An Objective Basis for Forecasting Tornado Intensity

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ABSTRACT

Although violent tornadoes comprise only 2.3% of tornado occurrences in the United States, they cause 68% of the fatalities attributed to tornadoes and severe thunderstorms. Despite these statistics, no attempt is made to forecast or warn of tornado intensity. A basis for this is provided in a study of more than 200 tornado events. Tornado intensity is best related to the magnitude of the vertical wind shear in the layer between the ground and 600 hPa. The results for this and other shear parameters are statistically highly significant when the data are grouped into two or three intensity classifications. Stability, as indicated by the "lifted index," and midtropospheric relative humidity, correlate poorly with tornado intensity. The relationships established have application to tornado forecasting and nowcasting.

1. Introduction

Tornadoes occur in many parts of the world (Fujita 1973) and cause death and destruction. Major occurrences include the tristate tornado, which caused 695 fatalities on 18 March 1925 in the United States (Grazulis 1984); an event in Bangladesh on 14 April 1969, which resulted in 540 deaths (Southern 1979; World Meteorological Organization 1970); and one in the Soviet Union on 9 June 1984 which resulted in an estimated 400 fatalities (Elsom 1987).

The forecasting of severe thunderstorms and tornadoes is based on the work of Fawbush et al. (1951) and Miller (1959, 1972). Attempts have been made to refine tornado forecasting methods using proximity sounding data. Darkow and Fowler (1971) found significant differences between wind soundings close to tornadoes and those further removed. Darkow and McCann (1977) found that environmental and storm relative winds increased at all levels with increasing tornado intensity; however, Maddox (1976) found only slight differences between mean soundings associated with tornadoes, destructive tornado outbreaks, and nontornadic severe thunderstorms. Schaefer and Livingston (1988) used empirical orthogonal function

analysis and discovered differences between summer- and springtime in convective instability, conditional instability, and the strength of the veering of the winds. The strongest tornadoes occurred in spring with strong veering and convective instability. Darkow (1969) studied temperature and dewpoint soundings close to, and well separated from tornadoes and found little difference in temperature structure but significant differences in moisture profiles. McNulty (1978) showed that most severe weather (severe thunderstorms and tornadoes) occurs in association with upper-tropospheric divergence. Maddox and Doswell (1982) gave a brief evaluation of accepted forecasting techniques and Schaefer (1987) reviewed 100 yr of scientific severe thunderstorm and tornado forecasts.

Although tornadoes vary greatly in intensity, and intensity rating schemes are in use (Meaden 1976; Fujita 1981), meteorologists do not attempt to differentiate between weak and violent occurrences in their forecasts. In the United States the F-scale (Fujita 1981) rating system is used. The importance of being able to forecast tornado intensity is demonstrated by statistics in Kelly et al. (1978), which show that F4 and F5 (violent) tornadoes comprise only 2.3% of tornado occurrences, but cause 68% of fatalities due to severe thunderstorms and tornadoes. Fatalities due to flash floods and lightning are not included in these statistics. If violent tornadoes are expected, civil authorities can be alerted and plan to cope with the damage and injuries which may result. When both weak tornadoes and flash floods are anticipated the danger from the latter phenomenon may be greater, and the response

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to a tornado warning, i.e., sheltering in a basement, will increase rather than decrease the danger. An accurate assessment of tornado intensity in this situation will enable emphasis to be given to flash flood warnings. Maddox and Grice (1986) indicate a need for forecasters to know when to give less attention to phenomena such as hail, wind and tornadoes and more to forecasting flash flood events.

The purpose of this paper is to provide a basis for forecasting tornado intensity, by identifying parameters which affect intensity and establishing the relationships between parameters and the F scale. Preliminary results of this work were presented by Colquhoun and Shepherd (1985).

2. Parameters investigated

Meteorological conditions associated with the development of thunderstorms and tornadoes are well known; however, causes of variations in tornado intensity have not been determined. The parameters subsequently described have been calculated, and their association with tornado intensity tested.

a. Stability

The lifted index (Galway 1956) is widely used as a measure of moist static stability. Rather than using the mean temperature and dewpoint of the 3000 ft layer above the ground, surface conditions were utilized. This method is used operationally at the National Severe Storms Forecast Center (NSSFC) (Hales and Doswell 1982).

b. Relative humidity

Dry air at midtropospheric levels is associated with tornado and severe thunderstorm occurrence (Fawbush et al. 1951; Petersen et al. 1984). In this paper mean 700 to 450 hPa relative humidity has been calculated.

c. Tornado velocity

The velocity of a tornado may be important because of its effect on wind speeds relative to the ground. If this is the case then the damage distribution associated with tornadoes should show more severe damage on one side of the tornado path. For an eastward moving, cyclonically rotating tornado, the most severe damage should be on the southern (northern) side in the northern (southern) hemisphere. The Wichita Falls tornado (Fujita 1981; see his Fig. 18) exhibited this damage distribution. If one can assume that a tornado's translation speed (s_t) is equal to the parent thunderstorm translation speed, and ignore friction, then the wind speed relative to the ground (s) is determined from

$$s = s_r + s_t \quad (1)$$

where s_r is the tornado wind speed due to rotation.

Of course other factors can influence tornado wind speed. There may be more than one vortex within the tornado circulation (Fujita 1970). However, if these do persist and rotate around the tornado center, the most damaging winds should be from about the same direction as the tornado's direction of motion.

In the thunderstorm project, Byers and Braham (1949) concluded that nonsevere thunderstorms move with the mean wind in the cloud layer. However, the most severe type of thunderstorm, the supercell, can move from a direction markedly different to the mean wind direction and at a slower speed (Chisholm and Renick 1972). One cannot use a single method to calculate the velocity of all types of thunderstorms.

