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13.2 PREDICTING SUPERCELL MOTION USING HODOGRAPH TECHNIQUES

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1. INTRODUCTION

Although supercells have been given considerable attention since Browning (1964), perhaps the least research effort has been directed toward predicting supercell motion. Despite this, knowledge of supercell motion has become increasingly important during the 1990s as: (i) more work has focused on storm-relative helicity (SRH) as a measure of supercell rotation (Davies-Jones et al. 1990; Droegemeier et al. 1993); and (ii) studies have addressed storm-relative winds for both tornadic and non-tornadic environments (Brooks et al. 1994a, 1994b; Kerr and Darkow 1996; Thompson 1998). From this it is apparent that reliable prediction of supercell motion prior to storm development has the potential to improve severe local storm warnings—implying the saving of lives and property.

Davies and Johns (1993) developed a method for predicting supercell motion based on a climatology of 31 central and eastern United States supercells (from Johns et al. 1990). This widely used method is defined as either: (i) 30° to the right of the 0-6 km AGL (all heights AGL hereafter) mean wind direction at 75% of the mean wind speed, if the mean wind speed is ≤ 15 m s^{-1}; or (ii) 20° to the right of the 0-6 km mean wind direction at 85% of the mean wind speed (hereafter referred to as the JDL method). This method has since been used extensively to estimate supercell motion from both observed data and output from numerical weather prediction models.

The JDL method is useful for the typical Great Plains supercell, but also has some limitations. For example, the JDL method works well in predicting supercell motion for traditional upper-right quadrant hodographs in the Northern Hemisphere (e.g., Fig. 1a); however, given other environmental situations (e.g., northwest flow; Johns 1984) the JDL method may produce less than desirable results (e.g., Fig. 1b). Keighton and Passetti (1998) present another example of when the JDL method fails over mountainous terrain. Since these 'non-classic' hodographs may be problematic to the forecaster, we will investigate alternative supercell motion prediction techniques.

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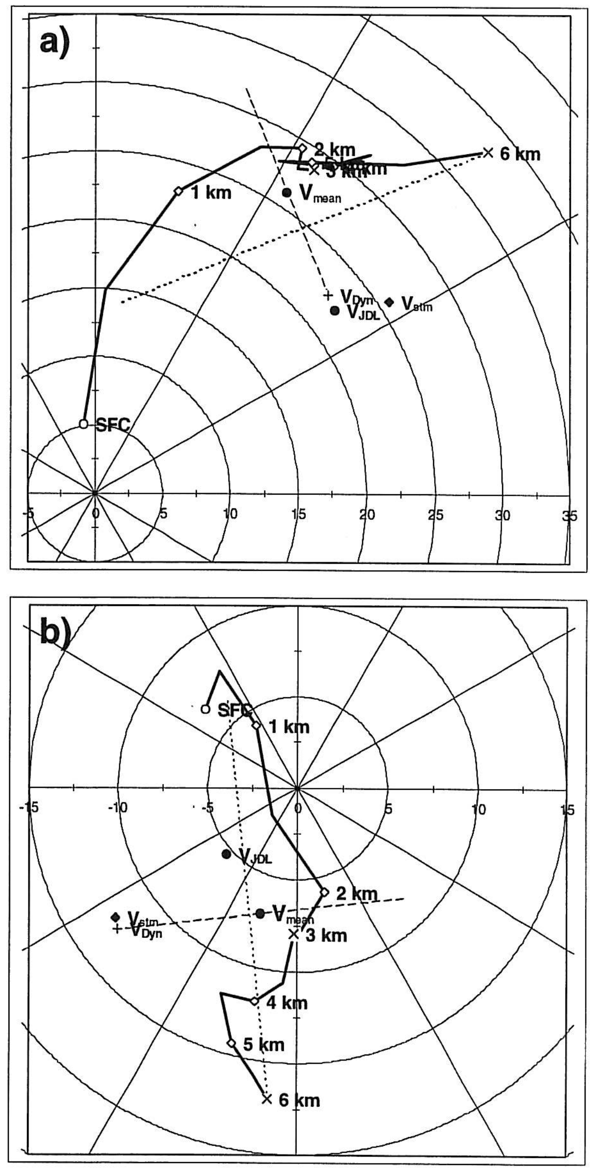

Figure 1. 00 UTC 0-6 km AGL hodographs (m s^{-1}) for: (a) LIT, 16 November 1988; and (b) CRP, 21 June 1996. The 0-6 km AGL mean wind is given as V_{mean}, supercell motion as V_{stm}, JDL estimate as V_{JDL}, and Dynamic estimate as V_{Dyn}. Dashed/dotted lines and the Dynamic method are discussed in the text.

