JP1.4 SYNOPTIC AND MESOSCALE PATTERNS ASSOCIATED WITH VIOLENT TORNADOES ACROSS SEPARATE GEOGRAPHIC REGIONS OF THE UNITED STATES: PART 1 - LOW-LEVEL CHARACTERISTICS

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1. INTRODUCTION

Violent tornado occurrences in the United States are associated with various types of weather systems. The low-level features that occur with these weather systems have been documented by numerous case studies and researchers. Johns et al. (1993 and 2000) and Edwards and Thompson (2000) have explored various surface, instability and low-level moisture parameters associated with violent United States tornadoes and tornadic supercells, respectively. In addition, Guerrero et al. (1998), Markowski (1998) and Johns et al. (2000) determined the location of the tornado, significant tornado and violent tornado compared to the surface low and boundaries, respectively. The purpose of this study is to build on prior research by identifying the low-level patterns and characteristics associated with violent United States tornadoes and to compare the similarities and differences of these patterns and characteristics across separate geographic regions of the United States.

2. METHODOLOGY

For Part 1 of this study, the 38 United States violent tornado episodes including 70 violent tornado tracks from 1993 to 1999 were examined. The "Storm Data" publication was used to determine the time and number of violent tornadoes that occurred in each event. The program, "Severe Plot" version 2.0, was obtained from the Storm Prediction Center and was used to determine the location of each violent tornado. The resulting United States map is shown in Figure 1 below. The tornado tracks for each event are circled.

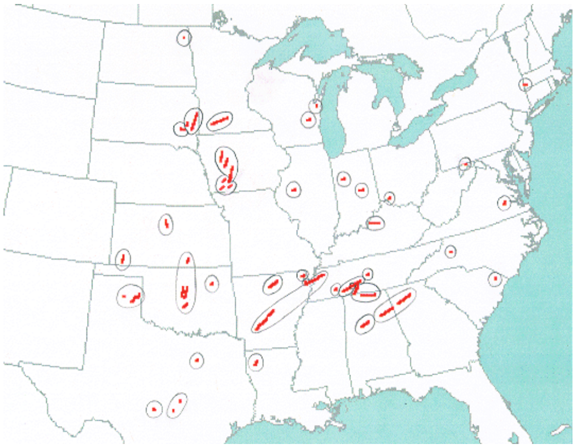

Figure 1: The F4 and F5 events are circled on this United States violent tornado map from 1993 to 1999.

For this paper, the United States was divided into five sections shown in Figure 2 to the right at the top of the page. The divisions were made so that the similarities and differences of the weather patterns associated with the violent tornado cases will be apparent on the circle plots using colors for each region. The Southern Plains are red, Northern Plains are blue, Upper Midwest is green, Southeast is purple and East is brown. There were eight events in the Southern Plains, six events in the Northern Plains, seven events in the Upper Midwest, 12 events in the Southeast and five events in the East.

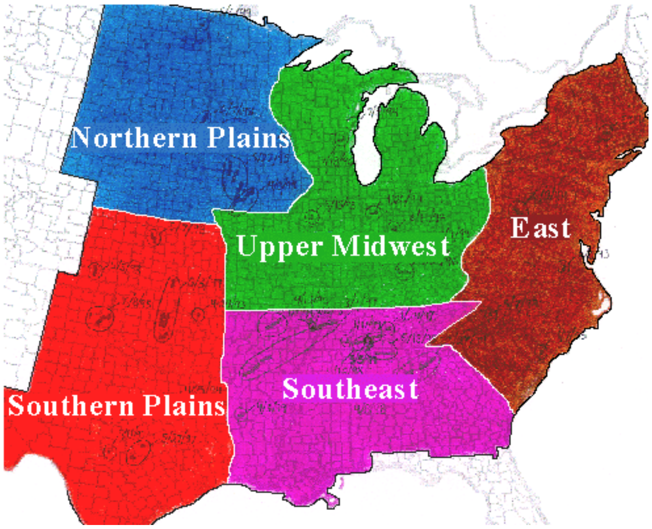

Figure 2: The map shows the designated regions of the United States for Part 1 of this study.

