AN INVESTIGATION OF THE JUNE 1984 BARNEVELD, WI TORNADO

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I. Introduction

On the morning of 8 June 1984, a powerful tornado struck the small community of Barneveld, WI located in the southwest part of the state. The synoptic setup for this event was not unusual of typical severe weather events that occur during the summer in the Midwest. A westerly upper-level jet was in place with southerly to southwesterly flow at lower levels along with warm, moist air that was out ahead of a very strong cold front to provide an ideal setup for a severe weather outbreak across the Upper Midwest. Two separate Mesoscale Convective Systems (MCS) would eventually form over Iowa on the evening of 7 June. The first developed over southwest Iowa and traveled to the northeast across Iowa and eventually into northern parts of Wisconsin (Figure 1). This system produced several tornadoes over Iowa and Wisconsin, but it was a another MCS that developed in southeastern Iowa a few hours later that would be the focal point for severe weather over southern Wisconsin. This particular cluster of storms formed late in the afternoon on 7 June and continued to intensify and strengthen even after sunset. By 0530z on 8 June the thunderstorm complex had arrived in southwestern Wisconsin and the first tornado touched down a few minutes later. At 0541z, a tornado touched down 5 miles to the southwest of Barneveld and for the next hour traveled to the northeast causing massive amounts of damage in its path. The village of Barneveld was almost completely annihilated with 90% of the village being damaged or completely destroyed with 9 fatalities and nearly 200 people injured. The tornado was rated as an F5 on the Fujita Scale, one of only two tornadoes in the history of Wisconsin to achieve such a rating.

The intriguing aspect of this tornado outbreak is not the manner in which it was synoptically setup; rather it was the behavior of the mesocyclone once it entered southern Wisconsin. The mesocyclone did not display the classic hook echo signature; instead it displayed spiral arms that rotated cyclonically around the meso-low center of the mesocyclone as it moved straight to the northeast. These spiral arms were responsible for the different tornadoes that occurred over southern Wisconsin and each spiral arm seemed to have caused a different tornado. The direct cause as to why the mesocyclone behaved in the manner that it did was not clear due to lack of credible equipment used at the time. Radar data was limited to the WSR-57 out of Neenah, WI and the WSR-74, which did have Doppler capabilities, out of Marseilles, IL. The main theory at the time regarding this behavior centered on the vorticity of both the meso-low and the spiral arm bands. Research done at the time concluded that the mesocyclone center had a large maximum in vorticity, while the spiral arm bands had smaller vorticity values yet it was the spiral arm bands that were responsible for the tornadoes.

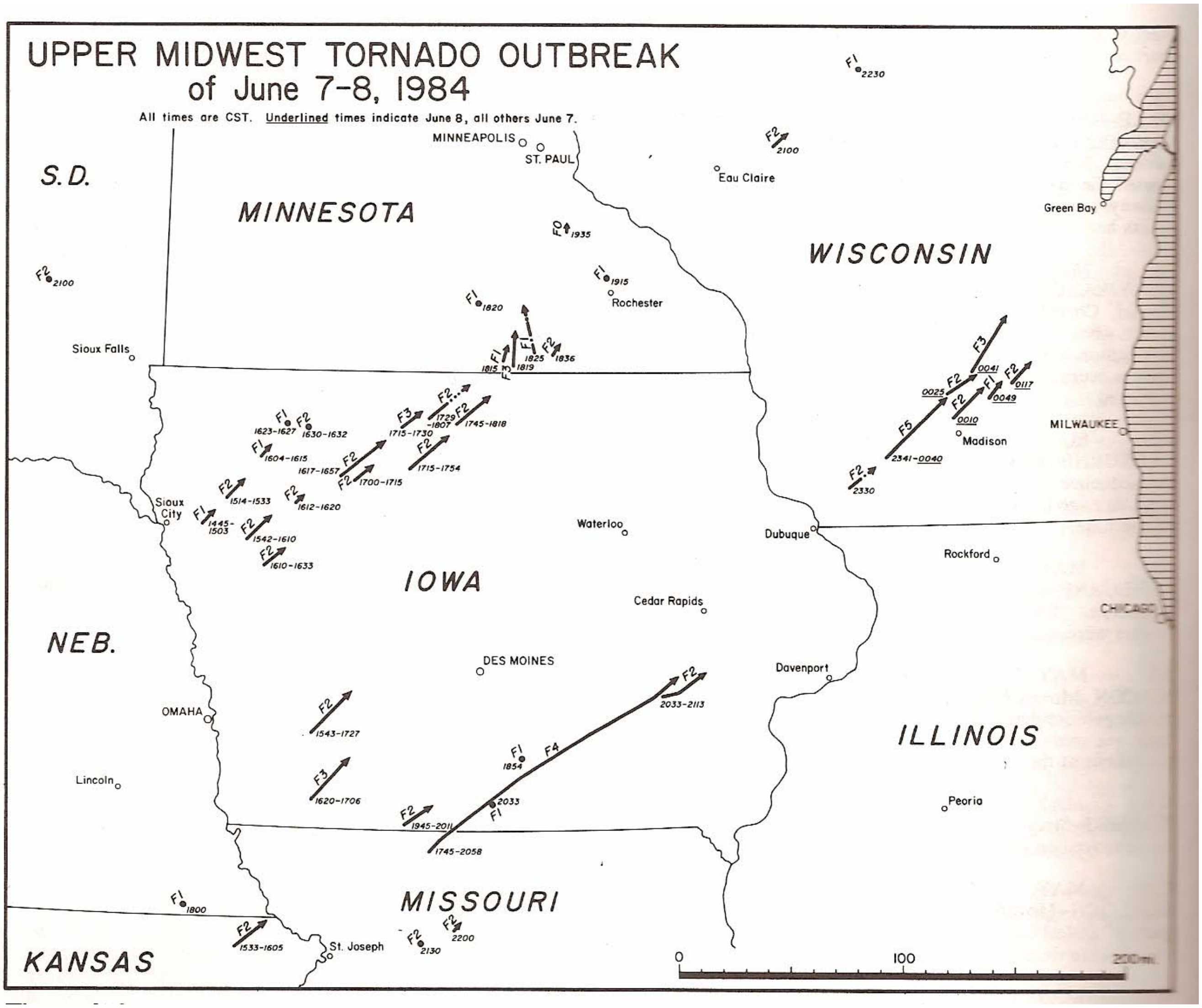

Figure 1 – Composite map complied by T.T. Fujita of the tornado tracks from the 7 June – 8 June 1984 tornado outbreak

This paper will focus on the synoptic setup leading up to the severe weather outbreak over southern Wisconsin and then focus in on the behavior of the actual mesocyclone that produced the tornadoes. The 8 June 1984 tornado outbreak over southern Wisconsin was setup due to strong synoptic forcing but directly caused by mesoscale processes and features of a mesocyclone that subsequently produced the tornadoes.