Evidence for a more physically-based method to predict supercell motion is present in the meteorological literature, both from a modeling and observational perspective. Weisman and Klemp (1986) suggest two components that may be used to predict supercell motion: (i) the influence of the mean wind on initial cell motion; and (ii) the interactions of the updraft with the sheared environment (i.e., due to favorable vertical pressure gradient forcing produced on the storm flanks). Modeling studies of supercells under various vertical wind shear and buoyancy profiles support this premise (Klemp and Wilhelmson 1978; Weisman and Klemp 1984, 1986; Rotunno and Klemp 1985; Droegemeier et al. 1993), as do various climatological studies of supercell hodographs (Chisholm and Renick 1972; Darkow and McCann 1977; Fankhauser and Mohr 1977; Bluestein and Parks 1983; Bluestein and Jain 1985; Brown 1993). In these examples, the composite supercell motion is generally 4 to 12 m s^{-1} to the right of the mean wind along a line roughly perpendicular to the mean vertical wind shear vector. Weisman (UCAR 1996) recently presented a method based on these observations, whereby supercell motion is predicted as 3 to 8 m s^{-1} off the 0-6 km pressure-weighted mean wind, and perpendicular to the 0-6 km mean vertical wind shear vector.

Another component that may also influence storm motion results from the interaction of the thunderstorm outflow (or cold pool) with the low-level vertical wind shear. This has a tendency to produce an additional propagation component downshear of the convective updraft, proportional to the low-level vertical wind shear magnitude (Rotunno et al. 1988; Weisman 1993). A perusal of the meteorological literature and the hodographs obtained for this study suggest high-precipitation (HP) supercells (Moller et al. 1990) are more strongly influenced by this effect (as opposed to other types of supercells), and many times are associated with (but independent of) bow-echo configurations (e.g., Moller et al. 1990, 1994; Brooks and Doswell 1993; Conway et al. 1996; Klimowski et al. 1998). This obviously complicates the problem of predicting supercell motion.

The objectives of this study are threefold. First, we develop a new technique to predict supercell motion based on the above observations (hereafter referred to as the Dynamic method), which is a modification of that presented by Weisman (UCAR 1996). In light of the perceived inadequacies of the JDL method, we tested these two methodologies for: (i) cases when the JDL method resulted in small forecast errors (i.e., 'classic' hodographs); and (ii) cases when the JDL method was not as effective (i.e., 'non-classic' hodographs). Second, we examine the effectiveness of the JDL method by simply translating the hodograph to the origin—making it more consistent with the Dynamic (shear-relative) method. We believe this will result in a more accurate estimate of supercell motion for the 'non-classic' hodographs. Finally, we explore relationships between the low-level vertical wind shear and supercells that deviate significantly from the mean wind. Based on our findings, we will make recommendations on ways to estimate supercell motion in the future.

2. DATA AND METHODOLOGY

2.1 Data development

Supercell hodographs and motions were gathered from a variety of sources. The primary data source consisted of 138 supercell occurrences and motions gathered by Thompson (1998) spanning 1995 to 1996. Second, the 33 supercell hodographs and motions used in Brown's (1993) composite study were obtained—see the references therein. An additional 31 supercell occurrences and motions were obtained from Davies and Johns (1993); they used these to derive the JDL method. Finally, 15 supercell occurrences and motions were gathered from the meteorological literature spanning 1973 to 1996 (references available upon request).

Since Thompson's (1998) reported supercells fell within ± 3 hours of sounding release time, no attempt was made to modify the soundings. The spatial criteria used in deriving an appropriate hodograph for supercells in the Thompson (1998) data set are as follows: (i) the sounding downstream of the supercell (i.e., the inflow region) was used unmodified in calculating supercell motion estimates; (ii) if the 'inflow' sounding was missing or unrepresentative, the next closest sounding was interrogated; and (iii) if the supercell was 'in-between' sounding locations, the corresponding soundings were linearly averaged to produce a composite hodograph. Soundings that were contaminated by convection or dryline passage were omitted. The hodographs provided by Brown (1993) were used without modification on our part; some already had been modified by the original authors. Similarly, the Johns and Davies (1993) soundings were not modified; however, if more than one sounding was listed for a case in their data set, the wind data were linearly averaged to form a composite hodograph as was done for the Thompson (1998) data set. The journal soundings were not modified, and were chosen based on a temporal constraint of ± 3 hours from sounding release time. For a good discussion on the methods, difficulties, and caveats of choosing 'representative' soundings, see Brooks et al. (1994a).

