# REVERSIBLE CAPE IN TROPICAL CYCLONE TORNADO REGIMES

Roger Edwards[1] and Richard L. Thompson
*Storm Prediction Center, Norman, OK*

## 1. BACKGROUND

Tropical cyclone (TC) tornadoes produced by supercells occur in characteristic thermodynamic environments of

- rich low-level moisture,
- high precipitable water and
- commonly (but not always) enhancement to CAPE by diurnal, diabatic surface heating.

These factors juxtapose with strong low-level shear magnitudes, high storm-relative helicity and enlarged hodographs to optimize supercellular tornado potential in TCs (e.g., McCaul 1991; Edwards et al. 2012a), especially in areas located north through south-southeast of center (e.g., Edwards 2012 and climatologies cited therein). Nonsupercellular tornadoes also occur in TCs; however, they tend to be less damaging, shorter lived, and often embedded within otherwise supercell-favorable environments (Edwards et al. 2012b).

Weak low- to mid-level lapse rates, only slightly greater than moist adiabatic in magnitude, typify TC tornado settings (Edwards et al. 2012a). As such, only minor adjustments to the boundary-layer conditions of a sounding in most TC environments can result in large changes in CAPE magnitude and depth (e.g., Fig. 1). This makes accurate and physically meaningful representations of such soundings crucial to diagnosing potential TC tornado threats in operational forecasting. Currently, common sounding-interrogation software such as the National-center version of the Sounding and Hodograph Analysis and Research Program (NSHARP; Hart and Korotky 1991), Bufkit (NWS/Warning Decision Training Branch 2014), and the Rawinsonde Observation (RAOB; Weather Graphics 2014) program, use pseudoadiabatic parcel theory to compute CAPE, typically with the virtual temperature correction (Doswell and Rasmussen 1994) applied by default.

Roff and Yano (2002) offer a detailed tutorial on the difference in CAPE between traditional, pseudoadiabatic parcel theory and that obtained via reversible processes [i.e., reversible CAPE (RCAPE)]. In short, the more common method for determining CAPE assumes that liquid water vanishes instantaneously upon condensation. The process thus is irreversible upon adiabatic descent. By contrast, RCAPE assumes the opposite extreme—*no* loss of liquid water—in turn compelling a greater parcel density related to water loading.

CAPE may be expressed as follows:

$$\mathrm{CAPE} = g \int_0^{\mathrm{LNB}} \frac{T_{\mathrm{vp}} - T_{\mathrm{va}}}{T_{\mathrm{va}}}\, \mathrm{d}z \qquad (1)$$

where $g$ is gravitational acceleration, LNB is the level of neutral buoyancy (highest vertical level at which buoyancy changes from positive to negative), $T_{vp}$ is the parcel virtual temperature (shaded red for ready comparison below), and $T_{va}$ is ambient virtual temperature. Regardless of parcel characteristics,

$$T_{\mathrm{va}} = T_{\mathrm{a}} \frac{1 + q/0.622}{1 + q} \qquad (2)$$

where $T_a$ is ambient temperature and q is the mixing ratio. However, CAPE and RCAPE differ in their treatment of parcel virtual temperature $T_{vp}$, where either version can be plugged into Eq. (1). For pseudoadiabatic CAPE (hereafter, simply CAPE),

$$T_{\mathrm{vp_p}} = T_{\mathrm{p}} \frac{1 + q^*(T_{\mathrm{p}})/0.622}{1 + q^*(T_{\mathrm{p}})} \qquad (3)$$

where $T_{vpp}$ is pseudoadiabatic virtual temperature, $T_p$ is parcel temperature and q* is parcel saturation mixing ratio. All condensate vanishes as soon as it appears. By contrast, RCAPE uses

$$T_{\mathrm{vp_r}} = T_{\mathrm{p}} \frac{1 + q^*(T_{\mathrm{p}})/0.622}{1 + q_{\mathrm{T}}} \qquad (4)$$

where r stands for reversible and $q_T$ is the parcel water content.

As manifestations of parcel theory, neither CAPE nor RCAPE considers entrainment, which should yield an intermediate result between the binary extremes of CAPE's full removal and RCAPE's complete retention of parcel condensate. Entrainment can be much more important to reducing CAPE than condensate loading—up to 4 times as much in tropical convective downdrafts outside TCs, based on 13 aircraft-based measurements (Wei et al. 1998). Estimations of entrainment are not attempted in our analyses at this time, however, given that:

- most operational forecasting software does not include entrainment estimations yet;

[1] *Corresponding author address:* Roger Edwards, Storm Prediction Center, National Weather Center, 120 Boren Blvd #2300, Norman, OK 73072; E-mail: roger.edwards@noaa.gov