For Part 1 of this study, we hand analyzed the surface lows, boundaries, thermal ridges and moisture ridges using observational maps from the National Climatic Data Center (NCDC). To analyze CAPE (Convective Available Potential Energy), we obtained the 1996 to 1999 ETA model data from the Cooperative Program for Operational Meteorology, Education and Training (COMET). To interpret the 1996 to 1999 data, we used the Scientific Applications Computer (SAC). We obtained the 1993 to 1995 ETA model data from the Scientific Services Division (SSD) of the National Weather Service Southern Region Headquarters. To interpret the 1993 to 1995 model data, we used PC Gridds. For the violent tornado events that occurred less than two hours from 00Z or 12Z, we used the corresponding model initialization. Where the violent tornado events occurred two or more hours from the initialized model time, we gathered both the initialized model before and after the violent tornado event time. Then, we interpolated to get an accurate representation of where the feature was at the time of the violent tornadoes. We then plotted the location of each feature along with the violent tornado on a map. Then, we overlaid a circle with the feature located at the center and plotted the location of the violent tornado within the circle compared to the meteorological feature near the time of occurrence.

3. RESULTS

The main goal during our research was to determine the location of each violent tornado compared to meteorological features. For Part 1 of this study, the features that we considered included the surface low, surface boundaries, surface dewpoints and CAPE centers. The plots on the following pages show the results of our research. The tornado tracks show the favorable area compared to each meteorological feature. For most of the graphics, the 200 and 400 mile range rings are shown. In our discussion, we may differentiate between violent tornado tracks and the violent tornado events when giving

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statistical figures. When the violent tornado is referred to, it means each individual F4 to F5 damage track. In effect, one long path tornado could produce two or more separate F4 to F5 damage tracks. When violent tornado event is mentioned, it includes all violent tornadoes that occurred during the severe weather episode. In addition, differentiation may be made between the Northern States and Southern States. The Northern States include the Northern Plains, Upper Midwest and East (from Virginia to the north). The east and west will be divided by the Mississippi River.

3.1 *Surface Low, Surface Boundaries and Dewpoint*

The left portion of Figure 3 shows each violent tornado track's relative position compared to the surface low. After detailed hand analysis, the position of the surface low relative to each violent tornado was determined. Each violent tornado event's surface low was plotted in the center of the circle with the vertical line being north and south. The resulting plot shows 91.4 % of the violent tornadoes in the northeast and southeast quadrant of the low. When all violent tornado events were considered, 35.5 % of them occurred in the northeast quadrant while 48.7 % occurred in the southeastern quadrant. When the individual tracks were considered, 46.4 % of them fell in the northeast quadrant while 45.0 % fell in the southeast quadrant. As a result, the northeastern quadrant events produced more violent tornado tracks per event (2.41) than in the southeastern quadrant (1.70). For the southwest quadrant, only 15.8 % of the violent tornado events and only 8.6 % of the violent tornado tracks occurred. Notice that most of the Northern Plains violent tornadoes occurred in the northeastern quadrant. In fact, most of the Great Plains' violent tornado events occurred in the northeast quadrant. Notice that seven of the eight Southern Plains violent tornado tracks southeast of the low were associated with only one event, May 3, 1999.

