

Case Study of the March 29, 1998 Tornado Outbreak in Southern Minnesota: Early Onset

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ABSTRACT

On March 29, 1998 a series of tornadoes broke out over Southern Minnesota, resulting in catastrophic destruction in the small towns of Comfrey and St. Peter. The outbreak was only the seventh to ever occur in the month of March in Minnesota. The following case study is an attempt to understand the synoptic and mesoscale forcings that occurred that resulted in the development of supercells on this day. A brief discussion of Minnesota climatology is included, as well as a synoptic analysis that leans heavily toward the influence of a low pressure system in South Dakota and accompanying warm front, and concludes with a mesoscale analysis that focuses primarily on the influences of a lower level jet in convective instability as well as vertical shear in the development of the supercell structure.

I. Introduction

In the afternoon and early evening of March 29, 1998 a series of tornadoes broke out in southern Minnesota, devastating the communities of St. Peter and Comfrey. In just over three hours, 14 tornadoes were reported, including one F3 and one F4, resulting in roughly \$230 million in damage. Two people lost their lives and at least 38 people were injured in one of the earliest outbreaks the state of Minnesota has ever seen. Debris from the F3 that struck St. Peter, causing significant damage to the Gustavus Adolphus campus, was recovered in the Twin Cities over 60 miles away. In a town of only around 10,000 residents, more than 500 homes were destroyed and another 1,700 were damaged. The following case study will be an attempt to understand the events that took place on

this day that resulted in the production of such violent supercells. It will also look into possible reasons for the timing of these tornadoes; in the state of Minnesota prior to March 1998, only six tornadoes had ever occurred in that month, and the earliest known tornado to occur in the month of March took place on the 18th in 1968. Such significant storms this early in the season are not typical by any means, and an investigation into reasons for this early outbreak will be uncovered throughout this case study. It is hypothesized that all of the typical forcings, both on the synoptic and mesoscale levels, were in place for the development for severe weather and simply that unusually high temperatures and moisture availability on this particular day aided in the early onset of the severe weather season in this year. A description of the climatology of Minnesota will be included to gain an understanding of the

standard conditions that occur here on average. A section on supercell development will provide insight into the conditions necessary for such occurrences and the outbreak will be analyzed according to these conditions. Finally, the synoptic and mesoscale forcings will be discussed in an attempt to gain a full understanding of this case.

II. Data

The data used in this case was provided by the University of Wisconsin-Madison's Department of Atmospheric and Oceanic Sciences. The data was analyzed using the GEMPAK and GARP interfaces, programs designed for the simple production of presentation quality visuals. The University of Wyoming's Department of Engineering website provided the soundings and sounding data used in the production of the cross sections. Some of the conceptual models and diagrams were provided by papers and lectures notes and will be referenced accordingly throughout the case study.

The data provided for this case included the 00Z data on the 29th as well as the 12Z data on the 29th, and the twelve hour forecast of the 00Z and the zero hour and 12 hour forecast of the 12Z data were primarily used in the analysis of this case.

III. Synoptic Overview

IIIa. Climatology of Minnesota

Overall, the state of Minnesota is characterized by huge changes in

temperature from season to season with temperatures capable of reaching as low as -60F (-51C) in the winter months and as high as 114F (45.5C) in the summer months. On average, temperatures range from around 13F to 73F throughout the year. In March in the southern portion of the state, temperatures average around 32F, increasing to about 47F by April. Southern Minnesota in particular is known for the high levels of humidity that accompany warm temperatures in the summer, with dew points capable of reaching as high as 70-80F (21-27C). In the spring when temperatures begin to increase, storm systems can develop as low pressures move in from the West and collide with warm, moist air that has advected from the Gulf of Mexico. In the summer months in fact, winds predominantly come from the south and southeast, providing the southern portion of the state with its high levels of moisture. Thunderstorm activity typical persists for 30-40 days out of the year, from the date of onset. Tornadoes in particular can occur anywhere from March to November, but typically occur in June, followed by July, May, and August. The southern portion of the state favors tornadic activity as it is in the northern corner of tornado alley. As will be highlighted in this analysis, temperatures at the end of March 1998 in southern Minnesota were much higher than the average, perhaps contributing to the early onset of the outbreak this particular season (MN DNR 2004).

