

ON THE USE OF SHEAR MAGNITUDES AND HODOGRAPHS IN TORNADO FORECASTING

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1. INTRODUCTION

Wind profiles in the low and mid tropospheric levels have long been known to be important in tornado development. Studies by Fawbush and Miller (1954) and others have shown that winds that veer directionally and increase in speed with height are a key element of tornadic thunderstorm environments. In severe weather forecasting, such wind shear has been largely inferred subjectively from comparing winds in the low levels (i.e. 850mb) to winds in the mid levels (i.e. 500mb).

In recent years, a few studies have addressed wind shear operationally from a quantitative standpoint by examining the specific magnitude of shear between surface and 4 km AGL (above ground level) in tornado situations. Rasmussen and Wilhelmson (1983) related 1200 GMT hodographs to mesocyclone formation and tornadic thunderstorms. Their work indicated a 0-4km AGL shear magnitude of $4 \times 10^{-3} \text{ s}^{-1}$ as a rough minimum shear guideline for tornadic thunderstorms, given sufficient instability and a clockwise curving hodograph (Davies-Jones, 1983). Referencing the same data, Weisman and Klemp (1986) suggested that tornadic thunderstorms occur in regimes of wind shear in excess of $3.5 \times 10^{-3} \text{ s}^{-1}$, and characterized such shear magnitudes as "moderate to strong". Leftwich and Wu (1988), using a different computational method, found violent tornadoes to be associated with wind shears generally in excess of 10 m s^{-1} in the 0-4km AGL layer. They developed an index combining shear and instability as a forecast tool in determining F4 to F5 intensity tornado potential over areas where tornadic thunderstorms were expected.

The above studies have all utilized 0-4km AGL wind shear. Research concerning storm processes and models of thunderstorms suggests it may be more appropriate to look at shear within a lower layer, such as 0-2km AGL. In his refinement of the descriptive model of supercell thunderstorms, Marwitz (1972) indicated that the most intense thunderstorm updrafts have their roots in the subcloud layer. A recent study by Bluestein et al. (1989) discussed a sounding released directly into the updraft and wall cloud of a tornadic thunderstorm in the Texas Panhandle. The lapse rate was found to be essentially "wet adiabatic" above the level of free convection (LFC), which was measured at roughly 1.5 km AGL. This suggests that virtually no entrainment affected the core of the updraft above the LFC. It then seems reasonable to assume that, in most cases, the primary air entrained into a supercell thunderstorm updraft originates from the layer within 2 km of the ground.

Davies-Jones (1983) identified tilting of cyclonic streamwise vorticity (associated with clockwise turning hodographs) as an origin of thunderstorm rotation. If the primary air entrained and tilted into the updraft is from the 0-2km AGL layer, then the nature of the wind fields in this layer should have an important effect on storm rotation. This idea receives support from the modeling experiments of Klemp and Wilhelmson (1978), which suggested that the type of storm that develops in a given wind environment was most responsive to hodograph changes in the 0-2km AGL layer. Marwitz (1972) noted that the strongest veering and wind shear in supercell thunderstorm environments was in the subcloud layer. McCaul (1988), in comparing tornadoes produced by hurricanes to

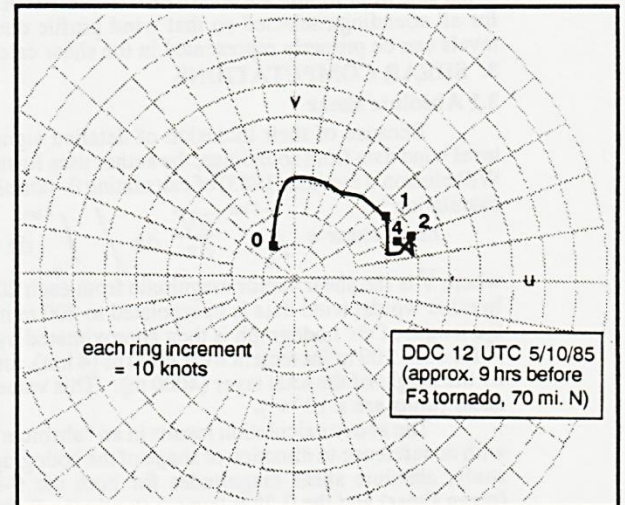


Fig 1. Dodge City, KS 0-4km AGL hodograph, 12 UTC 5/10/85.

Great Plains tornado episodes, found that the principle similarity in the strength of the wind shear values was in the lowest 2.5 km.

Qualitatively, the author has observed that a large portion of the hodograph length for soundings associated with tornado situations often resides in the bottom 2 km AGL. The hodograph preceding the strong tornadoes in north central Kansas on 5/10/85 is one such example (see Figure 1). More than 85% of the hodograph length is below 2 km AGL. An investigation to determine whether similar shear distributions occur commonly with tornadic hodographs seems appropriate.

In this study, the nature and magnitude of the 0-2km wind shear will be examined in relation to tornado development. Comparisons are made with 0-4km shear magnitudes, and diagnostic potential in forecasting is considered. All references to atmospheric layers in this paper (e.g., 0-2km or 0-4km) are understood to be above ground level (AGL).

2. CASES SELECTED

The author has chosen to examine only those situations that involve strong or violent tornadoes (F2 or greater intensity). This is done because such situations usually involve multiple tornadoes and cover a larger area in space and time. Therefore, the shear values obtained from proximity RAOB stations are more likely to be representative of wind environments where the tornadoes are occurring. This will avoid much of the "noise" contributed by weaker tornadoes, many of which develop from conditions independent of the larger scale shear profile (e.g., landspouts and gustnadoes).

To obtain a data set representative of varied situations, cases have been selected from all months of the year and from most sections of the country east of the Rocky Mountains. Fifty-four tornado cases of F2 or greater intensity have been selected from recent years (1980-1989). Each tornado occurrence is considered a case. In several instances, two or more cases from the same tornado outbreak or group of tornado occurrences

are used, each as a separate case.

The cases are evenly distributed east and west of the Mississippi River (27 occurrences each for both areas). Thirty-two cases occur during the cool season, and 22 cases occur during the warm season. Cool season is defined as November through April, warm season as May through October, after Johns and Sammler (1989). Four tornado occurrences associated with two hurricanes are included to represent shear characteristics for hurricane-induced tornadoes.

Soundings are selected that are generally closest in time and space to the tornado occurrence, either during or before, in the surface warm sector or immediately north of the surface warm front. "After" soundings are included for a few cases where the shear increased dramatically between sounding times. Wind data from significant level PPBB transmission is available for all soundings selected so that wind profile details in low levels can be properly represented in the shear calculations.

3. SHEAR COMPUTATIONS

3.1 Absolute shear

Because of their inclusion of detailed significant low level wind data from soundings, the author uses Rasmussen and Wilhelmson's method (1983) of calculating 0-4km shear. Their calculation is:

$$\text{mean shear} = \int_0^{4\text{km}} \frac{\partial \vec{V}}{\partial z} dz \Big/ \int_0^{4\text{km}} dz$$

where \vec{V} is the shear vector magnitude from each 200 m layer. In other words, wind data is interpolated to 200 m increments; the length of the hodograph is then approximated by summing \vec{V} for each 200 m increment over 4000 m (4 km), and dividing by the height of the total layer (4000 m). This value is a mean shear (units are $\times 10^{-3} \text{ s}^{-1}$).

