Mesoscale Supercell Dynamics of the Comfrey/St. Peter Tornado Outbreak March 29, 1998

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ABSTRACT

Certain aspects of the mesoscale supercell make this type of storm a challenge to predict for forecasters and meteorologists. Supercell storms have specific dynamics, including tornadoes, that make these convective systems difficult to forecast. Forecasters are confronted with predicting life-threatening weather systems that are constantly transforming. The synoptic conditions in late March, 1998 were conducive for a severe weather event in southwestern Minnesota. Also, the mesoscale aspects of the supercell that developed on March 29, 1998, permitted the cell to track more than a hundred and fifty miles that day [Woelm, 1999]. The specific mesoscale features and dynamics probably contributed to this supercell's longevity. A close examination of the mesoscale features of this storm and comparison with the schematics published by Lemon and Doswell [1979] will show exactly how and why this long-lasting and destructive tornadic event occurred.

I Introduction

a. Purpose

Severe weather events such as tornadoes, hail, strong winds, and heavy rainfall can have dangerous consequences including property and financial damage or even loss of life. The primary mission of the National Oceanic and Atmospheric Administration National Weather Service (NWS) is "…to provide weather forecasts and warnings to protect life and property within the United States" [Andra et al., 2002, pp. 559]. Therefore, it is the job of the meteorologists employed by this organization to produce accurate, and timely severe weather forecasts as well as issue warnings to alert the public of the hazardous weather conditions. Success stories such as the May 3, 1999 Oklahoma tornado outbreak, when an estimated 540 – 700 lives were saved, motivate forecasters to use all possible tools to produce clear, accurate forecasts and timely warnings [McCarthy, 2002, pp. 649]. Since significant loss of life, property damage, and financial burden can result from just one storm, the ability to accurately as well as consistently forecast these challenging mesoscale (small size) events is the primary goal for forecasters at the NWS. However, some features such as mesocyclones and tornadoes are extremely difficult to predict. Most often, models do not sufficiently account for such features, so although forecasters try to consider factors such as mesoscale supercell dynamics in their forecasts, these elusive enhancing elements usually go undetected until the supercell develops into a mature storm. Tornado warnings were issued across southwestern Minnesota on March 29, 1998, but the storm was so intense that two people died and many rural towns had significant property damage following the event.

b. Hypothesis

The early spring 1998 tornadic event in southwestern Minnesota caused a considerable comprehensive amount of damage and affliction. This was the greatest March tornado outbreak in Minnesota history and produced over $230 million dollars in damage [Woelm, 1999]. Meteorologist Scott Woelm ranks this event number one on his "Top 10 Minnesota Severe Weather Events 1990-1999" list because of the amount of damage and the very early annual timing of this event [1999]. The devastation this tornadic event brought to the Comfrey/St. Peter area was a direct result of ideal synoptic ingredients as well as key mesoscale meteorological features. The convection on the afternoon of the 29th of March, 1998 formed along a warm front extending from the southwest corner of the state to just south of the Twin Cities. This convection was enhanced by the mesoscale supercell dynamics, including an upper level jet from the southwest, mid-level flow from the south, moist surface inflow from the southeast, and localized region of low stability which drove the convection and tornadogenesis as seen by the supercell schematic according to Lemon and Doswell [1979].

II. Data

a. Data Sources

Systematic satellite analysis of the size and shape of the supercell that occurred on March 29 was done using satellite data and imagery from the GOES-8 (Geostationary Operational Environment Satellite) satellite, a NWS instrument. The horizontal plots of the upper level wind speed and low level moisture as well as the sounding that was plotted and analyzed used Eta Model derived data. The surface observations are based on the observed METAR data from March 29, 1998. Finally, the wind profiler data is based on observations taken in Wood Lake, Minnesota which is just to the northwest of where the supercell tracked that day.

III. Synoptic Overview

a. Large Scale Weather Pattern Late March, 1998

The general climate prior to the March 29th event was mild. The 1997-1998 meteorological winter (December-February) was one of the warmest on record with the month of February being abnormally warm. The average temperatures for December and January were 5-10 degrees warmer than the normals for each month. February was on average 15 degrees warmer and very dry. The whole winter ranks second warmest in the state and averages were about 5 degrees behind the warmest winter of 1877-1878 where the mean temperature was 26 degrees Fahrenheit (MN Climate, 1998). Also noteworthy is that 1998 was an El Niño year which, in the past, has climatologically suggested a much more mild winter for the mid-west portions of the United States. This mild trend of 1998 continued into the month of March. However, unlike the dry February, March was extremely moist. This is a result of the jet stream pattern typical of El Niño years. The northern polar jet stream and the southern subtropical jet stayed separate through the winter months. Thus, the warm, moist air stayed to the south of Minnesota through February. Yet, with the month of March came strong thunderstorms, which merged the two jet streams together. This creates conducive upper level conditions for storms to track farther north, and into Minnesota. Consequently, only a few days after the jets combined into a unified flow, the tornado outbreak that devastated Comfrey and St. Peter occurred [MN Climate March, 1998].

The synoptic conditions for March 29 were conducive for a severe weather event. **Figure 1** is a surface analysis valid at 1800Z in the early afternoon of the 29th of March. This figure shows a surface low pressure centered near Sioux Falls, South Dakota. Also, a warm front extends from southwestern Minnesota to near the Twin Cities region and the cold front is centered in Nebraska at this time. Notice the temperature and dew point temperature contrast across the warm front as well as the prominent wind shift. These aspects were analyzed to determine where the warm front was located across southern Minnesota just a few hours before the first tornado touched down.

