# Location and Frequency of Surface Lows and Lower-Tropospheric Jets for U.S. Violent Tornadoes

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Abstract

The Violent Tornado Webpage from the Storm Prediction Center has been used to obtain data for 182 events (404 violent tornadoes) in which an F4-F5 or EF4-EF5 tornado occurred in the United States from 1950 to 2014. The positions for the surface low, 850 mb jet, 700 mb jet and 500 mb jet have been recorded on a United States map for each three-hour period in which a violent tornado was observed. The position for each meteorological feature was determined using the North American Regional Reanalysis (NARR) from 1979 to 2014 and NCEP/NCAR Reanalysis from 1950 to 1978. After the positions were recorded, frequencies were calculated using a 170 statute mile grid on a U.S. map. Contours were drawn showing the frequency of occurrence for each meteorological feature. Surface lows were most frequent along a corridor from the central High Plains northeastward into the Upper Midwest and eastward to northern Illinois. For the 850 mb jet, two maxima were identified in the Great Plains with one in northeast Kansas and another in eastern Oklahoma. Other maxima for the 850 mb jet were located in western Kentucky and northeast North Carolina. For the 700 mb jet, the corridor of highest incidence was located from southern Kansas across eastern Oklahoma into western Arkansas with another maximum in western Tennessee. For the 500 mb jet, the highest incidence was located from western Oklahoma northeastward into southeast Kansas with additional maxima in southeast Missouri and north-central South Dakota.

## 1. INTRODUCTION

Over the years, many tornado climatology maps have been produced including maps showing the occurrence of violent tornadoes across the United States. For example, Concannon et al. (2000) produced a map of F4 and F5 tornadoes from 1921 to 1995 in Figure 1 below. This map shows a pronounced maximum in the Southern and Central Plains extending northward into southwest Iowa. A secondary maximum is located in the Southeast with a small maximum in the lower Ohio Valley. The greatest incidence of violent tornadoes for this time period was in the Southern Plains across central and southern Oklahoma.

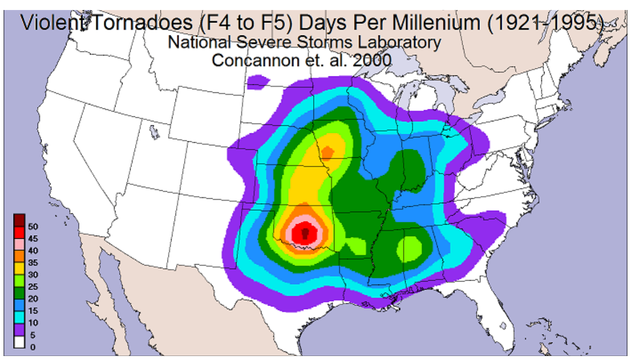



Figure 1. Map of F4 and F5 tornadoes (1921 to 1995) taken from Concannon et al. (2000). A maximum of incidence is noted in the Great Plains. Another maximum is located in the Southeast with a small one in the lower Ohio Valley. The greatest incidence is in the Southern Plains across central and southern Oklahoma.

Most recently in 2015, Patrick Marsh at the Storm Prediction Center (SPC) also produced a map of F4 and F5 tornadoes but the time period was shifted later to 1950 - 2011 (Figure 2 at the right). This map also shows a pronounced maximum in the Southern and Central Plains extending north-northeastward into central Iowa. Another maximum is located in the Southeast with a small maximum in the Ohio Valley. The greatest incidence of violent tornadoes in this time period was in the Southeast across northeast Mississippi and northern Alabama.

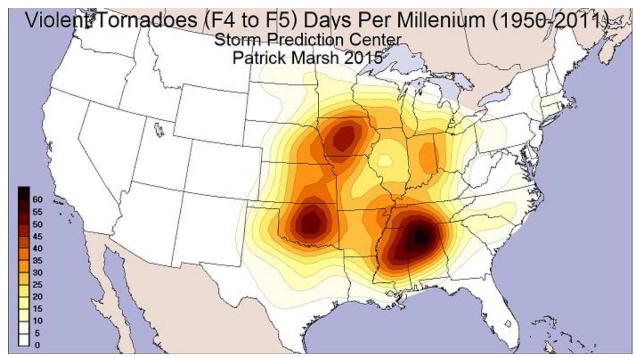



Figure 2. Map of F4 and F5 tornadoes (1950 to 2011) produced by Patrick Marsh from the Storm Prediction Center in 2015. Two maxima are noted in the Great Plains with one in central Oklahoma and another in central Iowa. Another maximum is located in the Southeast with a small maximum in the Ohio Valley. The greatest incidence is in the Southeast from northeast Mississippi into north-central Alabama.