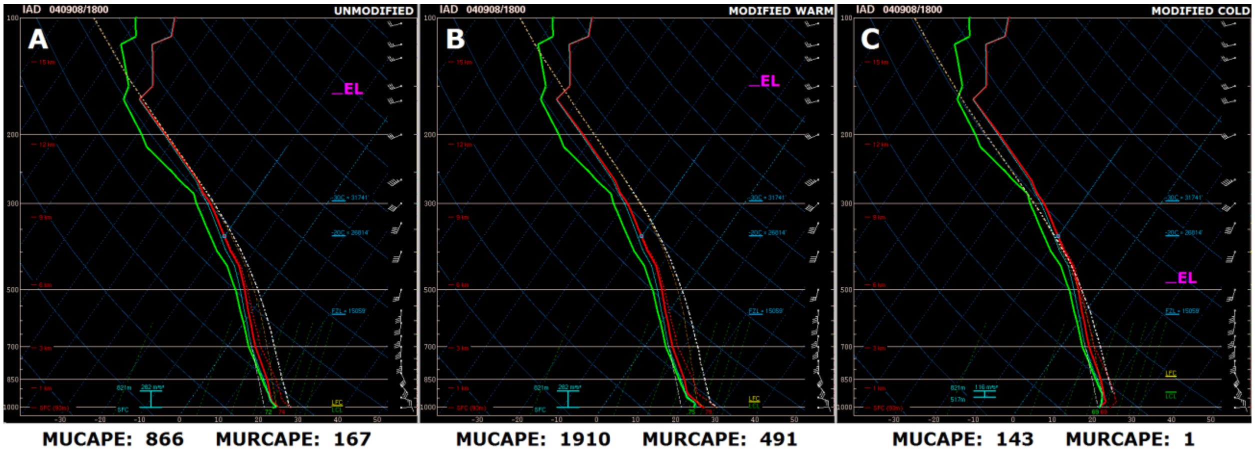


Figure 1: Skew *T*–log*p* diagrams of the Dulles, VA (IAD) sounding, 1800 UTC 8 September 2004—in proximity (as defined in the text) to four tornadoes produced by Tropical Depression Frances. Sounding is: a) unmodified, as observed; b) with surface temperature and dewpoint increased 5°F (2.7°C) and 3°F (1.7°C) respectively, using a thermally dry-adiabatic, constant-mixing-ratio assumption for the mixed layer; c) with surface temperature and dewpoint likewise cooled 5°F (2.7°C) and 3F (1.7°C) respectively. Most-unstable (MU) parcel CAPE and RCAPE (J kg$^{-1}$) values shown beneath each diagram. Parcel trace (dotted white line) and virtual temperature correction (dotted red line) shown for MUCAPE. Equilibrium level (EL), same as LNB, is highlighted in magenta. Cyan bar represents effective inflow layer (Thompson et al. 2007), which is surface-based for (a) and (b). *Click image to enlarge.*

- the various assumptions of entrainment used in midlatitude tornadic supercell settings may not be as valid for the much greater precipitable water (Edwards et al. 2012a), higher humidity, and implied lower evaporational constraints on deep TC convection; and
- CAPE and RCAPE without entrainment variables are more readily compared for the purpose of this preliminary investigation.

The RCAPE framework also assumes no evaporation; therefore, as conditions progressively favor less evaporation, RCAPE should become more physically valid. In the TC environment, liquid water is extremely abundant, and the high ambient moisture levels throughout the troposphere (e.g., Fig. 1 and comparisons of environmental precipitable-water estimates in Edwards et al. 2012a) should limit, but not eliminate, evaporation compared to drier, more baroclinic, midlatitude supercell settings. Based on those concepts, we suggest that RCAPE should be the *more situationally representative manifestation of parcel theory* than CAPE in a TC, to the extent that *any* parcel-theory-based measure of buoyant energy can succeed.

Unlike prior studies, this work applies RCAPE (and comparisons with CAPE) to balloon soundings in the TC environment, specifically with proximal tornadoes. Section 2 defines that proximity and documents our quality-control methods, while section 3 offers results of CAPE and RCAPE analyses. Conclusions and discussion follow in section 4.

## 2. DATA

To examine RCAPE and CAPE, we used observed proximity balloon soundings available for TC tornado environments during the 1995–2013 period of the Storm Prediction Center (SPC) TC tornado (TCTOR; Edwards 2010) dataset. The TCTOR reports were used since they constitute the most consistently constructed climatology with meteorologically based event-inclusion criteria. Convective modes for each tornado have not been examined yet to verify association with a supercell; however, environments of TC tornadoes of supercellular and nonsupercellular origins tend to overlap considerably (Edwards et al. 2012a,b).

CAPE and RCAPE each were calculated based on three parcels: 100-hPa mean "mixed layer" (ML), surface-based (SB) and most-unstable (MU). All sounding analyses herein use the virtual temperature correction (Doswell and Rasmussen 1994). All else equal, including parcel choice, the virtual temperature correction results in substantial increases in CAPE in warm, very moist environments with marginal conditionally unstable lapse rates through the troposphere. These conditions, of course, are very common in TCs (Edwards et al. 2012a); Fig. 1 offers an example.

