JP1.5 SYNOPTIC AND MESOSCALE PATTERNS ASSOCIATED WITH VIOLENT TORNADOES ACROSS SEPARATE GEOGRAPHIC REGIONS OF THE UNITED STATES: PART 2 - UPPER-LEVEL CHARACTERISTICS

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1. INTRODUCTION

Violent tornado occurrences in the United States are associated with various types of weather systems. The upper-level features that occur with these weather systems have been documented by numerous case studies and researchers. Johns and Sammler (1989) and Bluestein (1993) have identified various upper-level patterns associated with violent United States tornadoes and tornado outbreaks, respectively. In addition, Edwards and Thompson (1998), and Doswell et al. (1993) determined favorable weather patterns for significant tornadoes and tornadoes in general, respectively. The purpose of this study is to build on prior research by identifying the upper-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 2 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 tornado tracks can be seen on the United States map shown in Figure 1 of Part 1 (paper JP1.4).

For this paper, the United States was divided into five sections shown in Figure 1 below. 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. There were eight events in the Southern Plains (red), six events in the Northern Plains (blue), seven events in the Upper Midwest (green), 12 events in the Southeast (purple) and five events in the East (brown).

For Part 2 of the study, to analyze upper-level features, we used the initialized ETA model. We obtained

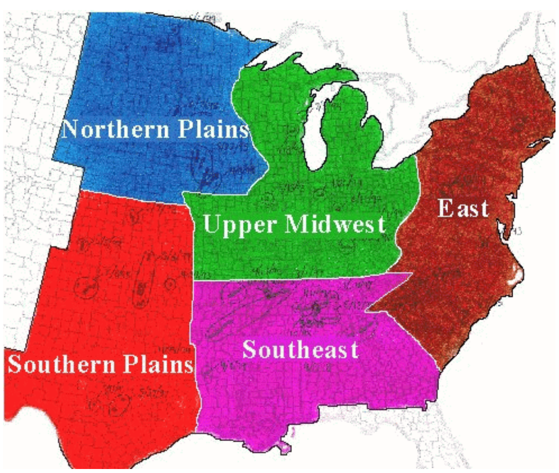

Figure 1: The map shows the designated regions of the United States for Part 2 of this study.

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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 which was GEMPAK data, we used the Scientific Applications Computer (SAC). In addition, for the 1997 to 1999 portion of the atmospheric jet study, we used archived ETA maps from the Air Resource Laboratory's (ARL) Realtime Environmental Application and Display System (READY). 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 data we used PC Gridds. The ETA model was available for all but one event. For the event where the ETA was missing, we substituted the initialized NGM model. 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 2 of this study, the features that we considered included the 500 mb positive vorticity center, 500 mb negative vorticity center, 850 mb jet, 700 mb jet, 500 mb jet and 300 mb jet. The plots on the following pages show the results of our research. The tornado tracks show the favorable area compared to each meteorological feature. On all the graphics, the 200 and 400 mile range rings are shown. In our discussion, we may differentiate between the violent tornado tracks and the violent tornado events when giving 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 several 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 *500 mb Positive Vorticity and Negative Vorticity*

The left portion of Figure 2 on the next page shows each violent tornado track's relative position to the 500 mb positive vorticity center. North and south is not taken into account on this plot. However, the orientation of the positive vorticity center is taken into account and runs along vertical line. The orientation of the vorticity center was considered perpendicular to the direction of the average geostrophic flow or height contour running through the vorticity center. Most of the time, the orientation was perpendicular to the movement of the vorticity center; however, the relationship is not perfect because vorticity centers do not always move exactly with the average geostrophic flow. We used any positive vorticity center or vorticity lobe with a value of 10 or above. In most cases, the associated positive vorticity center was clearly evident. However, a few of the PC Gridds events were harder to interpret because some of the PC Gridds model data had a greater minimum contour interval than the GEMPAK data viewed on the SAC. We used our best judgment to identify each vorticity center. In one case, no positive vorticity center was evident.