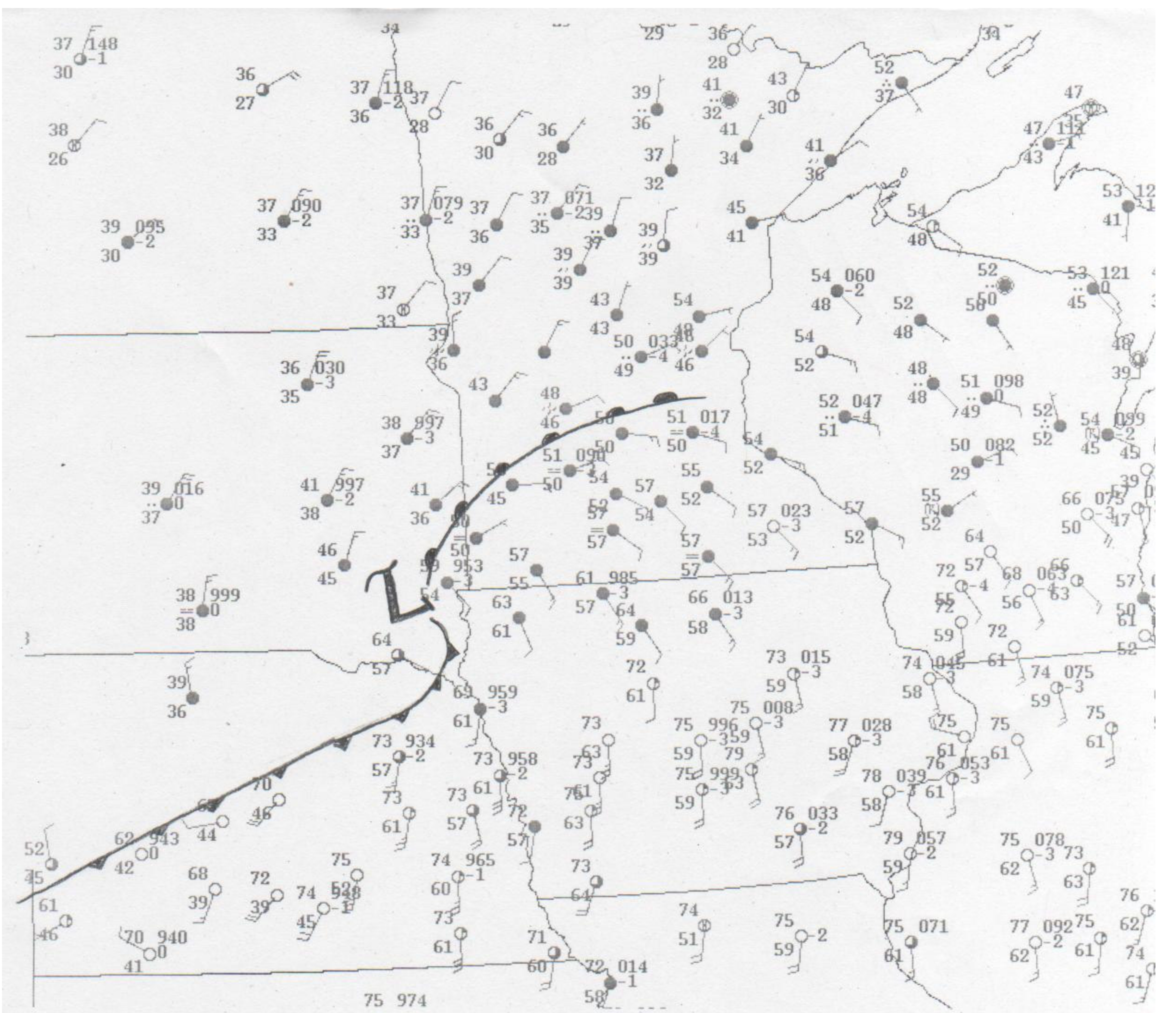

Figure 1. Surface Analysis: valid 1800Z 29 March 1998. The warm front extends from the southwest corner of Minnesota to the Twin Cities region.

Figure 2 is a horizontal plot of the isotachs (wind speeds in knots) at 300 mb also valid at 1800Z on the 29th of March. This figure shows that a fairly strong upper level jet is located just to the south and west of Minnesota. The left exit region of the jet, where the most upward vertical motion should occur, is centered over eastern South Dakota, southeastern North Dakota, and west-central Minnesota. The quasi-geostrophic forcing from this upper level jet contributed to the convection of this tornadic event. The warm front at the surface and the upward vertical motion driven by the quasi-geostrophic forcing of the jet coalesce at 1800Z making the synoptic conditions conducive for a severe weather event that afternoon.