### *a. Defining proximity specific to TC tornadoes*

What is the optimal definition of a proximity sounding, especially in the TC? Guidance is sparse and inconsistent in this area. In general terms, Brooks et al. (1994) discussed the variety of definitions theretofore used in the literature, and the difficulties related to choosing proximity-sounding criteria. However, their dataset did not include TC cases. The McCaul (1991) environmental climatology used arbitrary criteria for TC tornado reports within 800 km of TC center, followed by soundings taken within ±3 h and 185 km of a tornado report. That proximity definition matched Novlan and Gray (1974), who admitted that their proximity definition was "not very restrictive, but was necessary to obtain a sufficiently large data sample".

In evaluating proximity definitions, Potvin et al. (2010) discussed the balance in representativeness issues statistically among:

- Soundings launched so far from the tornadic supercell as to better represent the larger-scale setting than the near-storm environment (NSE). These maximize sample size but sacrifice representativeness for statistical robustness.
- Soundings launched so close to a tornadic cell as to be adversely affected by convective-feedback processes. These minimize sample size.
- An ideal "Goldilocks zone"—spatially and temporally positioned between the aforementioned extrema to offer the greatest probability of minimally convectively contaminated NSE sampling.

Potvin et al. (2010) statistically evaluated observed sounding parameters commonly used to diagnose environments of significant (rated EF2 and greater) tornadoes. The parameters included ML lifted condensation level (LCL), two measures each of vertical-shear magnitude, storm-relative helicity (SRH) and CAPE, as well as significant tornado (STP) and supercell composite (SCP) (Thompson et al. 2003), among others. In aggregate, an annulus of either 40–80 km at ±2 h or 0–40 km at 1–2 h from a tornado was determined to be most representative. However, the Potvin et al. dataset, developed originally by Craven and Brooks (2004), was overwhelmingly dominated by midlatitude (non-TC) supercells (J. Craven and C. Potvin 2014, personal communications).

Given the relatively small size of most TC supercells (e.g., McCaul and Weisman 1996; Spratt et al. 1997; Edwards et al. 2012a), and their occurrence in almost universally high-water-content, low-LCL environments (e.g., McCaul 1991; Edwards et al. 2012a) with weak low-level cold pools (McCaul and Weisman 1996), their thermodynamic influence on surroundings should be small compared to midlatitude supercells. As such, looser inner-proximity criteria may be warranted than Potvin et al. (2010) used for non-TC tornadoes. For that reason, and for sample-size considerations, we evaluated soundings launched 0–80 km from and nominally timed within ±2 h of TCTOR events. This compromise still is more restrictive than previous TC tornado sounding datasets cited above, and also more spatially and temporally proximal than the ±3-h, 111-km TC tornado sounding criteria used by Eastin and Self (2014) to assess supercell-motion predictors. When two soundings were in proximity of the same tornado, the closest sounding in time was used, unless the sounding needed to be expunged using the guidelines described below.

*b. Quality control*

Quality control was performed using subjective evaluation of soundings for bad or missing data. Soundings meeting aforementioned spatiotemporal criteria were culled from the analysis dataset if any of these applied:

- Thermodynamic profiles were truncated below the equilibrium level, rendering incomplete CAPE.
- Thermodynamic data were missing for a pressure depth >100 hPa amidst an otherwise complete sounding.
- The sounding was located in specified time and space thresholds, but near the circulation center and in a different quadrant (i.e., on the other side of the center), thereby placing it in a different kinematic environment and casting its overall representativeness into doubt.

Otherwise, obviously erroneous "spikes" in temperature or dew point, along with spurious autoconvective layers, were smoothed linearly in the vertical with data in adjoining layers until thermal lapse rates became dry adiabatic and dewpoint paths followed constant mixing ratio. Any moist absolutely unstable layers (MAUL; Bryan and Fritsch 2000) were smoothed manually until the absolutely unstable condition no longer was present—spurious MAULs were <25 hPa deep. Since kinematic parameters and dependent bulk indices (e.g., SCP, STP) were not evaluated in this phase of the study, soundings with bad or missing wind data were included in the analyses.

## 3. ANALYTIC METHODS AND RESULTS

Some soundings contained more than one tornado in their spatiotemporal proximity domains, and other tornadoes were sampled by more than one sounding (e.g., two soundings in the same place, both within temporal proximity criteria). As such, analyses were performed in two directions: with respect to the tornadoes and with respect to tornadic soundings. Parameters were computed using a Linux-based, batch-processing version of the SHARP software (Hart and Korotky 1991) with the capability of calculating RCAPE. There is considerable sample overlap across each perspective; but we present both here for completeness, and due to some differences in analytic approaches as documented below.

*a. Sounding-centric*

Sounding results are presented regardless of how many tornadoes occurred in the domain of each. As such, environments with multiple tornadoes in a small area are treated the same as those with singular events, in terms of intrinsic weighting. Quality control yielded an 88-sounding sample for these preliminary results. An average of two tornadoes occurred per sounding, with a median of one and a maximum of eight, representing 172 total tornadoes.

