On the Environments of Tornadic and Nontornadic Mesocyclones

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ABSTRACT

The authors investigated differences in the environments associated with tornadic and nontornadic mesocyclones are investigated using proximity soundings. Questions about the definition of proximity are raised. As the environments of severe storms with high spatial and temporal resolution are observed, the operational meaning of proximity becomes less clear. Thus the exploration of the proximity dataset is subject to certain caveats that are presented in some detail.

Results from this relatively small proximity dataset support a recently developed conceptual model of the development and maintenance of low-level mesocyclones within supercells. Three regimes of low-level mesocyclonic behavior are predicted by the conceptual model: (i) low-level mesocyclones are slow to develop, if at all, (ii) low-level mesocyclones form quickly but are short lived, and (iii) low-level mesocyclones develop slowly but have the potential to persist for hours. The model suggests that a balance is needed between the midtropospheric storm-relative winds, storm-relative environmental helicity, and low-level absolute humidity to develop long-lived tornadic mesocyclones. In the absence of that balance, such storms should be rare. The failure of earlier forecast efforts to discriminate between tornadic and nontornadic severe storms is discussed in the context of a physical understanding of supercell tornadogenesis. Finally, it is shown that attempts to gather large datasets of proximity soundings associated with rare weather events are likely to take many years.

1. Introduction

Supercell thunderstorms, characterized by the existence of a persistent mesocyclonic circulation, represent an important hazard to the public because of their connection with severe weather, such as hail, strong winds, and tornadoes. Burgess and Lemon (1990) indicated that, based on Doppler radar observations from the Joint Doppler Operational Project (JDOP) experiment, almost all of the observed mesocyclones were associated with some severe local storm event (large hail, damaging winds, and tornadoes) and approximately half produced tornadoes. As a result of the danger, significant effort has gone into identifying environmental conditions associated with supercells (e.g., Browning 1964; Chisholm and Renick 1972). Darkow (1968, 1969) used the concept of a proximity sounding, to be defined further below, to identify the environments associated with tornadoes. Rather than using the whole sounding, Rasmussen and Wilhelmson (1983) calculated low-level vertical shear of the horizontal winds and convective available potential energy (CAPE) from 1200 UTC soundings and proposed that nonrotating thunderstorms are found in environments with low shear and low CAPE, while tornadic storms occurred with high shear and high CAPE. More recent work based on similar approaches (e.g., Johns et al. 1993; Korotky et al. 1993) extended our knowledge of the range of tornadic environments to include high CAPE–low shear and low CAPE–high shear environments.

Darkow's approach to the characterization of the environment is quite distinct from that of Rasmussen and Wilhelmson. Darkow attempted to put strict limits on the spatial and temporal variability of the atmosphere at the expense of eliminating large numbers of cases, leading to questions about the statistical significance of the work. Also, the product of Darkow's work was a relatively detailed picture of the vertical structure of environments associated with tornadic storms. Rather than contrasting the tornadic proximity soundings with nontornadic proximity soundings, Darkow compared his proximity soundings to their nearest neighbors, which he called "check" soundings.

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Rasmussen and Wilhelmson, on the other hand, put fewer restrictions on the atmospheric variability, thus having the capability of producing a large dataset in a relatively short time (although they only used 13 cases), but also thereby leading to questions about how well the soundings represented the environment of the storms. Moreover, the product of Rasmussen and Wilhelmson's approach is a parameter space diagram that includes some partitioning of storm types to within regions of the parameter space. Turcotte and Vigneux (1987, results shown in Brooks et al. 1993) followed the methods of Rasmussen and Wilhelmson with a larger dataset using all soundings associated with severe thunderstorms from three years and all soundings associated with nonsevere thunderstorms from a single year in the forecast area of the Quebec Weather Centre. They discovered that a simple combination of shear and CAPE could discriminate well between the environments with severe and nonsevere thunderstorms, but not between tornadic and severe nontornadic environments. A long-range goal is to explore whether environmental parameters can help further by distinguishing between the environments of *tornadic* thunderstorms and *nontornadic severe* thunderstorms. Here, we consider the contribution of discriminating between tornadic and nontornadic *supercells* to that goal.

One interpretation of the results of Turcotte and Vigneux is that the successful discrimination between severe and nonsevere thunderstorms is, at least in part, a result of CAPE and low-level shear predicting the environments of supercell thunderstorms. While not all severe weather is associated with supercells and not all supercells produce severe weather, the lack of discrimination between tornadic and severe nontornadic thunderstorms using CAPE and low-level shear could be related to the observations of tornadic frequency in radar-detected mesocyclones reported by Burgess and Lemon (1990), that is, the presence of nontornadic mesocyclones. Numerical modeling (e.g., Weisman and Klemp 1982, 1984) and theoretical studies (Davies-Jones 1984; Rotunno and Klemp 1985) indicate that low-level shear in thermodynamically unstable environments is the origin of rotation in midlevels (i.e., 3–10 km AGL) of supercell thunderstorms. It now appears, however, that in supercells the occurrence of tornadoes is closely connected to the development of *low-level* mesocyclones (i.e., below 1 km AGL), which have their origins in the baroclinic generation of vorticity within evaporatively cooled downdrafts (Rotunno and Klemp 1985; Davies-Jones and Brooks 1993). That is, low-level mesocyclones develop by different processes than midlevel mesocyclones. If this is a correct picture of supercell tornadogenesis, such a process is not described by CAPE or low-level shear. Hence, it should not be surprising that those parameters cannot discriminate between tornadic and nontornadic supercell environments.

In assessing the differences between tornadic and nontornadic environments, a challenge has been the lack of information about environments producing nontornadic supercells. While datasets of soundings associated with tornadic environments have been developed (e.g., Darkow 1969), the comparable datasets for *severe* thunderstorms (e.g., Maddox 1976; Patrick and Keck 1987) have not necessarily been associated with *supercell* thunderstorms. Recently, Wood et al. (1994) have put together a dataset of tornadic and nontornadic mesocyclones based on observations from the Doppler radars at the National Severe Storms Laboratory (NSSL). These data have given us the opportunity to assess proximity soundings associated with both tornadic and nontornadic mesocyclones and to see if there are any differences in the environments associated with them.

After some considerations of the difficulties associated with proximity soundings and their selection, we describe both the mesocyclone and sounding datasets. Using the recent work of Brooks et al. (1994, hereafter BDW94), who proposed a conceptual model of the role of the environment in developing and maintaining low-level mesocyclones,[1] we then look for differences in the environments associated with tornadic and nontornadic mesocyclones. We close with a discussion of the implications of the results for forecasting and for the development of proximity sounding datasets for rare events.