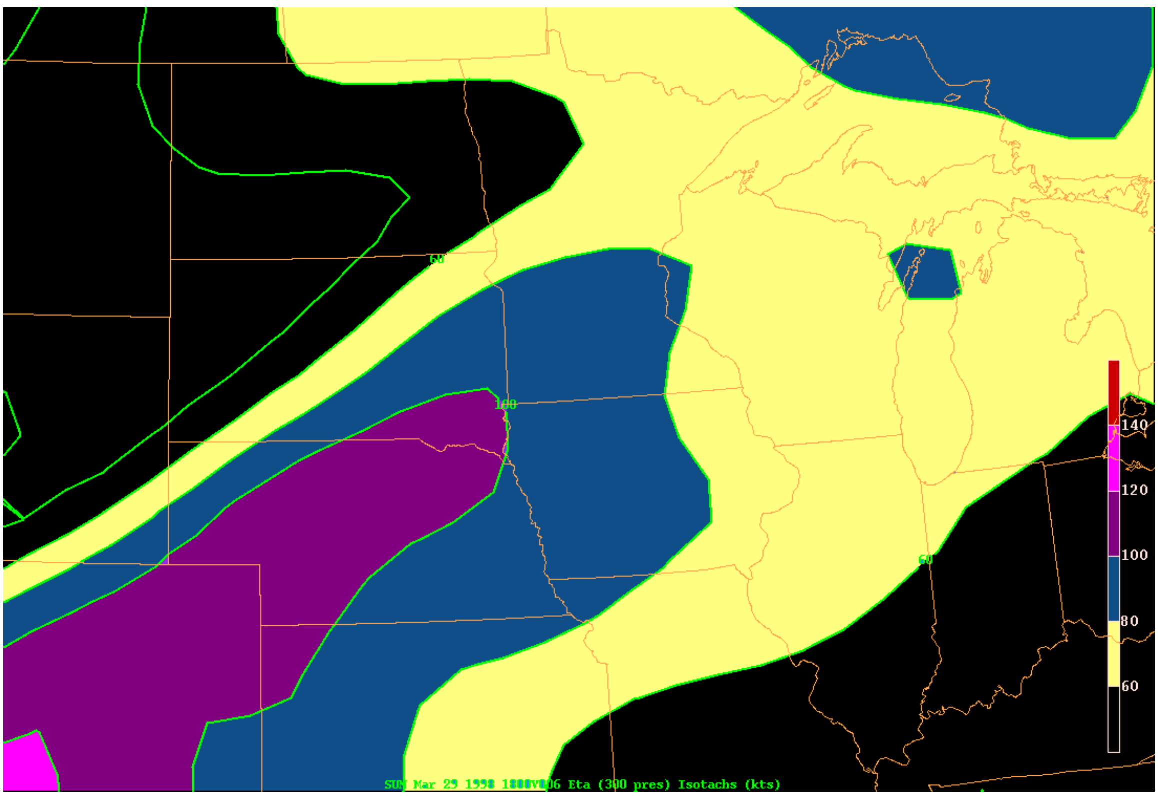

Figure 2. 300 mb Horizontal Plot: Wind speed (knots) valid 1800Z 29 March 1998. The left exit region of this jet is located over the southern part of Minnesota and eastern South Dakota.

IV. Mesoscale Analysis

a. Mesoscale Conditions on 29 March, 1998

The mesoscale conditions for this event involve certain aspects of the supercell at different levels within the storm. By using the conceptual model of the stages of a supercell according to Lemon and Doswell [1979], an analysis of this storm will show that the upper level jet from the southwest, a mid-level inflow from the south, and localized region of low stability all contributed to the supercell dynamics that drove the mesoscale convection on the afternoon of March 29, 1998. In order to understand how these dynamics functioned in this supercell, a close examination of the two dimensional conceptual supercell model as presented by Lemon and Doswell [1979] is necessary.

i. Horizontal Surface Weather Schematic in Two-Dimensions—Lemon and Doswell [1979]

Lemon and Doswell [1979] developed a complex supercell conceptual model at various levels in the atmosphere. One of the models they constructed is shown in **Figure 3**. **Figure 3a** shows the supercell storm schematic depicting horizontal distribution of surface weather. The structure includes two occluded gust fronts associated with the forward flanking downdraft and the rear flanking downdraft. The "classic" hook shape radar echo is shown with the light and moderate rain near the forward flanking downdraft region of the supercell and the hail region near the occlusion. **Figure 3b** is a radar image overlaying the satellite image valid 2215Z on March 29, 1998. The hook shape echo is seen on the radar in conjunction with the overall shape of the supercell as seen by the clouds in the satellite image. Also, the flanking line shown in Lemon and Doswell's model (**Figure 3a**) can be seen in the satellite features of **Figure 3b**. It seems that the radar and satellite from March 29, 1998 coincide with the conceptual supercell model presented by Lemon and Doswell [1979]. However, this model is only looking at the supercell in two dimensions. Supercells, in reality, have a three dimensional structure so another conceptual model by Lemon and Doswell needs to be closely analyzed before the conditions on the afternoon of March 29, 1998 can be assessed.

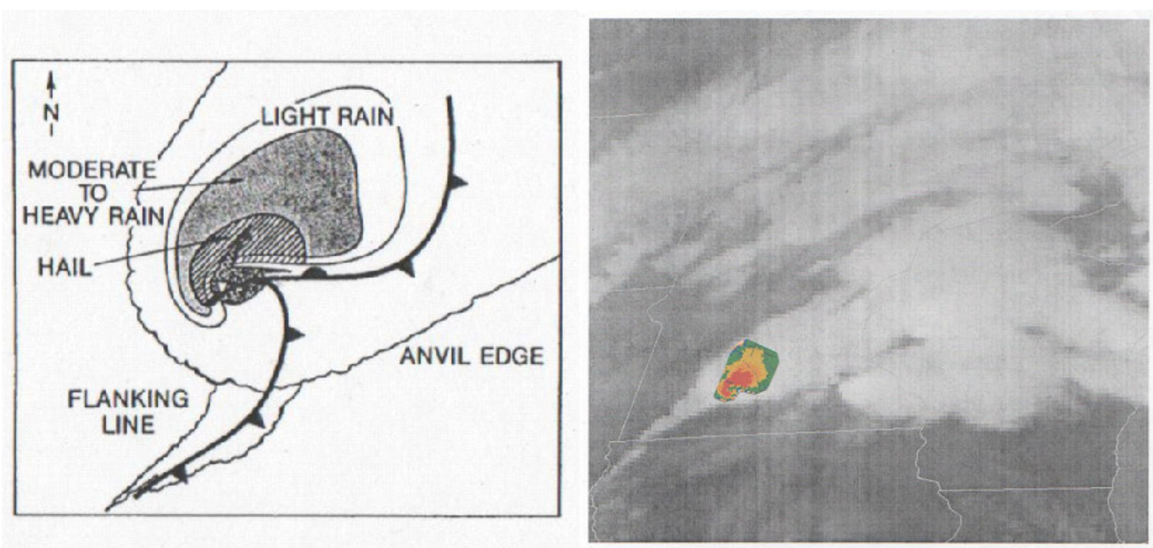

Figure 3. Horizontal Surface Weather Schematic: **a.** Lemon and Doswell [1979] surface weather diagram of a supercell **b.** Radar return overlaying satellite image valid 2215Z 29 March 1998 [Johnson, 2004]. Part **a** and **b** look similar in structure.