Distributions of each RCAPE and CAPE measure appear in Fig. 2. CAPE varies by up to two orders of magnitude from the $10^{th}$ to $90^{th}$ percentile of distribution for proximity soundings of TC tornadoes, similar to variability across the CAPE phase space for TC tornadoes documented in the McCaul (1991) observational dataset. RCAPE, even with smaller quartile size, whisker size and absolute median values per parcel than CAPE, varies by more than two orders of magnitude—because of the presence of

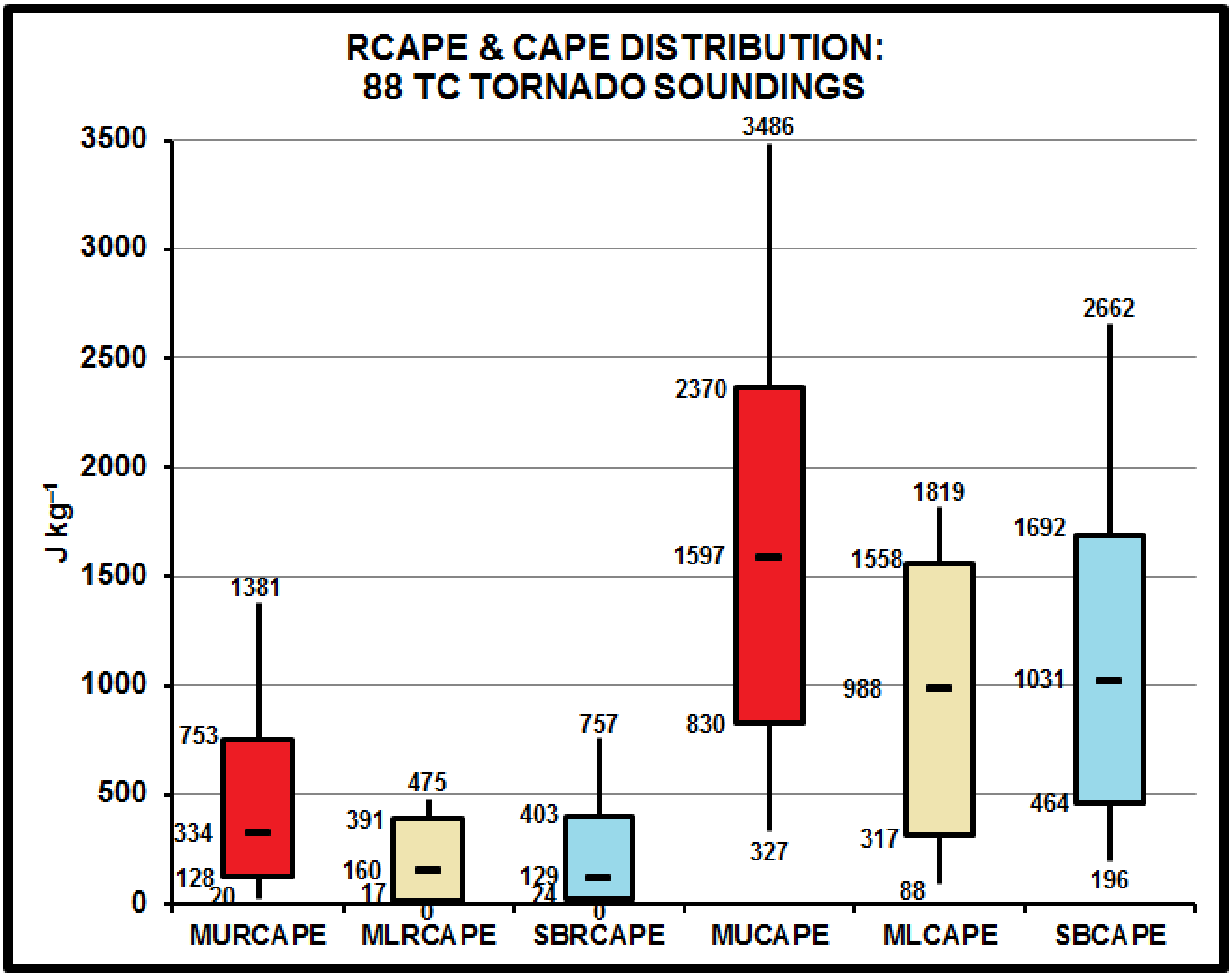


Figure 2: Box-and-whisker diagram of the distribution of each CAPE and RCAPE variable ($J\ kg^{-1}$) from the sounding-centric perspective, per section 4a. Boxes encompass $25^{th}$–$75^{th}$ percentiles, whiskers reach $10^{th}$ and $90^{th}$ percentiles, with black bar at median—all values labeled. Each parcel's box is colored the same from RCAPE to CAPE for ready cross-comparison.

zero and single-digit values[2]. Only five soundings (6%) yielded zeroes across all RCAPE measures. Median RCAPEs for MU, ML and SB parcels were 21%, 16% and 13% of CAPE medians, respectively. The inner quartiles of the CAPE and RCAPE distributions do not overlap for MU and SB parcels, and barely do for ML parcels, another manifestation of the substantial difference in RCAPE and CAPE in the TC tornado environment.