Both Figure 1 and Figure 2 show a minimum extending from the Ozarks in northern Arkansas northeastward into the mid to upper Mississippi Valley. Other small minima are located in eastern Kansas and western Kentucky. The authors hypothesized that many of the variations in violent tornado occurrence are due to the favored timing of atmospheric features. It is thought that the position of the Rocky Mountains and Gulf of Mexico play an important role in determining where violent tornadoes are more likely to occur in the United States. More specifically, minima in the Ozarks and mid to upper Mississippi Valley are likely due to a nocturnal minimum in the thunderstorm cycle. Furthermore, the minimum of violent tornadoes in eastern Kansas was hypothesized to be a less favorable area between the Southern Plains low-level jet predominantly in the early to mid-spring and the Central Plains low-level jet predominately in the late spring and early summer. To test these hypotheses, 404 violent tornadoes in the U.S. were analyzed to determine the most favorable locations historically for surface low pressure systems and atmospheric jets at varying levels.

## 2. METHODOLOGY

Barnes and Newton (1983) published a schematic showing a favorable pattern for severe weather episodes in the Northern Hemisphere. That schematic was later modified by Bob Johns (1993). We further modify the graphic in Figure 3 below.

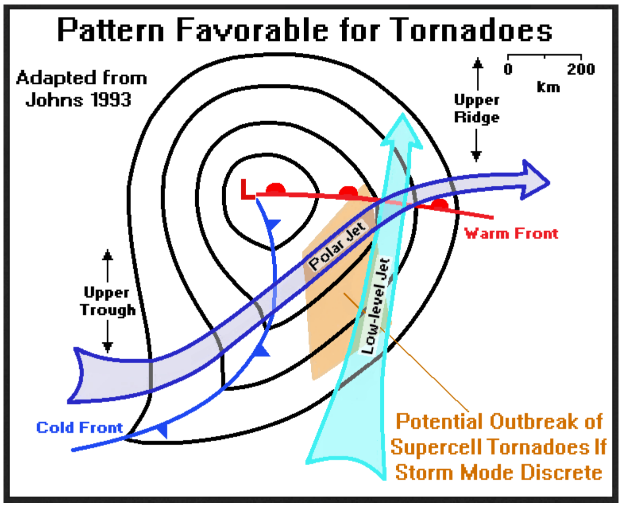



Figure 3. A severe weather schematic that has been modified from Johns (1993). Johns had also modified the graphic which was originally drawn by Barnes and Newton (1983). The surface low, low-level jet and mid to upper-level jet are important to a severe weather episode. The favored location for severe storms is across the warm sector between the low-level jet and mid to upper-level jet.

Johns suggested that the most favorable location for severe weather was across the warm sector between the low-level jet and mid to upper-level polar jet. This is especially true for tornado outbreaks which most often occur between the low-level and mid-level jets near the maximum of flow at 700 mb when discrete modes are favored. In addition, many tornado outbreaks occur near the exit region of a fast-moving 500 mb jet which enhances lift and deep-layer shear.

The overall pattern in Figure 3 resembles many violent tornado cases including the Super Outbreaks on April 27, 2011 and April 3 and 4, 1974. The setup is also similar to Super Tuesday (February 5, 2008) and Palm Sunday (April 11, 1965). The schematic highlights the importance of the surface low and jet structures at different levels in the atmosphere. For this reason, we chose to plot the positions of the surface low, 850 mb jet, 700 mb jet and 500 mb jet for a collection of violent tornado cases on U.S. maps.

To collect the data for this study, the Violent Tornado Webpage (*www.spc.noaa.gov/exper/outbreaks)* was used. On that webpage, violent tornado events are available from 1875 to 2014 but this study only includes events from 1950 to 2014. Events before 1950 were excluded due to the 20th Century Reanalysis being less reliable. From 1979 to 2014, the North American Regional Reanalysis was used and all violent tornado events were analyzed. From 1950 to 1978, the NCEP/NCAR Reanalysis was used but only for events where four violent tornadoes occurred within a 72 hour period. This was determined by the data available on the webpage. On the webpage, the two data sets encompass 65 years of analysis (1950-2014) including 182 events and 404 violent tornadoes rated F4 to F5 (EF4 to EF5 after February 1, 2007).

