

Wisconsin's 5th Largest Tornado Outbreak: A Case Study of 23 June, 2004.

Christopher Manzeck

(Submitted 5 May, 2009)

Department of Atmospheric and Oceanic Sciences, University of Wisconsin – Madison

ABSTRACT

On June 23, 2004, Wisconsin experienced its 5th largest tornado outbreak in recorded history. This outbreak was caused by a rapidly evolving synoptic system which allowed severe weather conditions to build into Wisconsin by the evening of June 23. Warm air advection out of the south-southwest along with moisture at the surface allowed for significant instability to build throughout the day on June 23. Severe thunderstorms that moved into Wisconsin in the afternoon and evening hours ahead of an advancing cold front encountered optimal conditions for rotating supercells such as high surface relative helicity and CAPE values, as well as sufficient instability represented by the Lifted Index. The combination of the synoptic evolution along with local mesoscale conditions allowed for this significant tornado outbreak to occur in southern Wisconsin.

I. Introduction

On June 23, 2004, Wisconsin experienced its fifth largest tornado outbreak in recorded history. A total of seventeen tornadoes touched the ground in central and southern Wisconsin that formed from a series of high precipitation supercells. These storms also produced large hail and damaging straight line winds, as is common with tornadic storms. Of particular interest with this day is the tornadic supercell that moved through Dane County, Wisconsin which caused damage in the state's capitol of Madison. The historic downtown area was spared, but the southern portion of the town in Middleton experienced the force of an EF-1 tornado. This outbreak was caused by a combination of rapidly evolving

synoptics from a stable atmosphere to one that became destabilized over southern Wisconsin. This then allowed for supercell storms to fire off in the warm sector of an advancing cold front and warm frontal system, with the main forcing for ascent in this storm being frontogenetic processes and surface heating. These storms were able to begin rotating due to higher levels of directional wind shear moving into southern Wisconsin, and high moisture contents allowed for most of the severe storms to be high precipitation supercells (Gehring, 2005).

This tornado outbreak is extremely large for the state of Wisconsin to experience. From 1971 to 2000, Wisconsin averaged a total of 21 tornadoes per year, with the peak month

being June for that time period. This tornado outbreak did occur in June, however the 17 tornadoes that were spawned by this system accounts for nearly a complete year's worth of tornadoes for Wisconsin (NWS Milwaukee). It is interesting to note that the initial severe weather outlook for this day issued by the Storm Prediction Center was a low probability (SPC Event Index). But the rapidly changing synoptic system allowed conditions to become favorable for supercell development during the late evening in southern Wisconsin (Gehring, 2005).

This case study will review several of the aspects that caused this widespread tornado outbreak on June 23, 2004. As a starting point, a conceptual model of a supercell will be discussed along with a brief description of what types of classical atmospheric conditions lead to supercell and tornado formation. Then, the broad synoptic situation and its evolution that led to this outbreak over Wisconsin will be examined. Following this will be an analysis of the smaller mesoscale features that led to the enhanced threat for supercells and severe weather over southern Wisconsin on the evening of June 23, along with a discussion on the formation of supercells and mesocyclones that can spawn tornadoes. Finally, of interest is the specific supercell that struck Madison, Wisconsin and some data and a mesoscale analysis are provided about that storm.

II. Data and Methodology

Data and analysis methods for this case study were provided in several ways. Upper air charts and model data was provided online by Unisys Weather. Also, the Storm Prediction Center's index of severe weather events provided much of the surface synoptic maps,

skew-t diagrams, hodographs and mesoscale discussions. A program called the Global Atmosphere Research Program (GARP) was used to analyze radar data and satellite data for this case, and the conceptual model is drawn using information given in a series of lectures by Greg Tripoli in 2009. Also, a Miller diagram is used to explain synoptic and mesoscale components that is based on a paper by Robert Miller from 1972. Two lectures on severe weather are also utilized that were given by teaching assistant Daniel Henz.

III. Conceptual Model / Background

Tornadoes of the variety that are discussed in this case study are spawned from supercell thunderstorms. These thunderstorms require special atmospheric conditions in order to exist. A supercell is classified as a convective storm that possesses a deep, persistent mesocyclone. In order to get this mesocyclone to form within a thunderstorm, the atmospheric profile needs to have a vertical wind profile to create this spin. This type of optimal wind pattern is called veering winds with height. An example of this wind profile would be winds at the surface starting out from the south-southeast and as one moves upward through the atmosphere the winds 'veer' to south and eventually westerly winds aloft. This type of wind profile generates helicity, which is the atmosphere's tendency to spin up, and high helicity values are generally conducive to mesocyclone development.

Another important ingredient to get deep convection is convective available potential energy, also known as CAPE. High CAPE values are generated when the surface temperature and dew point temperature are close together, but at upper levels the atmosphere cools

rapidly resulting in steep lapse rates. When a surface parcel is then lifted through the atmosphere, it can become positively buoyant and turn the CAPE into kinetic energy of a convective storm. Moisture content is also an important ingredient for supercell development, and especially tornado formation. When the surface dew point depression is low, then the lifting condensation level (cloud base) is consequently low, which is necessary to have a best chance for tornadogenesis. While CAPE and helicity are certainly not the only two ingredients necessary for supercell thunderstorms, they are widely considered two of the most important factors for diagnosing severe weather potential, short of a lifting mechanism.

The supercell is a distinct type of rotating thunderstorm, but the storms that effected Wisconsin on June 23, 2004 were classified as mainly high precipitation supercells. This simply means that the supercell storms that formed had extremely high rain amounts within the storm. **Figure 1** is a hand drawn conceptual model of a high precipitation supercell as viewed from the south, based upon a series of lectures given by Professor Greg Tripoli (2009).

The most distinct features of the high precipitation supercell are shown in the conceptual model. The features drawn are not to scale, however it is important to notice the arrow depicting 'warm moist inflow' into the updraft of the storm. The storm's moisture source comes from the surface. The wall cloud would form directly underneath the mesocyclone from within the storm, since the wall cloud is merely an extension of the mesocyclone beneath the main cloud base. Out of the mesocyclone is where any possible

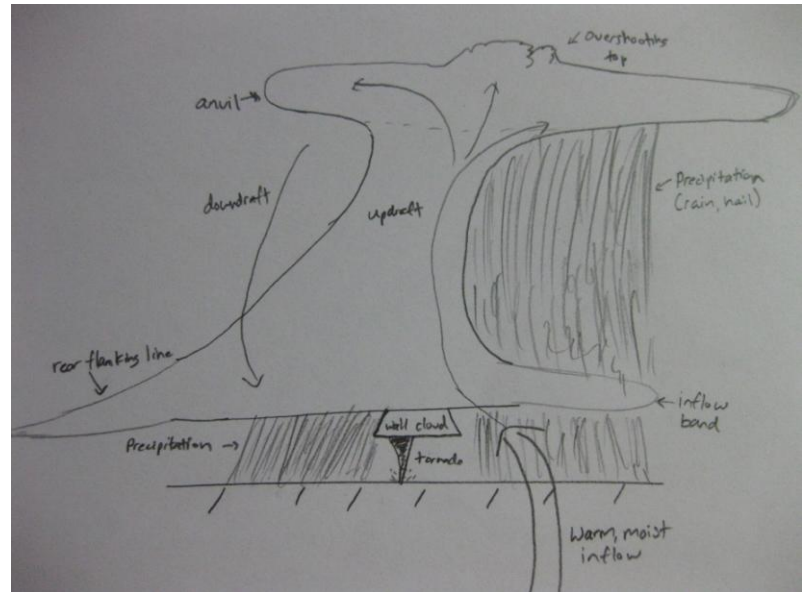


Figure 1: *Conceptual model of a High Precipitation (HP) Supercell. This is the general classification of thunderstorms that caused Wisconsin's 5th largest tornado outbreak. Existing thunderstorms that move into a high shear environment can begin to rotate producing mesocyclones, wall clouds, and tornadoes.*

tornado would form. It is important to note that the precipitation in this storm wraps all the way from the right part of the storm behind the wall cloud and to the rear of the storm. An overshooting top and anvil at the top of the storm generally occur near the tropopause, giving the storm tremendous height from the surface to around 300 hPa. The rear flanking line of clouds shown on the left of the model is formed from the downdraft on the backside of the storm, as it wraps around the storm it can create shallow lift and creates this attached flanking line of clouds to the back of the storm. In simple terms, the tornado can be thought of as a narrow extension of the mesocyclone all the way to the surface from the wall cloud. Supercells can go through cycles of producing wall

