April 13, 2006: Analysis of the Severe Thunderstorms that produced Hail in Southern Wisconsin

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ABSTRACT

On April 13, 2006 the states of Iowa, Wisconsin, and Illinois experienced severe thunderstorms that produced tornadoes, hail, and heavy rainfall. The storms began in Iowa at approximately 2300Z on April 13. The storm progressed eastward into Illinois and Wisconsin, and a two short hours later a severe thunderstorm was producing large hail over the Madison, WI area. Hail ranging in size from 1.75-3.00 inches in diameter was reported in Madison. The storms started at 9:30pm and last approximately 15 minutes. This storm was shown to be a type of Mesoscale Convective System (MCS) known as a Mesoscale Convective Complex (MCC). Any MCS is classified as a large, long- lived system that has severe thunderstorms and sometimes supercells that develop inside of the MCS as a whole. MSC cloud tops must reach 100,000 km^2 and have a temperature of at least –32 degrees Celsius. They also must cover 50,000 km^2 and last for at least 6 hours. To be classified as an MCC the cloud tops must be even colder at a temperature of –52 degrees Celsius. Through IR Satellite, which is the only way these systems can be identified, the severe thunderstorm that hit Madison, WI during the late evening hours on April 13, 2006 was declared an MCC. Many environmental factors led to the development of the MCS and subsequently the cell that hit Madison, WI. There was an upper level jet that was present to the west of Wisconsin, which contributed to the vertical motions of the storm. There was a warm and cold front that extended from the low in Canada. Associated with this warm front was a baroclinic zone that resulted in WAA. In the region of Iowa and Wisconsin the air was unstable, which was determined by looking at values of the Lifted Index. There was also a low level jet coming from the south that helped bring in the warm air and the moisture. From soundings taken at Davenport and a forecast sounding for Madison, large CAPE values, vertical shear, strong upper level winds, freezing level, and dry layers were identified. All of these features aided in the production of the storms and aided in sustaining the storms for the long period of time that they were observed.

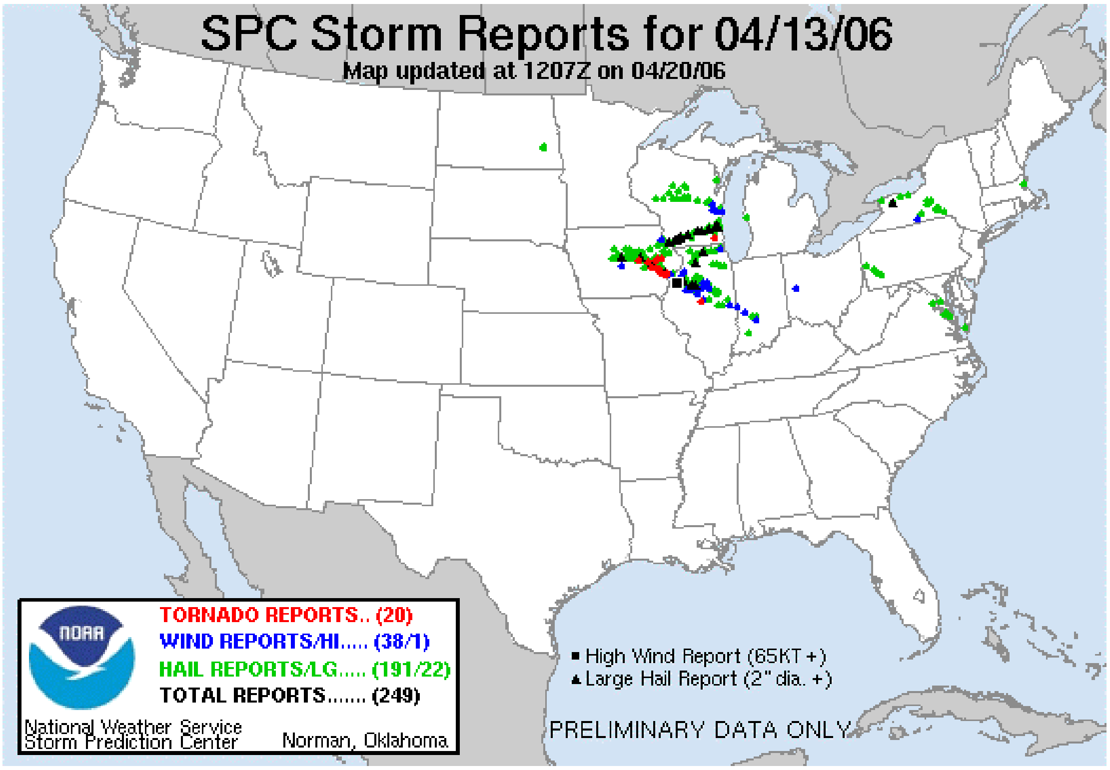

Figure 1: Storm Reports for 4/13/2006 from the SPC website. This shows the line that the storm followed through Southern Wisconsin, Iowa, and Illinois

I. Introduction

Severe thunderstorms and supercells are capable of producing many different types and severities of weather that range from heavy precipitation, hail, tornadoes, and even combinations of the three. The cells that occurred during the evening hours on April 13, 2006 in Iowa are an example of such a case. In Southern Wisconsin, in the area of focus for this case study, the severe thunderstorms produced heavy precipitation and large hail, whereas in Iowa the cells were able to produce tornadoes. Figure 1 is the storm reports for April 13, 2006, which shows the hail reports along the line in southern WI. Madison, WI experienced severe hail ranging from 1.75 – 3.00 inches in diameter. The storms started at 9:30pm and lasted 15 minutes. There is no doubt that hailstones this large caused a great amount of damage to cars and roofs all over Madison. This thunderstorm was part of a larger system known as an MCS, more specifically an MCC, which is an organization of separate cells that lasts on a much longer time scale than cells would on their own. This case study will prove that all the conditions necessary to produce an MCC, and more specifically the hail-producing thunderstorm in Madison, were present. The environment was unstable, there was a low level jet bringing in moisture, and there was warm and a cold front, which can help stem more convection. Also important to the development of an MCC is vertical wind shear and large CAPE values, which are also present in this particular case. Large CAPE, along with high wind shear and low freezing level, are also important to the thunderstorms that hit southern Wisconsin, Madison included.