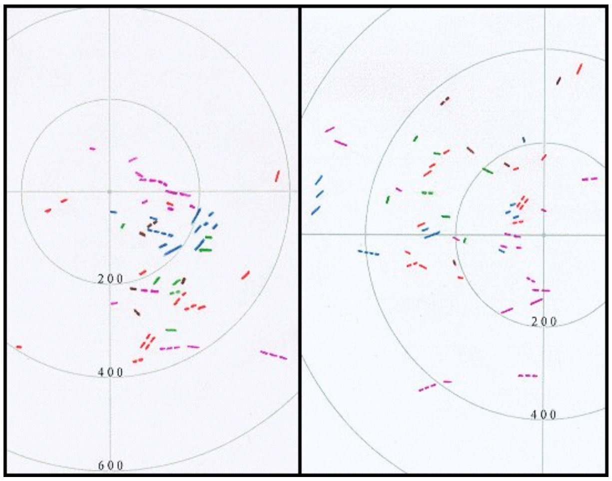

Figure 2: The plot to the left shows the violent tornado tracks with respect to the positive vorticity center. The plot to the right shows the violent tornado tracks with respect to the negative vorticity center. The vorticity center's orientation runs along the vertical line. In both plots, the Southern 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 left portion of Figure 2, a striking pattern emerged showing that over three-quarters or 76.3 % of the violent tornadoes occurred in the lower right quadrant with respect to the orientation of the positive vorticity center, regardless of geographic location in the United States. However, geographic location did play an important role in determining distance from the positive vorticity center. Most of the Northern Plains violent tornadoes occurred about 200 miles away from the positive vorticity center in the lower right quadrant. All but two of the Upper Midwest violent tornadoes occurred about 250 miles away in the lower right quadrant, while most of the Southern Plains violent tornadoes occurred about 325 miles away in the lower right quadrant. A general notation was made that as one goes north or northwest across the regional United States map, the violent tornadoes occurred closer and closer to the positive vorticity center and the value of the vorticity center increased. This is evident in the left portion of Figure 2 and also in Table 1. One possibility in the Great Plains is that the higher buoyancy usually prevalent in the Southern Plains compensated for the weaker dynamics there. In the Northern Plains, the stronger positive vorticity centers and greater dynamics may have compensated for the less overall CAPE and buoyancy there. As discussed on the next page, in the East and Southeast, higher low-level wind speeds may have compensated for the less overall CAPE and buoyancy there.

In the right portion of Figure 2, the plot shows the negative vorticity center in relationship to each violent tornado path. Notice that most of the violent tornadoes occurred in the upper left quadrant with the highest concentration located from just behind the negative vorticity center out to about 300 miles in the upper left quadrant. However, the relationship was not nearly as significant as that found for the positive vorticity center.

Geographic Region	Positive Vorticity Value
Southern Plains	$15.25 \times 10^{-5}\ s^{-1}$
Northern Plains	$25.83 \times 10^{-5}\ s^{-1}$
Upper Midwest	$19.00 \times 10^{-5}\ s^{-1}$
Southeast	$14.91 \times 10^{-5}\ s^{-1}$
East	$15.80 \times 10^{-5}\ s^{-1}$

Table 1: The average positive vorticity value associated with the violent tornado events for each geographic region is shown.

3.2 *Atmospheric Jets*

In addition to GEMPAK and PCGridds data, the Air Resource Laboratory's (ARL) Realtime Environmental Application and Display System (READY) was used to display archived atmospheric jet data using the ETA model. One advantage gained from using READY was that three hour increments of the ETA model were available instead of just 12 hour initializations. First, the position of the closest atmospheric jet core to the violent tornado event was identified. Then, the position of the highest wind speed in the jet at or nearest to the time of the violent tornado was plotted for 850 mb, 700 mb, 500 mb and 300 mb. Interpolation was done if the violent tornado event fell in between model time increments. Then, the orientation of the jet was noted by determining the average wind direction running through the core of the jet at that level. As a result, the orientation is parallel to the average wind direction running through the jet. After plotting the jet position and orientation, the circle plots in Figure 3 and Figure 4 were generated. In each graphic, the center of the atmospheric jet is in the circle's center with each violent tornado plotted with respect to the jet's position. The orientation of each jet is along the vertical line. Keep in mind that the atmospheric jet's movement is not always parallel to the jet's orientation. North-south direction was not taken into account. The nose of each jet would be in the middle to top portion of the circle.