Theoretical velocities of organized severe thunderstorm and nonsevere thunderstorms have been calculated by methods which can be utilized operationally. Nonsevere thunderstorm velocity has been calculated as the mean surface to 300 hPa wind velocity. Winds below cloud base have been included because updraft air originates from these levels. Organized thunderstorm velocity has been estimated using the method of Colquhoun (1980) and a wind profile from the surface to 450 hPa. The latter method is described in the following two paragraphs. More details are in Colquhoun (1980).

The basis of the method is the simple organized severe thunderstorm model shown in Fig. 1, a vertical cross section parallel to the severe thunderstorm velocity V_s . Figure 2 is a "horizontal" cross section of the inflow to the storm. Streamlines represent the horizontal boundaries of air entering the updraft or downdraft. The wind velocity relative to the storm, where the wind field is not affected by the storm, is $V(p) - V_s$.

FIG. 1. Vertical cross section, parallel to the storm velocity V_s , of the severe thunderstorm model described in this paper. Streamlines initially at the top and bottom of the inflow to the updraft (at pressures p_m and p_o) and downdrafts (at pressures p_t and p_m) are shown.

FIG. 2. A "horizontal" cross section showing the inflow at pressure p to the updraft or downdraft, relative to a severe thunderstorm whose direction of motion is $\hat{V}_S$. Streamlines represent the horizontal boundaries of air entering the updraft or downdraft. The wind velocity relative to the storm where the wind field is not affected by the storm, is $\mathbf{V}(p) - \mathbf{V}_S$, where $\mathbf{V}(p)$ is the wind velocity relative to the ground, and the width of the winds feeding the storm in this region is D .

Here D , the width of the winds feeding the storm in this region, is assumed constant and independent of pressure (p), and is measured perpendicular to the unit vector $\hat{V}_S$.

It is assumed that

a) equal quantities of air are brought into the storm by the updraft and downdraft and that the upper limit of downdraft air is 450 hPa (after Spillane and McCarthy 1969);

b) maximum storm intensity is reached when it moves with the velocity giving the maximum rate of inflow of air to the updraft/downdraft system; and

c) relative to the storm, the updraft approaches from the front and the downdraft from the back, or vice versa.

For any storm direction of motion, the speed can be determined by equating mass flux of the downdraft to that of the updraft, i.e.,

$$-\frac{D}{g} \int_{p_m}^{p_t} (\mathbf{V}(p) - \mathbf{V}_S) \cdot \hat{V}_S dp = \frac{D}{g} \int_{p_o}^{p_m} (\mathbf{V}(p) - \mathbf{V}_S) \cdot \hat{V}_S dp \quad (2)$$

where $p_t = 450$ hPa, p_o is surface pressure, and p_m is pressure at the level separating the inflows to the updraft and downdraft, this is determined when calculating the storm speed; g is the acceleration due to gravity; and D is set at unity. The total storm mass flux (R) is given by

$$R = -\frac{D}{g} \int_{p_o}^{p_t} |(\mathbf{V}(p) - \mathbf{V}_S) \cdot \hat{V}_S| dp. \quad (3)$$

The theoretical organized severe thunderstorm velocity

is the one giving the maximum value of R . It is calculated numerically by the following procedure:

1) For each direction from 2° – 180° (in steps of 2°):

- calculate the environmental wind component in that direction for all levels from the surface to 450 hPa;
- determine the pressure weighted mean ($\bar{s}$) of those components;
- derive the total flux using the values of the components relative to $\bar{s}$.

2) The severe thunderstorm direction is that giving the largest mass flux. A negative $\bar{s}$ indicates the reciprocal of the direction as being the storm direction.

3) The storm speed is the absolute value of $\bar{s}$ for the direction giving maximum mass flux.

This method produces results comparable with some of those from more sophisticated models. Weisman and Klemp (1982) simulate storms in unidirectional wind profiles and a variety of shears. In their Fig. 6 the simulated storm moved with a velocity of 285° , 23 m s^{-1} . The method of this paper, although it does not produce the modeled motion normal to the shear vector, gave a value of 270° , 22 m s^{-1} . The splitting storm which occurred on 3 April 1964 was simulated by Wilhelmson and Klemp (1981). The right-moving tornadic storm had a velocity 244° , 13 m s^{-1} , the Wilhelmson and Klemp model produced a velocity of 249° , 18 m s^{-1} and the model of this paper 242° , 14 m s^{-1} .

d. Relative helicity

Helicity (Lilly 1986) is a quantity thought to be related to the long life, organization and energy efficiency of supercell thunderstorms. Lilly (1986) shows that rotating supercell thunderstorms are characterized by high helicity. Bluestein and Jain (1985) express relative helicity (RHe) thus:

$$\text{RHe} = \frac{(\mathbf{V} - \mathbf{V}_c) \cdot [\nabla \times (\mathbf{V} - \mathbf{V}_c)]}{|\mathbf{V} - \mathbf{V}_c| |\nabla \times (\mathbf{V} - \mathbf{V}_c)|}, \quad (4)$$

where $\mathbf{V}$ is the wind velocity and $\mathbf{V}_c$ the thunderstorm velocity. The RHe values have been calculated using observed thunderstorm velocities and theoretical velocities (see above) for nonsevere and organized severe thunderstorms. A pressure weighted mean RHe was calculated from

$$\overline{\text{RHe}} = \frac{\sum \text{RHe}(L) \cdot \Delta p}{\sum \Delta p}, \quad (5)$$

where $\text{RHe}(L)$ is the relative helicity in a given layer L . The $\overline{\text{RHe}}$ values were calculated using wind data over pressure intervals ranging from the surface to 850 hPa to the surface to 300 hPa.

e. Vertical wind shear

Vertical wind shear has long been considered important in the development of severe thunderstorms

and tornadoes. Numerical modeling work by Weisman and Klemp (1982, 1984) indicates that thunderstorm type is dependent on the magnitude of the vertical wind shear. Low shears produced short-lived single cells, moderate shears, multicell storms, and high shears supercells. Recent theories of tornadogenesis (e.g., Klemp and Rotunno 1983) have emphasized the importance of vertical wind shear generated horizontal vorticity, which is tilted into the vertical by a storm. Experimental support is provided by Rothfus (1986) who describes the generation of a tornado-like vortex in a tornado vortex chamber designed to simulate strongly vertically sheared horizontal winds.

