Synoptic Environments Associated with Significant Tornadoes in the Contiguous United States

JAYSON A. PRENTICE

Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA

Mentor: JEREMY S. GRAMS

NOAA/NWS Storm Prediction Center, Norman, OK

ABSTRACT

A database of 274 tornadoes that were given ratings of (E)F2 or higher from 2002 through 2008 are examined by the use of both subjective and objective analysis. The collected environmental data consisted of the subjective classification of the synoptic regime at 500 hPa and surface, and objective analysis from RUC gridded analysis files. The synoptic environment of these significant tornadoes is compared to the pioneering work of Fawbush and Miller in hopes of updating the original classifications and methodologies that were presented in the 1950's and 1970's. This data may also be used to compile an up-to-date composite of the synoptic environments that are associated with significant tornadoes across the contiguous United States.

1. Introduction

Forecasting significant tornado events (defined as tornadoes producing damage rated at least F2 or EF2) are often challenging for operational meteorologists the day of the event, let alone preceding days. Numerical models have become much better in the past 10-20 years in regards to severe weather parameters and their availability to the operational meteorologist (Johns and Doswell 1992; Thompson et al. 2003). Parameters such as helicity, shear, convective available potential energy (CAPE), convective inhibition (CIN), and many others have all become daily forecasting tools thanks to proximity soundings (Rasmussen and Blanchard 1998; Thompson and Mead 2006) and an increase in computational power that allows rapidly updating forecast models at resolutions that were previously unmatched (Thompson et al. 2003). Despite these increases in accuracy of both quantitative and qualitative data with numerical models, significant tornado events still are by no means easy to forecast.

With so many severe weather parameters available to forecasters, many turn to a base set of parameters that can be used to verify the potential existence of a severe weather. However, even these parameters are not always useful for determining the threat of significant tornadoes. A study by Thompson and Mead (2006) indicated that of their five basic parameters used, just over half, 56 percent, of significant tornadoes had all five of those parameters at their suggested values present. The aforementioned study used values for their severe weather parameters as taken by hourly mesoanalysis fields, indicating that this forecast method can be used during the short term, within hours of the event. Many of the current forecasting tools for the operational forecaster rely on information that is provided in near real-time as Rapid Update Cycle (RUC) proximity soundings.

These proximity soundings not only provide standard pressure level plots, but severe weather parameters as well. While radiosonde soundings are only available at 00UTC and 12UTC, and only at limited locations throughout the contiguous United States (CONUS), these proximity soundings even at 40-km were found to be quite adequate in their computation of not only kinematic and thermodynamic profiles, but in their severe weather parameter calculations as well (Thompson et. al 2003).

To compliment these values derived from numerical models, many meteorologists may wish to use standard pressure levels to obtain information on the synoptic environment. This more conceptual approach to the synoptic scale and its' relationship to severe weather events has often been related by general "rules of thumb". The pioneering work by Fawbush and Miller (1951) began the use of actual synoptic environment distribution and its' relationship to tornadic storm development.

Fawbush and Miller (1951) indicated basic synoptic conditions that seem to warrant a risk of tornadoes over the area in which the conditions were met. This was the first use of an actual synoptic distribution to find common parameters that would aid in the forecasting of tornadoes. This led to the initial understanding that synoptic conditions must include 1) moist near-surface moisture being overcome by dry air, 2) a strong moisture axis, 3) an upper-level jet max that 4) transects the moisture axis below, 5) conditional instability, and 6) appreciable lifting. In addition to the synoptic air mass as described in 1951, Fawbush and Miller (1954b) noted that other specific air masses are also susceptible to tornado production in areas outside of the Great Plains, or Type I air mass. The Type II air mass, which was found to occur near the Gulf Coast, featured a warm and moist vertical air structure that led to conditional instability. Another air mass difference was wind speeds; Type II wind speeds were stronger in the low-levels, often not featuring an upper-level jet. The Type III air mass was associated with Pacific Coast systems that had a cold and moist vertical structure that led to conditional instability. Strong wind fields were also present in this type, and as in the case with all three types, the winds veer with height.

A total of five synoptic patterns would be associated with the eventual four tornado type air masses (Miller 1972, hereafter referred to as M72). Each pattern is distinguished by magnitude of surface low pressure systems, and whether height contours at 500 hPa were open or closed.

Synoptic pattern A would be classified to occur within the type I air mass, and occur within the zone of convergence between moist and dry air. Thunderstorms within this pattern would typically be isolated clusters, and were rapidly developing. Synoptic pattern B is associated with a strong low pressure center, and both warm and cold fronts. Thunderstorms with this pattern would typically form along or just ahead of the cold front, or highest area of convergence, likely leading to eventual squall line development. Patterns A and B are considered very similar, and would often transform from one to the other. The difference between the two patterns was the strong low pressure center that would occur with pattern B. Synoptic pattern C features a weak low pressure system, often corresponding with a weak warm, or stationary front. Pattern D is recognized by the presence of a rapidly deepening low pressure system at the surface, with a cut-off cold core low at 500mb. Pattern E is often related to pattern C, with both being patterns of the cold season, however, pattern E is distinguished by the presence of a strong surface low.

One of the first listings of key parameters needed for tornadoes was completed by M72 with the use of over 300 tornado cases. M72 arrived at a base set of parameters that he believed had importance to the forecasting of tornadoes. These key parameters among others are often still used today in the forecasting of tornadoes and severe weather in general. A brief overview of the parameters that were included in M72 and are pertainable to this study are presented in Table 1.

Both proximity soundings and synoptic environments have shown significance for the forecasting of significant tornadoes. Given the lack of recent research completed, a new distribution of significant tornado events, and their synoptic environment as determined by both surface analysis and 500mb analysis was created. The synoptic environment, combined with information from RUC proximity soundings could lead to an up-to-date documentation on the synoptic environments and their relationship to mesoanalysis or proximity sounding fields. An eventual goal may be for an increased recognition of significant tornado days based upon synoptic environments forecast by numerical models.

2. Data and Methodology

A database of tornadoes that were rated (E)F2 and higher over the contiguous United States from 2002 through 2008 was compiled. It was then narrowed by the exclusion of tornado's that occurred within six hours of each other and that were a part of the same region of convection, with the highest rated tornado included within the database, leading to a total of 274 tornadoes rated (E)F2 or higher. Each tornado was given a starting time of the nearest UTC hour, and a latitude/longitude as determined by the start of the tornadoes path using the National Climactic Data Center's (NCDC) StormData archives. The tornadoes were separated into geographic regions (Fig. 1) that were best defined by either geographic features (Rocky or Appalachian Mountains) or by typical low-level wind flow (Southeast vs. Plains). Additional separation of the geographic regions by seasons, defined as winter (Dec. - Feb.), spring (Mar. - May), summer (Jun. - Aug.), and fall (Sep. - Nov.), allowed sets of cases to be better suited for comparison with previous studies (Fig. 2). With the tornadoes occurring under different synoptic environments dependent on the season and geographic region, it was best to use these sub-selections of cases for which there was at least 25 cases. These sub-selections included the Northern Plains (summer), Southern Plains (spring), Midwest (spring), and Southeast (fall, winter, and spring).