b. The Three-Dimensional Evolution of a Supercell Thunderstorm—Lemon and Doswell [1979]

Lemon and Doswell [1979] developed a three dimensional conceptual model depiction of the evolution of the drafts, tornado, and mesocyclone in a developing supercell storm. **Figure 4** shows a four panel plot diagramming the evolution stages of the supercell thunderstorm. A strong updraft exists in **Figure 4a** with a prominent forward flanking downdraft. The inflow from the surface flow comes into the storm from a very different angle than the inflow from the upper level jet. The flows come into the storm nearly orthogonal to one another. The mid-level flow enters the storm with an angle between the upper and lower inflows. Therefore the turning of the winds with height or shearing is significant in this conceptual supercell model. Also, the upper level jet hits the updraft and begins to descend as seen in **Figure 4a and 4b**. This is how Lemon and Doswell [1979] explain the formation of the rear flanking downdraft. **Figure 4c** is a schematic of the occlusion stage, or the stage of the supercell's evolution when the tornado is most likely to occur. The rotation in the updraft in conjunction with the rotation of the downdraft creates a condensed region of rotation at mid-levels. This is the mesocyclone where the pressure is quite low compared to the rest of the storm. If a tornado occurs, the entire storm's energy is displaced into this small "straw" of positive vorticity [Tripoli, 2006]. Many times, the tornado marks the final phase of the supercell. The updraft and overshooting top often collapse when the tornado forms, but as **Figure 4d** shows, a new updraft or "daughter" cell forms which can begin the cycle again.

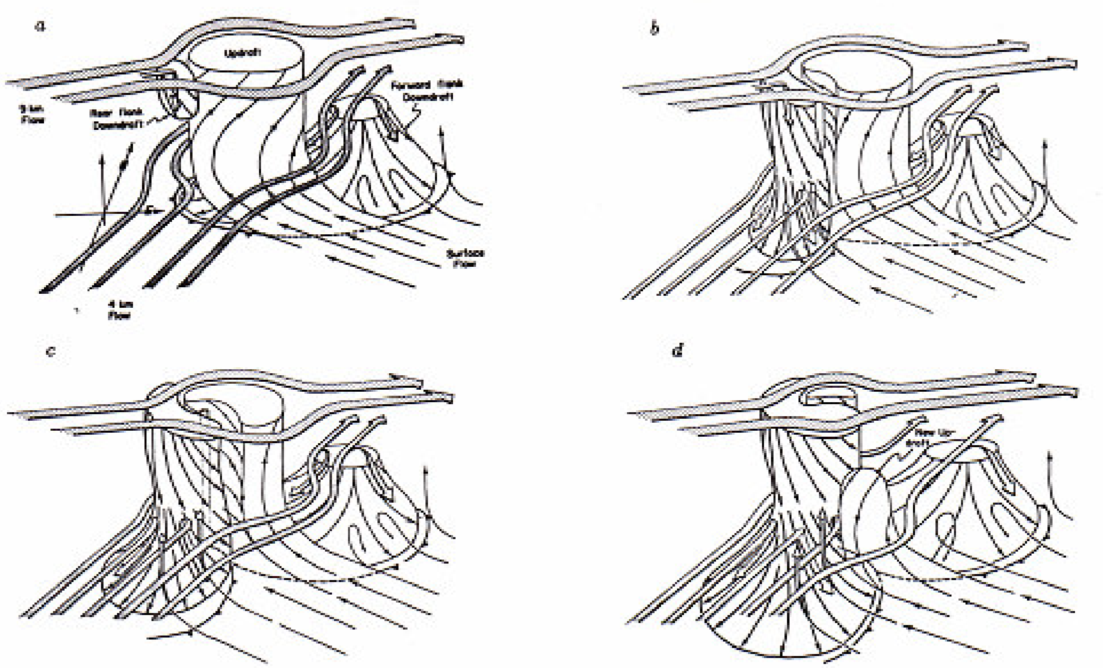

Figure 4. Conceptual model: Four panel schematic diagramming the evolution stages of the supercell thunderstorm [Lemon and Doswell, 1979].

The tornadic event on March 29, 1998 consisted of a long-lived supercell that spawned at least 14 tornadoes. The supercell tracked from the southwest corner of Minnesota to just south of the Twin Cities region, more than one hundred and fifty miles total. **Figure 5** shows the numerous tornado paths across southwest Minnesota on March 29, 1998. One of the tornadoes associated with this storm was an F4 (207-260 mile per hour winds) that remained on the ground for sixty seven miles. Minutes after this tornado dissipated, another F3 (158-206 mile per hour winds) tornado descended to the ground and trekked northeast for about nineteen miles. The remaining twelve tornadoes that occurred that day were ranked F2 (113-157 mile per hour winds) and F1 (73-112 mile per hour winds) in intensity. A close analysis of the supercell dynamics of that afternoon will show that the convection was enhanced by the mesoscale dynamics, including an upper level jet from the southwest, mid-level flow from the south, moist surface inflow from the southeast, and localized region of low stability which drove the convection and tornadogenesis as seen by the supercell schematic in **Figure 4**.