II. Data

Data for the analysis of this case study was gathered from multiple sources. The Unisys Weather and the Storm Prediction Center (SPC) websites were used to gather data on the upper air maps and surface maps. The University of Wyoming

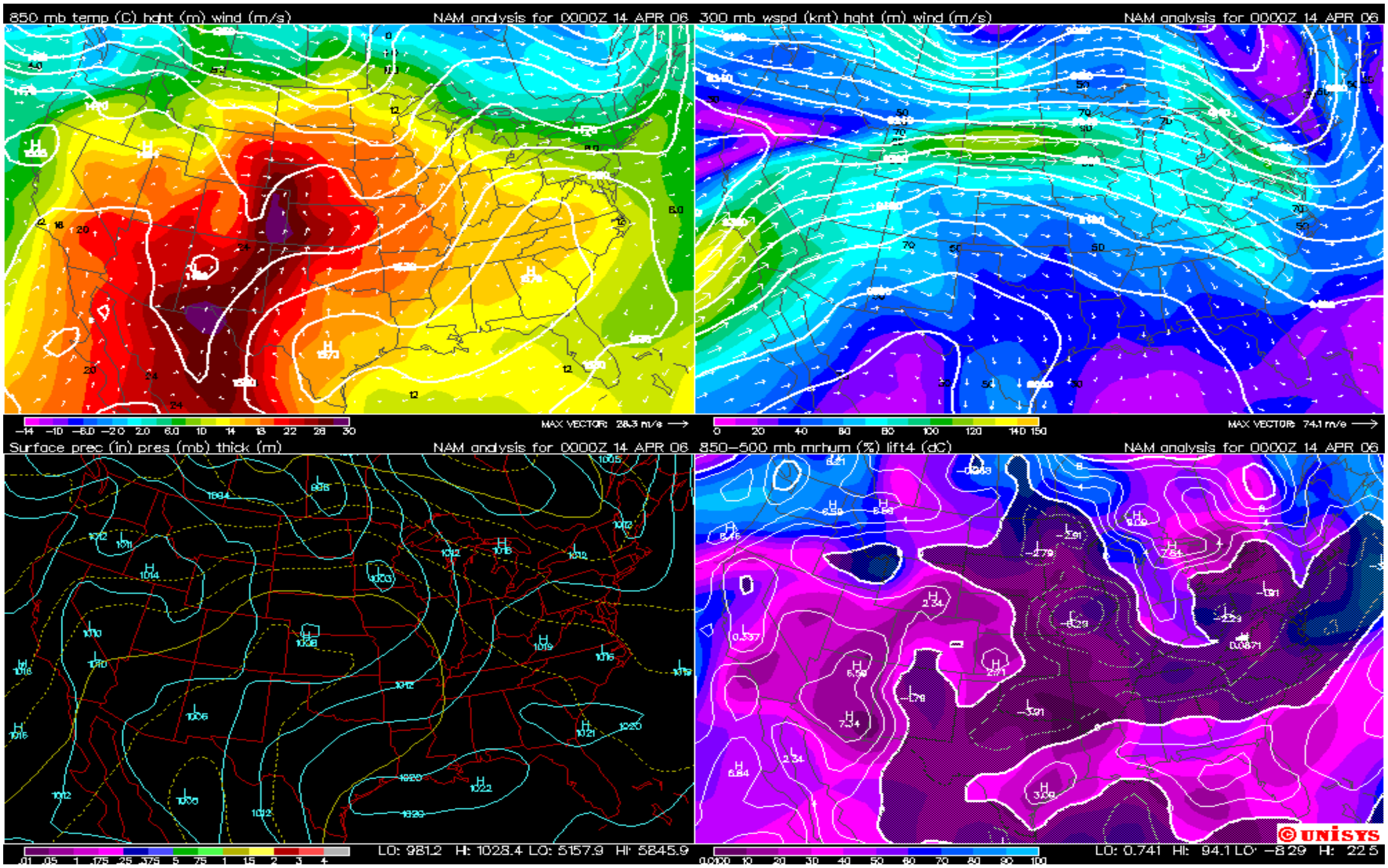

Figure 2: 850mb map, 300mb jet, surface map, and Relative Humidity and Lifted Index are shown in the upper left, upper right, lower left, and lower right respectively. These four maps are used to diagnose the synoptic setup on 4/13/2006

website was used to get sounding data for the storm regions. In addition to the above mentioned websites, two computer programs aided in analyzing the thunderstorms that occurred on April 13, 2006. The first of the two programs is known as the General Meteorological Package (GEMPAK). The second is called the General Meteorological Analysis and Rendering Program (GARP). GARP was used to create all radar images shown throughout the case study. The Milwaukee, WI National Weather Service was also useful for general information and actual hail reports. The SPC website was also helpful in retrieving hail reports because there were more documented though SPC than the NWS. All data was analyzed for 00Z on April 14, 2006.

III. Synoptic Overview

Figure 2 shows a four panel plot of 850mb temps and wind in the upper left, 300mb jet and height lines in the upper right, the surface height lines in the lower left, and the Lifted Index in the lower right hand panel. All figures are valid 00Z April 14, 2006, which is approximately two hours before the event occurred in Southern WI. In the 850mb map a clear baroclinic zone can be seen over Wisconsin. A baroclinic zone usually signifies the presence of a front, which will be discussed later. Another ingredient that is apparent on this 850mb map is warm air advection. The winds at 850mb level are southerly to southwesterly, which is advecting the warm and moist southerly air into the area. The jet that can be seen to the west of Wisconsin at

