

**An Examination of the Relationship of 0-2 km AGL  
"Positive" Wind Shear to Potential Buoyant Energy  
in Strong and Violent Tornado Situations**

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## 1. INTRODUCTION.

Numerical models suggest that wind shear and buoyant energy compensate for each other to some degree in the development of mesocyclone-induced tornadoes (See Weisman and Klemp, 1986). Several studies involving operational data have examined the wind shear/buoyant energy relationship in the development of tornadoes (e. g. Rasmussen and Wilhelmson, 1983; Leftwich and Wu, 1988) Most of these early studies were concerned with the wind shear in a relatively deep layer of the troposphere (e. g. 0-4 or 0-6 km AGL). Recently, however, interest has focused on the nature of the shear in the lower levels of the troposphere (0-3km AGL or lower).

The work of Bluestein et al. (1989) and others suggest that most of the air that is entrained into the rotating updraft of a tornado-producing storm cell appears to originate in that portion of the troposphere below the level of free convection (LFC). While the shear in this layer affects the strength of the rotation of the updraft (Davies-Jones, 1983), the potential buoyant energy of the air in this layer affects the upward acceleration of the updraft. Thus, both of these factors concerning the storm updraft appear to contribute to mesocyclone development.

In investigating the effects of low level shear on tornado development, Davies (1989) found that maxima in the 0-2 km AGL "positive" wind shear fields often correlate closely with areas of strong and violent tornado (F2-F5 intensity) occurrence. In this study we examine the relationship between 0-2 km AGL "positive" wind shear (PWS) and buoyant energy in strong and violent tornado situations. A comprehensive data set has been developed from a 10 year period of record. Analysis of this data set reveals several characteristics which may help a forecaster assess the potential for strong or violent tornado development.

## 2. METHODOLOGY

### A. Identification of tornado cases.

Identification of tornado cases was accomplished by systematically examining Storm Data for the 10 year period beginning on April 1, 1980 and ending on March 31, 1990. Only F2 or greater intensity tornadoes were considered as a potential case events. To qualify as an event, the tornado must be either:

i. part of an outbreak of tornadoes with a major axis of at least 100 nm in length and must include either: 1) six or more tornadoes within this outbreak area, including one F2 or greater intensity tornado and one F3 or greater intensity tornado separated by 60 nm or more, or 2) eight or more tornadoes within this area with at least three F2 intensity tornadoes with at least 60 nm between any two of them.

ii. any F3 or greater intensity tornado accompanied by a proximity sounding. For this study a proximity sounding is one in which the tornado event occurs 30 miles or less from the sounding site and one hour or less from the scheduled observation time. Also, the sounding must not be contaminated by outflow.

The "intensity" and "outbreak" criteria were employed for two reasons. One was an attempt to eliminate most of the non-supercell tornadoes (See Wakimoto and Wilson, 1989), and the other was to minimize interpolation problems.

In some of the large outbreak situations, more than one tornado event was selected as a case. The tornadoes were required to be separated by a distance of 200 nm or more or a time period of 10 hours or more. In deciding which outbreaks

should include multiple cases, consideration was given to those tornadoes of stronger intensity and efforts were made to prevent including tornadoes on the fringe of the outbreak area.

#### B. Wind shear calculations.

For consistency, we have changed the shear calculation originally used by Davies (1989) to reflect mean shear values in the same manner as in Rasmussen and Wilhelmson (1983). Their method of calculating mean shear is essentially to divide the hodograph length for a specified layer of the atmosphere by the depth of that layer. For the 0-2 km AGL layer, for example, one would divide the hodograph length (in  $m s^{-1}$ ) by 2000 m. In Davies' 1989 paper the 0-2 km layer was divided by 4000 m to accomplish a particular comparison between shear in the 0-2 and 0-4 km layers. Hence, all values for 0-2 km shear in Davies' earlier paper should be doubled to be consistent with the calculated values presented in the current study.

Also, simplified criteria for "positive shear" have been adopted for the current study. Whether a hodograph increases or decreases in speed with height depends largely on storm motion and the frame of reference. Therefore, the vertical speed change criterion utilized in Davies (1989) has been discontinued in favor of simply determining whether the wind profile turns clockwise ("positive shear") or counterclockwise ("negative shear") with height. The latter criterion is largely independent of the frame of reference. The 0-2 km hodograph is interpolated into 200 m layer increments (See Rasmussen and Wilhelmson, 1983); only the increments that do not turn counterclockwise are included in the "positive shear" calculation.