The relationships between tornado intensity and two vertical wind "shear" parameters are presented. The first parameter INIS is proportional to the length of a hodograph between two levels. It is defined by

$$\overline{\text{INIS}} = \frac{|\sum \text{IN}(L) \cdot \Delta p| + |\sum \text{IS}(L) \cdot \Delta p|}{\sum \Delta p}, \quad (6)$$

where

$$\text{IN}(L) = V_p \sin \theta, \quad (7)$$

and

$$\text{IS}(L) = |V_p| \cos \theta - |V_{p+\Delta p}|. \quad (8)$$

Here θ is the direction difference between V_p and $V_{p+\Delta p}$, wind velocities at pressures p and $p + \Delta p$; $\text{IN}(L)$ and $\text{IS}(L)$ are, respectively, the components of wind shear in a given layer (L), normal to, and in the direction of the wind at the base of that layer; and $\text{IN}(L)$ relates to directional wind shear and $\text{IS}(L)$ to speed shear. Components of INIS are illustrated in Fig. 3.

The second parameter, ISHR, is simply the magnitude of the "shear" between the surface and the required pressure level:

$$\text{ISHR} = [(u_p - u_{p_s})^2 + (v_p - v_{p_s})^2]^{1/2} \quad (9)$$

where p_s is the surface pressure, and (u_p, v_p) and (u_{p_s}, v_{p_s}) are the horizontal components of the winds at p and p_s , respectively. The $\overline{\text{INIS}}$ and ISHR values were calculated between p and p_s where p was varied in 50 hPa increments from 700 to 400 hPa.

3. Data used

Two hundred and eleven tornado events have been studied. Sources of soundings representative of tornado environments were rawinsondes from the University of Missouri (UM) tornado-proximity sounding dataset and hand drawn analyses at 50 hPa intervals of other selected tornado events. One tornado was associated with each sounding. Data from 36 events in the UM dataset were not included in the final statistics. Reasons for their omission were lack of tornado intensity or occurrence information in the National Severe Storms Forecast Center (NSSF) data, inaccurate theoretical

FIG. 3. Illustration of the constituents of the wind shear parameter INIS (see text for definition). Winds at pressures p and $p + \Delta p$ are V_p and $V_{p+\Delta p}$ and θ is the direction difference between V_p and $V_{p+\Delta p}$; IN , one constituent of INIS is the component of the wind shear vector AB perpendicular to $V_{p+\Delta p}$. The other constituent, IS , is the component of AB parallel to $V_{p+\Delta p}$.

severe thunderstorm velocity values because of large variations in wind direction, indications from the temperature and dewpoint sounding that a tornado was associated with a dry microburst rather than a severe thunderstorm, and storm affected soundings indicated by a tornado occurring very close in time and space to the sounding release point. Table 1 shows the numbers of tornadoes in each F classification and numbers of related soundings from each data source.

The second dataset was selected to increase the total number of tornado events in the F3–F5 classification. Years given highest priority were those when state climatologists were providing damage information. Soundings were obtained by carefully hand analyzing computer-plotted charts, and extracting wind and temperature data at the location of the strongest tornado within the time criteria. If two or more tornadoes of equal intensity occurred, the one closest to chart time was chosen. For most chart times only one tornado event was used. Two or more were utilized if there was a separation of at least 90 nautical miles (nm)

TABLE 1. Sources of tornado environment sounding data. Values in parentheses are the numbers of events for which parent thunderstorm velocity data were available.

Source	Tornado intensity classification (F scale)					
	0	1	2	3	4	5
No. from Univ. of Missouri dataset.	36 (19)	48 (36)	35 (25)	13 (11)	2 (2)	1 (1)
No. from analyses	0	0	0	21	39	16
Total	36	48	35	34	41	17

between tornado events. This is a subjective estimate of the distance that would ensure that the tornadoes were in different environments. Thirteen of the tornado events initially selected could not be used because of the lack or poor quality of data near the tornado. Unfortunately, most were F5 events. Consideration was given to using the data from the sounding nearest to the tornado location; however, inspection of the analyses showed that this approach would yield inferior data in most instances. This method was adopted in a few cases where the tornado was close to a rawinsonde location and a sounding derived from the analyses would have been almost the same.

Most of the 211 tornado events occurred on different days. The greatest number of multiple-event days within a category was three of F1 intensity, each day having two events. The next most frequent category was F5 with three events on April 4, 1974 and two on April 12, 1965. The separation of tornadoes ranged from 110 to 480 nm, and on 5 of the 8 days the distance was 200 nm or more.

Although the meteorological data came from two separate sets they are considered to be compatible. Evidence supporting this view is the lineal distribution of the mean F1–F5 ISHR values shown in section 4. Neither method of determining a sounding representative of the storm environment, but unaffected by the storm, will produce a perfect product. Errors inherent in the proximity-sounding approach are due to velocity gradients between the sounding and the storm and the effect of storms on the environment. Most of the UM soundings occurred to the east of the tornado (and storm). If the Browning (1964) model is applicable to most storms then these soundings will be more representative of the low-level inflow to the storm. Mid- and high tropospheric winds would be better represented by a sounding in the southwest quadrant relative to the storm. As storms affect their near environment, a sounding in this region will not be representative of the environmental air unaffected by the storm. Maddox (1976), in studying over 250 tornado-proximity soundings found that many taken within 37 km of a tornadic storm were unusual. He thought that the intense convection had modified the wind field of many of the close-in soundings.

