Synoptic and Mesoscale Influences Leading to the Development of the June 18, 2001, Tornado in Siren, WI

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ABSTRACT

On June 19, 2001, at 0120Z, an F3 tornado flattened the small town of Siren, WI, in northwest Wisconsin. As can be seen in Skew-T diagrams from the Chanhassen, MN, sounding site on June 18th and 19th, the daytime heating helped overcome the convective inhibition which left the atmosphere to freely convect with the large amounts of convective available potential energy. The small cap in the atmosphere was easy to overcome with the synoptic scale vertical motions and instability. One such synoptic scale forcing is the positive geostrophic absolute vorticity advection by the 300-700mb thermal wind at 500mb in central Minnesota. There is also evidence of Q-Vector convergence in west-central Minnesota twelve hours before the tornado began to form in east-central Minnesota. Another factor leading to vertical motion in this case can be seen in the negative laplacian of the temperature advection at 700mb. On the mesoscale side, a low level jet at 850mb brought moist air into the region which led to increased instability. The moisture advection caused a strong equivalent potential temperature inversion between 500 and 900mb over much of Minnesota and Wisconsin near the time of the tornado. An important ingredient for supercell formation, wind shear with height, was present in both its directional and speed form. All these factors led to a severe weather outbreak over northern Wisconsin and Minnesota including a violent tornado that killed three people, injured many more, and changed the shape of a town forever.

Introduction

Siren, WI, a town of approximately 850 people, was destroyed by an F3 tornado in the early evening hours of June 18, 2001. Two people died as a direct result of this tornado, another died later indirectly, dozens were injured, and about 150 people were left homeless. The death toll could have been much higher due to the fact that the town's tornado siren was not working. This was the result of a lightning strike that damaged it several weeks prior to the tornado. Also, residents of Siren were unable to receive updated warnings from television because the tornado took out the Northwestern WI Electric Co stations to the west of Siren in both Grantsburg, WI, and Falun, WI, which left Siren with no power. Due to these events it may seem like Siren had no warning of this tornado, but police chief Dean Roland drove through town with a bull horn advising residents to take cover. His warning coupled with the tornado watch, severe thunderstorm warning, and tornado warning that were issued for Siren by the Storm Prediction Center and National Weather Service may have saved dozens of lives. Although there were hundreds of buildings that were either severely damaged or destroyed completely, none of the town's five churches were affected. The tornado finally ended near Spooner, WI, after leaving a half-mile wide and 27 mile long path of destruction.

The interesting combination of synoptic and mesoscale events in the Midwest helped develop the supercell that generated the Siren tornado as well as other severe weather events that took place in Wisconsin on the same day. The mesoscale moisture variables set the stage for widespread instability over northwestern Wisconsin and a small amount of vertical forcing that resulted from the synoptic setup opened the door for deep convection that led to severe weather across the region. Synoptic forcings such as positive geostrophic absolute vorticity advection by the 300 to 700mb thermal wind at 500mb and an area of maximum warm air advection as indicated by the negative laplacian of the temperature advection at 700mb led to the development of a relatively strong negative omega maximum near Mille Lacs Lake in east central Minnesota at 12Z on the 18th. An area of Q-vector convergence in this region also contributed as a synoptic vertical forcing. Another synoptic feature that led to the development of this storm is a warm front that was oriented west-east just south of Siren that moved into the region during the day. This presented another lifting mechanism. The mesoscale instability features included moisture advection by an 850mb jet that brought very moist air into northern Minnesota and Wisconsin, advection of high mixing ratios into the region that developed a strong equivalent potential temperature (theta E) inversion between 500 and 900mb, and daytime heating that helped to overcome the convective inhibition and give rise to a large amount of convective available potential energy in the atmosphere. There were the trigger mechanism that shot off the loaded gun sounding that will be seen later in this paper. Another mesoscale feature leading to the development of this supercell was the wind shear that was present. A sounding from the the Chanhassen, MN, radiosonde site from the University of Wyoming taken at 00Z on the 19th indicates significant speed and directional shear, though it is not as prevalent as the shear seen in the 12Z sounding on the 18th. A sounding taken at 00Z on the 19th is especially useful because the tornado occurred in Siren at 0120Z on the 19th. The winds veer with height, and they also increase in intensity. This shear pattern favors the development of a right-moving supercell. Although there is no looped radar data available for this case, it can be determined that the supercell that formed the Siren tornado was a right mover due to the fact that it intensified in this shear environment.

The supercell associated with this tornado was a high precipitating (HP) supercell. A conceptual model of a HP supercell can be seen in Figure 1. The Siren tornado was most likely formed by a HP supercell rather than an ordinary supercell because the storm formed just north of a warm front. Also, large hail is a characteristic of a HP supercell as opposed to a regular supercell, and hail of 1.75” was reported just north of Siren near the time of

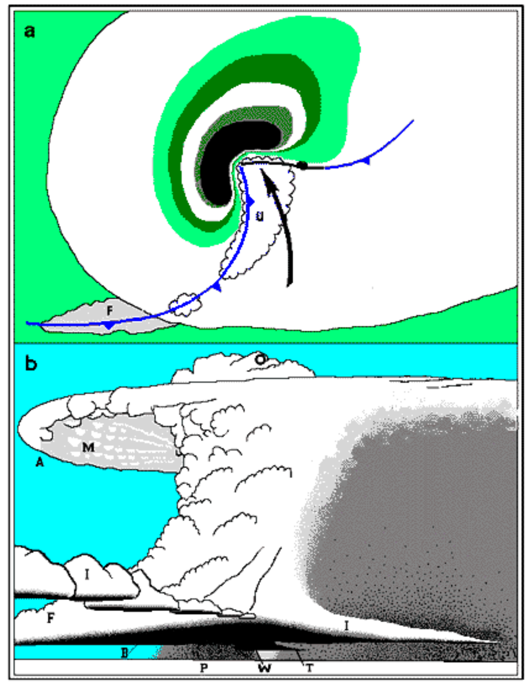

Figure 1. A conceptual model of a HP supercell as it would look from above (a), and how the supercell might look as viewed from the east or southeast (b). In (a), the regions of radar reflectivity are colored according to intensity with black being the most intense precipitation. The area inside the scalloped lines indicate the main updraft (u), and the black arrow indicates the surface inflow. Frontal symbols indicate the location of the gust front. In (b), features include an overshooting top (o), back-sheared anvil (B), wall cloud (w), tail cloud (T), inflow band (I), mammatus clouds (M) and regions of heavy precipitation (P). Image courtesy of dictionary.babylon.com.

the tornado. More impressively, hail 4.5 inches in diameter was reported in storms near Eau Claire, WI, during this severe weather outbreak.