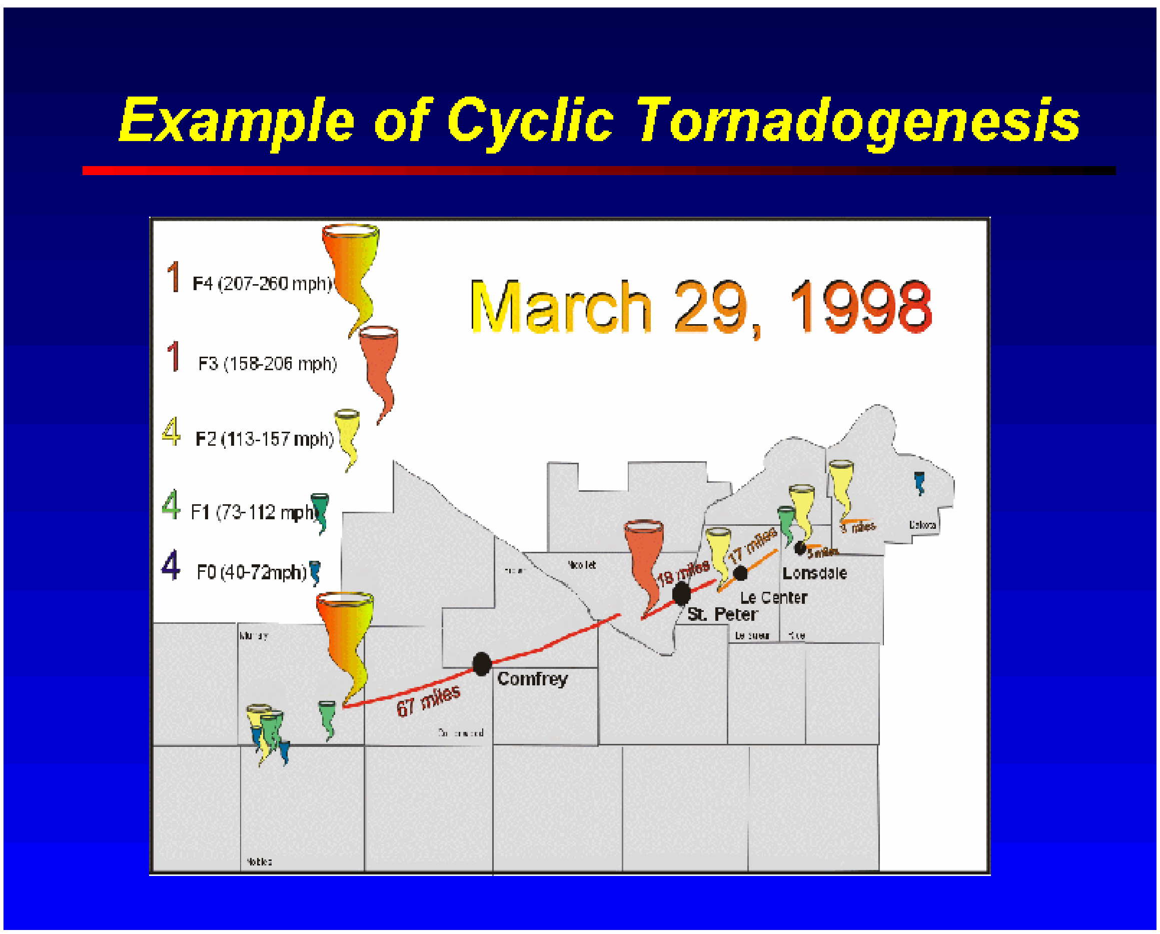

Figure 5. Tornado Paths: Numerous tornado touchdowns occurred on March 29, 1998 [Johnson, 2004].

i. Upper level Jet from the Southwest

In Lemon and Doswell's schematic, the upper and surface flows are almost perpendicular to one another. In **Figure 2**, the jet stream is orientated from the southwest to the northeast suggesting that the flow at the 300 mb level is also directed in this way. Besides looking at a horizontal plot of the isotachs, another way to get a sense of the wind speed and direction is to examine wind profiler data. Measurements throughout the day were made at a wind profiler station in Wood Lake, Minnesota. This station is about thirty five miles northwest of the track of the supercell. **Figure 6** is the wind profiler data that was observed on the afternoon of March 29, 1998. Throughout the afternoon, the flow at 9 km is consistently from the southwest direction. According to Lemon and Doswell [1979], if the upper level flow is from the southwest, the mid-level flow should be from the south, and the surface inflow should be from the southeast as seen in **Figure 4a**. This would produce optimal shearing for tornadogenesis and supercell evolution as depicted in the remaining parts of **Figure 4**. The mid-level flow will be assessed in the next section to see if it originates from the south.

