J 2.5 AN EXAMINATION OF SEVERE THUNDERSTORM DISCRIMINATION SKILLS FROM TRADITIONAL DOPPLER RADAR PARAMETERS AND NEAR STORM ENVIRONMENT (NSE) FACTORS AT LARGE RADAR RANGE

William E. Togstad^{1*}, Sarah J. Taylor², and Jeffrey Peters²

¹NOAA/NWS/Weather Forecast Office, Chanhassen, Minnesota ²NOAA/NWS/NCEP/Storm Prediction Center

1. Introduction

The original motivation for this research was to explore a variety of radar and near storm environment (NSE) parameters to determine if they could be statistically pieced together for the purpose of discriminating between supercell thunderstorms that produced F2 or greater strength tornadoes from nontornadic supercells beyond 80 km range of a WSR-88D radar. As it turned out, the most important finding was totally independent of Doppler radar products; this aspect of the research is discussed in great detail.

This work draws in part on data from three severe weather cases that occurred over the Minneapolis/St. Paul (MPX) county warning area (CWA) between 2000 and 2002. A fourth severe weather episode that involved an F2 tornado at Agency, Iowa was also added. The MPX severe weather cases include the Granite Falls, Minnesota F4 tornado of 25 July 2000, the Glenville, Minnesota F2 storm of 2 May 2001 and the Ladysmith, Wisconsin F3 tornado of 2 September 2002; the Agency, Iowa tornado œcurred on 11 April 2001. These storms share the common attribute of having occurred at over 80 km fom the nearest WSR-88D radar site.

In Section 2, VIL (vertically integrated liquid) time series are examined to determine their utility for issuing tornado warnings with at least 10 minutes lead time.

In Section 3, storm top divergence (STD) data are examined and tested on the four tornado cases. The purpose of these tests was again to determine if STD data were useful in discriminating between significant tornadic supercells and nontornadic severe storms on a given severe weather day. Section 4 summarizes our radar studies and expands the discussion to include older radar interpretation methodologies. We discuss why these radar pattern recognition methods remain viable to this day. In Section 5, the near storm environment (NSE) aspect of severe storm discrimination is explored. A brief summary of severe storm research from the 1960s is also provided. Following this research review, we examine and discuss a small sample of NSE graphics from our tornado cases.

Section 6 details statistical findings on severe storm discrimination from two large severe storm databases [e.g. Thompson et al. 2003, J.M. Davies 2004], including important differences between these two databases that may have influenced the results.

Section 6 also describes a two variable linear regression model that employed the 0-1 km bulk wind shear and the 0-3 km VGP (vorticity generation parameter) as predictors for the conditional probability of significant tornadoes. See Rasmussen and Wilhelmson (1983) for a complete description of the VGP.

In Section 7, an application of the regression equations for our four tornado cases is presented. In addition, we also apply one of our three regression equations on the Davies (2004) database. A statistical summary of this regression application is also included along with a parametric test.

Finally, Section 8 summarizes the research results. In addition to this research summary, some general comments are offered concerning additional work which might be pursued.

2. Vertically Integrated Liquid (VIL) time series

Monitoring the trend of VIL values leading up to tornado development can be viewed as an adaptation of the Lemon Technique (Lemon, 1977). In the past, radar meteorologists frequently examined a series of tilt scans on a WSR-57 radar in order to monitor cell top growth and decay; tornado warnings were frequently issued upon noting a collapse in the storm top. More recently, time series of VIL have been viewed in relation to Doppler radar derived rotational velocities. Researchers have noted an increase in low level rotational velocities on Doppler radar coincident with a pronounced decrease in VIL. See Peters and Kilduff (1993) and Murphy et al. (1994).

VIL data were collected for the Ladysmith, Wisconsin tornado, the Glenville, Minnesota tornado and the

^{*} Corresponding author's address:

¹⁷³³ Lake Drive West, Chanhassen MN 55317; 952-361-6671; Bill.Togstad@noaa.gov

Agency, Iowa tornado, but there was substantial missing VIL data for the Granite Falls, Minnesota storm. Time series of VIL are provided for two of these storms below (Tables 1-3):

 Table 1 Glenville Case 1 May 2001

The Glenville, Minnesota F2 tornado occurred at 0002 UTC.