All necessary sounding data were retrieved either from the National Climatic Data Center (NCDC) Radiosonde Data of North America 1946-1995 CD-ROM or from the on-line archive provided by the Forecast System Laboratory (FSL) for post-1995 data (www-frd.fsl.noaa.gov/mab/raob). The complete data set consists of nearly 225 supercell hodographs at 500 m intervals up to 7 km, along with the supercell motion. Only 125 are presented here as a precursor to a more extensive formal publication.

2.2 The Dynamic method

The Dynamic method is defined as: (i) 8 m s^{-1} either to the left (left-moving supercell) or to the right (right-moving supercell) of the 0-6 km mean wind (non-pressure-weighted); and (ii) constrained along a line which both is perpendicular to the 0-6 km mean vertical wind shear vector and passes through the 0-6 km mean wind. The mean vertical wind shear vector is defined as the vector difference between the 6 km wind and the 0-1 km mean wind (i.e., the 0-1 km mean wind is the 'tail'). The dotted lines in Figure 1 represent the mean vertical wind shear vectors; the dashed lines are perpendicular to the corresponding mean shear vector and pass through the 0-6 km mean wind. We chose the 0-1 km mean wind for the mean shear vector calculation in order to minimize the effect of varying surface winds; this has a stabilizing effect on the Dynamic method. The deviation from the mean wind was based on results presented in the next section.

2.3 Classification of hodographs

Based on the observations in the Introduction, we tested the JDL method against the new technique for both 'classic' and 'non-classic' hodographs. After examining Figure 1, as well as the many supercell hodographs available for this study, two of the three following criteria were required to define a hodograph as classic: (i) the 0-6 km mean wind was in the upper-right quadrant; (ii) the surface wind was ≤ 5 m s^{-1}; and (iii) the hodograph was not in the lower-left quadrant, and spanned ≤ 180°. If only one or less of the three conditions were met, the hodograph was labeled as non-classic.

The methods used to predict supercell motion were calculated in the same way for both classifications above. It is also important to note that we did not base our classic definition on the shape of the hodograph; rather, we tailored it to the orientation of the hodograph relative to the origin. This is based on numerous observations and common knowledge of the 'typical' central North American supercell hodograph (e.g., Chisholm and Renick 1972; Brown 1993).

Finally, an additional classification was made based on our observations of hodographs and HP supercells. Hodographs in which the supercell motion either deviated from the 0-6 km mean wind by greater than 15 m s^{-1}, or was greater than any of the winds on the 0-6 km hodograph, were classified as 'HP-type.' We are not inferring that all HP supercells deviate significantly from the mean wind; however, we do contend there is a tendency for this to occur. This is based on studies of HP supercells (e.g., Moller et al. 1990, 1994; Brooks and Doswell 1993; Conway et al. 1996; Klimowski et al. 1998), as well as examination of the hodographs used for this study. Nearly all of the Davies and Johns (1993) and journal hodographs we put into this category were labeled (by the original authors) as an HP supercell or as being associated with a bow echo.

3. RESULTS

Results from 125 supercell hodographs are presented in this paper: 80 classic, 27 non-classic, and 18 HP-type. The average deviation of the supercell motion from the 0-6 km mean wind for all cases was 9.0 m s^{-1} with a standard deviation of 3.7 m s^{-1}. In order to arrive at the 8 m s^{-1} deviation for the Dynamic method described above, we calculated the mean errors between the observed and predicted supercell motions for varying deviations from the 0-6 km mean wind. The mean error was minimized for all hodographs (4.7 m s^{-1}) and for the 80 classic hodograph subset (4.0 m s^{-1}) for this 8 m s^{-1} deviation. We also evaluated the Dynamic method using a: 0-7 km mean wind, 0-5 km mean wind, 0-4 km mean wind, and 0-6 km pressure-weighted mean wind. The errors progressively increased for these four variations in this order; however, the 8 m s^{-1} deviation still generally minimized the mean error. Results using the last two variations were significantly different from those using the 0-6 km mean wind.