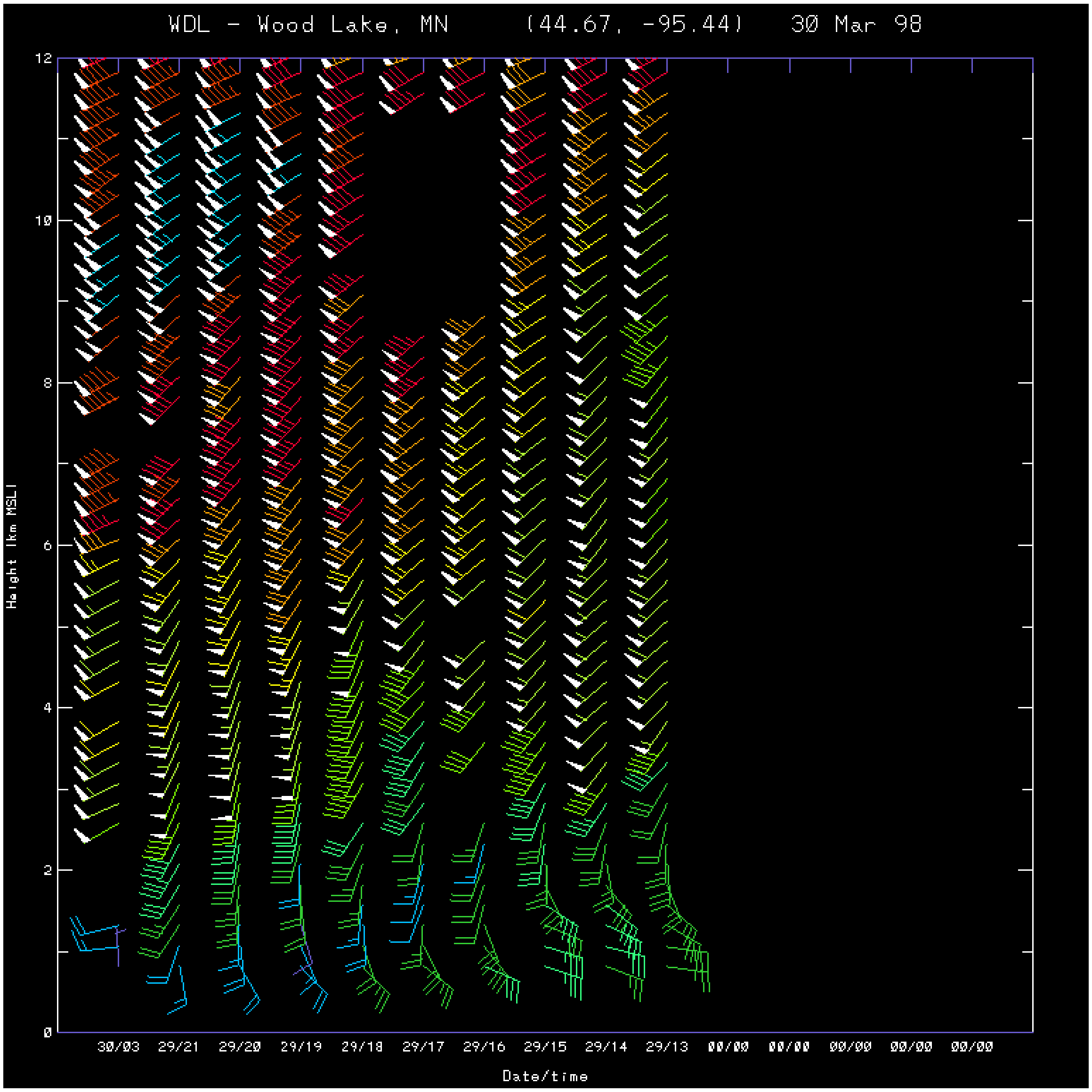

Figure 6. Wind Profiler Data: vertical wind profile data collected at the Wood Lake, MN station on the afternoon of 29 March 1998 [Bachmeier and Grauman, 1998].

ii. Mid-Level Flow from the South

According to **Figure 6**, the wind at mid-levels, or around 4 km as specified in Lemon and Doswell's conceptual model, is from the southwest for the early afternoon, but switches to a more southerly direction near the time of the tornado touchdown later in the afternoon. **Figure 6** also shows the winds veering with height consistently throughout the afternoon on March 29, 1998. Since the upper level and the mid-level flow coincide with Lemon and Doswell's model, the next constituent to examine is the surface flow direction and moisture to assess if it is directed from the southeast and whether or not it has ample moisture in order to contribute to the convection that afternoon.

iii. Moist Surface Flow from the Southeast

Figure 7 shows surface observations and model derived data from the Eta valid 1800Z 29 March 1998. **Figure 7a** shows the streamlines at this time based on the station observations and **Figure 7b** depicts a horizontal plot of relative humidity for the same time, as predicted by the Eta model. Based on the streamlines, the wind at the surface in southern Minnesota was from the southeast direction. Also, the moisture levels in southern Minnesota were extremely high with relative humidity values above 90%. The other important thing to note about this figure is that the stream lines are orientated such that the surface flow was bringing in moist air from northern Iowa and southeastern Minnesota which fed the supercell convection that afternoon.

The last component to address is the localized stability in this area just prior to the supercell formation. The upper and mid-level flow as well as the surface flow and moisture are all conducive for supercell development, but the stability needs to be low in order for a strong supercell and tornadogenesis to occur.

