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A STUDY OF THE PRE-STORM ENVIRONMENT OF TORNADIC QUASI-LINEAR CONVECTIVE SYSTEMS

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1. INTRODUCTION

Tornadoes are known to evolve from a variety of different parent storm types, including supercells, squall lines, and other convective systems. Trapp et al. (2004; hereafter, TTGB04) classified reported tornadoes in the United States from 1998–2000 by parent storm type: cell, quasi-linear convective system (QLCS), or other. It was found that tornadoes from QLCSs, such as squall lines or bow echoes, composed 18% of the reported tornadoes during the period of study. Because of this, it is imperative for the safety of human life and property that an adequate warning time is given for QLCS tornadoes.

Part of the tornado warning problem is due to rapid QLCS tornado development. It is possible for rotation to develop and form a tornado in only a few radar volume scans. Trapp et al. (1999) found that the majority of tornadoes that formed within QLCSs had non-descending tornadic vortex signatures (TVSs). These non-descending TVSs appeared, in the mean, just 5 min prior to the time the associated tornado began. This makes forecasting QLCS tornadoes an extremely difficult task for the operational meteorologist.

Unlike the well-known hook echo associated with supercell mesocylones, there are no widely accepted radar-based indicators of QLCS tornadoes (Trapp et al. 1999). The large areal extent of many QLCSs makes it difficult to determine the precise location where the greatest tornado threat may exist. According to Atkins et al. (2004), QLCS mesovortices are less likely to be detected than supercell mesocyclones, especially at larger distances from the radar.

Additionally, although much work has been done to determine the environments in which supercells may become tornadic, little effort has been made to determine the environmental conditions favoring QLCS tornadogenesis. These conditions could aid forecasters in making the decision whether or not to issue a tornado warning for a QLCS.

This study seeks to investigate pre-tornadic environments by examining soundings near tornadic cells and QLCSs and non-tornadic QLCSs in order to answer the following questions:

> Q.1 What are the convective parameters that reflect the environment in which these tornadoes are likely to form?
>
> Q.2 How do environments of tornadic QLCSs differ from those of non-tornadic QLCSs or tornadic cells?

These questions have remained unanswered in the literature, and are all related to a bigger question: do QLCS tornadoes form differently than cell tornadoes? This theoretical question is beyond the scope of this paper. Herein the focus is on the environmental differences between tornadic QLCSs, tornadic cells, and non-tornadic QLCSs. This work is part of a larger project on the topic of QLCS tornadoes, which includes modeling work and Doppler radar attribute studies (Manross et al. 2004, this volume). The answers to the above questions should benefit operational meteorologists.

2. DATA AND METHODOLOGY

The current study made use of tornado data classified by parent storm type from events between January 1998 and December 1999. TTGB04 classified 3828 individual tornadic events between January 1998 and December 2000 by parent storm type.

The TTGB04 data included the UTC time of tornado initiation, which was converted to local time for diurnal distribution comparisons. Latitude and longitude at initiation, also included, were useful for determining the proximity of tornadoes to atmospheric sounding locations.

Because near-tornadic environments vary quite a bit in time and space, limits must be set on the temporal and spatial distance between sounding launch and tornado initiation. Following Brooks et al. (1994), the spatial proximity limit used in this study was 100 miles (160 km) and the temporal limit was plus or minus one hour from nominal sounding times at 0000, 1200, or 1800 UTC. Using the time and location of each tornado initiation and the location of each rawinsonde site, tornadic events in proximity to soundings were selected.

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The highest F-scale ranking tornado associated with each sounding was used to classify the sounding. If a particular tornado was within the specified conditions of more than one sounding site, all proximity soundings were included, in order to make the dataset as large as possible.

After the list of all possible proximity soundings was complete, archived National Weather Service (NWS) soundings were gathered in text form from the online database at the University of Wyoming (UWYO 2003).

It would be advantageous to compare the pre-storm environments of tornadic and non-tornadic QLCSs to look for possible distinguishing characteristics. In order to develop a "null dataset" of non-tornadic QLCSs, a different method must be used than that used for tornadic systems. The database of tornadic and non-tornadic bow echo cases from Burke and Schultz (2003) was utilized, and other non-tornadic QLCSs were found from NCDC online radar data (NCDC 2003). Only those QLCS cases where severe weather was reported (wind or hail) were considered.