Time (UTC)	KMPX VIL	Time (UTC)	KARX VIL
2342	63	2343	67
2348	67	2348	
2353		2353	
2358		2358	
0005		0003	
0010	67	0008	
0015	67	0013	
0020		0018	67
0025	67	0023	

A few comments can be made concerning these other two storms. The thunderstorm cell that produced the F3 tornado at Ladysmith did indeed undergo about a 25 percent drop in VIL between 2050 UTC and 2102 UTC only to increase its VIL by 43 percent between 2102 UTC and 2115 UTC. The tornado struck 7 minutes later as VIL again trended down about 20 percent through 2121 UTC. However, a storm cell farther north (Table 2, 2nd col.) also went through a number of similar pulses but only produced hail. This indicates that determining which drop in VIL is most significant and should be followed up with a tornado warning is problematic as the first drop between 2050 UTC and 2102 UTC failed to produce a tornado.

Table 2 Ladysmith Case 2 Sep 2002

The Ladysmith F3 tornado occurred at 2122 UTC.

Time (UTC)	KDLH VIL [*]	Time (UTC)	KDLH VIL
2032	32	2032	57
2038	52	2038	>70
2044	47	2044	63
2050	63	2050	57
2056	52	2056	63
2102	47	2102	52
2108	53	2108	63
2115	67	2115	67
2121	53	2121	52

*refers to Ladysmith storm

The VIL time series for the Agency, Iowa F2 storm reveal a substantial 28 percent decrease as viewed from KDMX (Des Moines, IA) radar but the measured drop was only 16 percent as sampled at KDVN (Davenport, IA) radar. Because VIL levels in the Agency, Iowa case reflect low-topped convection, the VIL trend technique may not be as useful a severe weather indicator as it is for deeper storms.

In summary, the VIL trends from these two storms provide a great deal of ambiguity as to interpretation. The usefulness of the VIL trend in anticipated tornado development was of limited value and all that can be concluded is that more cases should be collected.

Table 3 Agency Case 11 Apr 2001

The Agency F2 tornado occurred at 2100 UTC.

Time	KDVN	Time	KDMX
(UTC)	VIL	(UTC)	VIL
, ,			
2019	27	2020	32
2025	32	2025	27
2031	32	2030	27
2037	32	2035	32
2043	32	2040	32
2048	27	2045	32
2053	27	2050	27
2058	27	2055	27
2103	23	2100	27

3. Storm Top Divergence (STD) data

We examined storm top divergence (STD) for our four tornado cases to determine its usefulness in identifying tornadic supercells. The premise is that by isolating storm cells with the highest STD, we could locate the storms with the most powerful, near steady state updrafts. For example, the quasi-steady state supercell has long been thought of as the storm cell most likely to produce tornadoes.

Conceptually, at the summit of the strongest supercell updrafts should also be the largest STD. Thus, the STD was selected as a logical measurement to examine in relation to the development of significant tornadoes. Previous research indicates that STD data are a very useful predictor of hail size (Witt et al. 1991).

Tornado reports were gathered for the four cases from Storm Data (NOAA 2000-2002), and then matched with archive II WSR-88D data on the Interactive Radar Analysis Software (IRAS) visualization software (Priegnitz 1995). The STD values were computed from archive II data in order to derive more detailed calculations, as archive III velocity data are often only archived in detail up through 64 knots.

The data were examined on a case by case basis in order to determine if storm type discrimination was possible from STD information on an individual severe weather day. In order to make this test operationally realistic and provide the warning forecaster with predictive lead time, the largest STD value was tallied for a storm over the three volume scans that occurred a minimum of three volume scans prior to the report of severe weather (i.e. approximately 18 to 30 minutes before the severe weather report).