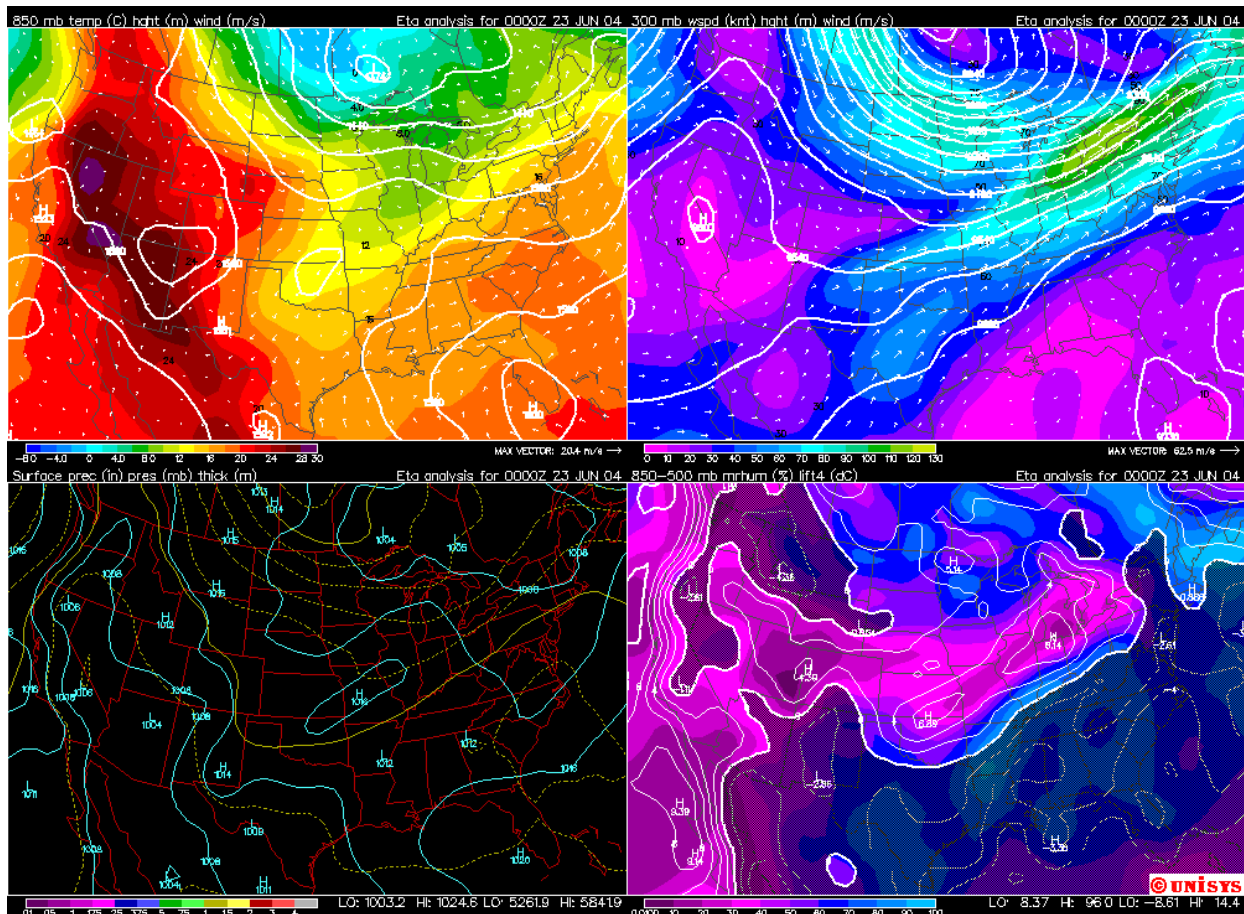
clouds and tornadoes when an updraft gets cut off from the inflow of moist air and another updraft starts at the back end of the thunderstorm, which can result in another wall cloud formation and potentially another tornado. This can be seen in **Figure 12** where one supercell produced a tornado five separate times in its life cycle. In the Mesoscale Evolution portion of this case study, details are provided on how a supercell can form and create a mesocyclone within itself, and the dynamics associated with these features.

IV. Synoptic Evolution

The synoptic setup on June 23 at 0000 UTC will be examined first to discuss the apparent lack of potential for

illustrates the change of conditions and potential for severe weather to occur in southern Wisconsin.

Beginning at 0000 UTC June 23, 2004, the atmosphere over southern Wisconsin was not indicative of a severe weather outbreak within the next 24 hours. During this time, a surface cold front was located on the border of **Figure 2 (below): 0000 UTC June 23, 2004. (a) Upper Left: 850 hPa Temperature in Celsius contours and wind vectors. (b) Upper Right: 300 hPa wind contours in knots. (c) Lower Left: surface pressure contours with 500 hPa thickness in yellow. (d) Lower Right: Lifted Index and relative humidity color fills.**



severe weather, and then the evolution of the synoptic system is tracked until 24 hours later at June 24 0000 UTC, which

Wisconsin and Illinois due to a relatively weak (1005 hPa) surface cyclone just north of Michigan, which can be seen in

Figure 2(c) on the lower left plot. Because of this cold frontal passage, the winds at 850 hPa were out of the west or northwest over Wisconsin, which advected cool, stable air from the north into the southern Great Lakes. The 850 hPa wind vectors are plotted in the upper left plot in **Figure 2(a)**. The surface analysis at 0000 UTC shows a weak temperature contrast in the 500 hPa thickness lines shown in yellow across the state of Wisconsin. The cold front passage causes a stabilization of the air in its wake, and this is visible in the lower right in **Figure 2(d)** where positive Lifted Index numbers indicate the atmosphere is statically stable for surface lifted parcels. When the Lifted Index number is positive, this indicates highly stable air, whereas a negative number indicates potential for thunderstorms to occur.

At the upper level of the atmosphere, the jet dynamics consisted of one strong jet streak of up to 110 knots over Michigan, northern Ohio and northern New York. This jet feature can be seen in the upper right plot in **Figure 2(b)**. By using the four quadrant model of a jet streak, one would see upper level convergence of the ageostrophic wind vectors in the left entrance region to that jet streak, which results in subsidence over southern Wisconsin at this time. Another, more weak jet streak of 80 knots was making its way around an upper level trough. This jet extended from northern Wisconsin back through Minnesota, North Dakota and northwards into Alberta, Canada. By once again making use of the four quadrant model of a jet streak, one can note that southern Wisconsin according to this jet is also under a region of upper level ageostrophic wind convergence. If this jet feature were to propagate

through the base of the 300 hPa trough, then at some later time one would expect southern Wisconsin to be near the right entrance region of the jet which would result in upper level divergence and rising motion at the surface. However, as seen later on, this jet feature did not evolve this way and was not the primary mechanism for firing off the deep convection that was seen in Wisconsin 24 hours later.