To complicate matters, tornadoes may result from cells ahead of the QLCS (such as on 24 April 2000 in LA and MS), but not from the QLCS itself. Since the associated tornado reports of Burke and Schultz (2003) did not distinguish the originating tornado parent type, it was difficult to determine whether a QLCS was truly non-tornadic. Additionally, it seems quite possible that some of the reported tornadoes could have occurred in a different part of the line, quite some distance from a particular sounding location. In order to avoid sampling an environment near any kind of tornadic system, only cases when no tornadoes occurred within the vicinity of the QLCS were used in the null dataset. It was also more difficult to clearly define a "proximity sounding" for these non-tornadic QLCS events. Following Burke and Schultz (2003), a sounding was considered in proximity if it was taken within 300 minutes and 300 km of the path of the bow echo apex as it appeared in radar data, was uncontaminated, and was ahead of the bow echo.

In order to retain only those soundings displaying pre-storm environmental characteristics, a visual quality control was performed on all of the soundings. Similar to Brooks et al. (1994), soundings which were convectively contaminated or that demonstrated dry line passage were classified as "bad." Soundings had to meet many important criteria in order to be labeled "good." First, balloon observations had to be available from the surface through at least 200 mb. The atmosphere had to have a strong positive lapse rate (closer to dry-adiabatic), especially in lower levels. The amount of CAPE had to be greater than the CIN, using standard definitions of the terms. The lifted index (LI) parameter had to be negative in a "good" sounding. There needed to be a relatively large dew point depression from the surface to $\sim$300 mb. Surface winds should have come from the southeast to southwest, and winds had to veer with height.

Conversely, soundings which met any of the following criteria were considered "bad" and omitted from the dataset: the balloon burst at lower levels, there was a weak (nearly moist adiabatic) lapse rate in lower levels, the CIN was greater than the CAPE (or CAPE $\sim$0), there was evidence of a dry line passage (enormous dew point depression in the lower atmosphere), the sounding was essentially saturated throughout nearly all levels, the LI was positive, if the precipitable water (Butler 1998) was relatively high, and/or the surface winds were relatively weak and from west to north.

Some soundings were not clearly pre- or post-event, and could not be immediately classified as good or bad. In these cases, NCDC radar data were visually inspected to compare the sounding location with the tornadic cell, tornadic QLCS, or non-tornadic QLCS in order to determine whether or not the sounding was characteristic of the pre-storm environment.

Overall, 59 soundings were gathered in proximity to tornadoes from cells and 30 soundings were gathered in proximity to QLCS tornadoes. From the non-tornadic severe QLCS events, 23 proximity soundings were gathered.

3. PRE-STORM ENVIRONMENTAL CHARACTERISTICS

The values of the sounding parameters were compared in order to see if there were any differences between pre-tornadic QLCS, non-tornadic QLCS, and pre-tornadic cell environments. Weisman and Trapp (2003) suggested that a minimum of 20 m s^{-1} of unidirectional shear over the 0–2.5 km or 0–5 km AGL layer produces significant cyclonic surface vortices in QLCSs. The present study found a mean bulk shear, the magnitude of the shear vector between the winds at the different layers, in the 0–1 km layer of 26.3 kt for tornadic QLCSs, 16.9 kt for non-tornadic QLCSs, and a mean value of only 18.1 kt for tornadic cells (Figure 1). Similarly, the average 0–3 km bulk shear for tornadic QLCSs was 37.6 kt, 30.4 kt for

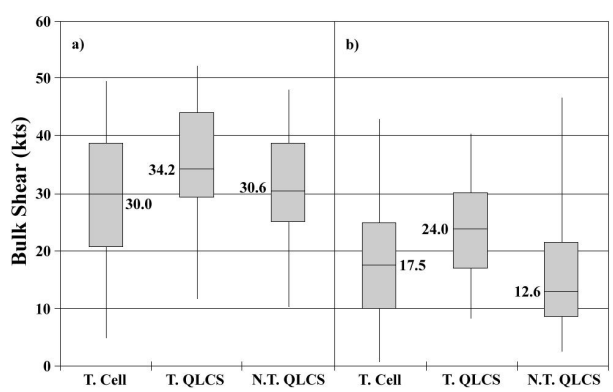

FIG. 1. Box and whisker plots of the distribution of a) 0–3 km and b) 0–1 km bulk shear in the lower atmosphere for tornadic cells (T.Cell), tornadic QLCSs (T.QLCS), and non-tornadic QLCSs (N.T.QLCS). Upper and lower quartiles are indicated by the shaded region. Median values for each plot are denoted by the center line and the number on the side.