The above calculation results in an "absolute" quantity, with no reference to direction or shape of the hodograph. In this study, absolute shear magnitudes for both the 0-4km layer (mean shear) and the 0-2km layer (actually the 0-2km portion of the 0-4km mean shear) are calculated for comparison purposes to see how much of the shear in each case occurs in the 0-2km layer.

3.2 Positive Shear

From the work of Davies-Jones (1983), it is clear that the shape of the hodograph is very important regarding processes that initiate rotation. Ideally, for a truly useful calculation of shear, hodographs that curve dominantly clockwise and increase in speed with height should be "maximized" in value, while hodographs that exhibit a significant degree of counterclockwise curvature and/or decrease in speed with height should be "discounted" in value.

A simple way of accomplishing this has been suggested by Robert Johns (1989) at the National Severe Storms Forecast Center. His idea is to include in the shear calculation only those segments of the hodograph that curve clockwise, and which maintain or increase speed with height. This approach will emphasize only those parts of the hodograph that contribute in a seemingly desirable or "positive" way toward a wind shear profile conducive for tornado development.

The following simple algorithm is then suggested: If the end point of a shear/hodograph segment is more than 5 degrees less directionally than the start point (indicating significant counterclockwise curvature), or is less in speed than 95% of the speed of the start point (indicating significant speed decrease with height), the shear/hodograph segment is *not included* in the calculation of the shear magnitude. The resultant value from this method of computing vertical shear is called "positive" shear.

Positive shear magnitudes are calculated for 0-2km and 0-4km to see if meaningful or useful values are obtained. As with absolute shear, the amount of positive shear in the 0-2km layer is compared with shear in the deeper 0-4km layer to see how much of the positive shear resides in the 0-2km section of the hodograph for each case.

4. RESULTS

Fifty-five soundings were used for shear calculations in 54 tornado cases (case #44 uses two soundings). The results are listed in Table 1. (The soundings marked with footnotes in cases #24 and #46 are listed only to illustrate how shear can increase between sounding times, and are not included in this discussion or in Table 2.) To make the data more meaningful, cases are listed in seasonal order beginning with cool season and progressing through warm season.

Some statistical results from Table 1 are summarized in Table 2. These are broken down by cool season and warm season to give emphasis to potentially representative seasonal values.

While detailed analysis of the data in Tables 1 and 2 is not attempted here, some important points are noted:

1. In 52 of 55 soundings used in the Table 1 shear calculations, the largest portion of the vertical wind shear magnitude through 4 km AGL is found in the 0-2km layer.

2. A seasonal variation in shear magnitudes associated with the tornado cases is evident. For example, the absolute shear average values for cool season in Table 2 are approximately $2 \times 10^{-3} \text{ s}^{-1}$ larger than those for warm season.

3. In all cases, the positive shear values retain most of their magnitude relative to the absolute shear values. This means that hodographs for the soundings in Table 1 predominantly exhibit an increase in speed and veering with height, as would be expected with tornadic hodographs.

The information in Tables 1 and 2 suggests some preliminary seasonal threshold values for shear on the subsynoptic scale associated with strong or violent tornado development. Noting the lowest values and corresponding comments listed in Table 2, the following threshold values are suggested:

0-2km shear:	$6.0 \times 10^{-3} \text{ s}^{-1}$ in cool season
	$4.0 \times 10^{-3} \text{ s}^{-1}$ in warm season
0-4km shear:	$8.0 \times 10^{-3} \text{ s}^{-1}$ in cool season
	$6.0 \times 10^{-3} \text{ s}^{-1}$ in warm season

Because positive shear corresponds well with absolute shear in tornado situations, the same general threshold values should apply for positive shear as for absolute shear.

It should be noted that a few cases examined do not fit the suggested guidelines. For example, the 0-2km absolute and positive shear values in cases #28 and #29 in Table 1 are significantly lower than the cool season $6.0 \times 10^{-3} \text{ s}^{-1}$ threshold suggested. This might be explained by the fact that these two exceptions are late April cases; as such they may possibly exhibit characteristics more representative of warm season than cool season. Johns and Sammler (1989) find that stronger instability is associated with violent tornado cases in the warm season, which may compensate for lesser shear magnitudes. Because strong instability cases can also occur in the cool season (though they are less common then), such cases may need to be treated as warm season cases. The specific cases in question probably fall into this category, in which case the shear values would fit the suggested guidelines quite well. This emphasizes that cool season thresholds, particularly in seasonal transition months, need to be used with caution and judgement according to the characteristics of the situation.

Johns and Sammler (1989) also show that the geographical frequency of violent tornado outbreaks has a distinct seasonal variation. They find that the axis of warm season outbreaks is located over the Central Plains, while the cool season axis is centered immediately east of the Mississippi River. This fact, when considered with the seasonal variation of shear magnitudes evident from Table 1 in this study, suggests that tornadic hodographs may exhibit a seasonal and geographical variation in character.

5. VARIATIONS IN HODOGRAPHS

In an attempt to focus on wind environment and hodograph extremes that might occur seasonally and geographically with strong and violent tornadoes, cool season soundings in Table 1 for cases east of the Mississippi River (16 soundings) are compared with warm season soundings for cases

TABLE 1.