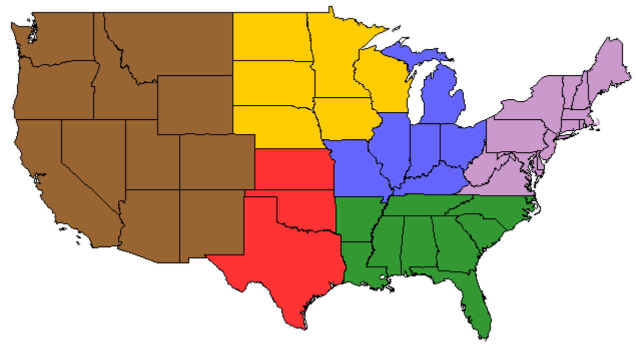

Figure 1. Geographic regions by color-filled groupings include West (brown), Northern Plains (yellow), Southern Plains (red), Midwest (blue), Southeast (green), and Northeast (purple.)

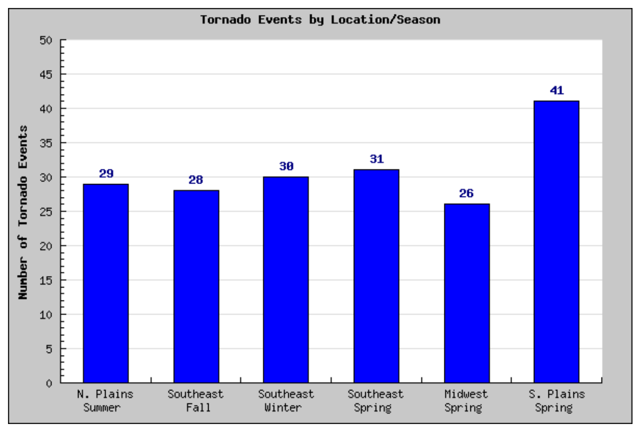

Figure 2. Distribution of tornadoes within database by both geography and season.

With specific latitude, longitude, and nearest hour of tornado start time determined, mandatory pressure level data was collected using the NCEP operational RUC model. For tornadoes occurring previous to 2005, the 40-km RUC model gridded analysis was available.

For tornadoes occurring during 2005 or thereafter, the 20-km RUC model gridded analysis used. At this point, any tornado that did not have this analysis archived was also eliminated from the database. The mandatory pressure level data that was collected from each RUC model gridded analysis can be found in Table 2. These RUC gridded analysis files were obtained not only for the tornado time, but also for 12 hours previous to the tornado.

Thermodynamic data was collected at several mandatory levels to allow insight on the thermodynamic profile of the environment, and specifically what changes were occurring at each level. Wind data was collected at the mandatory pressure levels of 300 hPa, 500 hPa, and 850 hPa due to their correspondence with the upper-, mid-, and low- level jets. Both pressure and height falls, have long been associated with the strengthening or weakening of a synoptic storm system, thus data for both surface pressure and 500 hPa heights were also collected.

Beyond the data provided by RUC model gridded analysis, subjective analysis was completed on both surface and 500 hPa charts as provided by either the NCDC Surface Data Archive (http://cdo.ncdc.noaa.gov/qclcd/), or the UCAR Image Archive (http://www.mmm.ucar.edu/imagearchive). The surface charts were analyzed both at 12 hour previous to the tornado, and at the time of the tornado to determine the magnitude of the nearest synoptic surface cyclone, and its' minimum mean sea level pressure. For instances in which the nearest hourly surface or 500 hPa data was unavailable, information was extracted bi-linearly to the time and location of the tornado.

Four separate categories were determined for surface cyclones: trough, weak, moderate, or strong. Trough indicated a cyclone that was located within an axis of relatively low atmospheric pressure, but was not associated with a closed pressure contour. All other categories were associated with a closed circulation around the cyclone, and the magnitude determined by the maximum pressure gradient within 1000 km was used. A maximum pressure gradient of less than 15 hectopascals (hPa) indicated a weak surface cyclone, while a pressure gradient greater than 30 hPa was classified as a strong surface cyclone. Those with a maximum pressure gradient of 15 to 30 hPa were therefore classified as moderate.

The mid-level (500 hPa) charts were subjectively classified to determine the synoptic regime that was present. The synoptic regime was divided into six categories by using the maximum height gradient within 1000 km at the same latitude. Instances where the height gradient was less than 50 m were classified as a zonal synoptic regime. A moderate amplitude synoptic regime was classified by a height gradient of 50 m to 200 m, and a strong amplitude synoptic regime was classified by the occurrence of a height gradient greater than 200 m. When a closed low was present at 500 hPa, they were also classified as being weak, moderate, or strong. A weak closed synoptic low featured a maximum height gradient less than 50 m, a moderate closed had a height gradient from 50 m to 200 m, and a strong closed had a height gradient greater than 200 m.

Lastly, a subjective analysis on the embedded synoptic wave was completed using the UCAR Image Archive. The operational NAM 500 hPa vorticity was used for this analysis. The embedded wave was given three

Table 1. Key parameters as found in M72 that are used as comparison with the reviewed cases

Parameter	Upper-level	Mid-level	Low-level	Surface
Dew Point			X	X
Geopotential Height Change		X		
Sea Level Pressure (& Change)				X
Wind Speed	X	X	X	

Table 2. List of mandatory pressure level data collected using RUC proximity soundings

Parameter	300 hPa	500 hPa	700 hPa	850 hPa	Surface
Dew Point				X	X
Geopotential Height		X			
Sea Level Pressure					X
Temperature	X	X	X	X	X
Wind Direction	X	X		X	
Wind Speed	X	X		X	

categories dependent on the strength of the upstream vorticity maximum. Weak was classified by a vorticity maxima of less than 20 x 10^{-5} s^{-1}, while moderate contains a vorticity maxima from 20 x 10^{-5} s^{-1} to 30 x 10^{-5} s^{-1}. A strong embedded wave was classified when a vorticity maxima greater than 30 x 10^{-5} s^{-1} occurred.

