# A Mesoscale Analysis of the March 29, 1998 Comfrey Tornado

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## Abstract

On March, 29, 1998, a severe weather outbreak occurred in southern Minnesota in which a single supercell produced thirteen tornadoes. One of the tornadoes grew to an F4 scale and demolished the small town of Comfrey, Minnesota. This tornado was on the ground for 1 hour and 25 minutes and covered 67 miles, making it the fifth longest track in Minnesota history. A detailed synoptic and mesoscale analysis is given to explain the setup to the severe weather event as well as why the tornado stayed on the ground for so long. The synoptic weather analysis showed ideal conditions with plenty of moisture transported into the Midwest and a strong low pressure system with an intense warm front provided the main lifting mechanism to cause convection. In the mesoscale analysis, it is shown that a combination of a continuous supply of warm, moist air, a restrengthened supercell, and the position of the warm front produced the most intense tornado seen in the month of March in Minnesota history.

## I. Introduction

Tornadoes are some of Mother Nature's most intriguing, yet devastating phenomena. The raw power of tornadoes forming from supercells can be quite immense. In general, a tornado can be formed from a number of favorable mesoscale and synoptic conditions working together to produce a supercell thunderstorm. Figure 1 shows a classic supercell adopted from Lemon and Doswell (1979) that more than likely will spawn a tornado. A mesocyclone will form inside the supercell with wind shear, typically veering winds with height with regards to a right-moving supercell. This rotating air will then be caught in the updraft of the supercell forming a cyclonically rotating mesocyclone. Intense rain bands begin to wrap around the backside of the mesocyclone forming the classic hook-echo feature seen on radar. Once these rain bands begin to wrap around the mesocyclone, the rear-flank downdraft may end up dragging the mesocyclone down toward the ground forming a tornado. Once a tornado is on the ground, the time it spends on the ground depends on the availability of warm, moist inflow and whether or not it can generate its own vorticity to produce helicity.

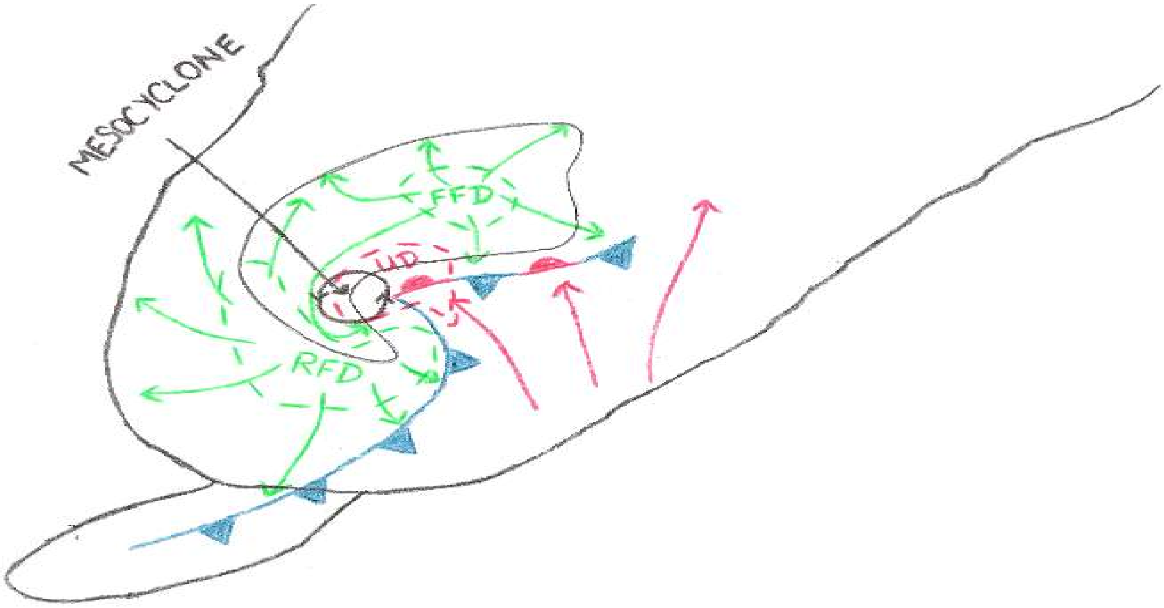
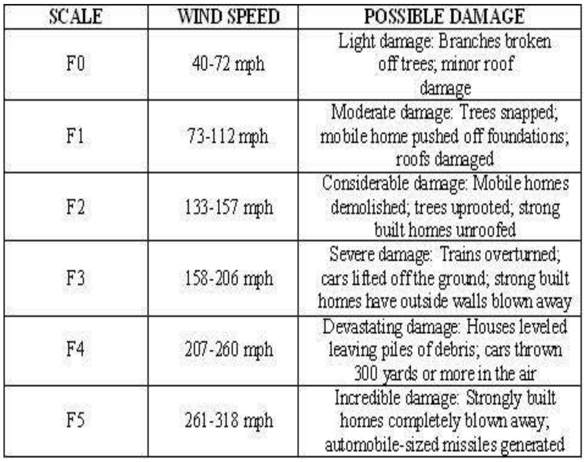


*Figure 1: Top view of a conceptual model of a classic supercell. RFD stands for rear-flanking downdraft, FFD stands for forward-flanking downdraft, and UD stands for updraft. The red arrows indicate warm, moist air coming in toward the updraft. The green arrows indicate rain-cooled air being dragged to the surface by the downdraft. This conceptual model is adopted from Lemon and Doswell (1979).*

During the afternoon and evening of March 29, 1998, a severe weather outbreak occurred in the upper Midwest in which a single supercell spawned thirteen tornado touchdowns alone in southwestern and south-central Minnesota. This vigorous supercell produced two tornadoes that reached at least F3 scale and caused major damage particularly in the towns of Comfrey and St. Peter. According to the National Weather Service, one of the major tornadoes produced by this large supercell traveled a total of 67 miles, making this the fifth longest tornado path length in Minnesota history (National Weather Service, 2008). What was unique about this tornado as compared to the other four that had longer tracks was that it remained on the ground the entire time. This paper explores the synoptic and mesoscale dynamics of the atmosphere that allowed for such favorable conditions to produce a severe weather outbreak in Minnesota, and also focuses on the development and sustainability of a strong tornado that ripped through Comfrey, Minnesota. This paper includes a climatological overview of Minnesota, a synoptic overview, a mesoscale discussion, conclusion, and acknowledgments and references. The mesoscale discussion also explores the possibilities of why these tornadoes were so severe and how the one that went through Comfrey was able to achieve a path length of 67 miles. The hypothesis for this case study is that the overall climatology of the US at the time, strong moisture influx, a vigorous upper level trough, and a dynamic low pressure system allowed for conditions to be very favorable for supercell development. The hypothesis for the sustainability of the tornado is that the mesocyclone was able to maintain its form probably due to strong vorticity generated by the supercell, while the supercell managed to recycle itself to maintain its own strength.

