3.2 TORNADO FAILURE MODES IN CENTRAL AND SOUTHERN GREAT PLAINS SEVERE THUNDERSTORM EPISODES

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1. INTRODUCTION

The majority of significant tornadoes (≥ F2 damage) in the United States are produced by right-moving supercell thunderstorms. The most active period in the continental United States for significant severe thunderstorms (≥ 5 cm (2 inch) diameter hail or ≥ 33 m s^{-1} (65 kt) wind gusts) and tornadoes typically occurs during the spring across the Great Plains (e.g., Brooks et al. 2003; Doswell et al. 2005). This frequency of supercell tornadoes and the consistency of the spring “storm season” make the Great Plains ideal to examine the environmental characteristics of tornadic supercells, via either field projects (e.g., Rasmussen et al. 1994) or proximity sounding studies (e.g., Thompson et al. 2003, hereafter T03).

Operational meteorologists have made substantial strides in forecasting supercells and associated tornado potential during the past decade utilizing an ingredients-based approach (Johns and Doswell 1992). The most widely accepted ingredients for supercells include: 1) sufficient buoyancy and 2) vertical wind shear through a substantial depth of the troposphere, based on numerical simulations (e.g., Weisman et al. 1982) and empirical proximity sounding investigations (e.g., Rasmussen and Blanchard 1998; T03). This forecast methodology can be extended to significant supercell tornadoes by including 3) measures of low-level vertical wind shear such as storm-relative helicity (Davies-Jones et al. 1990, hereafter SRH), and 4) measures of low-level moisture (e.g., lifting condensation level (LCL)) which can discriminate between non-tornadic and significantly tornadic supercell environments (e.g., Rasmussen and Blanchard 1998; Rasmussen 2003; T03).

Convective mode has garnered increased attention in recent years as another important ingredient in supercell tornado forecasting (e.g., Bluestein and Weisman 2000; Dial and Racy 2004). Specifically, the significant tornado threat is often greater when deep convection initiates as discrete elements and persists as discrete, right-moving supercells. While the significant tornado threat is not necessarily negligible with some linear convective systems (Trapp et al. 2005), the significant tornado potential is often reduced when convection evolves quickly into a linear mode. Therefore, a discrete convective mode can be considered as a fifth ingredient favoring significant supercell tornadoes.

A combination of the five aforementioned ingredients provides a relatively straightforward framework for identifying environments supportive of significantly tornadic supercells. In a preliminary effort to document the utility of this proposed approach to diagnosing significant supercell tornado potential, the Great Plains spring storm season has been examined for a 3 year period from 2003-2005. This prototype strategy must be tested in other regions and seasons (e.g., the Mississippi Valley in the fall and winter) before it can be applied reliably across *all* regions and seasons in the continental United States.

2. DATA AND METHODOLOGY

An arbitrary threshold of 50 combined large hail, damaging wind and tornado reports identified convective days (1200-1200 UTC) from 1 March through 15 June with multiple thunderstorms and substantial severe weather within the Great Plains domain (Fig. 1). A hierarchy of significant severe storm reports (most intense tornadoes, largest hail, and strongest wind gusts) was used to identify individual storm cases within a convective day. Events were considered separate if located more than 3 h or 200 km apart. The individual storms, identified via regional mosaics of WSR-88D 0.5^{o} reflectivity, were then examined for timing (nearest hour) and location of both storm initiation and the most intense severe storm reports. The radar reflectivity signatures were then subjectively categorized as 1) discrete, 2) linear, or 3) multi-cellular within an hour of initiation, and at the peak intensity phase.

Our focus was on the events producing significant severe weather (≥ F2 tornado damage,

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≥ 2 inch diameter hail, or ≥ 65 kt wind gusts), since these events result in a disproportionate threat to life and property. There are some inherent uncertainties in the severe storm reports (e.g., Doswell and Burgess 1988), thus we also collected data for cases approaching the significant severe criteria (e.g., ≥ F0 tornadoes, ≥ 1.75 inch diameter hail, or ≥ 53 kt wind gusts). These lower criteria were meant to reflect common reporting thresholds (e.g., Weiss et al. 2000) while avoiding an excessive number of "low end" cases, such as would result from using the minimum severe storm criteria of 0.75 inch diameter hail and generic "thunderstorm wind damage" reports.