Date & location of tornado occurrence	Sounding used (times GMT/UTC)	Sounding time approx. to tornado (F-scale); approx. distance/direction to tornado (statute miles)	(x 10 ⁻³ sec ⁻¹) Absolute Mean Shear			(x 10 ⁻³ sec ⁻¹) Positive Mean Shear		
			0-2km AGL segment (Col. 1)	0-4km AGL (Col. 2)	% 0-2km of 0-4km (Col. 3)	0-2km AGL segment (Col.4)	0-4km AGL (Col. 5)	% 0-2km of 0-4km (Col. 6)
1. 11/9/84 E. MO	00 SLO 11/10/84	During F2, 85 WSW	9.7	12.1	80%	6.9	7.4	93%
2. 11/10/84 N. AL	12 CKL 11/10/84	7 hr before F2, 50 NW	13.6	17.5	78%	10.8	11.6	93%
3. 11/15/87 E. TX	00 GGG 11/16/87	During F3, 40 N	7.6	11.5	66%	7.3	9.1	80%
4. 11/15/88 C. AR	00 LIT 11/16/88	1 hr before F3, 10 S	7.9	12.0	66%	7.9	10.3	77%
5. 11/18/85 N. AR	00 LIT 11/19/85	3 hr before F3, 125 N	7.3	12.5	58%	7.3	9.6	76%
6. 11/28/88 C. NC	00 GSO 11/28/88	6 hr before F4, 60 E	8.0	10.8	74%	8.0	10.8	74%
7. 12/2/82 N. AR	12 LIT 12/2/82	5 hr before F3, 135 NW	6.3	8.3	76%	6.3	7.6	83%
8. 12/2/82 N. AR	00 LIT 12/3/82	2 hr before F3, 75 NW	8.6	12.5	69%	8.6	12.5	69%
9. 12/2/82 S. IL	00 SLO 12/3/82	3 hr before F3, 45 W	7.1	9.5	75%	7.1	8.7	82%
10. 12/24/82 N. AR	00 LIT 12/25/82	During F4, 130 N	6.5	8.4	77%	6.5	8.4	77%
11. 12/24/88 C. TN	12 BNA 12/24/88	1 hr before F4, 20 SW	10.9	13.1	83%	10.9	13.1	83%
12. 1/7/89 S. IL	00 PAH 1/8/89	During F3, 100 NNE	9.8	14.6	67%	9.8	14.6	67%
13. 1/19/88 C. MS	12 JAN 1/19/88	5 hr before F4, 70 NE	6.9	8.7	79%	6.2	8.0	78%
14. 1/19/88 N. AL	00 CKL 1/20/88	During F3, 75 NE	6.9	9.3	74%	6.9	9.3	74%
15. 2/28/87 S. MS	12 JAN 2/28/87	3 hr before F4, 60 SE	6.5	9.4	69%	6.1	9.0	68%
16. 3/10/86 C. IN	12 DAY 3/10/86	8 hr before F3, 95 W	10.1	15.0	67%	9.0	9.7	93%
17. 3/10/86 C. KY	00 HTS 3/11/86	During F2, 100 W	9.5	15.0	63%	9.5	13.0	73%
18. 3/12/86 E. MS	12 CKL 3/12/86	7 hr before F4, 90 SW	7.1	9.6	74%	7.1	9.6	74%
19. 3/15/84 N. AR	00 LIT 3/16/84	During F4, 70 N	6.8	8.8	77%	4.2	6.2	68%
20. 3/28/84 N. SC	12 CHS 3/28/84	10 hr before F4, 130 NW	10.2	13.8	74%	10.2	12.6	81%
21. 3/28/84 E. NC	00 HAT 3/29/84	2 hr before F4, 110 W	6.3	11.2	56%	4.6	8.6	53%
22. 4/2/82 S. AR	00 GGG 4/3/82	During F4, 100 NNE	12.6	15.4	82%	11.8	14.0	84%
23. 4/19/86 W. TX	12 MAF 4/19/86	1 hr before F3, 95 E	9.7	20.8	47%	7.6	10.5	72%
24. 4/19/88 N. FL	00 AQQ 4/19/88 ¹	8 hr before F3, 100 NE	5.0 ¹	9.1 ¹	55%	4.7 ¹	8.8 ¹	53%
	12 AYS 4/19/88	3 hr after F3, 85 SW	12.6	17.7	71%	8.0	13.0	62%
25. 4/21/84 N. MS	00 JAN 4/22/84	During F3, 140 NNE	6.0	9.4	64%	6.0	8.8	68%
26. 4/25/84 C. NE	00 OMA 4/26/84	2 hr before F3, 120 W	9.3	12.8	73%	9.4	12.1	78%
27. 4/26/84 E. OK	00 OKC 4/27/84	4 hr before F4, 90 NE	7.0	12.3	57%	7.0	11.0	64%
28. 4/26/84 N. KS	00 TOP 4/27/84	3 hr before F3, 20 NW	4.9	9.9	49%	4.3	7.9	54%
29. 4/26/84 C. MN	00 STC 4/27/84	2 hr before F3, 50 SE	4.8	8.3	58%	4.7	8.3	57%
30. 4/27/84 E. WI	12 GRB 4/27/84	9 hr before F4, 30 SW	10.3	13.0	79%	7.0	8.7	80%
31. 4/29/84 N. OK	12 OKC 4/29/84	3 hr before F4, 75 NE	9.5	12.9	74%	9.5	12.9	74%
32. 4/29/84 E. MO	00 SLO 4/30/84	During F3, 100 WNW	11.3	15.1	75%	11.3	14.2	80%
33. 5/2/83 E. MI	12 FNT 5/2/83	4 hr before F3, 60 SE	6.8	10.1	67%	6.8	8.9	76%
34. 5/2/83 C. NY	00 ALB 5/3/83	1 hr before F3, 100 W	7.5	11.0	68%	7.5	9.4	80%
35. 5/5/89 W. NC	00 GSO 5/6/89	During F3+ ² , 100 SW	8.8	11.8	75%	8.8	11.8	75%
36. 5/7/86 TX Pnhdl	00 DDC 5/8/86	1 hr after F3, 125 S	7.8	13.1	60%	4.9	6.0	82%
37. 5/8/84 S. VA	12 WAL 5/8/84	7 hr before F3, 100 SW	5.8	10.8	54%	4.4	6.3	70%
38. 5/9/88 E. KY	00 HTS 5/10/88	2 hr before F3, 135 WSW	6.5	10.2	64%	3.9	7.6	51%
39. 5/10/85 N. KS	12 DDC 5/10/85	9 hr before F3, 70 N	9.7	11.0	88%	8.3	8.9	93%
40. 5/17/89 C. TX	12 VCT 5/17/89	2 hr before F2+ ² , 150 NW	7.3	13.4	54%	7.3	11.3	65%
41. 5/22/81 W. OK	00 OKC 5/23/81	During F4, 40 W	4.8	7.0	69%	4.8	7.0	69%
42. 5/31/85 W. PA	12 PIT 5/31/85	9 hr before F4, 50 N	8.4	10.7	79%	8.4	10.7	79%
43. 6/3/80 N. WV	12 PIT 6/3/80	9 hr before F4, 60 S	8.7	11.9	73%	6.9	8.8	78%
44. 6/3/80 C. NE	00 OMA 6/4/80 ³	1 hr before F4, 140 W	4.0	7.9	51%	3.6	6.8	53%
	00 LBF 6/4/80 ³	1 hr before F4, 130 E	4.8	8.7	55%	4.2	5.0	84%
45. 6/7/84 S. IA	00 OMA 6/8/84	During F4, 110 SE	10.1	13.7	74%	8.1	9.2	88%
46. 6/8/84 C. WI	00 GRB 6/8/84 ¹	5 hr before F5, 140 SW	3.3 ¹	6.7 ¹	49%	2.7 ¹	5.7 ¹	47%
	12 GRB 6/8/84	6 hr after F5, 120 SW	11.5	17.9	64%	11.5	15.0	77%
47. 6/11/84 C. NE	00 OMA 6/12/84	2 hr before F3, 125 W	5.0	8.4	60%	4.1	6.4	64%
48. 7/3/83 C. MN	12 STC 7/3/83	5 hr before F4, 45 SE	5.6	9.8	57%	4.8	5.5	87%
49. 7/28/86 E. NE	00 OMA 7/29/86	During F4, 110 NNW	4.0	6.2	65%	3.7	4.6	80%
50. 8/16/85 N. AL ⁴	00 CKL 8/17/85	During F3, 100 N	6.5	8.0	81%	6.5	8.0	81%
51. 8/17/85 N. SC ⁴	12 AHN 8/17/85	5 hr before F2, 80 ENE	4.9	8.1	60%	4.5	7.7	58%
52. 9/17/88 S. TX ⁵	12 DRT 9/17/88	During F2, 135 E	6.6	7.4	89%	6.6	7.4	89%
53. 9/17/88 S. TX ⁵	00 DRT 9/18/88	1 hr after F2, local	5.6	8.0	70%	5.6	7.1	79%
54. 10/14/86 S. VA	12 WAL 10/14/86	During F3, 100 SW	5.5	11.6	47%	4.2	9.0	47%

COOL SEASON

WARM SEASON

¹Not included in "average value" and "low value" calculations referred to in Table 2 because the "after" sounding is more representative of tornado environment than the "before" sounding due to a fast moving system.