One of the defining characteristics of this case study is the long-lived nature of the storm - the tornado was on the ground for 27 consecutive miles! Once the supercell had formed due to the strong convection and shear, the dynamic pressure gradient caused by the rotation in the storm formed a rigid wall of stability around the updraft and allowed the storm to continue pulling warm, moist air up from the surface into the storm without becoming entrained by dry air that would quickly dissipate the storm. The pressure inside the updraft is lower than the surrounding pressure. Due to the Ideal Gas Law, the temperature in the updraft must cool and therefore causes air parcels to condense quickly when they are sucked in. This forms the wall cloud and eventual condensation funnel and tornado that evolves from this setup.

This case study will investigate the role that the vertical forcings created by the synoptic setup allowed the atmosphere to nearly explode with convection due to the high instability caused by the mesoscale

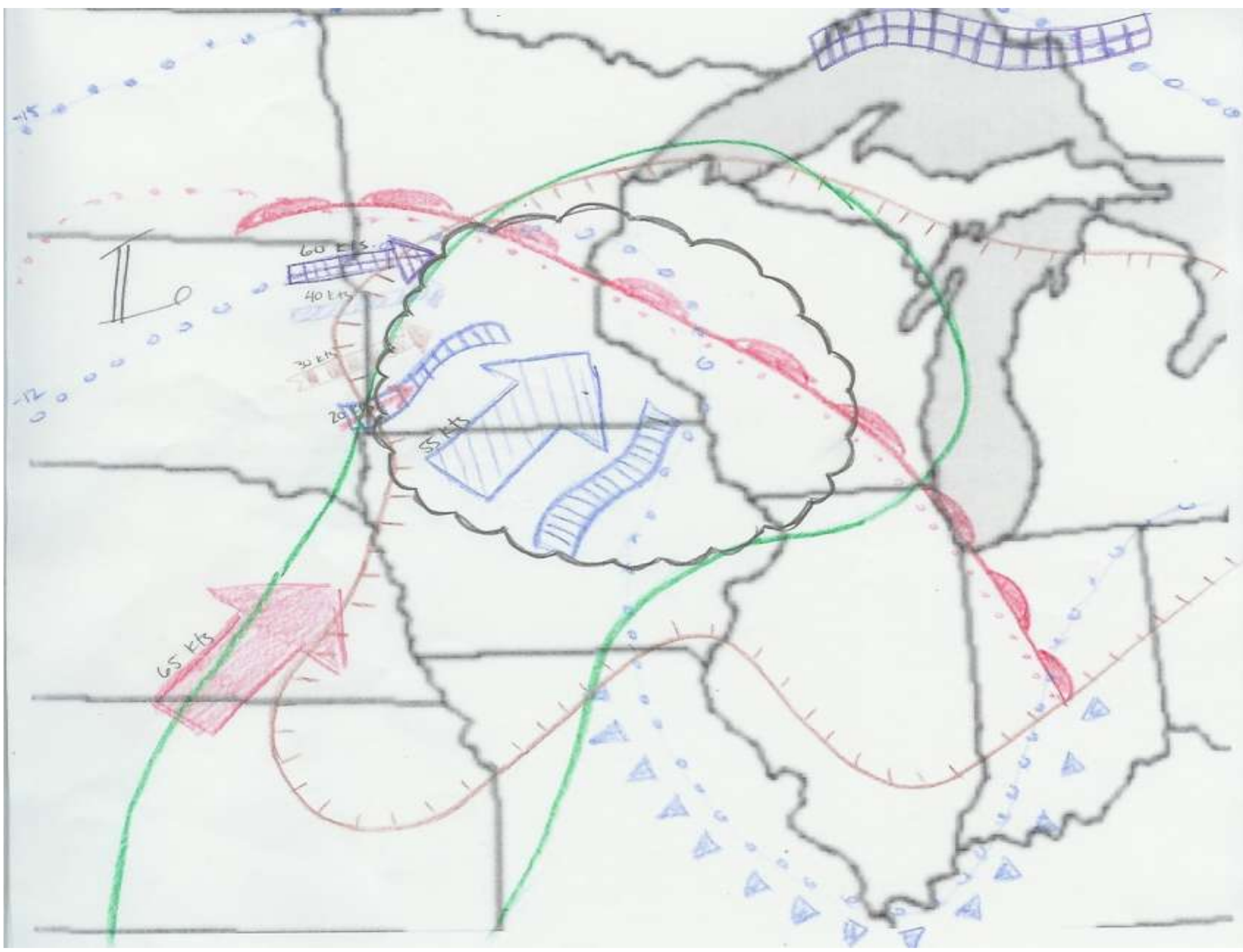

Figure 2. In this figure is a Miller Diagram based on Robert C. Miller's report. The features in this image were determined using ETA model data in GARP at 12Z on June 18, 2001. Key features in this figure are the 850mb moist tongue (green), the 700mb moist tongue (brown) and the veering winds with height. A warm front is draped across central Minnesota and Wisconsin and a low pressure center is located in north-central South Dakota. Combining all these features, the region determined to most likely to experience severe weather is enclosed by a dark gray scalloped line.

situation.

Data

The data used in this case study came from a variety of sources. First, GEMPAK and GARP images that were made used the ETA model. Next, the Miller Diagram that was created used data from GARP and was based on *Notes on Analysis and Severe-Storm Forecasting Procedures of the Air Force Global Weather Central* by Robert C. Miller. Information about the formation of supercell and their steady state was courtesy of a lecture given by Greg Tripoli, a professor at the University of Wisconsin – Madison. The information on severe weather indices was courtesy of a lecture given by Daniel Henz, a teaching assistant at the University of Wisconsin – Madison. Severe weather index values as well as soundings and hodographs were found on the University of Wyoming College of Engineering, Department of Atmospheric Science sounding site. The conceptual model of a HP supercell was courtesy of dictionary.babylon.com. Finally, knowledge of the storm's impact on the community of Siren and its surrounding areas comes from the author's personal experience with this event.