## II. Data

This case study uses computer generated forecast maps based using the GEMPAK and GARP programs. Data to produce these forecast maps were provided by the University of Wisconsin-Madison Department of Atmospheric and Oceanic Sciences. These forecast maps are primarily from the Eta 12 UTC model run, but maps provided by the National Weather Service will also be used. The 12 UTC run provides a better opportunity to forecast severe



| SCALE | WIND SPEED | POSSIBLE DAMAGE |
|---|---|---|
| F0 | 40-72 mph | Light damage: Branches broken off trees; minor roof damage |
| F1 | 73-112 mph | Moderate damage: Trees snapped; mobile home pushed off foundations; roofs damaged |
| F2 | 133-157 mph | Considerable damage: Mobile homes demolished; trees uprooted; strong built homes unroofed |
| F3 | 158-206 mph | Severe damage: Trains overturned; cars lifted off the ground; strong built homes have outside walls blown away |
| F4 | 207-260 mph | Devastating damage: Houses leveled leaving piles of debris; cars thrown 300 yards or more in the air |
| F5 | 261-318 mph | Incredible damage: Strongly built homes completely blown away; automobile-sized missiles generated |

*Table 1: The original Fujita scale for tornado intensity with descriptions of damages.*

weather than the 00 UTC run since most severe weather had already occurred by 00 UTC. RADAR images, storm-relative velocity images, and sounding information that were used in the mesoscale discussion section of the paper were taken from the GARP program as well as from the National Weather Service. Times used throughout this paper are on Greenwich, or UTC, time. It is important to note that in 1998 the daylight savings date was April 3, so local times are 6 hours behind UTC time. The tornado intensity ratings for this case study are based on the original F scale which can be seen in Table 1. A conceptual model and a Miller Diagram were used in this paper as well, in which these are referenced accordingly.

## III. Climatological Overview

March is a very dynamic month for weather, especially in the upper Midwest. Strong low pressure systems in the spring time in the upper Midwest bring about large swings in temperatures. Statistically, Minnesota receives the second most monthly snowfall in March. Also, before 1998, there had only been six tornado reports ever in the month of March in the history of Minnesota with the last one occurring March 20, 1991 (MN Climate, 2003). The last time a tornado of F2 scale or higher occurred in Minnesota during the month of March was March 25, 1981 (National Weather Service, 2008).

The average high temperature toward the end of March for southern Minnesota is approximately 50 degrees Fahrenheit (MN Climate, 2003). What is really interesting, however, is that Minnesota experienced an unusually mild winter during the 1997-1998 winter season. This was because of a strong El Niño presence in the eastern equatorial Pacific Ocean, which had an effect on the jet stream pattern as will be discussed in the synoptic overview as well as the mesoscale discussion.

## IV. Synoptic Overview

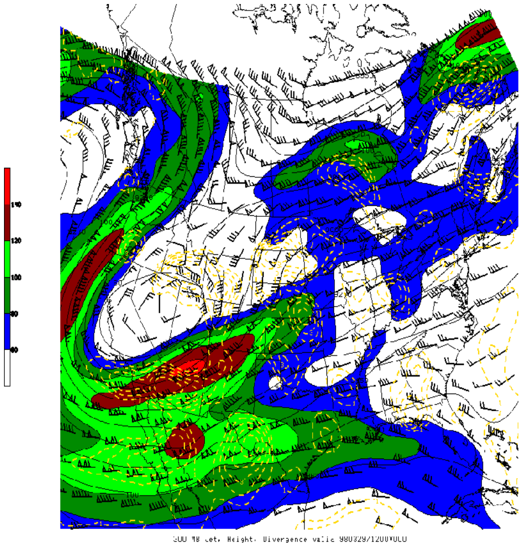


*Figure 2: Eta 12 UTC 300 mb Jet streaks, height, wind barbs, and ageostrophic divergence. The the color fills are wind speeds at 60 knots or higher, the black lines are heights, and the yellow dashed contours are ageostrophic divergence. Notice the divergence area over South Dakota and Minnesota due to the coupled jet streaks as well as the merging polar and subtropical jet streaks producing an area of strong difluence over the upper Midwest. Image generated from GEMPAK.*

The synoptic situation for March 29, 1998 helped produce very favorable conditions for severe storm development. Beginning at 300 mb, a highly amplified upper level trough existed with a closed off low pressure center over Nevada. It is interesting to note that this trough is positively tilted, meaning that the trough tilts to the east with increasing latitude, and positively tilted troughs normally are not associated with strong thunderstorm developments. A 140 knot jet streak formed over Arizona and New Mexico. Looking at Figure 2, it is clear that this jet streak formed from a merging of the polar and subtropical jet streak. Normally in an El Niño winter, the polar and subtropical jet streaks stay separate from each other (Wood, 2006). However, the flow resulting from the highly amplified trough caused the polar jet to drop south and round the trough axis, merging with the subtropical jet streak centered over the Mexican Plateau. The subtropical jet streak can then bring moisture over the United States in an El Niño winter. At 30 degrees north, the accompanying Sawyer-Eliasson circulation with the jet streak can reach the ground due to friction (Tripoli, 2009). This circulation created a strong area of difluence in the upper Midwest, particularly around South Dakota, Iowa, and Minnesota. There was also a smaller polar jet streak positioned in Manitoba and Ontario. The ageostrophic divergence of the left exit region of the jet streaks from the southwest and the right entrance region from the Canadian polar jet streak formed a maximum of ageostrophic divergence over central and southeastern South Dakota. Coupling the jet streak with a surface front from a low pressure system could then create a very sufficient lifting mechanism. The positively tilted trough could also be seen in the mid-levels of the atmosphere at the 500 mb and 700 mb levels. The significance of the position of the trough further showed that the mid and upper level flow into the Midwest came from the southwest, which aided in warm air advection into the upper Midwest.