The subsidence at mid and upper levels due to the two jet streaks near southern Wisconsin does, however, lead to a process called dynamic destabilization. When the weaker jet streak causes subsidence over southern Wisconsin, this acts to compact the distance between potential temperature lines in the lower levels of the atmosphere while it expands the distance between potential temperature lines at upper levels. The net effect of this compacting of potential temperature surfaces acts to warm the lower levels of the atmosphere while cooling the upper levels. The cooling at upper and mid levels causes lapse rates in temperature to increase, which results in a higher potential energy for convection to occur. Typically for severe weather to occur and release this potential energy, the jet streak would propagate to the East so the right entrance region could cause rising motion at the surface and help to initiate convection. While this does not occur in this case, the process of cooling upper level air to steepen lapse rates and add potential energy for convection still takes place (Lecture: Back).

Approximately 16 hours later, at 1600 UTC June 23, the synoptic setup had still not become favorable for severe weather. In the early morning now on June 23, the surface cold front was still slowly making its way towards the south

through extreme southern Wisconsin, associated with an occluded surface low in Ontario, Canada. This continued to keep most of southern Wisconsin in a layer of stable air. Surface high pressure to the southeast of this cold front was acting as a barrier for the cold

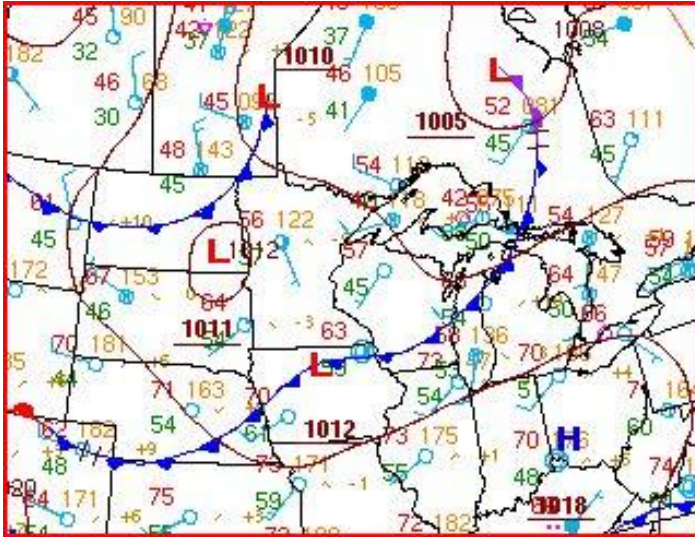


Figure 3: 1559 UTC June 23, 2004 HPC Surface Analysis. Two surface low pressure centers in Canada, with associated cold fronts. The front in Wisconsin is moving very slowly (nearly stalled) as the one in North Dakota is moving towards the southeast.

front, not allowing it to progress farther to the south and east. Also by this time, a second surface cyclone in southeastern Saskatchewan was also slowly making its way towards the east. This cyclone had a cold front associated with it also that was draped through South Dakota, Montana, and to the north into Canada. **Figure 3** highlights a Hydrometeorological Prediction Center (HPC) surface analysis at 1559 UTC from June 23. The first cold front through Wisconsin and the second one approaching from the northwest are visible on this surface analysis plot.

Also at this point in time, the upper air synoptic conditions did not differ

very much from their previous state at 0000 UTC June 23. The jet streak to the east of Wisconsin moved slightly farther to the east, and the jet streak in Minnesota and South Dakota strengthened by about 20 knots at its maximum. Since the cold air was still in place due to the cold front position in southern Wisconsin, the Lifted Index at 1600 UTC was still a positive value, indicating no chance for thunderstorms due to highly stable air. After this point in the morning though, the synoptic set-up at the surface begins to change rapidly from the two cold front setup that exists at 1600 UTC.

Only three hours later, by 1900 UTC, the surface cold front through southern Wisconsin had stalled out and the HPC analysis indicates it as a stationary front on the 1906 UTC surface analysis. Winds to the south of the stationary front remained out of the southwest, while winds to the north of the front were primarily out of the west or northwest. Moist air existed to the south of the stationary front, while relatively dry air with dew points about 10 to 15 degrees Fahrenheit cooler existed to the north of the stationary front.

What became important to notice now was the second low pressure center up in Canada and how its frontal structure evolved over the past three hours. The cold front itself had advanced to the southeast and was now pushing farther into western Minnesota, but the low was becoming vertically stacked. The front nearest to the low pressure had begun to occlude, and at the same time the southerly winds out ahead of the cold front began to organize a warm frontal circulation at the juncture of the cold front and occluded front. This can be seen in **Figure 4** in another HPC surface analysis from 1906 UTC June 23, 2004.

At this point, the threat for severe weather was at a slight level according to the Storm Prediction Center over southern Wisconsin and further to the east due to the presence of the stationary front (SPC Event Index). By the next time the HPC issued a surface analysis, the structure of the stationary front and warm front changed again, and this time it appeared more likely that a severe weather outbreak would occur. It will be important to compare **Figure 4** and **Figure 5** for the change in surface frontal position from 1900 UTC to 2200 UTC.

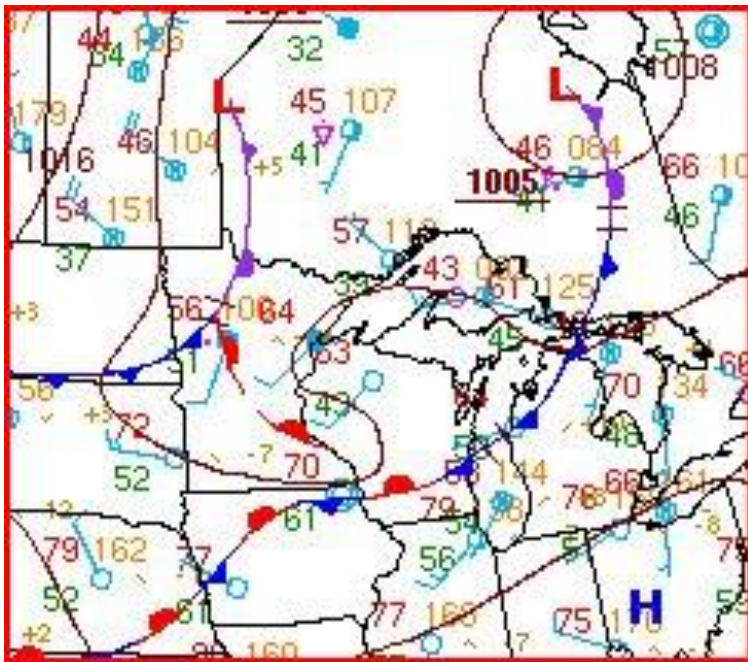


Figure 4: 1906 UTC June 23, 2004 HPC Surface Analysis. Two surface low pressure centers in Canada, with associated frontal systems. The front in Wisconsin is stalled as a stationary front, and a new warm front has formed at the juncture of the cold and occluded fronts in the western most cyclone.

At the next time a surface analysis was issued by the HPC, 2200 UTC, the frontal system had yet again evolved from its previous state only three hours

prior. This time, the portion of the stationary front that extended over southern Wisconsin previously, started to lift back towards the north. It was able to move back northwards because the warm front over Minnesota moving towards the northeast joined to the stationary front and helped to push it back towards the north as one much larger warm front that extended from Minnesota to lake Michigan. The warm front was still connected to the cold front from the original surface cyclone that was then near Hudson Bay.