Synoptic Overview

On the morning of June 18, synoptic conditions were looking favorable for the production of severe weather over the western Great Lakes area. A low pressure system situated over South Dakota brought warm, moist air from the Gulf into the Minnesota/Wisconsin area giving rise to

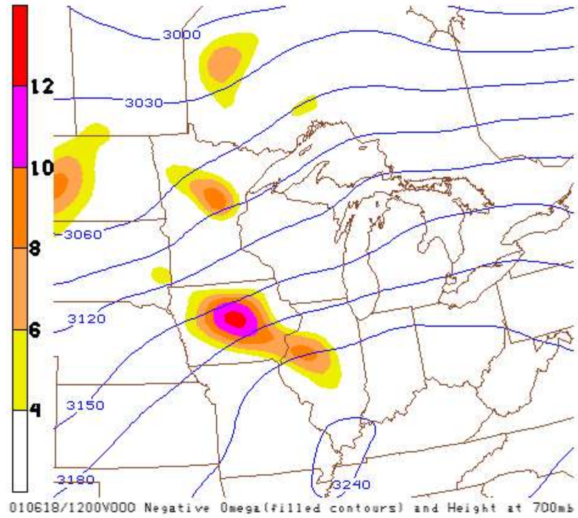

Figure 3. This plot is of height (blue contours) and negative omega (color fills) at 700 mb valid at 12Z on June 18.

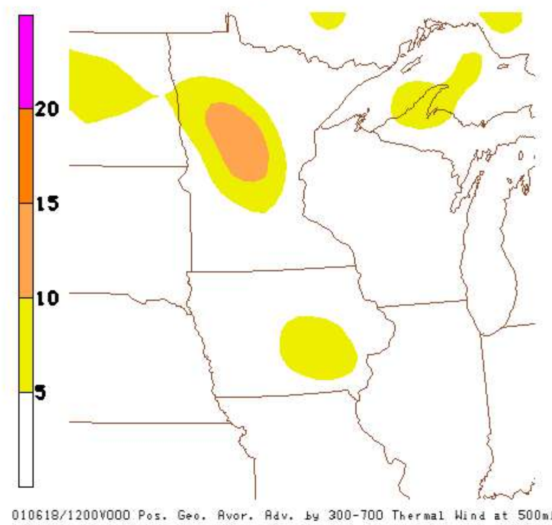

Figure 4. This is a plot of the positive geostrophic absolute vorticity advection by the 300 to 700mb thermal wind at 500mb valid at 12 Z on June 18.

high dew point temperatures. By 12Z, the dew point was already 62 degrees Fahrenheit at the Chanhassen, MN, sounding site. Another feature present at 12Z was a warm front that draped across central Minnesota and into Wisconsin, which can be seen in the hand-drawn Miller diagram in Figure 2. Throughout the day of the 18th, the front pushed north, and may have been one of the key lifting mechanisms for this event.

Using GEMPAK, a plot of was created to show large values of negative omega (rising motion) over regions of northern Minnesota and Wisconsin. This can be seen in Figure 3. Since the atmosphere was so unstable due to mesoscale moisture processes, only a small amount of vertical forcing was needed to result in large vertical velocities. One of the main culprits of this vertical velocity was positive absolute geostrophic vorticity advection by the 300 to 700mb thermal wind at 500mb. The 300 to 700mb thermal wind blows parallel to the thickness lines so areas of positive absolute vorticity advection are expected downstream of absolute vorticity maximums that have thermal wind blowing across them. A plot of positive absolute vorticity advection at 500mb by the 300 to 700mb thermal wind valid at 12Z on June 18th can be seen in Figure 4. An area of relatively strong positive absolute vorticity advection can be seen over central Minnesota. Another variable that can lead to vertical forcing is Q-vector convergence. A plot of 700mb Q-Vector convergence at 12Z on the 18th can be seen in Figure 5. There is an area of strong Q-vector convergence over west-central Minnesota. The convergence is located near

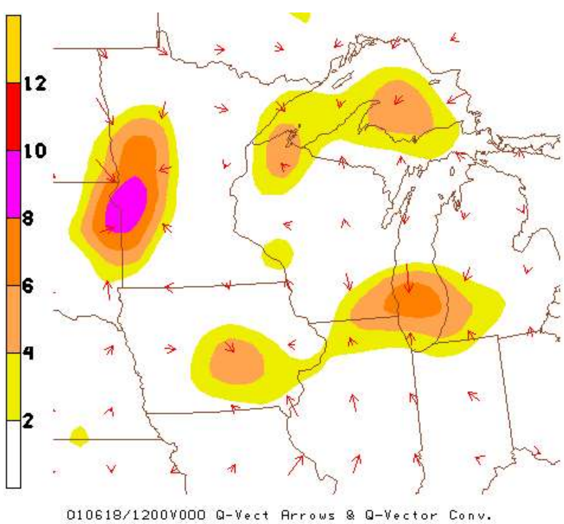

Figure 5. This is a plot of 700 mb Q-vectors (red arrows) and Q-vector convergence (color fills) valid at 12Z on June 18.

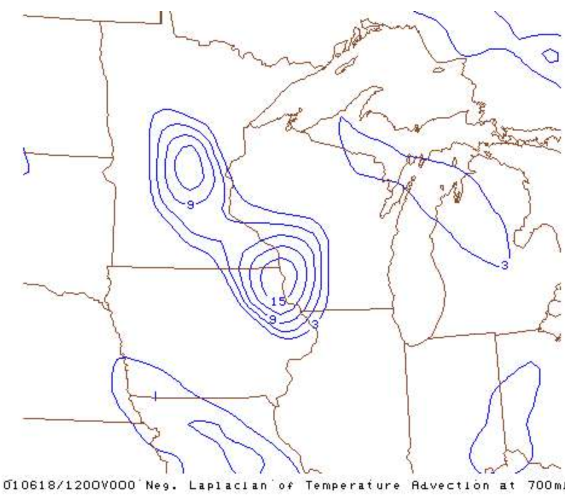

Figure 6. This image is the negative laplacian of temperature advection at 700 mb valid at 12Z on June 18. Only positive values are plotted to represent areas of maximum warm air advection.

the area of positive vorticity advection, and although they do not entirely match up, they merge in west-central Minnesota. Due to the near-alignment of the 500mb positive absolute vorticity advection and the 700mb Q-vector convergence, it would be expected that negative omega would occur in the same area to confirm the diagnosis of vertical motion in this region. However, in Figure 3, the a plot of 700mb negative omega, it can be seen that strongest vertical motions are evident in east-central Minnesota, away from the areas of strongest positive vorticity advection and Q-vector convergence. To help explain the location of negative omega, a third diagnostic, the negative laplacian of the temperature advection was brought in. The negative laplacian of the temperature advection can be used as a diagnostic for vertical motions because it is part of the traditional quasi-geostrophic omega equation. Where there is maximum warm air advection, there will be a minimum in the laplacian of temperature advection because the laplacian is the second derivative of a function. Therefore, a large positive value for the negative laplacian of temperature advection will portray a large amount of warm air advection. A plot of the negative laplacian of temperature advection can be seen in Figure 6 with a maximum which corresponds to the area of negative omega