Based on the entire data set, the Dynamic method is superior to the JDL method in terms of having a smaller mean error between the observed and predicted supercell motion (Table 1). Although the mean error is only 0.9 m s^{-1} less than the JDL error for all cases, the null hypothesis of equality of mean errors would be rejected at the 5% level for a two-tailed T-test (p-value ~10^{-4}; Wilks 1995). In addition, the results are similar when the HP-type hodograph cases are excluded, with the mean error for the Dynamic method decreasing to less than 4 m s^{-1} (Table 1). As was expected, no statistically significant difference was observed between the Dynamic method and the JDL method for the classic hodographs; however, the mean error differed by 0.5 m s^{-1} (Table 1). Most striking is the highly significant difference between the two methods for the non-classic hodograph cases; the mean error for the Dynamic method is 2.4 m s^{-1} less than the JDL error, and 83% of the cases were better predicted by the Dynamic method (Table 1). Finally, the HP-type cases were poorly forecast by both methodologies (10.8 to 10.9 m s^{-1} mean errors) with approximately double the mean error when compared to all cases.

Table 1. Number of supercell cases (#); mean errors (m s^{-1}) for the Dynamic (V_{Dyn}) and JDL (V_{JDL}) methods; percent of storm motions better predicted by V_{Dyn} (B.P.); two-tailed T-test for comparing means (T_{stat}); and the p-value (P_{val}).

Hodograph	*#*	V_{Dyn}	V_{JDL}	*B.P.*	T_{stat}	P_{val}
All Types	125	4.7	5.6	61%	-3.59	10^{-4}
Non-HP-type	107	3.7	4.7	63%	-2.93	10^{-4}
Classic	80	4.0	4.5	56%	-1.70	.093
Non-classic	27	2.8	5.2	83%	-5.52	10^{-5}
HP-type	18	10.8	10.9	50%	-0.07	.944

Upon translating the hodograph such that the surface wind was at the origin, the mean error for the JDL method was only reduced 0.2 m s^{-1} to 5.4 m s^{-1} for all supercell hodographs. One explanation for only this slight improvement is the large sample of classic hodographs (80) versus the much smaller sample of non-classic hodographs (27). However, even for the 27 non-classic hodographs the JDL error was still only 0.2 m s^{-1} less than the mean error for non-translated hodographs. This suggests only modest improvement can be gained in supercell motion estimation by the JDL method upon translating the hodograph to the origin; and thus the Dynamic method is still superior based on these data.

Since only a small set of HP-type hodographs have been collected, statistical inferences regarding these cannot be made with confidence. However, the data show a tendency for deviant supercell motion to be in the direction of the low-level vertical wind shear. Specifically, an additional component to the Dynamic method which is 8 m s^{-1} downshear in the direction of the 0-1 km to 3 km shear vector reduces the mean error from 10.8 m s^{-1} to 8.2 m s^{-1}. Some of the cases display substantial deviation from this modification, which may be due to external influences.

4. SUMMARY AND CONCLUSIONS

The Dynamic method is statistically superior to the JDL method for predicting supercell motion, especially for non-classic hodographs. This new method is physically-based, not sensitive to hodograph orientation (i.e., shear-relative), and supported by numerous observational and modeling studies. Since SRH and storm-relative flow concepts require knowledge of supercell motion, we suggest using the Dynamic method as a basis. Despite providing a more accurate prediction of supercell motion, the data show a range of supercell deviations from the 0-6 km mean wind (~70% of the cases from 5.3 to 12.7 m s^{-1}), thus the Dynamic method should be considered as a general guideline when predicting supercell motion. Furthermore, modifications to the method may be necessary in elevated terrain, where a shallower mean wind depth might be advantageous (e.g., 4 km works best for Keighton and Passetti 1998).

The Dynamic method assumes supercell motion is largely governed by internal processes. We are not suggesting external influences such as interaction with topography, outflow boundaries, and fronts do not contribute to the supercell motion, but these often are difficult to quantify *a priori*. Future work involves: (i) refining the Dynamic method for prediction of HP-type supercells, (ii) testing the Dynamic method for left-moving supercells; and (iii) assessing possible effects of the vertical moisture profile and static stability on supercell motion.

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6. REFERENCES

Bluestein, H. B., and C. R. Parks, 1983: A synoptic and photographic climatology of low-precipitation severe thunderstorms in the Southern Plains. *Mon. Wea. Rev.*, **111**, 2034-2046.

____, and M. H. Jain, 1985: The formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during spring. *J. Atmos. Sci.*, **42**, 1711-1732.

Brooks, H. E., and C. A. Doswell III, 1993: Extreme winds in high-precipitation supercells. Preprints, *17th Conf. on Severe Local Storms*, St. Louis, MO, Amer. Meteor. Soc., 173-177.

____, ____, and J. Cooper, 1994a: On the environments of tornadic and nontornadic mesocyclones. *Wea. Forecasting*, **9**, 606-618.

____, ____, and R. B. Wilhelmson, 1994b: The role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev.*, **122**, 126-136.

