

DEEP LAYER SHEAR AS A REFINEMENT TO CAPE & LOW-LEVEL SHEAR IN TORNADO FORECASTING

Jonathan M. Davies

P.O. Box 781106
Wichita, Kansas 67278

I. INTRODUCTION

CAPE (convective available potential energy) and low-level shear (i.e., helicity) are being used increasingly by forecasters in assessing potential for supercells. These parameters seem to relate well to processes associated with the development of midlevel mesocyclones, a defining characteristic of supercells (see Brooks, Doswell, & Cooper 1994, hereafter BDC94). Theoretically, streamwise vorticity in a low-level wind field with significant helicity is tilted into the vertical (Davies-Jones 1984) by a developing thunderstorm updraft in an unstable CAPE environment, inducing rotation in midlevels.

Because the majority of significant tornadoes are associated with supercells, the possibility of supercells implies the possibility of tornadoes, so that these parameters have been useful indirectly in forecasting tornadoes (e.g., Davies-Jones et al. 1990; Davies 1993). But because less than half of all supercells produce tornadoes (Burgess et al. 1993), operational experience and recent studies (see BDC94) indicate that these parameters alone contribute little to discrimination between tornadic and nontornadic supercell environments.

The modeling work of Davies-Jones and Brooks (1993) suggests that occurrence of tornadoes in supercells is connected with the development of low-level mesocyclones. Their work indicates that the origin of low-level mesocyclones is related to the baroclinic generation of vorticity within evaporatively cooled downdrafts. Brooks, Doswell, & Wilhelmson (1994, hereafter BDW94) incorporated this work into a conceptual model. This model builds on evidence that, while midlevel mesocyclones may help organize and distribute precipitation and downdrafts to set the stage for low-level mesocyclone development, low-level mesocyclones develop by different processes than midlevel mesocyclones. Because of this, it makes sense that low-level shear and CAPE are only one piece of the puzzle in assessing potential for supercells that may produce significant tornadoes.

In the conceptual model of BDW94, downdraft adjacent to and upwind of the main updraft in low levels (i.e., a rear flank downdraft) provides baroclinic generation of vorticity for low-level mesocyclone development. Intense downdrafts and resulting strong outflow are undesirable, as they would dominate the storm in low levels and inhibit the development of long-lived low-level mesocyclones. In essence, what is optimum is a rear flank downdraft that provides low-level generation of vorticity, but is not so strong as to produce intense dominating outflow.

One important element in the BDW94 model is the strength of midtropospheric winds. Stronger storm-

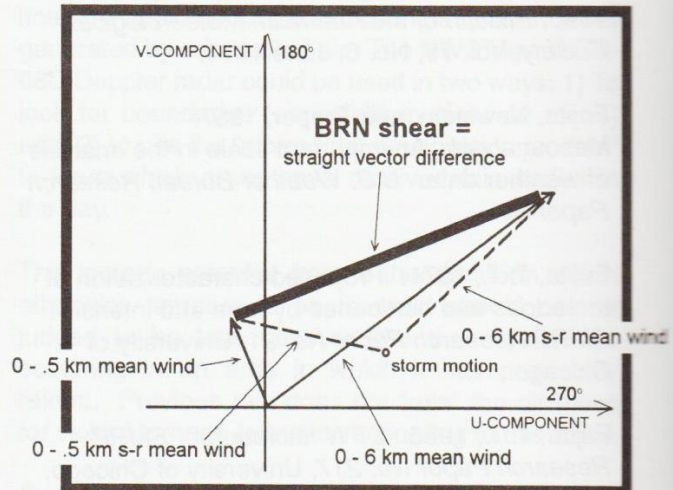


Fig. 1. Schematic showing bulk Richardson number shear (U , or BRN shear). Note that this magnitude does not change between ground-relative and storm-relative ($s-r$) frames of reference.

relative winds at midlevels would blow precipitation downwind from the updraft, discouraging development of intense downdrafts and strong outflow close to the main updraft. Hypothetically, if an "efficient" midlevel mesocyclone were to develop in such an environment, while much of the precipitation would be blown away from the updraft, some rain would still be circulated around to the storm's rear flank for non-dominating downdraft and significant vorticity generation at low levels. In such a situation, a desired balance would be achieved between midlevel winds and midlevel mesocyclone circulation, theoretically encouraging development of a significant low-level mesocyclone.