Further, we have made adjustments for hodographs exhibiting a slight backing of the winds below 400 m AGL before veering takes over above 400 m. This frictional boundary layer backing occasionally occurs (usually with 0000 UTC soundings) and will yield artificially low shear values, particularly when strong speed shear is present just above the ground level. Such situations are compensated for computationally by altering the surface winds slightly to eliminate any backing below 400 m AGL.

To make representative estimates of the 0-2 km positive shear from the operational network of radiosonde data, these general guidelines were followed:

- 1) If a tornado case occurred within 2 1/2 to 3 hours of the standard sounding time, within 65 nm of a sounding site, and within the same air mass as the sounding site, the shear value from the sounding was used directly.

- 2) For tornado cases falling within the same time range but more distant from the nearest sounding site, linear interpolation between soundings sites was employed.

- 3) For tornado cases more remote in both time and location, values were derived by analyzing the progression of surface and 850 mb wind features for the bracketing standard sounding times. Time and distance interpolation was performed by noting the apparent translation of maxima in the shear field during the bracketed period.

- 4) If key sounding data were missing, or contaminated by frontal passage or mesoscale outflow, the case was not included in the data set. In cases where only the very lowest portion of the sounding appeared to be unrepresentative (e. g., shallow outflow) substitution of uncontaminated surface wind data from a nearby station was made, and the case was included in the data set.

#### C. Buoyant energy calculations.

Values of the potential buoyant energy for soundings utilized in this study are determined by an algorithm described by Doswell, et al. (1982). The values are essentially equivalent to CAPE (Moncrieff and Green, 1972). To make representative estimates of CAPE from the operational network of radiosonde data, these guidelines were followed:

- 1) If a tornado case occurred within 1 1/2 hours of the sounding time, within 40 nm of the sounding site, and in the same air mass as the sounding site, the CAPE value from the sounding was used directly.

- 2) For tornado cases not satisfying the conditions in 1), the thermodynamic profiles of the surrounding soundings were examined. Interpolation of CAPE values between sounding sites (for both time and location) was only attempted if 1) the horizontal temperature gradients at the standard levels above the boundary layer appeared to be relatively weak, and 2) surface data and the temperature and moisture stratification in the boundary layer of the soundings indicated that any instability maximum (center or axis) associated with the case is adequately sampled by at least two nearby stations.

- 3) For tornado cases not satisfying 1) or 2), proximity soundings were constructed by using the proximity surface data, and interpolating (for time and/or location) from the surrounding soundings both the boundary layer thermodynamic profiles and the standard level data above the boundary layer. The CAPE values for these tornado cases were derived from the constructed soundings. Soundings were constructed for three-fourths (181 cases) of the cases utilized in the data set.

The procedure for determining the CAPE for a case differs considerably from that used to determine the shear value. One of the reasons for this difference is that in determining the CAPE, it was often necessary to consider the temperature profile through the depth of the entire

troposphere. Also, the thermodynamic patterns (particularly for moisture) can be quite complicated in the boundary layer. These complications required that proximity soundings be constructed in most cases in order to arrive at a representative CAPE value.

#### 4. RESULTS.

A total of 242 tornado cases were identified from the 10 year period between April 1, 1980 and March 31, 1990. The monthly distribution of cases is bimodal with a pronounced peak in the spring and a secondary peak in the fall (Fig 1). The geographical distribution of cases (Fig.2) shows a concentration along two axes: one from the southern Plains to the southern Great Lakes region and another through the Gulf coast states. The areal and temporal distribution of cases in this data set appear to be representative of the climatology for strong and violent tornadoes (Leftwich and Sammler, 1986; Fujita, 1987; and Johns and Sammler, 1989).

Figure 3 illustrates that strong and violent tornadoes are associated with an extremely wide range of both CAPE and PWS values. CAPE values range from 200 to 5300  $J\ kg^{-1}$  with about two-thirds (64%) of the cases exhibiting values between 1000 and 3000  $J\ kg^{-1}$ . Positive wind shear values range from 6.0 to 26.9  $\times 10^{-3}\ s^{-1}$  with three-quarters (75%) of the cases exhibiting values between 10.0 and 18.0  $\times 10^{-3}\ s^{-1}$ . The pattern of data points on Fig. 3 indicates that progressively stronger PWS values are required for strong and violent tornado development as the CAPE decreases. This agrees with the modeling results summarized by Weisman and Klemp (1986). The pattern also suggests that for any given CAPE value, there is a threshold minimum shear value below which strong tornado development is not likely to occur. The solid curved line on Fig. 3 represents an estimate of a "lower limit" curve connecting all of the threshold minimum shear values for the range of CAPE in the data set.