When each case was loaded, the time was set to the occurrence of the violent tornado using 3-hour increments from 1979 to 2014 and 6 hour increments from 1950 to 1978. The position of the surface low, 850 mb jet, 700 mb jet and 500 mb jet was found for each time at which there was at least one violent tornado. Some outbreaks had violent tornadoes spread out over more than one three-hour period. For that reason, those events have multiple positions plotted for each meteorological feature. In Figure 4 below, a hand plotted feature distribution map is shown. Each dot represents the location of an 850 mb jet which was found 248 times. If the associated violent tornado or tornadoes were in the Southern Plains, the dot is blue. Red is used for the Northern Plains. Green is used for the Southeast and Purple for the Northeast. The dot has been circled for features found using the NCEP/NCAR Reanalysis from 1950 to 1978.

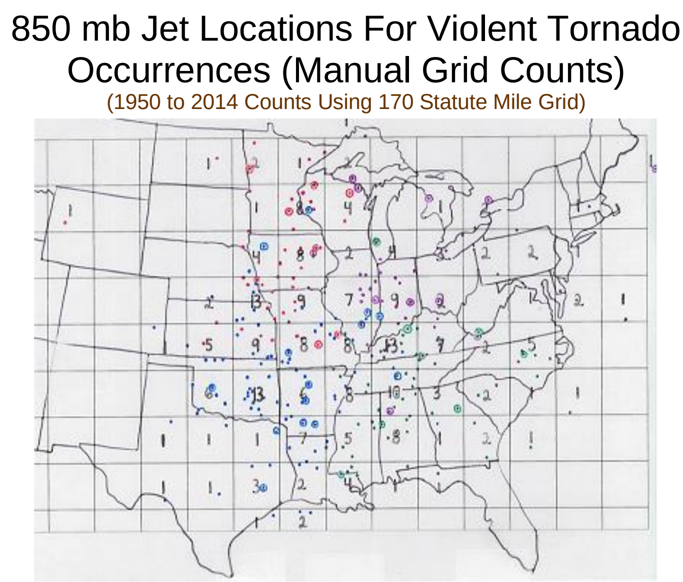



Figure 4. The hand plotted spatial distribution of the 850 mb jet for 182 violent tornado cases. The 850 mb jet was associated with a violent tornado 248 times.

After each map was complete, a 170 statute mile grid was overlaid onto the U.S. map. Then, the number of times each feature occurred within a grid box was counted. That number was then put in the middle of each grid box and contours were manually drawn. Due to the manual process used for this study, a slight amount of subjectivity was introduced into the grid counts and contouring scheme.

## 3. RESULTS

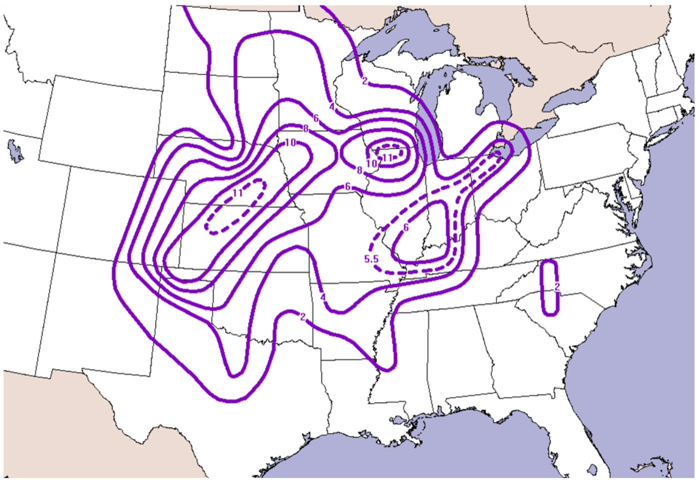
In Figure 5, the contoured maps are shown for each meteorological feature. Considering the map for