IIIb. Outbreak Overview

In the 1950's it was recognized by Fawbush and Miller that severe weather seemed to be consistently associated

with the location of mid to low level jet streaks, the location of convergence between moist and dry air and the extent to which moisture varied over the convergence zone (Miller 1972). They then developed five scenarios in which most severe storms could be categorized using these criteria, which allowed them to easily identify regions in which tornadic activity was most likely to occur. **Figure 1** shows the Miller Diagram associated with this particular event and highlights the region where severe weather would be likely to occur according to these variables. It seems

reasonable to begin an investigation of this sort with a Miller Diagram, as it shows a big picture of all the most important variables that interacted in the development of the storm. Throughout the analysis, this figure will be referred to often. Furthermore, a detailed description of each of the necessary conditions for supercell development, including instability, moisture flux, and synoptic forcing, will be provided accordingly as will be discussed in the Mesoscale Analysis portion of this case study.

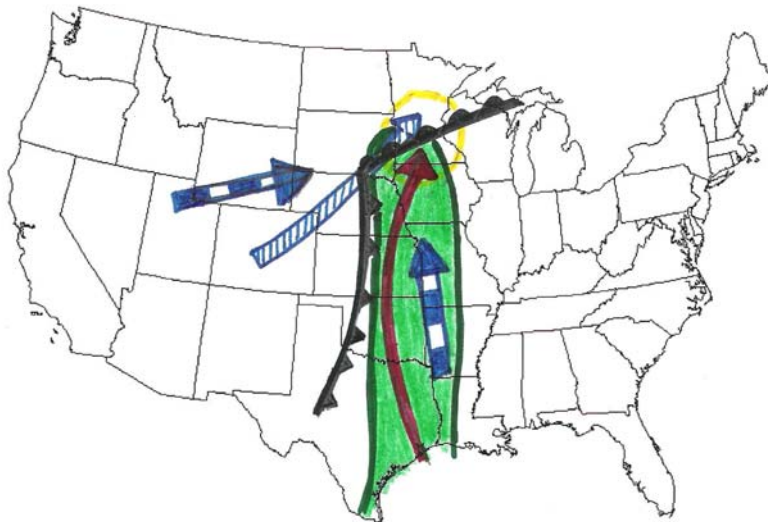


Figure1: Miller Diagram depicting the moisture flux in green, the mean flow at low levels from the south and at upper levels from the west, the upper level jet from the west, the lower level jet flowing up from the Gulf of Mexico and the warm and cold fronts. According to the diagnostics defined by Miller and Fawbush (Miller 1972), the convergence of these three variables identifies the region of maximum potential for severe weather, circled in yellow.

The major features associated with this outbreak stemmed from a strong low pressure system that was situated over South Dakota on the 29th of March, 1998. Associated with the low pressure was a warm front that brought uncharacteristically high temperatures to southern Minnesota, almost 25 degrees higher than normal, partially providing

the system with the necessary forcings for development. According to National Weather Service storm reports (2003), the system produced all of its tornadoes from about 3pm to 6pm on the 29th and this case study will focus primarily on the time period between 12Z on the 29th and 00Z on the 30th, roughly 6 am and 6 pm on the 29th. In this manner, the

majority of the development and existence of the system can be analyzed.

IIIc. Synoptic Overview

Figure 2 shows the satellite imagery of the supercell that spawned the tornadoes

in March 1998. The overshooting tops of the supercells that spawned the tornadoes in Comfrey and St. Peter are clearly visible from this image in the southern portion of Minnesota, along with the characteristic comma cloud and precipitation band associated with the low pressure system in South Dakota.