The data set displays seasonal and geographical differences in the combinations of PWS and CAPE associated with strong and violent tornado development. The cold season (November 1 to March 31) cases occur mostly in the eastern portions of the southern Plains and Gulf coastal region (Fig. 4) and exhibit CAPE values that are mostly weak to moderate (Fig. 5). Ninety-five percent of the cold season cases are associated with CAPE values of less than 2500  $J\ kg^{-1}$ .

Cases during the warm season (May 15 to August 31) generally occur farther west and north than the cold season cases (Fig. 6) and exhibit a wide range of CAPE values, from a weak 500  $J\ kg^{-1}$  to a strong 5300  $J\ kg^{-1}$  (Fig. 7). The two cases exhibiting CAPE values of less than 1000  $J\ kg^{-1}$  were associated with tropical cyclones. The two cases associated with derechos (Johns and Hirt, 1987) exhibit characteristically high CAPE values. Despite the wide range of values, note that over two thirds (68%) of

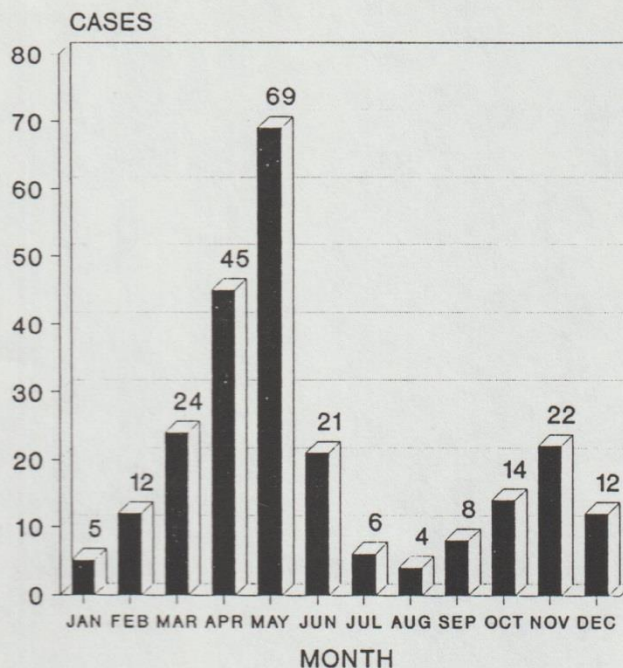


Fig. 1. Monthly distribution of all 242 tornado cases in the data set. Number above each bar is the number of cases that occurred during that month.

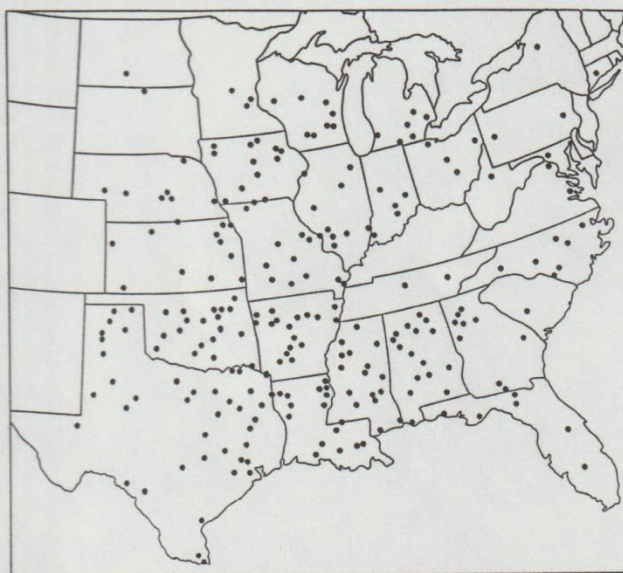


Fig. 2. Geographical distribution of all 242 tornado cases in the data set.

the warm season cases are associated with CAPE values of 2500  $J\ kg^{-1}$  or greater. This agrees with the findings of Rasmussen and Wilhelmson (1983).

Thirty-six violent tornadoes were included in the data set. Figure 8 illustrates that, as with the general data set, these cases display a wide range of CAPE and 0-2 km positive shear values. However, in most cases the violent tornadoes occur in an environment where the combination of CAPE and shear is well above the "lower limit" curve.

