

Jonathan M. Davies *
Wichita, Kansas

1. INTRODUCTION

Storm-relative (s-r) frames of reference have become increasingly recognized as important for assessing potential for supercells and tornadoes. Parameters such as s-r helicity (Davies-Jones et al. 1990) and s-r midlevel winds (Brooks et al. 1994, and Thompson 1998) are computed and used routinely as tools in many severe weather forecasts.

A problem with using forecast s-r parameters is the need to estimate a reasonable and representative motion for potential supercells, often well before convective initiation. Using a small dataset of radar-derived supercell motions and their related environments, Davies and Johns (1993, hereafter DJ93) showed that storm motion deviation from the mean environmental wind tends to increase on average as the mean wind strength decreases. Expanding on the storm motion deviation used by Maddox (1976), some general motion estimation guidelines were suggested: roughly 20° right of the mean wind and 85% speed when the mean 0-6 km wind is ≥ 30 kts, and more toward 30° right and 75% (30R75, as in Maddox) when the mean 0-6 km wind is < 30 kts. Similar guidelines or variations are currently used widely in generating many s-r forecast products.

The work by DJ93 did not include supercells in environments where the mean 0-6 km wind was less than 20 kts. Supercells do occur in these notably "weaker" wind environments, and recent case studies and observations suggest that motion deviations in these situations is considerably more to the right of the mean wind than typical estimation guidelines would indicate. An extreme example is the storm that produced the Jarrell, Texas tornado on 5/27/97, which moved more than 90° to the right of the mean wind. This motion was likely influenced by a stationary surface boundary and an unusually weak 0-6 km mean wind environment (10-12 kts) for a storm with supercell characteristics. In such cases, continuous development of the main updraft on a storm's right flank (Rotunno and Klemp 1982) and factors such as low-level boundaries appear to dominate storm motion in dramatic fashion. Such storm motion can have a major impact on s-r parameter values and their utility in an operational setting.

This paper will present a small set of supercell cases in environments where the 0-6 km mean wind is < 20 kts, showing that, on average, supercell motion deviates significantly more than 30° right of the mean wind in such situations. A case will be made for extending operational forecast supercell motion estimations increasingly to the right of the mean wind (as much as 60° to 90°) when 0-6 km winds average below 20 kts. An extended algorithm for estimating supercell motion in weaker wind environments will be suggested, and comparisons will be made between this and an algorithm used by Rasmussen and Straka (1997). The impact of extreme motion deviation on s-r parameters will also be shown.

* Corresponding author address: Jonathan M. Davies
8506 Peppertree, Wichita, KS 67226; e-mail: jdavies@feist.com

Table 1.

Soundings nr supercells in weak wind fields	event	<----- deg / kts ----->			
		0-6k wind	30R75 esmt	actual motion	right deviation
LBF/OMA 00z 6/4/80	F4 tor	212°17	242°13	320° 8	108° 47%
OMA 00z 5/16/92	F0 tor	218°14	248°11	280° 7	62° 50%
DDC 00z 5/1/93	no tor	239°19	269°14	290° 7	51° 36%
LBF/OMA 00z 6/13/93	F0 tor	229°18	259°14	305° 8	76° 44%
nr CLL 20z 5/27/97	F5 tor	242°11	272° 8	15° 12	133°109%

2. SUPERCELL CASES IN LESSER WIND ENVIRONMENTS

Soundings for capturing aspects of the background environment in reasonable proximity to supercells that occur in 0-6 km flow averaging less than 20 kts are not simple to locate. The dataset of background sounding environments from strong and violent tornado cases in DJ93 contains only 4 out of 242 tornado cases where environmental winds average < 20 kts, and storm motion is available for only one of those cases (the Grand Island tornadoes on 6/3/80). The aforementioned Jarrell, Texas tornado day provides another example, with a field sounding from Texas A&M University available some 50 miles east of ongoing storms. In addition to those two cases, the author located soundings for three weaker wind environment cases involving supercells observed in the field that were nontornadic or only briefly tornadic.