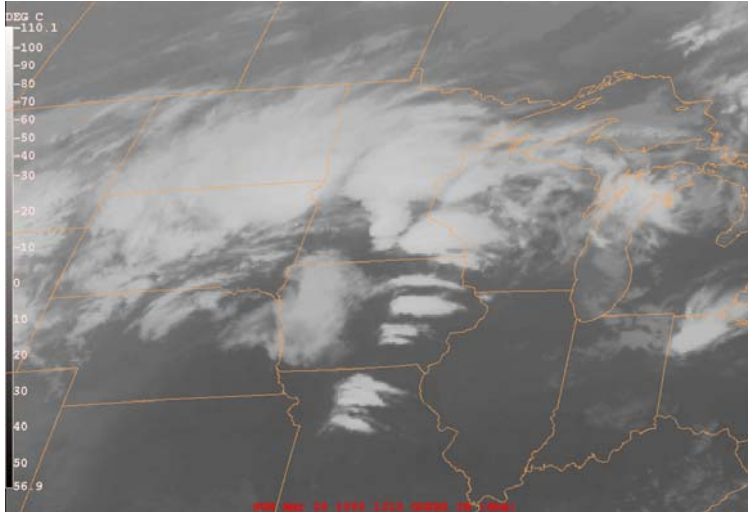


Figure 2: Visible Satellite taken at 1300UTC on the 29th. The overshooting tops of the supercells are identifiable in the southern portion of Minnesota.

Forcings for upward motion are of vital importance in the development of thunderstorms and supercells. Air must be rising in the atmosphere if clouds are to form. There are several synoptic scale features that can account for the forcing mechanism for upward vertical motions in the atmosphere. Those associated

with this case include the presence of a large low pressure system and accompanying warm and cold front, a weak baroclinic zone that allowed for low level frontogenesis along the warm front, along with slight positive vorticity advection by the thermal wind, as well as an upper level jet.

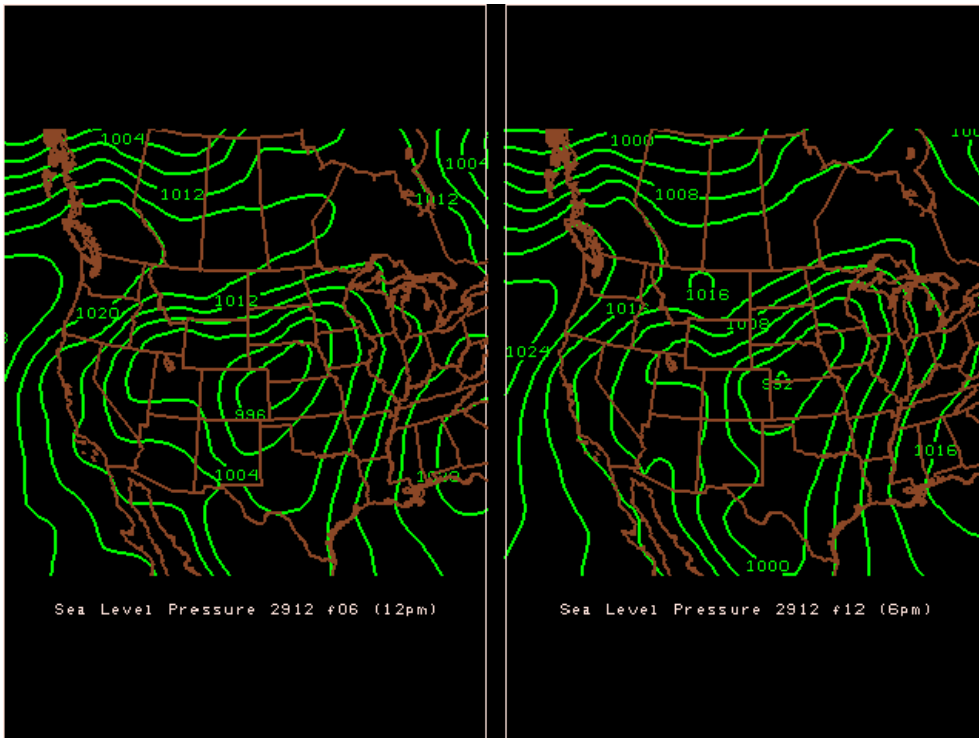


Figure 3: Sea level pressure at 18Z on the 29th and 00Z on the 30th. Note the location of the warm front through Southern Minnesota.