2. Problems with the definition of "proximity"

Underlying the use of proximity soundings is the idea that we want to sample "the environment in which an event formed." However, spatial and temporal variability within the "environment" of tornadoes and tornadic storms is the rule, rather than the exception; tornadic storms do not arise often in environments characterized by spatial and temporal homogeneity (Doswell 1982) on scales observable with the rawinsonde network. Recognition of this variability is implicit in Darkow's (1969) definition of a proximity sounding:

1. The sounding release point is within 50 statute miles (80 km) of a tornado.
2. The tornado occurred within 105 min after the balloon release (45 min before and one hour after the nominal sounding times at 0000 and 1200 UTC).

[1] Note that the conceptual model refers only to the development of low-level *mesocyclones*, not *tornadoes*. Brooks et al. (1993) discuss the possibility of nontornadic, low-level mesocyclones. The existence of such events could introduce a bias into the dataset, but in practice we observe tornadoes and not low-level mesocyclones. Until a large dataset of low-level mesocyclones exists, we can use only tornadoes as a proxy for low-level mesocyclones.

3. The sounding sampled the same air mass that gave birth to and sustained the tornado-bearing thunderstorm.

It is clear that the first requirement relates to the spatial variability within the environment, the second relates to the temporal variability, while the third is concerned with elimination of soundings that are not representative in some sense (including convective contamination). Let us consider each of these in turn.

The idea of searching for proximity soundings implicitly recognizes that the environment in which an event occurs is *not* horizontally homogeneous. That is, the spatial variation is assumed to be large enough that an event really needs to be rather close to the sounding release point if the "real" storm environment is to be sampled; the next closest sounding really will not do. In fact, the demonstration of that was shown in Darkow's comparison of his proximity sounding composite with the "check" composite. Darkow's upper limit on distance, however, is arbitrary and without objective foundation. That is, there is no quantitative analysis of the spatial variability that might be present in association with tornadoes, nor is there any sense of the case-to-case variability of the spatial structure. This is obviously a result of a lack of observations, a problem that hinders any study of proximity.

In much the same way, the second requirement (i.e., the temporal limit) recognizes that the tornado environment can change significantly in between sounding times, even beyond the normal diurnal changes. Some of Beebe's (1958) findings suggest that the evolution of the environment during the day takes the resultant sounding well away from the original "loaded gun" sounding, with its pronounced inversion and dry midlevels, toward something rather different. In fact, both Darkow's (1969) and Schaefer and Livingston's (1988) results seem to bear this out; their composite proximity soundings do not show the capping stable layer and dry lower midtroposphere exhibited by the classic "loaded gun" profiles. However, it might be that at least some of this character results from a "smearing" of the individual profiles in the compositing process (see Brown 1993). It is unclear at this time to what extent this smearing effect influenced the composite proximity soundings, or in *any* of the studies creating such composites. As with the spatial variability, the temporal variability and its case-to-case differences are not well known and there is no objective basis on which to establish a temporal cutoff.

Finally, consider the thorny issue of which candidate proximity soundings to delete from consideration (i.e., criterion 3, above). If the number of soundings gets too large, it becomes difficult to imagine personally inspecting each sounding. Moreover, even if the will to examine each individual candidate sounding is exercised, by whose standards are the soundings chosen for elimination? As with the other restrictions, this process is not rooted in any firm ground. Rather, it depends rather strongly on the background of the analyst; recognition of "problem" soundings is not a trivial issue. As with the other two constraints, little or no

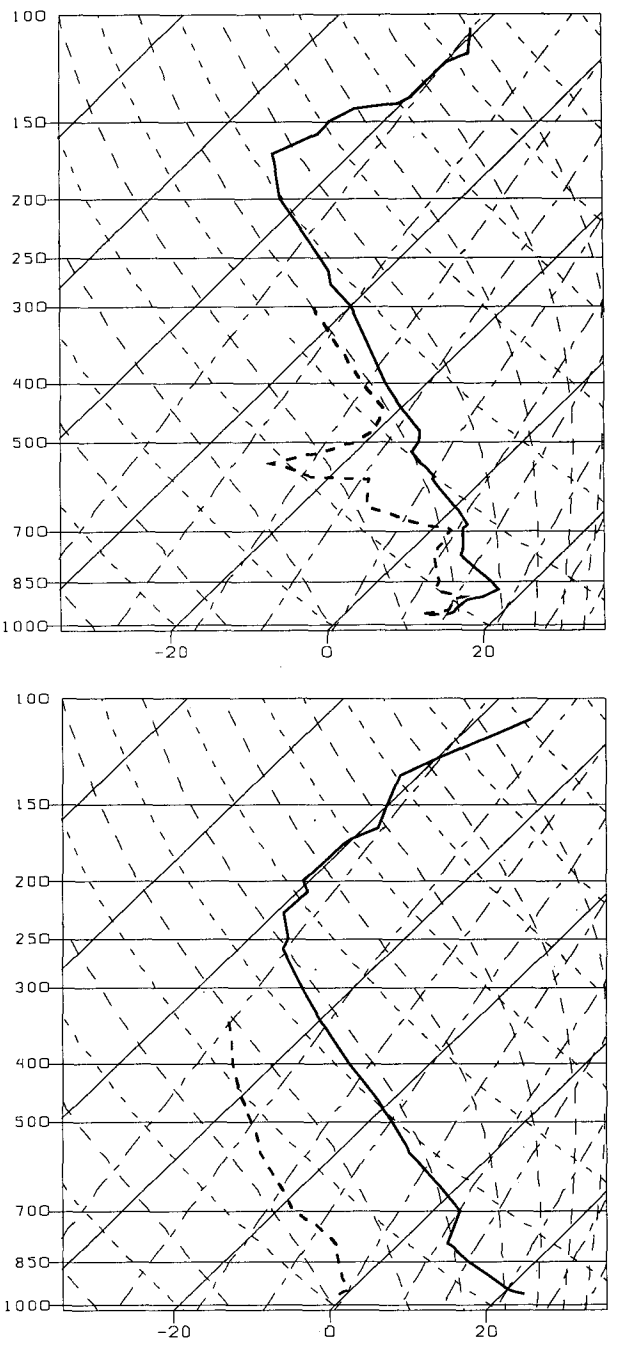

FIG. 1. Examples of rejected soundings. a) Convectively contaminated sounding from 0000 UTC 29 March 1988. b) Nonrepresentative sounding due to dry line passage from 0000 UTC 23 April 1978.

objective basis for development of standards exists at present. Whereas many soundings can be discarded from consideration relatively easily (Fig. 1), there are occasions when the soundings have more subtle problems that may or may not be recognized by a particular analyst. Schwartz and Doswell (1991) have suggested that soundings can have a wide spectrum of technical problems, some of which might well escape even fairly sophisticated numerical quality control schemes. In cases with strong mesoscale variability, it is also possible that soundings may indicate environments that are capable of supporting convection, but are not representative of the environment in which the storm forms.