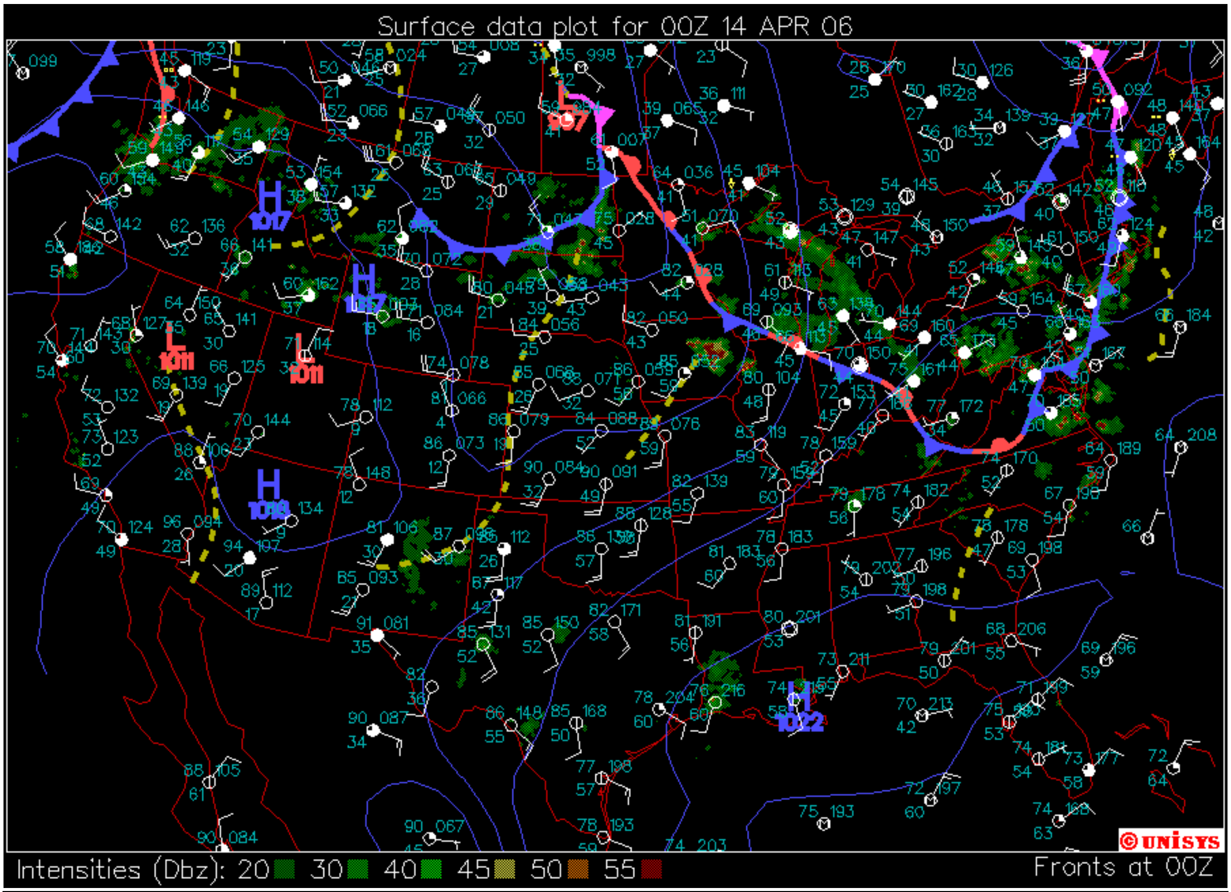

Figure 3: This is a surface map from Unisys Weather website, valid 00Z April 14, 2006. The map is showing a cold front and stationary front, but it is discussed and supported that this is more likely a warm front. Thunderstorms in Iowa can also be detected at this time.

00Z is not impressive in strength but it would be difficult to say that the supercells did not benefit from its presence in the area. Based on the direction of the winds that are observed on this panel, the jet would propagate/curve southeast putting Southern Wisconsin in the left exit region of the jet, which is the area of rising motion. So the presence of the jet would have contributed to some of the rising motion of the storm. The surface map in the four panel plot is not as helpful as the surface map from Unisys in Figure 3. This map shows a stationary front that goes right over southern WI. The position of the front seems to be accurate seeing how the stations to the southwest of the front are reporting temperature in the mid 70's and low 80's and stations to the northeast of the front are reporting temperatures in the low 50's and 60's. Based on the low in Canada and the cold front extending from the low in this figure it is more likely that this is a warm front and not a stationary front since this is the natural set up associated with a low. Also the baroclinic zone that was mentioned in figure 2 also lends evidence that this is actually a warm front. Also the wind direction on each side of the front is indicative of a warm front. The winds ahead of the front are southeasterly and the winds behind the front have shifted to southwesterly/westerly. These wind shifts are typical of an approaching and then passing warm front, so this is even more evidence that the stationary front is in fact a warm front. The map in the fourth panel of Figure 2 is showing relative humidity and lifted index values, which is an indicator of instability. Relative humidity is depicted by the color fills, blue being a higher value of relative humidity. Areas of shading versus non-shading depict the lifted index. The shaded areas represent areas of negative values for the lifted index. As can be seen from this panel there is a large area of instability stemming from Texas all the way north into the region of concern, Iowa and Wisconsin, and even farther north into the Dakotas and Minnesota. The larger the negative value the more unstable the air is in that area. The largest negative value in all of the shaded area is right over Iowa, which is where the convection started and eventually propagated its way into Southern Wisconsin, which also has a large negative lifted index value.

IV. Mesoscale Overview

Convection can form from many different environmental setups. Convection can form due to lake/sea breezes, fronts, and drylines are a few examples. Convection can also organize itself in different fashions. Isolated thunderstorms or supercells may develop, they may develop into squall lines, or they may even develop into what is known as Mesoscale Convective Systems (MCS). The storms that occurred in Southern Wisconsin, including Madison, were in fact part of an MCS. An MCS is a large convective system that has numerous areas of convection popping up inside of the system. There are certain criteria that must be met in order for a storm to be considered an MCS. The clouds must cover 100,000 km^2 with temperatures of at least -32 degrees Celsius; these conditions must last for at least six hours. A Mesoscale Convective Complex (MCC) is a type of MCS and is the type responsible for the convection in southern Wisconsin. An MCC has similar requirements as an MCS except it requires cloud tops to be at a temperature of –52 degrees Celsius instead of –32, and is only required to cover 50,000 km^2. The atmospheric ingredients that led to these thunderstorms inside the MCS will be diagnosed in this section.

The only way that an MCS or MCC can be identified is by looking at the infrared satellite data. The infrared is necessary since MCS's and MCC's are determined by cloud top temperature and this is what is shown through infrared satellite data. Infrared is also necessary for this particular case since the event occurred during the evening hours. Figure 4 shows the satellite

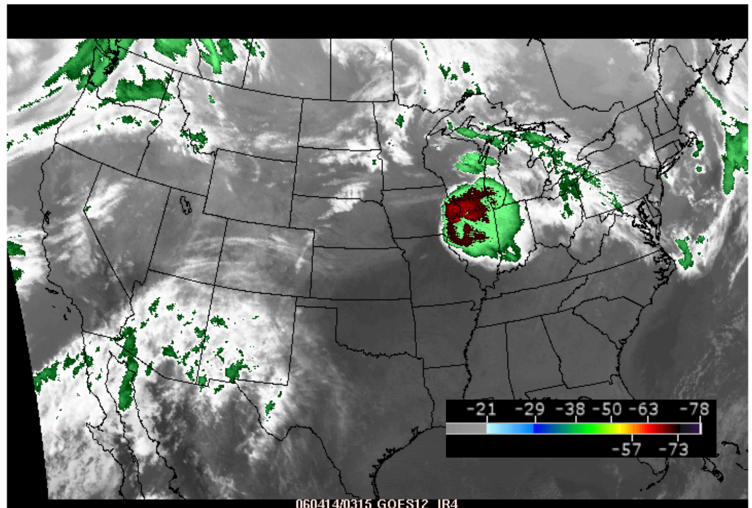

Figure 4: This is the GOES IR Satellite image from SPC. This supports the theory that the storms on April 13, 2006 were an MCC. The green colors represent temperatures of at least –38 degrees Celsius and the red colors represent temperatures of at least –63 degrees Celsius. This image is valid 0315Z. The circular motion and cloud tops temperatures persisted through the entire loop which started at 2315Z to 1115Z – 12hrs.

data retrieved from the SPC website. The IR satellite image was used from the SPC website because it utilizes colors which help denote the cloud top temperature that are most important. The satellite image is one time step of a 12-hour time loop starting at 2315 on April 13 and ending 1115 on April 14. During this 12-hour time loop, the system maintains the red color, which is a value of at least –62 degrees Celsius, well above the required –52 degrees. This figure has verified that the system was an MCC.

Conceptual Models are also very helpful in understanding the structure and formation of meteorological systems. Figure 5 shows a conceptual model of an MCC.