Figure 3 shows the propagation of the low pressure system from 18Z on the 29th to 00Z on the 30th, near the end of the severe weather activity in southern Minnesota. By 00Z on the 30th, the low pressure had deepened to 992 mb. The warm front can be seen stretching from roughly southern South Dakota, through southern Minnesota and past the northern portion of Wisconsin. Similarly, the cold front extends from Nebraska, down through Oklahoma and passes through central Texas. The

passage of the warm front brought warm temperatures uncharacteristically high for the end of March in southern Minnesota, peaking in the lower 60'sF as opposed to the climatological average which is generally just around 35-40F. The turning of the winds around the low pressure system also rotate in a counterclockwise manner, encouraging the flux of warm, moist air up from the Gulf. This situation can also be seen clearly in **Figure 4**.

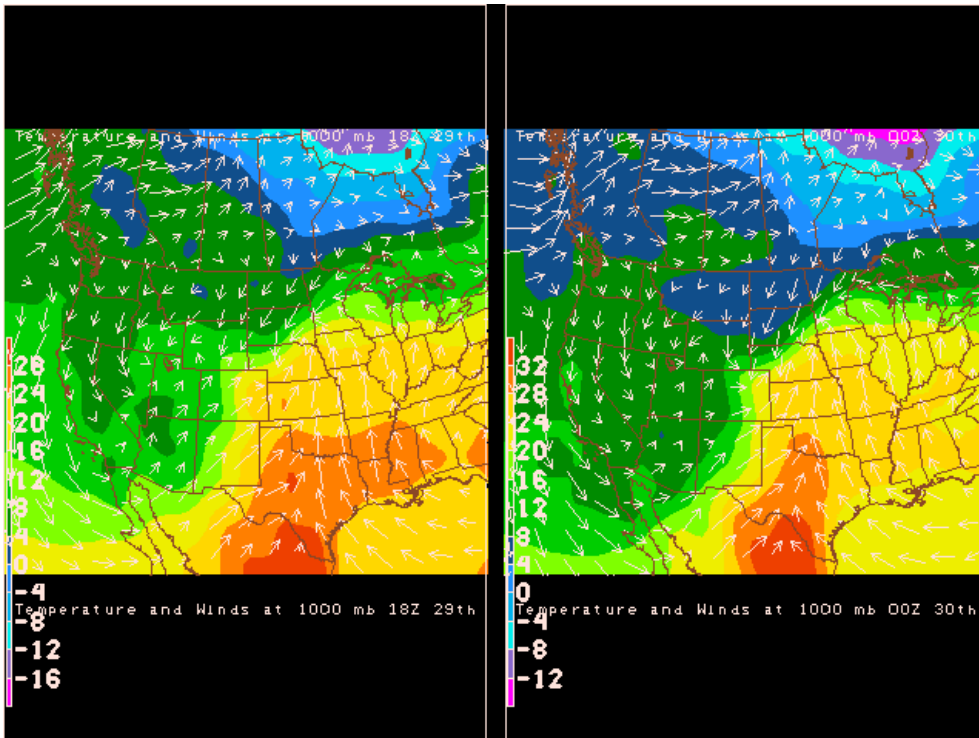


Figure 4: Temperature and winds plotted at 1000mb at 18Z on the 29th and 00Z on the 30th. Note the flow on the warm side of the cold front from the Gulf advecting warm, moist air up into Southern Minnesota. Also note the baroclinic zone associated with each front and the counterclockwise rotation of winds around the low pressure.