We already have seen evidence of this sort of problem when looking at the Doppler wind profilers in the Profiler Demonstration Network. We have evaluated the observed time trend of storm-relative environmental helicity, H, as discussed by Davies-Jones et al. (1990), Droegemeier et al. (1993), and Brooks et al. (1994), and defined by

$$H(\mathbf{c}) = -\int_0^h \mathbf{k}\cdot(\mathbf{V}-\mathbf{c})\times\frac{\partial\mathbf{V}}{\partial z}\,dz, \qquad (1)$$

where h is an assumed inflow depth, $\mathbf{c}$ is the storm motion vector, $\mathbf{V}(z)$ is the environmental wind profile, and $\mathbf{k}$ is the unit vector in the vertical. In several cases, tornadic storms passed close by a profiler and the observed temporal change in H from the hourly data was what one would expect: a sustained increase with time prior to the storm's passage. The 6-min data from one of those revealed a large "spike" in H on a quite short timescale (Fig. 2). In another case, with a supercell passing a profiler during its tornadic phase, there was little noticeable change in H (Fig. 3). Davies-Jones (1993) has examined a large number of special soundings taken on tornado outbreak days and found significant temporal and spatial variability, all within a set of what might be considered proximity soundings.

All of this suggests that the notion of "proximity sounding" is potentially a lot more complex than it might appear to be. It is possible that we can add significantly to our understanding through model simulation, which is arguably the most promising way to develop a firm foundation for establishing objective criteria defining "proximity." What is desperately needed is *validation* of the model simulations. It is to be hoped that the Verification of the Origins of Rotation in Thunderstorms Experiment (VORTEX), scheduled for the springs of 1994 and 1995 (Rasmussen et al. 1994) will be able to accomplish at least some of this needed validation. With these important caveats in mind, we go on to consider the currently available dataset of proximity soundings to nontornadic mesocyclones and compare them to a similarly obtained set of proximity soundings to tornadic mesocyclones.

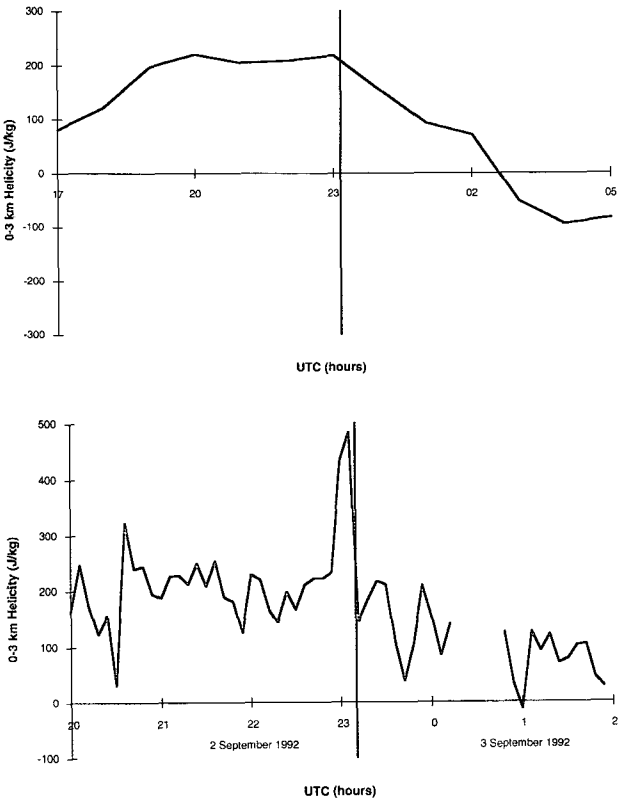

FIG. 2. Values of 0–3-km helicity (J kg^{-1}) from Purcell, Oklahoma, wind profiler associated with nearby passage of tornadic mesocyclone at approximately the time indicated by the heavy vertical line just before 0000 UTC 3 September 1992. a) Hourly data. b) Six-min data.

3. Dataset

a. *Mesocyclones*

The mesocyclone dataset is taken from that developed by Wood et al. (1994) and covers those mesocyclones observed from NSSL radars from 1975–1990. The definition of a mesocyclone is as given by Burgess (1976) and includes criteria on the shear value, the depth of the circulation, and its temporal continuity. To limit errors in the determination of storm motion, only those mesocyclones lasting at least 30 min are included. We have taken the mesocyclone motion and location as reported by Wood et al. (1994). The associated severe weather events (hail, damaging winds, or tornadoes) are included with the dataset, based upon reports in *Storm Data* and annual summaries for the NSSL Spring Program from 1971–1986.

b. *Soundings*

Archived soundings from the National Weather Service (NWS) rawinsonde site in the Oklahoma City area form the basis of most of the dataset. To increase

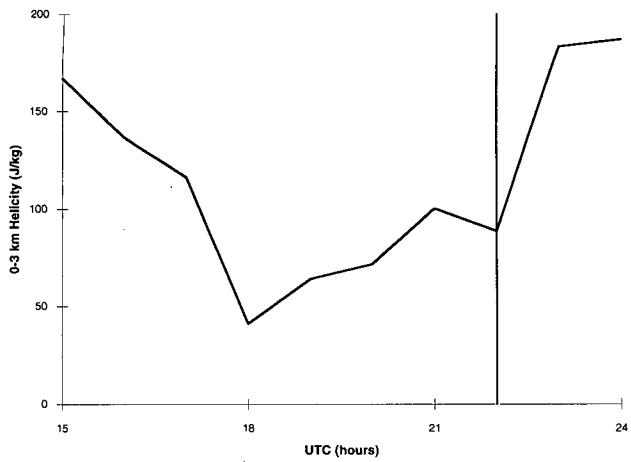

FIG. 3. Same as Fig. 2a except for Lamont, Oklahoma, wind profiler on 12 April 1991.

the number of soundings in the nontornadic mesocyclone category, we also have considered every appropriate case with special soundings taken during NSSL field programs through 1986. (If a tornadic mesocyclone was also in proximity to that sounding, it was included in the tornadic dataset.)

Two special sets of cases have also been added to supplement parts of the dataset. The first adds to the tornadic cases with soundings from two major tornado outbreaks. During the 1965 Palm Sunday outbreak (Fujita et al. 1970) and the 3–4 April 1974 outbreak (Fujita 1974), soundings that met our proximity criteria (discussed below) were taken as part of the routine NWS rawinsonde network at Flint, Michigan, and Dayton, Ohio, respectively. Given the nature of the storms on those days, it is virtually certain that they were supercells.