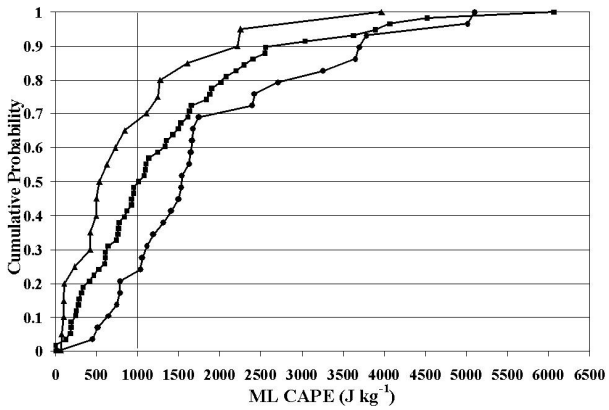

FIG. 2. Cumulative distribution function (CDF) of mean-layer CAPE in proximity to tornadic cells (squares), tornadic QLCSs (circles), and non-tornadic QLCSs (triangles).

non-tornadic QLCSs, and 29.6 kt for tornadic cells. The average 0–6 km bulk shear for tornadic QLCSs was 47.8 kt, 45.4 kt for non-tornadic QLCSs, and 44.4 kt for tornadic cells. Hence, there was not nearly as much of a difference in the deep-layer bulk shear values as in the low-level bulk shear values. To summarize, pre-tornadic QLCS environments tended to be characterized by higher values of low-level bulk shear than non-tornadic QLCS environments or pre-tornadic cell environments.

Other average parameters from tornadic QLCS, non-tornadic QLCS, and tornadic cell environments were compared. The mean layer (ML) CAPE (based on mean parcel values from the lowest 100 mb above ground level) for tornadic QLCSs had a mean value of 1892 J kg^{-1}, non-tornadic QLCSs had an average value of 902 J kg^{-1}, while the average tornadic cell environment had a ML CAPE of 1363 J kg^{-1}. Figure 2 shows the cumulative distribution function of ML CAPE by parent storm type. Notice that 67% of non-tornadic QLCS environments and only 24% of tornadic QLCS environments had less than 1000 J kg^{-1} ML CAPE. Conversely, the mean CIN for the tornadic QLCS, non-tornadic QLCS, and tornadic cell environment was 72.6 J kg^{-1}, 149.6 J kg^{-1}, and 93.3 J kg^{-1}, respectively. Thus, the pre-tornadic QLCS environment was generally characterized by a higher value of CAPE and lower value of CIN when compared to the non-tornadic QLCS and the pre-tornadic cell environment.

Several other parameters showed little difference in their average values between pre-tornadic cell and QLCS environments, but showed greater differences between tornadic and non-tornadic QLCS environments. For example, the ML-based level of free convection (LFC) height AGL for tornadic QLCSs, non-tornadic QLCSs, and tornadic cells had average values of 2270 m, 3838 m, and 2411 m, respectively. The ML lifted index had an average of -6.6 for tornadic QLCSs, -5.2 for tornadic cells, and was -3.2 for non-tornadic QLCSs. A number of other parameters also behaved similarly.

The supercell composite parameter (SCP) is a multi-parameter index that includes CAPE, 0–3 km storm-relative helicity, and bulk Richardson number (BRN) shear, and each parameter is normalized to supercell "threshold" values. This index has been developed and used by SPC forecasters for the past several years. The average ML SCP for tornadic cells was 2.2, was 1.0 for non-tornadic QLCSs, and was 7.3 for tornadic QLCSs. This result must be viewed with caution owing to the helicity calculation. The Bunkers et al. (2000) method was used to determine storm-relative motion, which is based on a presumed deviant motion of supercells (i.e., to the right of and slower than the mean wind); QLCS motion, however, can be comparably more aligned with and significantly faster than the mean wind (e.g., Corfidi 2004). Consequently, the helicity values calculated from pre-tornadic QLCS soundings may be overstated.

The mean-layer significant tornado parameter (SigTorn) is a multi-parameter index that includes the magnitude of the 0–6 km shear, 0–1 km storm-relative helicity, 100 mb mean parcel CAPE, and 100 mb mean parcel LCL height. The average SigTorn value for tornadic cells was 1.1, 0.3 for non-tornadic QLCS, and 7.4 for tornadic QLCS environments. Similar to SCP, this parameter also includes helicity and should be treated with the same caution.

