricane season: August and September,

[2] Left-moving (anticyclonic) supercells, a category parsed for midlatitude systems, did not appear in our TC data.

with lesser relative contributions along the fringes in July and October (Fig. 2). Tornadic supercells in TCs collectively accounted for 66% of all tornadic supercells nationwide during the month of September. This indicates that the predominant source of supercell tornadoes, in an otherwise reduced interval from late summer into early autumn, is TCs. The grid-filtered number of TC tornado events in this 2003-2008 dataset (534) was about 10% of the number of grid-filtered non-TC tornado events (5313—Smith et al. 2010), or approximately 9% of the total tally nationwide.

c. Storm-mode analyses

Of the storms responsible for TC tornadoes, 524 (79%) were unambiguously supercellular, 53 (8%) marginally supercellular, and the remaining 87 (13%) nonsupercellular. Among just the tornadic TC supercells, mesocyclone strength was classified as strong with 76 (14%), moderate with 129 (25%) and weak with 329 (63%). By contrast, weak (strong) mesocyclones were far more (less) common with TC than non-TC events. The values for non-TC tornadic supercells from the Thompson et al. (2010) dataset were 2178 (41%) strong, 1383 (26%) moderate, and 1751 (33%) weak.

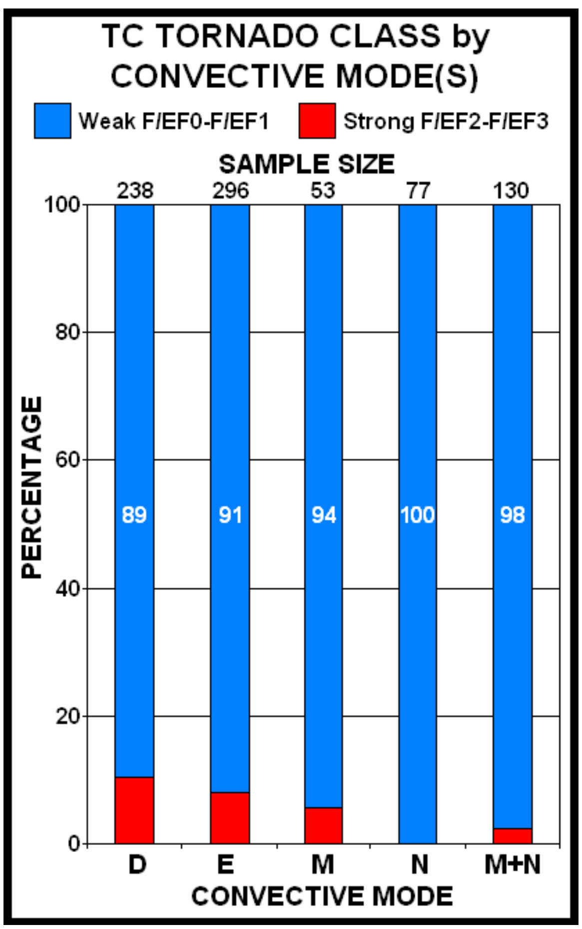

Figure 3. Percentages of weak and strong tornadoes per modal bin, as labeled: D is discrete supercell, E is embedded supercell, M is marginal (sub-criteria) supercell, N is nonsupercell, and M+N combines all modes not meeting supercell criteria. Percentages of weak tornadoes are given in white, on bars. Sample size for each mode is given atop the graph.

Hypothetically, strong mesocyclones should be more common in discrete than non-discrete TC supercells, given a lack of inflow disruption, outflow recycling, and merging processes that are more likely to occur with storms embedded in lines and clusters. Given the similar sample sizes of discrete versus non-discrete (embedded in clusters and lines) supercell modes, the predominance of various mesocyclone strengths can be compared readily. Weak mesocyclones tended to be slightly more common in non-discrete TC supercells (66%) compared to discrete (56%), while strong mesocyclones somewhat favored discrete supercell storms (17%) versus 12% for non discrete.

Compared to embedded midlatitude supercells, it is reasonable to consider if the lower likelihood of ingestion of adjacent cold outflow (and its attendant weakening of stronger mesocyclones) in a TC supercell is offset by the general tendency for weaker buoyancy. The answer is ambiguous, based solely on our results. In non-TC situations, non-discrete supercells also carried a slightly higher percentage of weak mesocyclones (34%) than discrete supercells (31%).