The second special set adds to the nontornadic cases. We have constructed soundings for a set of six storms that generated long (~100 km), narrow (~10–20 km) swaths of winds approaching 50 m s^{-1}, using nearby surface observations and the closest rawinsonde launch. The environments are characterized by moderate to high CAPE (more than 2000 J kg^{-1}) and significant low-level hodograph curvature leading to high helicity (approximately 200–400 J kg^{-1}). The high helicity distinguishes the environments of these storms from bow echo situations that have been modeled numerically using straight hodographs (Weisman 1993). Examples of these storms have been reported by Moller et al. (1990), Cummine et al. (1992), Brooks and Doswell (1993), and Smith (1993). Although there are no Doppler radar velocity observations for any of these events, there is at least some indication in the available radar reflectivity pictures and other data (interested readers should consult the references) to suggest that they were supercells. The existence of such storms in distinctive environments has been suggested by the conceptual model for low-level mesocyclogenesis of BDW94, which proposes that the storms have mesocyclones but are outflow dominated at low levels. The constructed pseudoproximity soundings provide information on those environments and are included for comparison purposes. However, since we have no hard evidence that the storms were supercells, and since the soundings are constructed, rather than observed proximity soundings, the cases are clearly distinguished in the analysis that follows and not included in the statistical comparisons.

c. *Determining proximity cases*

Our definition of a proximity case was driven by the need to obtain a reasonably sized dataset, so we began by counting the number of mesocyclone cases within a given distance to the Oklahoma City sounding site and time of the synoptic sounding times (0000 UTC and 1200 UTC). Although the total numbers of tornadic and nontornadic mesocyclones occurring within 160 km of the sounding site are roughly the same (Table 1), the tornadic cases dominate as tighter time and space restrictions are placed on the data. This is particularly true in the spatial dimension, with 64 of the 112 mesocyclones (57%) being tornadic within 160 km and 1 h, while 14 of the 19 (74%) of those within 40 km and 1 h were tornadic. If mesocyclones are uniformly distributed in space in the Oklahoma City area, we would expect a ratio of 1:4:16 events as the radius of the proximity definition increases from 40 to 80 to

TABLE 1. Distribution of mesocyclones by time and distance from synoptic sounding time (1200 UTC or 0000 UTC) from the period 1975–1990. Entries in tables are for number of mesocyclones within the time (in hours) in each row and distance (in km) in each column. The final entry is the number of mesocyclones with representative proximity soundings from the NWS rawinsonde network.

	Distance		
	40	80	160
a) Nontornadic mesocyclone distribution			
Time			
1	5	18	48
2	8	24	70
3	9	30	81
6	11	39	98
New proximity	3	10	18
b) Tornadic mesocyclone distribution			
Time			
1	14	28	64
2	16	36	86
3	16	37	90
6	21	47	105
NWS proximity	10	20	47

160 km. The nontornadic mesocyclones come relatively close to this, showing a slight bias toward more events being seen near the radar, possibly due to detection efficiency by the radar algorithm. The tornadic mesocyclones, on the other hand, are biased heavily toward events near the radar. This is perhaps due to a bias in the verification of tornadic events, with tornadoes more likely to be observed and verified in the immediate Oklahoma City vicinity in comparison to rural Oklahoma.

As a result of the small numbers of nontornadic mesocyclones near the sounding site, we chose to make the spatial proximity limit 160 km, larger than that chosen by Darkow (1969). This definition is as arbitrary as any other definition of proximity, but is driven by a desire to get a reasonably large dataset. Our choice illustrates the difficulties associated with obtaining a significant number of soundings for rare events. Because of concern with potentially rapid temporal evolution of mesocyclone environments, the temporal limit was set at plus or minus 1 h from the synoptic time. Since approximately 50%–60% of all mesocyclones in the dataset occur within 1 h of 0000 UTC, the temporal restriction did not cut out as many cases as even halving the spatial restriction would have. Each NWS sounding then was checked for its representativeness as discussed in section 2. Soundings were rejected for three primary reasons: CAPE less than 150 J kg^{-1}, CAPE less than the convective inhibition (represented by the negative area as a parcel is lifted on a thermodynamic chart), or soundings that did not extend to 300 mb. These criteria were chosen to eliminate outflow-contaminated soundings, those in which significant airmass changes had taken place (e.g., dryline or cold frontal passage), and to allow for computation of the CAPE. For no obvious reason, a much larger fraction of the nontornadic mesocyclones (30 out of the 48, 63%) within 160 km had to be discarded in this step than tornadic mesocyclones (17 out of 64, 27%). It is possible that this may indicate a different scale of relevant mesoscale processes for the nontornadic mesocyclones, although this idea has not been validated. Soundings associated with tornadic mesocyclones are more likely to have more than one mesocyclone in proximity compared to nontornadic soundings. As a result, the 18 proximity nontornadic mesocyclones are associated with 16 soundings, whereas the 47 tornadic mesocyclones are associated with 28 soundings.

As mentioned previously, 16 special NSSL soundings were used to supplement the dataset, particularly on the nontornadic side. With the further addition of the six extreme wind nontornadic storms and two tornado outbreak cases as supplemental soundings, the number of nontornadic mesocyclone soundings (after eliminating nonrepresentative soundings) was raised to 40 and tornadic mesocyclones to 52 in the final dataset.

4. Conceptual model of low-level mesocyclogenesis

The simple conceptual model of the development and maintenance of low-level mesocyclones presented in BDW94 focuses on the role of the storm-relative midtropospheric winds. The model suggests a way to parameterize the problem using important physical quantities that may distinguish between tornadic and nontornadic mesocyclones. For clarity, we include a brief summary of the conceptual model here.

Rotunno and Klemp (1984) describe the importance of baroclinic generation of vorticity in evaporatively cooled air for the development of low-level mesocyclones within supercells. Davies-Jones and Brooks (1993) show that the positive vertical vorticity is seen first within the rear flank downdraft of numerically modeled storms. BDW94 built upon those results, noting that another effect of the evaporatively cooled downdrafts is the generation of outflow, which can undercut the storm's midlevel mesocyclone. The strength and longevity of low-level mesocyclones is a function of the *balance* of baroclinic generation and outflow development. To evaluate their effects qualitatively, BDW94 looked at the horizontal redistribution of rain in numerically modeled supercells by the midlevel mesocyclone, which acts to wrap rain around the updraft, and the *storm-relative* environmental winds, which act to blow rain away from the updraft. For a given midlevel mesocyclone circulation, intensifying the midlevel storm-relative winds increases the amount of rain blown away from the updraft, thereby lessening the low-level baroclinic generation and the development of strong outflow. For very weak storm-relative, environmental winds, any low-level mesocyclones will occur early in the storm's life and will be short lived, with the outflow dominating the storm. For very strong storm-relative environmental winds, baroclinic generation will be small, but so will outflow. As a result, a low-level mesocyclone might be very slow to develop or perhaps might not develop at all, but the outflow will be relatively weak. In the middle, long-lived low-level mesocyclones might result if the mesocyclone circulation and storm-relative, midlevel winds are balanced in some sense. Thus, the model of BDW94 predicts three regimes of low-level behavior within supercell thunderstorms, depending on the balance of the midlevel mesocyclone intensity and the storm-relative winds over the vertical extent where the mesocyclone and precipitation coexist. In the conceptual model, the role of the midlevel mesocyclone in low-level mesocyclogenesis is to help produce the correct conditions at low levels by redistributing precipitation. Although it is conceptually possible for low-level mesocyclones to form in the absence of midlevel mesocyclones, it appears from observations and model simulations that convection typically does not develop low-level me-

socyclones in the absence of an existing midlevel mesocyclone.