Further attempts to classify pre-tornadic QLCS and cell environments, and pre-tornadic and non-tornadic QLCS environments were made by plotting one parameter against another. Few differences between the tornadic sounding parameters were evident in most of these plots; the data were often virtually indistinguishable. Ideally, the points from each parent storm type would be clustered in different regions of the plot. For example, the LCL height in meters ASL was plotted against the 0–1 km bulk shear (Figure 3). It was evident that both kinds of soundings reflect an environment of moderate low level shear and low LCL height. Most of the plots revealed similar or interchangeable results.

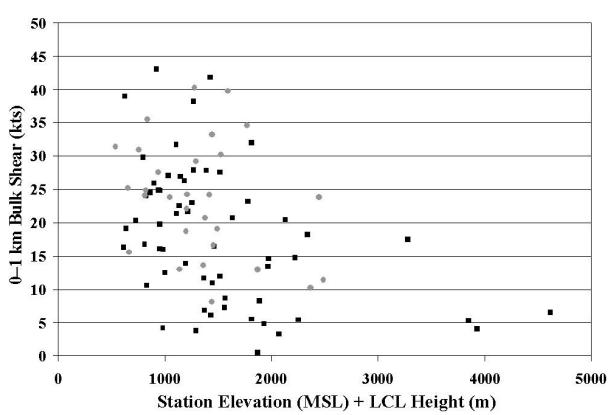

FIG. 3. Distribution of soundings in proximity to tornadic QLCSs (gray circles) and tornadic cells (black squares) showing the LCL height (MSL) versus the 0–1 km bulk shear (kts).

In order to see if it is possible to distinguish between the pre-storm environments of tornadic cell and QLCS environments or between the pre-storm environments of non-tornadic and tornadic QLCS environments, a linear discriminant analysis was performed (Wilks 1995). In the analyses comparing pre-storm environmental characteristics, 26 different sounding parameters were compared by linear discriminant analysis, yielding 325 possible combinations of two parameters. Of these combinations, not one correctly identified 70% or more of the observed tornadic QLCS or cell soundings (Figure 4). The probability of detection (correctly categorizing a tornadic QLCS sounding) was often slightly higher than the probability of false detection (categorizing a tornadic cell sounding as a tornadic QLCS sounding). Overall, the pre-tornadic environments reflected by these 26 parameters were extremely similar. The Kuipers skill scores (Wilks 1995) for all of the 325 parameter combinations were well below 0.4.

Figure 4 also shows the area under the curve (AUC) in the relative operating characteristic (ROC) graph beneath one observed point when it and the (0,0) and (1,1) corners were connected by straight lines (Swets 1996). This particular combination (0–1 km helicity versus the 2–4 km mean relative humidity) has an AUC value of 0.68, which is higher than random performance. Random performance, denoted by the "no skill" line, has an area of 0.5 and perfect performance would have an AUC of 1.0. The AUC index is particularly favorable because it does not depend on assumptions about underlying probability distributions. Most (248) of the AUC values of the tornadic sounding parameter combinations were above 0.5, and 57 combinations had AUC values at or above 0.6. Most of these parameters involved shear, lapse rates, CAPE, or relative humidity.

The best combination of discriminators between tornadic storms is the 0–1 km helicity versus the 2–4 km mean relative humidity. This combination successfully identified 76.7% of tornadic QLCS proximity soundings and 59.3% of the tornadic cell proximity soundings, and had a KSS of 0.36. Another excellent discriminator combination is the 0–1 km helicity versus the difference between the 0–6 km and the 0–1 km bulk shear. This combination successfully identified 69.5% of tornadic cell proximity soundings and 59.3% of the tornadic QLCS proximity soundings (Figure 5), and had a KSS of 0.33.