The left portion of Figure 3 on the next page shows each violent tornado path relative to the 850 mb jet. Notice the strong relationship with most of the violent tornadoes occurring to the left of the 850 mb jet. Most of the Great Plains and Upper Midwest violent tornadoes occurred in the left front quadrant of the jet. However, two of the Upper Midwest violent tornadoes were unusual, occurring well to the right of the 850 mb jet. The violent tornadoes in the Southeast occurred both in the left front and left rear quadrants of the jet, while the Eastern States occurred mainly in the left rear quadrant.

The right portion of Figure 3 shows the relative position of the violent tornadoes to the orientation of the 700 mb jet. Notice many of the violent tornadoes occurred in the jet nose, just ahead of the jet core or in the left front quadrant. The majority of the Southern Plains events occurred just ahead of the jet core. In contrast, most of the Northern Plains and East violent tornado events occurred to the left or in the left front quadrant. The Southern Plains, Upper Midwest and Southeast violent tornadoes were mostly concentrated along and just to either side of the axis of the 700 mb jet. Notice the many Southeast violent tornadoes that occurred in the right rear quadrant.

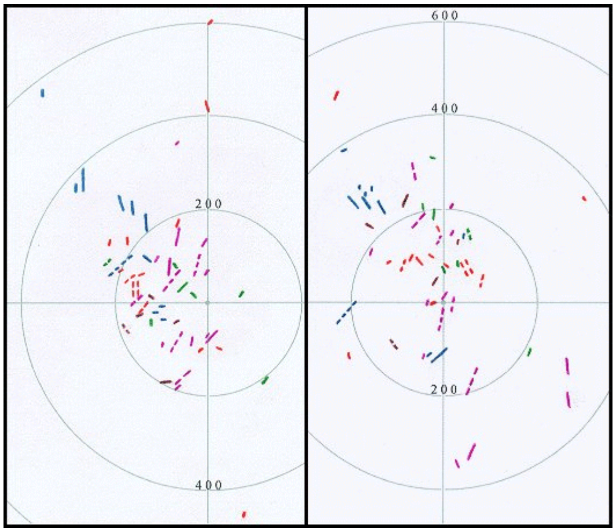

Figure 3: The plot to the left shows the violent tornado tracks with respect to the orientation of the 850 mb jet. The plot to the right shows the violent tornado paths with respect to the orientation of the 700 mb jet. The axis of each jet runs along the vertical line. In both plots, the Southern Plains 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.

The left portion of Figure 4 shows the relative position of the violent tornadoes to the orientation of the 500 mb jet. Notice many of the violent tornadoes occurred in the jet nose or in the left front quadrant of the 500 mb jet. A few of the events occurred to the right of or in the right rear quadrant of the 500 mb jet. Similar to the 700 mb jet, many of the Southern Plains violent tornado events occurred just ahead of the jet core in or near the jet nose. Again, like 700 mb, most of the violent tornadoes in the Northern Plains and East occurred in the left front quadrant. Notice that six of the seven Upper Midwest events occurred from about 125 miles just ahead of the jet core to about 125 miles to the right of the jet core.

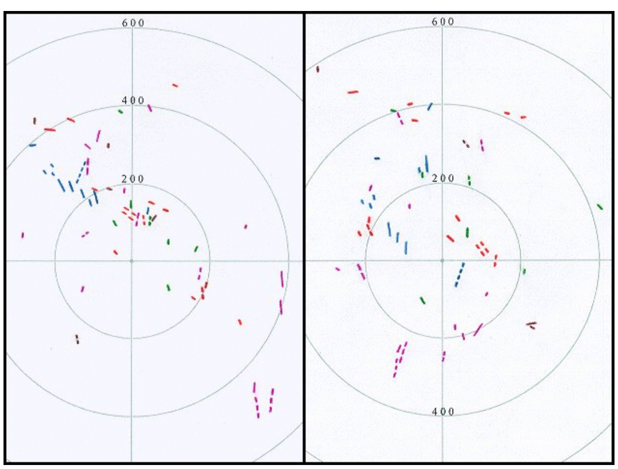

Figure 4: The plot to the left shows the violent tornado tracks with respect to the 500 mb jet. The plot to the right shows the violent tornado with respect to the 300 mb jet. The axis of each jet runs along the vertical line. In both plots, the Southern Plains are red, the Northern Plains are blue, the Southeast is purple, the Upper Midwest is green and the East is brown. The 200 and 400 mile range rings are shown.