For the individual case results, we obtained correlation coefficients between tornado activity and STD of 0.24 for the Granite Falls F3 case, -0.48 for the Glenville, Minnesota F2 and 0.91 for the Agency, Iowa F2 case. There were insufficient data to even consider computing a correlation statistic for the Ladysmith, Wisconsin F3 tornado case. Combined correlation statistics for all three cases was only 0.11 with a 95 percent confidence range of -0.21 to 0.41.

Thus, on an individual tornado day, the STD for the supercell associated with a significant tornado varied considerably. Based on this very small sample of three cases, the STD turned out to be a very poor tool for discrimination of tornadic supercells. Consequently, we decided not to pursue it further.

4. General Comments on the WSR-88D data for our case studies

Although examination of VIL trends and STD data failed to provide much in the way of storm type discrimination, several comments can be made about all four storms. In Fig. 1, a 0.5 degree reflectivity image for 2237 UTC from KMPX (Minneapolis, MN) radar is displayed; this is about 20 minutes before the Granite Falls F4 tornado occurred.



Figure 1 Reflectivity image (0.5 degree elevation) from KMPX at 2237 UTC on 25 July 2000.

Note that the thunderstorm cell that produced the tornado in Granite Falls was the cell immediately north of a well-defined break in the squall line. Severe weather radar meteorologists have historically noted a tendency for tornadoes to occur at the south end of squall lines, and on the southernmost cell of the

northern squall segment where a well defined break in the squall is observed. The knowledge of vulnerable points for tornado formation within squall lines certainly predates the WSR-88D.

For the Glenville, Minnesota F2 tornado case of 2 May 2001, figs. 2 and 3 show radar returns (both for 2348 UTC) of 0.5 degree reflectivity from the KMPX radar and 0.5 degree storm relative motion (SRM) data from KARX (La Crosse, WI), respectively. These radar data were sampled approximately 10 to 15 minutes before the storm passed through Glenville.



Figure 2 Reflectivity image (0.5 degree elevation) from KMPX at 2348 UTC on 1 May 2001.

In this instance, the tornadic supercell developed on the south end of a squall line. An examination of radar imagery for our Agency, Iowa F2 case (not shown) revealed that this storm was on the south end of a line of thunderstorms.

The tendency for tornadoes to form on the south end of a squall line or within break points along the line reflects the fact that these thunderstorm cells often experience an unrestricted low-level inflow of the most unstable air along the line. In fact, this aspect of unrestricted lowlevel inflow into developing supercells is emphasized in NWS instructions to our Skywarn observers.

Additionally, south end thunderstorm cells are in a position where strong new updrafts with a developing flanking line may interact with strong downdrafts from a more mature cell immediately to the north. See Lemon (1977), Weaver and Nelson (1982) and also Moncrieff and Green (1972).



Figure 3 Storm relative motion (SRM) image (0.5 degree elevation) from KARX at 2348 UTC on 1 May 2001.

For the Ladysmith, Wisconsin F3 case, KDLH (Duluth, MN) reflectivity (0.5 degree) and storm relative motion (0.5 degree) images are displayed in figs. 4 and 5, respectively.



Figure 4 Reflectivity image (0.5 degree elevation) from KDLH at 2121 UTC on 2 September 2002.

In this instance, the images are coincident with the tornado time. Radar data from KDLH was chosen rather than KMPX because the KDLH radar had a more favorable radar beam orientation from which to view the 0.5 degree velocity couplet. See again Fig. 5.

The tornadic supercell that produced the Ladysmith tornado developed on the south end of a broken squall line. Prior to the development of a new cell (see fig. 4) to its south, the Ladysmith storm was in a favorable



Figure 5 Storm relative motion (SRM) image (0.5 degree elevation) from KDLH at 2121 UTC on 2 September 2002.

position to ingest warm, humid and very unstable air into its rear flank. In particular, examine the very high dewpoint temperatures (i.e. in the low 70s F range) along with low temperature-dewpoint spreads from surrounding surface observation sites. Thompson et al. (2003) have pointed out that a large majority of significant tornadic supercells were associated with 0-1 km relative humidity in excess of 65 percent, which was certainly true in this instance.