The conceptual model suggests that it might be possible to distinguish between those environments associated with supercells that produce low-level mesocyclones and those that do not by looking at the environmental conditions associated with mesocyclones and considering parameters pertinent to the balance suggested in the model. As a measure of the tendency of the environment to support midlevel mesocyclones, we use helicity (H) defined in (1), above. Whereas previous studies have fixed the inflow depth (h) as a constant value, we have set h to be the value less than or equal to 3 km AGL that yields the greatest value of H for a given profile. An example of the vertical profile of H as h is varied, illustrating a case where h would be less than 3 km, is presented in Fig. 4. Allowing the depth of integration to vary recognizes the importance of helicity at the lowest levels in the atmosphere. It eliminates cases in which a thin layer of storm-relative backed winds might obscure the fact that the low-level environmental air is highly helical and supportive of rotating convection, as was the case in the soundings associated with the 28 August 1990 Plainfield, Illinois, tornadic storm (Doswell and Brooks 1993b). This approach should provide an upper bound on the value of the actual helicity in the air flowing into the storm. It is possible that this would lead to an overforecast of the probability of midlevel rotation within a storm. (For the most part the effect is small. Of the 92 cases presented here, only 13 had values of H that changed by more than 10%, and only 7 changed by more than 20% from the values obtained using h = 3 km.)

Defining the relevant value for the midlevel wind portion of the balance is not as easy. BDW94 used idealized hodographs and many different ways of defining the "midlevel wind" would give the same results for those idealized hodographs. With the complexity of *observed* hodographs, the issue is not so clear and different definitions might lead to a different ordering of the value of the "midlevel wind" for the hodographs. Many options exist for the definition, including the maximum wind, the minimum wind, or the average wind. For each of those options, the wind could be defined at a single level or through some depth. After investigating a number of options, we chose to use the minimum value between 2- and 9-km altitude of the storm-relative wind averaged over a depth of 1 km. Winds were interpolated to 250-m heights and converted into a storm-relative frame of reference. The average for a 1-km depth was found from 2 km through 9 km for each hodograph. The minimum value (v_{min}) then was used as our measure of the midlevel storm-relative wind. Physically, a low value for v_{min} represents a significant depth over which precipitation is not blown away from the mesocyclone, which leads to outflow dominating the low levels of the storm, cutting off the inflow.

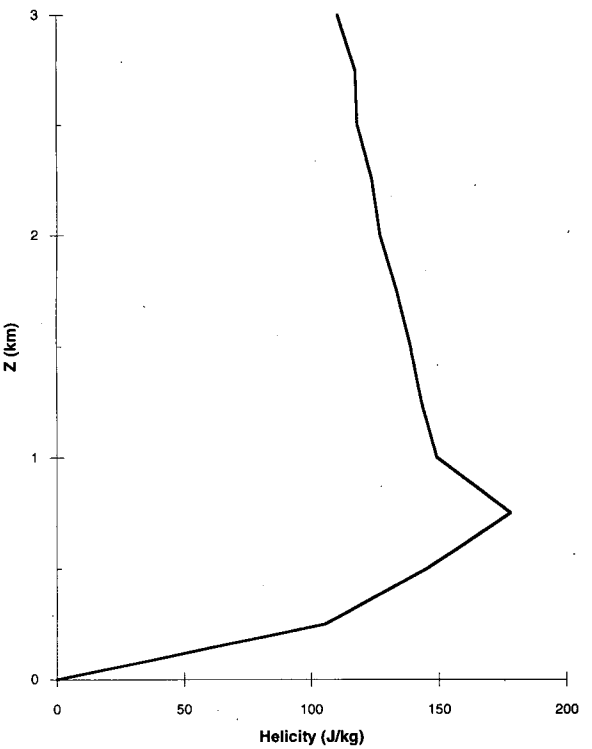

FIG. 4. Helicity (J kg^{-1}) from surface to height z calculated with winds from 0000 UTC 22 April 1985 sounding. The maximum helicity occurs with integration to 750 m.

Although they used only one thermodynamic profile in their numerical model simulations, BDW94 speculated that the thermodynamic structure could play an important role. In particular, the amount of moisture available at low levels of the storm should affect the amount of precipitation generated and, as a result, the potential for evaporation and baroclinic generation of vorticity. If an important step in low-level mesocyclogenesis is the horizontal redistribution of rain, then increasing the low-level moisture content means that the mesocyclone does not need to be as "efficient" at moving rain toward the rear flank region of the storm in order to get significant vorticity generation. Thus, the maximum water vapor content (q_{max}) in the boundary layer might be an important physical variable in low-level mesocyclogenesis. Whereas using this measure of moisture fails to take into account the potential evaporation of precipitation at low levels,[2] the soundings in the dataset tend not to be saturated at

[2] Davies-Jones and Brooks (1993) showed that the evaporation leading to the baroclinically generated low-level mesocyclone occurred in the lowest kilometer of numerically modeled supercells, so that we particularly emphasize low-level evaporation.

low levels. Thus, *for our cases,* there is sufficiently dry air at low levels for evaporation to take place and q_{max} acts as a proxy for the amount of evaporation. If our dataset, or future expansions of the dataset, includes saturated low-level environments, some measure of the relative humidity will need to be included to address the evaporation question more completely. As it is, with the present dataset, we could not distinguish any role of low-level relative humidity. Numerical model results have suggested that it is difficult to develop low-level mesocyclones in saturated environments, although a systematic study has not been carried out (Brooks et al. 1993).

5. Results

We have calculated many parameters of the soundings for all 92 mesocyclones in the dataset and will briefly present two results. Davies (1993) indicated that most strong tornadoes occur for values of Energy–helicity index (EHI) (EHI = CAPE $H/160\,000$) greater than 1 and violent tornadoes occur with EHI greater than 2.5. When EHI is calculated for our dataset (including nontornadic mesocyclones), however, it is seen that whereas EHI does a good job of defining environments with radar-observable mesocyclones, it does not discriminate well between tornadic and nontornadic mesocyclones (Fig. 5). This is not surprising; such a result is expected since the parameters leading to EHI (CAPE and helicity) are not directly related to the development of *low-level* mesocyclones. Although we have shown only this one example, similar results occur when other related combinations of low-level shear and instability are used. Identification of environments producing rotating storms appears rather good, but the discrimination between tornadic and nontornadic supercells is poor. Coupled with the Turcotte and Vigneux (1987) result, such parameters should be useful for identifying supercell environments but not determining whether supercells will produce tornadoes or not. Thus, these parameters are important in the severe weather forecasting process but additional information is necessary if we are going to make the next step in forecasting tornadoes.