The timing of the warm front coupling with the stationary front to move back north through Wisconsin occurred near the peak solar insolation, which helped to warm surface temperatures and increase instability during the afternoon and evening hours. **Figure 5** is a HPC surface analysis from 2207 UTC June 23, 2004 which shows the surface warm front coupled with the western most cyclone.

With the stationary front now coupled to the pre-existing warm front and pushing to the north, the front became frontogenetically active. The process of frontogenesis, without getting into the specific dynamics of the process, results in a thermally direct circulation. This frontogenesis process proves to be one of the main forcings for ascent during this severe weather outbreak. The area where the Madison tornado occurred also appears in the warm sector behind the warm front but ahead of the advancing cold front, and this triangular area is a common place for deep convection to occur under the right circumstances. These right circumstances are outlined in the following mesoscale evolution section later in the case study.

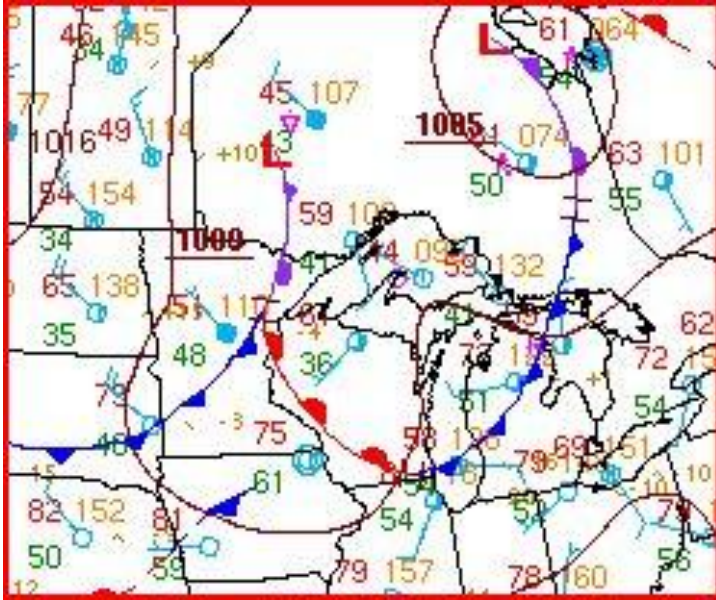


Figure 5 (left): 2207 UTC June 23, 2004 HPC Surface Analysis. Two surface low pressure centers in Canada, with associated frontal systems. Previous stationary front in southern Wisconsin, bringing with it warmer air and higher moisture contents now coupled with a warm front and has begun to push back northwards through Wisconsin.

By the evening of June 23 (0000 UTC June 24) the synoptic conditions at upper levels had begun to reflect the effects of the warm front lifting back north through Wisconsin. There was still very little upper level forcing for ascent, similar to the previous 24 hours.

The hour of 0000 UTC is very near to the peak of the tornadic activity. At the 850 hPa level, as shown in the upper left plot in **Figure 6(a)**, when compared to the previous **Figure 2** it is evident that the atmosphere at this point has warmed significantly from its previous temperature over southern Wisconsin. This indicates a 24 hour positive change of near 5 Celsius in the area of interest.

The warm front moving back through Wisconsin brought along with it more southwesterly winds at 850 hPa which advected more warm air into the region. The surface low in southwestern Ontario now is visible at 850 hPa and on the surface map in **Figure 6(c)** in the lower left hand plot, and is also visible on the 300 hPa map. The vertically stacked low pressure indicates this is still an occluded system, but the warm front remains actively frontogenetic through the 0000 UTC hour on June 24. A slight low pressure center developed at the intersection point of the warm and cold front with the western most cyclone which added some small positive vorticity advection that helped to provide synoptic lift after about 1900 UTC which allowed convection to develop in western Wisconsin and eastern Minnesota by that time (Gehring 2005).

The upper level forcing, as mentioned earlier, remains small even at 0000 UTC June 24 as convection is taking place in southern Wisconsin. Note the 300 hPa map in **Figure 6(b)** that indicates much of Wisconsin is still in the area of upper level convergence of the ageostrophic wind and thus providing subsidence at upper levels. This had been the case 24 hours prior to this time, which slowly acted to destabilize the upper level of the atmosphere by steepening the lapse rates and adding convective available potential energy. This will become important when analyzing the mesoscale evolution of this convective day in southern Wisconsin.

Wisconsin's 5th Largest Tornado Outbreak: A Case Study of 23 June, 2004.
(Manzeck, 2009)

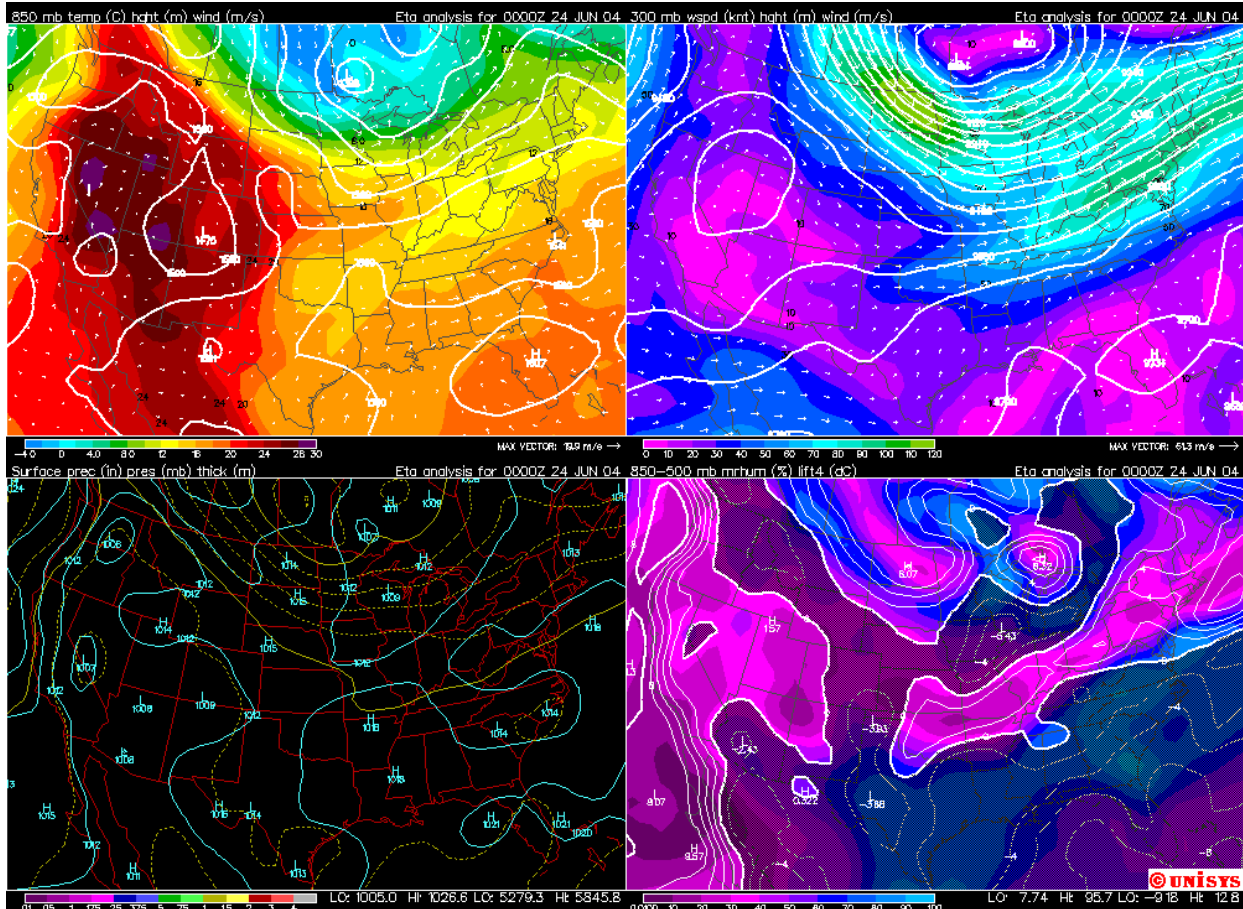


Figure 6 (below): 0000 UTC June 24, 2004. (a) Upper Left: 850 hPa Temperature in Celsius contours and wind vectors. (b) Upper Right: 300 hPa wind contours in knots. (c) Lower Left: surface pressure contours with 500 hPa thickness in yellow. (d) Lower Right: Lifted Index and relative humidity color fills.