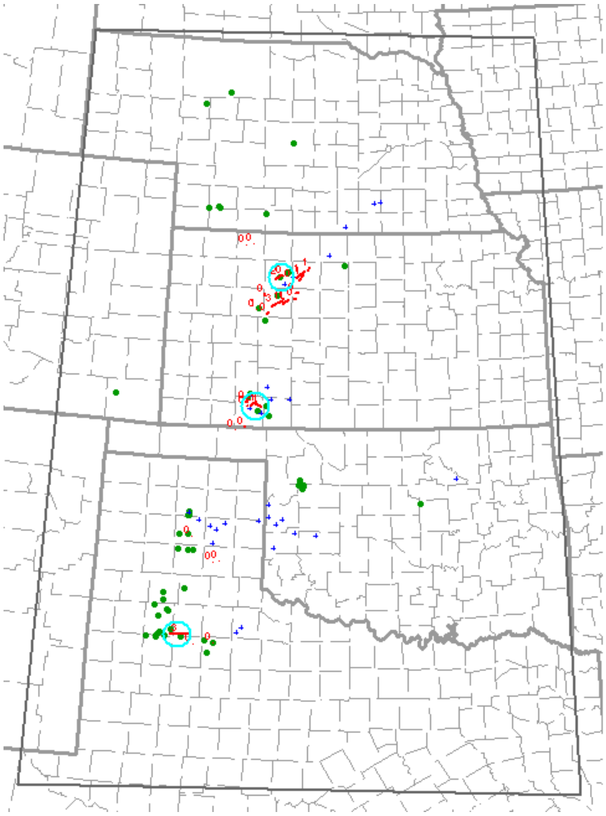

Figure 1: Examples of storm case selections from 9 June 2005. The central and southern Great Plains domain is bounded, and each storm case selected is circled in cyan. The initial case selection was based on the time of the first tornado producing ≥ F2 damage, followed by the largest hail or most intense thunderstorm wind reports. Subsequent cases must have been at least 200 km or 3 h apart.

The Storm Prediction Center hourly mesoscale analysis fields described by Bothwell et al. (2002) served as the basis for parameter values on a 40 km horizontal grid, and these data were available back through 2003. Grid point values of 0-1 km SRH (assuming right supercell motion estimate from Bunkers et al. 2000), 0-6 km bulk shear, 100 mb mean layer (ML) CAPE, and MLLCL height were derived for the initiation and peak intensity phase for each storm event. Threshold values for the four sounding-derived parameters were chosen based on the statistical distributions of each presented in T03, which is an independent sample. An ingredient that equaled or exceeded the 10th percentile values is considered sufficient for significant supercell tornadoes. An ingredient was considered "missing" if the grid point value was less than the 10th percentile for MLCAPE, 0-1 km SRH, and 0-6 km bulk wind difference, or if the MLLCL value was greater than the 90th percentile (see Table 1).

10th SRH1	10th SHR6	10th MLCAPE	90th MLLCL
75 $m^2 s^{-2}$	**18** $m s^{-1}$	**1000** $J kg^{-1}$	**1300** m AGL

Table 1: Significant tornado threshold percentile values for the four sounding-derived ingredients, based on T03. SRH1 = 0-1 km SRH, and SHR6 = 0-6 km bulk shear.

Convective modes other than discrete cells were also considered as a missing ingredient for significant supercell tornadoes. Convective mode identification was unclear in some cases. Most squall lines do begin as relatively discrete cells for at least a short period of time, while other "linear" events appear to consist of more discrete cells (high radar reflectivity) linked by relatively low radar reflectivity. In this study, predominant convective mode was not determined until 60 minutes after the appearance of the first radar "echo". Storms were considered discrete if the high reflectivity cores (≥ 40 dBz) were not connected to other storms, and the high reflectivity echoes maintained a horizontal aspect ratio of less than 4:1 (to allow discrimination between cells and short line segments).

3. RESULTS

3a. *Seasonal and event distributions*

A total of 223 storm cases were identified from 1 March through 15 June from 2003 through 2005. The cases were most common during May, and least common in March (Table 2). Thirty-six cases included tornadoes with F2-F5 damage, 142 cases included hail ≥ 2 inch diameter, and 49 cases included thunderstorm wind gusts ≥ 65 kt. A relatively small fraction of cases included multiple significant severe storm reports, with significant wind and tornadoes the least common combination, and significant hail and tornadoes the most common (Table 3). Overall, large hail was the most common severe storm event across the Great Plains in the spring, followed by damaging winds and tornadoes, respectively.

	MAR	APR	MAY	JUN	ALL
2003	4	12	45	24	85
2004	4	11	31	17	63
2005	0	20	30	25	75
ALL	8	43	106	66	223

Table 2: Number of central and southern Great Plains severe storm cases by month and year.

3b. *Convective mode*

A breakdown of cases by convective mode revealed even more pronounced differences in severe storm report tendencies. Per Table 4, the majority of the discrete storm cases were associated with ≥ 2 inch diameter hail, while only 5% of those discrete storms produced thunderstorm wind gusts of ≥ 65 kt. Significant severe thunderstorm winds were much more common with the non-discrete storm types, and significant tornadoes were more frequent with discrete storms. Large hail and damaging winds occurred at roughly the same frequency for the non-discrete storms.