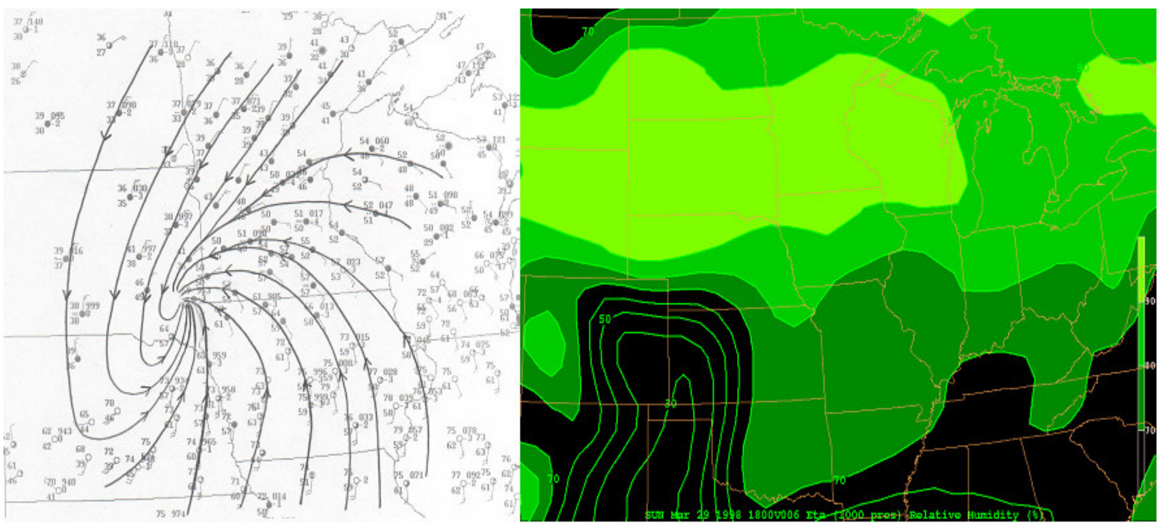

Figure 7. Surface Observations and Model derived data valid 1800Z 29 March 1998: **a.** Surface observations and analyzed streamlines **b.** Surface relative humidity as predicted by the Eta model.

iv. Low Stability

A local sounding derived from Eta model data is shown in **Figure 8**. This sounding is from New Ulm, Minnesota which is located near the region where the F4 tornado tracked. This schematic is valid at 0000Z 30 March, near the time the tornado hit St. Peter, and shows that the local environment was conditionally unstable at the time of tornadogenesis. Also, the wind profile in **Figure 8** is consistent with the wind profiler data from Wood Lake in **Figure 6** because both show veering winds with height which suggests warm air advection and shearing: two components that contribute to convection enhancement once triggered by a forcing mechanism.

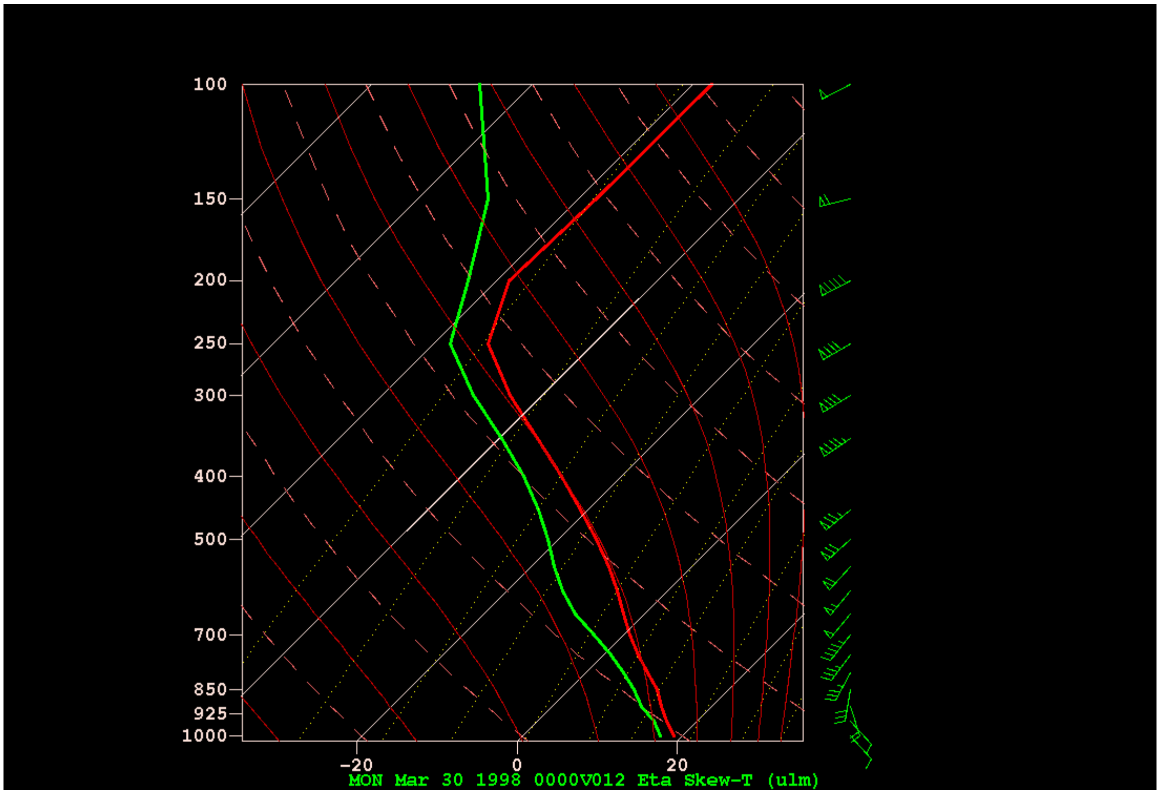

Figure 8. Model-derived sounding for New Ulm, Minnesota: valid 0000Z 30 March. Conditionally unstable profile suggests deep convection will occur if initiated.

v. Mature Supercell on 29 March, 1998

The supercell on March 29, 1998 was triggered by the warm front that extended across southern Minnesota. The supercell dynamics of that afternoon including an upper level jet from the southwest, mid-level flow from the south, moist surface inflow from the southeast, and localized region of low stability drove the convection and tornadogenesis as seen by the supercell schematic in **Figure 4.** A mature supercell evolved and had mesoscale dynamics similar to those diagramed by Lemon and Doswell [1979]. A vertical cross section from Windom, MN to Glencoe, MN, through the St. Peter supercell near the time the tornado touched down, is shown in **Figure 9**. The contours of equivalent potential temperature (θ_e) in green, give a sense of the moisture profile in the atmosphere, and show the characteristic "plume" feature of the supercell convection near St. Peter as well as the warm front to the north of the supercell. The black potential temperature (θ) contours tilt downward within the convection plum suggesting that the warm region is where the convection is occurring whereas the cooler region is out ahead of the warm front.