II. Data

The primary data used for this case study was gridded model data from the North American Regional Reanalysis (NARR) Model. The majority of the data analysis was done through use of the General Meteorology Package (GEMPAK) software program. Using GEMPAK, gridded data files could be analyzed and many different variables could be plotted at various different levels. Forecast model data could be used to produce maps of contoured

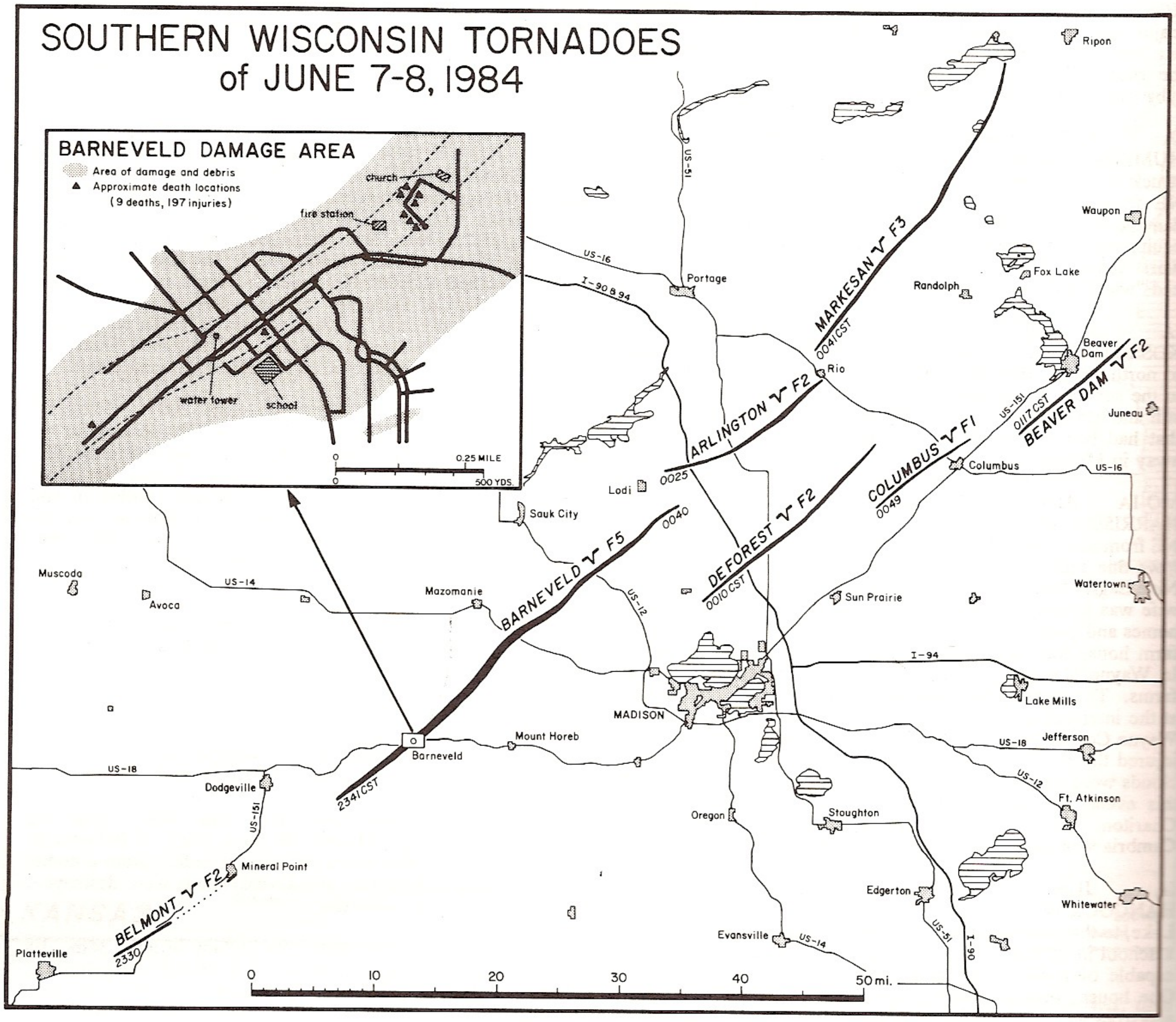

__Figure 2 –__ Detailed map complied by T.T. Fujita of the tornado tracks from the 7 June – 8 June 1984 tornado outbreak over southern Wisconsin. Fujita and his colleagues did extensive damage surveying to accurately depict the locations and tracks of the tornadoes.

variables or color-filled variables. Isosurface plots can be produced of several variables at a single level as well as several variables between two separate levels. In addition, vertical profiles such as soundings or cross sections can be produced from model data using GEMPAK. Scripts can be run with the GEMPAK files to create plots with a style to a users choosing. Use of the GARP program in GEMPAK can create the plots with much greater ease but with less freedom to change variables such as variable color scheme and background color.

The NARR Model Data was available in 3-hour increments which allowed data to be plotted every 3 hours. Since this event occurred nearly 25 years ago, there were limitations in the data that was available. Gridded surface and upper-air observations were not available, neither were gridded radar and satellite data. External sources had to be used to obtain hard copies of information such METAR reports and convective outlooks. METAR data was available in hourly increments, while convective outlooks were available for every 12 hours that included an outlook for the next 24 hours. Radar and satellite data was also sparse at this time so hard copies of limited radar and satellite data had to be obtained from external sources. Sounding data was obtained from external sources and from the University of Wyoming atmospheric sciences homepage.

The focus of this case study will be over a 24-hour period between 12z on 7 June 1984 and 12z on 8 June 1984. Synoptic analysis will be done at 6-hour intervals during this time period, while the majority of the mesoscale analysis will be done on 06z on 8 June when the F5 tornado was on the ground. The analysis focus will be over the Upper Midwest and, for more specific analysis, over south central Wisconsin.

III. Synoptic Overview

a. 7 June 1984 – 12z

On the morning of 7 June, a surface low was located in along the Nebraska/Kansas border with a minimum pressure of 995 hPa (Figure 3a). A cold front that is associated with the low extends southward along the trough axis into Kansas and Oklahoma. Warm air advection is occurring at the surface and lower levels as seen in Figure 3b. A southwesterly flow at 850 hPa is helping to advect warm, moist air from the southern United States and Gulf of Mexico northward into the Plains and Upper Midwest. The increased amounts of warm, moist air along with sunshine will help to create strong instability across the Plains and Upper Midwest thereby creating a good setup for possible severe thunderstorms. A shortwave wave in the 1000-500 hPa thickness can be seen over portions of Nebraska and Iowa at the 500 hPa level (Figure 3c). The shortwave features at 500 hPa are the only real visible features at this time as there are no high maxima in vorticity anywhere over the Midwest. The occurrence of the shortwave is a precursor to severe weather development as it will set off convection if it is in the presence of warm, unstable air; which is exactly what is going on at this time. A very strong upper-level jet is also in place at the 250 hPa level over the central Plains with a jet core of 100 knot speed located just to the south of the surface low in western Kansas (Figure 3d). This jet will play a big role in where the severe weather occurs as the left exit region of the jet and the location of the 500 hPa shortwave coincide pretty well. The left jet exit region is where mass divergence aloft takes place, which means convergence will take place at the surface. Surface convergence will induce upward vertical motion and in the presence of a shortwave, enhance the formation of precipitation. Storm development is inhibited at this time due to the time of day, but conditions started to become more favorable for severe weather development.

b. 7 June 1984 – 18z

Six hours later at 18z the surface low had moved into central Nebraska and now had a minimum pressure of 994 hPa (Figure 4a). A cold front/trough axis feature extends southward from the low into Kansas and the southern Plains. Abundant warm and moist air at the 850 hPa level was now being advected from the Kansas, Oklahoma and Texas at a much greater rate due to the very strong winds at this level (Figure 4b). The flow at this level was out of the southwest so that means the advection of warm air was being directed to into areas that were out ahead of the front and the low and thereby further enhancing the instability. A well-defined shortwave now can be seen at the 500 hPa level over northern Iowa and southern Minnesota (Figure 4c). This is the main feature at this level that sets off