The lower right plot in **Figure 6(d)** also indicates that the stability has decreased significantly due to moisture advection and warm air advection from the warm front. The area of negative Lifted Index around -4 over southern Wisconsin now indicates a potential for severe weather, given a forcing mechanism for ascent in that area. This is completely opposite of what the probability for severe weather was 24

hours later due to the passage of the previous cold front. The color fills in that plot also indicate the relative humidities are from the 70 to 80% range in southern Wisconsin which indicates that low level moisture has been advected into the area of interest for convection potential. At this point a majority of the convection in Wisconsin is already occurring due to the warm frontal frontogenesis, which results in rising motion on the warm side of the front. As the synoptic setup evolved through the morning and afternoon hours, it was definitely favorable for severe weather due to warm air in southern Wisconsin and frontogenesis providing lift by approximately 2000 UTC. The Storm Prediction Center issued a moderate convective outlook by 0100 UTC June 24, at almost the exact

time that storms began generating tornadoes in southern Wisconsin.

V. Mesoscale Evolution

At 1200 UTC on the morning of June 23, conditions in southern Wisconsin did not appear favorable for a significant severe weather outbreak during the afternoon, but the evolution of the synoptic conditions changed rapidly to increase the severe weather threat. As a result of the changing synoptics, the mesoscale conditions also rapidly changed to become more favorable for destabilization and significant severe weather to occur. In the following sections, a number of mesoscale parameters for severe weather will be discussed, and how they impacted storm development. The parameters important to this severe weather outbreak include directional wind shear, CAPE and Lifted Index. To examine these parameters a skew-t diagram and a hodograph will be analyzed along with a Miller diagram for general severe weather threat diagnosis.

a) Miller Diagram

The Miller Diagram began as a tool for analyzing severe weather potential that was started by Robert Miller and Ernest Fawbush in 1948. Tinker Air Force Base was struck by a tornado, and afterwards these two men were in charge of trying to forecast the potential for tornado producing storms and came up with the Miller Diagram as a tool for diagnosing severe weather potential (Dan Henz, 2009). Miller Diagrams today are still a useful tool in making a hand analysis of the potential for severe weather within a given area.

Figure 7 is a hand drawn Miller Diagram that is valid for 2000 UTC on June 23, 2004. The important area to note is the black dotted region in southern Wisconsin where the greatest

threat is diagnosed for tornado producing storms. The moisture tongue at 850 hPa is seen in the green line south of the warm front, and the 850 hPa wind direction is seen in the red arrows pointing out of the southwest. Also, it is important to note that the 700 hPa moisture content is contoured by a brown hatched line. When the atmosphere at 700 hPa and above is significantly dried out compared to lower levels, this adds to the potential for severe weather and can help in causing vigorous updraft speeds from surface lifted parcels. An elevated dry layer also means that the threat for mid-level convection is unlikely due to high

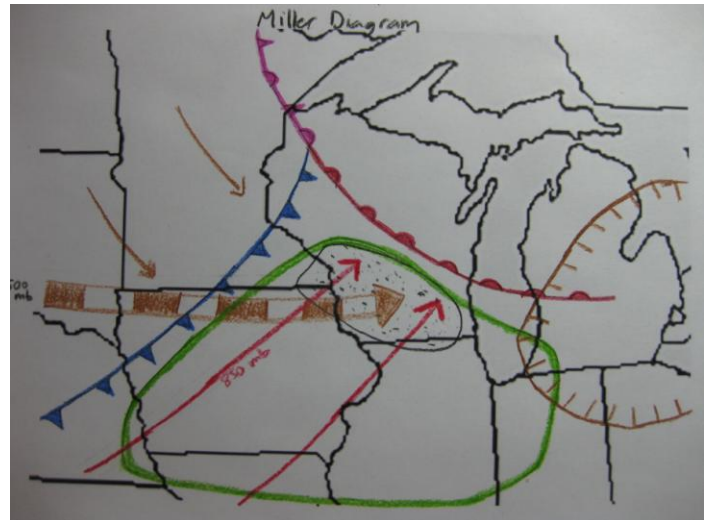


Figure 7: 2000 UTC June 23, 2004 Miller Diagram. Shown: 850 hPa moisture tongue (green), surface fronts, 700 hPa moisture (brown dashed), 500 hPa general flow (brown hatched arrow), and 850 hPa general flow (red arrow)

dew point depressions. The combination of the warm frontal region being frontogenetically active, along with the advancing cold front and influx of surface moisture from the south, provided for the necessary ingredients for surface parcel-based severe weather.

The veering wind profile with height can also be seen on the Miller Diagram, where the 850 hPa winds are out of the southwest, and the 500 hPa winds are more westerly. The change in wind direction with height even from the surface to 850 hPa could have caused a small amount of convergence and thus vertical lift in the area of southern Wisconsin, however since the wind speeds at the surface were relatively light, any convergence here would have not likely been enough to set off convection by itself. The active fronts were the main cause for convection during the afternoon on June 23, and this was enabled by the destabilization of the air ahead of the fronts in southern Wisconsin.

b) Destabilization / Initialization

Although the conditions in southern Wisconsin remained stable during the morning hours of June 23, a process of destabilization took place during the late morning and afternoon hours. A round of showers and thunderstorms that moved through the area of interest during the early morning hours on June 23 allowed for relatively stable conditions to be in place until about 1600 UTC. In the wake of this round of showers and storms, clear skies began to build in. The clearing skies then allowed surface temperatures to warm up into the mid 60's with dewpoints in the low 50's by late morning. However, since the warm front began to lift back north and the southerly winds increased across southern Wisconsin, the surface temperatures soared much higher, reaching the mid 70's by 0000 UTC, along with dewpoints near 60 degrees Fahrenheit.

Due to the influx of warmer temperatures and higher humidity from synoptic conditions, severe weather

parameters began to increase by 0000 UTC June 24. Farther towards the west, near the Wisconsin and Minnesota border, strong convection was initialized by the quickly advancing cold front and began to move towards southern Wisconsin. The clear skies had allowed temperatures to reach higher than expected, while southerly winds advected significant moisture into the area. When the advancing front encountered this relatively unstable surface layer, convection was initialized by 2200 UTC and quickly reached severe thunderstorm levels, with straight line damaging winds being the main threat at this time. The threat for tornadoes was not yet evident in southern Wisconsin however, as these storms advanced towards the southeast at about 55 miles per hour.

c) Severe Weather Parameters

Analysis of the atmosphere in southern Wisconsin by 0000 UTC June 24 began to identify a chance for storms to become supercells and potentially drop a few tornadoes. Severe weather parameters can be a useful tool to diagnosing the chance that convection could reach severe status. There are a couple of main parameters that are used often to diagnose supercell and tornado threat in conjunction with each other. The primary parameters that important to consider in this case are Convective Available Potential Energy (CAPE), Surface Relative Helicity (SRH) and the Lifted Index. A combination of the right conditions with these parameters can cause the potential for severe weather. On June 23 in southern Wisconsin, CAPE increased significantly throughout the day, as well as the SRH and speed shear values. The Lifted Index also became more and more indicative of severe weather as the day progressed and