Because we are dealing with highly complex processes on the storm scale that are poorly understood and difficult to measure temporally and spatially, assessing and predicting conditions that would encourage this theoretical balance seem largely beyond the scope of operational forecasting. On the other hand, some of the storm scale processes in the BDW94 model do appear to be related to midlevel wind flow within the larger scale environment, as well as the capacity of an environment to generate midlevel mesocyclones (relating to CAPE and low-level shear). Therefore, it seems reasonable that parameters relating to midlevel winds and resulting deep vertical shear, although difficult to define operationally, could be combined with CAPE and low-level shear as a useful refinement in some tornado forecasting situations.

The purpose of this paper is to experiment informally with several parameters in this regard, including deep layer shear that is part of the bulk Richardson number (Weisman and Klemp 1982).

II. SELECTED PARAMETERS

BDC94, working from the conceptual model of BDW94, used the minimum wind speed from storm-relative (s-r) winds averaged in 1 km "slices" from 2 km to 9 km AGL as a hypothesized way to measure the capacity of midlevel winds to move precipitation downwind from an updraft. Combining this with maximum mixing ratio and helicity found in the low levels of a sounding, they developed an experimental low-level "guideline", suggested as a means for roughly assessing a balance of environmental processes that might be conducive to long-lived mesocyclone development.

This current study will include as parameters for examination both the minimum s-r midlevel wind as computed in BDC94, and their resulting guideline for low-level mesocyclone potential. To compare soundings in the absence of their Fig. 6 scatterdiagram (not shown due to space limitations), their guideline parameter space is converted to a computation as follows:

$$q_{\max}^{\text{computed}} = -4.83 \ln (H / v_{\min}) + 28.52$$

(where $H = 0 - 3$ km s-r helicity, and
 $v_{\min} = 2 - 9$ km minimum s-r wind)

$$q_{\max}^{\text{observed}} = \text{observed maximum mixing ratio}$$

$$\text{Guideline value} = q_{\max}^{\text{computed}} - q_{\max}^{\text{observed}}$$

Guideline values falling between roughly 0 and -6 correspond to a parameter space they deemed generally conducive for long-lived mesocyclone development (see Fig. 6 in BDC94).

The shear portion of the bulk Richardson number (BRN, Weisman and Klemp 1982) is also examined in this study. BRN shear (U) is the straight vector difference in wind speed between the density-weighted mean wind over the lowest 6 km and the wind in the surface layer (bottom 500 m). It is in the denominator of the BRN:

$$\text{BRN} = \frac{\text{CAPE}}{1/2 U^2}$$

U (in m s^{-1}) represents deep layer shear that would help to strengthen a storm's updraft on its right flank (Rotunno and Klemp 1982). Additionally, relating to the BDW94 model in a very simplistic sense, this straight vector difference might be viewed as an average horizontal "distance" that a "parcel" of developing precipitation particles would travel downwind as it moves upward from its entry point into a developing updraft. It is notable that the BRN shear magnitude does not vary between storm-relative and ground-relative frameworks (see Fig. 1).

In addition to these parameters, a mean storm-relative wind in the midlevels (arbitrarily chosen here as 3 to 6 km AGL) is examined for comparison.

III. DATASET

The above parameters, along with CAPE, 0-3 km s-r helicity, and the resulting energy-helicity index (EHI,

Hart and Korotky 1991) were computed for a dataset of 60 soundings associated with severe weather occurring in environments that appeared conducive to supercells. All the soundings have significant combinations of CAPE and low-level shear, suggesting potential for midlevel mesocyclone development. Recognizing the ambiguity of the idea of "proximity" (see BDC94), the soundings were chosen using criteria similar to those used by BDC94. In order to develop a dataset of workable size, a less restrictive time requirement (+ or - 3 hrs) was used.