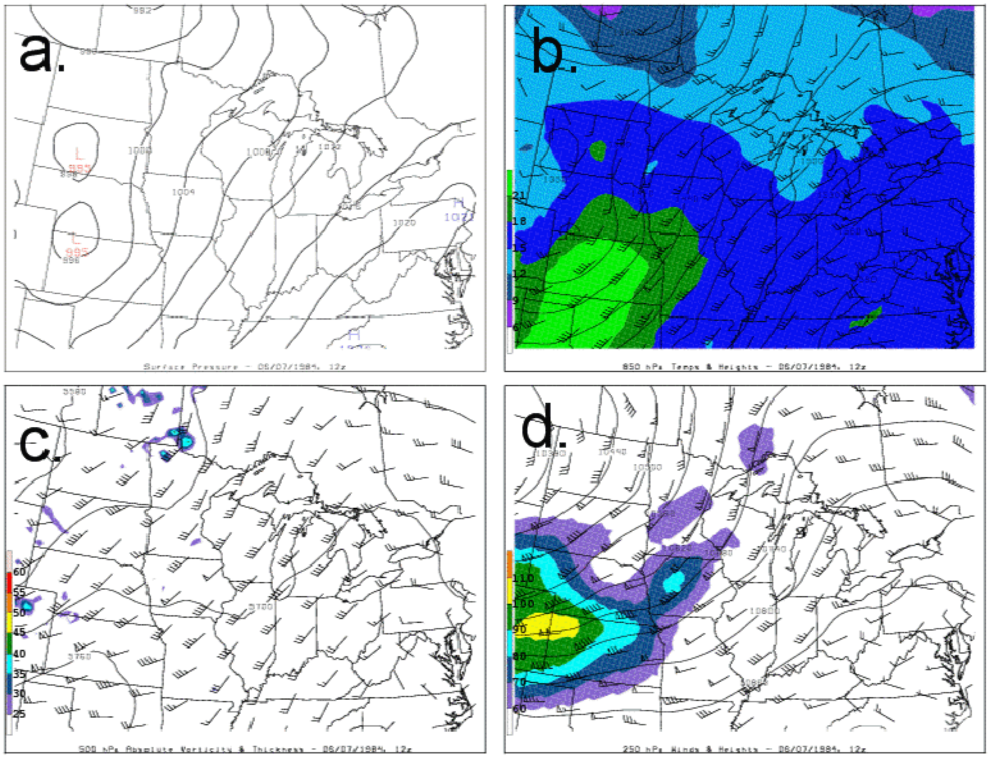

Figure 3 – *4-panel plot of (a) surface pressure, (b) 850 hPa temperatures and winds, (c) 500 hPa Absolute Vorticity with 1000-500 hPa Thickness, (d) 250 hPa heights and winds at 12z on 7 June*

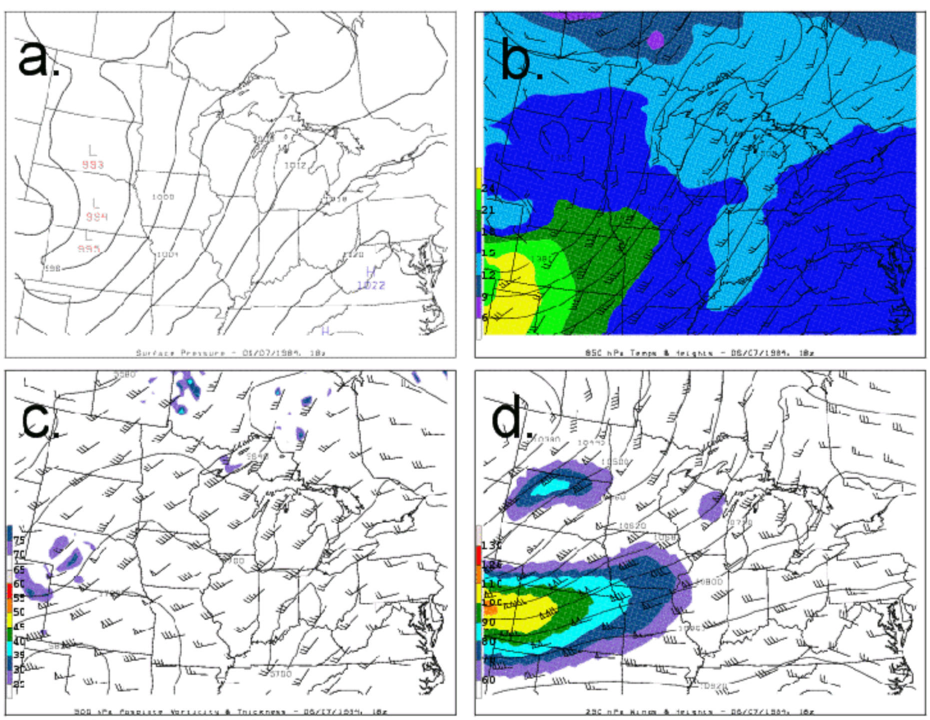

Figure 4 – *4-panel plot of (a) surface pressure, (b) 850 hPa temperatures and winds, (c) 500 hPa Absolute Vorticity with 1000-500 hPa Thickness, (d) 250 hPa heights and winds at 18z on June 7*

convection at this time as there are no large maxima in vorticity associated with the shortwave. Convection that is going to develop is not due to positive vorticity advection by the thermal wind. The only maxima in vorticty are located in western Nebraska and eastern Colorado near the surface low. This will act to further enhance the low-pressure system and deepen it further. The upper-level jet at the 250 hPa continued to propagate to the east now extends from the jet maximum of 100 knots over western Kansas into central and eastern portions of Iowa (Figure 4d). The jet has become much more elongated since 6 hours prior, which means along flow speed changes are going to be greater due to the elongation and the curvature of the jet. The left exit region of the jet is located over much of Iowa, also concurrent to the location of the 500 hPa shortwave. This is the region where convection would likely be initiated and three hours later, at 21z, the first tornado reports occurred over Iowa, Missouri and Kansas (see Figure 1).

c. 8 June 1984 - 00z

The surface low by 00z was now located over SE South Dakota and had a central minimum pressure of 992 hPa (Figure 5a). The cold front and trough feature still extends to the south, now into Nebraska and Kansas. The southwesterly flow at 850 hPa has also intensified to almost 50 knots at some locations over Kansas and Missouri which will greatly advect the very warm air that is in place over the southern Plains to the north (Figure 5b). Even though this time is very close to sunset, the strong low-level flow in the presence of the cold front extending from the deep low will continue to induce destabilization into the evening and into the overnight hours. The shortwave features that were previously visible at the 500 hPa level are not as visible in this time frame (Figure 5c) and could explain a lull in the strong tornadic thunderstorms that took place between 00z and 03z. The influence of vorticity is still non-existent with these storms as the only notable vorticity maxima are located near the surface low, which will further deepen the low. Even though the shortwave features are not as prevalent this time as previous, convective storms are still taking place at this time. This is not only due to the low-level warm air advection, but also due to the influence of the upper-level jet. The 250 hPa level jet had slightly weakened since the prior 6 hours with a jet maximum of 90-100 knots over Kansas (Figure 5d), but now had much greater curvature to it and is still quite elongated. The left exit region of the jet is located over eastern Iowa and southern Wisconsin; it is in this region where two mesoscale convection systems are propagating to the northeast with the aid of the southwesterly steering winds at mid to lower levels.