Since the conceptual model of BDW94 makes predictions about the development of low-level mesocyclones within supercells by considering the "balance" between the helicity and the storm-relative midlevel environmental winds, its validation against our observations is a critical test. To make visualization of the results easier, we divided H by v_{min} to reduce the two components in the wind balance down to one variable. A large value of H/v_{min} indicates that the mesocyclone circulation should dominate the midlevel winds, leading to outflow-dominated storms in the BDW94 model. Small values of this ratio indicate domination by the environmental winds, leading to little vorticity and outflow generation.

The observations (Fig. 6) can be interpreted to reveal three regions, consistent with the BDW94 conceptual model. Tornadic storms form in the middle for a given value of q_{max} and the region of tornadic mesocyclones on the diagram slopes toward lower values of H/v_{min} as q_{max} increases. The high H/v_{min} – high q_{max} regime is dominated by the nontornadic extreme wind events, as predicted by the conceptual model. The low q_{max} regime includes the average environmental conditions for low-precipitation (LP) supercells, as described by Bluestein and Parks (1983), who pointed out that tornadoes are not characteristic of LP storms. Some simple statistical measures can be used to test the discrimination between tornadic and nontornadic mesocyclones in Fig. 6. If the results are treated as categorical forecasts of tornado/no tornado, given the presence of a mesocyclone in midlevels, then a contingency table of our results can be constructed (Doswell et al. 1990), where the forecast is based on using the subjectively determined two parallel dashed lines on Fig. 6 as guidelines of discrimination (Table 2). Considering tornadic mesocyclones as "hits" and nontornadic mesocyclones as "misses," the discrimination is quite good and offers encouragement that forecasting of actual tornadic environments, rather than midlevel mesocyclone environments, may be possible.

6. Discussion

We wish to emphasize some important concerns about our results, particularly with respect to the size of the dataset. First, there are questions about the possibility of nonrepresentative soundings that are not *obviously* nonrepresentative, as discussed in section 2. We cannot have *complete* confidence that the soundings actually represent the environmental conditions in which the storms formed. Second, the verification dataset may have errors; the strong bias toward tornadic mesocyclones in the immediate Oklahoma City area indicates the possibility that storms farther away from the urban area are not being reported in the same way as the nearby storms. It is possible that a tornado associated with a *supercell* may, in fact, not be associated with a *low-level mesocyclone* of that storm, such as in the case of "gustnadoes" and "landspouts" (Doswell and Burgess 1993). At this time, the size of the dataset for very near soundings (less than 40 km) is so small for the nontornadic mesocyclones that we cannot even test this hypothesis. Finally, there are large areas of the parameter space that have not been sampled. It is possible that those conditions occur infrequently in the atmosphere, but it also is possible that we simply have not sampled them in this limited dataset.

The proximity sounding dataset is not sufficient to test the BDW94 model adequately. An independent, larger dataset is needed with observations from other geographic locations. It is somewhat instructive to

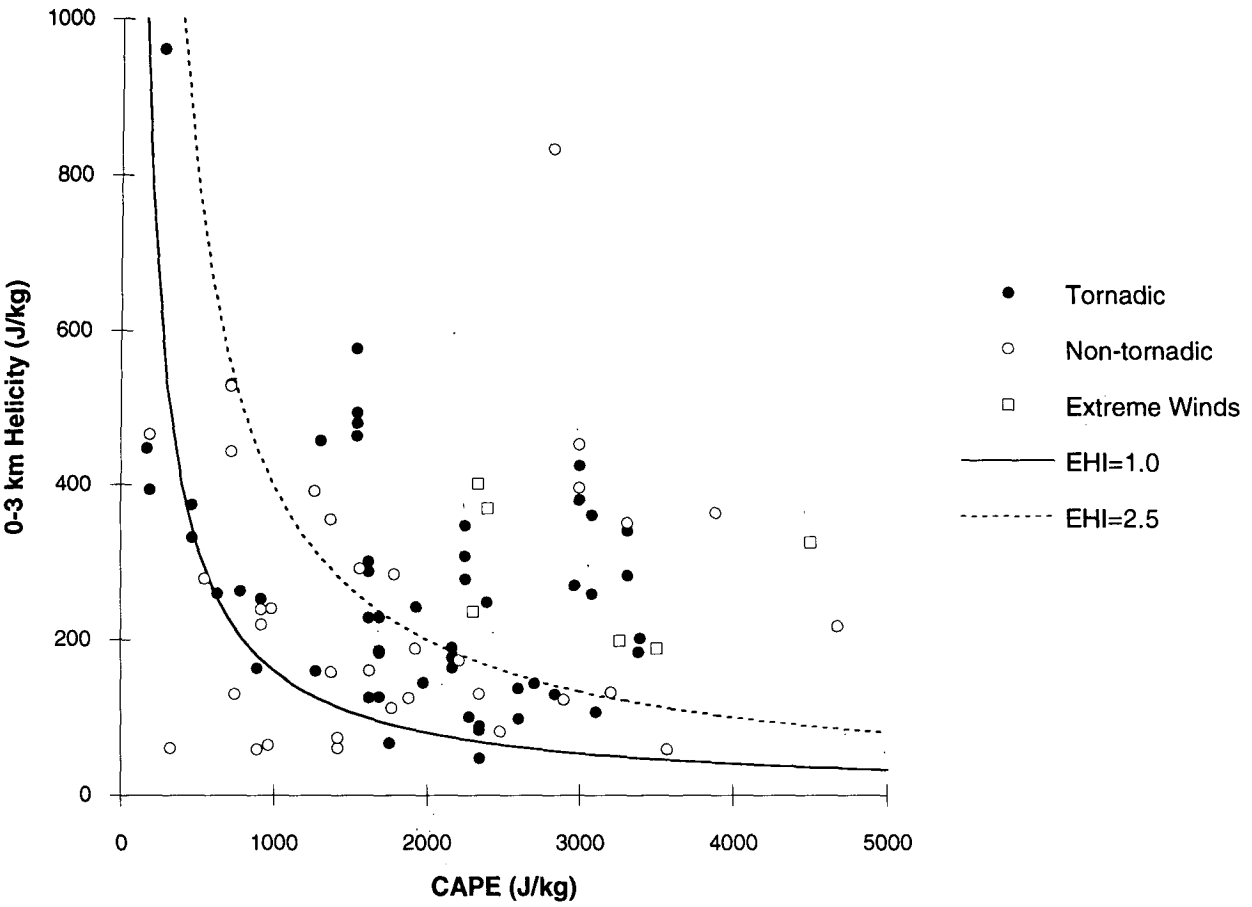

FIG. 5. CAPE and 0–3-km helicity values (both in J kg^{-1}) for proximity soundings. Energy–helicity index (EHI) isopleths of 1.0 and 2.5 are indicated by solid and dashed lines, respectively.