Of the observed tornadic and non-tornadic QLCS sounding comparisons, only one of the combinations successfully identified 70% or more of them (Figure 6): LCL height (AGL) and LCL height (ASL). This comparison is of little value, but it demonstrates that the LCL height is an important parameter for QLCSs. The Kuipers skill scores (KSS) for several of the QLCS parameter combinations were above 0.4; most of these involved low level wind shear parameters, ML CAPE, or relative humidity. The KSS was 0.63 for the combination of 0–1 km mean relative humidity and the LCL height (ASL). It was 0.8 for the combination of LCL height

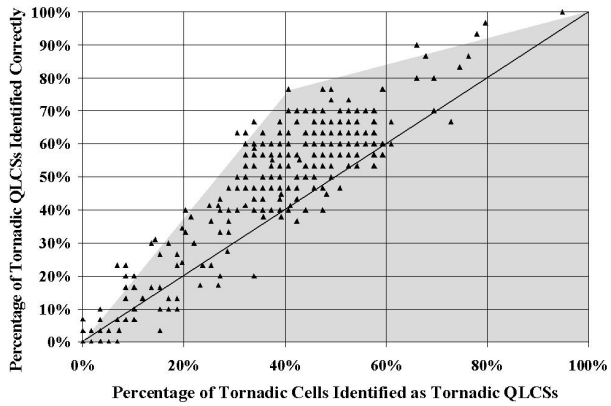

FIG. 4. Results of 325 linear discriminant analysis pairs between parameters that reflect the pre-storm environment of tornadic cells and tornadic QLCSs. The relative operating characteristic (ROC) compares the probability of false detection (x-axis) to the probability of detection (y-axis) of tornadic QLCSs. Black line indicates the "no-skill" line. The shaded area is the AUC, 0.68, under the point (40.7%,76.7%).

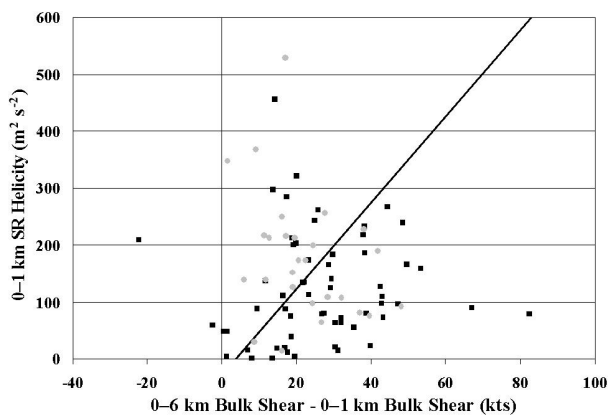

FIG. 5. Distribution of soundings in proximity to tornadic QLCSs (gray circles) and tornadic cells (black squares) showing the difference between 0–6 km bulk shear and 0–1 km bulk shear (knots) versus the 0–1 km storm relative (SR) helicity (m^2 s^{-2}). Solid line is the best discriminant line.

ASL and AGL, which again has little physical significance. Most (280) of the AUC values of the tornadic and non-tornadic QLCS sounding parameter combinations were above 0.5, 141 combinations had AUC values at or above 0.6, and 22 had AUC values at or above 0.7. Most of the latter parameters involved ML CAPE, shear, lapse rates, or relative humidity. The AUC for the LCL height combination was 0.9, and the combination of 0–1 km mean relative humidity and the LCL height (ASL) had an AUC of 0.82.

The combination of the 0–1 km helicity and the difference between the 0–6 km and the 0–1 km bulk shear discriminated fairly well between tornadic and non-tornadic QLCSs (Figure 7), correctly identifying 70% of the non-tornadic proximity soundings and 63% of tornadic proximity soundings. The KSS for this combination was 0.46, and the AUC was 0.73. Since the difference between the

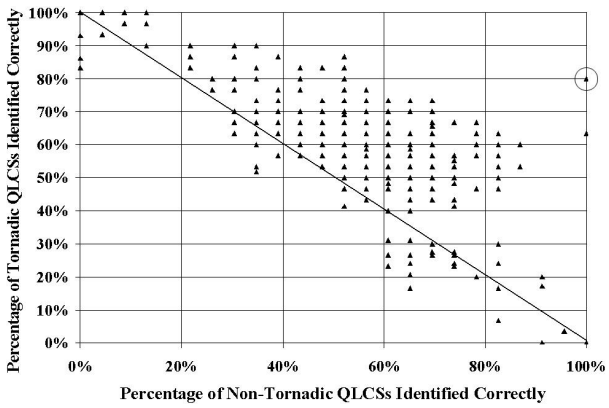

FIG. 6. Similar to Figure 4, but parameters reflect the pre-storm environments of tornadic and non-tornadic QLCSs. Circled point is the comparison of LCL height ASL and AGL.

average values of 0–6 km bulk shear and 0–1 km bulk shear is greatest near tornadic QLCSs, it is not surprising that it is part of a combination of parameters that discriminates tornadic QLCSs quite well.