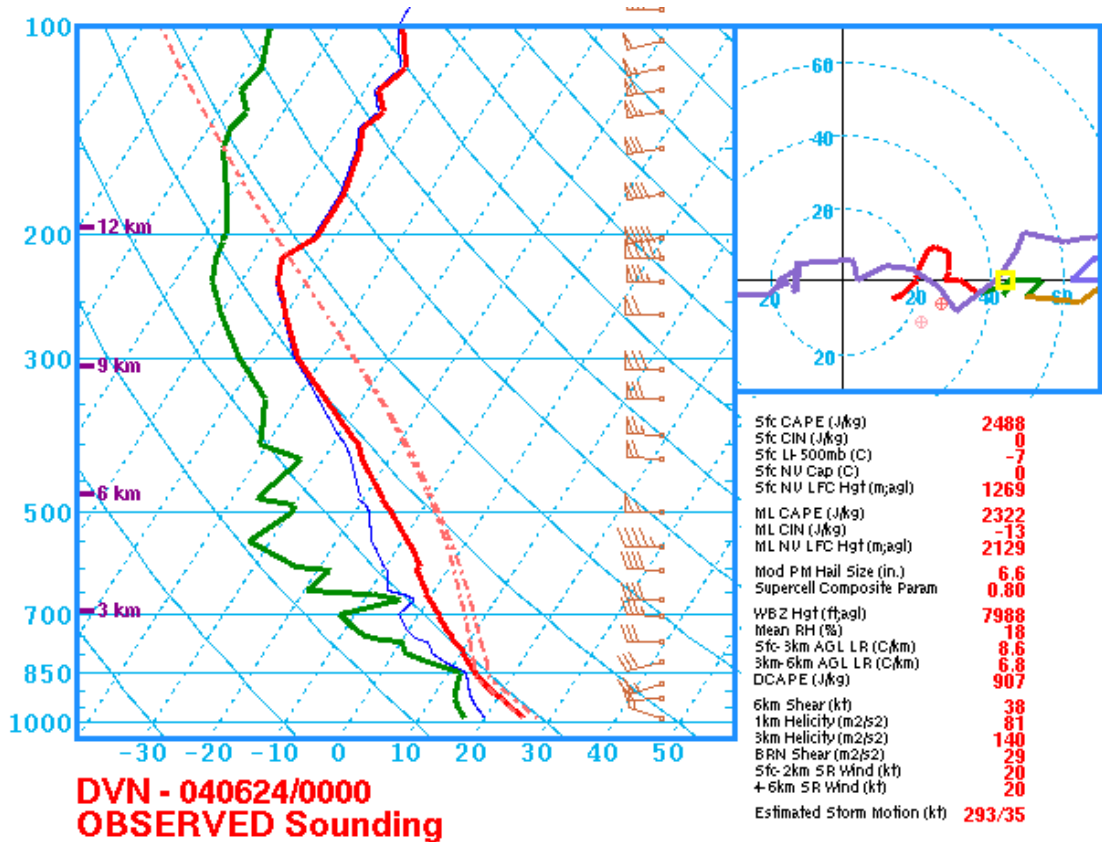


Figure 8: 0000 UTC June 24, 2004 sounding from Davenport, Iowa. Note the high CAPE value of 2322 J/Kg. This hodograph shows a slight veering wind with height above the surface, but since this sounding is not taken from southern Wisconsin, a hand drawn hodograph is provided in Figure 10 as a more accurate representation of helicity in southern Wisconsin.

destabilization processes took place, as already explained.

In order to achieve a level of positive buoyancy within convection, there must be a positive quantity of CAPE within the atmosphere. CAPE can be thought of as buoyant energy, and on a skew-t diagram as shown later is defined as the area between the parcel and environment temperatures from the level of free

convection to the equilibrium level (Henz 2009). Generally, values of 1000 joules per kilogram or greater of CAPE is accepted as a threshold for severe weather potential. Values above this can cause significant updraft speeds to cause deep convection.

During the day on June 23 in southern Wisconsin, CAPE values began to rise from zero in the morning hours (as often CAPE is zero due to the diurnal radiational temperature inversion) to values exceeding 1000 J/Kg by 0000 UTC June 24. This increase in CAPE was made possible by increasing the surface temperature along with surface dew point temperatures as described in the synoptic analysis and Miller Diagram, which allowed for a lower level of free convection in the

atmosphere and therefore an increase in CAPE. **Figure 8** is a skew-t diagram from 0000 UTC June 24, on which the value for CAPE is seen at a level above 1000 J/Kg. Note that the skew-t for this case study was not taken from southern Wisconsin because past radiosonde observations are not available for this area. Therefore, the closest site that demonstrated a significant CAPE value was chosen, and this radiosonde observation came from Davenport, Iowa. It is important to note that while CAPE values were significant, convective inhibition values remained small, which means that the amount of lift required in order to realize the convective potential energy was small for the southern Wisconsin area.

While values of CAPE in southern Wisconsin ranged from 1000 to 15000 J/Kg which can result in severe thunderstorms, another parameter needs to be considered for the potential of tornadic supercells to exist. The primary method by which meteorologists diagnose the tendency for storms to begin to rotate in a cyclonic manner is called helicity. For severe weather and tornadoes to occur, the helicity within the bottom 0 to 3 kilometers is considered most important, and this is referred to as surface relative helicity (SRH).

Positive SRH values are generated when the vertical wind profile veers with height. During this tornado outbreak, the winds at the surface in southern Wisconsin were generally out of the south-southwest, and they veered to the west and west-northwest up to 500 hPa. Starting at 1200 UTC, SRH values throughout Wisconsin were below 40 m^2/s^2 , and therefore the threat for convection to rotate at this time was near zero. However, due to the warm air

advection from the southwest and prevailing surface winds that switched from the west-northwest to the south-southwest, helicity values increased throughout the day in southern Wisconsin, to the point where they finally reached values around 250 m^2/s^2 . **Figure 9** is an image of SRH Shear over the Midwest region from the Storm Prediction Center's Index of severe weather events which shows most of southern Wisconsin in an area of 200 to 250 SRH Shear values.

This situation is relatively typical of the warm sector in a developed surface



Figure 9: SRH Shear in Wisconsin valid at 0000 UTC June 24, 2004. Values of 200 to 250 can be seen in green in southern Wisconsin where the tornado outbreak occurred on the evening of June 23.

cyclone for SRH Shear values to be indicative of severe weather. Warm air advection nearly always has this characteristic of veering winds with height, so it comes as no surprise that SRH Shear values in southern Wisconsin increased to values indicative of rotating supercell thunderstorms. The dynamics of the rotating supercell thunderstorm will be briefly considered in the section titled "Madison, WI Supercell" where a

closer look is taken at an individual storm that produced a tornado within the city limits of Madison, Wisconsin.

Another way to visualize veering winds with height is on a diagram called a hodograph. On this diagram, the wind speeds and directions are plotted so that when a wind profile turns clockwise this represents veering winds with height and therefore a potential for thunderstorms to rotate as they encounter a veering winds with height environment. **Figure 10** is a hand drawn hodograph from Milwaukee, Wisconsin (near Madison) at approximately 0000 UTC. The wind vector positions on the hodograph were analyzed using ETA model at its initialization time of 0000 UTC June 24, using GARP to display a wind profile on a skew-t from KMKE. This clockwise pattern once again indicates that the environment in southern Wisconsin is loaded with rotation potential and increases the chance for supercell thunderstorms and tornadoes. The clockwise pattern is caused by the wind speeds increasing with height, along with veering back towards the west-northwest. While wind shear with height allows thunderstorms to sustain their updrafts, directional wind shear allows mesocyclones to develop and sustain themselves within supercell thunderstorms.