At the surface at 18 UTC, a strong 994 mb low pressure system was centered over central Nebraska with a warm front extending northeast into southeastern South Dakota, then eastward across the Minnesota-

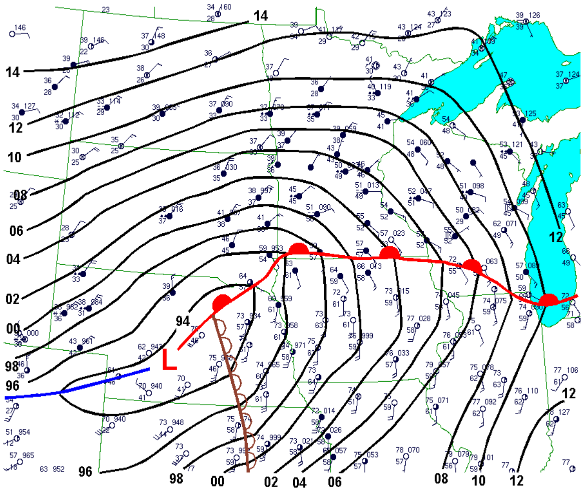


*Figure 3: 18 UTC surface observations. The warm front extends from southeastern South Dakota to the Minnesota-Iowa border. This progression of the warm front becomes vital to the development and sustainability of the supercell as seen in the Mesoscale Discussion section. Image courtesy of the National Weather Service.*

Iowa border as seen in Figure 3. The warm front provided the main lifting mechanism to set off convection in South Dakota and Minnesota. Temperatures north of the warm front were still in the lower-mid 50s with dewpoints in the upper 40s. South of the warm front, however, temperatures ranged from the mid-60s to the mid-70s with dewpoints in the upper 50s and lower 60s. By 21 UTC, approximately 50 minutes before the storm system that produced the intense supercell developed the major tornado, the low pressure system was positioned in northeastern Nebraska. The warm front extended from southeastern South Dakota through southern Minnesota. Temperatures north of the warm front still remained in the mid-50s while temperatures south of the warm front increased to nearly 80 degrees with dewpoints in the mid-60s. The dewpoint depression south of the warm front was too large for possible tornado development. Right along the warm front at 21 UTC, temperatures were in the mid-60s with dewpoints reaching into the low-60s as well, creating a much lower dewpoint depression and making the conditions much more conducive for major convection. The time evolution of the positioning of the surface low and the warm front became very

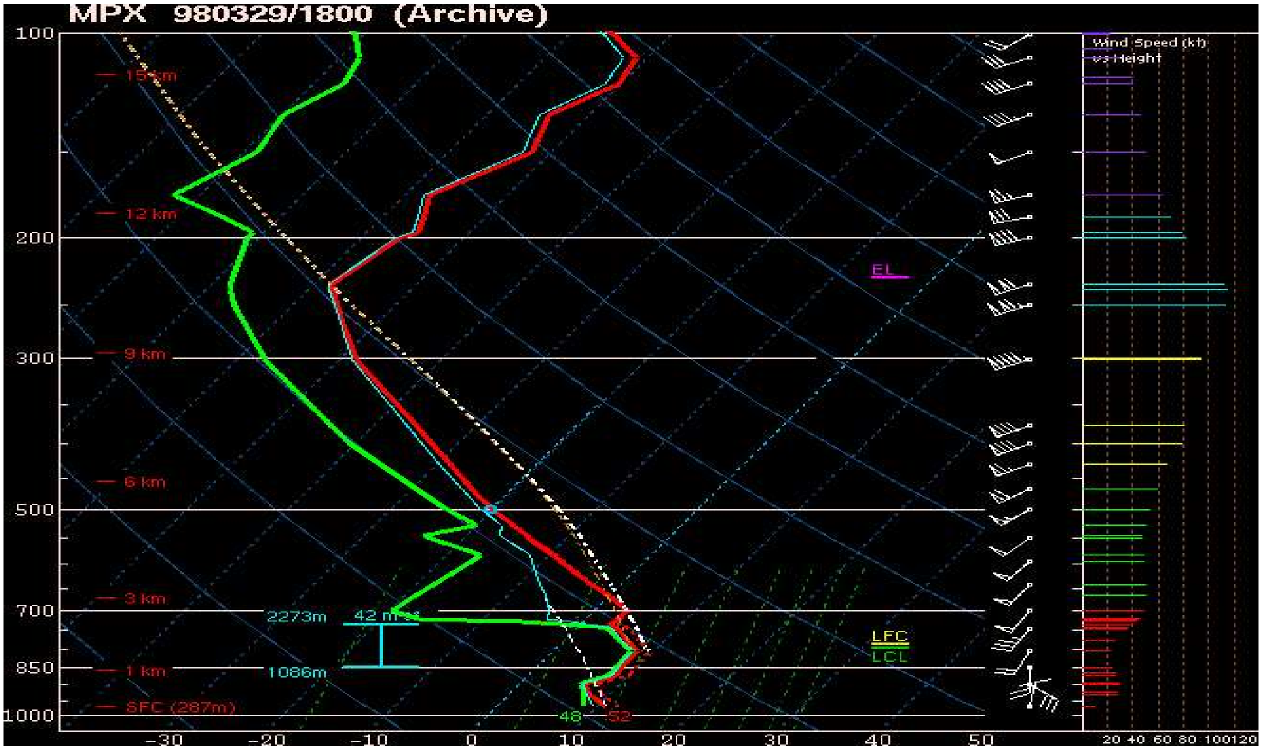


*Figure 4: 18 UTC sounding from Minneapolis/St. Paul, Minnesota (MPX). The sounding does show characteristics of a loaded gun sounding. The lower levels show strong moisture transport with dry mid-levels above the boundary layer. The LCL and LFC levels are fairly low as well. There is no surface-based CAPE with this sounding. The Most Unstable CAPE (MU CAPE) approached 1400 J/kg which indicates elevated convection due the warm front. Sounding courtesy of the National Weather Service.*

critical to supercell development, as will be discussed in the mesoscale discussion.