Table 1 gives the 0-6 km mean wind, 30R75 estimated motion relative to this wind, and actual storm motions for these 5 cases. Note that all the storm motions are further to the right than the 30R75 assumption, and in 4 of the 5 cases more than 60° right of the 0-6 km mean wind.

To develop a larger data set, and because forecasting situations require use of forecast sounding profiles in addition to actual soundings, the author examined an archive of selected FD (forecast diagnostic) wind and temperature forecasts during 1992-1998, and found 23 cases where both the 12 hr forecast data and reasonable estimates of actual mean supercell motion were available. Table 2 (next page) lists these cases similar to Table 1, with estimated actual storm motions from field observations or radar over a period of > 1 hour. It should be noted that actual storm motion speeds (kts) were more variable and somewhat difficult to assess, and therefore may be less accurate than the directional deviations (degrees). The 23 cases average a motion 64° right of the 0-6 km mean wind, with the majority (82%) averaging a motion speed that is 65% of the mean wind.

Breaking the cases down into 3 ranges of environmental mean wind strength, Table 3 (next page) suggests that, on average, the weaker the mean wind, the further the supercell deviation to the right. However, no organized pattern of speed diminution relative to the mean wind was evident for the same ranges, other than the fact that speed of motion tended to average less than 70% for most of the data set as a whole.

Table 2. |<----- deg / kts ----->|

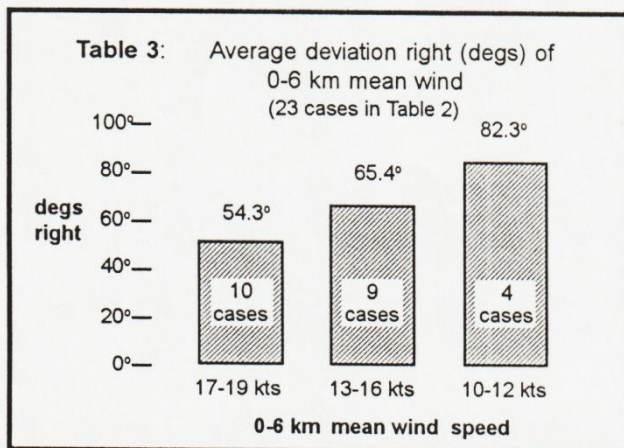
FD fcst sndgs nr sprclls in weak wind fields	event	0-6k wind	30R75 esmt	actual motion	right deviation
3/17/92 nr P28 (f-ob)	no tor	205°18	235°14	255° 8	50° 44%
5/15/92 nr OLU (f-ob)	F0 tor	227°17	257°13	280° 7	53° 41%
6/19/92 nr ICT (f-ob)	no tor	272°14	302°11	330° 20	58° 140%
6/27/92 ne AMA (rdr)	F4 tor	264°19	294° 14	295° 10	31° 53%
4/30/93 nr DDC (f-ob)	no tor	239°17	269°13	290° 7	51° 41%
6/12/93 nr GRI (f-ob)	F0 tor	236°17	266°13	305° 8	69° 47%
6/13/93 nr TOP (f-ob)	no tor	259°15	289° 11	340° 8	81° 53%
5/6/94 nr PNC (f-ob)	F1 tor	272°19	302°14	310° 10	38° 53%
6/1/94 ne of CNK (f-ob)	no tor	249°17	279°13	310° 14	61° 82%
7/2/95 nr ICT (f-ob)	no tor	246°14	276°11	290° 8	44° 57%
5/24/96 nr GBD (f-ob)	no tor	206°16	236°12	340° 5	134° 31%
6/18/96 e of ICT (f-ob)	no tor	276°13	306°10	330° 8	54° 62%
7/24/96 nr LAA (f-ob)	no tor	303°12	333° 9	360° 10	57° 83%
7/25/96 nr MCK (f-ob)	no tor	276°13	306°10	340° 5	64° 39%
5/27/97 nr TPL (rdr)	F5 tor	258°10	288° 8	015° 12	117°120%
6/11/97 nw CDS (f-ob)	F3 tor	272°19	302°14	340° 16	68° 84%
6/12/97nr ICT (rdr)	no tor	274°13	304°10	290° 8	18° 62%
6/29/97 nr PNC (f-ob)	no tor	262°12	292° 9	330° 10	68° 83%
6/30/97 nw BBW (f-ob)	no tor	248°17	278°13	320° 13	72° 76%
8/13/97 nr GCK (rdr)	no tor	260°14	290°11	340° 12	80° 86%
8/18/97 nr LBL (rdr)	F0 tor	227°16	257°12	285° 12	58° 75%
9/12/97 n DDC (rdr)	no tor	273°11	303° 8	360° 8	87° 73%
5/21/98 nr HSI (rdr)	no tor	215°18	245°14	265° 15	50° 83%