Another good combination of discriminators between pre-tornadic and non-tornadic QLCS environments is the 0–1 km bulk shear versus the 850–500 mb lapse rate (Figure 8). Of the non-tornadic QLCS proximity soundings, 52% were correctly identified, while 87% of the tornadic QLCSs were correctly identified. The KSS for this combination was 0.42, and the AUC was 0.71. This discriminating pair may indicate that tornadic QLCSs favor steeper low to mid-level lapse rates. This provides more instability and thus stronger updrafts, giving the storms a greater potential for vortex stretching and stronger surface cold pools. Stronger low-level shear results in more upright convection at the leading edge of the QLCS, which should mean more vertical stretching and stronger, longer-lived QLCSs.

4. DISCUSSION

The nontrivial number of tornadoes that develop from QLCSs argues the need to understand the environments in which QLCS tornadoes form. For that reason, the pre-tornadic environments were examined through the means of proximity soundings.

After comparing many of the sounding parameters in proximity to non-tornadic QLCSs, tornadic QLCSs, and tornadic cells, it was evident that the pre-tornadic QLCS environment is characterized by higher values of low-level bulk shear and CAPE. Few other differences were evident from these assessments. A linear discriminant analysis demonstrated the similarity between these sounding parameters, especially in either type of pre-tornadic environment. Thus, if an environment favorable for tornadogenesis develops a QLCS, meteorologists should certainly not rule out the possibility of tornadoes.

The goal of this study was to find a small set of parameters that can distinguish between different kinds of storms, specifically tornadic versus non-tornadic QLCSs and tornadic cells versus tornadic QLCSs. If the environmental characteristics of tornadic QLCSs that differ from those of non-tornadic QLCSs could be identified, these might aid weather personnel in forecasting and warning for QLCS events. Pre-tornadic QLCS environments were determined by soundings to have, on the whole, high values of 0–1 km bulk shear, 0–3 km bulk shear, and mean layer CAPE, and low values of CIN (Q.1). The low-level shear and CAPE values for soundings in proximity to tornadic QLCSs are greater than those close to non-tornadic QLCSs or tornadic cells (Q.2). The amount of CIN is lower near tornadic QLCSs. Thus, it can be concluded that QLCSs tend to produce tornadoes in environments characterized by high values of low-level shear and instability.

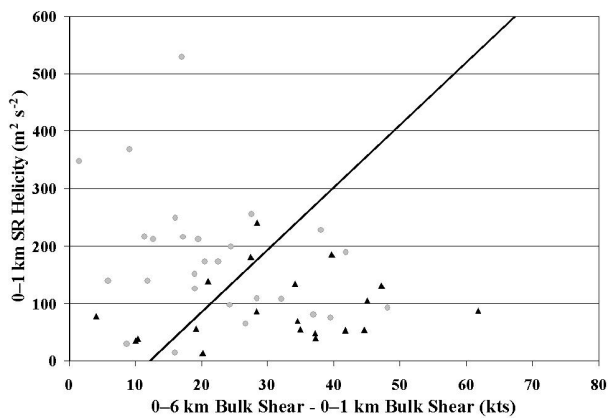

FIG. 7. Distribution of soundings in proximity to tornadic QLCSs (gray circles) and non-tornadic QLCSs (black triangles) showing the difference between 0–6 km bulk shear and 0–1 km bulk shear (knots) versus the 0–1 km storm relative (SR) helicity ($m^2\ s^{-2}$). Solid line is the best discriminant line.

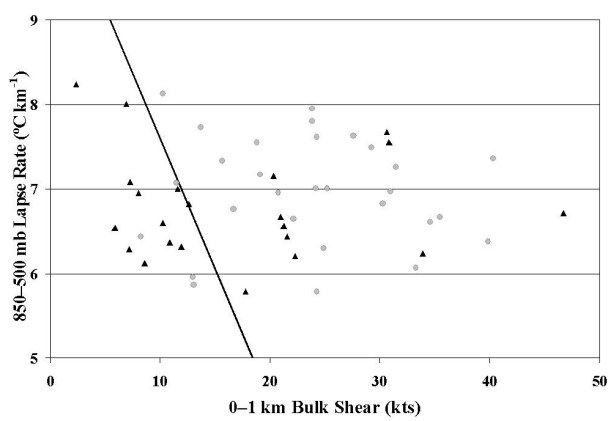

FIG. 8. Distribution of soundings in proximity to tornadic QLCSs (gray circles) and non-tornadic QLCSs (black triangles) by the 0–1 km bulk shear (knots) versus the 800–500 mb lapse rate (°C km^{-1}). Solid line is the best discriminant line.