Table 1. Fraction of 2003-2008 tornado damage rating occurrence for TCs and non-TC supercells.

Damage (F/EF)	TC	Non-TC
≥4	.00	.01
3	.01	.04
2	.09	.11
1	.33	.30
0	.58	.55

Another hypothesis is that TC supercells with strong mesocyclones, and especially discrete supercells, should produce a higher (lower) rate of strongly (weakly) rated tornadoes[3]. Only 53 (8%) of all TC tornadoes overall were rated strong (EF/F2 or EF/F3). Strong tornadoes were far more common with full supercells than marginal or nonsupercells (Fig. 3), and constituted a slightly higher share of tornadoes with discrete versus non-discrete supercells. No nonsupercellular tornadoes exceeded

[3] Damage ratings, especially in the F Scale era, are not necessarily direct functions of actual tornado intensity (Doswell and Burgess 1988), but instead, mere *indicators*, and even then, only if a suitably robust target is hit to represent max tornado winds. Given the small, brief nature of TC tornadoes in general, and their occasional spatial juxtaposition with hurricane damage, undersampling issues raised by Doswell and Burgess *may* apply here. No violent (F4-F5) tornadoes occurred in the dataset. Further, since maximum F Scale rating was the grid-box filter, the actual ratio of weak tornadoes is higher than in tornado events presented here.

F/EF1. Comparisons of damage ratings with midlatitude, non-tropical tornadic supercells (Table 1) indicate that significant (≥F/EF2) tornadoes are somewhat more common with non-TC supercells, but not as much as the aforementioned difference in mesocyclone strength suggests. This indicates an influence from the characteristically smaller scale of TC supercells in mesocyclone assessment, as well as from environmental characteristics (Section 3d). Sample sizes for damage rating classes *within* each of the smaller mode bins (e.g., each form of marginal supercell or of strict nonsupercell) were too small to draw meaningful conclusions.

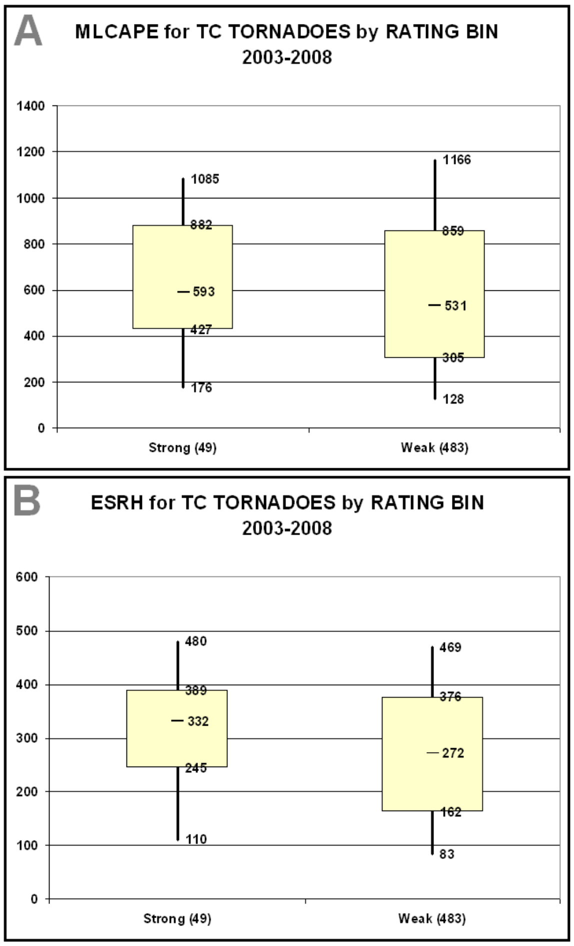

Figure 4. Box-and-whiskers diagrams, where percentile extents and corresponding values represent $25^{th-}75^{th}$ for boxes, 10^{th}-90^{th} for whiskers, and $50^{t,h}$ at the inbox bar, for **a)** MLCAPE and **b)** effective SRH. Abscissa labels include sample size in parentheses; ordinate represents parameter magnitude.

d. Environmental results

Using observed soundings, McCaul (1991) showed juxtaposition of high storm-relative helicity (SRH) and at least weak CAPE[4] in TC tornado environments, with buoyancy increasing outward from the center. Additional derived parameters such as most unstable (MU) parcel CAPE, lowest 100-hPa mean-mixed layer (ML) CAPE and effective (Thompson et al. 2007) storm-relative helicity (ESRH) were analyzed in TC tornado environments, along with several other shear-based and kinematic parameters. Environmental data were available for up to 532 of the 534 fully supercellular TC tornado events.