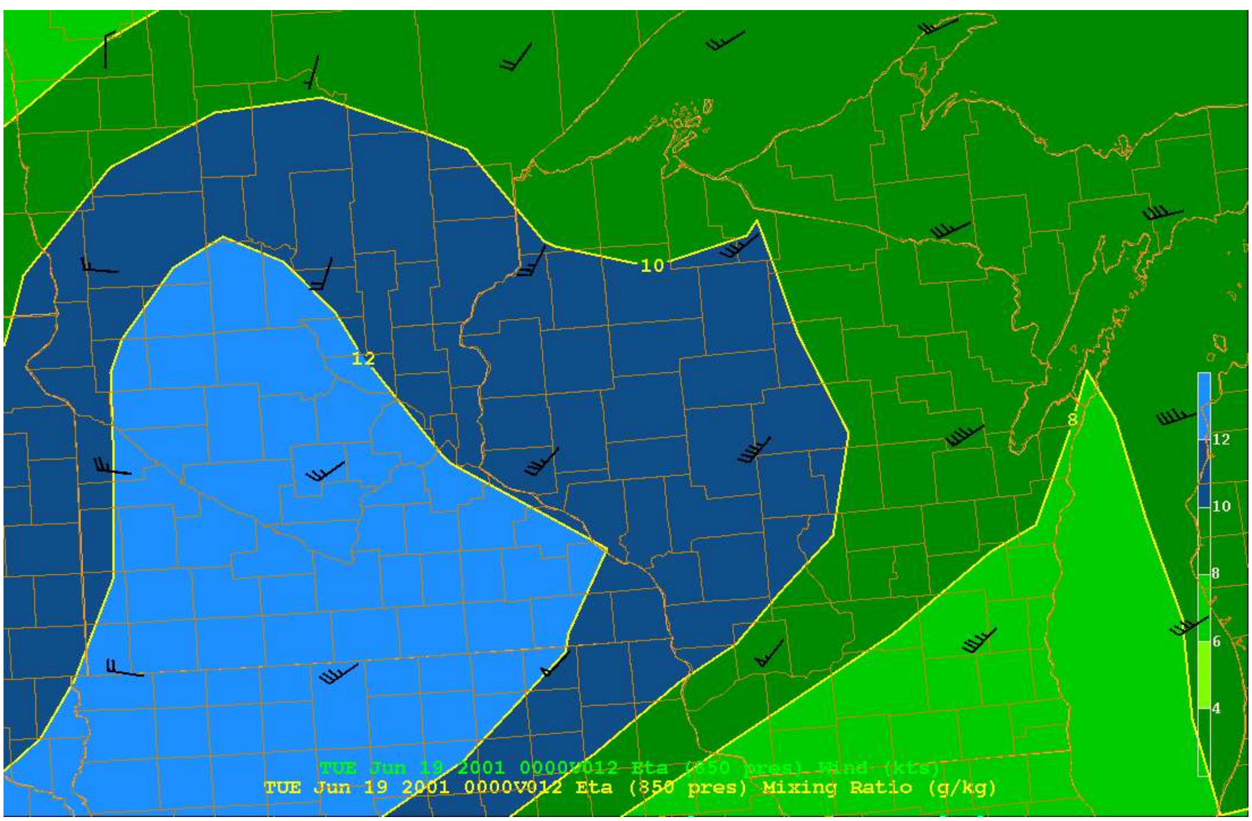

Figure 7. This is a plot made using GARP of the 850mb mixing ratio (color fills) and 850mb wind valid for 00Z on the 19th. In this image we can see areas of moist air being advected into regions of less moist air. This moisture advection led to conditional instability across northern Minnesota and Wisconsin.

seen over east-central Minnesota in Figure 3.

Mesoscale Analysis

The Miller Diagram in Figure 2 connects all the major levels of the atmosphere (surface, 850mb, 700mb, 500mb, jet) on a synoptic and mesoscale basis and is valid for 12Z the morning of June 18th. As mentioned earlier, a surface front was draped across central Minnesota and Wisconsin and pushed northward throughout the day. Two additional features that can be seen on this diagram are the moist tongues at 850 and 700mb and the veering winds with height. The 850mb moist tongue, seen in green, encompasses the entire state of Wisconsin, southern Minnesota, and much of Iowa. Although not depicted in this image, the moist tongue at this level extends as far south as Austin, TX. Usually a dry tongue is depicted in the 700mb level on a Miller diagram, but in this case there is a 700mb moist tongue. This is because the elevated mixed layer begins at 700mb, so this level is still moist. Depicted in brown, the 700mb moist tongue also encompasses Wisconsin and southern Minnesota, most of Iowa, as well as much of Michigan, Illinois, and Indiana. When combined, it can be seen that Wisconsin, southern Minnesota, and Iowa all had a very deep moist layer above the surface. The veering winds with height can be seen with the arrows depicting the direction of the winds in western Minnesota. The small red arrow shows the wind at 850 mb, while the larger red arrow depicts the 850mb jet in eastern Nebraska with a maximum intensity of 65kts. A brown arrow shows the direction of the wind at 700mb while at 500mb a skinny blue arrow depicts the mean flow at this level. There was also a jet at 500mb in south-central