5. AVENUES FOR FUTURE WORK

The continued collection and tornado classification by parent storm type using the TTGB04 definitions would greatly increase the size of the QLCS tornado dataset and allow for better comparisons. The third year of QLCS tornado observations and the second and third years of cell tornado observations could be used to develop a larger proximity sounding dataset. Furthermore, other non-tornadic QLCS proximity soundings could be collected and analyzed using the same methods. The addition of proximity soundings to these datasets could help discern other discriminating parameter combinations, or support the findings of this study. The comparison of many other sounding parameters and the use of multiple-parameter combinations could provide additional discriminating groups. The environmental comparisons could head down a new path by utilizing RUC model soundings or the National Centers for Environmental Prediction–National Center for Atmomspheric Research (NCEP–NCAR) 40-Year Reanalysis (Kalnay et al. 1996) data. There are many possibilities.

The literature suggests that high values of unidirectional shear in the lower atmosphere play a role in the formation of tornadoes from QLCSs. Thus, the hodograph curvature would be very useful to evaluate in order to see if it will discriminate adequately between tornadic cells, tornadic QLCSs, and non-tornadic QLCSs.

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REFERENCES

Atkins, N.T., J.M. Arnott, R.W. Przybylinski, R.A. Wolf, and B.D. Ketcham, 2004: Vortex structure and evolution within bow echoes. Part I: Single-Doppler and damage analysis of the 29 June 1998 derecho. *Mon. Wea. Rev.,* submitted.

Brooks, H.E., C.A. Doswell III, and J. Cooper, 1994: On the environments of tornadic and nontornadic mesocyclones. *Wea. Forecasting,* **9,** 606–618.

Bunkers, M.J., B.A. Klimowski, J.W. Zeitler, R.L. Thompson, and M.L. Weisman, 2000: Predicting supercell motion using a new hodograph technique. *Wea. Forecasting,* **15,** 61–79.

Burke, P.C., and D.M. Schultz, 2003: A climatology of cold-season bow-echoes over the continental United States. *Wea. Forecasting,* submitted.

Butler, B., Precipitable Water at the VLA-1990-1998, MMA Memo No. 237, 1998.

Corfidi, S.F., 2004: Cold pools and MCS propagation: Forecasting the motion of downwind-developing MCSs. *Wea. Forecasting,* **18,** 997–1017.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77,** 437–472.

Manross, K.L., R.J. Trapp, and G.J. Stumpf, 2004: WSR-88D RADAR characteristics of quasi-linear convective system tornadoes using the NSSL Severe Storm Analysis Program. Preprints, *22nd Conference on Severe Local Storms,* Hyannis, MA, Amer. Meteor. Soc., this volume.

NCDC, cited 2003: Online Radar Data/Storm Events Database. [Available online at http://www.ncdc.noaa.gov/oa/radar/radardata.html.]

Swets, J.A., 1996: *Signal Detection Theory and ROC Analysis in Psychology and Diagnostics.* Lawrence Erlbaum Associates, Inc., 308 pp.

Trapp, R.J., E.D. Mitchell, G.A. Tipton, D.W. Effertz, A.I. Watson, D.L. Andra Jr., and M.A. Magsig, 1999: Descending and non-descending tornadic vortex signatures detected by WSR-88Ds. *Wea. Forecasting,* **14,** 625–639.

Trapp, R.J., S.A. Tessendorf, E.S. Godfrey, and H.E. Brooks, 2004: Tornadoes from squall lines and bow echoes. *Wea. Forecasting,* accepted.

UWYO, Department of Atmospheric Science, cited 2003: Atmospheric Soundings. [Available online at http://weather.uwyo.edu/upperair/sounding.html.]

Weisman, M.L., and R.J. Trapp, 2003: Low-level mesovortices within squall lines and bow echoes. Part I: overview and dependence on environmental shear. *Mon. Wea. Rev.,* textbf31, 2779–2803.

Wilks, D.S., 1995: *Statistical Methods in the Atmospheric Sciences.* International Geophysics Series, Vol. 59, Academic Press, 464 pp.