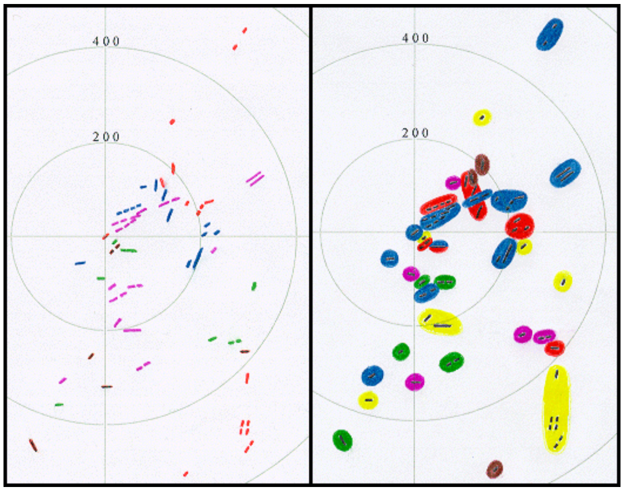

Figure 3: The circle plot to the left shows the position of 70 violent tornado tracks relative to the surface low. The Southern Plains are red, the Northern Plains are blue, the Southeast is purple, the Upper Midwest is green and the East is brown. The circle plot to the right shows the surface boundary associated with each violent tornado event. Cold front (27.0 %) is blue, warm sector (18.9 %) is yellow, warm front (16.2 %) is red, prefrontal trough (16.2 %) is green, pressure trough (13.5 %) is purple and dryline (8.1 %) is brown. The 200 and 400 mile range rings are shown.

The right portion of Figure 3 shows the type of boundary associated with each violent tornado event. Notice, most of the warm front and cold front cases occurred to the northeast or to the east of the surface low center. All of the prefrontal trough and pressure trough cases occurred south and southeast of the surface low center with the exception of the inverted pressure trough case to the northeast. Two of the dryline cases were northeast of the surface low center and one was to the south southeast. The warm sector cases favored the southeast quadrant.

Detailed surface analysis was done to determine the boundary associated with each violent tornado event. Below in Figure 4, the type of boundary associated with each event is shown. A few of the cold fronts were actually stationary fronts. However, most of these fronts had been cold fronts and had become stalled. Because of this, they are shown as cold fronts. The front in Kentucky exhibited warm front characteristics early in the event and cold front characteristics later in the event. This front is shown as both a cold and warm front.

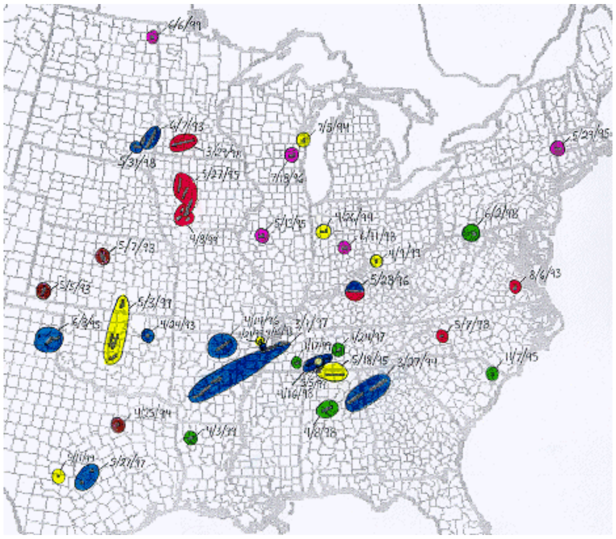

Figure 4: The map shows the type of boundary associated with each violent tornado event. Cold front (27.0 %) is blue, warm sector (18.9 %) is yellow, warm front (16.2 %) is red, prefrontal trough (16.2 %) is green, pressure trough (13.5 %) is purple and dryline (8.1 %) is brown.

Notice that most of the cold front cases were in the Southern States. The warm front cases occurred in the Northern Plains and in the East. The prefrontal trough cases occurred mostly in the Southeast and the pressure trough cases occurred in the Northern States. Notice the violent tornado event that was associated with the inverted trough case occurred in North Dakota and was designated as a pressure trough case. The dryline cases were confined to the Southern Plains. The warm sector cases were found in all regions except the Northern Plains and East.

After analyzing surface dewpoint, all the events appeared to be associated with moisture advection tongues of varying strength. Although somewhat subjective, a technique was developed to plot the circle in the right portion of Figure 5 on the next page. It shows point X determined by the dewpoint advection tongue and moisture gradient in relationship to the violent tornado paths. To execute the technique, the surface dewpoint moisture advection tongue was identified using two degree Fahrenheit intervals. The highest dewpoint pool in the tongue was noted and the average surface wind direction at the tip of the area was determined. The wind vector was projected from the tip of the area within the tongue to the first moisture gradient with a moisture density of greater than two degrees for a 30 mile distance. The point of intersection of the vector to the edge of the tight gradient was designated as Point X. An example of this method is shown in the left portion of Figure 5. Point X and the violent tornado tracks are both shown in black just south of Oklahoma City. After Point X was found for all the violent tornado events, a plot was made by putting Point X in the circle's center with each violent tornado family position plotted with respect to Point X. The resulting plot is shown in the right portion of Figure 5. North and south runs along the vertical line with the 100 and 200 mile range rings shown. Notice the tight relationship found for this technique. Most of the violent tornadoes were within 100 miles of Point X. In fact, 57.1% of the violent tornadoes fell in the two small areas just southwest and just north of Point X. This indicates that a large number of the violent tornadoes formed along tight moisture gradients oriented in a southwest to north or northeast direction downstream from a moisture advection tongue.