The subjective analysis was completed as a comparison to what M72 had found by using similar characteristics. The patterns that he had used were mentioned previously in the introduction, with each being classified by whether or not they had a strong surface low, and whether or not they had closed height contours at 500 hPa. Two sets of patterns, A and C, and B and E, have similar characteristics when it comes to the surface low strengths and 500 hPa height countours. Thus, it was important to clarify how you can distinguish the patterns. Both patterns A and B were described to have a southwesterly jet aloft (500 hPa), while patterns C and E were to have more westerly flow aloft. This characteristic difference at 500 hPa was used to separate the patterns, whereas any case in which the 500 hPa wind direction was greater than 245 degrees was said to have a westerly jet aloft. Cases where the wind direction at 500 hPa was equal to or less than 245 degrees featured a southwesterly jet aloft and were classified as such.

3. Results

a) Synoptic Environment

i) TEMPERATURES

The average temperatures (Fig. 3) at the mandatory pressure levels typically varied 10 degrees Celsius from the 10^{th} to 90^{th} percentile. Although general values are of importance, for example, using 700 hPa temperature in determining the potential inhibition present, the change in temperature over the short-term may often lead to ideas on how the synoptic conditions are changing. A look at the thermodynamic changes at the tornado location and time (Fig. 4) shows where the largest variability occurs. Both 300 hPa and 500 hPa temperatures were not found to vary more than ±2 degrees Celsius, while 700 hPa temperatures did have an additional degree of variability. The average 700 hPa temperature change in the 12 hours was just below zero; indicative of slight cooling at this level often existed.

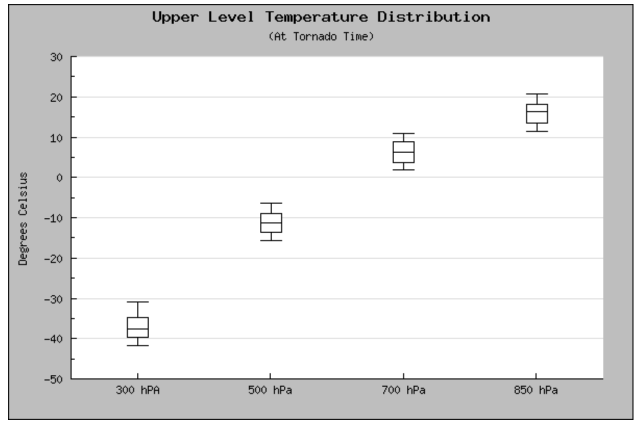

Figure 3. Upper level temperatures at tornado time for the mandatory pressure levels.

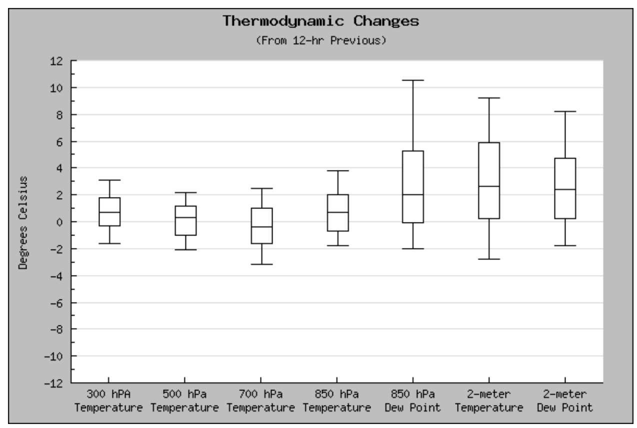

Figure 4. Thermodynamic changes from 12 hours previous to tornado.

The two lowest levels, 850 hPa and 2-meters, were found to have the most dramatic changes in both temperature and dew point. At both levels these changes were positive, or both warming and moistening of these two layers were occurring prior to the tornado event. The additional heating and moistening in these lowest levels can easily contribute to an increase in available energy for a surface-based parcel of air. A closer look at both 850 hPa (Fig. 5a) and 2-meter dew point (Fig. 5b) values indicate where and when moisture is often greatest. At 850 hPa it is undoubtedly the Northern Plains and its' summer events that see the highest moisture with a 16 degrees Celsius average. Both spring and fall in the Southeast, as well as spring in the Southern Plains feature similar dew point values while it is the Midwest spring and Southeast winter that are found to have the lowest values. With cooler temperatures during the winter throughout the atmosphere the lower dew points can be expected, and thus are not necessarily a negative factor for significant tornado events. Similar results are shown at 2-meters, with the Northern Plains summer followed closely by the Southeast fall as having the largest values. All spring and winter season cases are shown to have lower values, although only the Southeast winter shows consistency in having lower dew point temperatures.

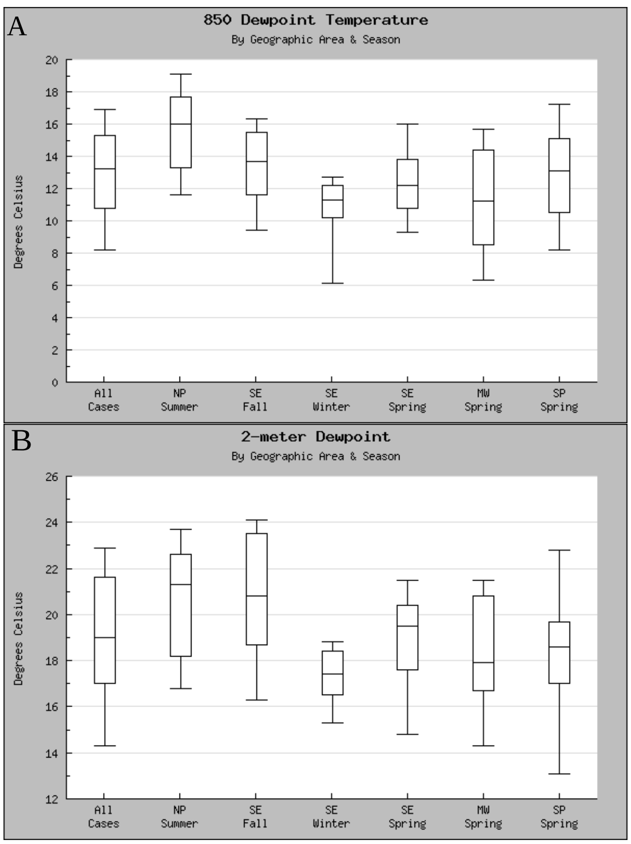

Figure 5. Dew point temperature at a) 850 hPa and at b) 2-meters.

ii) WINDS

Upper-level winds (300 hPa) were found to average 32 m s^{-1} for all cases with a 14 m s^{-1} spread between the average and both the 10th and 90th percentile. The change in the 300 hPa wind speeds over the previous 12 hours did indicate slight strengthening of the winds with an average 4 m s^{-1} increase. Directionally, the upper-level winds were typically west-southwest, with only a few degrees of change in the previous 12 hours (Fig. 6a). Although the average change was backing with time, both strong veering and backing occurred with cases. The seasonal distribution of the upper-level winds conformed well with climatology, as the wind speeds were greatest during the winter months (40 m s^{-1} average) and weakest during the summer months (24 m s^{-1} average). This was also shown when cases were distributed geographically and seasonally (Fig. 6b), with the lowest values occurring in the Northern Plains summer cases and highest values during the Southeast winter cases. For the spring season, the Southern Plains and Midwest were fairly identical while the Southeast had a 13 m s^{-1} higher average. The Southeast also appears to be an outlier in the range of wind speeds present during events with the fall season incurring a much higher range of values.