consider the impact of the proximity criteria we used on the future development of a dataset of proximity soundings for mesocyclonic storms, as detected by the operationally deployed WSR-88D radars. (We note that the current operational mesocyclone detection algorithm in the WSR-88D system is different than that of the NSSL work upon which our study is based. In particular, it has no time continuity constraint and, therefore, "inflates" the number of mesocyclones. This will necessitate some adjustment in future studies.) If we assume the occurrence of reported tornadoes implies the presence of low-level mesocyclones, we can use the reported tornado climatology to estimate the frequency of obtaining midlevel mesocyclone proximity soundings. In turn, this leads to an order-of-magnitude estimate of how long it would take to acquire a dataset of 250 soundings (as done by Maddox 1976). Since no climatology of nontornadic mesocyclones exists, we make the assumption that the spatial distribution of nontornadic mesocyclones is similar to that of tornadoes. On the basis of the tornado climatology of Kelly et al. (1978), about 1/17 of the total number of tornadoes that occur within 160 km of *any* of the network rawinsonde sites are, in fact, within 160 km of the site at Oklahoma City. That is, the frequency of tornado proximity soundings nationwide should be about 17 times that of Oklahoma City. Since, in the 16 years of our study, 23 *nontornadic* mesocyclones were in temporal proximity to the NWS sounding at Oklahoma City, we can use the ratio of nontornadic to tornadic mesocyclones from our study to estimate that about 25 nontornadic mesocyclones would be sampled by a proximity sounding nationally each year. Thus, it should take roughly 10 years of national rawinsonde data collection with WSR-88D observations to collect 250 nontornadic proximity soundings nationally. Given the uncertainties in developing this estimate, a bound of 5–20 years might be reasonable for gathering this large dataset. Observations in special field projects (e.g., VORTEX) could be used to supplement the dataset and decrease that time.

Turning to the question of finding proximity soundings for events observed with the operationally deployed WSR-88D radars, it is clear that the problem with obtaining a sufficient number of cases is the infrequency of soundings in both space and time, relative to the space and timescales of the events in question. By expanding the definition of "proximity" one can obtain greater numbers of proximity soundings, but presumably this would be at the expense of smearing out the results owing to temporal and spatial variability of the environments.

A potentially useful method for trying to establish proximity criteria would be to use numerical models to simulate the evolution of the environment. To begin with, a mesoscale model could be run for a large number of tornadic (or mesocyclone) events, and then the spatial and temporal variability could be assessed. To the extent that the model atmosphere behaves similarly to the real atmosphere, it could provide useful information on the atmospheric variability. This would be nontrivial because it would be necessary to stratify the cases according to the nature of the events in question; when considering tornadoes, it would be extremely important to distinguish supercell tornadoes from nonsupercell tornadoes. For mesocyclones, it might be quite relevant to distinguish between different supercell types (Moller et al. 1994).

The difficulties do not stop there, however. We have evaluated the changes in pertinent environmental parameters (e.g., CAPE and H) within a numerical cloud model that was initiated with horizontally homogeneous initial conditions. Effects of the convection cause

TABLE 2. Contingency table for categorical tornado forecasts using dashed lines in Fig. 6 as tornadic/nontornadic discriminator. Summary measures of the skill of the forecast include Probability of Detection = 0.83, False Alarm Ratio = 0.17, Critical Success Index = 0.70, and Heidke Skill Score = 0.56.

	Forecast		
	Yes	No	Total
Observed			
Yes	43	9	52
No	9	25	34
Total	52	34	86

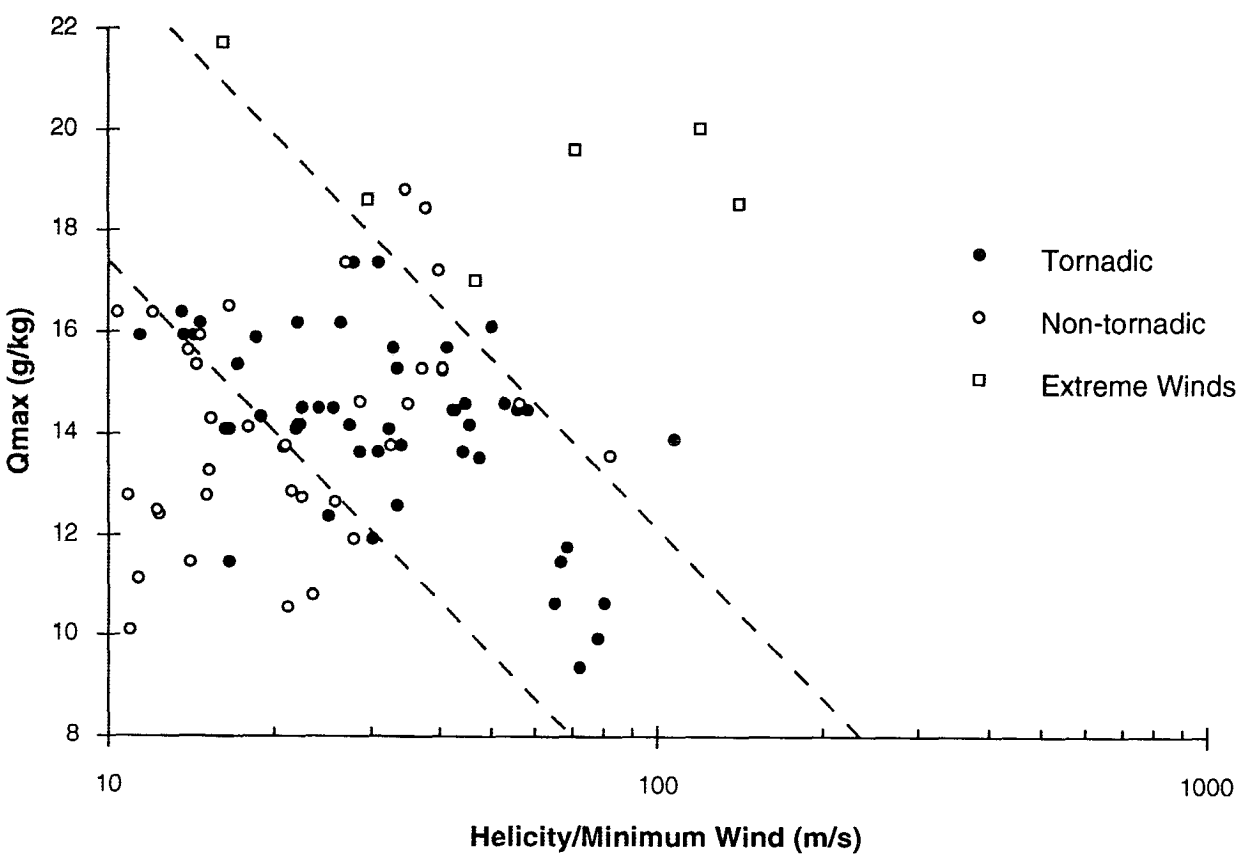

FIG. 6. The H/v_{min} (m s^{-1}) and maximum water vapor content (q_{max}) in g kg^{-1} for proximity soundings. Note that horizontal axis is logarithmic. Dashed lines delineate three regions of environmental conditions as discussed in text and used to generate categorical forecasts in Table 2.