Thirty soundings meeting these criteria, but associated with nontornadic severe or only very brief/weak tornado events, were located from 1990-1995. Because such soundings are hard to come by, they were located first, and were labelled the "nontornadic" half of the dataset. Next, another 30 soundings meeting the same criteria, but from significant or long-lived tornadic events, generally rated strong or violent and mostly from 1990-1995, were selected for comparison.

Apart from the looser time restriction for soundings, there are other notable differences here from the study by BDC94. No radar data is used directly, and storm motions are estimated based on methodology from radar observations in Davies and Johns (1993). Also, nontornadic severe cases were selected according to the observed presence of significant CAPE and low-level shear, not specific radar confirmation of a midlevel mesocyclone (although many of the nontornadic cases did involve radar-based tornado warnings). Unlike BDC94, there is no attempt to distinguish extreme straight-line wind cases. Finally, BDC94 gave no information as to length or intensity of tornadoes in their dataset. In the current study, although 7 of the "nontornadic" cases involve very brief/weak tornadoes that may or may not have been associated with mesocyclones, the primary severe weather was nontornadic. Hence, their inclusion as "nontornadic" cases. In contrast, all the tornadic cases involve long-lived or strong/violent tornadoes.

The following section suggests some highlights of comparison between the nontornadic and tornadic sounding groups.

IV. EXAMINATION RESULTS

Parameter means (\bar{x}) for the two groups (Table 1) show the tornadic half of the dataset to exhibit higher or stronger magnitudes for virtually all parameters:

Table 1.	Nontornadic \bar{x} (SD)	Tornadic \bar{x} (SD)
CAPE	2439 J kg ⁻¹ (1100)	2461 J kg ⁻¹ (1150)
Helicity	257 m ² s ⁻² (150)	387 m ² s ⁻² (190)
EHI	3.7 (1.8)	4.9 (1.8)
BRN shear	12.6 m s ⁻¹ (3.5)	15.7 m s ⁻¹ (2.8)
2-9k s-r min	9.6 kt (2.6)	12.4 kt (3.6)
3-6k s-r mean	13.7 kt (3.8)	18.5 kt (4.5)
LLmeso guide	-4.1 (4.0)	-6.0 (3.5)

Standard deviations (SD) are shown in parentheses.

CAPE and helicity combine to produce significant EHI means ($\text{CAPE } H / 160000 \geq 2.0$, see Davies 1993) for both groups, suggesting good potential for midlevel mesocyclones across the dataset, as noted earlier. Midlevel storm-relative winds (expressed in knots for this study)

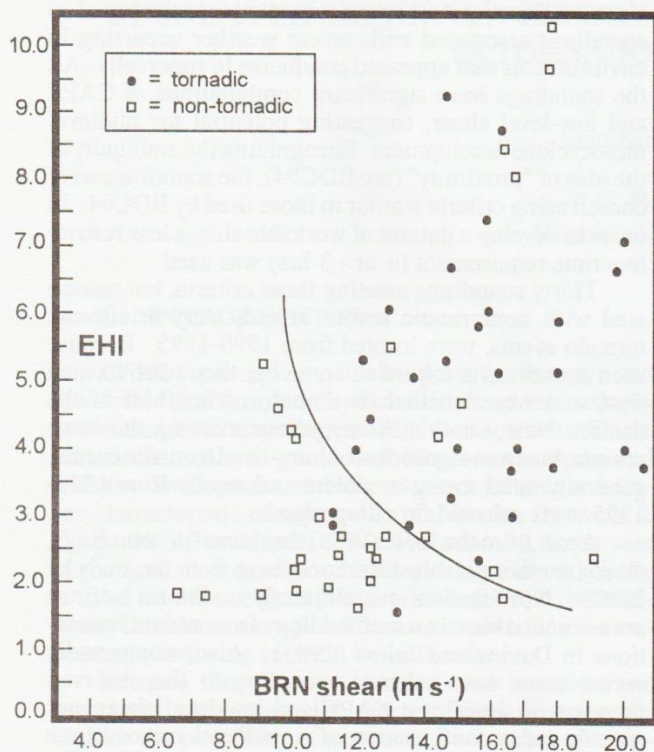


Fig. 2. Scatterdiagram showing distribution of energy-helicity index (EHI) and bulk Richardson number shear (BRN shear) for dataset of 30 tornadic (dots) and 30 nontornadic (open squares) cases (see text). Above the curve, 73% of the cases are tornadic; below the curve, only 13% of the cases are tornadic.

average higher in the tornadic subset for both the 2-9 km minimum means and the 3-6 km means, as do the BRN shear means¹. So, in a general sense, it appears that these midlevel wind parameters for the tornadic subset are "more favorable" for moving precipitation downwind from an updraft according to the BDW94 model discussed earlier.