RCAPE was universally less than CAPE by virtue of its physical properties, consistent with the concept presented in Roff and Yano (2002). The magnitude of the *distribution of* those differences (Fig,. 3) is very similar regardless of parcel choice, even as the magnitude of the *differences themselves* is slightly smaller for ML parcels. The latter is consistent with the operationally known tendency for ML parcels to yield lower total values of CAPE than SB and MU parcels in environments where the effective inflow parcel (Thompson et al. 2007) is rooted at or near the surface—a condition pervasive in TC tornado situations (Edwards et al. 2012a). These results lend confidence to the validity of RCAPE specifically in the TC tornado setting; whereas RCAPE utility in TCs as a whole has been established (albeit with different lifted-parcel choices and software methods) by Molinari et al. (2012).

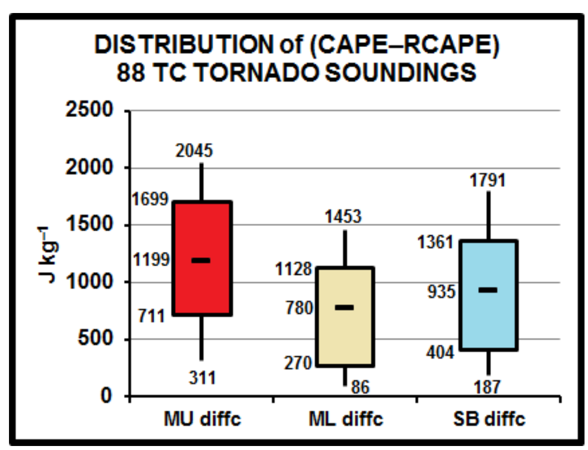


Figure 3: As in Fig. 2, but for the distribution of *differences between* RCAPE and CAPE (sounding-centric).

[2] Negative CAPE is not computed operationally at SPC and was not included in this study.

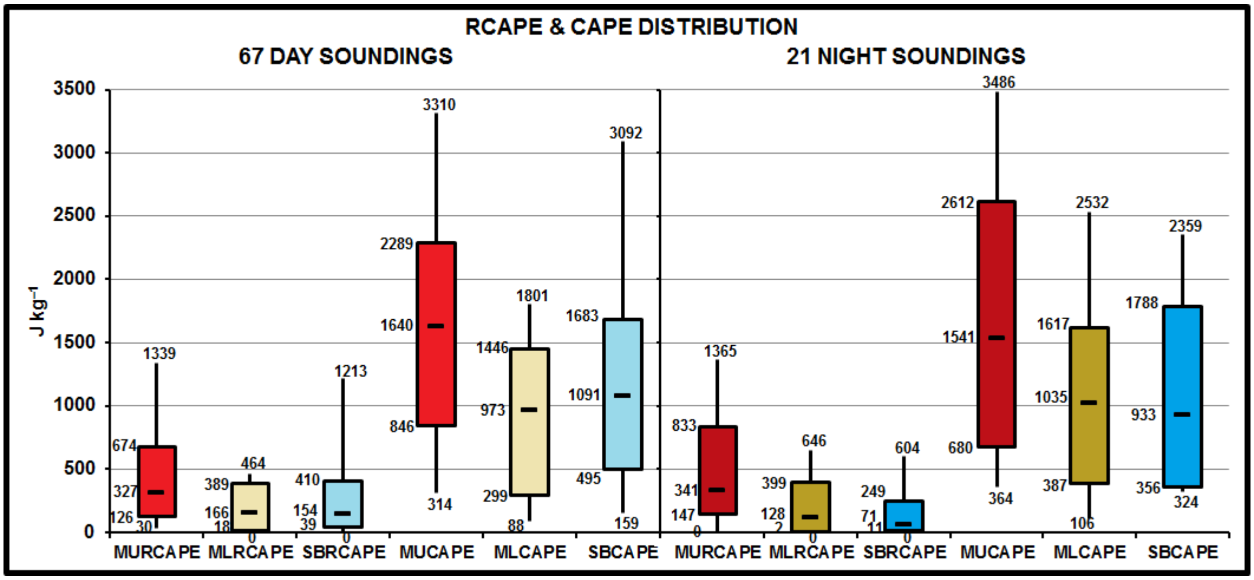


Figure 4: As in Fig. 2 but sorted by soundings taken day and night (as defined in the text). Corresponding color shading darkened in boxes representing nighttime sounding analyses. *Click image to enlarge.*