Figure 4 displays temperature and winds at 1000 mb. Several important points must be made about this figure in reference to this case. First and foremost is the circulation of the winds around the low pressure system, which correlates nicely with **Figure 3**. It is also important to note the warm air advection occurring south of Minnesota along with the extremely strong winds associated with this advection. It is easily apparent that warmer temperatures are being advected into the region providing moisture and adding to the temperature increase already associated with the warm front in this region. The location of the warm and cold fronts is also identifiable in this figure, with the warm frontal zone extending directly through southern Minnesota and the cold front extending through Nebraska and central Texas. The weak baroclinic zone

associated with the warm front influenced mild lower frontogenesis. On the synoptic scale, this mild frontogenesis could be partially responsible for the upward vertical motions occurring in this region that were necessary for the development of severe weather. In the larger picture, and for the sake of brevity, a figure showing this lower level frontogenesis has not been included as this forcing alone could not have been responsible for the total UVM and as will be discussed as follows must have only played a small role.

Further investigation of this case showed that both positive vorticity advection by the thermal wind and the presence of a moderate upper level jet also aided in the upward vertical motions present in this case. **Figure 5** shows positive vorticity

advection by the thermal wind, the left picture being 06Z on the 29th, before the initiation of the supercells, and 00Z on

the 30th, near the end of the life cycle of the supercells.

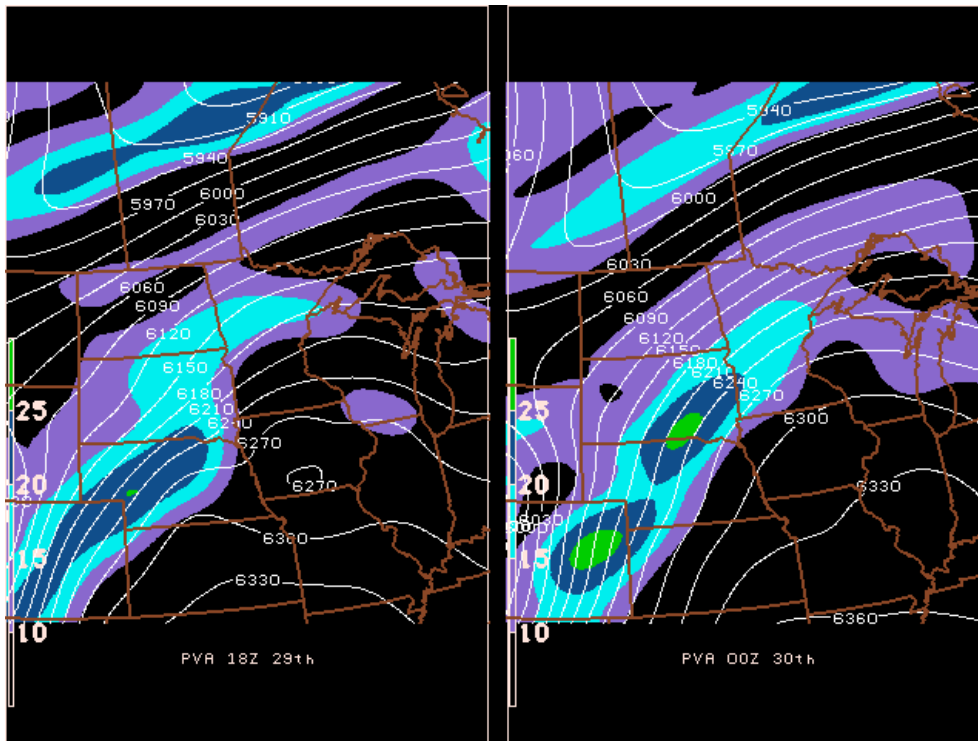


Figure 5: Positive vorticity advection by the thermal wind at 18z on the 29th and 00Z on the 30th, indicating regions of upward vertical motion in Southern Minnesota.