However, the ranges of values (not shown) for the midlevel wind parameters in both groups are quite wide, so that specific distinguishing features between both subsets are not apparent at a glance. A simple statistical examination of the dataset does reveal some notable relationships. Dichotomizing the parameters related to midlevel wind as independent variables by "low" ("unfavorable") and "high" ("more favorable") values gives the following results:

Low (% cases tornadic)	High (% cases tornadic)
BRN shear < 11.0: 0%	BRN shear \geq 11.0: 61%
2-9k s-r min < 9: 25%	2-9k s-r min \geq 9: 59%
3-6k s-r mean < 13: 15%	3-6k s-r mean \geq 13: 60%
LLmeso > 0 or < -6: 53%	LLmeso 0 to -6: 46%

¹ The SHARP program (Hart and Korotky 1991) computes BRN shear as the complete BRN denominator ($1/2U^2$), rather than U alone as done here and in Davies and Johns (1993). For example, 11 m s^{-1} in this study equates to a value of $61 \text{ m}^2\text{s}^{-2}$ using the SHARP program.

Statistically, for a parameter to exhibit a practical degree of difference between tornadic and nontornadic groups, a wide difference in percentage separating the "low" and "high" categories (the epsilon) is desired, along with a large percentage of tornadic cases falling into the "high" category for that parameter. Using this criteria, BRN shear performs well in this regard among the parameters in Table 2, followed closely by 3-6 km s-r mean wind, and then 2-9 km s-r minimum wind.

Surprisingly, no distinguishing ability is seen in Table 2 using the low-level mesocyclone guideline from BDC94. Only 46% of the cases falling inside the guideline parameter space deemed "high" or "favorable" (values 0 to -6) were tornadic, while more than half (53%) of the cases falling outside the "favorable" space were tornadic.

If one uses CAPE and low-level shear (e.g., EHI) in combination with the first three parameters in Table 2, some further improvement in strength of relationships is obtained:

Low (% cases tornadic)	High (% cases tornadic)
EHI < 2.5 or BRN shear < 11.0: 9%	EHI > 2.5 and BRN shear > 11.0: 72%
EHI < 2.5 or 2-9k s-r min < 9: 21%	EHI > 2.5 and 2-9k s-r min > 9: 75%
EHI < 2.5 or 3-6k s-r mean < 13: 17%	EHI > 2.5 and 3-6k s-r mean > 13: 72%

Here, the use of EHI values > 2.5 (similar to Davies 1993) widens the epsilon for each of the three parameters, while also helping to capture over 70% of the tornadic cases. Note that the values separating "low" and "high" categories in Table 3 are only guidelines (not thresholds!) suggested by simple statistical analysis of our 60 sounding dataset.

Because BRN shear and EHI together yield the largest epsilon between "low" and "high" categories for our dataset, Fig. 2 is shown to illustrate the general relationship of BRN shear and EHI for all 60 cases using a scatterdiagram. This shows the tendency for environments involving significant tornadoes to exhibit larger BRN shear, along with more CAPE and low-level shear (e.g., EHI). Note that most of the tornadic cases fall in the right center or upper right section of the diagram.

Table 3 suggests that any of the three midlevel wind parameters shown might be useful in assessing the possibility for supercells with potential to produce significant tornadoes, particularly when combined with an assessment of CAPE and low-level shear. The next section will focus on using BRN shear and EHI in this regard.