Note: all cases occurred during p.m., except 5/21/98 (a.m.). Actual motions were estimated from field observations (f-ob) or radar (rdr) as noted in parentheses.

3. SUGGESTIONS FOR ESTIMATING MEAN STORM MOTION

The results above strongly suggest that, in a bulk or average sense, preset storm estimations of 30R75 relative to the mean wind are inappropriate for most supercells that develop in 0-6 km mean wind environments less than roughly 20 kts. In stronger wind environments, cell motion is probably dominated by the stronger low to mid tropospheric flow. In lesser wind environments with moderate to large CAPE that are still capable of supporting supercells (i.e., mean 0-6 km flow 10-19 kts), it is likely that cell motion is dominated by more subtle factors such as low-level boundaries and ongoing updraft development on a storm's right flank.

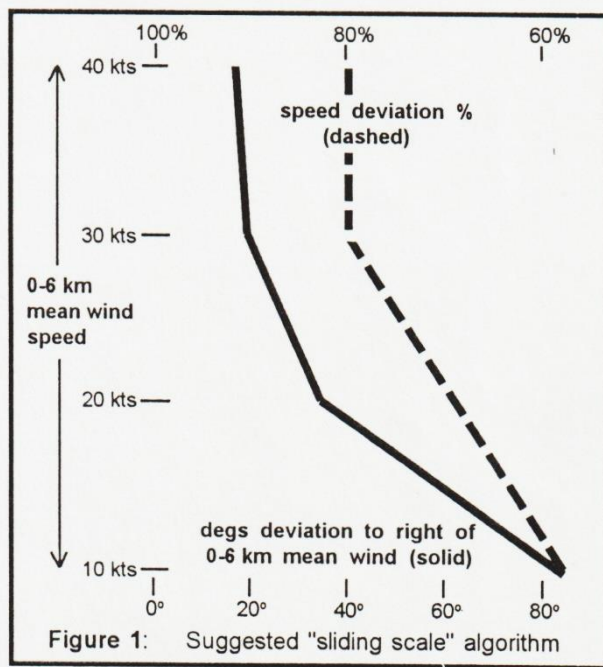
One way of addressing this issue might be a sliding scale of storm motion estimation that goes increasingly further to the right of the mean wind at lesser speeds as



the 0-6 km wind environment weakens. Figure 1 shows a suggested "sliding scale" algorithm for right deviation (solid line, degs) and speed (dashed line, %) relative to 0-6 km wind strength, incorporating results from the previous section and extending the work of DJ93 to lesser wind fields. The scale lines in Fig. 1 are approximated as follows:

0-6 km wind (mws)	direction deviation (degs)	speed
mws ≥ 30 kts	(-mws/4) + 27.5	.80(mws)
mws 20-29 kts	(-mws/.67) + 64.7	(mws/.8) + 47.5
mws 10-19 kts	(-mws/.2) + 135	(mws/.8) + 47.5