d. 8 June 1984 – 06z

The most intense severe thunderstorm activity over southern Wisconsin took place right around 06z on 8 June. The surface low was now located over central Minnesota with a central minimum pressure of 992 hPa (Figure 6a). The cold front and trough associated with the low now extended down through Minnesota, Iowa, and Missouri into Kansas. The 850 hPa level winds were now even stronger in intensity with winds of upwards to 60 knots over Missouri (Figure 6b). The result of this was the continuation of the massive warm air advection into the Midwestern states, which is evident by temperatures upwards of 15 to 18 degrees Celsius at 1:00 in the morning! The warm air advection is allowing the air to remain very unstable during the overnight hours,

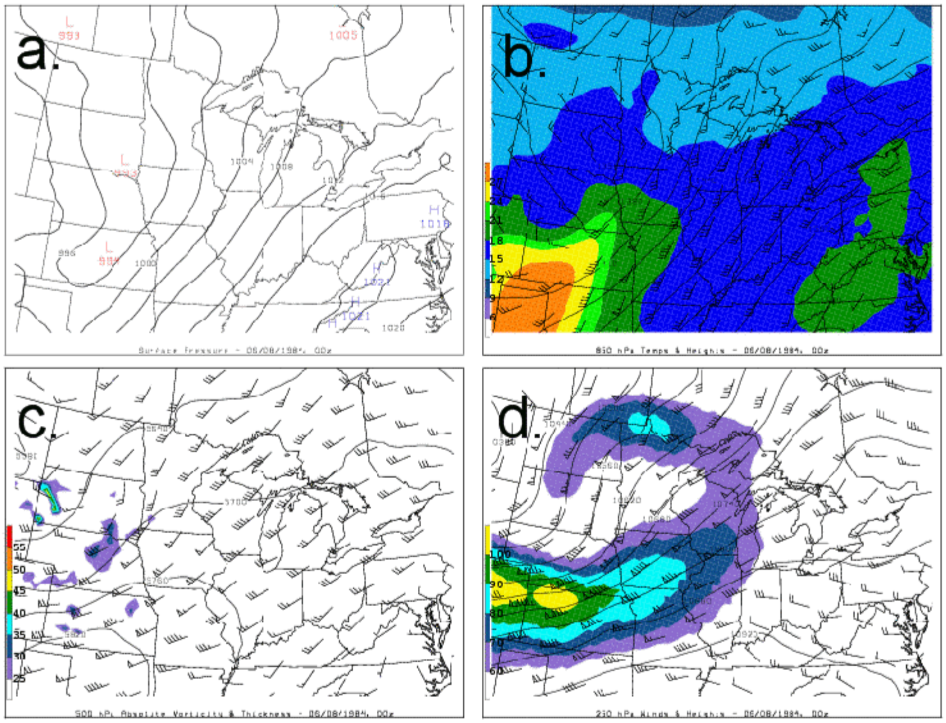

Figure 5 – *4-panel plot of (a) surface pressure, (b) 850 hPa temperatures and winds, (c) 500 hPa Absolute Vorticity with 1000-500 hPa Thickness, (d) 250 hPa heights and winds at 00z on 8 June*

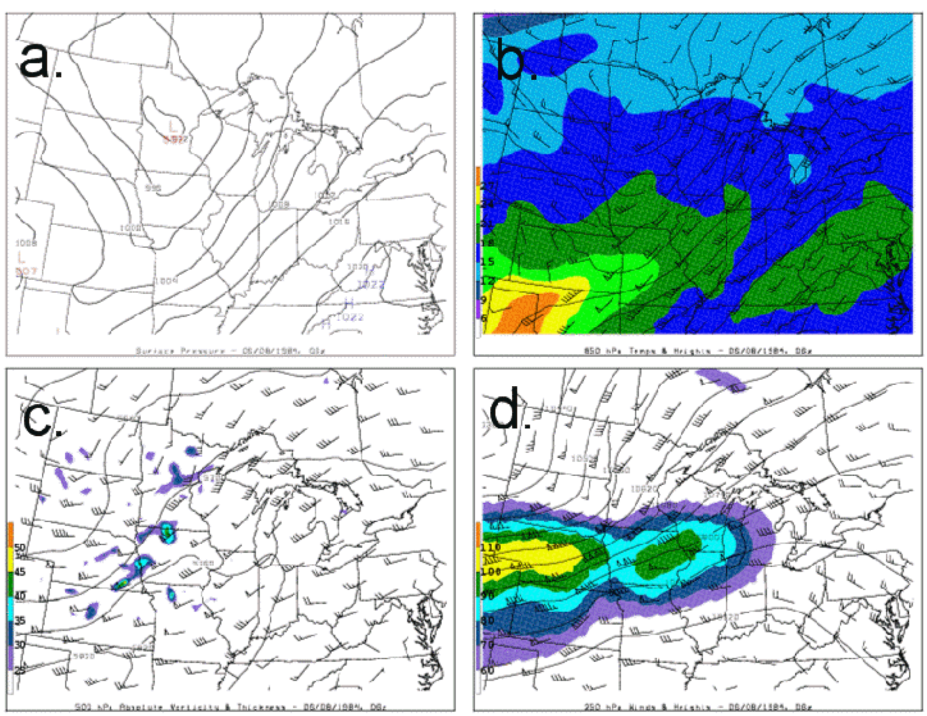

Figure 6 – *4-panel plot of (a) surface pressure, (b) 850 hPa temperatures and winds, (c) 500 hPa Absolute Vorticity with 1000-500 hPa Thickness, (d) 250 hPa heights and winds at 06z on 8 June*

which allowed thunderstorm development to increase and also become quite strong. Shortwave features are once again visible at this time over Iowa, Illinois and Wisconsin; this is the region where the strongest convective storms were occurring (Figure 6c). Evidence of possible PVA forcing is seen for the first time over Iowa and parts of Nebraska in the presence of vorticity maxima near the low and out ahead of the cold front. Any storms that developed in that region were likely a result of frontal and PVA forcing. The upper-level jet at 06z is no longer curved in nature, but now is instead much more linear (Figure 6d). The jet maximum is now located over much of Nebraska with a speed of over 100 knots. The left exit region of the jet was firmly in place over the southwestern portion of Wisconsin coupled with the 850 hPa level warm air advection and the 500 hPa shortwave. This provided an ideal synoptic setup for severe weather to occur and this was the time that the tornado that affected Barneveld was on the ground.

IV. Mesoscale Overview

Several factors played a role in the development of the mesocyclone that produced the multiple tornadoes over southern Wisconsin on that night. These factors included the presence of wind shear (the changing of winds with height), instability (brought about by daytime heating and strong warm, moist air advection from the southern Plains) and a strong southerly low-level jet (that continued to advect warm and moist air to Wisconsin well past sunset). This sort of setup is quite ideal for severe weather/tornado development and can be represented with a conceptual model of a mesocyclone that produces a tornado (Figure 7). On Figure 7, the three arrows to the left represent winds at different levels that feed into the mesocyclone. The green arrow represents low-level southerly warm and moist inflow, the purple arrow represents mid-level southwesterly flow and the blue arrow represents upper-level westerly flow (a jet). Instability creates a lifting mechanism for a parcel in the form of an updraft (red arrow), as this air reaches higher levels it cools and sinks downward in the form of a downdraft (dark blue arrow). The cool downdraft parcel will condensate as it sinks and form precipitation. The rain-cooled downdraft creates a gust front at the surface (represented by a drawn cold front). Low-level and mid-level flows are going in slightly different directions which mean that the winds are also changing directions with increasing upward height. If the updraft and downdraft are tilted, they will not cancel each other out and the storm will allow growing. Wind shear in the mesocyclone can also be depicted by a horizontal "roll vortex" at mid-levels and if the updraft is strong enough then the "roll vortex" will become vertical and possibly produce a tornado. Each of the three main ingredients: instability, shear and a low-level jet were in place when the Barneveld tornado struck.