Soundings also were sorted by bins corresponding to nocturnal (0600 and 1200 UTC) and diurnal (1700, 1800, 1900, 2100, and 0000 UTC) influences. No other sounding times were found in proximity to tornadoes. These temporal bins correspond to time-lagged surface thermal effects of (lack of) insolation inland from the U.S. Gulf and Atlantic coasts. TC tornado distribution peaks during the day (Edwards 2012 and climatologies cited therein); for example, nighttime tornadoes (after 0000 UTC) comprise 29% of the 1995–2010 TCTOR total. Similarly, the 21 nocturnal soundings represent 24% of those analyzed herein. Median values for ML and SB parcels were larger during the day for RCAPE, and for MU and SB values of CAPE. However, those for MURCAPE and MLCAPE actually were higher at night. A small nocturnal sample size may be a factor in this seemingly counterintuitive finding. However, so may be yet-unknown physical factors. Considerable overlap existed between distributions of RCAPE during day and night, and CAPE as well (Fig. 4), with a small tendency for higher 10$^{th}$- and 90$^{th}$-percentile (whisker) values at night. The antihypothetical findings of slightly higher night values, by some measures, warrants larger sample-size analysis to better ascertain statistical robustness.

*b. Tornado-centric*

A total of 172 TC tornadoes fell within the 88 quality-controlled soundings; their locations relative to TC center (Fig. 5) spatially resemble those of the major TC tornado climatologies (Edwards 2012) in concentrating northeast through south-southeast of center. In this perspective, soundings can be included more than once, as each tornado is an independent data point and multiple tornadoes can share the same proximity sounding. Environments containing a relatively dense spatiotemporal concentration of tornadoes, therefore, are more heavily weighted in these results, as some of their soundings recur from one tornado to another. From an operational perspective, this can be argued as a valid approach due to the higher forecasting priority placed on tornado concentrations, and the environments supporting them, as opposed to isolated or marginal threats. Furthermore, in this framework, events can be analyzed for CAPE and RCAPE by tornado characteristics (e.g., damage rating). Again, a tornado within the radius of more than one valid sounding (still, after aforementioned quality control) was assigned the values of the sounding closest in time.

Consistent with climatological spatial distributions of CAPE from TC center (e.g., McCaul 1991) as a precedent, we hypothesized that all measures of both CAPE and RCAPE should increase outward in the tornado-proximity environment. Accordingly, the statistical distribution of each CAPE and RCAPE parcel was determined by radial annuli from center as follows (Figs. 5 and 6): inner-core region ($r$ <100 km, 38 tornadoes), middle (100–399 km, 75 tornadoes) and outer ($r$ ≥400 km, 59 tornadoes). While acknowledging that actual TC size can vary greatly, this should offer at least a coarse view of any modulation of buoyancy in the tornado-proximity environment, by distance from the cyclone center.

As expected, all measures of CAPE and RCAPE were maximized for tornadoes occurring in the outer annulus (i.e., >400 km from the center) of the TC circulation, albeit with overlap in the distributions. The distributions of CAPE and RCAPE each strongly overlapped between middle and inner portions of TCs, where clouds and precipitation tend to be most dense. However, the inner-core region appeared to be very slightly favored for CAPE and RCAPE at 75$^{th}$ and 90$^{th}$ percentile thersholds—an antihypothetical result, albeit amidst a weak signal overall.