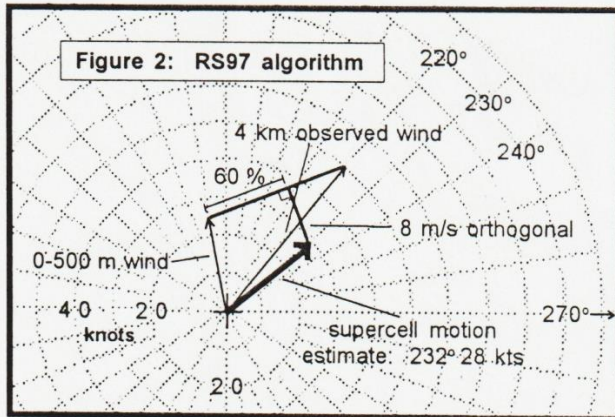
Because we are attempting to estimate storm motion in only a bulk/gross sense, Fig. 1 is certainly not intended to represent any kind of "exact" relationship. The issue of storm motion is very complex, and is influenced by interacting factors that are not well understood or simple to assess. It is therefore important to understand that the Fig. 1 "scale" is suggested only as a starting point for estimating supercell motion. Orientation of nearby low-level boundaries may provide additional clues to adjustments regarding storm motion estimation.



4. ANOTHER STORM MOTION ALGORITHM

Rasmussen and Straka (1997, hereafter RS97) have suggested a storm motion algorithm based on low-level inflow to a storm rather than the deep layer mean wind. Their algorithm uses the vector difference between the boundary-layer mean wind (e.g., 0-500 m AGL) and the observed wind at 4 km AGL as plotted on a hodograph. The storm motion estimate is a new vector drawn from the hodograph origin to a point 60% of the magnitude and 8 m s⁻¹ orthogonal to the right of this vector difference (see Figure 2, next page).

Using the 23 cases from Table 2, comparisons were made between the RS97 algorithm and the algorithm suggested in Fig. 1, and also a straight 30R75 motion assumption. These results compared to observed storm motions are summarized in Table 4. It can be seen that, while the 30R75 assumption results in large storm motion estimation errors that average more than 30° less than the actual rightward



directional deviations, both the sliding scale algorithm suggested in Fig. 1 and the RS97 algorithm perform reasonably well regarding average errors (within 10° of the actual deviations). On average, the sliding scale algorithm tends to slightly underestimate the rightward motion deviation, while the RS97 algorithm tends to slightly overestimate the deviation. Speed estimations for both algorithms, on average, seem adequate.

Also shown in Table 4 are the average errors for a composite or mean storm motion estimation based on averaging both the sliding scale and RS97 algorithms. This compromise produces the least amount of right deviation error, on average, in the dataset. While one cannot make detailed conclusions from a relatively small group of cases, it does appear that both the sliding scale algorithm and the RS97 algorithm, or a composite/mean of the two, result in workable supercell motion estimations that are a significant improvement over a simple 30R75 preset motion assumption.

Table 4. Comparison of algorithms: average storm motion estimation errors relative to observed storm motion (23 cases)

30R75		sliding scale(SS)		RS97		composite SS/RS97	
degs	spd	degs	spd	degs	spd	degs	spd
-33.5°	+1.3kts	-4.8°	+0.1kts	+7.2°	+0.4kts	+1.4°	+0.5kts

degs: - is left of observed motion; + is to right of observed motion.
 speed: - is an underestimate of speed; + is an overestimate.
 (values closest to 0 indicate least average errors)

5. IMPORTANCE OF STORM MOTION AND STORM-RELATIVE FRAMEWORK

A scheme for reasonable or useful estimation of storm motion is important because storm-relative flow is physically significant for the generation and maintenance of supercells regarding low-level flow and shear (e.g., see Davies-Jones and Burgess 1990) and midtropospheric flow (e.g., see Brooks et al. 1994). The Jarrell, Texas tornado day appears to provide an extreme example of this importance.