Mid-level (500 hPa) wind speeds were typically 5 to 10 m s^{-1} slower than the upper-level winds, with the average speed for all cases nearly 27 m s^{-1}. The direction of 500 hPa winds at the time of tornado was typically west-southwest (Fig. 7a), with changes being similar to that of the upper-levels. The changes in speeds were also similar with an average increase of 6 m s^{-1}. The geographical and seasonal distributions (Fig. 7b) indicate similar trends with the summer Northern Plains cases having the slower winds while the Southeast incurs the faster wind speeds. Continuing similar trends, the Southeast springtime events have a higher average than that of the Southern Plains and Midwest springtime events.

The low-levels (850 hPa) featured wind speeds averaging 19 m s^{-1}, with a range of nearly 9 m s^{-1} between the 10th and 90th percentiles. At the time of the tornado, 850 hPa winds were typically from the southwest (Fig. 8a), however, the range of direction was significantly higher than the other levels. Cases ranged from having winds from the west-northwest to nearly easterly. The changes in wind direction over the previous 12 hours were found to vary nearly 100 degrees at times in

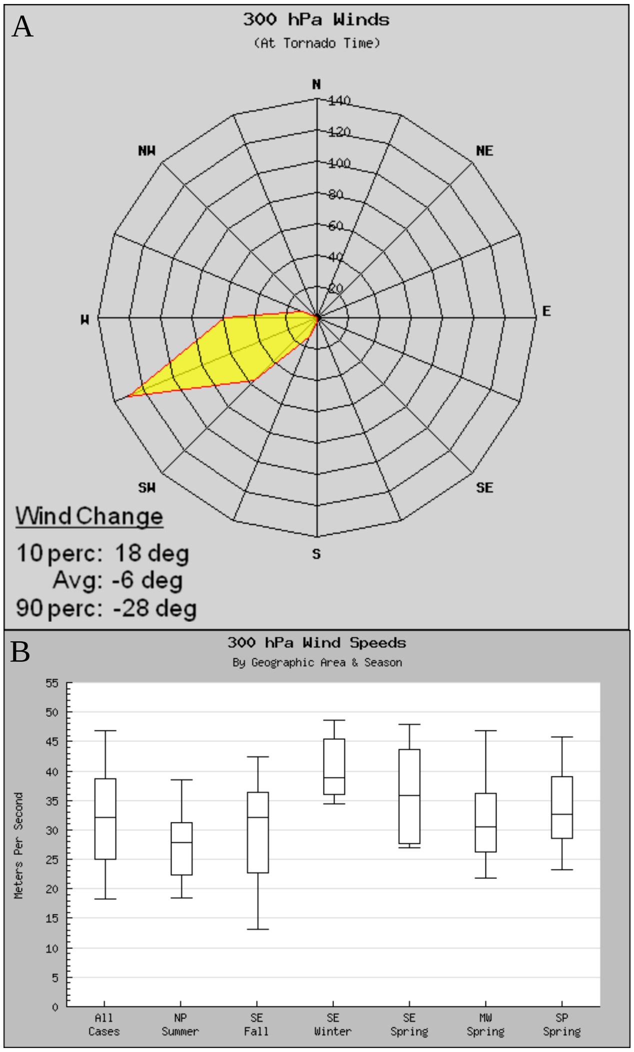

Figure 6. a) 300 hPa wind direction and change over 12 hours previous to tornado and b) 300 hPa wind speeds separated by geography and season.

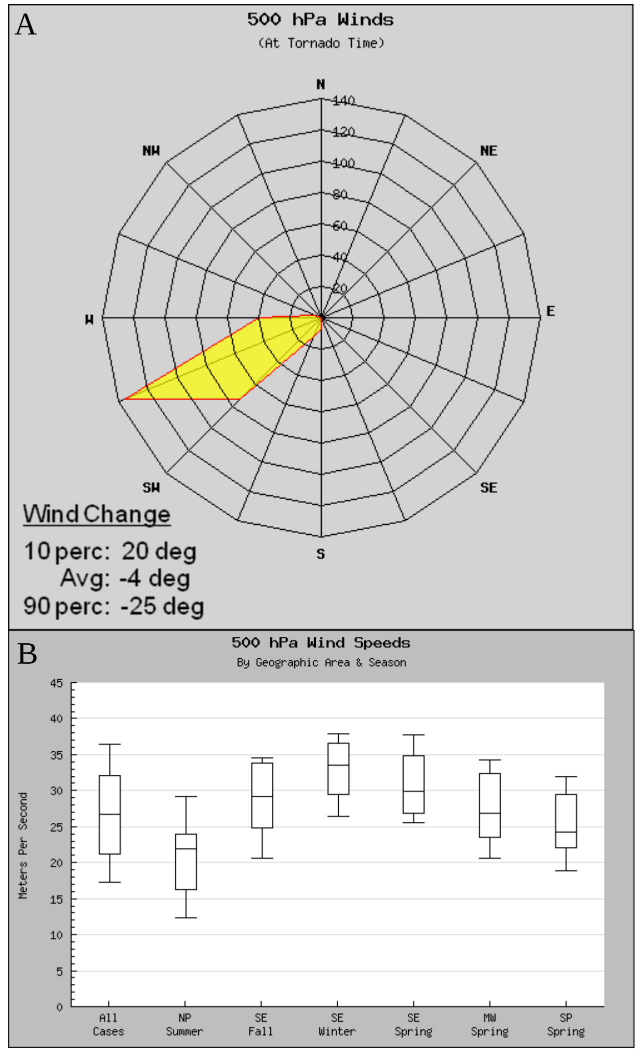

Figure 7. a) 500 hPa wind direction and change over 12 hours previous to tornado and b) 500 hPa wind speeds separated by geography and season.

direction (veering or backing). These significant changes in wind direction may be associated with frontal passages that occurred over the course of the previous 12 hours. Other frontal passages may also have yielded the larger range of values at the low-levels at the time of tornado due to the time of tornado being rounded to the nearest hour. An example of this error may come when the boundary associated with the storm already passed through the point where the tornado occurred between the tornado occurrence and the nearest hour time used to collect RUC analysis data. Geographically and seasonally (Fig. 8b), little difference from the other levels seems to occur. The strongest winds speeds are once again present in the Southeast during the winter, while the weakest speeds are during the Northern Plains summer events.