In summary, although working with supercell storms at large radar range can be a daunting task, basic radar interpretation along with establishing a habit of viewing reflectivity and velocity displays from surrounding radars can go a long way towards helping the severe weather meteorologist diagnose severe storm potential. The importance of viewing multiple radars when dealing with storms at the outer ranges of your local Doppler radar simply cannot be overemphasized!

5. Near Storm Environment

Research from the 1960s described discrete thunderstorms within highly sheared environments in great detail, speculating on the impact of this shear on thunderstorm circulation and movement. See Browning and Ludlam (1962), Browning (1964) and Newton (1966). However, it was not until numerical cloud modeling studies (e.g., Weisman and Klemp 1982, 1984) clearly demonstrated the relationship between the convective available potential energy (CAPE) and the wind shear, and their influence on the storm evolution and preferred storm type.

Within the spectrum of severe convection, the development of tornadic supercells has long been related to interactions with low-level boundaries (e.g., Miller 1972). Later work continued to emphasize the importance of such boundary interactions on the

development of tornadoes (Maddox et al. 1980 and Markowski et. al. 1998). With the importance of such boundaries in tornadogenesis established, recent research on severe storm discrimination has increasingly turned to the temperature, wind and moisture profiles in the lowest levels of the atmosphere (e.g., Rasmussen and Blanchard 1998 and Davies 2002).

In addition to observational and modeling research on severe convection, the analysis of proximity soundings has been prominent over the years (e.g., Darkow 1969, Darkow and Fowler 1971, Maddox 1976, and Rasmussen and Blanchard 1998). However, because of the slow accumulation of observed proximity soundings, researchers have begun to explore the use of RUC (Rapid Update Cycle) model profiles as a valid proxy to severe convection (Thompson and Edwards 2000, Davies 2002, and Thompson et al. 2003). The availability of RUC profiles for severe storm research has even helped initiate an examination of NWS tornado warnings (Davies 2004).

Great emphasis has been placed on incorporating the NSE information in severe weather operations at local National Weather Service forecast offices in recent years. Operational forecasters monitor NSE data by reviewing RUC and LAPS (Local Analysis and Prediction System) profiles on their AWIPS (Advanced Weather Information Processing System) workstations and by also examining VAD and profiler data in order to determine changes in wind shear over their county warning area of responsibility. In addition, the SPC now provides considerable assistance during heightened threats of severe weather with their very popular Hourly Mesoscale Analysis Page (Bothwell et al. 2002). See www.spc.noaa.gov/exper/mesoanalysis/.



Figure 6 0-3 km VGP for 2100 UTC 25 July 2000 (arrow depicts approximate location of Granite Falls, MN).



Figure 7 0-3 km VGP for 0000 UTC 26 July 2000 (arrow depicts approximate location of Granite Falls, MN).

Sample graphics from the SPC analysis scheme for 0-3 km VGP are shown for the 25 July 2000 Granite Falls tornado case in figs. 6 and 7. It should be noted that the Granite Falls tornado occurred at 2257 UTC on 25 July 2000, with an increasing trend of 03 km VGP shown from 2100 UTC 25 July 2000 to 0000 UTC 26 July 2000 (figs. 6 and 7, respectively). A RUC proximity sounding from the Thompson (2003) dataset valid for this event indicated a 0-3 km VGP value of 0.29.

6. A NSE based regression model for the conditional probability of F2 or greater strength tornadoes

While an early goal was to develop a statistical regression model that would discriminate between tornadic and nontornadic supercells, the task proved to be exceptionally difficult. In fact, the first attempt at developing a four variable regression equation based on discriminant analysis resulted in an equation that only explained 15 percent of the variance!

In order to help with the search for valid predictor variables for a regression study, we were provided with two EXCEL files containing a variety of convective parameters that had been computed from RUC severe storm proximity soundings, provided by Thompson et al. (2003) and Davies (2004).