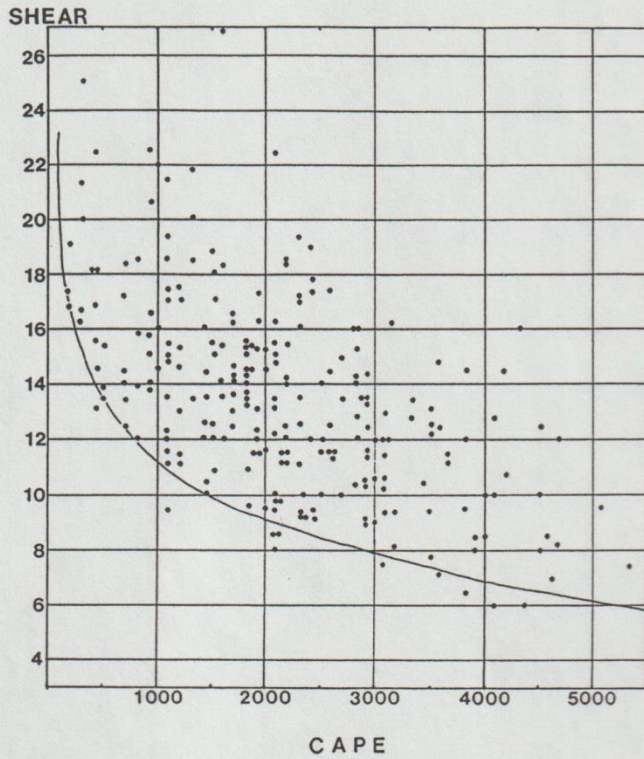


Fig. 3. Scatter diagram showing the relationship between convective available potential energy (CAPE) and 0-2 km AGL positive wind shear for the 242 tornado cases. Solid curved line is a suggested lower limit of combined CAPE/low level shear value that would support the development of strong or violent mesocyclone-induced tornadoes.

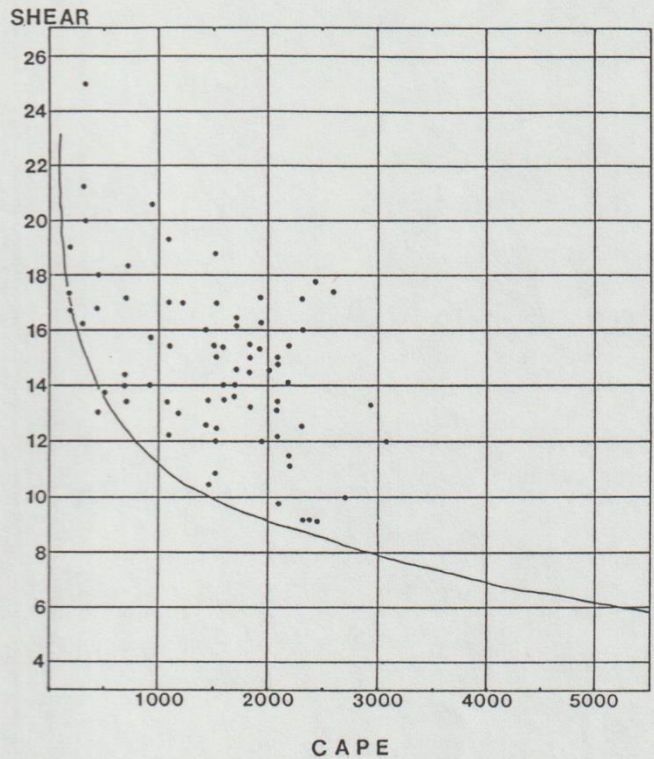


Fig. 5. As in Fig 3., except for the 75 cold season (Nov. 1 to Mar. 31) tornado cases.