## V. Mesoscale Discussion

### A. Triggering Convection

Moving down to the mesoscale features for this storm, it was also clear that the atmosphere produced very favorable conditions for good convection throughout the afternoon of March 29. One of the most interesting and unique aspects of atmospheric conditions that helped develop the severe storm outbreak concerned the position of the subtropical jet streak as a result of the climate. Since the winter was unusually mild due to a strong El Niño, convection seen along the Inter-Tropical Convergence Zone (ITCZ) moved more into the Central Pacific (NWS JetStream, 2008). Convection due to the ITCZ creates divergence aloft, and energy from the outflow enhances the subtropical jet streak. The subtropical jet streak then becomes a dynamic flywheel and can transport energy a

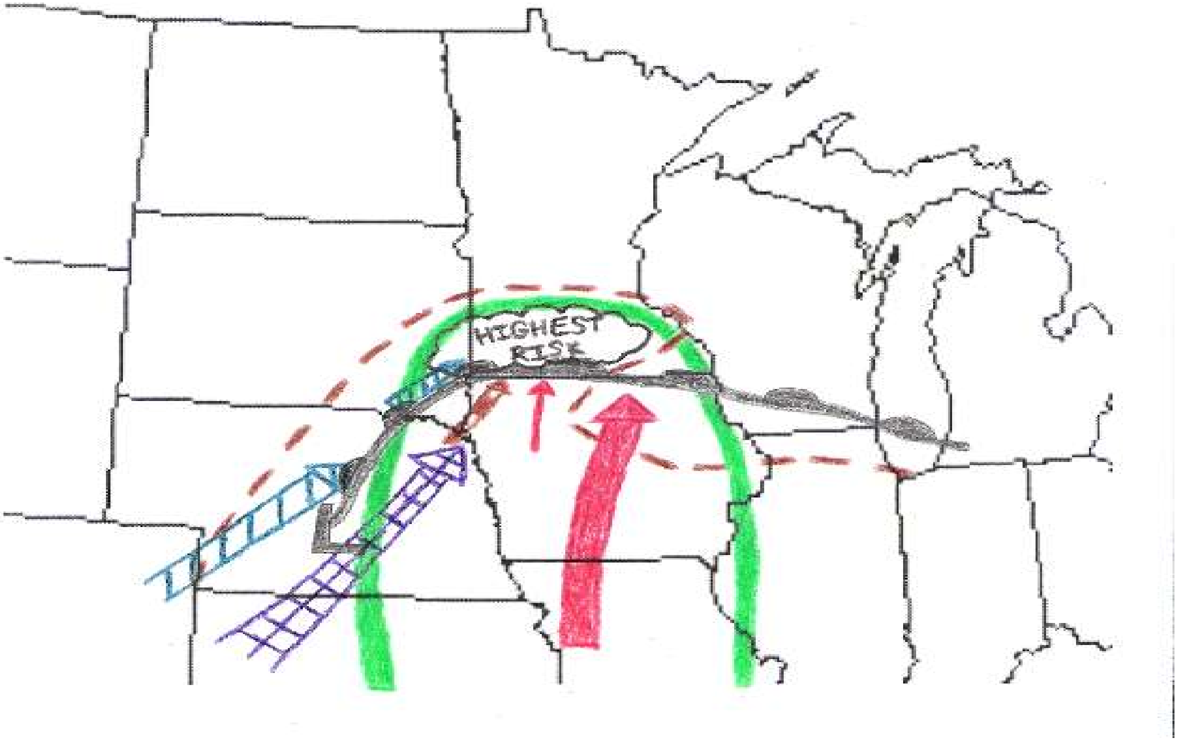


*Figure 5: Miller Diagram for severe weather potential. The large red arrow indicates the low-level jet and the small red arrow shows the general 850 mb flow. The moisture tongue is drawn in green. The 700 mb dry tongue is highlighted by the brown dashes, and the 700 mb general flow is shown by the small brown arrow. The 500 mb general flow is the small blue arrow and the 500 mb jet is the large blue arrow. The large purple arrow shows the 300 mb jet. The surface low and corresponding warm front are colored in gray. The general flow shows veering winds with height. The convergence of the flow puts the highest threat in southern Minnesota as highlighted in black. This diagram is based on diagrams proposed by Fawbush and Miller (1972).*

long distance, as seen with the subtropical jet streak over the Mexican Plateau.

One of the most informative soundings of the conditions of the atmosphere can be seen in Figure 4, which is from Minneapolis/Saint Paul, Minnesota (MPX), at 18 UTC, approximately two hours before the thunderstorms erupted in southeastern South Dakota. In the lower levels of the atmosphere, particularly at 850 mb, a low level jet can be seen bringing a very large moisture influx as well as warmer temperatures into the upper Midwest. The moisture transport definitely aided in the severe weather development as it provided more environmental instability and even lowered the dewpoint depression. A smaller dewpoint depression then in turn can lower the LCL, increasing the threat of tornadic development with supercell formation. The lower levels of the sounding showed dewpoints reaching into the lower 50s with temperatures rising to the low-mid 50s. The winds in the lower levels at this time were out of the south and southeast at approximately 20 knots, further indicating the presence of moisture influx from the Gulf of Mexico.

At the 700 mb level, it is clear to see from the sounding that the air became significantly drier than in the lower levels. The wind also shifted to more of a southwesterly flow at approximately 50 knots. This is typical with severe storm development as it increases atmospheric instability in the mid levels of the atmosphere by bringing dry desert air from the Mexican Plateau into the upper Midwest. An elevated mixed layer can also be seen around 700 mb. The elevated mixed layer typically comes from the desert southwest which allows for steeper lapse rates and ultimately “loading the gun”. The combination of the different levels of the atmosphere produced a bullseye region of potential convection and severe weather outbreaks in southern Minnesota and southeastern South Dakota as seen by the Miller Diagram in Figure 5.