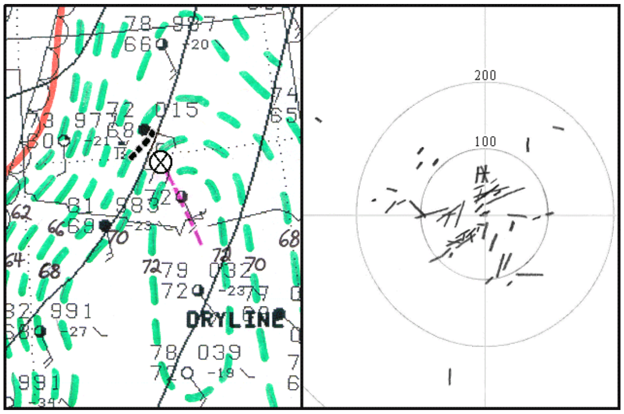

Figure 5: The dewpoint analysis for May 3, 1999 is to the left with Point X just south of Oklahoma City. The circle plot for Point X is to the right with Point X at the center and the violent tornado families plotted in relationship to Point X. The 100 and 200 mile range rings are shown.

A few other characteristics were determined from temperature and dewpoint including the location of the moisture ridge and thermal ridge compared to the violent tornado event's location. In the Great Plains, it was found that 78.6 % of the violent tornadoes occurred between the moisture ridge and thermal ridge. In 85.7 % of the cases, the thermal ridge was west of the moisture ridge. The violent tornado events in the Upper Midwest showed similarities to the Great Plains events. Conversely, the Southeast and East violent tornado events were different. Of nearly half (47.1 %), the violent tornadoes occurred west of both the moisture and thermal ridge. Opposite the Great Plains cases, in 52.9 % of the cases, the thermal ridge was east of the moisture ridge.

Table 1 below shows the average temperature, dewpoint and lifting condensation level at the time and location of the violent tornado for each region. Notice, the Southern Plains average temperature at the point of the violent tornado was much warmer than any other region. This contributed to much higher lifting condensation levels in the Southern Plains. The dewpoints with the violent tornadoes were highest in the Upper Midwest. In contrast, the lowest temperatures and dewpoints were found in the Northern Plains. Notice, the lowest lifting condensation levels were east of the Mississippi River.

Region	Temp	Dewp	LCL(ft)	Boundary	LCL(ft)
Southern Plains	76.9	65.4	2426.1	Dryline	2397.7
Northern Plains	69.5	61.8	1655.2	Cold Fr	2018.5
Upper Midwest	75.6	68.6	1488.9	Warm Sec	1801.3
Southeast	70.8	63.8	1516.3	Warm Fr	1612.5
East	70.4	63.4	1466.4	Prefront Tr	1409.3
				Pressure Tr	1238.8

Table 1: The average temperature, dewpoint and LCL (in feet) at the time and location of each violent tornado.

3.2 *Convective Available Potential Energy (CAPE)*

In the left portion of Figure 6, the circle plot was generated by locating the CAPE center of maximum instability associated with each event and plotting the position of each violent tornado in relationship to the CAPE center. Although, most of the violent tornado events had a clear CAPE center nearby, a few of the cases had only higher CAPE areas that were not completely closed off. For those cases, we looked for a large area of higher CAPE closed off on at least three sides. These areas were largely evident, and only a minimum of subjective reasoning was needed. Another problem was that the 1993 PC Gridds data did not show CAPE. We studied a sample of events and determined that the CAPE center and Lifted Index center were well related with a minimum of variability. As a result, we substituted Lifted Index for CAPE for the six 1993 events to determine the instability center and orientation. In the left portion of Figure 6, the vertical and horizontal lines represent north-south and east-west directions. It was found that almost two-thirds (65.0%) of the violent tornado events in the Southern Plains, Northern Plains, and Upper Midwest were clustered in the northern quadrant within 225 miles from the CAPE center. The violent tornado events in the Southeast and East tended to be further from the CAPE centers. There was a small percentage of events that were more than 400 miles from the CAPE center.