Parameter distributions for weak (F/EF0-1) and strong (F/EF2-3) tornado environments in TCs show some discrimination ability between categories, but with considerable overlap across all variables tested. Figure 4 provides two examples for MLCAPE and ESRH, where values for the strong tornadoes tended to be larger, especially through the 75th percentile. Some compression of the ends (whiskers) of the distributions also was evident in most variables and parameters for strong TC tornadoes, but it is unknown if this is a function of actual meteorological distribution or the sample size being an order of magnitude smaller for strong tornadoes. Similar relative patterns appeared in numerous other parameters, both kinematic and thermodynamic, as well as in bulk indices derived from them, i.e., supercell composite parameter (SCP) and significant tornado parameter (STP, not shown, after Thompson et al. 2003)[5]. Such overlap in distributions also may be a function partly of the considerable spatial overlap between weak and strong tornadoes in the outer envelope of many TCs (where the majority of both classes tends to occur), and of the relatively coarse 40 km grid length of the mesoscale analysis that may not resolve storm-scale differences or structures within a TC (e.g., inter-band slots of clearing) that may play a role in supporting more robust supercells and tornadoes.

Environmental parameters previously shown to be robust in midlatitude, supercellular tornado environments were analyzed for the TC cases and compared with up to 5285 of the 5313 non-TC (midlatitude) tornadoes from Thompson et al. (2010) that were associated with right-moving supercells. Several of these results are shown in Fig. 5. In general, thermodynamic variables (e.g., Fig. 5a) differentiated the tropical and nontropical tornado environments better than the kinematic ones. Shear-based parameters for TC events did show slightly tighter distributions on the margins (exemplified by ESRH in Fig. 5b), but otherwise were similar to their non-TC counterparts. The primary difference between midlatitude and TC tornado situations in this study centers on moisture, as indicated by total precipitable water (PW, Fig. 5c). The 10th percentile of the PW distribution for TCs matched the 90th for nontropical tornadoes, with the middle 50% well-separated. This reflects the specialized thermodynamic environment of TCs, which are very

[4] McCaul's (1991) SRH used an assumed 0-6 km AGL mean wind for storm motion; whereas ours uses the Bunkers et al. (2002) algorithm. We also computed CAPE using both a 100 hPa AGL mean mixed-layer (ML) parcel and the most unstable (MU) parcel in the lowest 300 hPa.

[5] Baker et al. (2009) showed some promise with observationally derived SCP and STP in the landfall phase of TC Ivan (2004), which was one motivator for testing them across numerous TCs here.