It is especially clear at 00Z on the 30th that upward vertical motion due to PVA by the thermal wind should be occurring just over south-central Minnesota, directly over the region of interest.

Figure 6 shows the progression of an upper level jet at 300 mb, at 12Z on the 29th, 18Z on the 29th, and 00Z on the 30th. At 12Z on the 29th, a relatively strong jet can be seen approaching from the west southwest, with the left exit region located over South Dakota and the southwestern corner of Minnesota. Ageostrophic divergence at the left exit region and right entrance regions of upper level jets indicates regions of upward vertical motions in the atmosphere and are thus important

synoptically. At 18Z on the 29th, the left exit region is more located towards the northern portion of Minnesota, but by 00Z on the 30th, the jet moving in from the west has merged with a jet descending from the north, and southern Minnesota is located precisely between a right entrance region and left exit region of each respective jet. While the left exit region of the jet roughly corresponds to the upward vertical motion associated with the region of interest, it doesn't match closely enough to be believable as a major player in this forcing. It does, however, clearly indicate the direction of the flow at upper levels, as will thus be referred back to when discussing the mesoscale analysis.

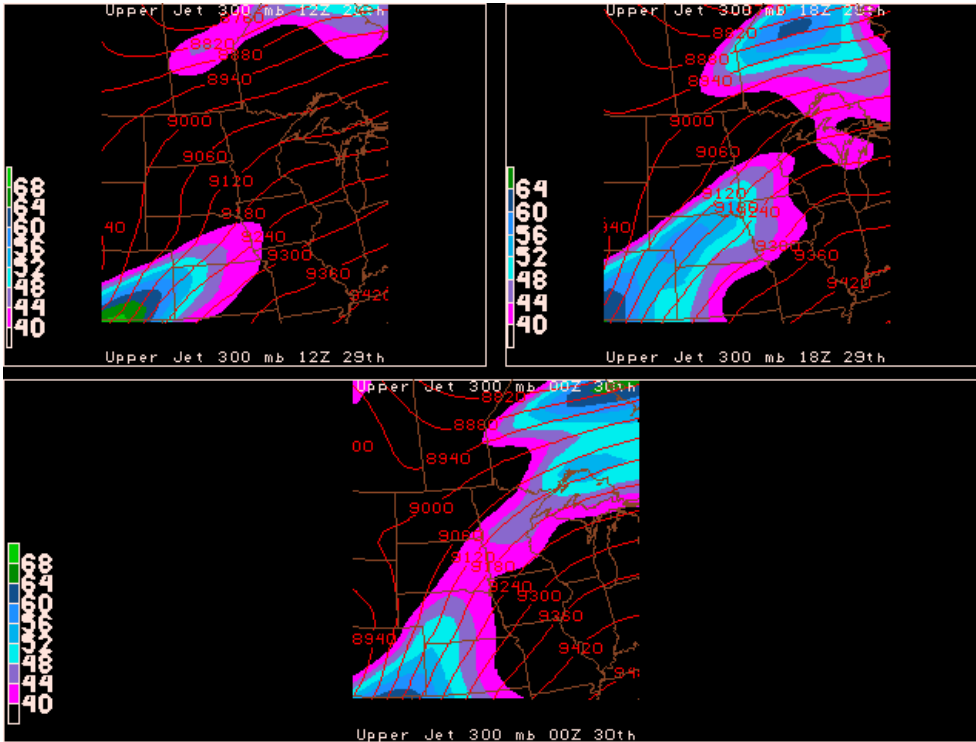


Figure 6: Progression of upper level jet at 300 mb at 12Z, 18Z on the 29th and 00z on the 30th. Note the left exit region of the jet as well as the right entrance region of the jet in the final panel, all correlating with regions of upward vertical motion. This plot also clearly indicates the direction of the mean flow at upper levels.