The severe weather indices also began to show signs of an increasing potential for severe thunderstorms as well tornado development. One of the most telling signs of potential severe weather is the right curving hodograph seen in Figure 6. The strong right curving hodograph indicates a strong veering, or clockwise, wind pattern with height profile which is indicative of possible tornado development especially in right moving supercells. The storm-relative helicity values at MPX were quite high, which reinforced the strong right-curving hodograph. The lowest 1 km storm-relative helicity value at MPX was 641 $m^2/s^2$, which is significant because storm-relative helicity values greater than 450 $m^2/s^2$ show very high potential for supercell formation and tornadoes (Knutsvig, 2009). Another telling index of potential severe weather was the Severe Weather Threat, or SWEAT, index. The SWEAT index looks at low level moisture

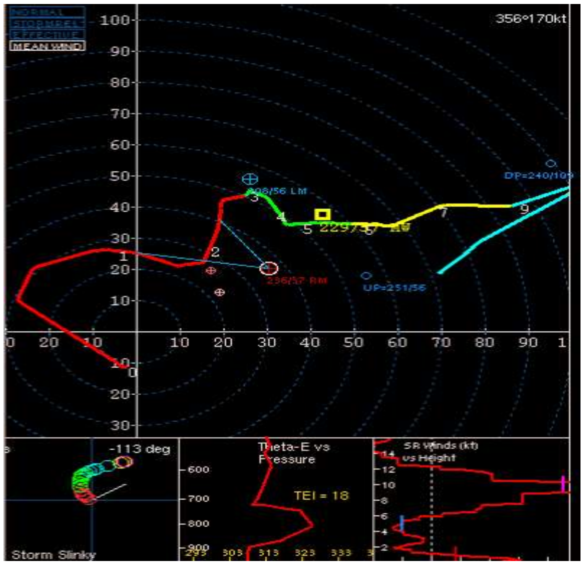


*Figure 6: 18 UTC hodograph taken from Minneapolis/St. Paul, Minnesota (MPX). Wind direction is based on the direction the wind is coming from. The directions are also backwards compared to a compass, with south at the top and west to the right. A strong right-curving hodograph indicates a veering wind profile that increases the potential of tornado development. Image courtesy of the National Weather Service.*

as well as instability, but also takes into account wind velocities at upper and lower levels. According to sounding information gathered by the University of Wyoming, The SWEAT index at 18 UTC in MPX was 461.9. Generally, tornadoes are possible with thunderstorms when the SWEAT index reaches to more than 400 (Henz, 2009). The Total Totals index, which looks at overall static stability as well as moisture content at the 850 mb level, was 56.40 at 18 UTC. Generally with this index, values greater than 55 possess high potential for severe thunderstorms and scattered tornadoes. The surface CAPE values were still zero, an indication that the lower atmosphere was still too capped and stable near the Twin Cities for convection to occur. However, the Most Unstable CAPE (MU CAPE) values were just over 1400 J/Kg. The MU CAPE indicates the amount of CAPE present when the most moist parcel in the lowest 300 mb of the troposphere is lifted to the Level of Free Convection (LFC). The MU CAPE levels are a great indication that elevated convection is occurring, which is very typical with lifting caused by a warm front.

The position of the surface warm front became quite vital as well to where the severe storms begin to fire as well. Moving south of the warm front surprisingly created an environment that inhibited thunderstorm development. Looking at a sounding from Omaha, Nebraska, as seen in Figure 7, the warm front actually provided a stronger inversion in the atmosphere. This could have been due to the timing of the frontal passage as it moved through Omaha around 12 UTC. The warming of the lower levels created a stronger cap, and without any other type of synoptic forcing, there could not have been any type of convection to form south of the warm front. The best place for convection to occur then was either along or just north of the warm front. This notion seemed to parallel the thinking of meteorologists at the National Weather Service Twin Cities office (National Weather Service, 2008).

The warm front provided the main lifting mechanism to trigger convection. It

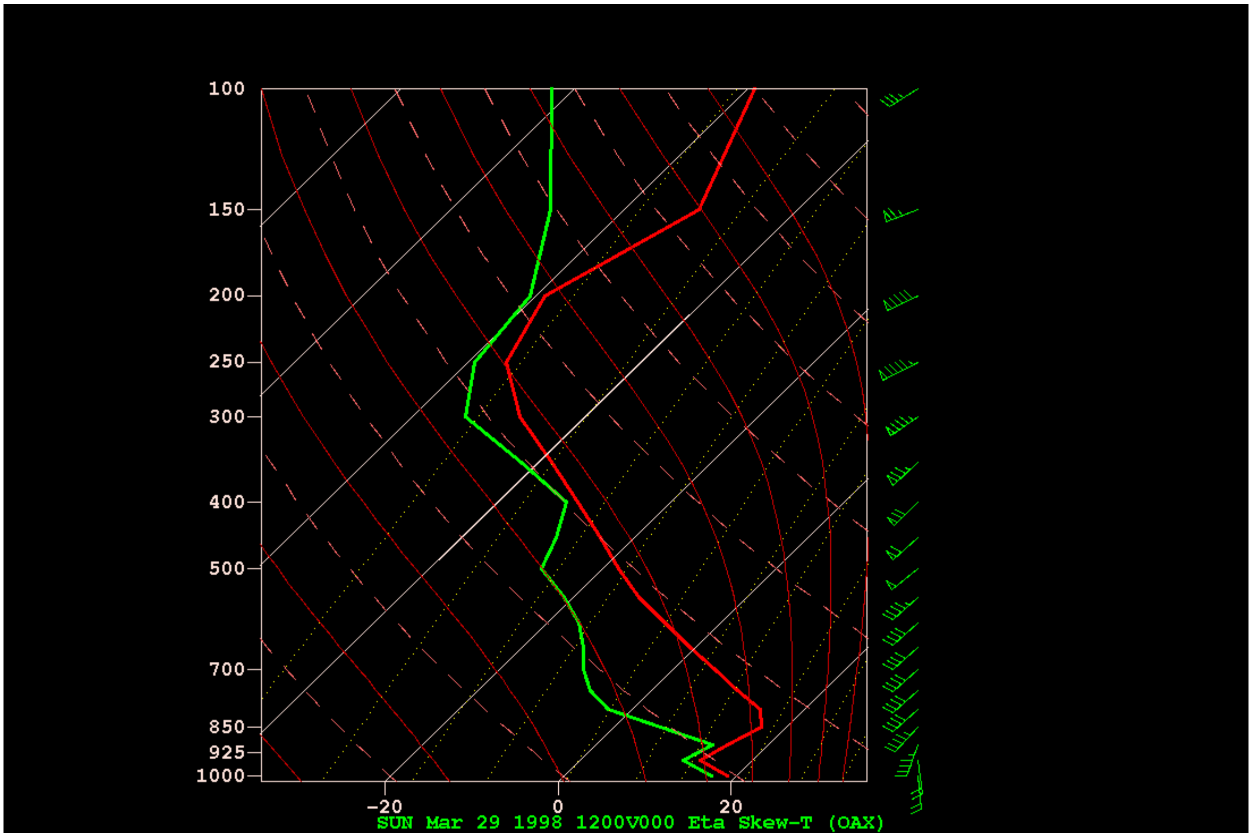


*Figure 7: 12 UTC sounding taken from Omaha, Nebraska (OAX). This sounding shows the warm frontal passage through the area, which puts a large cap on the atmosphere. Without any other kind of forcing after the warm front passes through, no convection can form. Sounding generated through GARP.*

was possible that the ageostrophic divergence from the coupled jet streaks could have provided some enhancement of the lifting to break through the cap, but it is very unlikely that the divergence alone could have broken the cap to cause convection.