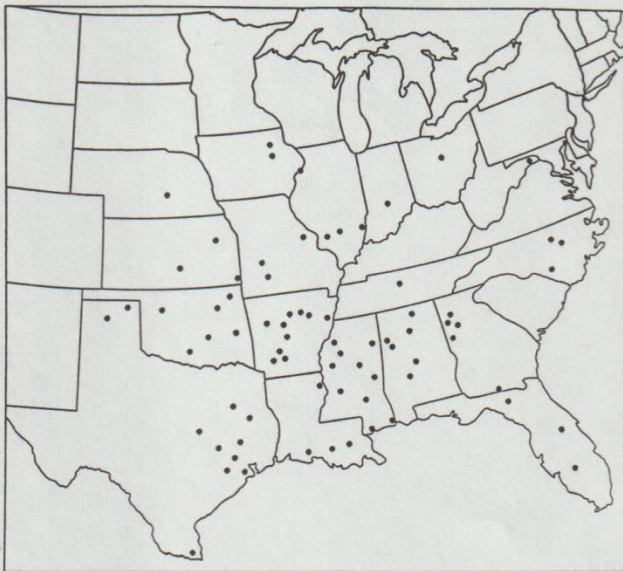


Fig. 4. Geographical distribution of the 75 cold season (Nov. 1 to Mar. 31) tornado cases.

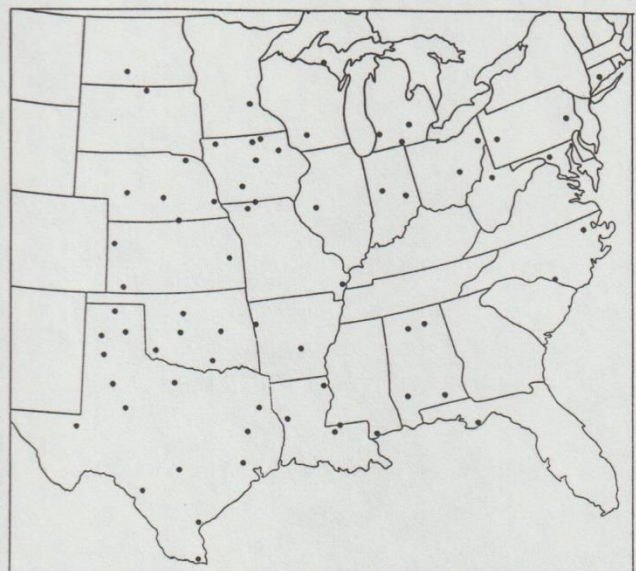


Fig. 6. Geographical distribution of the 69 warm season (May 15 to Aug. 31) tornado cases.

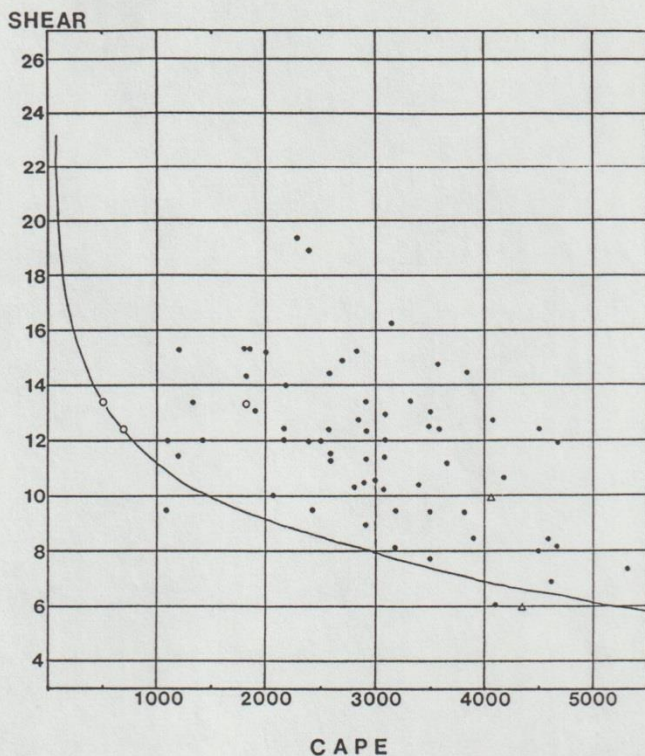


Fig. 7. As in Fig 3, except for the 69 warm season (May 15 to Aug. 31) tornado cases. The non-shaded circles represent tornado cases associated with tropical cyclones. The non-shaded triangles represent tornado cases associated with derechos.