V. POTENTIAL APPLICATION

The following brief examples suggest how BRN shear might combine with an assessment of potential for midlevel mesocyclones (using CAPE and low-level shear) to hint at more favorable areas for significant tornadoes when forecasting supercells and severe weather over a large area. These two examples make use of FD forecasts combined with current surface data (as in Davies 1993), and might be useful as "nowcast" suggestions in an

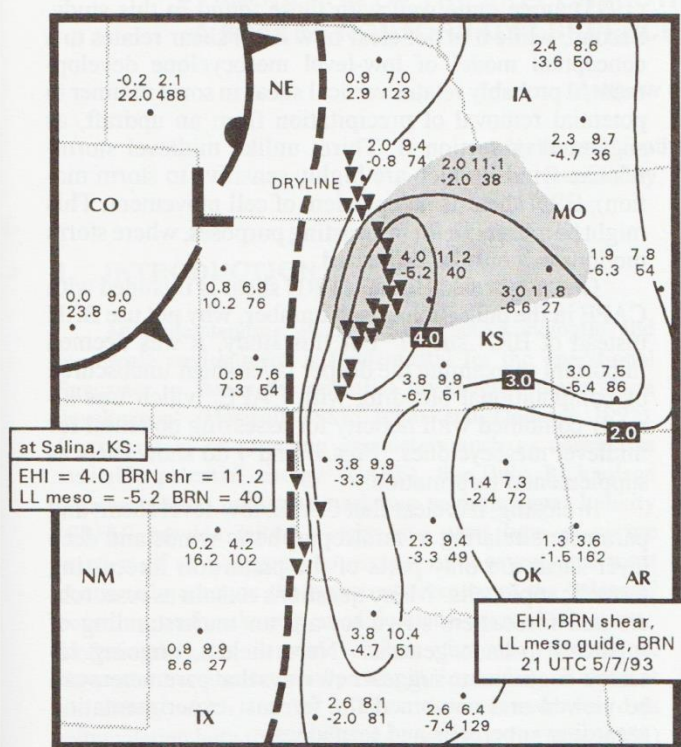


Fig. 3. Energy-helicity index (EHI), BRN shear, low-level mesocyclone guideline (from BDC94), and BRN derived by blending 21 UTC 5/7/93 surface observations with 12 hr FD forecast valid 00 UTC 5/8/93. BRN shear $\geq 11.0 \text{ m s}^{-1}$ is shaded. EHI is analyzed (solid lines) for values ≥ 2.0 and ≥ 3.0 . Surface features are shown. Tornado reports (triangles) are from Storm Data. The strongest tornadoes occurred in Kansas and Nebraska.

evolving situation. How well these examples would translate to other forecast model data (e.g., the Eta model) and a variety of forecast situations is an issue of experimentation and experience.

May 7, 1993: This day saw an outbreak of afternoon and evening tornadoes with storms stretching from South Dakota to Texas, occurring ahead of a dryline and upper trough coming out into the plains. The most significant tornadoes (some strong to violent in intensity) occurred with supercells from central Kansas into south-central Nebraska, while storms further south tended to be nontornadoic, or produced tornadoes that were brief and weak.

Fig. 3 is a mid-afternoon forecast based on the morning FD data, updated by surface observations. Note that CAPE and low-level shear appear quite favorable for midlevel mesocyclones over a large area (represented by EHI values > 2.0). However, BRN shear throughout the plains appears to be generally weak. The only exception is a maximum area of deep layer shear across part of Kansas and southeast Nebraska, where BRN shear greater than 11 m s^{-1} coincides with strong CAPE and low-level shear (EHI values near 4.0). Is it only a coincidence that this general area is where the most significant tornadoes occurred?