# Data Maps for Meteorological Features Associated with U.S. Violent Tornadoes 1950 to 2014

## 182 Events Including 404 Violent Tornadoes

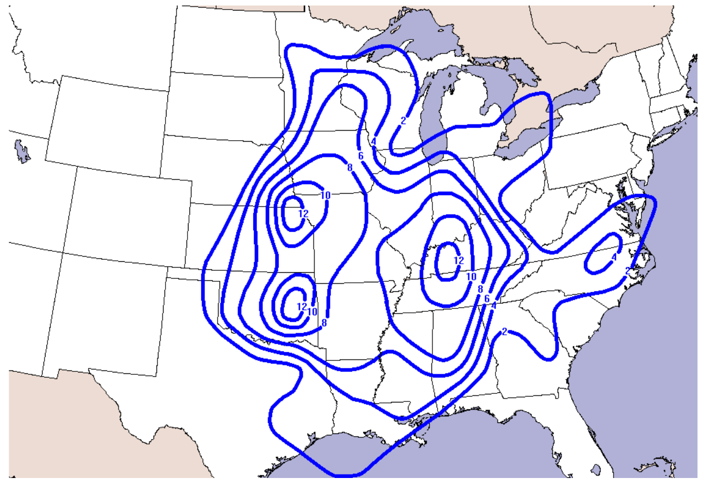
1950-1978 NCEP/NCAR Reanalysis, 1979-2014 North American Regional Reanalysis

Surface Low Frequency For
Violent Tornado Occurrences
(Contoured Map Using 170 Statute Mile Grid)



Surface Low

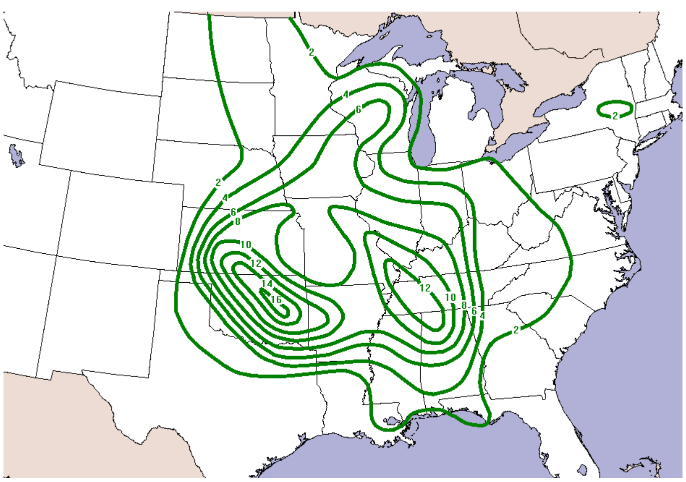
850 mb Jet Frequency For
Violent Tornado Occurrences
(Contoured Map Using 170 Statute Mile Grid)



850 mb Jet

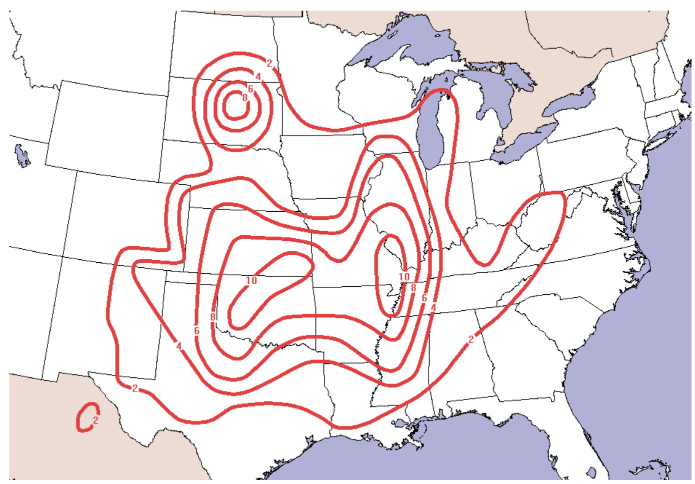
All Tornadoes EF4 to EF5
or F4 to F5

700 mb Jet Frequency For
Violent Tornado Occurrences
(Contoured Map Using 170 Statute Mile Grid)



700 mb Jet

500 mb Jet Frequency For
Violent Tornado Occurrences
(Contoured Map Using 170 Statute Mile Grid)