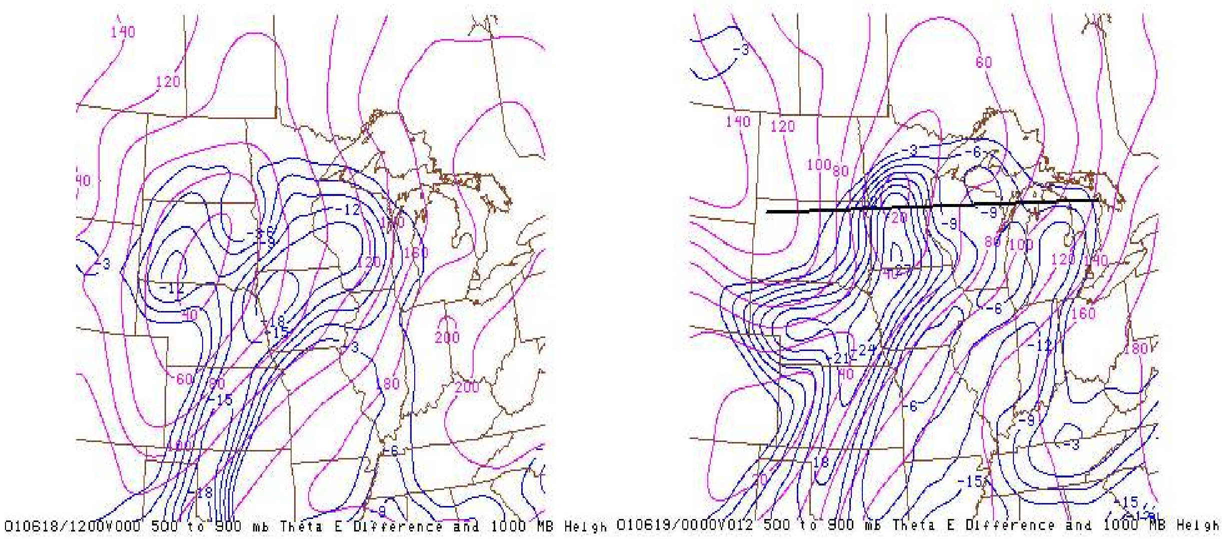

Figure 8. This plot shows the 1000 mb height (pink contours) and 900 mb theta E values subtracted from 500 mb theta E values (blue contours). Only negative values are plotted to show areas of instability. The image on the left is valid for 12Z on June 18, and the image on the right is valid for 00Z on June 19. It is evident from these plots that instability increases during this twelve hour time period. The horizontal black line in the image on the right shows where the cross-section was drawn for Figure 9.

Minnesota shown in the large blue arrow with a maximum wind speed of 55kts. Speed shear lines can be seen on either side of this arrow. Finally, the mean flow at 300mb is seen in the purple arrow with an average wind speed of 60kts. There were two jets at this level, but neither appear on this diagram because they are so far from the Midwest. One jet maxima extended over northern Idaho and west-central Montana while the other was just southwest of Hudson Bay in central Ontario. Due to the jet over Ontario, a speed shear zone developed over northern Lake Superior which is depicted in a wavy purple line. Also, with the jet situated over Ontario, northern Wisconsin was located at a right jet entrance region, which may also have played a small role in synoptic vertical forcing over this region. By combining all these features, a dark gray scalloped enclosed area represents the region most likely to see severe weather.

Widespread instability over the Midwest the morning of June 18th was a key factor in the explosive response initiated by the synoptic vertical forcings. The image of 850mb mixing ratio and 850mb winds in Figure 7 shows that there was strong moisture advection forecasted for much of northwest Wisconsin at 00Z on the 19th. A jet at 850mb is what led to such strong

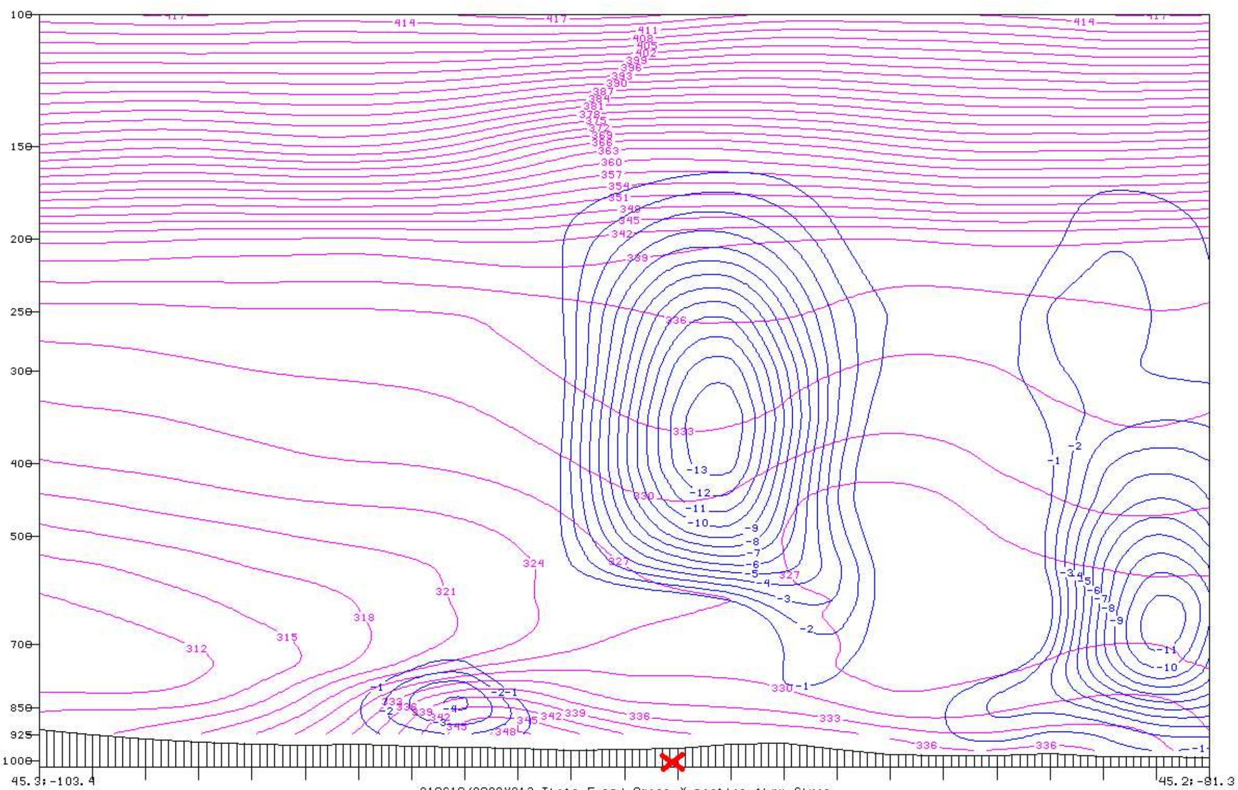

Figure 9. A cross-section showing theta E (pink contours) and omega (blue contours). The red X shows is representative of the location of Siren. The theta E inversion extends from the surface up to 500 mb. The region of largest negative omega nearly aligns with the location of Siren and extends up to 160 mb.