Below are the FD 12 hr forecast wind/temperature profiles transmitted for San Antonio and College Station valid at 00 UTC 5/28/97:

DATA BASED ON 271200Z, VALID 280000Z. TEMPS NEG ABV 24000
 FT 3000 6000 9000 12000 18000 24000 30000 34000 39000
 SAT 1512 1807+19 2506+12 2911+06 2922-10 2719-22 252538 252649 262660
 CLL 1911 2311+17 2515+11 2616+05 2820-11 2719-23 252438 252549 242660

For a point near Austin, these decode and interpolate to:

FT 3000' 6000' 9000' 12000' 18000' 24000' 30000'
 AUS 17012 20509+18 25011+12 27514+06 28521-11 27024-23 25025-38
 34000': 24538-49 39000': 25026-60

At 2150 UTC, the F4 Pedernales Valley tornado was in progress around 20 miles to the WNW of Austin. Using the 2153 UTC Austin surface observation ($T = 84^\circ\text{F}$, $T_d = 75^\circ\text{F}$, wind from 080° at 8 kts), this forecast profile suggests a surface-based CAPE near 5300 J kg^{-1} and a 0-6 km mean wind from near 260° at only 10-11 kts. Note below how the 0-3 km s-r helicity (SRH) and, in particular, the 3-6 km mean s-r winds vary between using a 30R75 storm motion assumption and a storm motion more representative of supercells observed earlier and further north:

storm motion estimate	0-3 km SRH	3-6 km s-r wind	EHI
$290^\circ / 8 \text{ kts}$ (30R75)	$88 \text{ m}^2 \text{ s}^{-2}$	9 kts	2.9
$10^\circ / 10 \text{ kts}$ (~actual)	$120 \text{ m}^2 \text{ s}^{-2}$	20 kts	4.0

Most dramatic is the increase in midlevel s-r flow, which *more than doubles* with the observed storm motion. These values appear quite supportive of tornadic supercells (Thompson 1998). Such enhanced s-r flow should strengthen an updraft through precipitation displacement downwind (Brooks et al. 1994), and updraft interaction with deep layer shear (Weisman and Klemp 1986).

The sliding scale algorithm from Fig. 1 and the RS97 algorithm yield the following results:

storm motion estimate	0-3 km SRH	3-6 km s-r wind	EHI
$345^\circ / 6 \text{ kts}$ (sliding)	$101 \text{ m}^2 \text{ s}^{-2}$	15 kts	3.3
$350^\circ / 11 \text{ kts}$ (RS97)	$126 \text{ m}^2 \text{ s}^{-2}$	17 kts	4.2

Both algorithms are a considerable improvement over a 30R75 motion assumption when compared to observed storm motion. In this case, the RS97 algorithm comes a little closer to observed average storm motions than afternoon, and does a better job of representing forecast diagnostic s-r parameters for this particular situation. A northeast-southwest surface boundary across central Texas likely had a major impact on storm motion in this unusually weak wind environment for strong and violent supercell tornadoes.

In map form, Figures 3 and 4 (next page) emphasize potential errors that can result from generating s-r fields using a common 30R75 motion estimation in weaker wind environments instead of a more realistic scheme. Both figures use 22 UTC surface observations blended with 12 hr FD forecast data valid 00 UTC 5/28/97 to suggest a diagnostic analysis of EHI (Davies 1993, using SRH) and s-r midlevel winds (Thompson 1998). The difference is that Fig. 3 uses a 30R75 motion, while Fig. 4 uses the sliding scale algorithm from Fig. 1. In particular, note the differing positions of the 15 and 20 kt s-r midlevel wind isopleths. Unlike the 30R75 scheme, the sliding scale algorithm does a good job of suggesting that s-r midlevel winds potentially supportive of tornadic supercells actually extend southward over the Austin area where EHI values are also significant. It seems that in weaker wind environments, s-r midlevel flow is particularly sensitive to storm motion, which appears to be best estimated using the sliding scale and/or RS97 algorithms.

6. SUMMARY

The data presented in this paper strongly suggest that supercells in 0-6 km mean wind fields less than roughly 20 kts typically deviate far right of the 0-6 km mean wind.