Errors in determining an environmental profile from analyses are mainly due to inaccuracies in the analyses, particularly when strong wind velocity gradients occur. The fact that more accurate data can be obtained from analyses rather than using the nearest sounding is shown by the standard practice in numerical weather prediction of deriving grid point data from analyses (usually objective). Also, when subjective analyses were used in aviation meteorology, it was standard practice to use them as a basis for wind forecasts.

Surface based lifted index values were calculated from the data in the UM dataset, as were mean 700 to 450 hPa relative humidities. Lifted indices for the other events were obtained utilizing surface temperatures and dewpoints at the tornado location derived from surface analyses, and 500 hPa temperatures at the same position from 500 hPa analyses.

Tornado intensities in the F0 to F3 classifications were determined from the NSSFC listings; F4 and F5 events were as determined by Grazulis (1984). Each UM proximity sounding was associated with the most intense tornado occurring within 90 nm and 90 min of the sounding location and release time, respectively. The same time constraint applied to data from the other set. Because of the small number of F5 tornadoes, the time limitations for events in this classification was extended to 3 h.

The accuracy of the tornado intensities assigned to events is not high. Kelly et al. (1978) infer this by grouping their tornado statistics into F0/1, F2/3 and F4/5 classes. McDonald and Abbey (1979) made a comparison of tornado data in the records of the University of Chicago (UC) and the NSSFC. There were significant differences in the number of tornadoes and the F-ratings assigned. Grazulis (1984) found an approximate 50% difference in NSSFC and UC events rated at F4/5 and reconciled the differences in these two datasets. He notes that there are approximately 5000 discrepancies in F0–F3 categories. Even in the reconciled dataset there are doubts about the ratings assigned to some events. Doswell and Burgess (1988) suggest that many intensity ratings may be in error by two categories or more.

The UM dataset also contains information on the velocity of the parent thunderstorm of most (94) tornadoes. Darkow (personal communication) indicates that this was derived from radar data over a 1 h period centered on the reported starting time of the tornado. The total time was broken into three overlapping 30 min periods. One 30 min period went from 30 min before tornado touchdown to touchdown time, the middle period from 15 min before touchdown until 15 minutes after, and the final period from tornado touchdown until 30 minutes after. The parent-storm movement assigned was a weighted average of the three velocities with the middle period having a double weight. Directions were rounded to the nearest 5°.

TABLE 2. Mean values ($\bar{x}$) and standard deviations (s) of $\overline{\text{INIS}}$ (m s^{-1}), ISHR (m s^{-1}), lifted index ($^{\circ}\text{C}$), 700 hPa–450 hPa relative humidity (percent), observed severe thunderstorm speed (m s^{-1}), and $|\text{RHe}|$ in tornado intensity classifications (F scale). There were few values of the last three parameters in the F4 and F5 categories; hence, means and standard deviations are not shown.

Parameter	Tornado intensity classification (F scale)											
	0		1		2		3		4		5	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
$\overline{\text{INIS}}$ surface–700 hPa	2.28	1.24	3.66	1.47	4.74	2.09	4.62	1.73	5.75	1.64	5.76	1.46
surface–450 hPa	1.63	.84	2.65	1.24	3.42	1.38	3.74	1.0	4.27	.89	4.94	.80
ISHR surface–700 hPa	8.8	4.6	14.8	5.1	17.9	6.9	18.9	6.5	22.6	5.4	23.9	4.5
surface–600 hPa	11.5	5.4	18.3	5.7	21.2	6.5	24.1	6.1	27.9	6.9	30.6	6.9
surface–500 hPa	15.1	7.2	21.1	7.2	25.3	8.8	27.9	6.9	31.6	7.1	35.9	7.8
Lifted index	–5.4	2.8	–4.6	2.7	–5.1	3.3	–5.2	2.8	–5.6	3.4	–7.2	2.8
700 hPa–450 hPa relative humidity	47.1	16.4	49.8	17.2	51.1	17.3	40.6	14.9				
Observed thunderstorm speed	9.8	4.5	14.0	6.6	18.0	8.2	16.6	5.4				
$ \text{RHe} $ lower tropospheric	.46	.26	.50	.26	.51	.29	.62	.21				
tropospheric	.31	.19	.36	.23	.43	.18	.48	.21				

4. Results

Mean values and standard deviations of parameters were calculated using data in each F classification. Those shown in Table 2 are for shear parameters calculated over intervals which best discriminate between F categories, the lifted index, relative helicity in the lower troposphere and through most of the troposphere, observed thunderstorm speed, and 700–450 hPa relative humidity. Only data from the UM dataset have been used where values in the F4 and F5 classifications are not shown. There are insufficient data here for reliable statistics.

The ability of the parameters to discriminate between F categories was tested using Student's t test. This test was used by Bluestein and Jain (1985) to decide whether environmental parameters were significantly different when various types of squall lines and isolated supercells occurred. The t value is used here to indicate the confidence that the mean values of two populations

are different. There are inaccuracies in the datasets which are discussed in section 3; however, because of the large number of tornado events, most mean parameter values should be accurate. It is highly likely that some lesser intensity events are included in the F5 category. For parameters which show increasing mean values with increasing tornado intensity, their inclusion may produce an underestimate of the true mean F5 value. In other intensity categories, one would expect the inclusion of stronger and weaker events to result in an accurate mean value.