Both the Thompson and Davies databases, hereafter referred to as T03 and D04, respectively, employed a correction for virtual temperature (Doswell and Rasmussen 1994). In addition, both D04 and T03 used mean layer temperature and moisture data (i.e. over the lowest 100 mb layer in the profile) to compute their convective indices.

However, the D04 RUC sounding file differed from T03 in that profiles were collected near convection that had triggered NWS tornado warnings. On the other hand,

T03 proximity soundings were associated with observed supercells. In addition, D04 employed surface data to interpolate both temperatures and moisture in the lowest levels of the RUC profile, while T03 made no such corrections. See Thompson et al. (2003) and Davies (2004) for more specifics on these data samples.

Initially, both datasets were merged with only the MLCIN¹, MLLCL, 0-3 km VGP and 0-1 km bulk shear variables retained. The data sort feature on EXCEL helped uncover the variables that appeared to have the greatest impact on tornado frequency. For example, it quickly became apparent that tornado frequency all but stopped after MLCIN reached -150 J/kg. Similarly, MLLCL values in excess of 2000 meters appeared associated with greatly reduced tornado frequency. Therefore, profiles with CIN in excess of -150 J/kg could be segregated from the remaining proximity sounding data. In addition, MLLCL was dropped as an individual predictor.

From the remaining data that was unrestricted in terms of MLLCL height, but had the above mentioned -150 J/kg MLCIN restraint, we developed a two variable linear regression equation based on 0-3 km VGP and 0-1 km shear. *The predictand selected was observed F2 or greater strength tornado frequency*.

Class intervals for 0-3 km VGP data were assigned for every 0.10 value of this parameter, while 0-1 km shear was broken down every 5 knots between 10 and 25 knots and for every 10 knots above 25 knots of shear. Tornado frequencies, 0-1 km bulk shear and 0-3 km VGP values were averaged over each class in order to obtain more accuracy. The resulting linear regression equation explained 90 percent of the variance for these averaged predictors and tornado frequencies. See Table 4 for the data that were used to construct the first regression equation along with a summary of regression statistics in Table 5.

	0 – 3 km VGP				
		> .4	.34	.23	< .2
(kts)	> 35	.708	.660	.500	
-	25-35	.683	.645	.350	.235
shear	20 -25	.578	.481	.263	.300
sh	15 -20	.483	.388	.214	.095
k K	10 -15	.278	.195	.170	.058
5	< 10	.143	.107	.063	.023
-	Tornado frequencies (F2 or greater)				

Table 4Table of averaged tornado frequencies enteredas a function of averaged values of 0-1 km shear [(kts)left-most column] and 0-3 km VGP (top row). See textfor more details.

TERM	Coefficient	95% confidence interval
Intercept	229	324 to134
0-3 km VGP	.792	.553 to1.032
0-1 km shear	.0149	.012 to.018

Table 5 Summary of regression statistics²

In order to compute linear regression coefficients for a conditional tornado probability model that was based on our individual tornado and severe weather reports rather than from averages, a discriminant function was computed where 0.0 was assigned to values for the predictand with a non significant tornadic report (i.e. zero probability of an F2 or greater tornado) and 1.0 was assigned to a report of an F2 or greater tornado (i.e. 100 percent probability of such a storm). The resultant regression coefficients were remarkably similar to those computed for our model that was based on averaged data. The statistical summary (Table 6) for merged T03 and D04 appears below:

TERM	Coefficient	95% confidence interval
Intercept	200	276 to125
0-3 km VGP	.847	.613 to1.08
0-1 km shear	.014	.010 to.017

Table 6 Summary of regression statistics for mergedT03 and D04 (616 profiles)

In order to complete the analysis, we segregated T03 and D04 and computed individual regression samples for each. The regression summaries appear below in Tables 7 and 8:

TERM	Coefficient	95% confidence interval
Intercept	309	409 to209
0-3 km VGP	1.26	.847 to1.67
0-1 km shear	.017	.012 to.022

Table 7 Summary of regression statistics for T03(317 profiles).

TERM	Coefficient	95% confidence interval
Intercept	191	324 to057
0-3 km VGP	.833	.511 to 1.16
0-1 km shear	.012	.007 to.016

Table 8 Summary of regression statistics for D04(299 profiles).