a. *Instability & Shear*

The warm air advection that took place for over a day prior to the tornado outbreak allowed the atmosphere to become very moist and unstable at lower levels near the surface. Daytime heating also allowed for warming and instability to increase and for convection to occur if the proper forcing existed. A good indicator of the instability in a given area is the measure of Convective Available Potential Energy (CAPE), which basically represents the amount of energy an unstable parcel would have if it were lifted

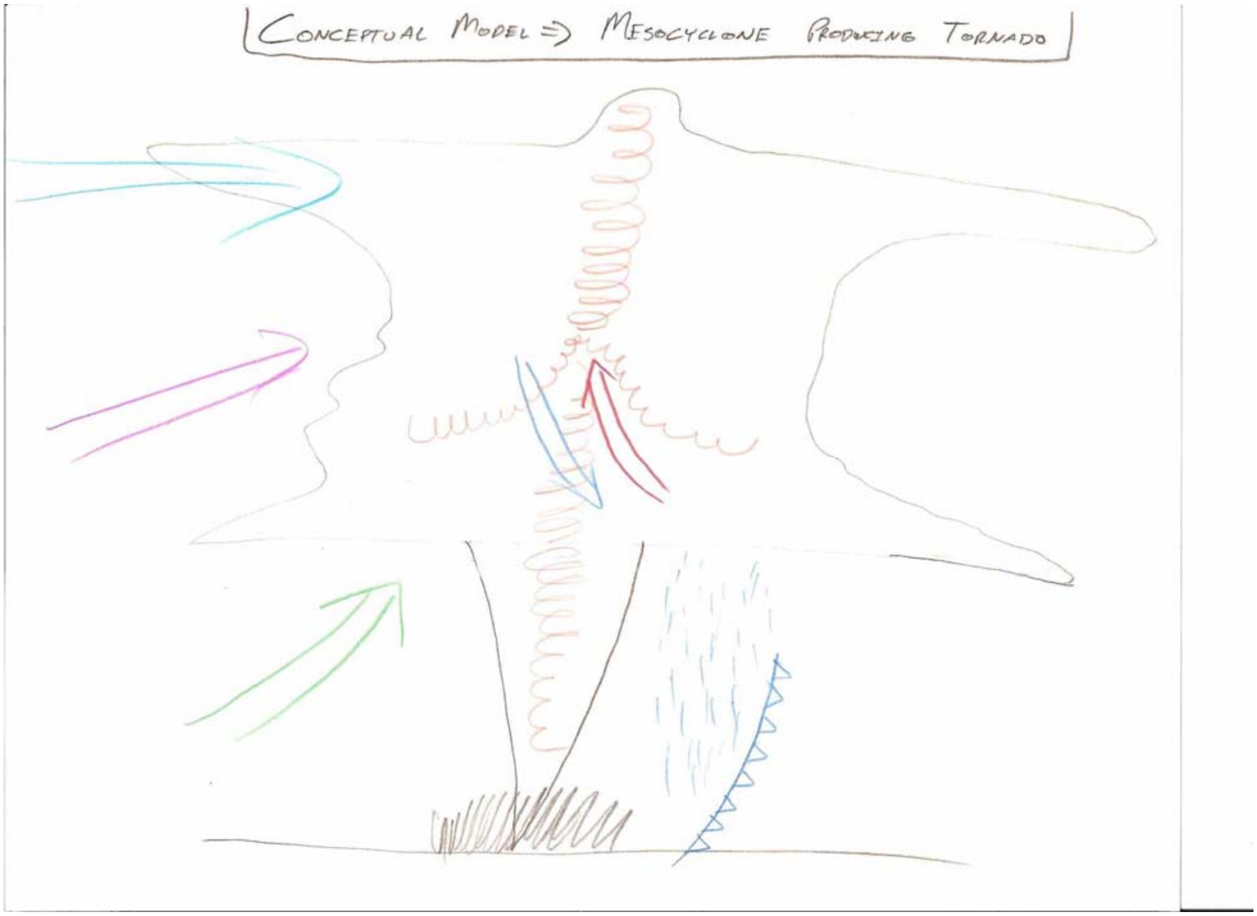

Figure 7 – *Conceptual model of mesocyclone producing a tornado*

upward. CAPE compares a lifted parcels temperature to that of its environment, so warm and moist air that is unstable will often lead to high values of CAPE. The more CAPE a parcel has, the more energy is in place that could be converted into kinetic energy in the form of a thunderstorm.

For much of the day low-level flow was out of the south to southwest direction, while mid-level flow was out of the west to southwest. This change of wind direction with height also means that winds are veering with height. Through the properties and dynamics of the thermal wind balance, veering winds are often associated with warm air advection. This means that not only the low-level winds are advecting warm and moist air, but it is also the wind shear playing a role in advecting the warm and moist air. The main role of wind shear, of course, is to produce rotation in a mesocyclone and from that possibly forms a tornado. Another way to gauge the likelihood of supercell or mesocyclone development is to look at the bulk Richardson number; which is simply the ratio of CAPE over wind shear. CAPE and bulk Richardson values can be easily calculated using a vertical skew-t sounding.

Due to the historical nature of this event, many soundings weren't available for 7 June and 8 June 1984 and thus the soundings used in this case study were from Topeka, KS (TOP) and from Green Bay, WI (GRB) at 00z on 8 June. Even though Topeka, KS was far displaced from the active severe weather, it was in an ideal location for a weather balloon to be advected closer to the active weather, thanks to the upper-level flow. Figure 8a shows the Topeka sounding with some interesting features on it. One is the presence of a warm and moist boundary layer with a capping inversion at the top of the boundary layer. Above it a much drier elevated mixed layer, which indicates that lapse rates will be steep and that CAPE values are likely high. This is indeed the case as the calculated CAPE for the Topeka sounding was well over 2000 J/kg – quite indicative of severe weather. The calculated bulk Richardson number was around 15, which is indicative of a good balance between instability and wind shear and also more favorable for supercell development. The wind profile at Topeka was exactly like it was described earlier in this section – veering with height, indicative of vertical shear and possible rotation in a mesocyclone. The sounding at Green Bay (Figure 8b) was not as ideal for identifying severe weather but still yielded some fairly impressive stability index values. CAPE was calculated to be just less than 1000 J/kg – indicative of moderate instability; while bulk Richardson was calculated to be around 15 – which meant that the shear that does exist was enough to balance the CAPE. Notice also how the winds are veering with height, just as they were in Topeka.

b. Low-level Jet

The unique aspect of this tornado outbreak was that the tornadoes that occurred in southern Wisconsin all did so after 0530z (1230 AM local time). Often severe storms will die out after sunset because of a loss of daytime heating and therefore a loss in instability. One way that instability can remain is through a low-level jet advecting ample amounts of moisture to a region.