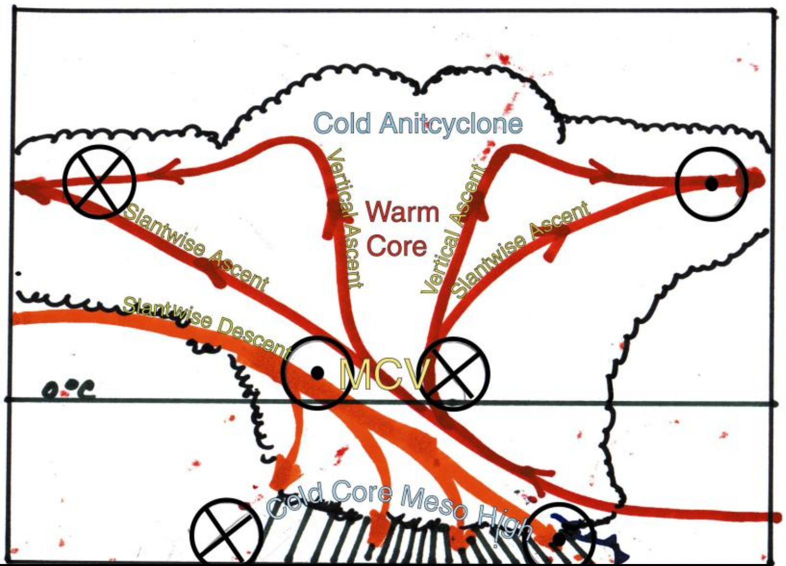

Figure 5: Conceptual model of an MCC taken from Tripoli lecture 13. This conceptual model shows the cold anticyclone aloft, warm core, and cold core meso high at the surface. The rotating Mesoscale Convective Vortex is a result of the ascent and descent creating the rotation, almost like a pinwheel effect.

This conceptual model shows the multiple ascents that occur in an MCC. There are two vertical ascents and two slantwise ascents. The slantwise descent is caused by entrainment of the cold dry air. This entrainment is also what is responsible for creating the cold core meso high and the lower level of the MCC. The entrainment of air basically gets pooled down at the surface, hence creating the cold core meso high. The coupling of the ascent and descent helps maintain the MCV or Mesoscale Convective Vortex that is seen in the mid levels right above the melting level. The ascent and descent creates a sort of pinwheel affect helping to maintain the rotation at this level. The fact that it sits right near the melting level is not a coincidence. In the vicinity of the melting layer a structure of cooling is produced, which enhances potential vorticity (PV) at this level and this helps grow the MCV as well. The cold anticyclone aloft feeds into the jet streak to the north. This outflow enhances the storm and is also an important feature lending to its longevity. It is able to maintain the system because the outflow creates a dynamic flywheel, which stores the energy in the system. With stored energy the convection is able to persist even if the environmental factors that were supplying the energy before are no longer present.

One important feature to the formation of an MCC is a low level jet. This jet was responsible for bringing the warm, moist air from the South into the southern Wisconsin area. A GEMPAK plot was created and is shown in Figure 6. The lower level jet extends across the states of Kansas, Missouri, Iowa, Illinois, and Southwestern Wisconsin. It is oriented in the southwest/northeast directions and if compared to the 850mb and Lifted Index maps shown in Figure 2, it is clear that this jet is advecting the warm and moist air right into the area of unstable air.

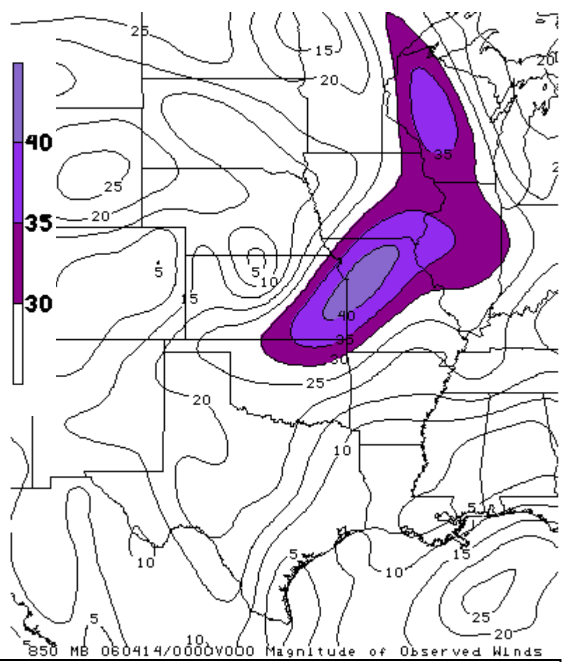

Figure 6: 850mb jet valid 00Z 4/14/06.