²F-scale not available - intensity estimated.

³Two soundings are shown as both are equidistant from tornado occurrence and appear to be representative of tornado environment.

⁴associated with remnants of Hurricane Danny ⁵associated with remnants of Hurricane Gilbert

TABLE 2.

(from data in Table 1)

	COOL SEASON			WARM SEASON		
	0-2km	0-4km	% 0-2km of 0-4km	0-2km	0-4km	% 0-2km of 0-4km
Absolute Shear Average	8.5	12.2	70%	6.8	10.3	66%
Positive Shear Average	7.7	10.4	75%	6.1	8.9	74%
Absolute Shear Lowest Value	4.8 ¹	8.3		4.0	6.2	
Positive Shear Lowest Value	4.2 ²	6.2 ³		3.6 ⁴	4.6 ⁵	

¹30 of 32 soundings >= 6.0 (94%)

²28 of 32 soundings >= 6.0 (88%)

³31 of 32 soundings >= 7.4 (97%)

⁴21 of 23 soundings >= 3.9 (91%)

⁵21 of 23 soundings >= 5.5 (91%)

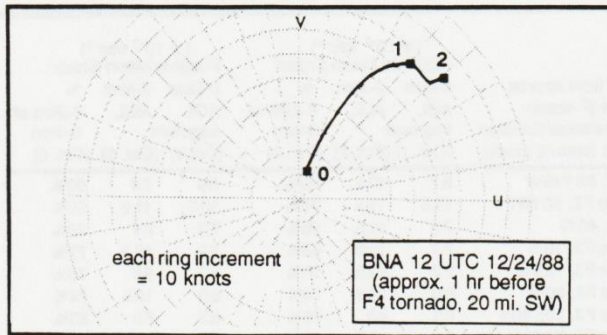


Fig. 2a. Nashville, TN 0-2km AGL hodograph, 12 UTC 12/24/88

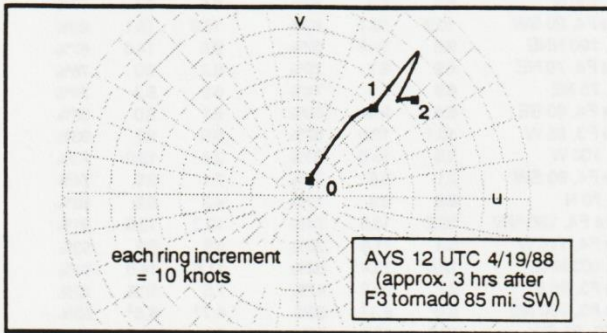


Fig. 2b. Waycross, GA 0-2km AGL hodograph, 12 UTC 4/19/88

further west (12 soundings). Three different hodograph characteristics of these data subsets are compared in Table 3.

TABLE 3.	Avg. directional difference	Average 0-2km AGL absolute shear	Average maximum wind in 0-2km AGL layer
Cool/ E. U.S	45 degrees	$8.8 \times 10^{-3} \text{ s}^{-1}$	60 knots
Warm/ C. U.S.	77 degrees	$6.3 \times 10^{-3} \text{ s}^{-1}$	35 knots

Significantly, the average directional difference between surface and 2 km in the cool season/eastern U.S. cases is about 50% of the average exhibited by warm season/central U.S. cases. Absolute 0-2km shear values average approximately 40% greater for cool season/eastern U.S. cases, and the associated low level wind fields appear to be nearly twice as strong. These comparisons suggest that tornadic hodographs in the winter and early spring, particularly in the eastern United States, are typically characterized more by speed shear than by directional shear in the bottom 2 km. This is in contrast to tornadic hodographs in the warm season, particularly in the central plains, which are generally characterized more by directional shear than by speed shear.

Two examples of 0-2km hodographs from the cool season/eastern U.S. soundings examined in Table 3 are shown in Figure 2. Both hodographs exhibit a strong shear magnitude which is accomplished *without a great deal of curvature* (note that Figure 2b is nearly linear in character). Hodographs such as these are a significant departure from the "helical" looping shape (e.g., Figure 1 in section 1) that is frequently associated with central plains tornado situations. The two different types of wind profiles probably represent extremes of shear characteristics that are encountered among tornadic hodographs. While the two types of hodographs exhibit seasonal and geographical preferences as noted above, neither type is confined to a specific area of the country or a specific season, and various gradations occur between the two extremes.

6. CASE STUDIES

Two case studies selected from Table 1 are now presented to compare the diagnostic potential of four different shear magnitude products: 0-4km absolute shear, 0-2km absolute shear, 0-4km positive shear, and 0-2km positive shear.

6.1 N.C. Kansas/S.C. Nebraska tornadoes, 5/10/85

This case has been discussed previously by Barlow (1988) and Davies-Jones and Zacharias (1988). Tornadoes of F3 and F4 intensity occurred in the afternoon and evening with thunderstorms in north central Kansas and south central Nebraska. The storms developed east of a north/south dryline and a moisture convergence center over northwest Kansas, and moved northeastward. Other weaker tornadoes occurred with thunderstorms over southern North Dakota. The atmosphere was quite unstable from Kansas into the Dakotas.

Figs. 3a and 3b show 0-4km and 0-2km absolute shear values calculated from 12 UTC 5/10/85 sounding data. Both analyses are quite similar, indicating a large area of maximum shear across eastern Nebraska and Kansas. Unfortunately, neither analysis does much to help define the areal extent of tornado threat in relation to tornado occurrences. Both analyses depict shear magnitudes that are well above suggested seasonal threshold values across nearly all of the central and northern plains.

The positive shear analyses valid for the same time in Figs. 3c and 3d offer a more useful picture of the shear field. Two areas of maximum shear emerge in both depictions, one in Kansas and one in North Dakota. Both maxima correspond well to tornado occurrences later in the day, and suggested seasonal threshold values do a reasonable job delineating the threat areas. In this case, the two positive shear analyses are essentially the same, though the 0-2km analysis does a better job diagnostically in bringing out the details and strength of the shear maxima.

6.2 Raleigh tornado, 11/28/88

A detailed discussion of this case by Browning et al. (1989) is found elsewhere in this volume. A significant feature at sounding time 00 UTC 11/28/88 was a northeast/southwest boundary over east central North Carolina, well ahead of a cool front further west. The boundary separated warm unstable air to the east from rain cooled air to the west, and moved westward slightly during the evening. Thunderstorms developed along the boundary around 05 UTC, and an F4 intensity tornado occurred at Raleigh about 06 UTC.