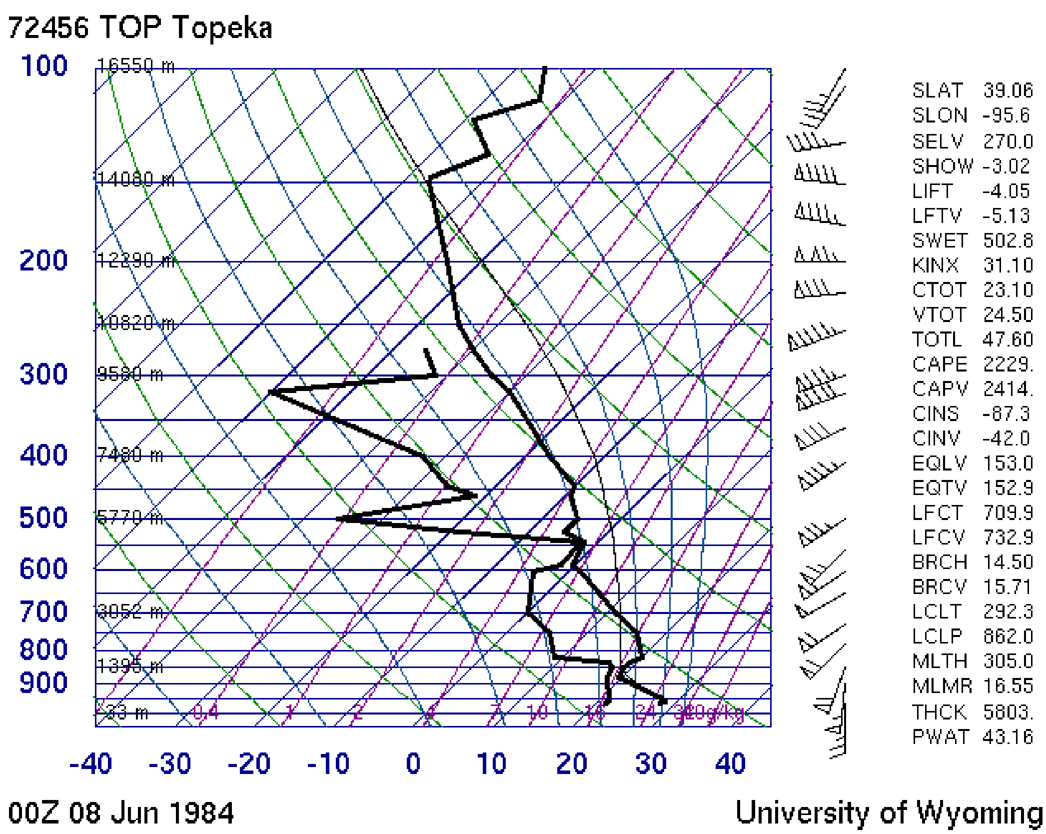

Figure 8a – *Skew-T plot from 00z on 8 June from Topeka, KS (TOP)*

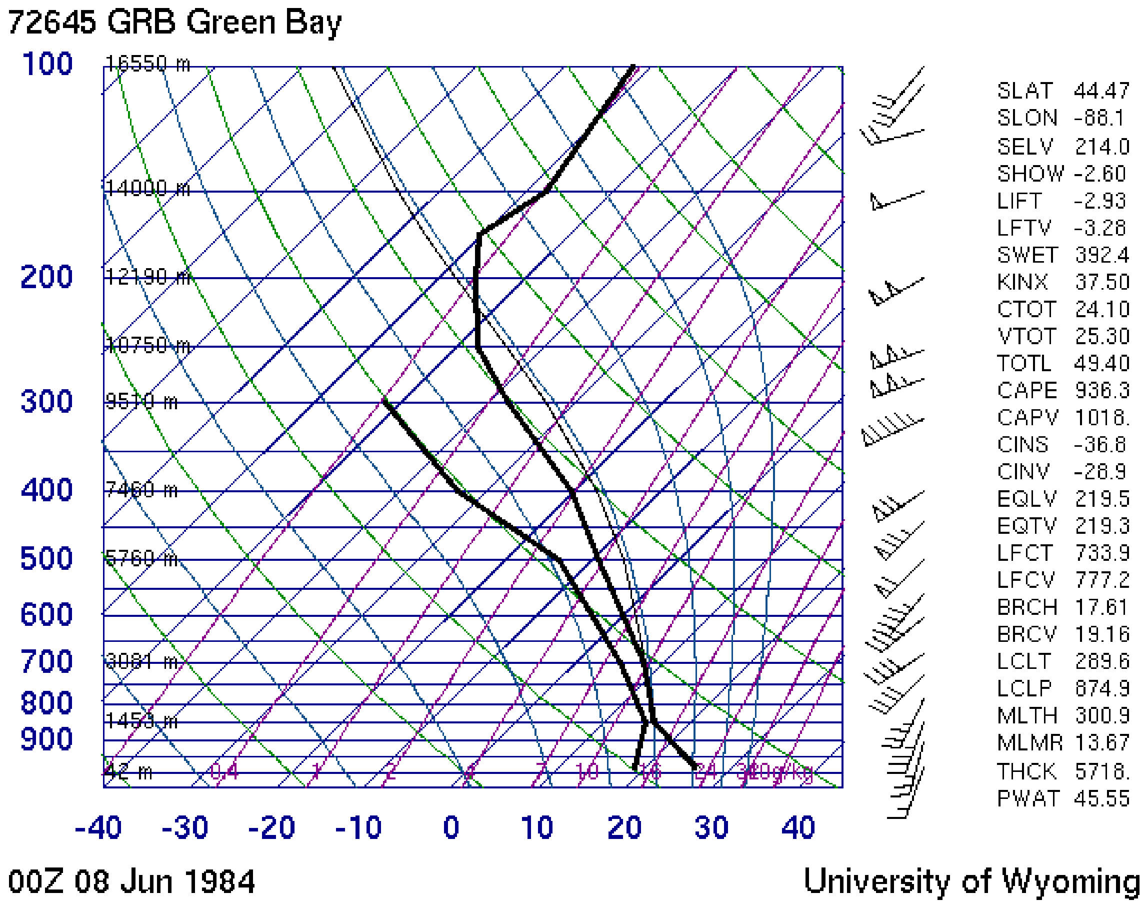

Figure 8b – *Skew-T plot from 00z on 8 June from Green Bay, WI (GRB)*

A low-level jet is a wind maximum found at lower levels (usually 850 hPa) and is usually situated on top of a nocturnal boundary layer inversion. The nocturnal inversion acts to trap high amounts of moisture that either came from the Gulf of Mexico or through evapotranspiration processes in crops. The low-level jet will act to then advect the large amounts of moisture, usually northward, and not only increase the amount of moisture in a given area but also increase the instability of the atmosphere as well. As the inversion becomes deeper, the magnitude of the low-level jet also increases. This can be seen in Figure 9, where between 00z and 09z the magnitude of the low-level jet increased with time and as dew point values remained virtually unchanged ahead of the cold front the magnitude of the low-level moisture advection increased as well. This rampant low-level moisture advection was one of the main reasons that thunderstorms were able to develop at the time they did.

c. 8 June 1984 – 06z Tornadoes

As previously mentioned, the first tornado touchdown in southern Wisconsin occurred at 0530z (see Figure 2) and after that point 6 more tornadoes formed in the span of about 2 hours. The synoptic setup was near perfect as a 500 hPa shortwave was in place along with the left exit region of a jet to force upward vertical motion. Couple this with the low-level jet bringing mass amounts of moisture into the region (Figure

10) and a volatile situation was in place, Figure 11 (cross section) shows where the convection is occurring in the theta-e contours, as well as where the moist tongue is located. The upward contours of theta-e near the middle of the cross section represent where convection is taking place. In addition, the low-level jet affecting the area is also drawn in on the map to indicate that the greatest moisture advection is actually taking place out ahead of the convection.