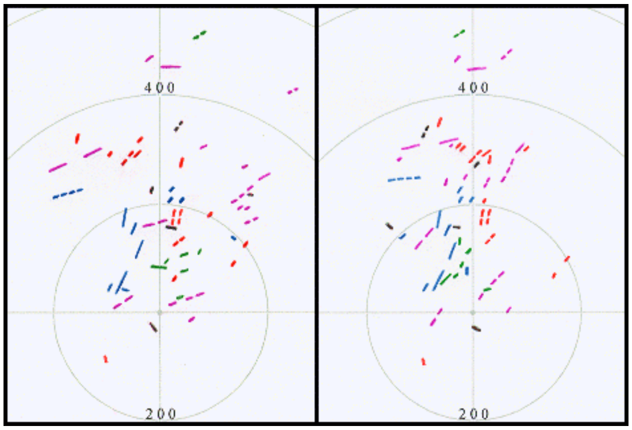

Figure 6: To the left is a plot with the max CAPE center in the circle's center and the position of the violent tornado tracks plotted directionally around it (north and south run along the vertical line). The circle plot to the right shows the CAPE center in the circle's center and the relative position of the violent tornado tracks plotted with respect to the axis of instability. The axis of instability runs along the vertical line. In both plots, the Southern Plains are red, the Northern Plains are blue, the Southeast is purple, the Upper Midwest is green and the East is brown. The 200 and 400 mile range rings are shown.

In the right portion of Figure 6, the circle plot was generated by noting where the violent tornado event occurred in relation to the orientation of the instability axis extending from the CAPE center. The boundary layer wind was determined to verify the orientation of the instability axis. The vertical line represents the direction of the axis of instability associated with the CAPE center. The violent tornadoes tended to cluster tightly around the instability axis and were less spread out when compared to the directional circle plot in the left portion of Figure 6. Notice that the Northern States violent tornadoes tend to occur along or just to the west of the instability axis, while the Southern States violent tornadoes tend to occur along or just to the east of the instability axis. Of all the regions, the Upper Midwest violent tornadoes occurred closest to the CAPE center with the Southeast violent tornadoes spread out the most.

Below in Table 2, the average CAPE, precipitable water and 850 mb through 500 mb mixing ratio values at the location and time of the violent tornadoes are shown. For several events, CAPE and precipitable water were not available. As a result, five out of the 38 violent tornado events were left out for CAPE and six were left out for precipitable water. Notice the much higher CAPE values and higher 850 mb mixing ratios associated with the Southern Plains and Upper Midwest violent tornadoes. In contrast, notice the low CAPE values for violent tornadoes across the Southeast and East. In addition, the precipitable water values, 700 mb mixing ratio and 500 mb mixing ratio were lower for the Great Plains.

	CAPE	Precip.	Mixing Ratios (g/kg)		
Region	J/kg	Water (in.)	850 mb	700 mb	500 mb
Southern Pla.	3410	1.11	10.8	3.9	1.0
Northern Pla.	1520	1.00	8.4	3.9	1.1
Upper Mid.	2486	1.37	10.5	5.4	1.6
Southeast	1158	1.38	9.5	4.8	1.6
East	938	1.31	9.4	5.4	1.6

Table 2: Average values of CAPE, precipitable water, and mixing ratios are shown by geographic region for the violent tornado events.