The right portion of Figure 4 shows the relative position of the violent tornadoes to the orientation of the 300 mb jet. There is no distinct pattern, unlike the circle plots at lower levels. However, a weak pattern can be seen with many of the violent tornadoes occurring in the left front quadrant or to the right of the 300 mb jet. Similar to the 850, 700 and 500 mb plots, most of the Northern Plains events occurred in the left front quadrant. Most of the Southern Plains events occurred in the left front quadrant or just to the right of the 300 mb jet. Most of the Southeast violent tornadoes occurred in the rear quadrants.

In Table 2 below, the average wind speeds at 850 mb through 300 mb at the location and time of the violent tornadoes are shown. One thing to notice is that the Great Plains violent tornadoes were associated with lower wind speeds at low to mid-levels than those found further east. The higher CAPE and buoyancy in the Southern Plains and the greater dynamics in the Northern Plains may have compensated for the weaker low to mid-level wind speeds found in the Great Plains, whereas the higher wind speeds at low to mid-levels in the Southeast and East may have helped compensate for the weaker CAPE and buoyancy there.

In Table 3 below, the average wind speed difference between different levels is shown. Notice that the highest low to mid-level speed shear was located in the East. It is a possibility that this was a factor coupled with low lifting condensation levels that helped violent tornadoes in the East where dynamics were relatively weak and CAPE was relatively low. Notice that the average speed difference from 850 to 500 mb had a fairly tight range of around 16 knots in the East to around 23 knots in the Southeast with an overall average of about 20 knots for all regions.

Region	850 mb Wind Sp.	700 mb Wind Sp.	500 mb Wind Sp.	300 mb Wind Sp.
Southern Plains	23.4	33.9	42.4	50.8
Northern Plains	29.2	37.3	50.7	70.3
Upper Midwest	35.7	42.9	55.9	65.6
Southeast	40.3	47.1	63.4	71.5
East	33.8	48.2	49.6	60.8

Table 2: The average wind speeds from 850 mb to 300 mb for the violent tornadoes in each region.

Region	850 to 700 mb Sp.Shear	700 to 500 mb Sp.Shear	500 to 300 mb Sp.Shear.	850 to 500 mb Sp.Shear	700 to 300 mb Sp.Shear
South Pl.	10.5	8.5	8.4	19.0	16.9
North Pl.	8.1	13.4	19.6	21.5	33.0
Upper Mid.	7.2	13.0	9.7	20.2	22.7
Southeast	6.8	16.3	8.1	23.1	24.4
East	14.4	1.4	11.2	15.8	12.6

Table 3: The average wind speed differences between different levels for the violent tornadoes in each region.

In Figure 5 on the next page, the actual wind speeds are shown for the violent tornado events. Notice that at 850 mb and 700 mb, the range of wind speeds is the least. The Great Plains show the weakest wind speeds at low to mid-levels. Of the 11 lowest speeds at 850 mb and 700 mb, 81.8 % are Great Plains events. In contrast, of the top ten highest wind speeds at 850 and 700 mb, 90.0 % are in the Southeast or East where dynamics and instability were relatively low. The trend also continued up to 500 and 300 mb. Out of the lowest 12 wind speeds at 500 mb, nine were Great Plains events. Out of the top 11 wind speeds at 500 mb, eight were violent tornadoes in the Southeast or East. A similar but much weaker pattern shows up at 300 mb.