While the differences in the regression coefficients between D04 and T03 can not be directly explained, the increase in both variable coefficients is proportionally about the same (i.e. about 1.5). This means that a

¹ Note that ML refers to the 100 mb mean layer nearest the ground.

² All statistical analysis completed in this research was done with ANALYZE_IT software.

conditional tornado probability model based on T03 is more responsive to changes in both 0-1 km shear and 0-3 km VGP than a model based on D04. Perhaps the closer range of T03 proximity soundings to severe convection resulted in a more accurate measurement of both these variables. On the other hand, perhaps interpolation of surface moisture and temperature data with D04 made those RUC profiles more realistic. At this stage of research, an explanation for these dataset differences must remain mere conjecture.

A physical explanation as to why 0-1 km bulk shear and 0-3 km VGP do such a fine job in explaining the variance in conditional tornado probabilities can be appreciated with a brief review of the vorticity equation in horizontal coordinates (See pp. 349-351 of Haltiner and Martin 1957). In Haltiner and Martin's derived equation, changes in vorticity (i.e. total derivative) occur through a combination of convergence (divergence) involving vertical stretching (shrinking), a vortex tube term (also called tilting term) and a solenoidal term.

The 0-3 km VGP term is proportional to the magnitude of a storm's updraft from the level of free convection (LFC) to the storm's equilibrium level. This is because VGP incorporates the square root of CAPE, which directly relates to peak updraft strength through parcel theory. Thus, the VGP variable is proportional to lowlevel vorticity generation that occurs near the base of a supercell due to vertical stretching and the induced lowlevel convergence that results from this stretching.

In addition, the inclusion of average shear in the 0-3 km layer of the atmosphere in combination with the CAPE term provides a rough estimate as to the amount of horizontal vorticity (below 3 km agl (above ground level)) that may be tilted into vertical vorticity by the storm updraft.

Viewed in this way, 0-3 km VGP accounts for two of the three terms that appear in the Haltiner and Martin derived vorticity equation. It is important to point out that vorticity generation through solenoidal forcing is neglected from this discussion and this obviously is not realistic near supercell convection. However, it is readily appreciated that VGP probably represents a very good first guess on very important physical processes that lead to increasing vorticity within the lower levels of a developing supercell thunderstorm.

Inclusion of the 0-1 km bulk shear as a predictor helps account for horizontal vorticity closest to the ground and potentially can be converted to vertical vorticity through tilting. The presence of such vorticity might very well be a key factor that determines if a developing funnel cloud is able to reach the surface.

Viewed from the above perspective, both CIN and LCL can be viewed as physical breaks on the tendency to increase low-level vorticity immediately beneath the base of a supercell thunderstorm. This may explain why we were able to get a realistic regression formulation by first segregating our data on the basis of CIN.

7. Application of regression equations

Conditional tornado probabilities were computed for our four tornado cases with regression estimates from combined and partitioned D04 and T03 (Table 9). RUC sounding values of the study parameters for all 4 tornado cases are shown in Table 10.

Case	D04 and T03	D04	T03
Granite Falls MN	23.9	22.1	29.4
Glenville MN	41.6	37.9	51.6
Ladysmith WI	65.2	60.7	85.6
Agency IA	51.0	45.8	62.0

Table 9 Conditional Tornado Probabilities

	cin (J/kg)	0-3 km VGP	0-1 km shr (kts)	LCL (meters)
Granite Falls MN	-47	.29	14	1068
Glenville MN	-67	.31	26	1139
Ladysmith WI	-23	.54	29	668
Agency IA	-28	.26	36	857

 Table 10 Table summarizing the four study parameters for our four severe weather cases:

Depending on the choice of warning threshold, most of these storms could have had successful tornado warnings issued for them based on their NSE attributes alone. However, the Granite Falls F4 was clearly the most challenging storm of the four.