Figure 7 displays upward vertical motion at 00Z on the 30th. It is immediately obvious that a region of local upward vertical motions is occurring over the southern portion of Minnesota in association with this severe storm event, as would be expected that there should. It has been discussed in the following analysis possible forcings for such UVM, and will be concluded that it is the result of several forcings working together. The relatively significant warm front and subsequent baroclinic zone produced a region of

mild frontogenesis which partially accounted for the vertical motions. A relatively strong region of vorticity advection by the thermal wind into southern Minnesota also partially accounted for rising motions, and finally the left exit region, and right entrance region two upper level jet produced a local area of ageostrophic divergence that aided in vertical motions in this region. The upward vertical motions are indeed maximized in the southern portion of the state over St. Peter and coincides nicely with the area of

maximum potential for severe weather activity shown in the Miller Diagram in

Figure 2.

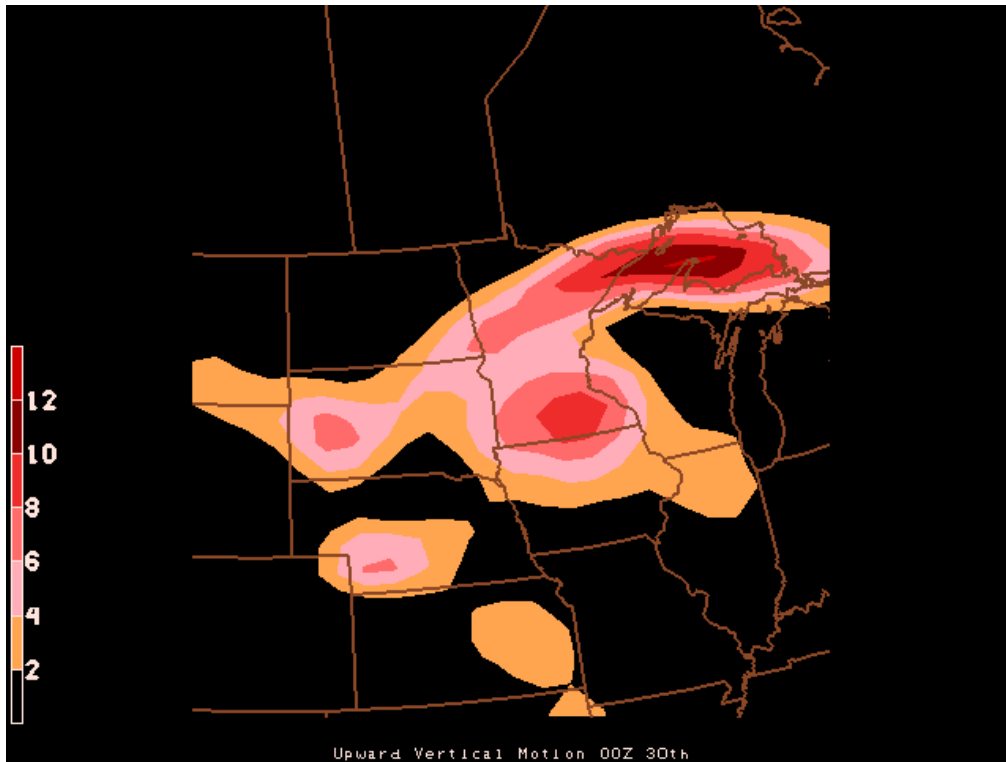


Figure 7: Omega plotted at 00Z on the 30th. The synoptic forcings highlighted combine to result in the region of upward vertical motion illustrated here that correlates well with the region of severe weather associated with this case.