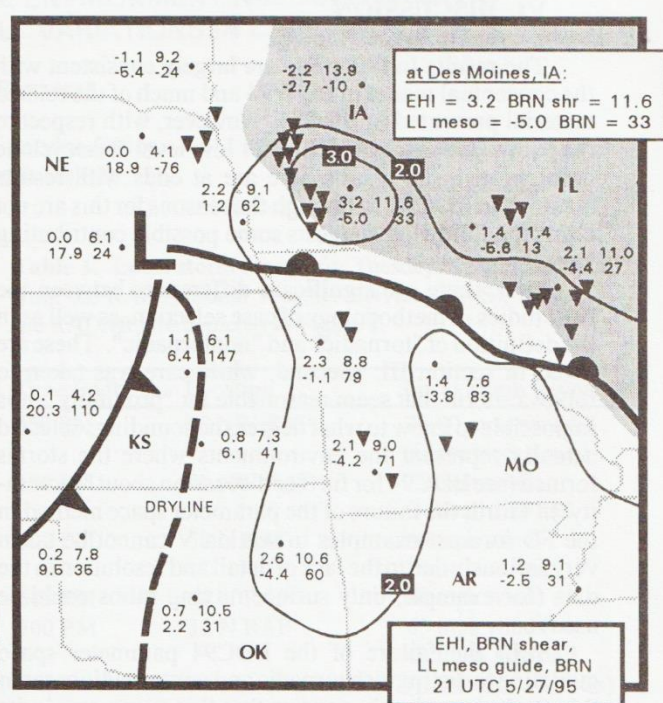


Fig. 4. As in Fig. 3, except using 21 UTC 5/27/95 surface observations with 12 hr FD forecast valid 00 UTC 5/28/95. Tornado reports are preliminary. The strongest tornadoes occurred in Iowa.

While certainly not a precise analysis relative to tornado occurrence, the BRN shear does seem to suggest a rough focus regarding supercell tornado potential in what is otherwise a widespread area of significant CAPE and low-level shear. In contrast, estimated low-level mesocyclone guideline values (as in BDC94, also shown in Fig. 3) do little to suggest a focus for tornado potential, ranging from 0 to -6 ("favorable") over a large area.

May 27, 1995: The mid-afternoon forecast based on morning FD data and updated surface observations (Fig. 4) suggests an area of significant CAPE and low-level shear (EHI > 2.0) extending along a warm front from central Illinois to central Iowa, then southward across western Missouri into northeast Oklahoma. BRN shear is significant ($> 11 \text{ m s}^{-1}$) across Iowa and Illinois, but not further south, where values are mostly weak.

In this case, tornadoes were most numerous with storms in Illinois and particularly Iowa, where several large and damaging tornadoes occurred. Storms further south in Missouri produced tornadoes that were fewer and generally weak. Although Fig. 4, like Fig. 3, is not very detailed or precise relative to specific tornado occurrence, the BRN shear does seem to suggest a better focus for supercell tornado potential north of the warm front. This is most notable over Iowa, where CAPE and low-level shear appear strongest (EHI > 3.0).

As in the previous example, the low-level mesocyclone guideline from BDC94 does not appear useful in this case as a refining parameter (Fig. 4).

VI. DISCUSSION

The results in this study are largely consistent with the conceptual model in BDW94 and much of the related material presented in BDC94. However, with respect to the parameter space guideline for low-level mesocyclone development, the results here are at odds with results obtained in BDC94. Although the reasons for this are not clear, the following suggests some possible contributing factors.

First, there are significant differences between the two studies in methodology of case selection, as well as in the definition of "tornadic" and "nontornadic". These are noted in section III. Second, while care was taken to follow criteria that seem reasonable for "proximity", it is impossible to know to what degree the soundings selected actually represent the environments where the storms formed (see BDC94 for further discussion about "proximity"). Third, the failure of the parameter space method in the FD forecast examples in section V cannot be taken very seriously due to the lack of detail and resolution in the data (for example, only surface mixing ratios could be used).

Still, the failure of the BDC94 parameter space guideline to distinguish tornadic and nontornadic cases in this study may simply suggest that this parameter in its current formulation is operationally weak for practical assessment of environment relative to the BDW94 model. The variable resolution and accuracy of current observational networks and forecast models may have much to do with this.

A specific weakness in the parameter space method appears to be the use of helicity *alone* as an indicator of an environment's tendency to support midlevel mesocyclones. As noted in Johns and Doswell (1992) and Johns et al. (1993), a substantial number of supercells and tornadoes occur in environments of high CAPE and relatively *low* helicity. The wide use of CAPE and helicity in current supercell forecasting, and the observation in BDC94 that EHI does a good job of defining environments with radar-observable mesocyclones, support the idea that the likelihood of midlevel mesocyclones may be better assessed using a *combination* of CAPE and helicity. This in turn suggests the importance of *integrating* CAPE and low-level shear with parameters that appear to relate to low-level mesocyclone theory.