500 mb Jet

Figure 5. Contoured maps for the positions of meteorological features associated with 182 violent tornado events from 1950 to 2014. The upper left map shows the surface low distribution. Surface lows were most commonly located from the Central Plains northeastward into the mid to upper Mississippi Valley with a secondary maximum from the Mid Mississippi Valley into the lower Great Lakes. The upper right map shows the 850 mb jet distribution. 850 mb jets were most commonly located in the Great Plains, lower Ohio Valley and northeastern North Carolina. The Great Plains low-level jet distribution was split with a maximum in eastern Oklahoma and another in far northeast Kansas. The lower left map shows the 700 mb jet distribution. 700 mb jets were most commonly located in east-central Oklahoma and western Tennessee. The maximum for 700 mb jet in east-central Oklahoma was the strongest signal on the four maps. The map at the lower right shows the 500 mb jet distribution. 500 mb jets were most commonly located in northern Oklahoma, far southeast Missouri and in northern South Dakota.

surface low at the upper left in Figure 5, the maximum occurrence was located from western Kansas northeastward into western Iowa with another maximum in northern Illinois. The narrow corridor oriented from southwest to northeast in the Central Plains appears to be related to the surface low track associated with upper-level systems moving from the Rockies into the Great Plains. This surface low track is far enough north to allow for a large moist sector to be in place across the southern and central Plains. It is also ideal for the development of a dryline across Oklahoma and Kansas. A secondary surface low track shows up from southeastern Illinois northeastward to northwestern Ohio. This appears to be the favored location of surface lows on the second day when the upper-level system is approaching the Mississippi Valley.

The map for the 850 mb jet at the upper right in Figure 5 shows a somewhat similar distribution of surface lows except shifted southeastward. There are three maxima including one in the Great Plains, a second in the Ohio/Tennessee Valleys and a third from North Carolina into Virginia. The evenly spaced corridors from west to east may be associated with the daily progression of upper-level systems as they move eastward from the Great Plains into the eastern U.S. Based on this map, violent tornado outbreaks are favored on day one in the Great Plains, day two in the Ohio/Tennessee Valleys and day three from the Carolinas into Virginia as upper-level systems travel eastward across the United States.

The climatology for the 850 mb jet is also split in the Great Plains with a maximum in eastern Oklahoma and another maximum in far northeast Kansas. A relative minimum is located in southeast Kansas. The eastern Oklahoma maximum is mostly associated with dryline Southern Plains cases in the early to mid-spring. The maximum in far northeast Kansas is mostly associated with late spring and early summer systems as they come out of the central High Plains and move northeastward toward the upper Mississippi Valley. The climatological maximum for the 850 mb jet in eastern Oklahoma may be responsible for the high incidence of violent tornadoes in central Oklahoma throughout the years. Many studies with varying foci have suggested that Oklahoma is a favored location for low-level jet development.

One such study, Cook et al. (2008), found that the low-level jet maximum in the Southern Plains (Oklahoma) is related to the position of the Rocky Mountains and western edge of the Gulf of Mexico. As upper-level systems come out of the Rockies and into the High Plains, low-level moisture return is favored across east Texas and east-central Oklahoma. A strong north-to-south moisture gradient is likely to be aligned with the western edge of the Gulf of Mexico creating a Southern Plains dryline. Dryline development is further enhanced by the rapid increase in elevation from east to west across the Southern Plains.

The map for 700 mb at the lower left in Figure 5 shows a maximum in eastern Oklahoma and another in western Tennessee. The eastern Oklahoma maximum is the strongest signal on all four maps. It is co-located with the 850 mb jet maximum in eastern Oklahoma. This suggests that the Southern Plains jet is deep and more often associated with strong upper-level systems during the early to mid-spring. Further north into far northeast Kansas, the 850 mb jet maximum is not co-located with a maximum for the 700 mb jet. This suggests that the Central Plains low-level jet is not as deep and more likely associated with late spring and early summer cases in which relatively weaker upper-level systems are moving out of the central Rockies in the northern stream. The maximum for the 700 mb jet in western Tennessee is located just to the south of the 850 mb jet maximum suggesting a deeper low-level jet that is more likely associated with early to mid-spring cases on the second day after systems move out of the Rockies and eastward across the central U.S.