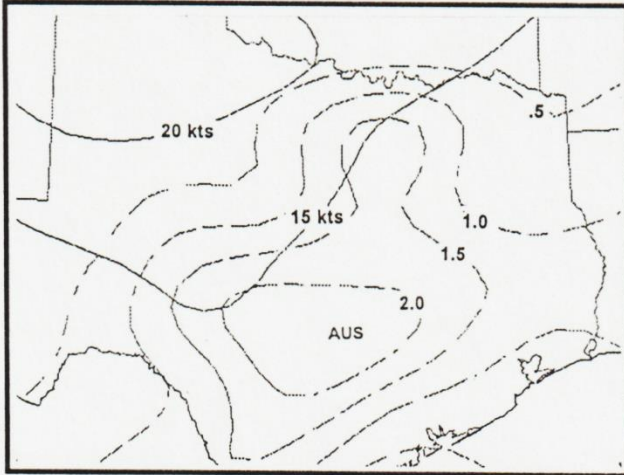


Figure 3. Analysis of 3-6 km AGL s-r winds (solid lines) and EHI (dashed lines, using 0-3 km SRH) for 22 UTC 5/27/97, using 30R75 supercell motion estimate. Analysis blends 22 UTC surface data with 12 hr FD forecast valid 00 UTC 5/28/97. Austin, Texas (AUS) is indicated.

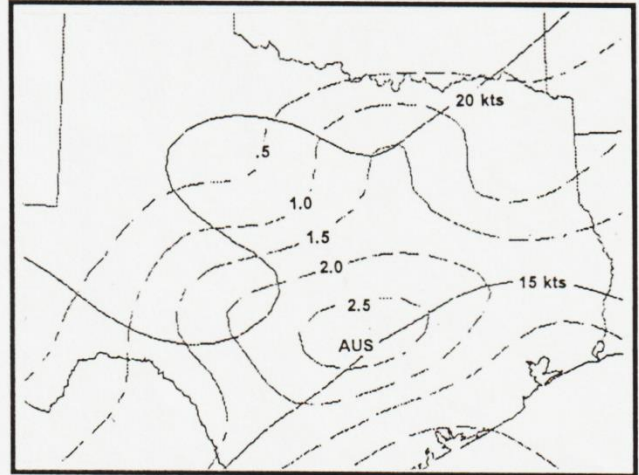


Figure 4. As in Fig. 3, except using a supercell motion computed from the sliding scale algorithm in Fig. 1. Note in particular the southeastward extension of significant 3-6 km s-r winds compared to Fig. 3.

This deviation is much further to the right than a 30R75 motion as used in Maddox (1976) or as part of the scheme suggested by Davies and Johns (1993). This strong deviation from the mean wind in weaker wind fields is not reflected in many operational schemes used to generate storm-relative products for severe weather forecasting.

As shown in the prior section, the large rightward deviation in these cases can have a major impact on s-r wind assessments, particularly in situations with large CAPE but relatively weak wind fields. The data in Table 2 suggest that supercells (and even violent tornadoes) can occur in 0-6 km mean wind fields as weak as 10-12 kts if the storm motion orientation is such that significant midlevel s-r flow is generated. Mean 0-6 km wind fields less than 10-12 kts do not appear capable of supporting supercell development.

A "sliding scale" algorithm expanding on the work of Davies and Johns (1993) has been suggested from Fig. 1 as a starting point for estimating supercell motion. This involves scaling the movement increasingly rightward as mean environmental flow decreases from strong (> 30 kts) to moderate (20-30 kts) to weak (10-19 kts) in the 0-6 km layer. Comparison of this algorithm to one used by Rasmussen and Straka (1997) based on low-level inflow suggests useful results and operational utility for both algorithms as a crude estimate of supercell motion prior to convection. Operationally, it may be useful to compare motions between algorithms to note similarities or differences, or to simply average the results.

The main point coming out of this study is that a simple "preset" supercell motion estimate of 30R75 is not appropriate for computing storm-relative products, particularly in weaker wind environments associated with some supercells. Based on the data studied, a couple more useful algorithms have been suggested.

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