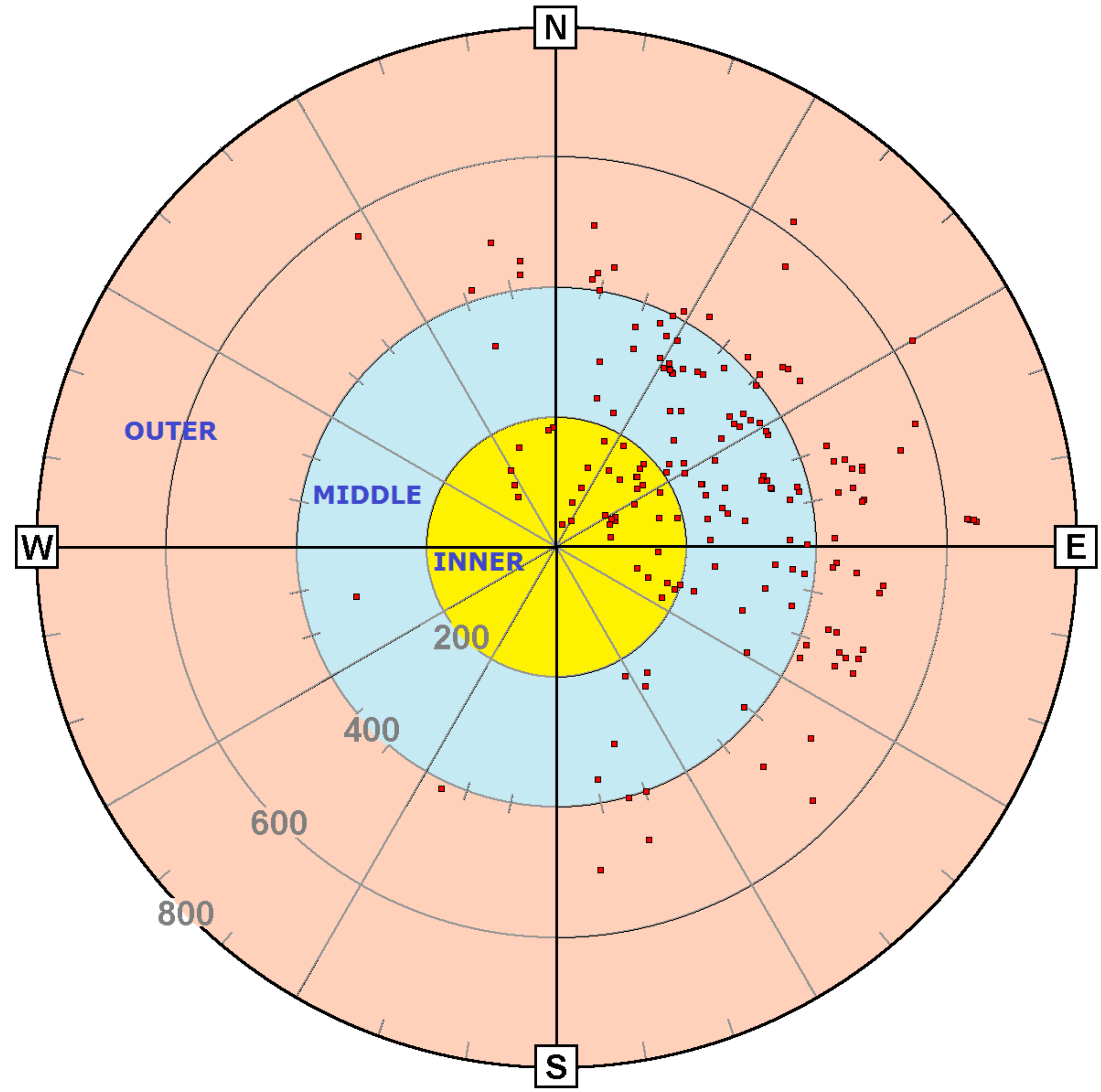


Figure 5: Polar plot of TC tornado start points (red) used herein with respect to true north (N) and radii from center (km), following the convention of Edwards (2010). Inner, middle and outer annuli also labeled.

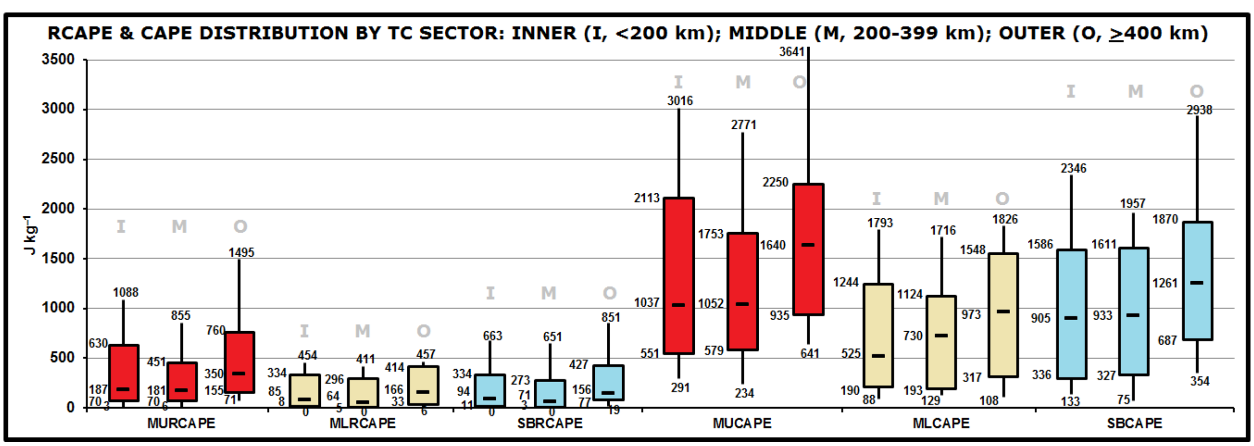


Figure 6: As in Fig. 2, but from the tornado-centric perspective (section 4b) and grouped by annuli from TC center (per Fig. 5): I (inner, <200 km), M (middle, 200-399 km) and outer (O, ≥400 km). *Click image to enlarge.*

Of the 172 tornadoes used herein, the damage rating (via F or EF scale; Edwards et al. 2013) was distributed as follows: 105 EF0s (61%), 52 EF1s (30%), 15 EF2s (9%), and none rated EF3 or above. The EF2 occurrence percentage is slightly higher than the 6% significant-tornado figure for 1995–2013 TCTOR data. When distributing the parcel measures of RCAPE and CAPE by tornado rating (not shown), there is considerable overlap amongst all three bins, even between EF0 and EF3, in most parcel measures. The most pronounced distinction—still with some overlap—was in the $50^{th}$-$75^{th}$ percentile bin (upper box portions) and $75^{th}$-$90^{th}$ percentiles (upper whiskers) for EF2 tornadoes using SB parcels, for both CAPE and RCAPE.