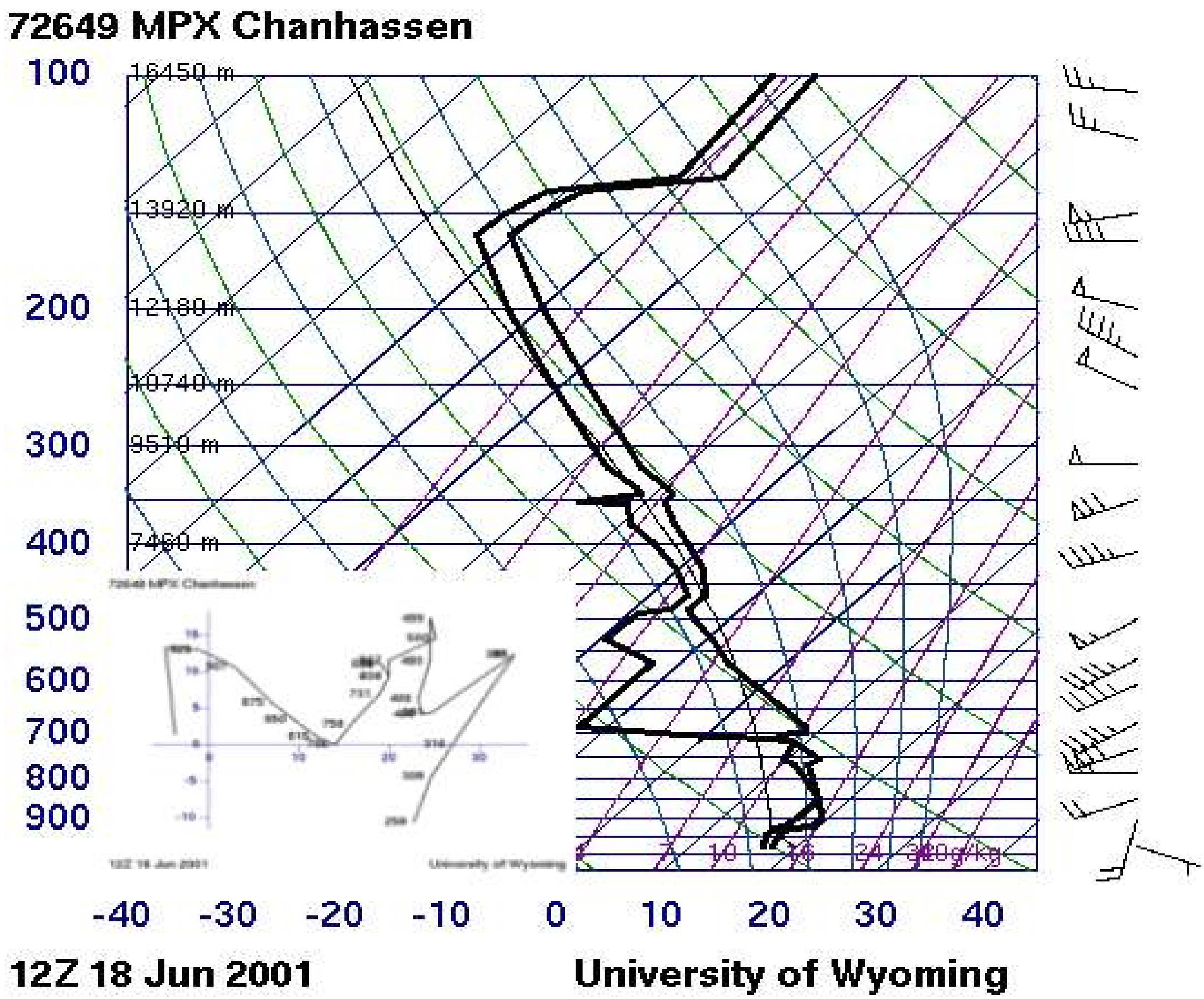

Figure 10. This is a skew-t log-p image with a hodograph embedded in it, both courtesy of the University of Wyoming sounding site. Both the sounding and the hodograph are valid for 12Z on June 18, 2001.

advection at this level. Moisture advection at low levels leads to a high value of theta E at the same level. High values of theta E may indicate instability, but to be sure of this, theta E at lower levels in the atmosphere must be compared to theta E values higher in the atmosphere. This comparison can be seen in Figure 8 where the values of theta E at 900mb are subtracted from the values of theta E at 500mb and plotted along with 1000mb height contours. The first image is a 00 hr forecast from 12Z on the 18th, and the second image is a 12 hr forecast valid at 00Z on the 19th. The negative values indicate areas where theta E was higher at 900 mb than at 500 mb and was thus conditionally unstable. Higher negative values are indicative of higher conditional instability. During the twelve hours between these images it is evident that