With wind shear typically used as a key factor in tornado development, it would appear as if the shear in the Northern Plains would be weaker than the other geographic areas due to their weaker wind speeds. However, the directional changes over the Northern Plains were found to be much larger than that of the other areas (Thompson et al. 2008) suggesting that both speed and direction play an important role in magnitude of shear.

iii) HEIGHTS AND PRESSURE

Mid-level heights (500 hPa), and more specifically, mid-level height falls have been used to determine the synoptic strength of a storm system for several decades. The average 500 hPa height for all cases was 5743 meters,

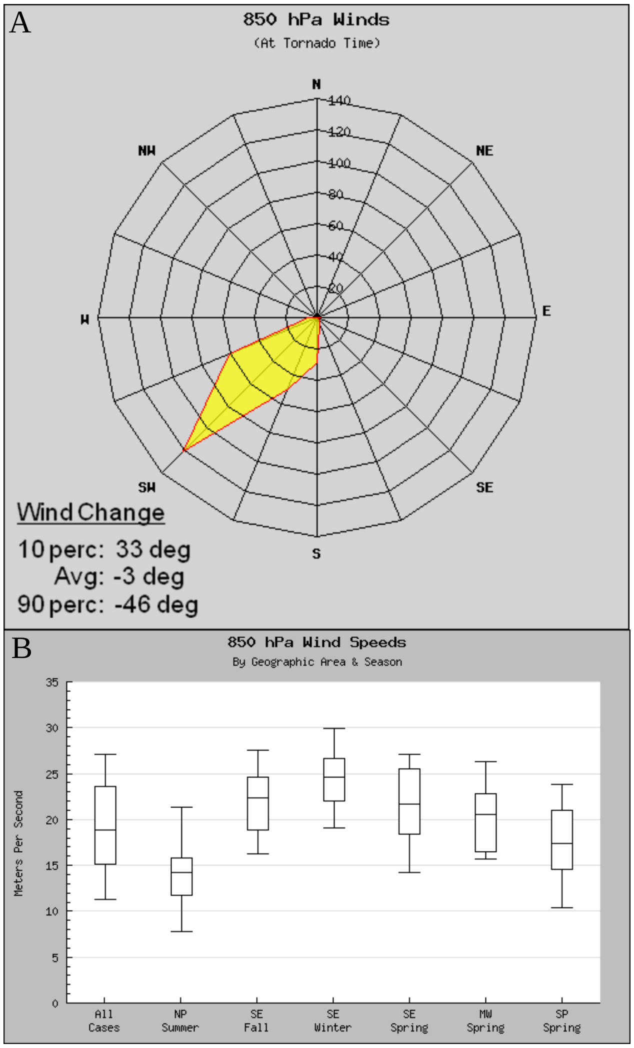

Figure 8. a) 850 hPa wind direction and change over 12 hours previous to tornado and b) 850 hPa wind speeds separated by geography and season.

with the highest heights occurring during the Plains summer cases when separated by geography and season (Fig. 9a). These results come as no surprise due to the warmer regime that is present during the summer months, thus as expected the Southeast winter cases held some of the lowest heights. However, the Midwest spring regimes featured some of the lowest heights as well, indicating that synoptic regimes during significant tornadoes in the Midwest may be some of the strongest.

As mentioned, it is often the height falls that are deemed the key factor in determining the synoptic system strength. Height falls for all cases averaged nearly a 30 meter decrease over the 12 hour period before the tornado occurrence. The greatest height falls typically occurred with the Southeast winter events (Fig. 9b), with both the spring events in the Midwest and Southeast also having average height falls that were greater than the overall average. The Northern Plains summer events had much smaller height falls, with a mean of around 10 meters, when compared to other regions. The lack of height falls indicate that the strength of the synoptic systems needed for significant tornadoes may also be dependent upon the thermodynamic profile. Occasions where the thermodynamics are not as strong, such as the Southeast winter, Southeast spring, and Midwest spring, the synoptic system may have to be significantly strong whereas when a thermodynamic field yields intense instability, such as the Northern Plains summer, the synoptic system may not have to be as strong to create conditions favorable for significant tornadoes.

Similar to the 500 hPa heights, surface pressure, and surface pressure falls, are both important to the strength of the synoptic system as a whole. Seasonal variations in pressures do exist, with higher pressures seen on average over the contiguous United States during the winter months due to the colder, denser air that is present. These seasonal variations do show when viewing the average surface pressures at the tornado locations (Fig. 10a), with higher pressures present during the winter over the Southeast. The Southeast fall and spring also feature higher pressure values when compared to the spring in both the Southern Plains and Midwest. Thus, using surface pressure falls may yield a better comparison to the strength of the synoptic cyclone by eliminating the effect of seasonal pressure variation. Surface pressure falls and their distribution (Fig. 10b) show similar results to that of the height falls, with the greatest falls occurring in the Southeast winter and the Midwest spring while the Northern Plains summer cases and the Southern Plains spring had the smallest pressure falls. With similar results coming from both 500 hPa height falls and the surface pressure falls, it can be hypothesized that a strengthening synoptic system will likely contain greater falls in both height at 500 hPa and in surface pressure.

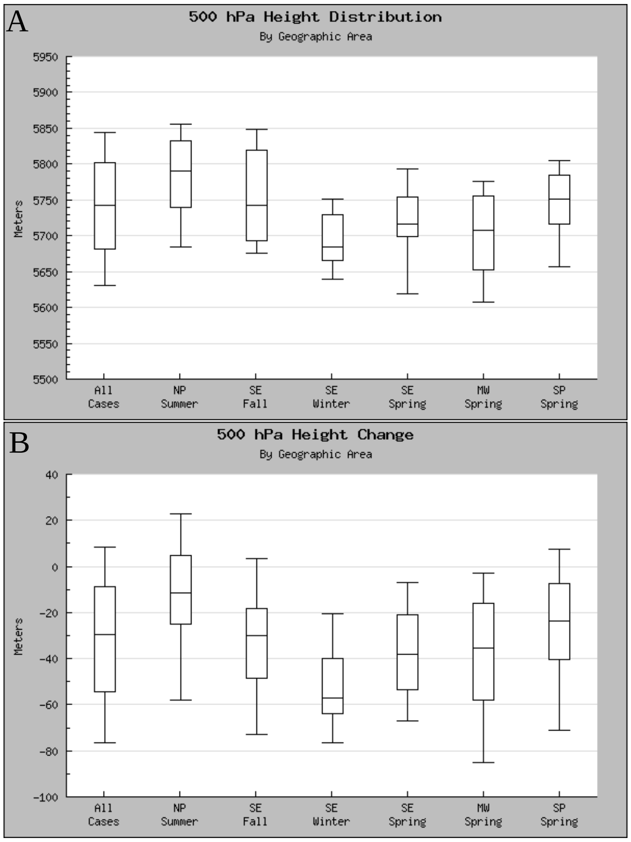

Figure 9. a) 500 hPa heights separated by geography and location and b) 500 hPa height change over 12 hours previous to tornado separated by geography and location.