4. SUMMARY AND FUTURE WORK

Many similarities and differences were found among violent tornado episodes across separate geographic regions of the United States at the surface and with respect to instability. The most significant findings of Part I include the following. With respect to the surface low, most violent tornadoes in the Great Plains occurred in the northeast quadrant. In contrast, most violent tornadoes east of the Mississippi River occurred in the southeast quadrant or southwest quadrant of the surface low. Violent tornadoes formed along many types of boundaries favoring prefrontal troughs in the Southeast, cold fronts in the Southern Plains and Southeast, drylines in the Southern Plains, warm fronts and pressure troughs in the Northern States, and inverted troughs in the Northern Plains. As far as low-level moisture is concerned, most of the violent tornado episodes were associated with low-level moisture advection tongues. Typically, the violent tornado event occurred downstream of the moisture advection tongue near a tight moisture gradient often, but not necessarily associated with a boundary. The violent tornadoes in the Great Plains tend to be between the moisture and thermal ridge with the moisture ridge to the east. In contrast, the violent tornadoes east of the Mississippi River commonly occurred west of both the moisture and thermal ridge with the thermal ridge east of the moisture ridge. The Great Plains had higher lifting condensation levels, lower precipitable water values and lower 500 mb and 700 mb mixing ratios while the Upper Midwest, Southeast and East had lower lifting condensation levels, higher precipitable water values and higher 500 mb and 700 mb mixing ratios. With respect to CAPE maximum centers, most of the violent tornadoes occurred from northwest to northeast of the CAPE center from the CAPE center out to 325 miles. The violent tornado episodes were plotted tighter around the orientation of the CAPE axis than they were directionally from the CAPE center. The Southern Plains and Upper Midwest were typically higher CAPE cases and the Southeast and East were typically lower CAPE cases. Most of the Northern States violent tornadoes occurred just to the west of the instability axis whereas most of the Southern States violent tornadoes occurred just to the east of the instability axis. For a webpage of this study using colors for each region, go to http://www.srh.noaa.gov/ama/html/Violenttornadoes.html.

Future work will include radar analysis of the development of these violent tornadic storms using the NSSL algorithms. With continued research, a greater awareness of the characteristics associated with violent tornadoes will emerge which should help us better forecast these deadly events in the future.

5. REFERENCES

Bluestein, H. B., 1993: Synoptic-Dynamic Meteorology in Midlatitudes, Volume II, Observations and Theory of Weather Systems, Oxford University Press, 465-526.

Doswell, C. A., III, S. J. Weiss, R. H. Johns, 1993: Tornado Forecasting: A Review. The Tornado: Its Structure, Dynamics, Prediction, and Hazards. *Geophys. Mongr.*, **79**, Amer. Geophys. Union, 557-571.

Edwards, R., and R. L. Thompson, 2000: RUC-2 supercell proximity soundings, Part II: an independent assessment of supercell forecast parameters. Preprints, 20th Conf. Severe Local Storms, Orlando FL, Amer. Meteor. Soc., 435-438.

Grazulis, T. P., 1997: Significant Tornadoes Update, 1992-1995, The Tornado Project of Environmental Films, 1392.

Guerrero, H., J. C. Broyles, and D. Eastlack, 1998: Forecasting tornado location across the Dakotas and Minnesota, Preprints, 19th Conf. Severe Local Storms, Minneapolis, MN, Amer. Meteor. Soc., 301-304.

Johns, R. H., J. C. Broyles, D. Eastlack, H. Guerrero, K. Harding, 2000: The role of synoptic patterns and temperature and moisture distribution in determining the locations of strong and violent tornado episodes in the north central United States: a preliminary examination, Preprints, 20th Conf. Severe Local Storms, Orlando FL, Amer. Meteor. Soc., 489-492.

Johns, R. H., J. M. Davies, and P.W. Leftwich, 1993: Some wind and instability parameters associated with strong and violent tornadoes. Part II: Variations in the combinations of wind and instability parameters. The Tornado: Its Structure, Dynamics, Prediction, and Hazards. *Geophys. Mongr.*, **79**, Amer. Geophys. Union, 583-590.

Leftwich, P. W. and W. R. Sammler 1986: Forecasting violent tornadoes, Preprints, 11th AMS Conference on Forecasting and Analysis, 114-118.

National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, 1993-1999: *Storm Data.*

Whiting, R. and R. Bailey, 1957: Some Meteorological Relationships in the Prediction of Tornadoes. *Monthly Weather Review*, **85**, 141-149.