The map for 500 mb jet at the lower right in Figure 5 is similar to the 700 mb jet distribution except the highest incidence of the 500 mb jet is located just to the northwest of that at 700 mb. Also, a maximum for the 500 mb jet is evident in the Northern Plains. This suggests that the mid-level jet is an important player for Northern Plains violent tornadoes which are more likely to take place in the summer when the low-level flow is considerably weaker than in the spring.

Considering all four maps, a clear west to east progression appears to be present with strong signals for day one and day two as systems move away from the Rockies and through the central U.S.

## 4. EXAMPLES

A couple tornado outbreak cases are shown in this section that are representative of the position of atmospheric features for the violent tornado climatology. The first example on the following page in Figure 6 at the left occurred on May 3, 1999, in which central Oklahoma experienced a major tornado outbreak including 3 F4s and 1 F5. On this day, the surface low was located in western Nebraska, west of the climatological track. The 850 mb jet and 700 mb jet more closely aligned with violent tornado climatology while the 500 mb jet was slightly to the north of the climatological maximum. While many things about the May 3, 1999 outbreak were atypical, the jet structure was similar to many Southern Plains tornado outbreaks. Of note, the majority of the violent tornadoes on May 3, 1999 occurred to the left of the low-level jet and in the right entrance region of the mid-level jet.

The second case on April 3 and 4, 1974, is shown in Figure 7. This event was also very closely aligned with violent tornado climatology. The surface low was located near the maximum in far northern Illinois evident in Figure 5. While the 850 mb jet was just to the east of the climatological maximum, both the 700 mb jet and 500 mb jet were located nearly on top of the highest incidence climatologically. Of note, the tornado outbreak occurred along a corridor aligned with the axis of the low-level jet and was located from the left exit region of the mid-level jet southward to the eastern side of the mid-level jet.