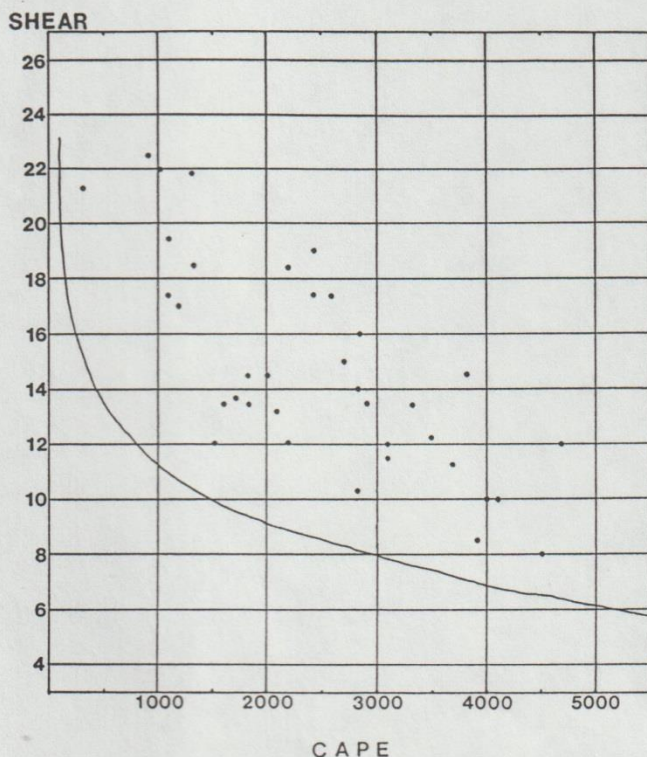


Fig. 8. As in Fig. 3, except for the 36 violent tornado (F4 and F5 intensity) cases.

## 5. DISCUSSION AND IMPLICATIONS FOR THE FORECASTER.

The results of this study strongly suggest that low level wind shear and buoyant energy compensate for each other in regard to the development of mesocyclone-induced tornadoes. Further, the pattern on Fig. 3 suggests a "lower limit" curve that defines the combination of CAPE/PWS values (ESP values; energy/shear potential values) below which occurrences of multiple strong or violent tornadoes are not likely. The results of Fig. 8 suggest that the ESP diagram may have some utility in determining the strength of a tornado outbreak situation. It appears that the likelihood of violent tornadoes (F4-F5) becomes greater the higher one goes above the "lower limit" curve.

Even though the nature of the "updraft" appears to be a key ingredient in the recipe that results in mesocyclone-induced tornado development, the forecaster must examine the effects of other contributors to get the total picture. The authors have observed some instances where the ESP value is relatively strong and no mesocyclone-induced tornadoes develop despite the presence of strong convection. In these instances, the winds in the lower midtroposphere were very weak (less than 25 kt). This suggests the forecaster must use the ESP values in conjunction with the BRI (Bulk Richardson number) calculated over a deeper layer (e. g. 0-4 or 0-6 km AGL). The latter index gauges dynamic effects on the updraft (See Rotunno and Klemp, 1982) as well as the likelihood of an updraft to be sustained in a given shear/buoyancy environment.

Forecasters should also realize that storm motion is not considered in the PWS calculations. Therefore, a supercell whose motion is deviating considerably from the average supercell motion would be "too low" on the ESP diagram because the PWS calculation would not detect the enhanced storm-relative shear. Most of the supercells that exhibit extreme deviation from the steering flow tend to be isolated events. Three situations in which operational experience suggests that such supercells are most likely to occur are: 1) with derecho producing convective systems (or rapidly moving bow echoes); 2) with tornado events in the High Plains region involving pronounced directional shear, relatively weak steering flow, and moderate to strong instability (Doswell, 1980); and 3) with thunderstorm/thermal boundary interactions (Maddox et al., 1980). The criteria in the current study were designed to eliminate such events. However, note on Fig. 7 that two derecho events were included in the data set, and the ESP value for one case falls below the "lower limit" curve.

Because of the limitations in the current operational data network (both in time and space), utility of the ESP diagram as a forecast tool is limited. NMC model forecasts of the thermodynamic and wind variables hold some hope of increasing its utility. However, the importance of

accurately measuring the atmospheric variables by remote sensing is at the heart of making better forecasts. The new technology that is coming on line during the next few years (e. g. profilers and NEXRAD) holds promise of adding utility to the ESP diagram as well as other forecast tools. The NEXRAD low level wind data may be particularly helpful in assessing the value of the low level wind shear. However, any help diagnosing the low level thermodynamic variables, particularly moisture, appears more distant. This is unfortunate since the CAPE values are particularly sensitive to the nature of the moisture profile in the lowest 100 mb layer AGL. The authors' experiences in constructing proximity soundings suggest that inferring the moisture profile from surface data only, can often be misleading.

The authors have assimilated a large data set. Future plans include testing a number of accepted and new methods of assessing the wind fields and thermodynamic parameters on the data set.

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