We also sorted tornadoes by TC strength at the time of each event, using the same NHC and post-NHC classifications as in the TCTOR dataset. RCAPE and CAPE values were grouped according to events occurring in hurricanes (43 tornadoes), tropical storms (TSs, 64 tornadoes) and tropical depressions or weaker (collectively TDs, 65 tornadoes). Although tornadic TDs have occurred at landfall, the TD bin in TCTOR (Edwards 2010), and in this dataset, typically indicates progressively greater inland extent of the TC circulation during its decay phase. As such, indicators of buoyancy were expected to be larger with TDs than TSs and hurricanes. Across all three parcels, this was true—both for CAPE and RCAPE (not shown), albeit with some interquartile overlap. With great overlap in instability distributions, hurricanes showed a very slightly higher CAPE and RCAPE shift than TSs; in other words, the TS was the classification with weakest CAPE and RCAPE.

## 4. CONCLUSIONS and AVENUES for FURTHER EXAMINATION

As noted above, the small sample size may be introducing counterintuitive results in nocturnal vs. diurnal comparisons of TC tornado soundings. A larger dataset will be needed to support or refute preliminary findings of slightly higher nighttime values by some measures, as well as to perform analyses by more deeply iterative breakdowns (e.g., by classification or annulus on a day vs. night basis, or by geographic region). This can be accomplished by expanding temporally beyond the current TCTOR domain and/or enlarging the spatiotemporal radii of the proximity definition. The risks of those approaches, respectively, involve potential sounding unrepresentativeness (Potvin et al. 2010) and artifices introduced by secular changes in TC tornado-reporting and -recording practices before the mid-1990s (Edwards 2010).

Analyses of nearly 2500 dropsonde measurements within 1000 km of TC centers (Molinari et al. 2012) suggest the following:

- RCAPE without latent heat of fusion (LHF) is about half that of CAPE;
- RCAPE that includes LHF is similar to CAPE, consistent with earlier research cited therein; and
- Use of LHF and entrainment with RCAPE (liquid-water loading) yields the most consistent spatial similarities to the observed radial convective distributions in TCs.

However, that study appears not to have considered a potentially influential aspect: documented errors in dropsonde RH sensors (Wang 2005). Such errors include 1) a time-lagged response (and occasional failure) of RH saturation after entering clouds, and 2) excessive humidity readings below cloud base from wet sensors. The combined effects of such instrument errors and the virtual temperature correction on dropsonde-based CAPE computations of all sorts are unknown, and outside the scope of our present study. Still, such concerns are worth examining for the sake of refining the understanding of dropsonde utility in sampling buoyancy in TCs.

Based on those factors, our findings so far, and the aircraft-based measurements of Wei et al. (1998), one valid avenue would be to compare CAPE and RCAPE with LHF and/or entrainment, using balloon rawinsonde datasets and employing the virtual temperature correction for operational consistency and relevance. Again, the results in Fig. 3 of Molinari et al. (2012) show a very close magnitude match between no-entrainment, no-LHF CAPE (as we have analyzed herein) and no-entrainment, LHF RCAPE. Furthermore, LHF is a real, physical process in deep, moist convection above the warm-cloud zone. This suggests that we should test LHF RCAPE. In doing so, hypothetically, we would see small disparities in statistical distributions between that and no-LHF CAPE (i.e., similarly positioned boxes and whiskers as those on the right halves of Figs. 2 and 6).

Since this study deals specifically with tornadic environments, and since the bulk of TC tornadoes arise from supercellular convective modes (Edwards et al. 2012a), the buoyancy boost from the pressure perturbation (i.e., the "pressure buoyancy force" in Schlesinger 1975) may be worth accounting for during the CAPE computation. This perturbation typically is ignored, as it is much less than the influence of parcel and environmental virtual temperatures—but not necessarily for supercells. A pressure-perturbation term ($p'/\overline{p}$) for the right side of Eq. 1 can be tested either in addition to or independently from such influences as LHF or entrainment.

Finally, our calculations were very difficult to cross-check directly with those of Roff and Yano (2002) and Molinari et al. (2012), because of multivariate differences in software, vertical-interpolation routines, source instrumentation, use or non-use of the virtual temperature correction and entrainment, differences in lifted parcels, and perhaps unknown factors. Preliminary calculation of several tropical soundings provided to us by those authors yielded differing specific values of CAPE and RCAPE. However, qualitatively, the relative behavior of CAPE and RCAPE in our calculations (most closely matching the "no fallout, undiluted, no fusion" procedure in Molinari et al. 2012) of their soundings, as well as in our dataset, was similar. Additional reconciliation of computational and parcel-lift methods between datasets will be necessary in order to compare them more meaningfully and quantitatively.

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