Figures 4a and 4b show 0-4km and 0-2km absolute shear magnitudes for 00 UTC 11/28/88. Both figures, as in the previous case, exhibit seasonally high shear values over most of the analysis area, and do little to suggest a meaningful area of potential tornado threat. In this case the two analyses are notably different from each other. The "tongue" of stronger shear magnitudes in Figure 4b that extends into central North Carolina is interesting, but of little quantitative value in selecting a potential threat area.

Figures 4c and 4d show 0-4km and 0-2km positive shear magnitudes valid for the same time. As in the Kansas/Nebraska case, these analyses are a notable improvement diagnostically over the absolute shear analyses. In particular, 0-2km positive shear (Figure 4d) offers the most useful depiction for diagnosing the low level shear field. This analysis narrows the potential strong/violent tornado threat (when using suggested seasonal threshold values) to mainly central and eastern North Carolina and southeast Virginia, which is where tornadoes occurred. In contrast, 0-4km positive shear threshold values (Figure 4c) encompass an area too large to be diagnostically useful.

7. DISCUSSION AND SUMMARY

Several important points concerning shear magnitudes and hodographs associated with strong/violent tornado development are suggested by this study:

- As discussed in section 1, it appears that the magnitude of the vertical wind shear in the 0-2km layer (rather than in the deeper 0-4km layer) may have the most direct impact on enhancing updraft rotation in tornadic supercell thunderstorms. This idea is supported by the fact that most of the shear magnitude in 95% of the tornado case soundings examined resides in the bottom 2 km of the hodograph. Above this layer, the mid level flow (3-7km AGL) is probably more representative of downdraft air (Zipser, 1969). The rear flank downdraft has

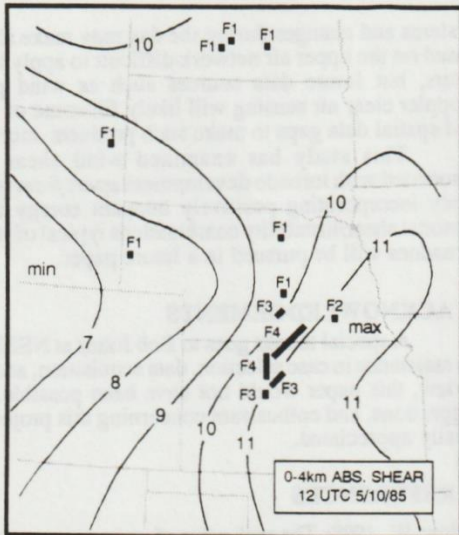


Fig. 3a. 0-4km AGL absolute shear valid 12 UTC 5/10/85, analysed for values¹ $\geq 6.0 \times 10^{-3} s^{-1}$. Tornado occurrences are indicated by square dots (brief touchdown) and lines (longer path). F-scale intensities $\geq F1$ are indicated.

Fig 3b. 0-2km AGL absolute shear valid 12 UTC 5/10/85, analysed for values¹ $\geq 4.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 3a.

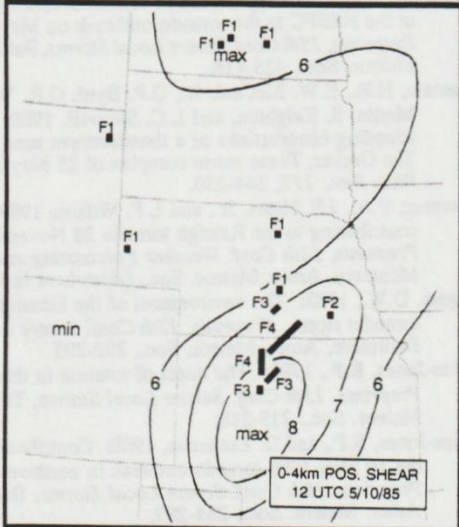
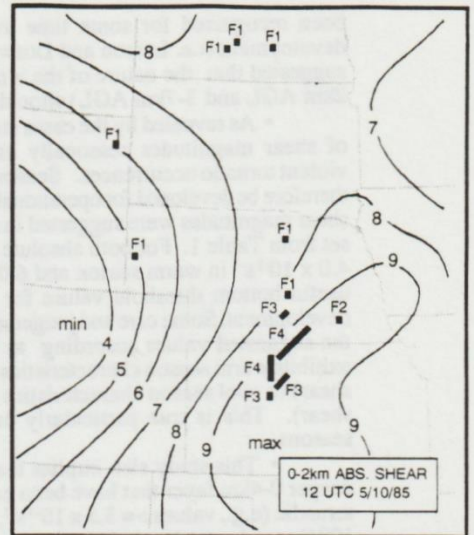
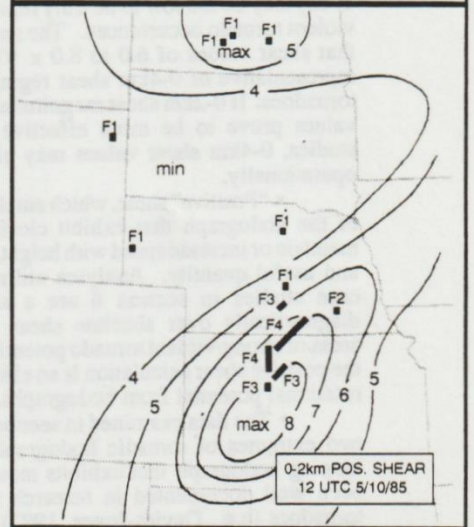


Fig 3c. 0-4km AGL positive shear valid 12 UTC 5/10/85, analysed for values¹ $\geq 6.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 3a.

Fig 3d. 0-2km AGL positive shear valid 12 UTC 5/10/85, analysed for values¹ $\geq 4.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 3a.



¹values \geq suggested seasonal threshold values from section 4 are used.

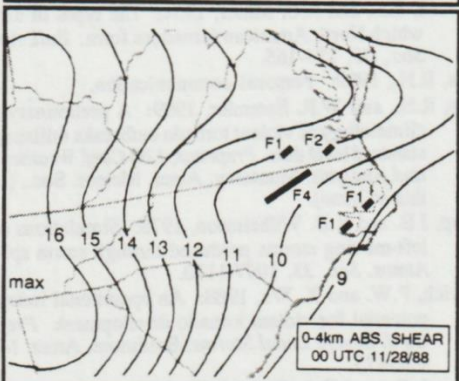


Fig. 4a. 0-4km AGL absolute shear valid 00 UTC 11/28/88, analysed for values¹ $\geq 8.0 \times 10^{-3} s^{-1}$. Tornado occurrences are indicated using same conventions as in Fig. 3a.

Fig. 4b. 0-2km AGL absolute shear valid 00 UTC 11/28/88, analysed for values¹ $\geq 6.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 4a.