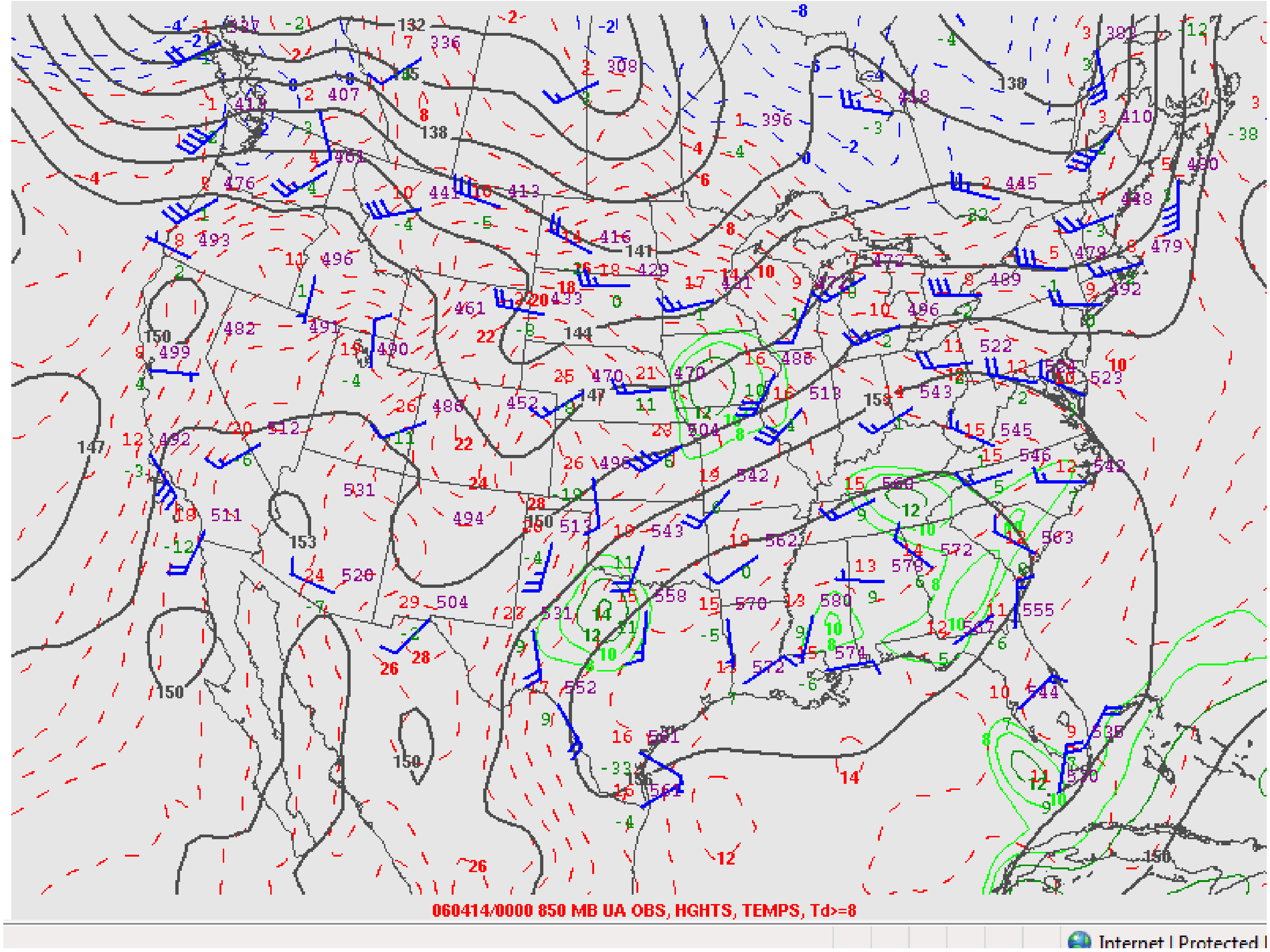

Figure 7: 850mb map from Unysis Weather. This map shows upper air observations, height lines, 850mb temperatures and dewpoints. The dewpoints, which denote areas of moisture, are the green contours and are the important feature on this map. A high degree of moisture is located in Iowa where it can be advected by the low level jet into Wisconsin.

Another beneficial figure to show the advection of moisture into Southern Wisconsin is the 850mb map from SPC shown in Figure 7. This figure shows the dewpoint values in green contours, which is representative of moisture. The area of greatest moisture is positioned right over Iowa in the path of the low level jet. The jet will therefore be able to advect that moisture into Wisconsin helping to setup and later helping to fuel the convection that occurred in Southern WI. This jet is most likely a cyclone induced low level jet. They typically occur in the warm sector of a mid-latitude cyclone, which is exactly where this low level jet can be found. The low level jet that contributed to the formation of the thunderstorms on April 13, 2006 were on the lower end with regards to speed. These jets typically move at speeds ranging from 40-70 knots at the 850mb level and the jet in this case was approximately 40 knots. This moisture that the low level jet is advecting into Southern Wisconsin, will increase the sustainability of the thunderstorms.

Atmospheric soundings are a very useful tool and tell a lot about the environment in the surrounding area. Figure 8 and Figure 9 show two soundings that represent the environments of both Iowa and Madison, respectively. The first sounding is from Davenport (DVN), Iowa. The sounding is taken at 00Z on April 14, 2006, which is 7pm on April 13, 2006.

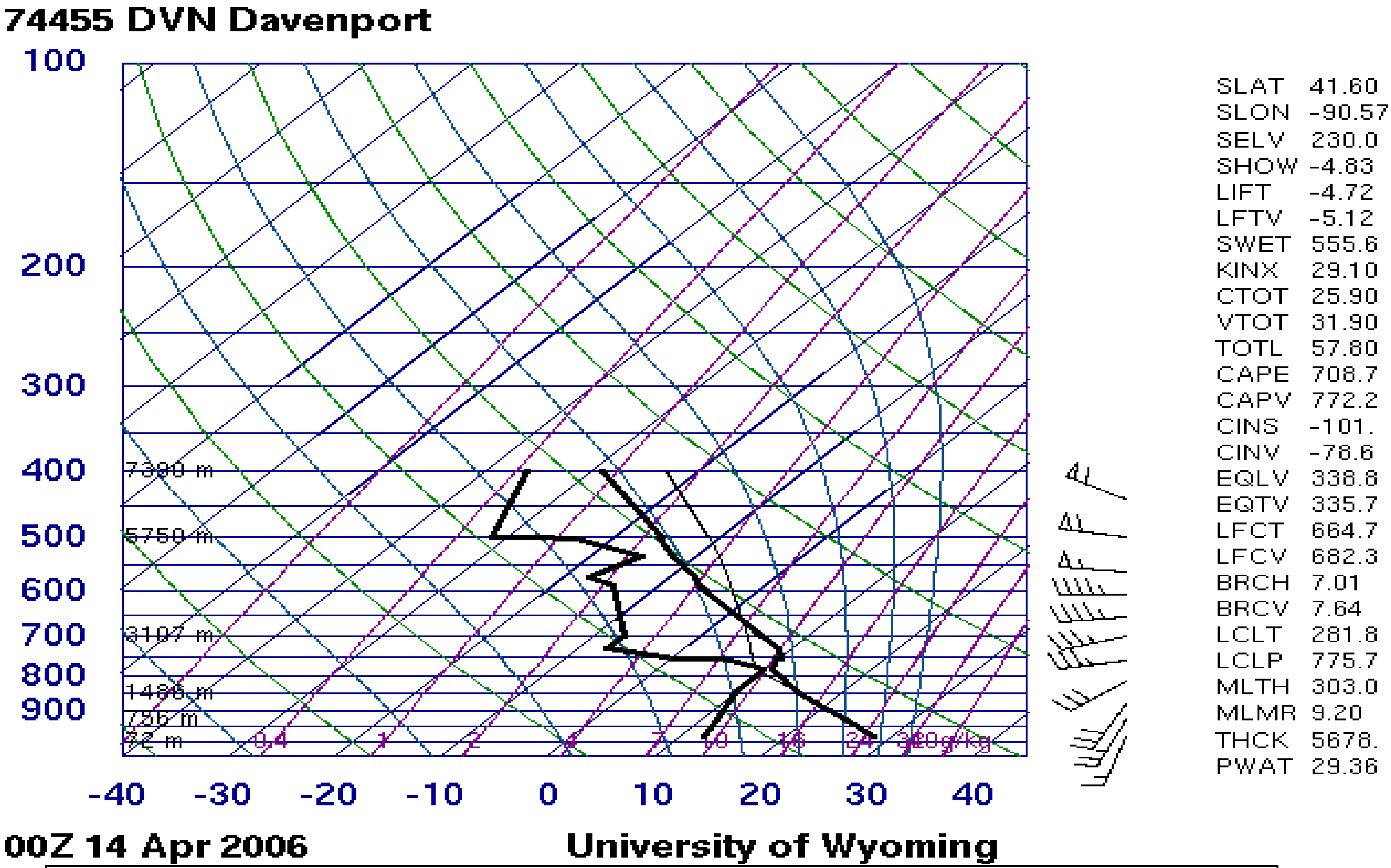

Figure 8: DVN Sounding valid 00Z April 14, 2006. Sounding stops most likely due to storms.