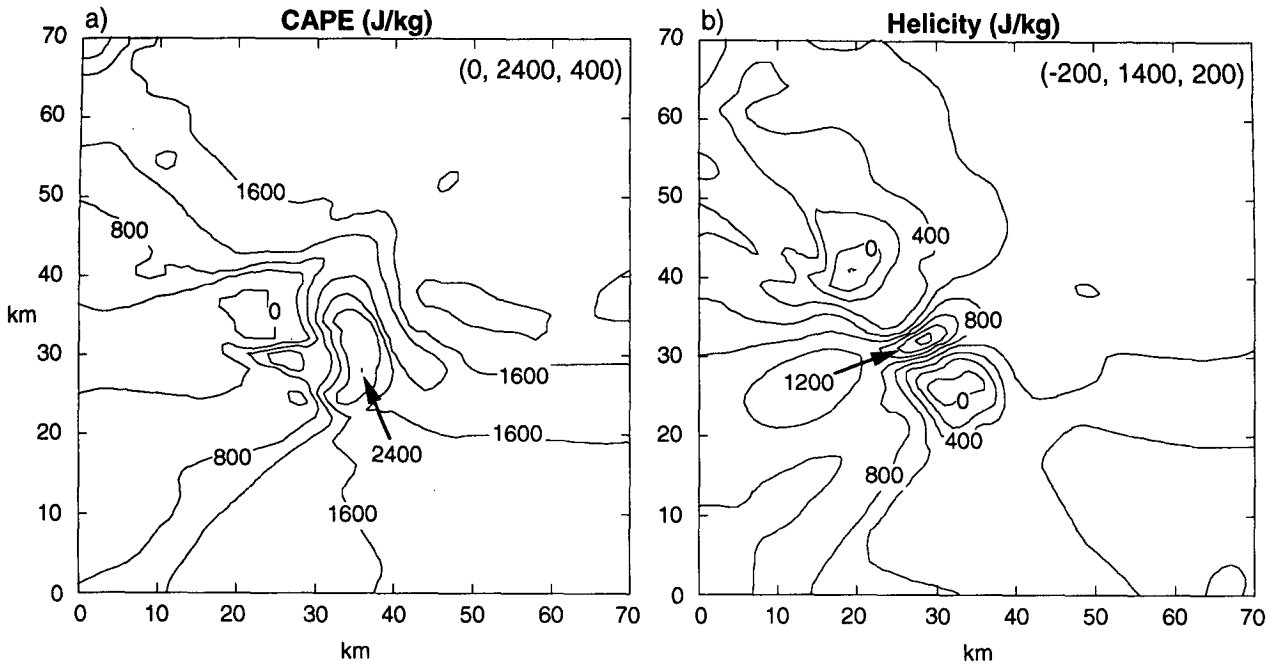

FIG. 7. Horizontal cross sections of a) CAPE and b) helicity at 7200 s of numerical supercell simulation started from horizontally homogeneous conditions with CAPE $\approx$ 2000 J kg^{-1} and helicity $\approx$ 600 J kg^{-1}. Horizontal axes labeled in km. Figures in parentheses indicate minimum contour value, maximum contour value, and contour interval in figure.

large changes in these parameters on time and space scales comparable to the convective storm and extending beyond the boundaries of the convective updraft–downdraft couplet into regions of the environment that show no obvious signs of convective contamination (Fig. 7). Thus, it is possible that a difference of only a few km in space, or a few minutes in time could result in radical differences in the associated soundings. In situations where convection is ongoing at release time, these convectively forced effects could create a great deal of concern for how to interpret the observations.

We close by emphasizing the importance of looking at the suggested pattern in Fig. 6 as a *guideline* rather than a *threshold* (Doswell and Brooks 1993a). We deliberately chose a very simple way of partitioning the parameter space and, as the dataset increases in size, it is quite possible that the actual partitioning may be more complex. Forecasters should be aware that even if the proximity soundings derived from a large dataset do provide accurate information about the nature of the storms that form, those soundings will, as a rule, not be available at the time that a forecast is completed. As a result, the challenge is to anticipate the formation of the environments and to be aware of the possible weather events associated with likely environmental conditions. We want to discourage the use of "magic numbers" as a way of forecasting what is going to occur.

Our results support the idea that in using parameters effectively for forecasting, the physical relationship between the parameters and the weather events being forecast must be understood. Whereas the parameter space analyses employing CAPE and shear parameters show skill in forecasting supercells, they have not demonstrated any skill beyond the detection of supercells at tornado/no tornado discrimination simply because those parameters are not pertinent to all of the processes leading to supercell tornadoes. Thus, they provide an important step in the forecasting process, but are not complete in and of themselves. Naturally, there is as yet no *complete* understanding of supercell tornado genesis, but the numerical simulations and observations on which the conceptual model in BDW94 is based have been given a significant test within this study and the results support the conceptual model. The conceptual model may provide another step in the forecasting process since it appears that some significant skill in discriminating between the environments associated with tornadic from nontornadic mesocyclones will be possible in the future. Development of a firmly established notion of the tornadic storm environment could well form an important part of creating tornado warning strategies using the new WSR-88D radars. Our results suggest that a strategy based on radar data alone is much less powerful than one which considers parameters based on observations of the storm environment (profilers, surface observations, etc.) *in combination* with the radar observables.

Finally, although our results show apparent skill in the tornado/no tornado discrimination task, there are some detection failures and false alarms scattered within Fig. 6. Given all the uncertainties associated with forecasting tornado occurrence, a logical suggestion would be to interpret these results in a probabilistic way. That is, within the parameter space, there are regions where the probability of a tornado is substantially higher than in other regions. We have shown a categorical interpretation with two simple straight lines; given the current limitations of the dataset, this represented the simplest possible interpretation. However, as the proximity dataset grows, future efforts should include construction of tornado probability contours in this parameter space in a systematic way.

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