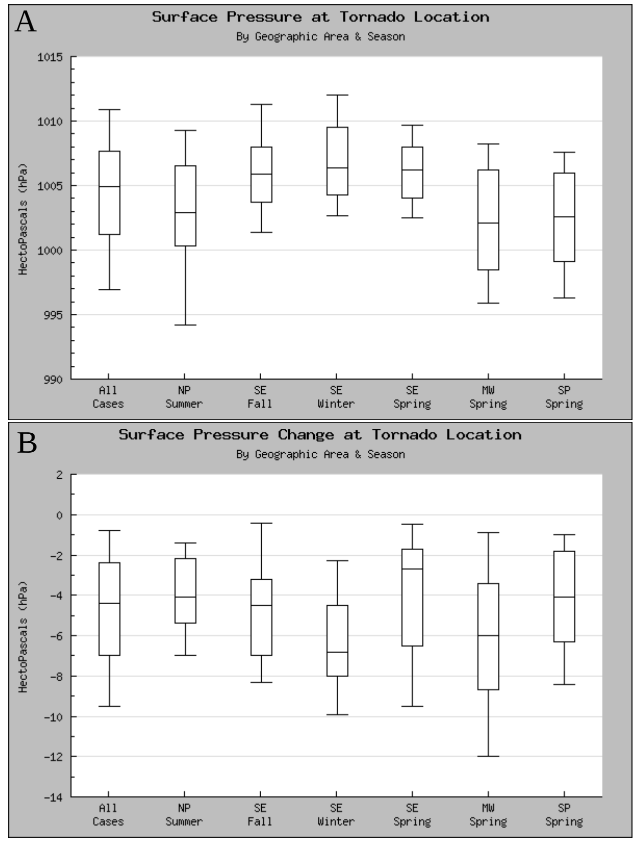

Figure 10. a) Surface pressure separated by geography and location and b) surface pressure change over 12 hours previous to tornado separated by geography and location.

iv) MILLER COMPARISON

The mandatory pressure level data that was collected using the RUC gridded analysis was compiled for comparison with a listing of key parameters that M72 deemed important for tornado formation. The parameters and their values (Table 1) as determined by M72 were given thresholds of weak, moderate, and strong, and can be directly compared to the values found and described in this section.

The upper-level jet from M72 had an expected range of 28 m s^{-1} at its' weakest, to upwards of 44 m s^{-1} for the strong cases. The comparison between those values and those completed here did not yield favorable results (Fig. 6b), with over 36% (100 of 274) having 300 hPa wind speeds less than 28 m s^{-1}. On the strong threshold, only 16% (43 of 274) had wind speeds at 300 hPa greater than 44 m s^{-1}. The unfavorable results may be explained by a difference in analysis. M72 used values for the upper-level winds at the axis of the jet stream, whereas the cases analyzed here were done so with RUC proximity soundings providing the upper-level wind speeds. Instances where the jet stream was not directly above or near the tornado location could have much lower values than those derived by M72.

Mid-level (500 hPa) wind speeds provided significantly better agreement than that of the upper levels. With the previous study indicating 18 m s^{-1} to 26 m s^{-1} as expected values, 88% (240 of 274) had wind speeds greater than the 18 m s^{-1} (Fig. 7b) described as weak by M72. Over half, (148 of 274) had wind speeds at 500 hPa greater than 26 m s^{-1}, representing a majority of those above the strong threshold.

The height change at 500 hPa was also considered a key parameter. M72 showed that a decrease in at least 30 meters indicated a weak synoptic system, while greater than 60 meters was the threshold for a strong synoptic system. Results (Fig. 9b) indicated that only 49% (135 of 274) had height decreases of 30 meters or greater at 500 hPa. Only 20% (55 of 274) had more than 60 meters in height decrease, with many of those cases occurring during the winter events.

The low-level jet (850 hPa) and its' wind speeds in M72 was given an expected range of winds from 10 m s^{-1} to 18 m s^{-1}. Much like the mid-level wind speed results, the low-level jet yielded good agreement (Fig. 8b). 253 of the 274 (92%) of the cases had wind speeds greater than 10 m s^{-1}, while 147 of 274 (54%) had wind speeds greater than 18 m s^{-1}.

An additional low-level feature that was listed as a key parameter was the availability of low-level moisture (850 hPa dew point). Low-level moisture was found to typically range well above that of the expected range of 8° to 12° C given in M72. 92% (251 of 274) of all cases realized a greater than 8° C dew point (Fig. 5a). Many of those below this threshold came from Southeast winter events which may not have been a keen interest in M72. The strong threshold was well surpassed, with 64% (175 of 274) having greater than a 12° C dew point.

Surface moisture (dew point) was also believed to be a key parameter in tornado occurrences, with a value of 13° C classified as a weak threshold to greater than 18° C for a strong threshold (M72). Nearly all (262 of 274) cases had at least 13° C dew point, with 61% (167 of 274) being above the strong threshold (Fig. 5b).

Both surface pressure (Fig. 10a), and 12 hour surface pressure falls (Fig. 10b) were also compared. Surface pressures of at most 1010 hPa were classified as a weak threshold for tornado occurrence, with less than 1005 hPa being used as a strong threshold (M72). 86% (236 of 274) of cases did have lower than 1010 hPa surface pressures, with 50% (138 of 274) having a 1005 hPa surface pressure or lower. Pressure falls were expected for the moderate threshold, indicating that a pressure increase may still be associated with tornadoes, although considered weak in M72. Pressure falls greater than 5 hPa were considered under the strong threshold, indicative of strong upward motion. Steady pressure (no change) or any pressure fall was found to occur in 93% (256 of 274) of the cases, while 45% (123 of 274) of the cases did incur pressure falls equal to or greater than 5 hPa.

b) Synoptic Patterns

i) 500 HPA

Synoptic patterns at 500 hPa were heavily skewed in favor of a moderate amplitude synoptic regime (Fig. 11) with 54% (148 of 274) of all cases. This moderate amplitude regime was found to occur frequently throughout all four seasons, although spring and summer did make up a majority with 39% (57 of 148) and 28% (41 of 148) of cases respectively. Geographically, the regime was not present in one region significantly more than another.