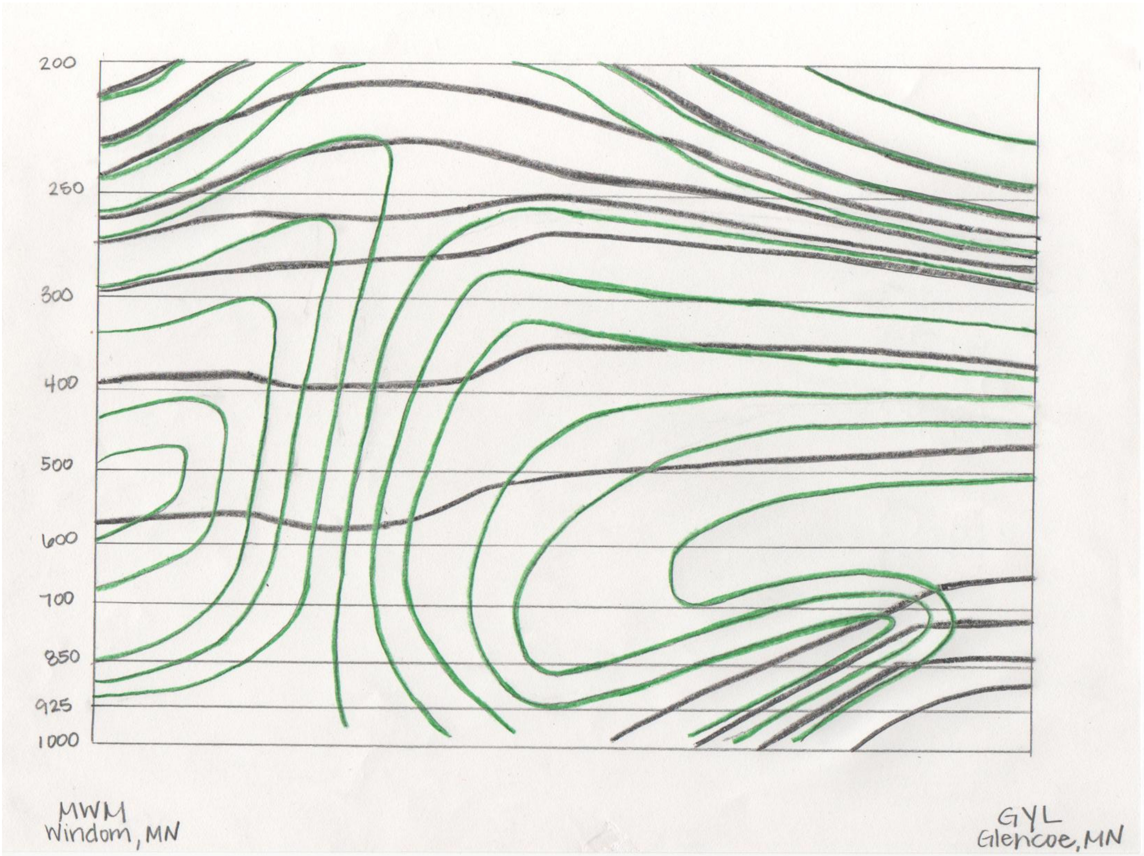

Figure 9. Vertical Cross Section: Equivalent potential temperature (θ_e) contoured in green and potential temperature (θ) contoured in black valid at 0000Z 30 March 1998.

V. Conclusion

a. Summary

The severe weather outbreak in southern Minnesota the afternoon of the 29th of March, 1998 was a massive and violent supercell that formed along the warm front. The supercell dynamics of that afternoon drove the convection and tornadogenesis, as seen by the schematic created by Lemon and Doswell [1979]. The upper level jet orientated from the southwest to the northeast across southern Minnesota as seen in **Figure 2**, the mid-level flow from the south as depicted by the weather profiling data in **Figure 6**, and the surface streamlines and relative humidity plot in **Figure 7** (which demonstrate that the surface winds were moist and from the southeast) all suggest that the mesoscale dynamics described by Lemon and Doswell [1979] were the dynamics that drove this system. Finally, the sounding in **Figure 8** from New Ulm, Minnesota shows that the atmosphere was very conditionally unstable and had veering wind shear, which allowed the convection to intensify rapidly and tornadogenesis to occur.

This intense storm had mesoscale supercell features that were consistent with those produced by Lemon and Doswell [1979]. These features allowed the storm to track for great distances and last for a long period of time. The numerous tornado touchdowns are explained by stage four as seen in **Figure 4d**. Since the supercell had appropriate mesoscale dynamics, the storm was able to cycle through Lemon and Doswell's stages numerous times throughout the afternoon.

b. Extensive Applications

The idea that mesoscale supercell dynamics can enhance convection when atmospheric conditions are conducive to severe weather is important to consider in future events. Since supercells are a challenge to forecast in the long-term, mesoscale atmospheric conditions just prior to a convective event should be taken into consideration. Forecasters should be aware that the intensity of a storm may be enhanced by mesoscale dynamics including shearing and the formation of a mesocyclone. Keen awareness of the model presented by Lemon and Doswell [1979] and the ability to apply these conceptual concepts to atmospheric conditions or specific meteorological cases may lead to better severe weather forecasts and prevention of future causalities associated with these dangerous tornadic events.

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