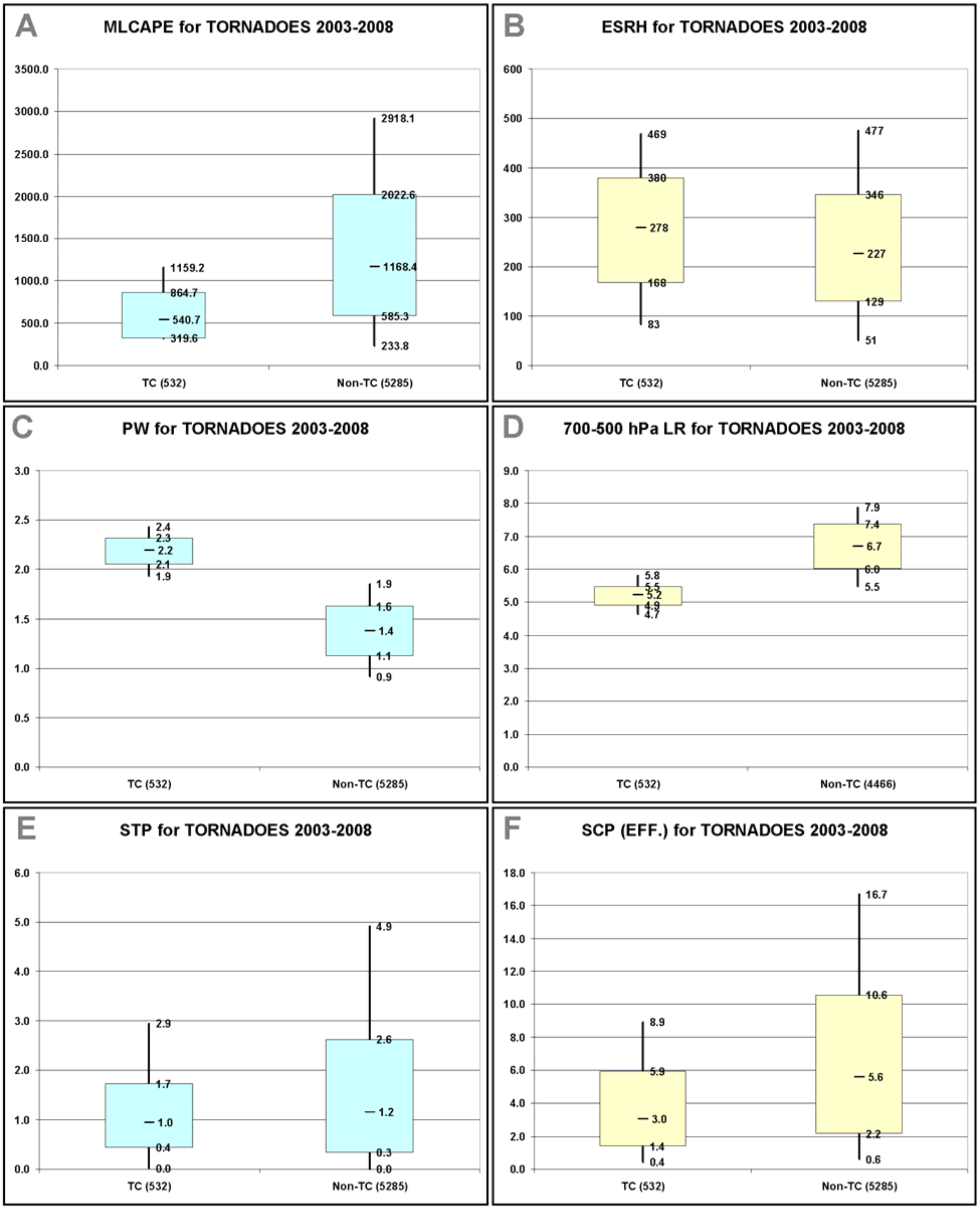

Figure 5. As in Fig. 4, but for the following parameters in TC and non-TC tornadic supercell datasets: **a)** MLCAPE (J kg^{-1}), **b)** effective SRH (m^2 s^{-2}), **c)** precipitable water (in), **d)** 700-500 hPa lapse rate (ºC km^{-1}), e) significant tornado parameter (fixed-layer), and f) supercell composite parameter (effective layer).