In order to more rigorously test the statistical significance of our regression equations, we completed parametric tests on part of D04 with the Student t test. Our purpose was to determine if there was a statistically significant difference between the means of estimated conditional tornado probability for the tornado soundings in D04 over the mean value of estimated conditional tornado probability for a matching set of nontornadic soundings. For the 104 F2 and above ranked tornadoes in D04, we computed Student t test values of 5.91, 5.92 and 5.88 for D04, T03 and merged D04 and T03 derived regression equations, respectively.

In all three instances, these parametric tests provide confidence levels above .99 for either the one or two sided tests. Thus, the regression equations derived from this research, do indeed discriminate between F2 and greater strength tornadoes from reports of other nontornadic severe thunderstorm reports, at least in a conditional probability sense.

Distributions of computed conditional tornado probability for tornadoes and other severe weather reports in D04 are shown in Figs. 8 and 9. Even without the Student t parametric test, the differences in these distributions are clearly visible.



Figure 8 Histogram of conditional tornado probabilities computed from regression equation for the F2-F5 tornadoes in D04. See text for details.



Figure 9 Histogram of conditional tornado probabilities computed from regression equation for nontornado severe storm reports in D04. See text for details.

Note in particular how frequencies in the non-tornadic severe weather report probability distributions are clustered in lower values, while tornado frequencies of occurrence increase after the conditional tornado probability exceeds 30.

It should also be pointed out that on a case by case basis, there will be instances where the application of a conditional tornado probability will fail just as is the case with an individual forecast generated from other statistical techniques (e.g., model output statistics (MOS)). These conditional tornado probabilities can only be expected to show skill over long intervals of time and hopefully point warning meteorologists in the right direction in terms of issuing NSE based tornado and severe thunderstorm warnings.

8. Summary and Conclusions

In this research project, four upper Midwest severe weather cases were examined that occurred between 2000 and 2002. The purpose of this study was to search out a means of discriminating between nontornadic supercells from supercell storms that produced significant (F2 or greater) tornadoes at a distance of 80 km or more from a WSR-88D radar site. At no time did we consider tornadoes of F0 or F1 intensity.

We examined VIL trend and storm top divergence data for the radar portion of our research. While we found that a drop in VIL coincided with tornado activity in a number of instances, there were other instances where tornadoes occurred in the absence of such a signal. In addition, our research on VIL trend was limited a great deal by the loss of data we encountered in the archive files we examined. The storm top divergence (STD) data also failed to provide any signal for anticipating significant tornadoes.

In addition to our radar research, we examined the near storm environment (NSE) aspect of severe storm discrimination. Our research involved the examination of two datasets (D04 and T03) containing proximity sounding data for both nontornadic severe weather reports and tornadoes of F2 or greater strength.

We narrowed our original convective parameters (i.e. MLCIN, MLLCL, 0-3 km VGP and 0-1 km bulk shear) down to two (VGP and shear) that were used to develop regression equations for predicting the conditional probability of F2 or greater strength tornadoes. It is important to note that any application of our research would only be valid if applied to supercell thunderstorms.

Somewhat differing regression results were obtained from the D04 and T03 datasets, and the reason for such differences is not clear. Additional research on this topic certainly appears warranted. In addition, it would appear advisable that the statistical methodology should be tested on more independent cases to determine its general utility for making operational warning decisions. If it is determined that these research findings have general validity, a number of operational applications can be envisioned. For example, it may be possible to make better use of severe weather staffing, in terms of sectorizing warning responsibility on an individual severe weather day. In addition, under certain circumstances, the lead time for some tornado warnings at distances greater than 80 km from the radar may be substantially improved through the issuance of aNSE based warning, rather than delaying a warning for the purpose of obtaining either more Doppler radar information or a Skywarn spotter report.