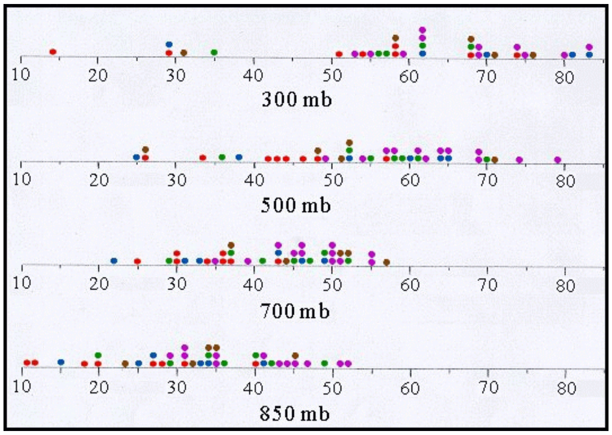

Figure 5: Wind speeds in knots at the time and location of each violent tornado are shown. The Southern Plains are red, the Northern Plains are blue, the Southeast is purple, the Upper Midwest is green and the East is brown.

Figure 6 below shows the relationship between CAPE and 700 mb wind speeds associated with the location and time of each violent tornado. Notice the high concentration of violent tornadoes that occurred with CAPE values of less than 2000 J/kg and 700 mb wind speeds above 40 knots. Most of these events were in the Southeast and East. In contrast, most of the Great Plains violent tornadoes were associated with relatively low 700 mb wind speeds. In the Southern Plains, CAPE was generally high and in the Northern Plains, CAPE was generally low. The lower bound threshold for CAPE was around 450 J/kg. All but three violent tornado events occurred with 700 mb wind speeds of 30 knots or higher with almost two-thirds or 63.6 % of the events occurring between 40 and 55 knots.

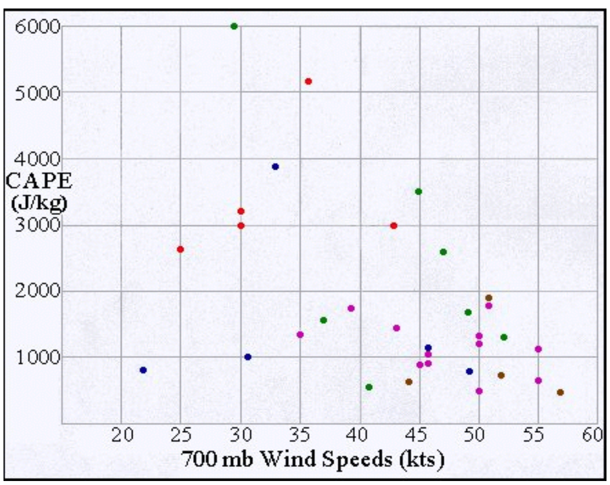

Figure 6: CAPE (J/kg) and 700 mb wind speeds (knots) are shown for the violent tornado events. The Southern Plains are red, the Northern Plains are blue, the Southeast is purple, the Upper Midwest is green and the East is brown.

4. SUMMARY AND FUTURE WORK

Many similarities and differences were found among violent tornado episodes across separate geographic regions of the United States at upper-levels. The most significant finds of Part 2 include the following. With respect to the 500 mb positive vorticity center's orientation perpendicular to the average 500 mb height, almost all of the violent tornadoes occurred in the lower right quadrant from the positive vorticity center out to 400 miles. The Northern Plains and Upper Midwest violent tornadoes were closer to the vorticity center and were associated with higher vorticity values, corresponding to greater dynamics there. In the Southern Plains, Southeast and East, vorticity values were lower with the Southern Plains violent tornadoes furthest away from the vorticity center. And considering atmospheric jets, most of the events were clustered tightly to the left of the 850 mb jet from the middle of the left front quadrant down to the middle of the left rear quadrant out to 225 miles from the 850 mb jet center. With respect to the 700 mb jet, most events were clustered in the nose, in the left front quadrant or along the axis of the 700 mb jet. And with respect to the 500 mb jet, most violent tornadoes were clustered in the left front quadrant and to the right of the 500 mb jet. The 300 mb jet circle plot showed only a weak pattern but more events occurred in the left front quadrant and to the right of the jet core. Finally, considering wind speeds, the violent tornadoes in the Great Plains were generally associated with weaker low to mid-level wind speeds which may have been compensated in the Southern Plains by higher CAPE environments and in the Northern Plains by greater dynamics. The violent tornadoes in the Southeast and East were associated with greater low to mid-level wind speeds which may have helped compensate for the lower CAPE environments. 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.

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