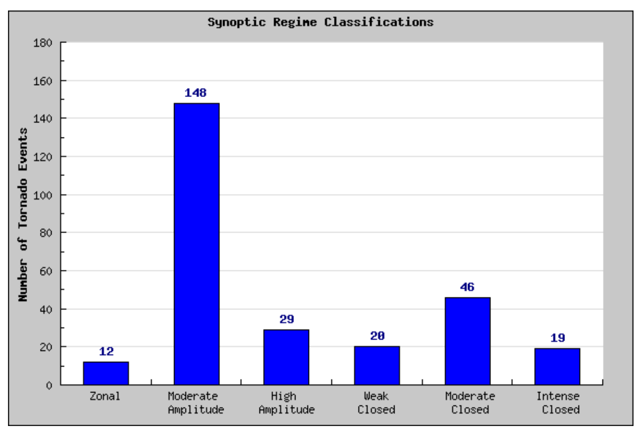

Figure 11. **S**ubjective analysis of synoptic regime classifications.

The second most common regime found to occur was a moderate closed low at 500 hPa with nearly 17% (46 of 274) of all cases. This regime does appear to have a variation dependent upon the season, with 63% (29 of 46) of the occurrences happening during the spring.

Geographically, this regime was most prominent in the Southeast with 46% (21 of 46) of the occurrences. The Southern Plains and Midwest featured 24% (11 of 46) and 20% (9 of 46) of this regime respectively.

A high amplitude trough represented an additional 11% (29 of 274) of the synoptic regimes, with the seasonal variation being in favor of winter and spring. Geographically, a high amplitude trough was most likely to occur in the Southeast and Midwest comprising of nearly 80% (23 of 29) of its' occurrences.

The zonal (12 of 274), weak closed (20 of 274), and the strong closed (19 of 274) regimes each represented 7% or less of the total cases. But, some seasonal and geographic characteristics should still be noted. The spring and summer represented 92% (11 of 12) of all zonal cases, indicating that weak synoptic regimes are likely to only occur when other parameters are favorable, for example, CAPE (Convective Available Potential Energy). Of the 20 weak closed regime cases, 9 (45%) occurred in the fall, 5 (25%) in the summer, and 6 (30%) in the spring. A strong closed regime at 500 hPa was more frequent in the spring (8 of 19 cases), but also occurred in all three other seasons. Geographically, a zonal regime is near equally likely to occur in the Midwest, Southeast, and Southern Plains regions; the weak closed is prominent in the Southeast with 50% (10 of 20) of all weak closed cases; and the strong closed also occurring more often in the Southeast with 42% (8 of 19). The latter may be related to landfalling tropical cyclones (TCs) affecting this region.

Of the 274 cases, 259 had a reputable 500 hPa chart that included vorticity that was used to measure the magnitude of the embedded wave. The results did not indicate any clear relationship existed between the strength of the embedded wave (Fig. 12). Geographically, the Southeast did feature differences with the number of weak waves being much lower compared to both moderate and strong. Also, the Southern Plains featured a larger number of weak waves when compared to the number of moderate and strong.

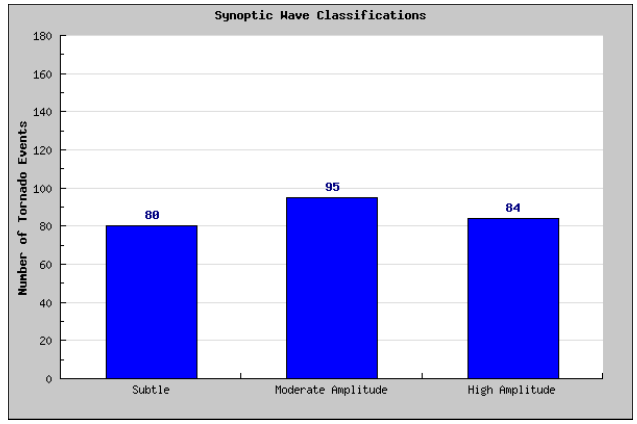

Figure 12. Subjective analysis of the embedded synoptic wave classifications.

ii) SURFACE

Surface cyclone intensity was subjectively classified at 12 hours previous to the tornado, and at the time of the tornado to compliment the surface pressure data compiled with RUC gridded analysis. A comparison from 12 hours previous to the time of the tornado (Fig. 13a) shows a noticeable difference in the number of weak classifications. This is represented by a large majority (83% or 220 of 274 cases) that either had no change in category classification, or strengthened either one or two categories. This leaves only 17% (54 of 274) of cases in which the low weakened by a category or more, some of which can be contributed to land falling TCs that produced significant tornadoes.

These results conform nicely to the change in minimum surface low pressure of the synoptic cyclone (Fig. 13b). While a large portion of the cases only changed by 5 hPa either way, those in which did have greater changes typically occurred with falling pressures. Once again those that had large increases in pressure over the 12 hour period may have been a result of land falling TCs.

iii) MILLER COMPARISON

All 274 cases were able to be identified as a synoptic pattern described by M72. The distribution of the patterns (Fig. 14) show that pattern D was found to occur the most in the cases reviewed. This pattern occurred 85 out of the 274 cases (31%), however, this pattern

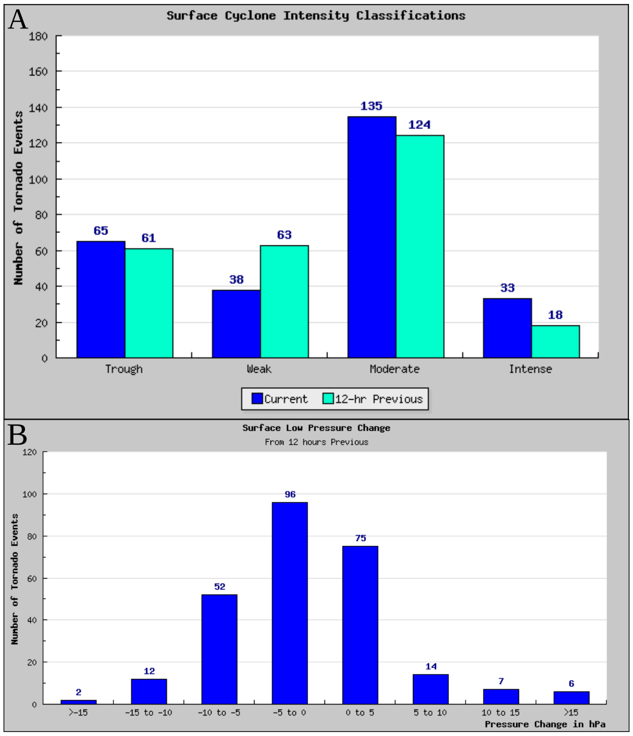

Figure 13. a) Subjective classification of surface cyclone intensity at time of tornado, and 12 hours previous. b) Surface low pressure change over the 12 hours previous to tornado.

includes any instance in which the 500 hPa heights were at closed contours. With the reviewed cases being ones that caused significant tornadoes, it would be expected that the synoptic regime is significant itself. The closed contoured heights at 500 hPa are a sign of such a strong synoptic system, which is especially important during the cool season tornadoes. Although pattern D was not expected by M72 to be one of the more prominent patterns for tornadoes, it certainly does not disagree with his expectations of this being a tornado producing pattern.