May 3, 1999 - Central Oklahoma

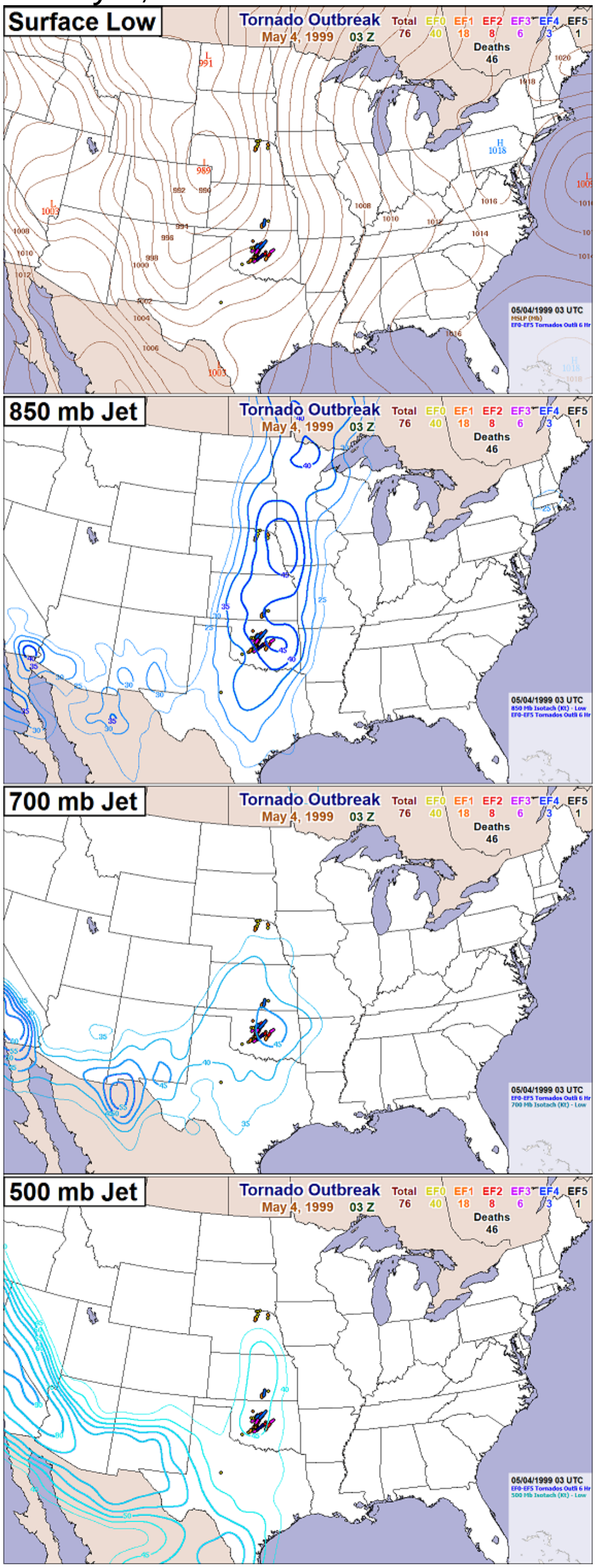



Figure 6. The position of the surface low, 850 mb jet, 700 mb jet and 500 mb jet are shown for the tornado outbreak that occurred on May 3, 1999. The event was close to climatology especially at the 850 mb and 700 mb levels in Figure 5. The tornado outbreak occurred just to the west of both the 850 mb and 700 mb jets in the right entrance region of the 500 mb jet.

April 3, 1974 - OH and TN Valleys

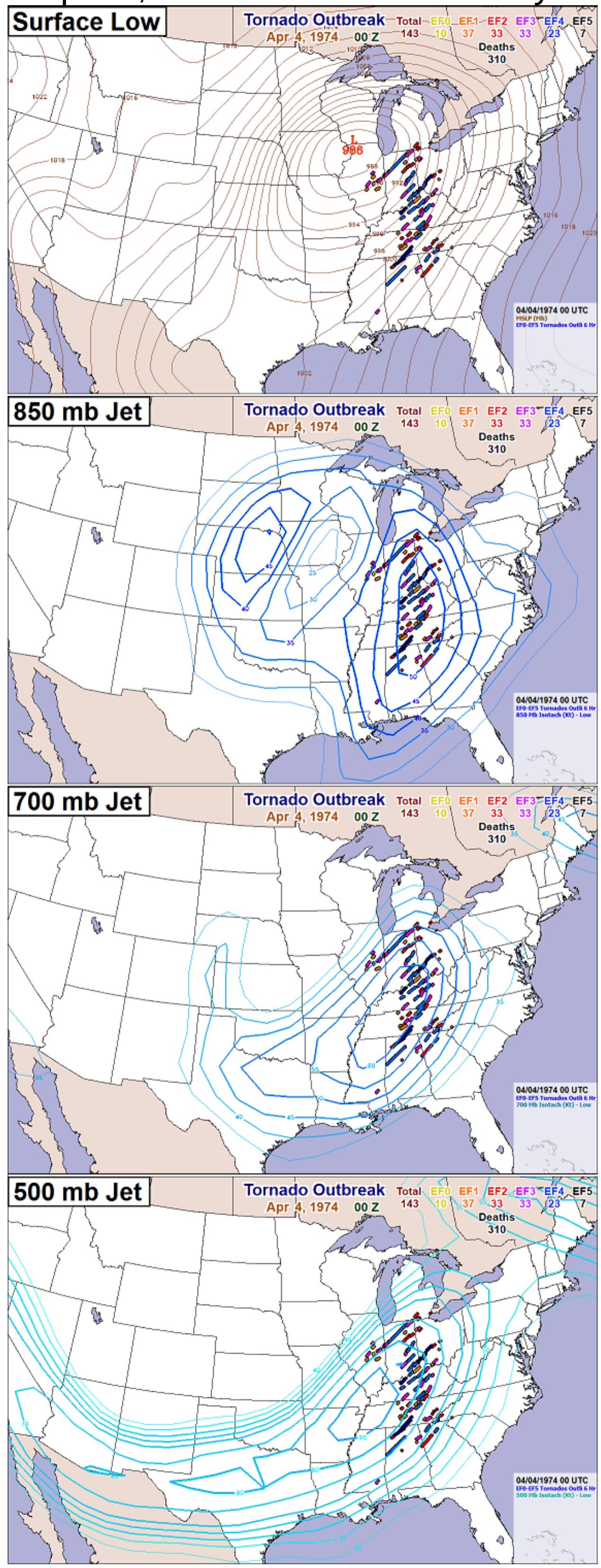



Figure 7. The position of the surface low, 850 mb jet, 700 mb jet and 500 mb jet are shown for the major tornado outbreak that occurred on April 3 and 4, 1974. The event was close to climatology for historical tornado outbreaks. The surface low, 850 mb jet, 700 mb jet and 500 mb jet occurred very close to climatological maxima located in the Mississippi Valley evident in Figure 5.