Although briefly mentioned earlier, the Lifted Index is another useful diagnostic tool for identifying the potential for severe weather. For this section, refer to **Figure 6(d)** for a plot of the Lifted Index at 0000 UTC June 24.

The Lifted Index measures the amount of positive buoyancy of a surface lifted parcel at the 500 hPa level of the atmosphere. This can also be visualized on an atmospheric sounding, but is plotted in **Figure 6(d)** also. This

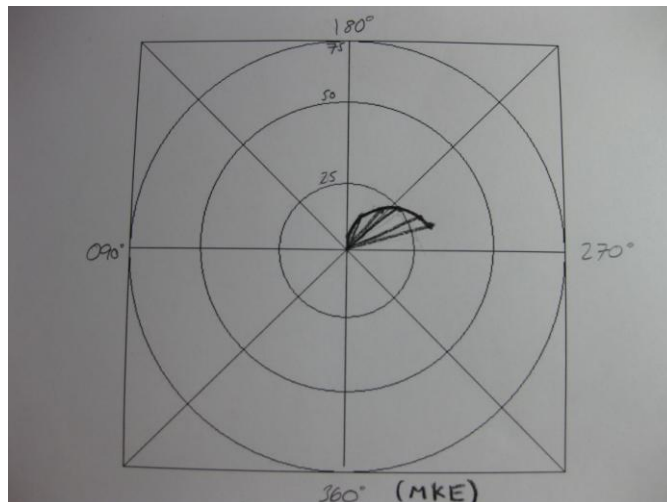


Figure 10: Hand Hodograph analysis from MKE at 0000 UTC June 24, 2009. Wind vectors are drawn towards the direction the wind is blowing from. Note the clockwise signature indicating veering winds, generating positive helicity.

measure of stability is taken by subtracting the environment's temperature from the surface lifted parcel's temperature at 500 hPa. When the lifted parcel value is larger than the environment parcel, this results in a negative number for the Lifted Index. The smaller the number is negative, the greater the chance is considered for severe weather given a lifting mechanism at the surface. Values of -4 or lower represent the probability of severe thunderstorms, with tornadoes probable (Henz, 2009). **Figure 6(d)** indicates the Lifted Index is smaller or equal to -4 in southern Wisconsin.

d) Precipitation Evolution

Beginning around 2300 UTC on June 23, a broken line of severe thunderstorms developed just ahead of the rapidly advancing cold front near LaCrosse, Wisconsin. Along with this broken line of storms, one discrete storm to the south of this line erupted and began to travel in the east-southeast

direction with the main cluster of convection to the north. This precipitation as mentioned earlier was initialized by the active cold front and warm front which provided sufficient lift to break the small cap and realize the 1000 to 1500 J/Kg of CAPE in the southern Wisconsin region. As this convection moved towards the east-southeast, discrete storms within the broken line, along with the one storm to the south began to encounter the environment where SRH Shear values were at or above 200 m²/s². Once these storms entered the higher shear region, they began to rotate as individual storms within the line of severe convection. The lone storm to the south also began to rotate, and this is the storm that produced a tornado that passed through Madison, Wisconsin as the whole frontal system approached from the west. With all the severe parameters that have been analyzed, along with the synoptic situation, the ingredients were in place for a tornado outbreak over southern Wisconsin. Although it was not initially predicted well by numerous computer models, it was apparent by 0000 UTC on June 24 that strong storms entering the southern Wisconsin area would encounter a high shear regime and have a chance to produce tornadoes (Gehring, p.127). The large scale tornado outbreak has been justified thus far, and now the specific storm that passed through Madison, Wisconsin is analyzed.

e) Madison, WI Supercell

Although the supercell that hit Madison only produced an EF-1 on the Enhanced Fujita scale, it is a significant tornado since Madison is a highly populated area and is the state's capitol. The EF-1 rating is defined as a tornado with wind speeds estimated to range

from 86 to 110 miles per hour (SPC Enhanced F Scale). Storm surveyors after the supercell struck determined the Madison tornado to be EF-1 strength with winds estimated at 100-110 miles per hour.

The tornado that struck Madison, Wisconsin around 8:30 pm local time dropped down from a high precipitation supercell. This supercell developed as a high precipitation severe thunderstorm encountered a region of high instability due to daytime heating and warm air advection, along with high SRH Shear values which initialized rotation within the storm. This rotation within the storm is produced from a vortex tube that initially begins horizontal to the ground. As the storm becomes more vigorous, this vortex tube gets tilted vertically in the middle by the main updraft within the storm, which produces two vertical vortex tubes, one that spins anti-cyclonically on the north side of the storm and one that spins cyclonically on the south side of the storm. The veering winds with height profile that was in place over southern Wisconsin tended to promote the vortex tube with positive vorticity, that is, the vorticity vector within the rotating tube was pointed in the positive Z direction. While the cyclonically rotating tube becomes reinforced by the wind profile, the anti-cyclonic vortex tube gets destroyed by the positive vorticity background shear, since the anti-cyclonic vortex has its vorticity vector pointed in the negative Z direction. This process of splitting the vortex tubes in a storm causes a right moving storm and a left moving storm. The left mover contains the anti-cyclonic vorticity tube and quickly tends to die as it propagates to the left relative to the initial storm motion. The right moving storm maintains itself with a cyclonic

rotation within which is the mesocyclone. This storm tends to move to the right relative to the initial storm motion (Tripoli, 2009).

This exact process of storm splitting and mesocyclone development is visible from a NEXRAD reflectivity image from Sullivan, Wisconsin. As the strong thunderstorm moves towards the east and encounters higher SRH Shear values in southern Wisconsin, the storm splits shortly after crossing the Wisconsin and Minnesota border. The left moving storm propagates to the north and fades as it merges with the existing broken line of rotating embedded supercells. The right moving storm then maintains itself and pulls a slight move to the south, pushing it along an east-southeast path directly towards the city of Madison. As long as the supercell encounters a favorable environment for the mesocyclone to exist, it will continue to spin and contain the threat to drop down a tornado from its lowered cloud base (Tripoli, 2009).

The reflectivity of this supercell by the time it reached Madison was about one and a half times the size of Dane County, about 5,000 square kilometers. An image of the base reflectivity as the supercell passed right over Madison and spawns a weak EF-1 tornado is shown in **Figure 11**. This same supercell retracted its tornado but maintained its mesocyclone as it exited Dane county, and then re-strengthened as it entered Jefferson and Walworth Counties and spawned another tornado, also an EF-1.

The tornado that struck Dane County began at 7:35 pm local time 3 miles southwest of Middleton and ended at 7:44 pm local time 2 miles southwest of Madison. While the tornado was on the ground, it produced an average damage path width of around 150 yards

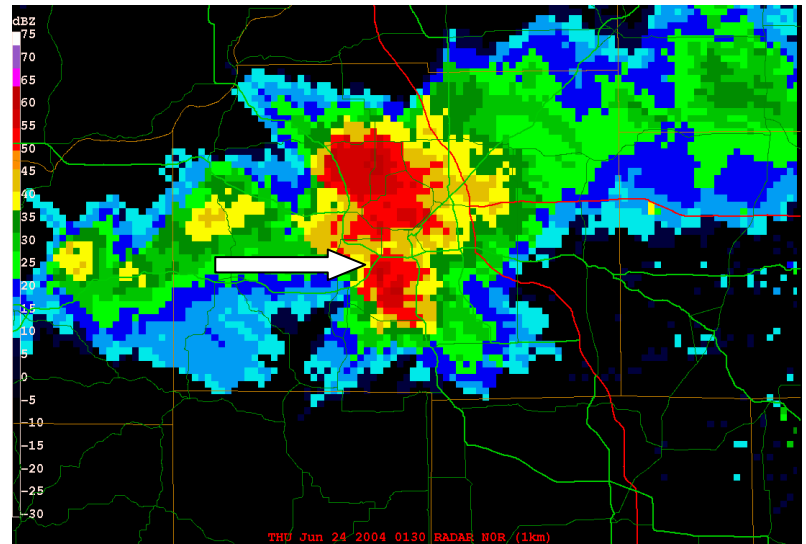


Figure 11: Base reflectivity image from June 24, 2004 0130 UTC. Shown is the supercell that spawned the EF-1 tornado over Madison, WI. The white arrow indicates the position of the tornado as it passed through Madison. along a path of 8 miles (NCDC Event Record).