Brown, R. A., 1993: A compositing approach for preserving significant features in atmospheric profiles. *Mon. Wea. Rev.*, **121**, 874-880.

Browning, K. A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. *J. Atmos. Sci.*, **21**, 634-639.

Chisholm, A. J., and J. H. Renick, 1972: The kinematics of multicell and supercell Alberta hailstorms. Alberta Hail Studies, Research Council of Alberta Hail Studies, Edmonton, Canada, Rep. 72-2, 24-31.

Conway, J. W., H. E. Brooks, and K. D. Hondl, 1996: The 17 August 1994 Lahoma, OK supercell: Issues of tornadogenesis and bow echo formation. Preprints, *18th Conf. on Severe Local Storms*, San Francisco, CA, Amer. Meteor. Soc., 52-55.

Darkow, G. L., and D. W. McCann, 1977: Relative environmental winds for 121 tornado bearing storms. Preprints, 10th *Conf. on Severe Local Storms*, Omaha, NE, Amer. Meteor. Soc., 413-417.

Davies, J. M., and R. H. Johns, 1993: Some wind and instability parameters associated with strong and violent tornadoes. Part I: Wind shear and helicity. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards, Geophys. Monogr.*, No. 79, Amer. Geophys. Union, 573-582.

Davies-Jones, R. P., D. W. Burgess, and M. Foster, 1990: Test of helicity as a tornado forecast parameter. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 588-592.

Droegemeier, K. K., S. M. Lazarus, and R. Davies-Jones, 1993: The influence of helicity on numerically simulated convective storms. *Mon. Wea. Rev.*, **121**, 2005-2029.

Fankhauser, J. C., and C. G. Mohr, 1977: Some correlations between various sounding parameters and hailstorm characteristics in northeast Colorado. Preprints, *10th Conf. on Severe Local Storms*, Omaha, NE, Amer. Meteor. Soc., 218-225.

Johns, R. H., 1984: A synoptic climatology of northwest flow severe weather outbreaks. Part II: Meteorological parameters and synoptic patterns. Mon. Wea. Rev., 112, 449-464.

____, J. M. Davies, and P. W. Leftwich, 1990: An examination of the relationship of 0-2 km AGL "positive" wind shear to potential buoyant energy in strong and violent tornado situations. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 593-598.

Keighton, S., and V. Passetti, 1998: Anticipation and observation of a northern Arizona supercell over high terrain. Preprints, *16th Conf. on Weather Analysis and Forecasting*, Phoenix, AZ, Amer. Meteor. Soc., 124-126.

Kerr, B. W., and G. L. Darkow, 1996: Storm-relative winds and helicity in the tornadic thunderstorm environment. *Wea. Forecasting*, **11**, 489-505.

Klemp, J. B., and R. B. Wilhelmson, 1978: Simulations of right- and left-moving storms produced through storm splitting. *J. Atmos. Sci.*, **35**, 1097-1110.

Klimowski, B. A., M. R. Hjelmfelt, M. J. Bunkers, D. Sedlacek, and L. R. Johnson, 1998: Hailstorm damage observed from the GOES-8 satellite: The 5-6 July 1996 Butte-Meade Storm. *Mon. Wea. Rev.*, **126**, 831-834.

Moller, A. R., C. A. Doswell III, and R. Przybylinski, 1990: High-precipitation supercells: A conceptual model and documentation. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor. Soc., 52-57.

____, ____, M. P. Foster, and G. R. Woodall, 1994: The operational recognition of supercell thunderstorm environments and storm structures. *Wea. Forecasting*, **9**, 327-347.

Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.*, **42**, 271-292.

____, ____, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.*, **45**, 463-485.

Thompson, R. L., 1998: Eta model storm-relative winds associated with tornadic and nontornadic supercells. *Wea. Forecasting*, **13**, 125-137.

UCAR, 1996: Anticipating convective storm structure and evolution. University Corporation for Atmospheric Research, Cooperative Program for Operational Meteorology, Education, and Training (COMET).

Weisman, M. L., 1993: The genesis of severe, long-lived bow echoes. *J. Atmos. Sci.*, **50**, 645-670.

____, and J. B. Klemp, 1984: The structure and classification of numerically simulated convective storms in directionally varying wind shears. *Mon. Wea. Rev.*, **112**, 2479-2498.

____, and ____, 1986: Characteristics of isolated convective storms. *Mesoscale Meteorology and Forecasting*, P. S. Ray, Ed., Amer. Meteor. Soc., Boston, 331-358.

Wilks, D. S., 1995: *Statistical Methods in the Atmospheric Sciences.* Academic Press, San Diego, 467 pp.