## B. Formation of the Supercell and Mesocyclone

Convection began in southeastern South Dakota approximately at 19 UTC. The formation of the convection into a supercell followed very closely to the classic supercell evolution proposed by Lemon and Doswell (1979). The initial convection began as multi-cellular thunderstorms, very typical with the beginning stages of supercell development. One cell out of this cluster of thunderstorms more than likely forms a stronger updraft than the other cells, typically seen on the right rear flank (Lemon and Doswell, 1979). The reason for this was that there are no obstructions to inhibit the warm moist inflow. The storm continued to intensify with a strong inflow. One of the characteristics seen through RADAR reflectivity that indicates the presence of a strong updraft is a Bounded Weak Echo Region (BWER), which can be seen in Figure 8. This cell then began to steer to the right of the mean flow around 21 UTC, in which a supercell was then born.

Another classic signature of a supercell is the presence of a mesocyclone. What distinguishes supercells from typical cellular thunderstorms is the mesocyclone. As stated in the introduction section, a mesocyclone typically forms from vertical wind shear. Looking once again at the Minneapolis/St. Paul, Minnesota, sounding in Figure 4, it is very clear that the winds rotate clockwise with height, indicating a veering wind profile. This is extremely important to creating strong rotation in this supercell. The vertical wind shear associated with this veering wind profile produces a rotating tube of air. When the air gets caught in the strong updraft of the supercell, the rotating tube of air becomes perpendicular to the ground instead of parallel. The rotation then becomes cyclonic, enhancing the vorticity and helicity of right moving supercells. The vorticity in the mesocyclone produces walls of inertial stability which act to fight against dynamic entrainment. The supercell then only allows for warm, moist parcels of air to lifted into the updraft from the surface. This allows for supercells to last on the order of hours instead of minutes like in regular airmass thunderstorms.

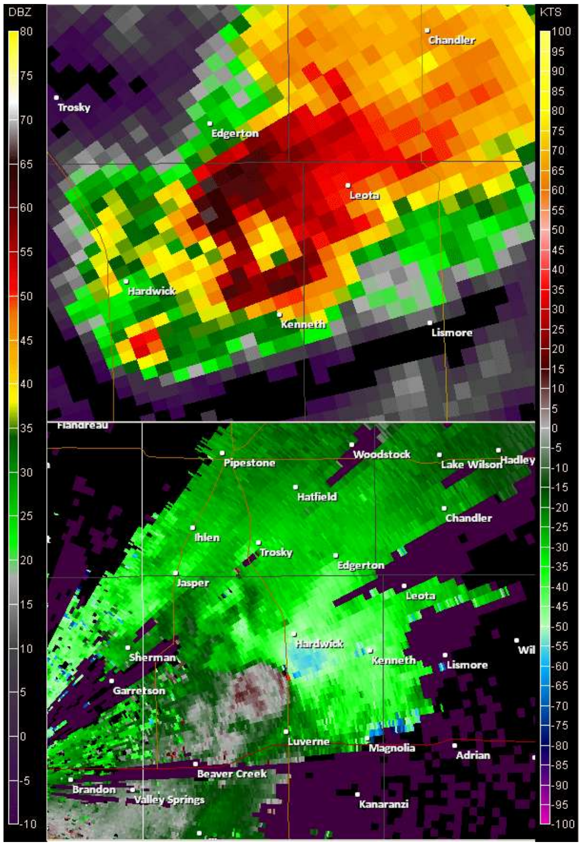


*Figure 8: Top image: RADAR showing a Bounded Weak Echo Region at 21:08 UTC. Bottom image: storm-relative velocity taken at 20:58 UTC. The left color table shows RADAR DBZ while the right color table shows storm-relative velocity values. Both images indicate a very strong updraft as the thunderstorm rapidly intensifies into a supercell. Images taken from the National Weather Service.*

Once the mesocyclone is in place, vorticity sheets form, which is due to the transport of momentum into the updraft. Geostrophic adjustment takes place in which the mass adjusts to the wind, also creating a dynamic pressure gradient. This dynamic pressure gradient forms a dynamic low pressure in the area of the mesocyclone since mass is being evacuated out the mesocyclone. The dynamic low pressure helps to increase in the low-level lifting on the downshear side and descent on the upshear side, which enhances the storm inflow (Klemp, 1987).

### C. Tornado Development and Sustainability

The first major tornado produced by the supercell occurred in eastern Murray County of Minnesota at 21:50 UTC. The dynamic low pressure formed from the rotating updraft causes the temperature of the updraft to decrease as well via the ideal gas law relationship in that pressure is proportional to temperature. With a lower temperature in the updraft, warm, moist parcels that get caught in the strong updraft cool at a much lower height and clouds form in the updraft at a lower height than most of the cloud base around the updraft. This lowering cloud base in the updraft is considered to be the wall cloud. According to Professor Greg Tripoli, a mesoscale meteorology professor at the University of Wisconsin-Madison who studies tornado formation through computer models, tornadogenesis occurs with an interaction between the rotating updraft and the rear-flanking downdraft. Vorticity forms from air being pulled down by the rear-flanking downdraft interacting with air being pulled up from the rotating updraft, which causes a tube of rotating air. The rear-flanking downdraft then pulls the tube of air down to the ground, causing air at the ground to begin to rotate. This rotating air at the surface then gets pulled back into the updraft, and the interaction of the voriticty at the ground and a lowering rotating updraft produce a tornado. Professor Tripoli's notion of tornadogenesis seems to be confirmed in a paper done by Robert Davies-Jones of the National Severe Storms Laboratory in Norman, Oklahoma and can be seen in Figure 9.