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REFERENCES

- Bothwell, P.D., J.A. Hart, and R. L. Thompson, 2002: An integrated three-dimensional objective analysis scheme in use at the Storm Prediction Center. Preprints, 21st Conf. on Severe Local Storms, San Antonio, TX., Amer. Meteor. Soc., J117-J120.
- Browning, K.A., and F.H. Ludlam, 1962: Airflow in convective storms. *Quart. J. Roy. Meteor. Soc.*, **88**, 117-135.
- 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.
- Darkow,G.L., 1969: An analysis of over sixty tornado proximity soundings. Preprints, 6th Conf. on Severe Local Storms, Chicago, IL. Amer. Meteor. Soc., 218-221.
- Darkow, G.L., and M.G. Fowler, 1971: Tornado proximity wind sounding analysis. Preprints, 7th Conf. on Severe Local Storms, Kansas City, MO., Amer. Meteor. Soc., 148-151.
- Davies, J. M., 2002: On low-level thermodynamic parameters associated with tornadic and nontornadic supercells. Preprints, 21st Conf. on Severe Local Storms, San Antonio, TX, 603-606.
- Davies, J. M., 2004: Estimates of CIN and LFC associated with tornadic and nontornadic supercells. *Wea. Forecasting*, in press.

- Doswell, C.A., III, and E.N. Rasmussen, 1994: The effect of neglecting the virtual temperature correction on CAPE calculations. *Wea. Forecasting*, 9, 625-629.
- Haltiner, G. J., and F.L. Martin, 1957: "Dynamic and physical meteorology", McGraw-Hill, 349-351.
- Lemon, L. R., 1977: Severe storm evolution: its use in a new technique for radar warnings. Preprints, 10th Conference on Severe Local Storms, Boston, MA, Amer. Meteor. Soc.,77-80.
- Maddox, R.A., 1976: An evaluation of tornado proximity wind and stability data. *Mon. Wea. Rev.*, **104**, 133-142.
- Maddox , R.A, L.R. Hoxit, and C.F. Chappell, 1980: A study of tornadic thunderstorm interactions with thermal boundaries. *Mon. Wea. Rev.*, **108**, 322-336.
- Markowski, P. M., E. N. Rasmussen, and J. M. Straka, 1998: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting*, **13**, 852-859.
- Miller, R.C., 1972: Notes on analysis and severe s torm forecasting procedures of the Air Force Global Weather Center. AWS Tech. Report 200 (Rev.), Headquarters, Air Weather Service, Scott AFB, IL,106 pp.
- Moncrieff, M.W., and J.S.A. Green, 1972: The propagation of steady convective overturning in shear. *Quart. J. Roy. Meteor. Soc.*, **98**, 336-352.
- Murphy, R.A., K.J. Pence, J.A. Westland, and R.E. Kilduff, 1994: A comparison study of VIL vs. rotational velocity associated with tornadic thunderstorms. Postprints, *1st WSR-88D Users Conf.*, Norman, OK, 259-265.
- Newton, C.W. 1966: Circulations in large sheared cumulonimbus. *Tellus*, **18**, 669-713.
- Peters, B.E., and R. E. Kilduff, 1993: Early impressions of the East Alabama WSR-88D. NWS Southern Region Technical Attachment, SR/SSD Fort Worth, Texas, 5 pp.
- Priegnitz, D.L., 1995: IRAS: Software to display and analyze WSR-88D radar data. 11th International Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology, Boston, MA. Amer. Meteor. Soc., 197-199.
- Rasmussen, E.N., and D.O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148-1164.

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

NOAA, 2000-2002: Storm Data, National Climatic Data Center, Asheville, NC.

Thompson, R.L., and R. Edwards, 2000: RUC2 supercell proximity soundings, part I. Preprints, 20th *Conf on Severe Local Storms*. Orlando, FL, Amer. Meteor. Soc., 431-434.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Mon. Wea. Rev.*, **18**, 1243-1261.

Weaver, J.F., and S.P. Nelson 1982: Multiscale aspects of thunderstorm gust fronts and their effects on subsequent storm development. *Mon. Wea. Rev.*, **110**, 707-718.

Weisman, M.L., and J.B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. Mon. Wea. Rev., **110**, 504-520.

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

Witt, A. and S.P. Nelson 1991: The use of single-Doppler radar for estimating maximum hailstone size. J. Appl. Meteor., **30**, 425-431.