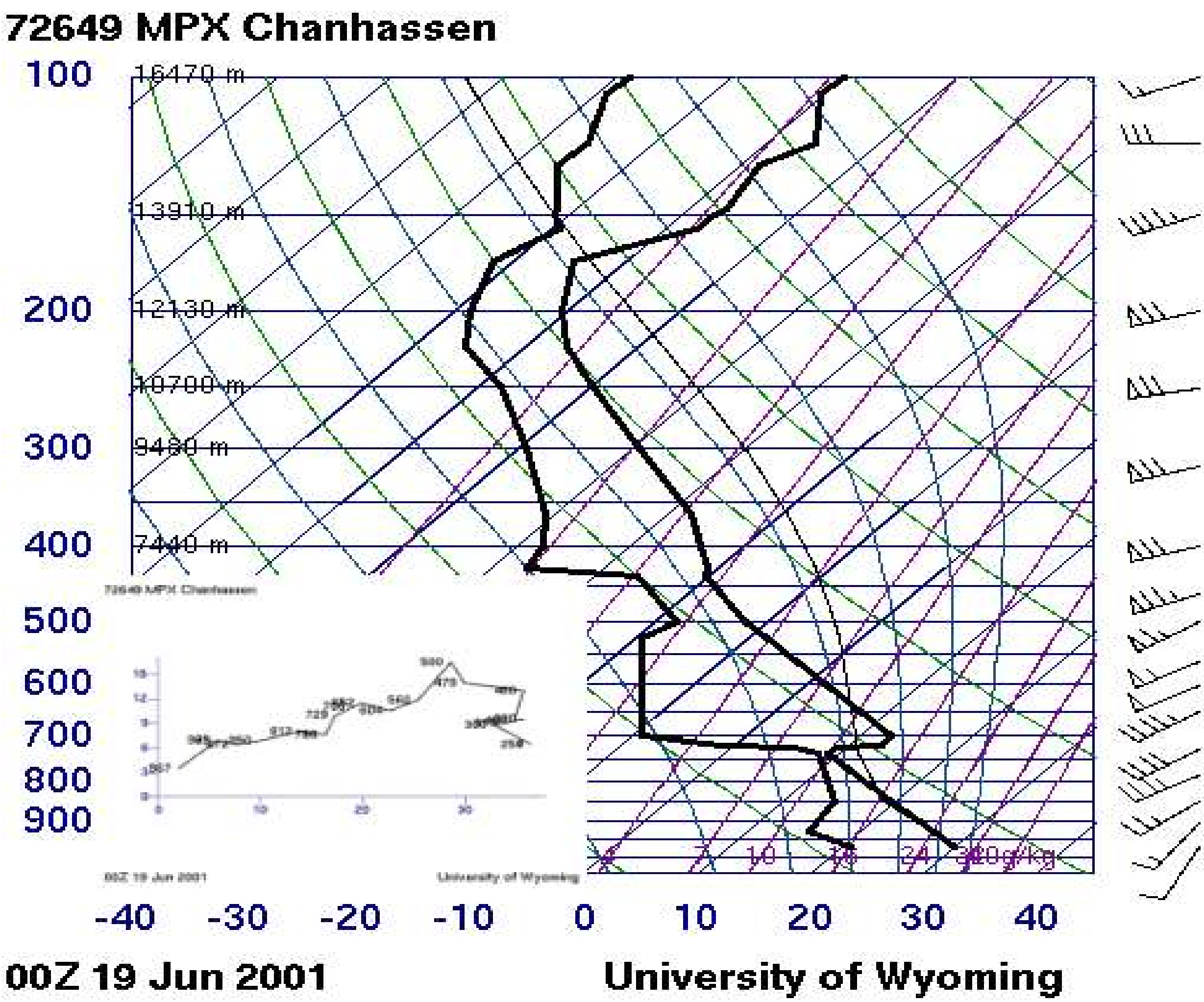

Figure 11. This is a skew-t log-p image with a hodograph embedded in it, both courtesy of the University of Wyoming sounding site. Both the sounding and the hodograph are valid for 00Z on June 19, 2001.

conditional instability increased in central Minnesota. This increase was most likely caused by the daytime heating and the low-level moisture advection. In the second image in Figure 8 there is a black horizontal line drawn. This line indicates the axis along which the cross-section in Figure 9 lies. The cross-section was drawn in this orientation so that it would pass through Siren, WI, the location of which is indicated by a red x in Figure 9 and is valid at 00Z on the 19th. In this figure, the variables plotted are theta E and omega; only negative values of omega are plotted to indicate the locations of rising air. As expected, a theta E inversion was evident at the surface and extended up to about 500mb over the region of Siren. There were three areas where negative omega was significant: one was shallow and located over the area of strongest instability; another

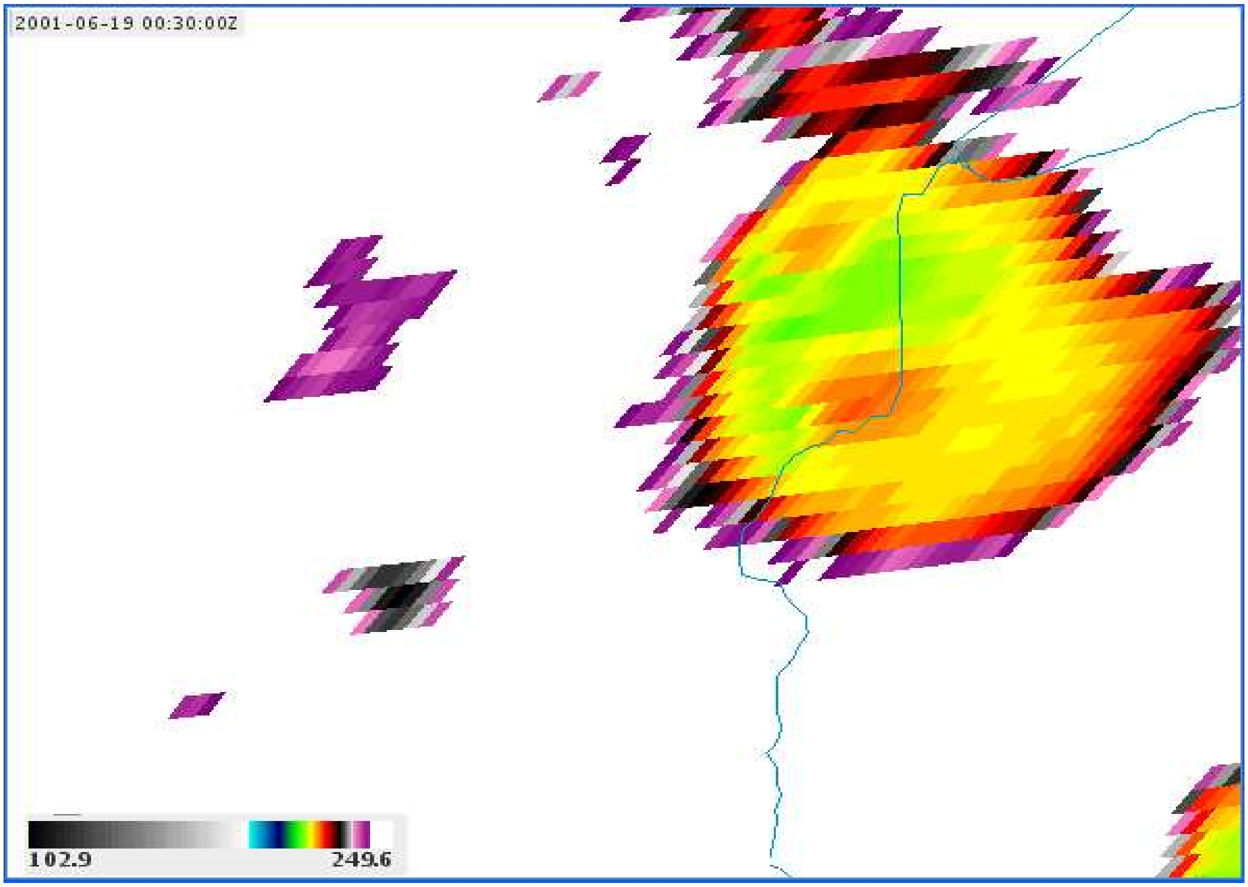

Figure 12. This is a McIDAS-V generated image using GOES8 satellite data. The enhanced-v shown in green is an indication of strong updrafts. A full explanation can be found in the text. This image is valid for 0030Z on June 19, 2001.