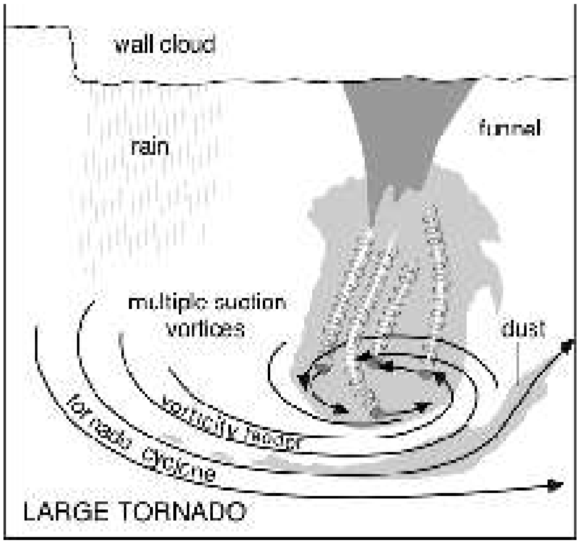


*Figure 9: Picture depicting tornado formation. Vorticity generated by the interaction between the rotating updraft and the rear-flanking downdraft gets pulled to the surface by the rear-flanking downdraft. This causes air at and near the ground to begin to rotate, and once it gets caught up in the updraft again a tornado will form. Image taken from the Robert Davies-Jones paper "Tornadogenesis in Supercell Storms - What We Know and What We Don't Know"*

Figure 10 shows a four panel radar time evolution plot of the supercell after the tornado touches down. What was extremely interesting about this tornado was the amount of time it stays on the ground. The

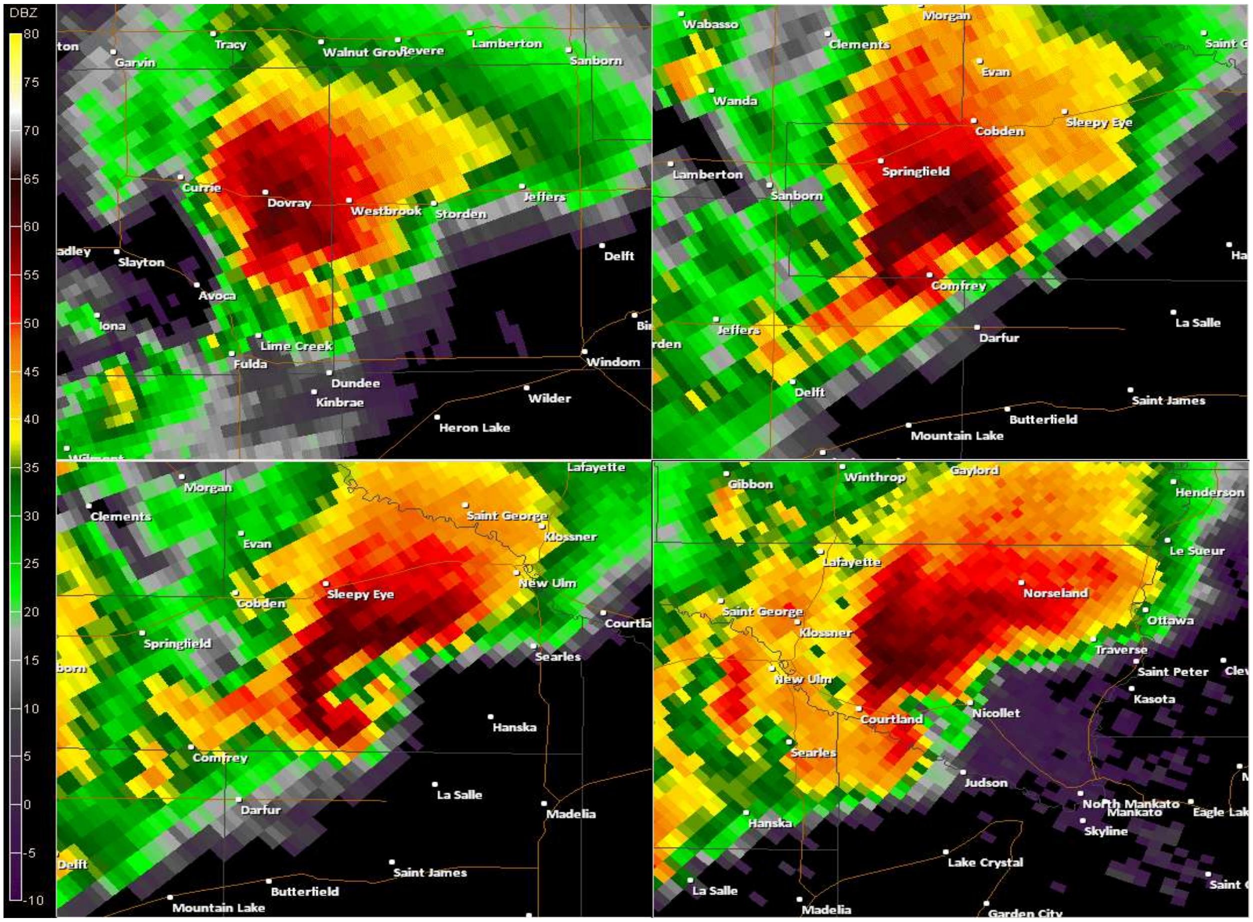


*Figure 10: RADAR 4-Panel plot of the tornado that goes through Comfrey, MN. Upper left: RADAR at 21:48 UTC, two minutes before the tornado touched down. Upper right: tornado reaches Comfrey, MN, at 22:27 UTC. Lower left: tornado reaches maximum intensity (F4 strength) at 22:42 UTC. Lower right: tornado dissipates at 23:13 UTC. The hook echo stays together through the entire time evolution, indicating a strong mesocyclone. Images in this 4-panel plot are taken from the National Weather Service.*

tornado covered a total of 67 miles in approximately 1 hour and 25 minutes. When the tornado was on the ground, the radar signatures show that the mesocyclone was almost becoming rain wrapped. A rain wrapped mesocyclone meant that the rear flanking gust front began to occlude. If the occlusion of the rear flanking gust front happens, the downdraft would undercut the inflow. This could ultimately lead to the dissipation or weakening of the supercell as it would be limited or even no access to the warm moist inflow. The rear flanking gust front occlusion can be thought of as analogous to cold air cutting off the supply of warm air to an extratropical cyclone in its occlusion stage.