Table 3 shows t values calculated from data in individual F classes using parameters in Table 2 which showed some discrimination. The shear parameters $\overline{\text{INIS}}$ and ISHR show the most significant results. Values of t have also been calculated for those parameters with the data grouped into three and two combinations of F classification, and the results are shown in Table 4. All are significant at less than the 0.001 probability level. Surface to 600 hPa ISHR produced the most significant results.

TABLE 3. Values of t calculated by comparing data in the F classifications shown and using parameters indicated. Significance levels (probabilities) are in parentheses.

F classification data compared	Lifted index	$\overline{\text{INIS}}$ Surface–450 hPa	ISHR			RHe		Observed severe thunderstorm speed
			Surface–700 hPa	Surface–600 hPa	Surface–500 hPa	Lower tropospheric	Tropospheric	
0/1	–1.39 (.10)	–4.29 ($<.001$)	–5.56 ($<.001$)	–5.54 ($<.001$)	–3.79 ($<.001$)	–0.62 (.60)	–0.79 (.50)	–2.50 (.02)
1/2	0.76 (.30)	–2.69 (.01)	–2.35 (.05)	–2.20 (.05)	–2.41 (.02)	–0.10 ($>.90$)	–1.31 (.20)	–2.09 (.05)
2/3	0.16 (.90)	–1.06 (.30)	–0.59 (.60)	–1.89 (.10)	–1.34 (.20)	–1.15 (.30)	–0.57 (.60)	0.50 (.70)
3/4	0.55 (.30)	–2.40 (.02)	–2.70 (.01)	–2.46 (.02)	–2.29 (.05)			
4/5	1.62 (.10)	–2.67 (.01)	–0.88 (.40)	–1.37 (.20)	–2.04 (.05)			

TABLE 4. Values of t calculated by comparing data in the two and three groups of F classifications shown using parameters indicated.

F classification data compared	INIS Surface-450 hPa	ISHR		
		Surface-700 hPa	Surface-600 hPa	Surface-500 hPa
0 and 1; 2 and 3	-6.98	-6.12	-6.95	-6.32
2 and 3; 4 and 5	-4.55	-4.25	-5.04	-4.56
0, 1 and 2; 3, 4 and 5	-9.57	-8.56	-10.18	-9.23

It is important to consider the scatter of data when assessing the usefulness of a parameter for forecasting purposes. This is done in section 5. Scatter is also incorporated in the t values of Tables 3 and 4, as population variance is a term in the denominator of the equation used to calculate t .

5. Discussion

a. Tornado intensity

The statistically highly significant results in Tables 3 and 4 associated with the vertical wind shear indices suggest, but do not necessarily prove, that vertical wind shear is the primary determinant of tornado intensity. Their credibility is enhanced by the vertical wind shear-related tornadogenesis theories of Klemp and Rotunno (1983). Additionally, Davies-Jones (1984) indicates that many of the observed properties of tornadoes are explained by the tilting and stretching of initially horizontal vortex tubes. Horizontal vorticity is dependent on vertical wind shear.

The highly significant t values in Table 3, obtained when comparing vertical wind shears in the F0 and F1 classifications, may have occurred, at least in part, because of a significant proportion of gustnado-type tornadoes (Doswell 1985, p. 108) and landspouts (Bluestein 1985; Brady and Szoke 1988) in the F0 group. These can be associated with colliding outflows from nonsevere thunderstorms rather than the type of tornado described by Lemon and Doswell (1979), produced by organized severe thunderstorms or supercells. Gustnado and landspout intensities are not related to vertical wind shear. They occur in environments of weak shear.

TABLE 5. Values of constants (a and b) in regression equations relating F-scale tornado intensities to the vertical wind shear parameters (P) shown. The form of the equations is given in equation 10. The first value (in parentheses) given of a should be used when the units of P are m s^{-1} (kt).

Vertical wind shear parameter (P)	a	b
Surface-450 hPa INIS	1.453 (0.748)	-2.57
Surface-700 hPa ISHR	0.315 (0.162)	-3.19
Surface-600 hPa ISHR	0.251 (0.129)	-3.13
Surface-500 hPa ISHR	0.222 (0.114)	-3.42

Further evidence supporting the validity of the results associated with the vertical wind shear parameters was obtained by randomly selecting dependent (about three-quarters of the tornado events) and independent (the remaining events) samples, developing regression equations using the mean dependent sample parameter values in F categories, and comparing dependent and independent sample errors. These were derived from the differences between the observed F values and those indicated by the regression equations. There was little difference between the errors of the two samples.

Regression equations were in the form

$$F = aP + b \quad (10)$$

where F is the Fujita tornado intensity, P the parameter value and a and b are constants. Values of a and b are shown in Table 5. Values of a are given for use with parameter values in meters per second or knots.

Although there were insufficient data to calculate mean values of midtropospheric relative humidity and $|RHe|$ in the F4 and F5 categories, the mean values in the other classifications do not indicate that they are strongly related to tornado intensity. Similarly, the mean lifted index values show that stability cannot be used to discriminate between tornado intensity classifications. This result is of interest in view of the find-

TABLE 6. Comparison of average absolute theoretical severe and nonsevere thunderstorm direction (deg) and speed (m s^{-1}) errors, associated with thunderstorms producing F0 to F3 tornadoes. Numbers of events in each F category are shown in Table 1 in parentheses.