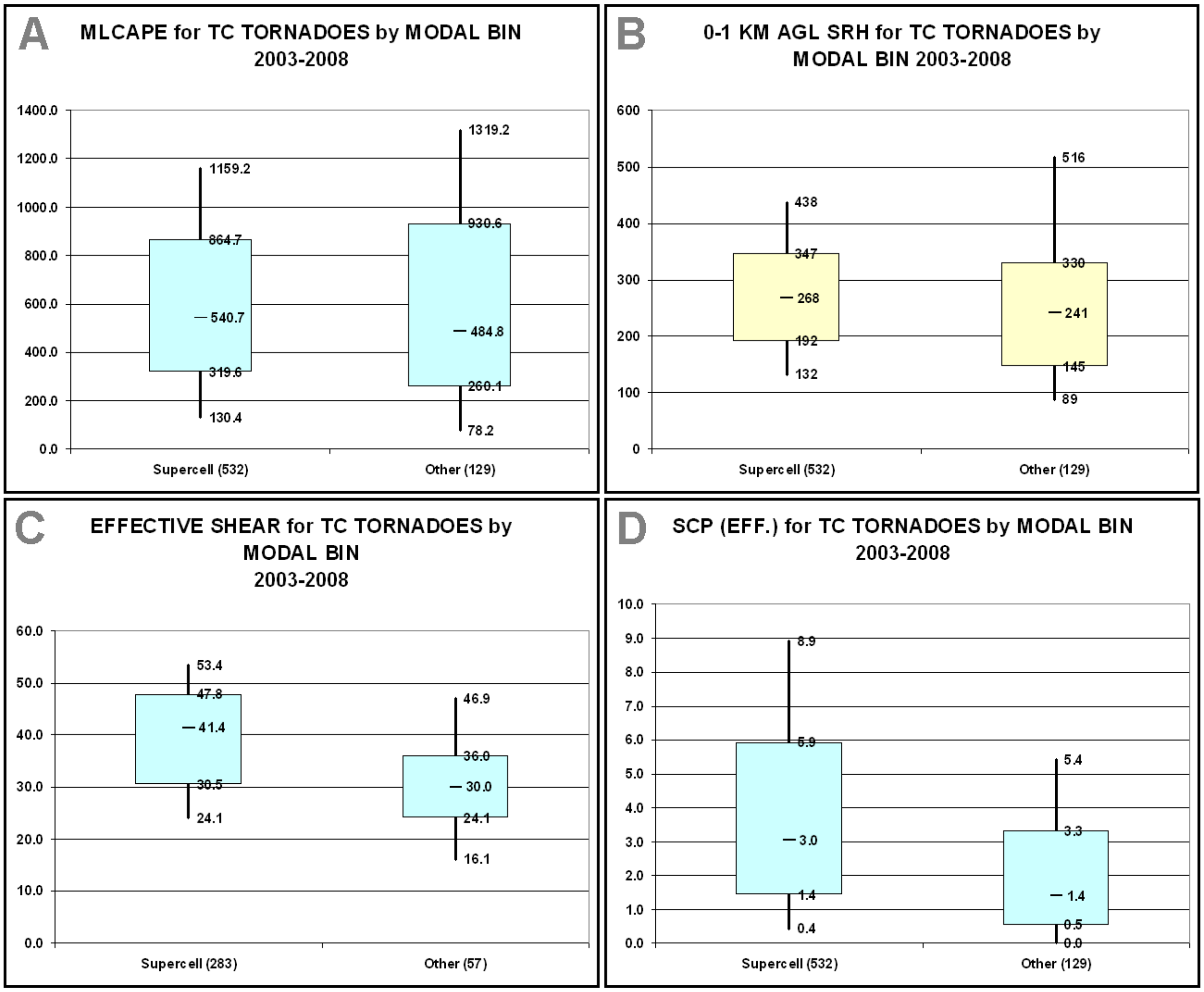

Figure 6. As in Fig. 4, but for the following parameters in TC supercells and in the remainder of TC tornadic storms ("other"): **a)** MLCAPE (J kg^{-1}), **b)** 0-1 km AGL SRH (m^2 s^{-2}), **c)** effective shear magnitude (bulk wind difference, kt), **d)** supercell composite parameter..

rich in deep-tropospheric moisture. As such, TC supercell environments were decidedly weaker in middle-level lapse rates (e.g., Fig. 5d), which contributed to a weaker overall and more compressed distribution of buoyancy (e.g., Fig. 5a). This extended to parameters such as SCP (Fig. 5d) that incorporate CAPE as part of their formulation.

In principle, as in midlatitudes, TC tornadic supercell environments should feature more favorable values of various shear measures than in other tornadic convective modes, but with lower values of buoyancy (Thompson et al. 2010). We compared environmental parameters and bulk indices for those two basic categories in order to maximize sample sizes, by including the "marginal" storms (failing to completely meet supercell criteria) with nonsupercells in the "other" bin. Most kinematic and thermodynamic variables, along with the STP, exhibited little if any meaningful discrimination between supercells and the nonsupercell modes (e.g., Fig. 6a-b). Exceptions (Fig. 6c-d) were noted in the distributions of the effective shear magnitude (bulk wind difference, after Thompson et al. 2007), and in turn, the effective layer version of the SCP, given the latter's dependence on effective shear. A relatively high value of SCP, therefore, may be of some value in diagnosing a potential TC supercell tornado situation, given other favorable features analyzed within the system (i.e., presence of boundaries).distinction regarding buoyancy (Thompson et al. 2010). We compared environmental parameters and bulk indices for those two basic categories in order to maximize sample sizes, including the "marginal" storms (failing to meet supercell criteria) with nonsupercells in the "other" bin. Most kinematic and thermodynamic variables, along with the STP, exhibited little if any meaningful distinction between supercells and the rest (e.g., Fig. 6a-b). The exceptions (Fig. 6c-d) were rooted in the high end of the distribution of the effective shear magnitude (a.k.a. bulk wind difference, after Thompson et al. 2007), and in turn, the effective version of the SCP, given the latter's dependence on the former. A very high SCP, therefore, may be of at some limited value in diagnosing a supercell tornado situation in a TC, given other favorable features analyzed within the system (i.e., boundaries).