	H	W	T	ALL	HW	HT	WT
SIG	.637	.220	.161	.004	.063	.099	.000
ANY	.749	.256	.363	.018	.076	.260	.022

Table 3: Percentage of storm cases with hail (H), wind (W), tornado (T), all three severe types (ALL), hail and wind (HW), hail and tornado (HT), and wind and tornado (WT). The SIG row denotes hail ≥ 2 inch diameter, wind ≥ 65 kt, or ≥ F2 tornadoes. The ANY row includes hail reports ≥ 1.75 inch diameter, wind ≥ 53 kt, and ≥ F0 tornadoes. The categories with multiple report types are mutually exclusive. Only measured or estimated wind gusts were considered, regardless of damage reports.

	Hail	Wind	Torn
(137) discrete	0.77	0.05	0.23
(86) non-discrete	0.43	0.49	0.05

Table 4: Percentage of SIG severe storm reports (see Table 3) by convective mode. The numbers in parentheses show sample size, and the non-discrete group includes both lines and multicell clusters.

3c. *Environmental characteristics*

Of the 36 significant tornado cases, 56% met all five conditions (discrete storm with all four environmental ingredients at least sufficient). Eleven of the 36 significant tornado cases (31%) were missing one ingredient, and 86% were missing no more than one ingredient. Considering the entire case sample, 52 (23% of total) met all five conditions, of which 20 (38%) produced significant tornadoes. Thus, the five ingredients can be considered *necessary but not sufficient* for significant supercell tornadoes.

Only 3-8% of the significant tornado cases were associated with 0-1 km SRH, 0-6 km bulk shear, or MLCAPE values less than the 10th percentile. A larger percentage (31%) of the significant tornado cases were associated with MLLCL values above the 90th percentile threshold. Of the 16 significant tornado cases that did not meet all five conditions, 11 were missing only one ingredient, and only five cases were missing two ingredients. None of the significant tornadoes occurred when more than two of the five ingredients were missing. Non-discrete convection and the MLLCL were the two most common missing ingredients (see Table 5).

Convective mode influenced the significant tornado threat to roughly the same extent as the 0-1 km SRH, 0-6 km bulk shear, and the MLCAPE. Only 5% of the non-discrete storms produced significant tornadoes, and 84% of the non-discrete storms were nontornadic. Conversely, 23% of the discrete storms produced significant tornadoes, and 49% were tornadic. The percentage of discrete storms that produced significant tornadoes increased to 38% when the four sounding-derived ingredients were also present.

	SRH	SHR	CAPE	LCL	ND	M2	M3+
ST	.08	.03	.06	.31	.11	.14	.00
T	.18	.22	.36	.73	.22	.20	.13
SH	.25	.23	.18	.46	.26	.30	.17
H	.36	.36	.24	.48	.36	.32	.32
SW	.37	.41	.29	.45	.86	.35	.41
W	.57	.71	.14	.71	.86	.43	.57

Table 5: Percentage of missing significant tornado ingredients for each event class (sample size): ST (≥ F2 tornado, 36), T (F0-F1 tornado, 45), SH (≥ 2 inch hail, 142), H (1.75 inch hail, 25), SW (≥ 65 kt wind, 49), W (53-64 kt wind, 7). ND=non-discrete storms, M2 = missing two ingredients, and M3+ = missing ≥ three ingredients.

4. DISCUSSION AND CONCLUSIONS

Employing the ingredients-based approach to forecasts of significant tornadoes, as part of forecasts for substantial severe thunderstorm episodes, can result in a modest probability of detection (~56% of significant tornado events). Our case selection methodology allowed only one grid point value to characterize the environment at the peak intensity phase for each storm case. The distribution (and time rate of change) of ingredients can infer somewhat different significant tornado threat levels than the single, static grid point values. Also, allowing some leeway in the grid point characterization of the storm environment (i.e., one ingredient falling just outside the "favorable" range) results in a higher probability of detection (86%) for significant tornado events.

The probability of a significant tornado was roughly four times greater for discrete convection versus non-discrete convection in the spring across the Great Plains (23% versus 5%). The probability of a significant tornado increased to 38% when storms remained discrete and all four sounding-derived ingredients were sufficient for supercell tornadoes based on the work of T03 (see Table 1). Still, a majority of storm cases with all five ingredients present did not result in significant tornadoes.

Significant tornadoes were least probable (3-8% of the storm cases) when 0-1 km SRH, 0-6 km bulk shear, or MLCAPE were below the 10th percentile values derived from T03. Non-discrete convective modes limited the significant tornado threat slightly less than to the two vertical wind shear ingredients, while the LCL height was the least reliable discriminator. False alarms are inevitable given the complicated nature of supercell tornado forecasting, though forecaster confidence in a *reduced* significant tornado threat can be reinforced when multiple ingredients are missing, or one ingredient is well outside the range of values established by T03.

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