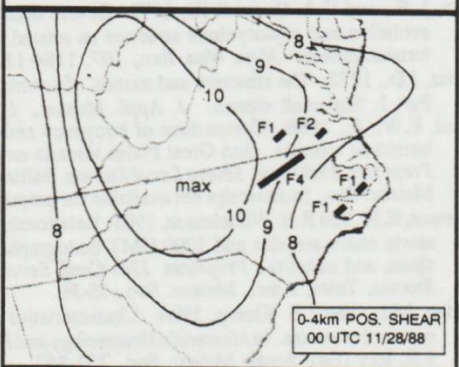
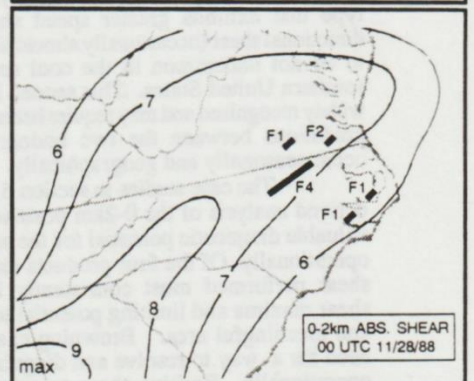
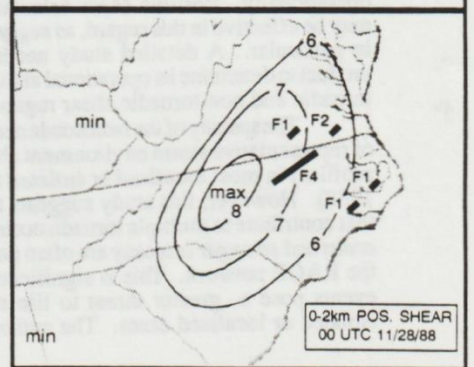


Fig. 4c. 0-4km AGL positive shear valid 00 UTC 11/28/88, analysed for values¹ $\geq 8.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 4a.

Fig 4d. 0-2km AGL positive shear valid 00 UTC 11/28/88, analysed for values¹ $\geq 6.0 \times 10^{-3} s^{-1}$. Tornado occurrences as in Fig. 4a.



been recognized for some time to be important in tornado development (i.e. Lemon and Doswell, 1979). Therefore, it is suggested that the nature of the winds in these two layers (0-2km AGL and 3-7km AGL) should be examined *separately*.

- As revealed by the cases studied, there is a wide range of shear magnitudes seasonally associated with strong and violent tornado occurrences. Seasonal threshold values should therefore be developed for operational use. Preliminary threshold shear magnitudes were suggested in section 4 based on the data set from Table 1. For both absolute and positive 0-2km shear, $4.0 \times 10^{-3} \text{ s}^{-1}$ in warm season and $6.0 \times 10^{-3} \text{ s}^{-1}$ are suggested as useful bottom threshold values for strong or violent tornado development. Some care and judgement are required in applying the suggested values according to whether a given situation exhibits warm season characteristics (strong instability/weaker shear) or cool season characteristics (weaker instability/strong shear). This is true particularly during transition between seasons.

- This study also implies that shear magnitudes in the deeper 0-4km layer that have been previously characterized as tornadic (e.g., values $\geq 3.5 \times 10^{-3} \text{ s}^{-1}$, see Weisman and Klemp, 1986) may be too low to be truly representative of most strong/violent tornado occurrences. The results from Table 1 suggest that shear values of 6.0 to $8.0 \times 10^{-3} \text{ s}^{-1}$ or greater are more representative of 0-4km shear regimes that produce stronger tornadoes. If 0-2km shear magnitudes and associated threshold values prove to be more effective diagnostically in future studies, 0-4km shear values may also become less relevant operationally.

- "Positive" shear, which emphasizes only those portions of the hodograph that exhibit clockwise curvature and that maintain or increase speed with height, seems to be a meaningful and useful quantity. Analyses utilizing positive shear in the case studies in section 6 are a significant improvement diagnostically over absolute shear in delineating workable areas of strong/violent tornado potential. This fact suggests that the positive shear calculation is an effective way of quantizing rotational potential from hodographs.

- The data examined in section 5 suggests that there are two extremes of tornadic hodograph types. The clockwise looping hodograph that exhibits mostly directional shear has been well documented in research relating to Great Plains tornadoes (e.g., Davies-Jones, 1983). A tornadic hodograph type that exhibits greater speed shear and less curvature/directional shear (occasionally almost *linear* in character) appears to be not uncommon in the cool season in the eastern and southern United States. This second hodograph type is not as widely recognized and may require better documentation. Various gradations between the two hodograph extremes probably occur seasonally and geographically.

- The case studies in section 6 suggest that a sounding-derived analysis of the 0-2km positive shear field could have valuable diagnostic potential for the severe weather forecaster operationally. Of the four products examined, 0-2km positive shear performed most consistently in resolving significant shear maxima and limiting potential tornado threat to a useful and meaningful area. Browning et al (1989) emphasize the need for a way to resolve and diagnose low level wind shear operationally. Positive shear calculated for the 0-2km layer may be effective in this regard, as suggested by the Raleigh case in particular. A detailed study needs to be done using this product to determine its operational ability to distinguish between tornadic and non-tornadic shear regimes.

The sparsity of the radiosonde network precludes detection of representative storm environment characteristics (e.g., shear profiles) in most *localized* or *isolated* tornado cases (Burgess, 1988). However, this study suggests that the shear processes that contribute to multiple tornado occurrences involving *wider areas* and *stronger intensity* are often possible to diagnose using the RAOB network. This is significant because such tornado events pose a greater threat to life and property than most isolated or localized cases. The author recognizes that faster

systems and changes during the day may make shear analyses based on the upper air network difficult to apply beyond a few hours, but future data sources such as wind profilers and Doppler clear air sensing will likely fill some of the temporal and spatial data gaps to make such products more applicable.

This study has examined wind shear magnitudes associated with tornado development *apart from instability*. A study incorporating positively buoyant energy to determine seasonal shear/instability combinations typical of strong/violent tornadoes will be pursued in a future paper.

8. ACKNOWLEDGEMENTS

A special thanks goes to Bob Johns at NSSFC. Without his assistance in case selection, data acquisition, and manuscript review, this paper would not have been possible. His ideas, suggestions, and enthusiasm concerning this project have been greatly appreciated.

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ADDENDUM TO "ON THE USE OF SHEAR MAGNITUDES AND HODOGRAPHS IN TORNADO FORECASTING" (PAPER 2.11)

12th Conference on Weather Analysis and Forecasting
Monterey, California, October 2-6, 1989

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CLARIFICATION OF 0-2km SHEAR COMPUTATIONS

There has been some confusion about my calculation of 0-2km shear values in the preprint paper, so some clarification is needed, as well as a reassessment of how I presented the 0-2km shear values.