The current study does suggest that there are several potentially useful parameters relating midlevel winds to the theoretical model of BDW94 *in a generalized way*. These parameters include minimum and average storm-relative winds for layers approximating the midlevels of the troposphere, and BRN shear. The results and examples in this study suggest that these parameters might be useful for tornado forecast situations when used in combination with CAPE and low-level shear.

As a refining parameter, BRN shear has several possible advantages of physical relevance for forecasting. First, BRN shear is a measure of the deeper shear known to be important in supporting strong updrafts through vertical pressure gradients (Rotunno and Klemp 1982). From this perspective, BRN shear magnitudes found to be associated with tornadic supercells in Davies and Johns

(1993) agree quite well with those found in this study. Second, while it is not clear how BRN shear relates to a conceptual model of low-level mesocyclone development, it probably relates vertical shear in some manner to potential removal of precipitation from an updraft, as suggested in section II. Third, unlike midlevel storm-relative winds (which are highly sensitive to storm motion), BRN shear is independent of cell movement. This might be a strength for forecasting purposes, where storm motions can only be estimated.

One might ask: Because BRN shear is included with CAPE in the bulk Richardson number, why not use BRN instead of BRN shear? For this study, it was deemed important to examine the deeper layer shear unobscured by computational blending with CAPE, which was already combined with helicity for assessing potential for midlevel mesocyclones. Figs. 3 and 4 do show BRN as supplemental information.

In closing, it is clear that CAPE, low-level shear, and parameters relating to midtropospheric winds and deep layer shear are only parts of the picture in forecasting tornadic supercells. Many questions remain as researchers and forecasters strive toward an understanding of supercell tornado genesis. Nevertheless, ongoing research continues to suggest new ways that parameters can be viewed and combined for forecast experimentation regarding supercells and tornadoes.

REFERENCES

- Brooks, H.E., C.A. Doswell III, and R.B. Wilhelmson, 1994: On the role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev.*, **122**, 126-136.
- , C.A. Doswell III, and J. Cooper, 1994: On the environments of tornadic and nontornadic mesocyclones. *Wea. Forecasting*, **9**, 606-618.
- Burgess, D.W., R.J. Donaldson, and P.R. Desrochers, 1993: Tornado detection and warning by radar. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 203-221.
- Davies, J.M., 1993: Hourly helicity, instability, and EHI in forecasting supercell tornadoes. Preprints, *17th Conf. Severe Local Storms* (St. Louis, MO), Amer. Meteor. Soc., 107-111.
- , and R.H. Johns, 1993: Some wind and instability parameters associated with strong and violent tornadoes. Part I: Wind shear and helicity. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 573-582.
- Davies-Jones, R.P., 1984: Streamwise vorticity: The origin of updraft rotation in supercell storms. *J. Atmos. Sci.*, **41**, 2991-3006.
- , and H.E. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 105-114.
- , D. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. Severe Local Storms* (Kananaskis Park, Alberta), Amer. Meteor. Soc., 588-592.
- Hart, J.A., and W.D. Korotky, 1991: The SHARP workstation - v1.50. A skew T/hodograph analysis and research program for the IBM and compatible PC. User's manual. NOAA/NWS Forecast Office, Charleston, WV., 62 pp.
- Johns, R.H., and C.A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588-612.
- , J.M. Davies, and P.W. Leftwich, 1993: Some wind and instability parameters associated with strong and violent tornadoes. Part II: Variations in the combinations of wind and instability parameters. *The Tornado: Its Structure, Dynamics, Prediction and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 583-590.
- Rotunno, R., and J.B. Klemp, 1982: The influence of the shear-induced vertical pressure gradient on thunderstorm motion. *Mon. Wea. Rev.*, **110**, 136-151.
- Weisman, M.L. and J.B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504-520.