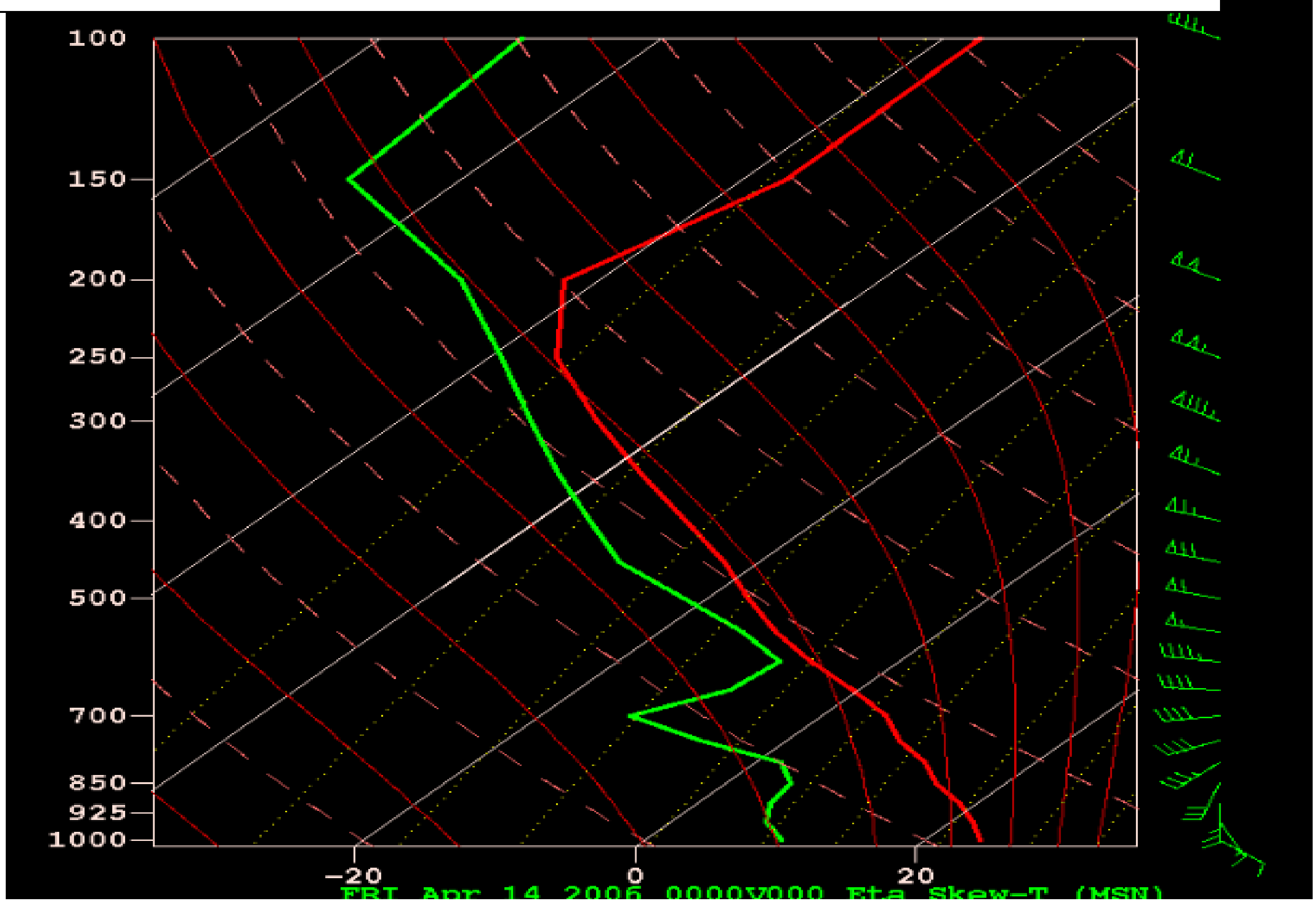

Figure 9: Forecasted sounding for MSN made with GARP. Valid 00Z April 14, 2006.

Unfortunately the entire DVN sounding is not available and it is most likely due to the fact that this is right around the time when the storms were initializing in Iowa. The balloon was most likely destroyed by the storm once it reached 400mb. Since the sounding does not extend past 400mb, there is no way to know what the environment above this level was like. The CAPE value of 708.7 J/kg that is reported on the sounding is therefore not correct and does not seem that impressive. However, another interesting thing to note on this sounding is that there is a slight inversion around 775mb, which results in a somewhat elevated mixed layer. This inversion will act as a cap to the environment, but as soon as this cap is broken the storm will be able to use all the moisture that was being trapped in the elevated mixed layer as fuel and keep it going.

Since the Davenport sounding did not show the entire environment a forecasted sounding for Madison, WI was produced to attain an in depth look at the environment surrounding the storms that occurred on April 13, 2006. This forecasted sounding is also for 00Z on April 14, 2006, so it is in fact a couple hours before the convection began in Madison. However, it is still a good representation of the type of environment that these storms were forming in. From this sounding, the area of CAPE (Convective Available Potential Energy) can be visualized much better, even though a value cannot be determined from this forecasted sounding. The area of CAPE in this sounding still may not look like a lot, but this is two hours before the event so it is probable, since a hail-producing thunderstorm occurred, that these features were enhanced in the two hours.

Another important feature to take from both the Davenport and Madison sounding is the vertical wind shear. Both soundings show the winds veering with height, the Madison sounding in Figure 9 portrays it a little bit better than the Davenport sounding, but it is evident in both. Veering winds with height means that the winds from the surface up to roughly 700mb turn clockwise. So for example, in the Madison sounding, the winds at the surface are southeasterly and become westerly around the 700mb level, hence, turning in the clockwise direction. Veering winds with height are associated with warm air advection; however, the warm air advection is dependent on wind speed. The winds speeds in the Madison sounding start out weak at the surface but by 925mb they have already increased to 25 knots and up to 30 knots at 850mb. These results are conducive with and aid in the warm air advection mentioned earlier. This also results in dynamic lifting, which will contribute to sustaining the severe thunderstorms inside the MCS.

The Madison Sounding in Figure 9 will be analyzed even further to discuss the features that are important to the large hail formation that occurred due to the thunderstorm passing through Madison. These features are a low freezing level, large CAPE values, dry mid-level air and strong upper level winds/shear. The 00Z Madison (MSN) forecast sounding definitely shows dry mid-level air and strong upper level winds. Right at about 700mb the dewpoint drastically moves toward the left hand side of the skew-T, which results in a lower dewpoint temperature and therefore a drier atmosphere. This dry layer helps create a lower freezing level. A freezing layer below 650mb is usually sufficient for a thunderstorm to produce hail that will reach the surface before melting. The MSN sounding has a freezing level that is a little above 700mb, which puts it below the 650mb criteria. Along with the wind shear at the surface that was previously mentioned the environment portrayed by this sounding has strong upper level winds. The upper level winds around 500mb and 400mb is 60-70 knots. This is a significant strength for this level seeing as sometimes jets at 300mb can be at these speeds. The strong upper level winds serve to tilt the updraft in the storm, which allows the storm to live longer. This is because once the updraft is tilted it is separated from the downdraft and therefore will not be destroyed. A stronger updraft allows for stronger upward vertical motions. Large CAPE values will also help increase the strength of the upward vertical motions. Unfortunately an exact value of the CAPE cannot be calculated from the forecasted sounding. As was previously stated, the CAPE may not seem too impressive or large at this time period, but based on the size of hail recorded in Madison it is safe to say that the CAPE was significant enough.