According to the storm report from the National Climatic Data Center, at least 194 residential homes had minor damage (roof/siding) while 11 sustained major damage (windows/roofs). Total residential home damage was estimated at about \$410,000, while \$246,000 more in damage was inflicted to businesses, and the UW-Madison Research Park had about \$749,000 in damages. At least 1000 large trees were damaged which resulted in 2000 homes losing their electrical power from the tornado. Although the total damage estimated to property totaled approximately \$1.5 million for this 8 mile damage path, luckily no injuries or deaths were reported in this highly populated area of southern Madison (NCDC Event Record).

However, this was only one tornado of a total 17 that struck southern Wisconsin on June 23, 2004. The tornado outbreak unfortunately caused one death and 23 other injuries, while total property damage was estimated at \$28.8 million. Along with the property damage, approximately \$3.1 million in crop damage was lost. Overall this day ranks as Wisconsin's fifth largest tornado outbreak since modern records began. The strongest tornado reported came from the embedded line of supercells to the north of Dane County, where one particular storm dropped a tornado five

separate times. The strongest of these tornadoes was estimated at an EF-3 rating with winds ranging from 175 to 200 miles per hour. **Figure 12** is a schematic courtesy of the National Weather Service office in Sullivan, Wisconsin of the total storm reports from June 23, including individual tornado paths drawn in pink.

VI. Conclusion

The afternoon and evening of June 23, 2004 was not initially seen as a very high risk day for a tornado outbreak in southern Wisconsin. However, rapidly evolving synoptic conditions brought a warm front back through the area which brought with it warmer temperatures and dewpoints than were originally expected. The evolution of the surface fronts allowed for many mesoscale conditions to become favorable for mesocyclone and supercell development. The existing storms that moved into southern Wisconsin encountered a regime of veering winds with height, high amounts of CAPE, and unstable air as indicated by the Lifted Index. Dew point depressions in the area were small enough to support low cloud bases and therefore once the CAPE of around 1500 J/Kg, SRH Shear of 200 m²/s² and Lifted Indices of less than -4 built in, a tornado outbreak was looming. These storms began to rotate once they entered southern Wisconsin, producing a total of 17 confirmed tornadoes in one day, including one supercell thunderstorm that dropped a tornado in and near the city of Madison.

One important point to take away from this case study is the fact that severe weather is difficult to forecast, even within only one particular day. Computer models are not always correct, and a rapidly changing environment under the right conditions could produce

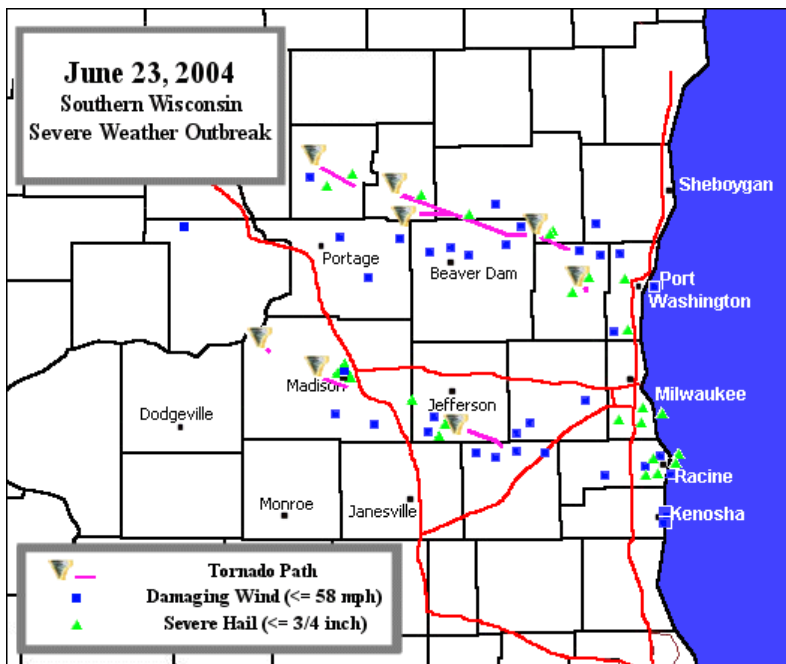


Figure 12: June 23, 2004 Tornado outbreak in southern Wisconsin. Tornado paths are shown in pink with 'vortex icons' while wind damage is shown by blue squares and severe hail is denoted by green triangles. Note the series of 5 tornado paths to the north of Portage and Beaver Dam resulting from one particular embedded supercell, and the tornado path going through Madison, WI.

a widespread severe weather outbreak without much warning time at all. It is my hope that research within the field will be able to help improve lead times for evolving systems like the one described in this case study and hopefully provide greater confidence in a potential widespread severe weather outbreak.

VII. References

- Back, Larissa. Lecture: *Convective / Mesoscale Instability and how to generate it via synoptic scale processes (January 2009)*.
- Henz, Daniel. Lectures: *Miller Diagrams (April 2009)*. *Stability Indices (February 2009)*.
- Gehring, Mark G. National Weather Digest. *The Wisconsin Tornado Outbreak of 23 June 2004*. Vol. 31, no.2 2007. P. 122-136.
- National Climatic Data Center, Event Record Details. Wisconsin, Dane County Tornado. <<http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~561620>>. Accessed April 2009.
- NWS Milwaukee/Sullivan, WI. *Tornado Outbreak June 23, 2004*. <<http://www.crh.noaa.gov/mkx/document/tor/062304.php>>. 2005. Accessed April 2009.
- Storm Prediction Center. Index of Severe Weather Events. *Severe Thunderstorm Event: June 23, 2004*. <<http://w1.spc.woc.noaa.gov/exper/archive/events/040623/index.html>>. 2004. Accessed April 2009.
- Storm Prediction Center. *Enhanced F Scale for Tornado Damage*. <<http://www.spc.noaa.gov/faq/tornado/ef-scale.html>>. 2007. Accessed April 2009.
- Tripoli, Greg. Lecture: *Cumulus Clouds (February 2009)*.

Unisys Weather. *Upper Air Charts: 04/06/23, 04/06/24*. <http://www.weather.unisys.com/archive/eta_init/>. Accessed April 2009.

VIII. Acknowledgements

I would like to acknowledge Professor Greg Tripoli and teaching assistant Dan Henz for not only providing information vital to this case study, but for giving me the opportunity to research such an interesting topic of my choosing. Without these people, my knowledge and expertise on the subject of this case study would have been severely limited. I would also like to thank Pete Pokrandt for providing access to compiled data from June 23, 2004 in southern Wisconsin. A few discussions with fellow classmates Joseph Hoechst, Bryan Heth and Matt Serwe also aided in providing more direction and helped to clarify some aspects of this case study.