was quite strong and located far to the east but is not relevant to this case; and the most intense area of negative omega was nearly over the area of Siren. This region of negative omega begins at 800mb and extended well past the tropopause to an impressive 160mb. Theta E and negative omega were plotted together to demonstrate that high instability near the surface indicates that a parcel of air near the ground would need only a slight amount of upward forcing to achieve substantial vertical motions. This can also be seen in the skew-t log-p diagrams from the University of Wyoming website in Figures 10 and 11. The 12Z sounding for the 18th in Figure 10 demonstrates an elevated mixed layer that started at 700mb and extended up to 570mb. This “loaded the gun” for later in the day. Another important feature of this sounding is the very high dew point. At 12Z the dew point was already 62 degrees Fahrenheit. There was not a lot of convective available potential energy (CAPE) and the convective inhibition (CIN) was high which is favorable for severe thunderstorm production because this prevents many small clouds from forming throughout the day and instead is able to build an incredible amount of energy. In the 00Z sounding on the 19th there was much more CAPE (2823 J/Kg), much less CIN (-24.7 J/Kg), and a very deep,well-mixed boundary layer present. Also, the dew point temperature had risen to an oppressive 69.5 degrees Fahrenheit with the dew point depression (the difference between the surface temperature and dew point) being 16 degrees Fahrenheit. The lifting condensation level (LCL) was at 850mb or 1442m, while the level of free convection was above the elevated mixed layer at 650mb or 3658m according to the 00Z sounding in Figure 11. The Equilibrium Level (EL) was at about 165mb which is above the tropopause which was situated at around 175mb. Since the EL was above the height of the tropopause, this indicated a very strong updraft in the storm, and most likely had overshooting tops. Another characteristic of overshooting tops can be seen in Figure 12. This is a McIDAS-V satellite image taken in the 10.7um channel showing cloud top temperature (in Kelvin) at 4km resolution in northern Minnesota and Wisconsin at 0030Z. The enhanced-v feature appears when a thunderstorm has an overshooting top and protrudes into the stratosphere. The mean stratospheric flow cannot penetrate the intense updraft is diverted around it, creating a v-shaped cold region around a relatively warm region that indicates the top of the anvil cloud and most likely the height of the tropopause. By using the data probe tool in McIDAS-V, the maximum and minimum cloud-top temperatures can be determined for the supercell on the Minnesota/Wisconsin boarder. The coldest part of the overshooting top (in green) was 212K or -61.15 degrees Celsius, and the warmest part of the cloud top (near the overshooting top, depicted in red) was 219K or -54.15 degrees Celsius. Using the text data from the University of Wyoming sounding site, this puts the overshooting top at 195mb and the anvil top at 230mb. The discrepancy between the heights found on the Chanhassen sounding and those calculated in McIDAS-V could be due to the fact that Siren, WI, is 80 miles from the Chanhassen sounding site and conditions could easily vary over this distance.

Since helicity values could not be found for this case study, shear in the atmosphere can be determined by looking at the hodographs for Chanhassen for 12Z on June 18th and 00Z on the 19th from the University of Wyoming sounding site. The 12Z hodograph is located in the bottom left corner of the 12Z skew-t in Figure 10. This hodograph has a very distinct clockwise curl in the low levels of the atmosphere which indicates veering winds with height and can be verified in the wind profile on the skew-t. This wind profile favors a right-moving supercell. The 00Z hodograph, which is located in the bottom left corner of the 00Z sounding in Figure 11, shows much less of a curling wind profile. This may indicate that shear actually decreased throughout the day, possibly due to the passage of the frontal system through the Twin Cities.

Another valuable feature of the Wyoming site's soundings is that they calculate many common severe weather indices. Unfortunately, helicity was not able to be calculated, but it can be assumed that is it present due to the veering winds with height. The first severe weather index is the Lifted Index which is able to determine conditional instability between the surface and 500mb. With increasing negativity, a higher potential for severe weather is achieved with values less than negative four indicating severe thunderstorms probable and tornadoes possible. The Lifted Index for this case was -7.86 at 00Z on the 19^{th}. The K Index is another index that displays conditional instability, but it also takes moisture into account. A K Index value above 21 indicates a greater than 20% chance of thunderstorms. The K Index value for this case was 24.10, which indicated around a 40% chance for thunderstorms. Another index is the Total Totals Index which is the sum of the Vertical Totals and Cross Totals Indices. The Total Totals Index compares moisture at 850mb and 500mb to the temperature at 500mb to determine conditional instability. A Total Totals Index value of above 55 indicates numerous scattered, heavy showers and scattered tornadoes. The Total Totals Index value for this case was 58. The next important index is determining the potential for severe weather is the Severe Weather Threat (SWEAT) Index. This index is useful because it takes many variables into consideration: speed shear with height, directional shear with height, moisture and conditional instability in the way of the Total Totals Index. A SWEAT Index value above 400 indicates severe thunderstorms and possible tornadoes. The SWEAT Index value for this case was 501.8 which was well above the potential tornado threshold. The final severe weather index is the Bulk Richardson Number. This index finds the ratio between the CAPE and the vertical speed shear. A Bulk Richardson Number between fifteen and forty indicates favorable conditions for supercell development. Values above forty indicate that there is not enough shear to generate a supercell while a number below fifteen indicates that there is not enough CAPE. The Bulk Richardson Number for this case was 31.61 which falls within the threshold for supercell formation. All of these severe weather indices indicate severe weather and possible tornado formation for northern Minnesota and Wisconsin. This allowed the Storm Prediction Center in Norman, OK, to issue a tornado watch for the area which gave citizens living in this region time to prepare for such an event.

Conclusion

In investigating the synoptic and mesoscale influences that led to the development of the severe weather outbreak that occurred on June 18, 2001, including an F3 tornado that devastated the small town of Siren, WI, there were three major contributors. The first was both speed and directional shear that was present in the atmosphere. The veering winds with height favored the development of the right-moving supercell that caused the Siren tornado. The second contributer was high levels of instability caused by mesoscale processes. This conditional instability can be seen in a deep theta E inversion layer between 500 and 900mb. The theta E inversion was a result of the moisture advection and warm air advection at lower levels, and especially at 850mb by a jet at this level. Conditional instability can easily be seen in the Skew-T diagram from the Chanhassen, MN, sounding site by means of the CAPE. Finally, due to this instability, only small vertical forcings were necessary to achieve strong vertical velocity. One major component of the vertical forcing was negative laplacian of the temperature advection. The region where this feature is seen coincides well with the region where negative omega is located. Other vertical forcings in the region are positive absolute vorticity advection by the 300 to 700mb thermal wind at 500mb and Q-vector convergence at 700mb. Two more forcings that played a small role may be the ageostrophic divergence that was present at the right jet entrance region over northern Wisconsin and frontal lifting caused by the warm front that pushed into the Siren area throughout the day of June 18th. These forcings received a large reaction over Siren due to the large amount of convective available potential energy where vertical motion can be seen up to 160mb. After surviving a storm with so much energy, the survivors of the Siren tornado will always keep a wary eye on the sky because, with tornadoes, there is always a next time.

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