Radar is another helpful tool when analyzing any sort of severe weather system. The storms intensity, size, and path can all be figured out with the use of radar. Figure 10 is a four panel plot of the storms that occurred on April 13, 2006. The top left panel is a cluster of storms that begin in Iowa and is valid 0046Z on April 14, 2006. This is the initial cluster of convective storms that are part of the MCS. The upper right hand corner is valid 0133Z and documents the first cell moving into Southern Wisconsin. The lower left hand panel shows a strengthening cell moving into Dane County and is valid 0215Z. The final panel is valid 0233Z, so shortly after the time of the third panel, and shows the progression of the cell farther into Dane County. It is not as easy to see in the radar images as it was in the satellite images, but the storms do seem to have the somewhat circular shape that is typical of MCS's. Now MCS's cannot be classified by looking at just radar, but by looking back at the IR satellite image in figure 4, the cloud tops do cover the entire area of convection seen on the radar.

One way to show multiple features that influence a storm's development is through the use of a Miller Diagram. This is a diagram created by Robert Miller and Ernest Fawbush. These diagrams are typically used to forecast tornadoes, but they can be used to show the synoptic and mesoscale features that are important to any storm event. Miller Diagrams use a color scale to differentiate between the levels that the feature is observed and also the type of feature being represented, may it be a front or the mean flow, for example. Figure 11 is the Miller Diagram for the storms on April 13, 2006. It is showing the most important synoptic and mesoscale features the led to the development of the storm in Madison, WI. The green dashed section is the moist tongue, and the green arrow inside the moist tongue represents the low level jet that is responsible for carrying the moisture into Southern Wisconsin. The warm front and cold front are depicted as well because their presence is what allowed for a lot of the situations to set up as they did. Also the position of the warm front was important to the formation of hail in Madison, WI. Its position resulted in Madison being in the cold sector and therefore allowing temperatures to remain low enough that hail could form.

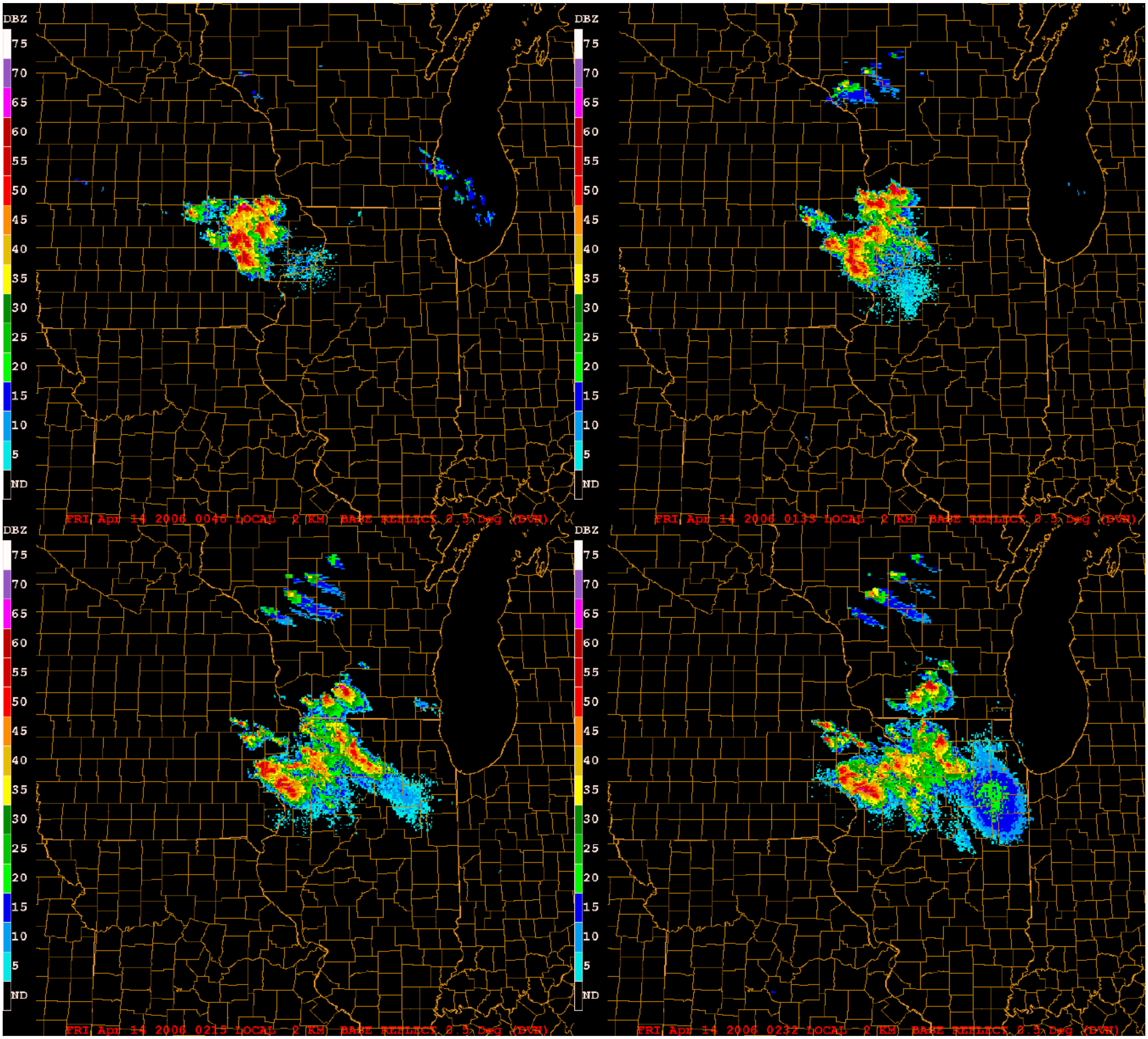

Figure 10: Four panel plot showing the progression of the thunderstorms that occurred during the evening hours on 4/13/2006. The upper left hand panel is valide 0046Z, right upper panel is valid 0133Z, lower left panel is valid 0215Z, and the final panel is valid 0232Z. This figure shows the cells that start in Iowa and then make their way into Southern WI. The third panel shows the storm intensifying and by the fourth panel, which is only 15 minutes later, it has seemed to decrease. However it is still presenting high DBZ levels.