Error	Tornado intensity classification (F scale)			
	0	1	2	3
Average absolute theoretical severe thunderstorm direction error (deg)	59	29	29	19
Average absolute theoretical nonsevere thunderstorm direction error (deg)	36	28	23	28
Average absolute theoretical severe thunderstorm speed error (m s^{-1})	5.4	5.6	7.3	3.5
Average absolute theoretical nonsevere thunderstorm speed error (m s^{-1})	3.7	4.7	5.0	6.4

FIG. 4. Vector mean velocities (full bold lines) of parent severe thunderstorms which produced (a) F0, (b) F1, (c) F2, and (d) F3 tornadoes. Also shown are vector mean theoretical nonsevere (full lines) and severe thunderstorm (dashed lines) velocities. Numbers of events used to calculate vector mean velocities are shown in parentheses in Table 1.

ings of Bluestein and Jain (1985) that stability is similar for most types of squall lines and isolated supercells. These two studies suggest that stability cannot be used to differentiate between various types of thunderstorms and the phenomena they produce. It should be emphasized, however, that instability is necessary for thunderstorm development, and that dry midtropospheric air is associated with the development of organized severe thunderstorms. The mean tropospheric $|\overline{RHe}|$ values are similar in magnitude to those calculated by Bluestein and Jain for supercell storms (except for the mean of the F0 events). They found significant differences between relative helicity values of supercells and storms in broken lines. High relative helicity may be necessary for rotating supercell thunderstorms.

Values of $|\overline{RHe}|$ were also calculated using theoretical severe and nonsevere thunderstorm velocities. They indicate that $|\overline{RHe}|$ is predominantly underestimated when using the theoretical nonsevere thunderstorm velocity and overestimated using the theoretical severe thunderstorm velocity. The accuracy of the results were similar in calculating lower tropospheric $|\overline{RHe}|$. The theoretical severe thunderstorm velocity produced much more accurate tropospheric $|\overline{RHe}|$ results.

b. Velocities of tornado-producing thunderstorms

The t values in Table 3, obtained by comparing observed thunderstorm speeds in the F0 and F1, and F1 and F2 classifications, are significant at better than the 95% confidence level when comparing observed severe thunderstorm speeds. However, the mean thunder-

storm speed associated with F3 tornadoes is lower than that for F2 events. This indicates that tornado intensity is not related to tornado translation speed. The small number of storms in the F3 dataset (11) suggest that this may not be a valid conclusion. Other evidence to the contrary is that mean theoretical severe and nonsevere thunderstorm velocities (not shown), calculated using the complete dataset, increase with increasing F category.

Comparison of observed and theoretical storm velocities (Table 6) shows that for the F0–F2 events the theoretical nonsevere storm velocity is a more accurate indicator of tornado-producing storm velocity than the theoretical severe thunderstorm velocity. The contrary holds for the F3 events. In most cases (see Fig. 4), the observed velocity was between the two theoretical velocities. This result is at variance with the often quoted (Doswell 1985; Browning 1986) typical supercell velocity (Chisholm and Renick 1972), where the deviation from the mean wind direction is greater than the difference between the mean wind and mean shear directions, and also with Fenner (1976) who indicates that severe thunderstorms move in the direction of the mean wind shear. However, they are in accord with the results of Bluestein and Jain (1985) who investigated nine Oklahoma supercell events.

Correlating tropospheric relative helicity with the observed difference between the surface to 300 hPa mean wind direction and the tornadic storm direction of motion showed no significant relationship for F1–F3 events. A negative correlation coefficient, significant at the 0.02 probability level, was obtained for the F0 events.

FIG. 5. Median, 25 and 75 percentile, and extreme values of (a) surface-600 hPa ISHR (m s^{-1}) and (b) surface-450 hPa INIS (m s^{-1}).

c. Operational application

The scatter in the data illustrated in Fig. 5, and the t values in Table 3 indicate that attempts to correctly forecast tornado intensity in individual F categories will not be successful. However, use of the regression equations (Eq. 10 and Table 5) and the randomly selected independent data give some encouragement. The independent data were used to derive integer F values which were compared with those observed. The integer values were obtained by giving negative predictions a zero value, those greater than 5 a value of 5, and all other predictions the value of the nearest integer. For surface-600 hPa (surface-700 hPa) ISHR, 40% (42%) of the F values derived from the regression equations were correct and 83% (72%) within one F class. Average percentages expected by chance are 17% and 44% respectively, indicating that the method has considerable skill.

If this method is used operationally, it is suggested that the threshold index values for F0 tornadoes be set at the same as those for weak tornadoes shown in Table 7. These have been set at the 25 percentile values of F0 events. These may be too low as it is almost certain that some of the F0 events were gustnadoes or landspouts. The threshold values could be adjusted on the basis of operational experience. Operationally, the results will not be as good as indicated in the previous paragraph and forecasts may need to be in two or three groups of tornado intensity categories.

Table 7 shows the values of indices to be associated with three groups of F classifications: weak, F0 and F1; strong, F2 and F3; and violent, F4 and F5 tornadoes. The ISHR values in Table 7 and subsequent tables are shown to an accuracy of 0.1 m s^{-1} . It is not implied that this accuracy can be attained. Initially, values were in knots and whole numbers, and these have been converted to meters per second.

An indication of the scatter in the three groups of data is given in Table 8, which shows the percentage of tornado events in a given category lying within and outside the values in Table 7. The narrow range of parameter values linked with strong tornadoes is partially responsible for the small percentage of these events falling within this range. Other causes of scatter, more fully discussed earlier, are the inaccuracies of the tornado intensity ratings and the wind data.

Table 9 provides information similar to Table 8, except that the data are in two groups. All of the parameters have more than 60% of occurrences within the range specified for forecasting purposes.

Given an accurate forecast of a parameter and the occurrence and rating of a tornado, what is the probability of an intensity rating in the category indicated by the parameter? Tables 10 and 11 give this information based on the data in this study for three and two groups of tornado-intensity categories, respectively. Surface-600 hPa ISHR gives the best results for both

TABLE 7. Values of parameters to be associated with three groups of tornado intensity classifications.