However, instead of occluding and shrinking, the supercell went through a recycling phase in which it deviated to the right of the main flow once again. When a supercell deviates to the right, it generates its own vorticity which in turn generates more positive helicity to sustain itself. The angle in which the inflow winds shrink, and when looking at how the wind changes over time with regards to the storm, the winds are actually backing with respect to time. This may seem contradictory to supercell development, but it is important to remember that veering winds with *height* support right moving supercells while backing winds over *time* also help with supercell development. It is also important to remember that the track of the supercell followed the synoptic warm front northeast through southern Minnesota. The wind profile north of the warm front had a more easterly direction while the wind direction south of the warm front was more southerly. The wind direction can be seen from the surface observations in Figure 3. The orientation of the winds along the warm front could have provided a larger than normal backing wind profile over time in the lower levels of the atmosphere, which would allow the supercell to generate much higher amounts of positive vorticity and positive helicity when it deviated to the right of the mean flow. The added amounts of positive vorticity and helicity could have kept the mesocylone strong for a longer period of time. Also, throughout the time the tornado was on the ground, there was nothing to the south of the supercell that could inhibit the inflow of warm, moist air from the Gulf of Mexico due to a lack of synoptic forcing mechanisms. With a continuous supply of warm moist air to the south of the supercell as well as being in the prime position along the warm front, it is very possible that the combination of these features produced a very long-lived tornado.

A very interesting feature with regards to the evolution of the tornado in this case was the strengthening of the tornado after it passes through Comfrey. Although the tornado ripped through Comfrey at an F3 scale, the tornado increased in intensity to an F4 scale. It seemed that the increase in tornado intensity coincided with the recent recycling phase of the supercell. During the recycling phase, not only does the supercell generate its own positive vorticity and helicity, but a new tower forms after the occlusion process begins to occur in the older tower. The mesocyclone evolves to move along with the newly formed tower. Once the supercell is done recycling itself, the supercell is newly strengthened and can produce a stronger tornado.

## VI.Conclusion

A detailed synoptic and mesoscale analysis has been given for the Comfrey tornado case on March 29, 1998. The hypotheses in the introduction of the paper proved to be correct. A combination of very favorable synoptic and mesoscale conditions led to the formation of a violent tornado. A strong low pressure system with a warm front extending from southeastern South

Dakota into southern Minnesota produced the main lifting mechanism to break the cap and cause deep convection. There may have also been some enhanced lifting from a strong difluence zone created by the merging of the polar and subtropical jet streaks, but the lifting mechanism for this storm mainly was surface-based. The position of the warm front turned out to be very important for the development of the supercell and tornado formation.

On the mesoscale level, a low-level jet pushed warmer temperatures and moisture into the upper Midwest. A sounding from Omaha revealed, however, that convection south of the warm front was not likely as the atmosphere was strongly capped and there was a lack of sufficient synoptic forcings. The wind profile from the sounding in Minneapolis/Saint Paul, Minnesota, showed a strong veering wind profile which increased the potential of supercell and tornado development. A dynamic low pressure from the mesocyclone allowed for a low-level wall cloud to form. The dynamics of vorticity generation from the interaction of the rotating updraft and the rear-flanking downdraft helped create vorticity in the downdraft which causes air near and at the surface to begin to rotate. Once the tornado touched down at 21:50 UTC, the supercell began to go through a recycling phase in which it steered to the right of the main flow. This recycling phase created a new tower which caused another strong updraft area and allowed the supercell to restrengthen. The recycling phase also caused the supercell to generate its own positive vorticity and positive helicity as it produces a backing wind over time profile relative to the storm. The supercell also traveled along the warm front which aided in increasing the backing wind profile over time. Because the atmosphere was capped south of the warm front, there was nothing to inhibit the supply of the incoming moisture from the Gulf of Mexico. The combination of the recycling phase and a continuous supply of warm, moist air from the south caused a violent, long-lived tornado.

The tornado that ripped through Comfrey, Minnesota traveled a total of 67 miles in approximately 1 hour and 25 minutes, making it the fifth longest tornado track in Minnesota history as seen in Figure

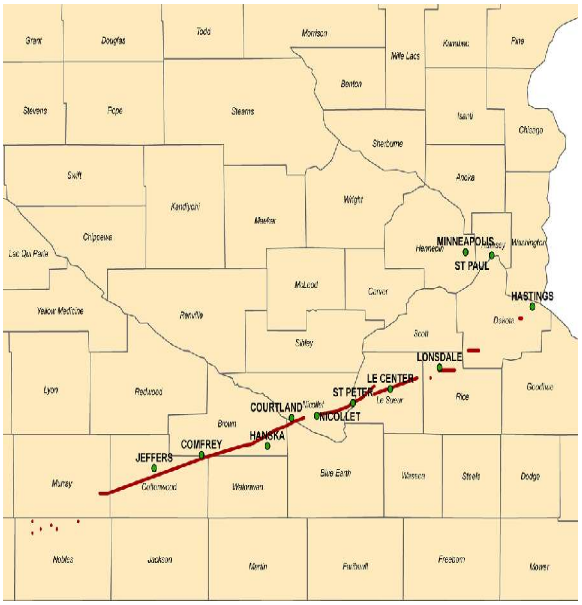


*Figure 11: Tornado tracks for March 29, 1998 across southern Minnesota. Image taken from the National Weather Service.*

11. Only six tornadoes touched down in the month of March before March 29, 1998. However, this one supercell produced thirteen tornadoes through southern Minnesota. The tornado that went through Comfrey caused approximately $75 million in damage, and about 75% of the buildings in the town sustained damage from the tornado. Another strong F3 tornado that formed just after the dissipation of the Comfrey tornado went through the town of St. Peter, Minnesota, causing approximately $120 million in damages, with heavy damages especially to Gustavus Adolphus College. Overall, the storm damage in southern Minnesota as surveyed by the federal government was estimated to be $235 million (NCDC, 2009). Unfortunately, two people lost their lives as a result of the tornadoes. The National Weather Service in the Twin Cities forecasted the severe weather outbreak extremely well. They issued tornado warnings for the areas where the thirteen tornado touchdowns occurred with approximately fifteen minutes of lead time. Because of their extraordinary efforts, they were awarded the presigious bronze medal by the United States Department of Commerce (National Weather Service, 2008).

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