All 0-4km shear values in Table 1 in the preprint paper were calculated as mean shear values, according to Erik Rasmussen's method (Rasmussen and Wilhelmson, 1983). Using Figure 1 on the next page as an example, this would be:

$$0\text{-}4\text{km mean shear} = \frac{0\text{-}4000\text{m hodograph length}}{\text{depth represented}} = \frac{44 \text{ m s}^{-1}}{4000 \text{ m}} = 11 \times 10^{-3} \text{ s}^{-1}$$

In contrast, 0-2km shear values in the preprint paper were not calculated as mean shear values, but rather, *in terms of (or as a portion of) the 0-4km mean shear*. From Figure 1, this would be:

$$0\text{-}2\text{km portion of } 0\text{-}4\text{km mean shear} = \frac{0\text{-}2000\text{m hodograph length}}{0\text{-}4000\text{m depth}} = \frac{40 \text{ m s}^{-1}}{4000\text{m}} = 10 \times 10^{-3} \text{ s}^{-1}$$

This way, the 0-2km shear could be compared to the 0-4km shear in the same way one would compare hodograph lengths. From Figure 1 and the examples above, this comparison would be $.010 \text{ s}^{-1} / .011 \text{ s}^{-1} = 91\%$, meaning 91% of the 0-4km mean shear resides in the 0-2km layer.

In retrospect, to accomplish this type of comparison, I now see it would have been more appropriate and less confusing to compare hodograph lengths directly (i.e., $40 \text{ m s}^{-1} / 44 \text{ m s}^{-1} = 91\%$ in Figure 1) to obtain the percentages in Table 1 in the preprint paper. More importantly, it would be more consistent to present the 0-2km shear values in strict terms of Erik Rasmussen's definition of mean shear, which would be calculated as follows from Figure 1:

$$0\text{-}2\text{km mean shear} = \frac{0\text{-}2000\text{m hodograph length}}{\text{depth represented}} = \frac{40 \text{ m s}^{-1}}{2000\text{m}} = 20 \times 10^{-3} \text{ s}^{-1}$$

For consistency, I have recalculated Table 1 and shown the 0-2km *mean* shear values (see next page). *Representing the shear this way, the 0-2km shear values will be exactly twice those shown in my original Table 1 in the preprint volume.* The 0-2km mean shear will be larger than the 0-4km mean shear in most tornadic cases, which the Table 1 revision reflects in 51 of 54 cases.

Using 0-2km mean shear, the lower limit of shear required for strong or violent tornado development is approximated by values around 7 or $8 \times 10^{-3} \text{ s}^{-1}$. Winter tornado episodes appear to require 0-2km shear values of generally $12 \times 10^{-3} \text{ s}^{-1}$ or greater to compensate for weaker instability at that time of year. As pointed out in the poster session, a study in combination with instability (potential buoyant energy) is in progress.

I would like to thank Erik Rasmussen, whose suggestions and ideas have been most helpful the past few months, resulting in several improvements.

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Rasmussen, E.N. and R.B. Wilhelmson, 1983: Relationships between storm characteristics and 1200 GMT hodographs, low-level shear and stability. *Preprints, 13th Conf. on Severe Local Storms*, Tulsa, Amer. Meteor. Soc., J5-J8.

TABLE 1.