4. DISCUSSION

Examination of associated storm modes indicates that TC tornadoes are far more common with supercells, with a steadily greater potential for stronger (EF1-EF2) events as convective organization goes from nonsupercell to discrete supercell. However, mesoscale environments of strong and weak tornadoes in TCs are often very similar based on the results of this study. The great relative abundance of moisture in the TC setting, far more so than kinematic measures, seems to account for most of the difference between TC and midlatitude tornado environments.

While supercell tornadoes form the bulk of TC tornado events, some TC tornadoes are not spawned by supercells. Consistently successful diagnostic foci for NSTC tornadoes likely are elusive on currently available gridscales of automated diagnoses, reinforcing the need for frequent, often manual analysis of the TC environment to assess the presence and character of subtle baroclinic and kinematic boundaries inside the cyclone envelope (e.g., Edwards and Pietrycha 2006). Even then, the explicit predictability of NSTC tornadoes could stay very poor for a long time, given:

- The relatively sparse sample size of documented NSTC tornadoes,
- The lack of obvious dissimilarities in mesoscale environments between TC tornadoes from supercell and nonsupercell origins,
- Their typically weak and short-lived nature,
- Virtually nonexistent direct documentation (i.e., photos, video, mobile radar sampling) of NSTC tornadoes, including supposed eyewall tornadoes, rendering their true frequency highly uncertain, and
- The lack of real-time, finescale observational data that can help forecasters to diagnose, with suitable precision, any small-scale (i.e., 10^0-10^1 km and min in space and time respectively) patterns of convergence, instability and vorticity.

At this time, it is not known the extent to which nonsupercell environments are similar those of midlatitude nonsupercell tornadoes, such as in concentrations of vertical vorticity and convergence (e.g., Caruso and Davies 2005), or if other, altogether different process are at work.

As noted in Section 1, prior studies have found important influences of poorly resolved, small scale processes on TC tornado potential. Clearly, considerable further study is needed for better documentation of the near-storm tornado environment in TCs, both supercellular and not, for better differentiation of tornadic versus nontornadic regimes in the operational setting. Given the gridscales employed herein, near storm-scale processes, such as in situ cold pool generation, likely will not be known in an operational setting except through highly fortuitous dropsonde deployments in the near-offshore area for supercells approaching the coast. The chances of such sampling being performed regularly and reaching the forecaster in time to influence the warning decision appear quite minuscule for now. Still, the relative position of a storm with respect to the band within which it is embedded may provide conceptual clues as to its potential for interaction with, and movement along, possible small scale baroclinic boundaries generated from within the convective band and aligned parallel to its axis, especially near the inner edge of the band where cyclonic vorticity and convergence also are maximized (Powell 1990a).

From the framework of numerical guidance and research, some of these issues may be investigated through higher-resolution TC modeling. Future plans for the Hurricane Weather Research and Forecasting model (HWRF) include 3-km and/or 1-km moving inner nests (Zhang et al. 2010), which conceivably could resolve some tornadic storms and their immediate environments within the TC envelope. With such modeling on the way, assessment of its capabilities to diagnose both supercell and nonsupercell tornado regimes in TCs should be performed.

Better physical and conceptual understanding of the NSTC tornado regime and process clearly is needed to handle the forecast challenge, especially in differentiating tornadic from nontornadic convection in similar regimes, away from analytically resolvable foci of baroclinic and kinematic boundaries (Edwards and Pietrycha 2006). One way to attack these problems in an observational sense may be a devoted field program at least loosely analogous to VORTEX but re-strategized for the challenging logistics of the TC supercell environment. In particular, a large sample size of mobile soundings and dropsondes in the *inland* TC supercell environment could provide observational verification of environmental fields such as those provided by various operational model-analysis grids, the relatively coarse-resolution gridded fields examined herein, and the related SPC mesoanalysis package (Bothwell et al. 2002).

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