Pattern B includes cases in which a moderate or strong surface low was present, and was comprised of a southwesterly 500 hPa jet. This pattern accounted for nearly 28% (76 of 274) of the classified patterns. This regime was noted to be one of the more prominent ones by M72, with both a strong amplitude regime at 500 hPa and a strong surface low pressure system it should be expected that a combination such as this be responsible for a large number of tornadoes.

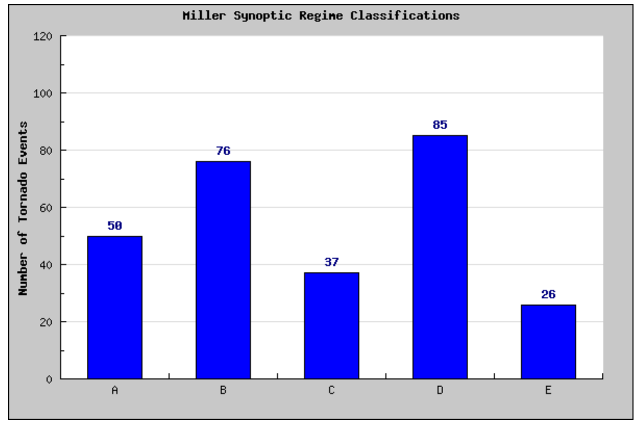

Figure 14. Subjective classification of synoptic regimes based upon the regimes of Miller (1972).

Patterns A and C were responsible for 18% (50 of 274) and 14% (37 of 274) of the cases respectively. Both of these patterns feature a weaker low pressure system, and weaker regime at 500 hPa. The two patterns were separated by the occurrence of either a southwesterly, or westerly jet, in the cases reviewed it does appear that a southwesterly jet is slightly more likely than the westerly jet at 500 hPa.

Pattern E was only accountable for 9% of the cases (26 of 274), the least of the five M72 patterns. This pattern is closely related to that of pattern B which accounted for a much larger portion of the cases. Pattern E is classified as such when there is a strong amplitude regime at 500 hPa with a typically moderate to strong surface low pressure system. The pattern is distinguished by a westerly jet at 500 hPa, rather than the southwesterly one that is featured in the B pattern. While it is expected that the strong synoptic regimes occur more often with the significant tornadoes, the distribution between the southwesterly and westerly jets once again shows that a southwesterly jet at 500 hPa occurs more often with significant tornadoes than a westerly jet.

4. Discussion and Conclusions

A total of 274 tornadoes that were rated (E)F2 or higher from 2002 through 2008 were compiled, with synoptic environment determined through both subjective and objective classifications. The goal was to observe how well the previous studies, completed at the latest in the 1970's, did in observing the synoptic environments that tornadoes occurred in.

Through the objective classifications, the use of RUC gridded analysis allowed direct comparision to that of M72 and his key parameters associated with tornado occurences. Nearly all of the key parameters were found to hold true in a majority of the cases that were reviewed. Wind speeds at both the mid-levels and low-levels were found to be consistent with that of M72 with expected values of at least 18 m s^{-1} and 10 m s^{-1} needed at 500 hPa and 850 hPa respectively. Upper-level wind speeds were found to be lower in values than what M72 found. However, it is important to recognize that the value at the tornado location may not be the maximum within the upper-level jet that is potentially upstream of the tornado's location.

The change in heights at 500 hPa from 12 hour previous to the tornado did yield similar results to that of M72 as well. The median height fall was 30 meters, equal to the expected value of the moderate threshold. The strong threshold was not exceeded by as many cases as expected, but once again the height falls may have been greater upstream and not necessarily at the tornado location.

Low-level moisture fields largely reproduced the expectations of M72 with dew points at 850 hPa exceeding 8° C, and surface dew points exceeding 13° C. Surface pressure and surface pressure falls over the 12 hours previous to the tornado were also very similar to the values found in M72.

Synoptic pattern classifications were also consistent to what M72 had found, with patterns featuring a southwesterly mid-level jet occurring more often that those which featured a westerly mid-level jet. The more prominent pattern for these significant tornado cases was also found to be the two synoptic patterns with either closed contours, or high amplitude contours of heights at 500 hPa.

With the key parameters and synoptic patterns being largely replicated by the results found in the cases reviewed here, it is suggested that only slight adjustments for significant tornadoes are needed. Additional clarification on parameters and their location with respect to the tornadoes may also be useful. These clarifications may include that the jet stream maxima may not be co-located with the tornado, and that height falls at both the tornado location, and upstream of the tornado, would be useful in determining the synoptic system strength.

A majority of the patterns mentioned in M72 still hold true to those that were found to exist in the reviewed cases. However, as with any broad coverage of parameters, there are still some instances in which the synoptic pattern may not fit into an exact pattern. Such examples may include when there is northwest flow at both the upper-levels and mid-levels. While such cases aren't prominent tornado producers, they still do occur and are not featured in any one of the M72 patterns explicitly. It may also be of use to separate pattern D as described by closed height contours at 500 hPa into at least two patterns to cover instances in which the closed contours represent a strong synoptic regime during the warmer months, rather than the cooler season synoptic cold core lows (Davies 2006).

5. Acknowledgements

Heather Moser from the University of Oklahoma for her help with Python scripting to use with the RUC gridded analysis files. Also to my mentor's colleague Rich Thompson (SPC) for his aid in the development of this thesis topic, and for additional research opportunities.

6. References

Davies, J. M., 2006: Tornadoes with cold core 500-mb lows. Wea. Forecasting, **21**, 1051-1062.

Fawbush, E. J., R. C. Miller, 1954b: The types of airmasses in which North American tornadoes form. Bull. Amer. Meteor. Soc., **35**, 154–165.

——, R. C. Miller, and L. G. Starrett, 1951: An empirical method of forecasting tornado development. Bull. Amer. Meteor. Soc., **32**, 1-9.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. Wea. Forecasting, **7**, 588-612.

Miller, R. C., 1972: Notes on analysis and severe-storm forecasting procedures of the Military Weather Warning Center. AWS Tech. Rep. 200 (rev.), Air Weather Service, 181 pp.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. Wea. Forecasting, **13**, 1148-1164.

Thompson, R. L., and C. M. Mead, 2006: Tornado failure modes in central and southern Great Plains severe thunderstorm episodes. *Preprints*, 23rd Conf. Severe Local Storms, St. Louis, MO, Amer. Meteor. Soc. (CD ROM).

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

——, J. S. Grams and J. A. Prentice, 2008: Synoptic environments and convective modes associated with significant tornadoes in the contiguous United States. *Preprints*, 24th Conf. Severe Local Storms, Savannah, GA, Amer. Meteor. Soc.