As was shown in Figure 2, the paths of the tornado touchdowns were relatively straight. However, radar data at the time was out-of-date in comparison to modern radar technology, so there was difficulty in analyzing the exact (or near exact) behavior of the mesocyclone. A study done by Professor Charles Anderson (of what was known at the time at the UW Department of Meteorology) analyzed radar outline echoes of the tornado outbreak. He used radar echo outlines from the WSR-57 radar in Neenah, WI and the WSR-74 Doppler radar in Marseilles, IL. What Professor Anderson and his colleagues discovered was that instead of a classic hook echo shape, tornado formation resulted from the formation of spiral arm bands out of the main mesocyclone center and it was the individual rotation of the spiral arms that produced the tornadoes. The tornadoes produced from the spiral arm bands moved with the propagation direction of the mesocyclone – to the northeast – and not with the direction of the spiral arm bands (cyclonically).

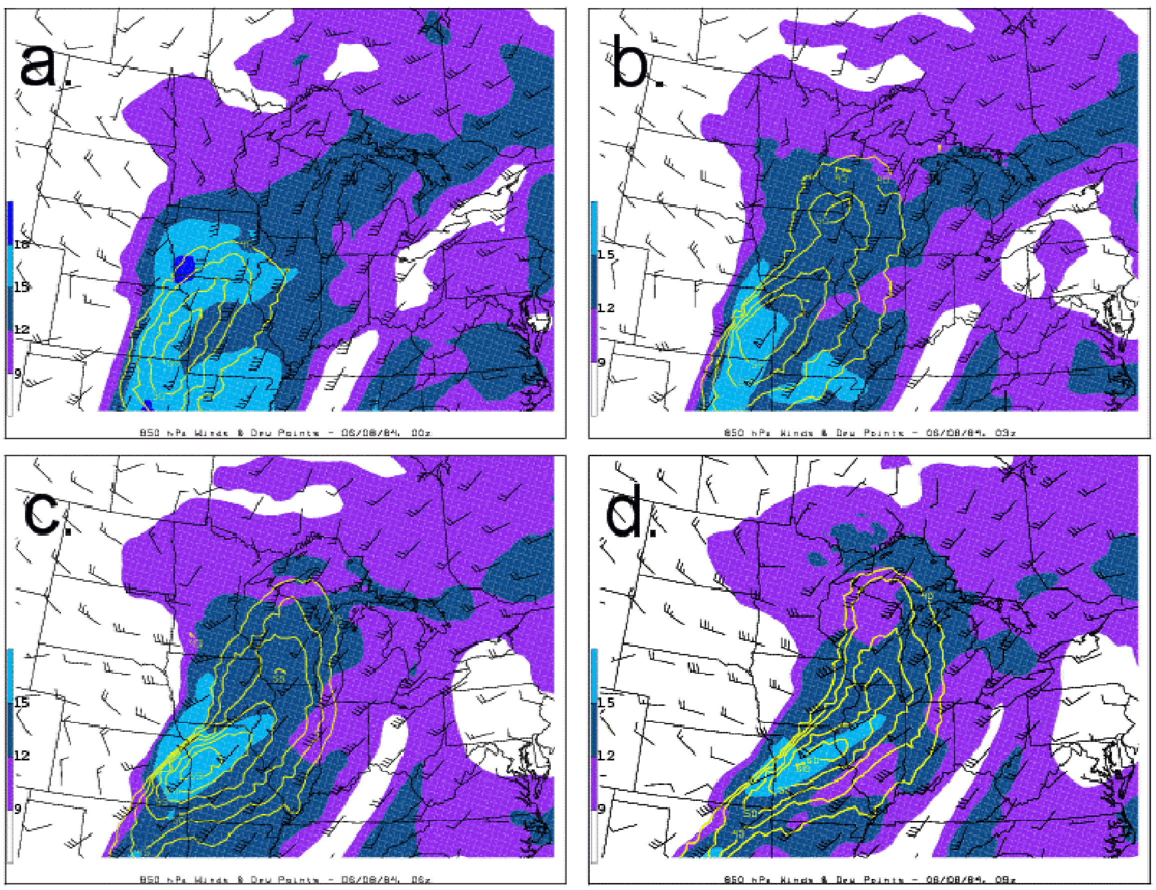

Figure 9 – *4-panel plot of 850 hPa dew points (greater than 9 degrees Celsius) and winds (greater than 40 knots) from (a) 8 June – 00z, (b) 8 June – 03z, (c) 8 June – 06z, (d) 8 June – 09z*

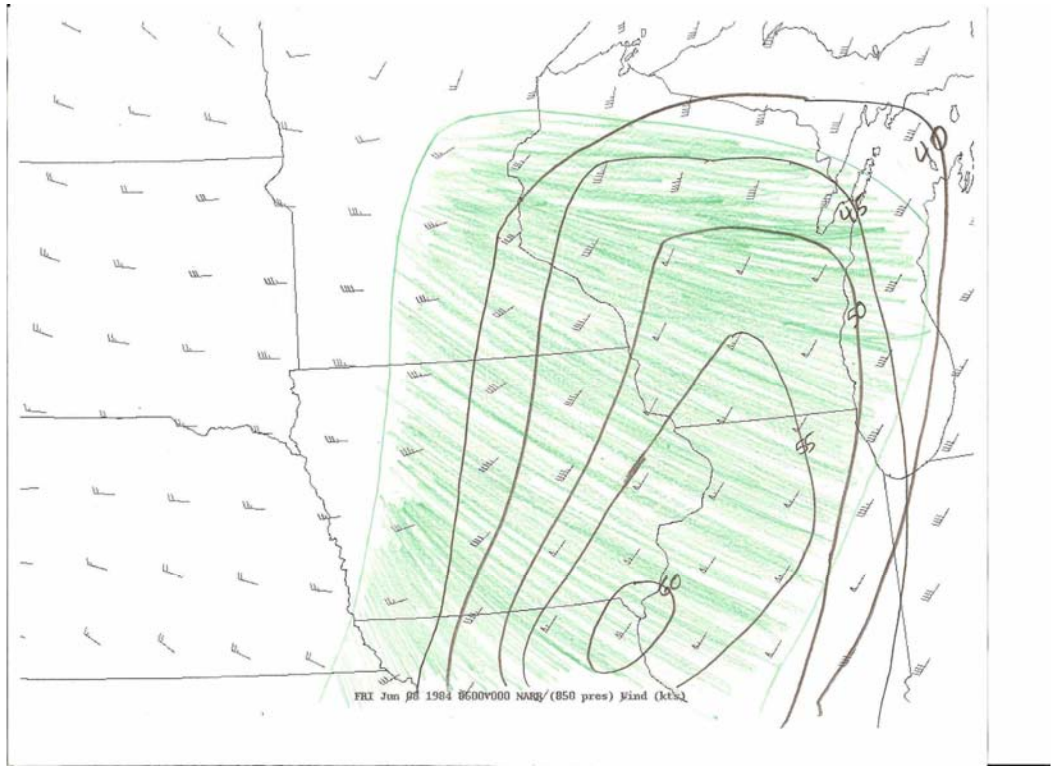

Figure 10 – *Hand-drawn analysis of 850 hPa dew points (green shading, greater than 12 degrees C) and winds (black contours, interval of 5 knots starting with 40 knots) from 06z on 8 June*