Date & location of tornado occurrence	Sounding used (times GMT/UTC)	Sounding time approx. to tornado (F-scale); approx. distance/direction to tornado (statute miles)	(x 10 ⁻³ sec ⁻¹) Absolute Mean Shear			(x 10 ⁻³ sec ⁻¹) Positive Mean Shear		
			0-2km AGL shear (Col. 1)	0-4km AGL shear (Col. 2)	0-2km > 0-4km shear? (Col. 3)	0-2km AGL shear (Col. 4)	0-4km AGL shear (Col. 5)	0-2km > 0-4km shear? (Col. 6)
1. 11/9/84 E. MO	00 SLO 11/10/84	During F2, 85 WSW	19.4	12.1	Yes	13.8	7.4	Yes
2. 11/10/84 N. AL	12 CKL 11/10/84	7 hr before F2, 50 NW	27.2	17.5	Yes	21.6	11.6	Yes
3. 11/15/87 E. TX	00 GGG 11/16/87	During F3, 40 N	15.2	11.5	Yes	14.6	9.1	Yes
4. 11/15/88 C. AR	00 LIT 11/16/88	2 hr before F3, 40 NNW	15.8	12.0	Yes	15.8	10.3	Yes
5. 11/18/85 N. AR	00 LIT 11/19/85	3 hr before F3, 125 N	14.6	12.5	Yes	14.6	9.6	Yes
6. 11/28/88 C. NC	00 GSO 11/28/88	6 hr before F4, 60 E	16.0	10.8	Yes	16.0	10.8	Yes
7. 12/2/82 N. AR	12 LIT 12/2/82	5 hr before F3, 135 NW	12.6	8.3	Yes	12.6	7.6	Yes
8. 12/2/82 N. AR	00 LIT 12/3/82	During F3, 40 N	17.2	12.5	Yes	17.2	12.5	Yes
9. 12/2/82 S. IL	00 SLO 12/3/82	3 hr before F3, 45 W	14.2	9.5	Yes	14.2	8.7	Yes
10. 12/24/82 N. AR	00 LIT 12/25/82	During F4, 130 N	13.0	8.4	Yes	13.0	8.4	Yes
11. 12/24/88 C. TN	12 BNA 12/24/88	During F4, 20 SW	21.8	13.1	Yes	21.8	13.1	Yes
12. 1/7/89 S. IL	00 PAH 1/8/89	During F3, 100 NNE	19.6	14.6	Yes	19.6	14.6	Yes
13. 1/19/88 C. MS	12 JAN 1/19/88	5 hr before F4, 70 NE	13.8	8.7	Yes	12.4	8.0	Yes
14. 1/19/88 N. AL	00 CKL 1/20/88	During F3, 75 NE	13.8	9.3	Yes	13.8	9.3	Yes
15. 2/28/87 S. MS	12 JAN 2/28/87	3 hr before F4, 60 SE	13.0	9.4	Yes	12.2	9.0	Yes
16. 3/10/86 C. IN	12 DAY 3/10/86	8 hr before F3, 95 W	20.2	15.0	Yes	18.0	9.7	Yes
17. 3/10/86 C. KY	00 HTS 3/11/86	During F2, 100 W	19.0	15.0	Yes	19.0	13.0	Yes
18. 3/12/86 E. MS	12 CKL 3/12/86	7 hr before F4, 90 SW	14.2	9.6	Yes	14.2	9.6	Yes
19. 3/15/84 N. AR	00 LIT 3/16/84	During F4, 65 N	13.6	8.8	Yes	8.4	6.2	Yes
20. 3/28/84 N. SC	12 CHS 3/28/84	10 hr before F4, 130 NW	20.4	13.8	Yes	20.4	12.6	Yes
21. 3/28/84 E. NC	00 HAT 3/29/84	2 hr before F4, 110 W	12.6	11.2	Yes	9.2	8.6	Yes
22. 4/2/82 S. AR	00 GGG 4/3/82	During F4, 100 NNE	25.2	15.4	Yes	23.6	14.0	Yes
23. 4/19/86 W. TX	12 MAF 4/19/86	1 hr before F3, 95 E	19.4	20.8	No	15.2	10.5	Yes
24. 4/19/88 N. FL	00 AQQ 4/19/88	8 hr before F3, 100 NE	10.0 ¹	9.1 ¹		9.4 ¹	8.8 ¹	
	12 AYS 4/19/88	3 hr after F3, 85 SW	25.2	17.7	Yes	16.0	13.0	Yes
25. 4/21/84 N. MS	00 JAN 4/22/84	During F3, 140 NNE	12.0	9.4	Yes	12.0	8.8	Yes
26. 4/25/84 C. NE	00 OMA 4/26/84	2 hr before F3, 120 W	18.6	12.8	Yes	18.8	12.1	Yes
27. 4/26/84 E. OK	00 OKC 4/27/84	4 hr before F4, 90 NE	14.0	12.3	Yes	14.0	11.0	Yes
28. 4/26/84 N. KS	00 TOP 4/27/84	4 hr before F3, 45 NNE	9.8	9.9	No	8.6	7.9	Yes
29. 4/26/84 C. MN	00 STC 4/27/84	3 hr before F3, 50 SE	9.6	8.3	Yes	9.4	8.3	Yes
30. 4/27/84 E. WI	12 GRB 4/27/84	9 hr before F4, 30 SW	20.6	13.0	Yes	14.0	8.7	Yes
31. 4/29/84 N. OK	12 OKC 4/29/84	3 hr before F4, 75 NE	19.0	12.9	Yes	19.0	12.9	Yes
32. 4/29/84 E. MO	00 SLO 4/30/84	During F3, 100 WNW	22.6	15.1	Yes	22.6	14.2	Yes
33. 5/2/83 E. MI	12 FNT 5/2/83	4 hr before F3, 60 SE	13.6	10.1	Yes	13.6	8.9	Yes
34. 5/2/83 C. NY	00 ALB 5/3/83	1 hr before F3, 100 W	15.0	11.0	Yes	15.0	9.4	Yes
35. 5/5/89 W. NC	00 GSO 5/6/89	During F3+ ² , 100 SW	17.6	11.8	Yes	17.6	11.8	Yes
36. 5/7/86 TX Pnhdl	00 DDC 5/8/86	1 hr after F3, 125 S	15.6	13.1	Yes	9.8	6.0	Yes
37. 5/8/84 S. VA	12 WAL 5/8/84	9 hr before F3, 100 SW	11.6	10.8	Yes	8.8	6.3	Yes
38. 5/9/88 E. KY	00 HTS 5/10/88	2 hr before F3, 135 SSW	13.0	10.2	Yes	7.8	7.6	Yes
39. 5/10/85 N. KS	12 DDC 5/10/85	9 hr before F3, 70 N	19.4	11.0	Yes	16.6	8.9	Yes
40. 5/17/89 C. TX	12 VCT 5/17/89	3 hr after F3, 150 NW	14.6	13.4	Yes	14.6	11.3	Yes
41. 5/22/81 W. OK	00 OKC 5/23/81	During F4, 40 W	9.6	7.0	Yes	9.6	7.0	Yes
42. 5/31/85 W. PA	12 PIT 5/31/85	9 hr before F4, 50 N	16.8	10.7	Yes	16.8	10.7	Yes
43. 6/3/80 W. PA	12 PIT 6/3/80	6 hr before F4 ² , 25 NE	17.4	11.9	Yes	13.8	8.8	Yes
44. 6/3/80 C. NE	00 OMA 6/4/80 ³	2 hr before F4, 140 W	8.0	7.9	Yes	7.2	6.8	Yes
	00 LBF 6/4/80 ³	2 hr before F4, 130 E	9.6	8.7	Yes	8.4	5.0	Yes
45. 6/7/84 S. IA	00 OMA 6/8/84	During F4, 110 SE	20.2	13.7	Yes	16.2	9.2	Yes
46. 6/8/84 C. WI	00 GRB 6/8/84	5 hr before F5, 140 SW	6.6 ¹	6.7 ¹		5.4 ¹	5.7 ¹	
	12 GRB 6/8/84	6 hr after F5, 120 SW	23.0	17.9	Yes	23.0	15.0	Yes
47. 6/11/84 C. NE	00 OMA 6/12/84	2 hr before F3, 125 W	10.0	8.4	Yes	8.2	6.4	Yes
48. 7/3/83 C. MN	12 STC 7/3/83	5 hr before F4, 45 SE	11.2	9.8	Yes	9.6	5.5	Yes
49. 7/28/86 E. NE	00 OMA 7/29/86	During F4, 110 NNW	8.0	6.2	Yes	7.4	4.6	Yes
50. 8/16/85 N. AL ⁴	00 CKL 8/17/85	4 hr after F3, 100 N	13.0	8.0	Yes	13.0	8.0	Yes
51. 8/17/85 N. SC ⁴	12 AHN 8/17/85	5 hr before F2, 80 ENE	9.8	8.1	Yes	9.0	7.7	Yes
52. 9/17/88 S. TX ⁵	12 DRT 9/17/88	During F2, 135 E	13.2	7.4	Yes	13.2	7.4	Yes
53. 9/17/88 S. TX ⁵	00 DRT 9/18/88	1 hr after F2, local	11.2	8.0	Yes	11.2	7.1	Yes
54. 10/14/86 S. VA	12 WAL 10/14/86	During F3, 100 SW	11.0	11.6	No	8.4	9.0	No

¹These soundings are not considered representative of tornado environment; they are shown only to suggest how the shear increased from "before" to "after" in the specific case. The "after" sounding is considered more representative in these cases.

²F-scale not available - intensity estimated.

³Two soundings are shown, as both are equidistant from tornado occurrence and appear to be representative of tornado environment.

⁴associated with remnants of Hurricane Danny ⁵associated with remnants of Hurricane Gilbert

COOL SEASON

WARM SEASON

Table 1. Revised version reflecting 0-2km shear values as true mean shear, rather than as a portion or segment of the 0-4km mean shear. Note that in most cases the 0-2km mean shear is greater than the 0-4km mean shear. Also, sounding times/distances/directions relative to tornado have been revised for accuracy in several cases.

In Fig. 1, approximation of the length of the hodograph "loop" by breaking it down into smaller measurable increments that are added together or "summed", results in these approximate lengths: 0-2km length = 78 kts or 40 m s⁻¹, 0-4km length = 85 kts or 44 m s⁻¹

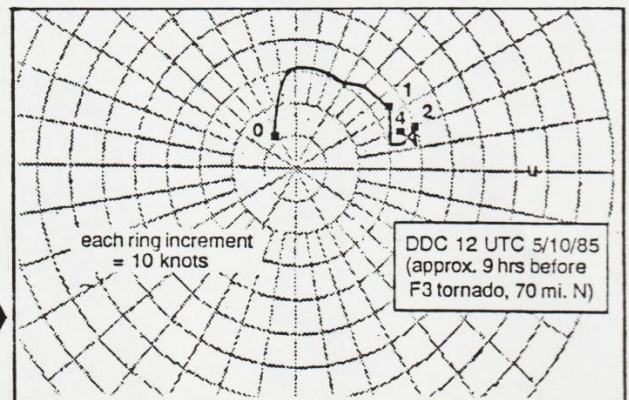


Fig 1. Dodge City, KS 0-4km AGL hodograph, 12 UTC 5/10/85.