Tornado intensity	INIS Surface-450 hPa [m s ⁻¹ (kt)]	ISHR [m s ⁻¹ (kt)]		
		Surface-700 hPa	Surface-600 hPa	Surface-500 hPa
Weak (F0 and F1)	1.0 (1.9) to 3.1 (6.0)	5.7 (11) to 16.0 (31)	7.7 (15) to 19.6 (38)	10.8 (21) to 23.2 (45)
Strong (F2 and F3)	3.2 (6.1) to 4.0 (7.8)	16.5 (32) to 20.6 (40)	20.1 (39) to 25.8 (50)	23.7 (46) to 29.4 (57)
Violent (F4 and F5)	>4.0 (7.8)	>20.6 (40)	>25.8 (50)	>29.4 (57)

groupings of data. However, figures in Table 9 indicate that successful forecasting of strong tornadoes is unlikely using three intensity categories. Better results can be expected with two categories.

Accurate forecasts in two categories would be helpful in at least two ways. First, they would separate tornado events which produce most fatalities (F3 to F5) from the weaker occurrences. Second, a decision could be made whether a tornado watch or warning should have priority over other advices. In the United States, severe thunderstorm and tornado warnings usually have priority over flash flood warnings; but situations occur where the latter phenomenon poses the greater threat to life and property. Maddox and Grice (1986) describe an event of this nature.

Tornado-intensity forecasts made using the various methods described in this section may occasionally be incompatible. This is because the regression lines derived from the smaller dataset do not necessarily pass through index values at the divisions of the two and three groups of tornado-intensity categories. Additionally, the gradients of the regression lines are affected by the anomalously low F0 category mean parameter values. When discrepant forecasts occur, use of results from the larger dataset is recommended.

A study of values of surface-450 hPa INIS and surface-600 hPa ISHR, on 7 days when more than one

tornado event was used, suggests that they will be useful in discriminating between tornado magnitudes on multiple event days.

The use of shear parameters to forecast tornado intensity is illustrated using data on one of the most serious tornado outbreak events in recent years, which is described by Hoxit and Chappell (1975) and Miller and Sanders (1980). Figures 6(a), (b), and (c) show, respectively, the spatial distribution of the above two shear parameters and "lifted indices" over the eastern United States at 0000 UTC on 4 April 1974. The heavy dashed line encloses the locations of tornadoes of at least F3 intensity between 2100 UTC 3 April and 0200 UTC 4 April 1974. These events occurred almost exclusively where the shear parameter values were greater than those indicated in Table 9 as being necessary for tornadoes of at least F3 intensity. There are also large areas where F3 events were not reported and shear values are indicative of their occurrence. Consideration of other organized severe thunderstorm forecasting parameters, such as stability, presence of trigger mechanisms, and midtropospheric air of low relative humidity, is necessary to more closely define the location of these events using meteorological data. This is demonstrated by considering the lifted index values in Fig. 6(c). Negative surface-based lifted indices are usually required for thunderstorm development. This con-

TABLE 8. Percentage of tornado events of the given intensity having parameter values less than, within, or greater than the range indicated. Tornado events are in three intensity groups.

Parameter	Tornado intensity	Parameter range	Percentage of tornado events having parameter values less than, within, or greater than the range indicated.		
			Less than	Within	Greater than
INIS (surface-450 hPa) (m s ⁻¹)	Weak	1.0-3.1	17	61	22
	Strong	3.2-4.0	35	27	38
	Violent	>4.0	33	67	
ISHR (surface-700 hPa) (m s ⁻¹)	Weak	5.7-16.0	14	58	28
	Strong	16.5-20.6	38	26	36
	Violent	>20.6	33	67	
ISHR (surface-600 hPa) (m s ⁻¹)	Weak	7.7-19.6	14	57	29
	Strong	20.1-25.8	29	42	29
	Violent	>25.8	36	64	
ISHR (surface-500 hPa) (m s ⁻¹)	Weak	10.8-23.2	16	52	32
	Strong	23.7-29.4	35	23	42
	Violent	>29.4	34	66	

TABLE 9. Percentage of tornado events of the given intensity having parameter values less than, within, or greater than the range indicated. Tornado events are in two intensity groups.

Parameter	Tornado intensity F ratings	Parameter range	Percentage of tornado events of the given intensity having parameter values less than, within, or greater than the range indicated.		
			Less than	Within	Greater than
INIS (surface-450 hPa)	0 to 2	1.0 (1.9) to 3.6 (7.0)	12	65	23
[m s ⁻¹ (kt)]	3 to 5	>3.6 (7.0)	28	72	
ISHR (surface-700 hPa)	0 to 2	5.7 (11) to 18.5 (36)	10	66	24
[m s ⁻¹ (kt)]	3 to 5	>18.5 (36)	36	64	
ISHR (surface-600 hPa)	0 to 2	7.7 (15) to 22.7 (44)	11	71	18
[m s ⁻¹ (kt)]	3 to 5	>22.7 (44)	28	72	
ISHR (surface-500 hPa)	0 to 2	10.8 (21) to 26.8 (52)	10	66	24
[m s ⁻¹ (kt)]	3 to 5	>26.8 (52)	32	68	

straint markedly reduces the area where thunderstorms, and tornadoes greater than F2 intensity, are expected.

d. Operational application methods

The relationships established between tornado intensity and vertical wind "shear" could be utilized for both forecasting and nowcasting. As analysis is an essential step in the forecasting process, parameter values would be calculated from rawin network data then plotted and analyzed. Hourly (or more frequent) updates of potential tornado intensity could be obtained from surface wind data and either observed 600 or 500 hPa wind velocities, or prognoses at these levels.