## 5. CONCLUSION

In this study, a large collection of tornado cases including 404 violent tornadoes were analyzed to find the position of the surface low, 850 mb jet, 700 mb jet and 500 mb jet. After the position of each feature was determined for each of the 182 events when the violent tornadoes occurred, a contoured plot was made showing the resulting distributions.

Surface lows most commonly occurred along a corridor from western Kansas northeastward into western Iowa and then eastward into far northern Illinois. A second surface low track was located from southern Illinois northeastward into northwest Ohio.

The 850 mb jet was most common in eastern Oklahoma, far northeast Kansas, western Kentucky and northeast North Carolina. The maxima for the 850 mb jet are similar to the surface low maxima in that multiple corridors are spaced from west to east suggesting an eastward progression of upper-level systems as they move across the central and eastern U.S. The minimum that is located between the Great Plains and Ohio/Tennessee Valleys along with a minimum in the southern Appalachian Mountains appear to be related to the diurnal cycle in thunderstorm activity. Specifically, violent tornadoes are less favorable during the late night and morning hours, which appears to contribute to a minimum in the distribution over the Ozarks and Appalachian Mountains.

A minimum in the 850 mb jet occurrence also occurs in eastern Kansas between maxima in eastern Oklahoma and far northeast Kansas. The maximum in eastern Oklahoma appears to be related to the Southern Plains dryline for early to mid-spring cases whereas the far northeast Kansas maximum appears to be related to late spring and early summer cases. This climatological split for the Great Plains low-level jet confirmed the hypothesis of the authors. Further north, a maximum for the 850 mb jet was not evident in the Northern Plains. This is because the 850 mb jet distribution was more spread out. The favored 850 mb jet location for Northern Plains violent tornadoes was in eastern Nebraska, Iowa or southern Minnesota.

For the 700 mb jet, maxima show up in eastern Oklahoma and western Kentucky. The eastern Oklahoma maximum for the 700 mb jet is co-located with the 850 mb jet maximum suggesting that the low-level jet is deep for Southern Plains cases on average, which would be associated with strong systems in the early to mid-spring. The weaker signal for the 700 mb jet in the Central Plains suggests that the low-level jet is shallower there. This could be associated with relatively weaker systems moving from the Central Plains northeastward toward the Upper Mississippi Valley during the late spring and early summer.

For the 500 mb jet, maxima show up in northern Oklahoma, far southeast Missouri and northern South Dakota. The 500 mb jet maxima in northern Oklahoma and far southeast Missouri are located to the west of the 850 mb jet maxima in each region by 150 to 175 statute miles suggesting the presence of a strong upper-level system. A maximum for the 500 mb jet is also located in the Northern Plains. Among the four maps, that signal on the 500 mb jet map is the strongest for the Dakotas. This suggests that the mid-level jet is important to violent tornadoes in the Northern Plains during summer when low-level flow is weaker across much of the Great Plains.

Although the meteorological record for violent tornado events is relatively short, reliable reanalysis data has recently become available for events from 1950 to present. By using reanalysis data to make climatological maps of the surface low, 850 mb jet, 700 mb jet and 500 mb jet, meteorologists can better understand typical patterns that are favorable for violent tornadoes.

## 6. REFERENCES

Barnes, S. L., and C. W. Newton, 1983: Thunderstorms in the synoptic setting. Thunderstorm Morphology and Dynamics, E. Kessler, Ed., University of Oklahoma, 75–112.

Concannon P. R., H. E. Brooks, C. A. Doswell III, 2000: Climatological risk of strong to violent tornadoes in the United States, Preprints, 2nd Conf. Environ. Appl., Long Beach CA.

Cook, K. H., E. K. Vizy, Z. S. Launer, C. M. Patricola, 2008: Springtime intensification of the Great Plains low-level jet and Midwest precipitation in GCM simulations of the twenty-first century, Journal of Climate, 21, 6321-6340.

Johns, R. H., 1993: Meteorological conditions associated with bow echo development in convective storms, Wea. Forecasting, 8, 294-299