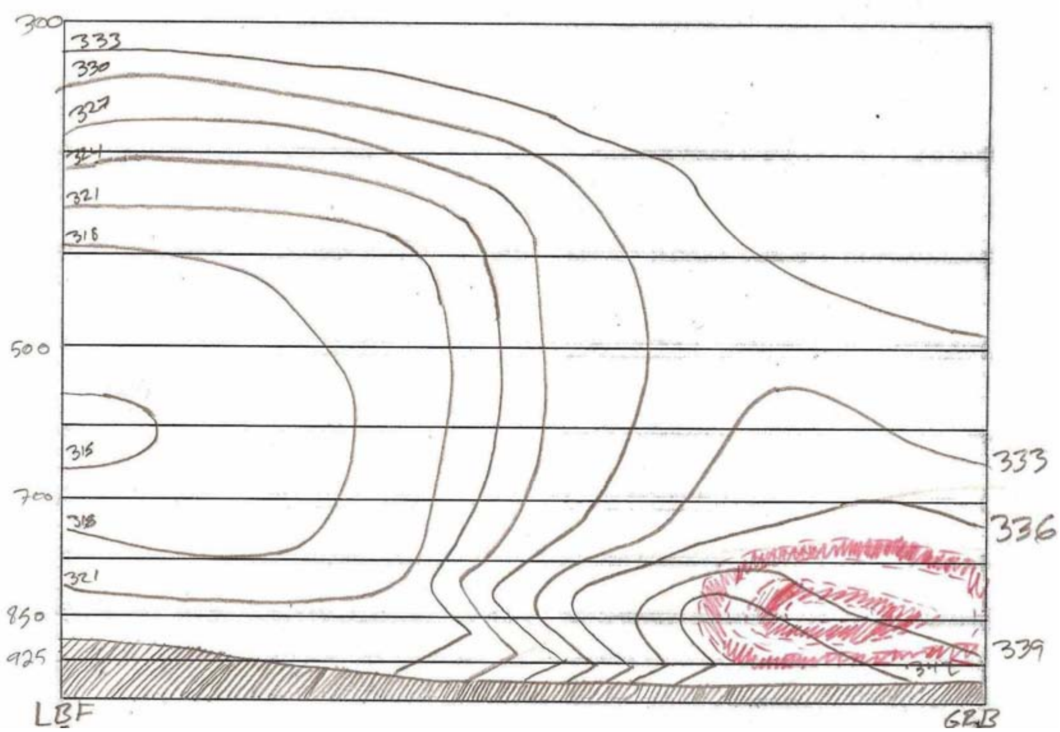

Figure 11 – *Hand-drawn cross section of theta-e (black contours) and low-level jet (red contours and shading) from North Platte, NE (LBF) to Green Bay, WI (GRB) valid 06z on 8 June*

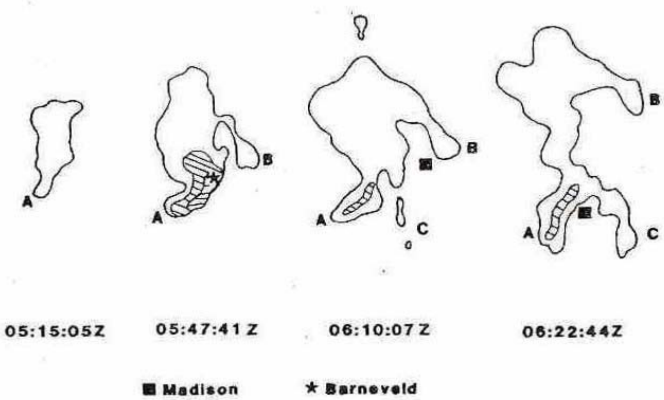

Fig. 1. Neenah, WI radar outlines of most intense echo of spiral mesolow at different times. Additional echo levels are from Marseilles, IL radar. Position of spiral arms A,B, and C are shown with respect to Barneveld and Madison.

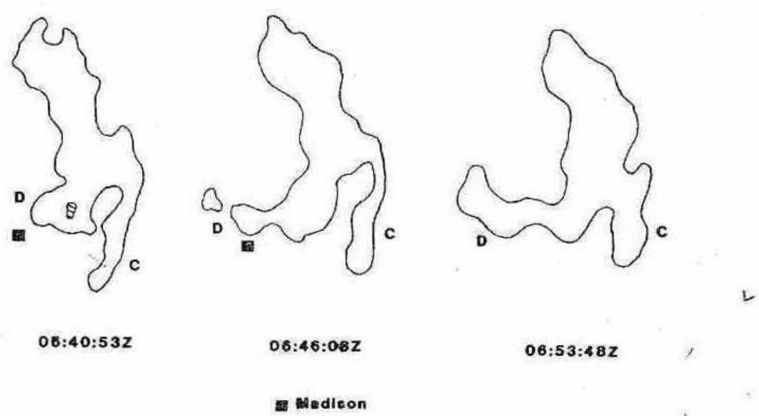

Fig. 2. Same as Fig. 1 except spiral arms C and D are now the principal features.

Figure 12– *Figure from Anderson 1985 depicting the evolution of the various spiral arm bands associated with the mesocyclone. Explanation of lettering scheme is in this paper and in Anderson paper.*

Figure 12 shows the radar echo outlines from Anderson's paper on his research with various times with Barneveld and Madison denoted when necessary. While the radar echo outlines are not geographically oriented in a fixed manner, he labels the various spiral arms and conjectures which arm was associated with what tornado. Using Figure 2 as a reference, he surmises that spiral arm band A produced the Belmont and the Barneveld tornado; spiral arm band B produced the Deforest tornado; spiral arm band C produced the Columbus tornado; and spiral arm band D produced the Beaver Dam tornado. Anderson also concluded that the mesocyclone itself did indeed produce the remaining 2 tornadoes – the Arlington and Markesan tornadoes.

The manner in which Anderson and his colleagues tracked the movement of these radar echoes was by taking observation data from microbarograph stations located across the city of Madison and taking velocity and directional measurements. From this, the angular velocity and equivalent vorticity were calculated to judge how strong the rotation was, in comparison to the tornado it produced. The results of Anderson's work were compared to the damage control studies done by Dr. T.T. Fujita of the University of Chicago. There were some discrepancies between the two separate researchers – such as the initiation time for many of the tornadoes. This sort of mesocyclone was extremely unique at the time and research was hampered by a lack of good technology, which may explain why this event was never greatly pursued further. Advances in radar made this case obsolete and new cases were out there ready to be analyzed by countless researchers and scientists.

V. Summary/Conclusions

The aftermath of the tornado outbreak was substantial: 9 people lost their lives in Barneveld and 200 more were injured, 90% of the village was either damaged or completely destroyed, the total cost of the damage all across southern Wisconsin topped out at over $40 million. The synoptic setup for this outbreak was not an atypical one: warm, moist air was advected northward at lower-levels while in the presence of a mid-level shortwave and upper-level divergence in the left exit region of a jet. The presence of a low-level jet allowed the storms to remain strong well past 06z by keeping the air very moist and unstable. The behavior of the mesocyclone was an unusual one but the hypothesis by Prof. Anderson provided a good stepping stone for further work to be done on this case even though no major endeavor was ever undertaken. Overall, the Barneveld tornado of June 1984 will go down as one of the worst disasters in the history of southern Wisconsin and will be a memory for many that will soon not go away.

VI. References/Acknowledgements

The author wishes to thank Holly Hassenzahl for her assistance on preparing and ironing out the fine details of the case study, as well as for preparing the gridded data for computer analysis. The author also wishes to thank Alex Harrington for providing surface observations and convective outlooks for this severe weather event, as well as for radar and sounding data.

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