The development of tropospheric wind profilers (Hogg et al. 1983) raises the possibility of the real-time quasi-continuous assessment of tornado intensity, utilizing a nowcasting and warning system such as the Program for Regional Observing and Forecasting Services (PROFS) (Reynolds 1982). Severe thunder-

storms could be identified from radar data using the techniques of Lemon (1977). "Shear" values derived from profiler data representative of the thunderstorm environment would be the basis of assessment of potential tornado intensity. With the report of a tornado by a spotter, the shear parameter values would also be the basis for an estimate of tornado intensity. Ideally one would need two wind profiles, one representative of winds feeding the storm updraft and the other of winds feeding the downdraft. This assertion is supported by the tornado mean proximity soundings of Maddox (1976), which show that mean winds relative to the storm veer through at least 90 deg between the surface and midtroposphere, and the observed spatial variability of winds in many tornado environments. Because of the spatial and temporal variability of wind profiles it would be important to have a dense network of profilers.

Successful operational forecasting using the results of this study will depend on accurate prediction of shear parameter values. Mesoscale numerical models, such as developed by Gauntlett et al. (1984) and Leslie et al. (1985) could be utilized to produce forecasting pa-

TABLE 10. Percentage of tornado events with values of parameters in the given range which were classified as weak, strong or violent.

Parameter	Parameter range	Tornado intensity		
		Weak	Strong	Violent
INIS (surface-450 hPa) (m s ⁻¹)	<1.0	100		
	1.0 to 3.1	65	31	4
	3.2 to 4.0	26	40	34
	>4.0	10	36	54
ISHR (surface-700 hPa) (m s ⁻¹)	<5.7	100		
	5.7 to 16.0	59	33	8
	16.5 to 20.6	32	40	28
	>20.6	10	34	56
ISHR (surface-600 hPa) (m s ⁻¹)	<7.7	85	15	
	7.7 to 19.6	65	24	11
	20.1 to 25.8	31	47	22
	>25.8	7	32	61
ISHR (surface-500 hPa) (m s ⁻¹)	<10.8	92	8	
	10.8 to 23.2	62	30	8
	23.7 to 29.4	37	33	30
	>29.4	10	39	51

TABLE 11. Percentage of tornado events with values of parameters in the given range, which were classified in the F ranges 0-2 and 3-5.

Parameter	Parameter range	Tornado intensity	
		F0-F2	F3-F5
INIS (surface-450 hPa) (m s ⁻¹)	<1.0	100	
	1.0 to 3.6	75	25
	>3.6	30	70
ISHR (surface-700 hPa) (m s ⁻¹)	<5.7	100	
	5.7 to 18.5	70	30
	>18.5	33	67
ISHR (surface-600 hPa) (m s ⁻¹)	<7.7	100	
	7.7 to 22.7	77	23
	>22.7	24	76
ISHR (surface-500 hPa) (m s ⁻¹)	<10.8	100	
	10.8 to 26.8	73	27
	>26.8	32	68

FIG. 6. Values of (a) surface to 450 hPa INIS (m s^{-1}); (b) surface to 600 hPa ISHR (m s^{-1}); and (c) "lifted index" ($^{\circ}\text{C}$) over eastern United States at 0000 UTC on 4 April 1974. The heavy dashed line encloses the locations of tornadoes of intensity F3 or more between 2100 UTC 3 April and 0200 UTC 4 April.

rameters in the way described by Mills and Leslie (1985). As the tornado-intensity parameters alone are not sufficient for forecasting purposes, other parameters would need to be considered. Colquhoun (1987) has produced a decision-tree method of forecasting thunderstorms, severe thunderstorms, and tornadoes. Shear parameter values would be used at steps 6, 8 and 9 in the decision tree, to decide on the occurrence of organized severe thunderstorms and the intensity of tornadoes. Because of the suspected presence of gustnado and landspout events in the database used in this study,

there is considerable doubt about whether the base shear values will separate organized severe thunderstorms from other types. As suggested earlier, the threshold values could be adjusted on the basis of operational experience. Also, further work is planned, aimed at achieving this separation in the dataset used here.

6. Conclusions

Two hundred and eleven tornado events have been studied to determine the relationships between tornado

FIG. 6. (Continued)

intensity, as indicated by the Fujita intensity scale, and meteorological parameters. Meteorological data used were tornado proximity soundings from the University of Missouri and soundings at tornado locations derived from analyses.

Tornado intensity was found to be most strongly related to the magnitude of the vertical wind shear between the surface and 600 hPa. Results associated with this and other shear parameters were statistically highly significant, according to the t test, when the data were grouped into weak, strong and violent tornado categories. Tropospheric relative helicity was not strongly related to tornado intensity; however, high mean values were associated with F1 to F3 events. Midtropospheric

relative humidity and "lifted index" also displayed a limited ability to discriminate between tornado-intensity classifications. Tropospheric relative helicity and midtropospheric relative humidity results were obtained from datasets having few F4 and F5 events. Some results indicated that more intense tornadoes were associated with faster-moving parent thunderstorms. Further observed storm velocity data relating to F3 to F5 tornadoes are required before firm conclusions can be drawn.

The results could provide a basis for forecasting the intensity of tornadoes in two or three groups of tornado intensity categories, but must be used in association with other essential forecasting parameters. Accurate

FIG. 6. (Continued)

wind forecasts would be necessary. Their maximum utility may be in a short term warning mode where the magnitude of the surface to 600 or 500 hPa wind "shear" could be used, based on surface hourly data and analyses or prognoses at the upper levels. Nowcasting systems such as PROFS, incorporating data from a dense tropospheric wind profiler network, could be utilized to calculate parameter values which would then be a basis for estimating the intensity of reported tornadoes or those produced by thunderstorms identified as severe. A particularly useful application will be in situations where both tornadoes and flash floods are likely. Accurate assessment of tornado intensity will

enable forecasters to decide whether a tornado or flash flood warning should have priority.

Given the large number of tornado events in the full dataset, there is a high degree of confidence in the validity of the results obtained using it. Confidence is further enhanced by the results of a regression analysis of randomly selected dependent and independent data selected from the complete dataset.

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