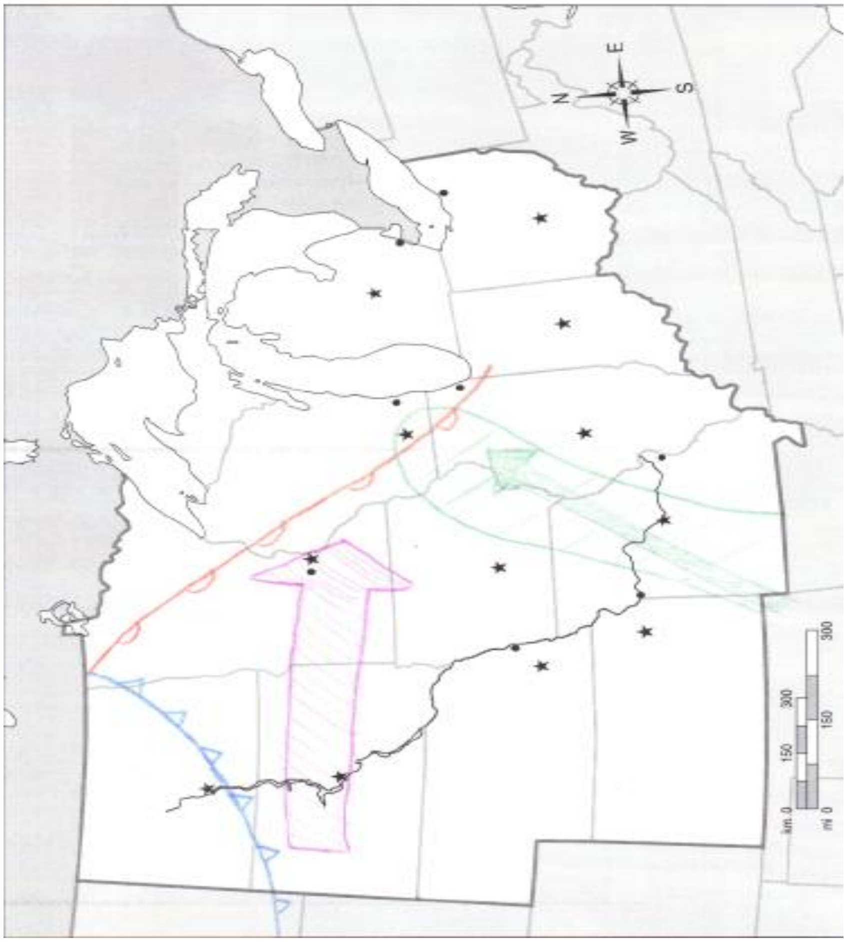

Figure 11: Hand drawn Miller Diagram. This diagram shows the 850mb jet in the green arrow, the moisture tongue in the green dashed section, the 300mb jet in the purple arrow, the warm front, and cold front. All of these features played some role in the formation of the thunderstorms that developed on April 13, 2006.

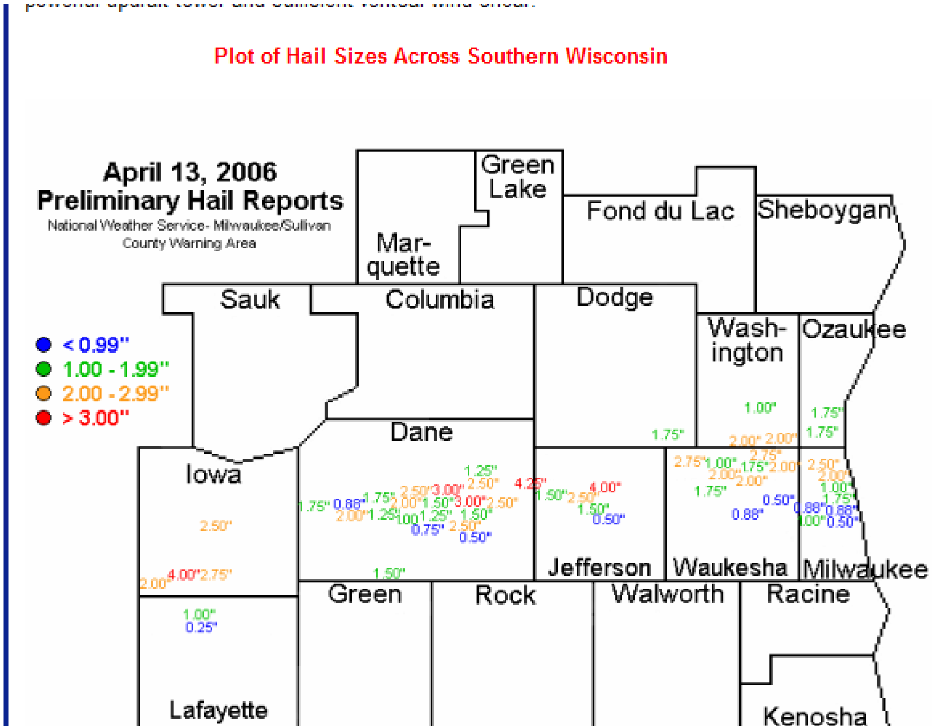

Figure 12: NWS Plot of Hail Size produced by the storms April 13, 2006. Iowa, Dane, and Jefferson Counties saw the largest hail values of 4.00 and 4.25 inches.

V. Conclusion

Multiple factors played into the severe thunderstorm events that occurred on the night of April 13, 2006 in Madison, WI. The storms initiated in an ideal environment in Iowa and that environment was maintained allowing the storms to propagate eastward into Wisconsin. Synoptically there was a jet streak to the northwest of Wisconsin, putting the left exit region of the jet right in the vicinity to contribute to the rising motions of the thunderstorms. There was also presence of a warm front that extended from the low in Canada right along the border of Southern Wisconsin and Iowa. The presence of the warm front, along with wind directions that were southwesterly, allowed for there to be WAA in the area. There was also high negative values of the Lifted Index in Iowa, which implies instability in the environment. Through evaluation of satellite data, this storm was discovered to be an MCC, which is a specific type of MCS. The GOES-12 IR Satellite supports that this storm is indeed an MCC, seeing as it meets the spatial, temperature, and duration requirements. The outflow from the MCC was able to feed into the upper level jet, which helped to maintain the MCS. After it was shown to be an MCC, the mesoscale features that played into the storm formation in Madison could be diagnosed. There was a low level jet at 850mb that helped to advect moisture into Wisconsin. The sounding from DVN and MSN both showed vertical wind shear with height, decent CAPE values, and high upper level winds. CAPE is important because it provides the storm with the necessary energy to get started. The strong upper level winds are important because they cause the updraft to tilt and therefore prevent it from being destroyed by the downdraft. A stronger updraft results in stronger upward vertical motions. This again allows the storm to be longer lived. A strong updraft is also conducive to the production of large hail. All of these features allowed for the storms to produce the 1.75-3.00 inch hail that fell on Madison on the unforgettable night of April 13, 2006.

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Professor Tripoli for use of his lecture notes and also answering questions.