IV. Mesoscale Analysis

The previous section provided an overview of the large scale forcings associated with the development of the severe weather event over southern Minnesota in March 1998. Upward vertical motions were shown to be relatively significant over the region of interest, the first step in understanding what occurred that day to result in such a violent eruption of supercell development. The Miller Diagram

illustrated in the beginning of this analysis highlighted several of the synoptic features associated with this case, such as the upper level jet, and the following section will be an attempt to understand the remainder of the variables, including moisture, the lower level flow and the resulting destabilization the allowed for the development of tornadic activity.

IVa. Supercell Development

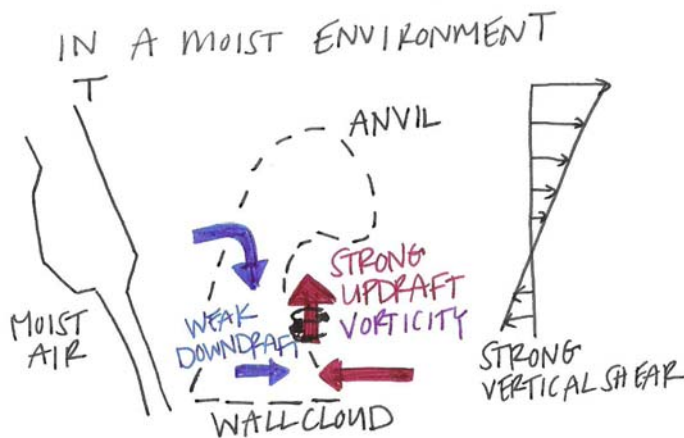


Figure 8: Conceptual Model of a supercell developing in a moist environment (as described by McNulty et al 1995).

The National Weather Service defines a supercell as a large, rotating severe thunderstorm in which winds at the surface flow in contrast to winds aloft, inducing the characteristic rotation. Strong updrafts and downdrafts are associated with this type of system, in which the updrafts pull up warm, moist air providing the supercell with energy so that it can survive for several hours. Tornadoes, hail, and heavy rains can all be associated with storms of this type. An unstable atmosphere, in which warm, moist air is trapped beneath a cooler, drier layer (such as an inversion) is ideal for the formation of supercells. When some sort of synoptic lift is added into the system, the warm layer can rapidly burst through the inversion or cap, resulting in sudden convection. Shearing of the winds with height cause the system to rotate as the system develops, eventually resulting in the formation of a supercell. Low-level winds from the southeast and upper level winds from the west provide ideal wind shear through which these cells can develop. In the late spring and summer months, winds from the southeast provide warm moist air from the Gulf, which can then collide with the drier air

that has advected in from the west over the Rockies. In a study done by McNulty of the Weather Service Forecast Office (1995) it was determined that severe weather in the Midwest peaks in the summer months due to a northwestward shift in the winds from the winter through spring. In agreement with the National Weather Service, it was also highlighted that there are three characteristic features necessary for the initiation of severe weather activity; convective instability, moisture, and a source of lift. **Figure 8** shows a conceptual model depicting this process. Convective instability is defined as a situation in which drier air overrides a warm, moist layer, trapping it beneath the layer. Upon the introduction of some sort of lifting mechanism, or enough energy builds up beneath the cap, the warm moist layer can explosively break through the dry layer and produce rapid and deep convection. The introduction and/or continued supply of moisture at lower levels can increase static stability, enhancing this process and thus playing a key role in the development of severe weather. Over the southern and central plains moisture advection by the low-level jet from the Gulf of Mexico

supplies these regions with the moisture needed for the initiation of thunderstorms. Finally, synoptic scale forcings, as well as mesoscale forcings, can provide the lift needed for the unstable layer to break through the cap and induce deep convection. It is important, however, to remember that the synoptic lifting itself can not trigger convection if the moisture and convective instability needed for rapid convection are not also present. Upon the system encountering a region of strong vertical wind shear, the environment is appropriate for the development of supercells.

The upper level jet did not appear to coincide well enough to be convincing as a primary forcing for upward vertical motions, but did however give a good sense of mean flow in the upper atmosphere which will be important when discussing vertical shear in the mesoscale analysis, as will be discussed in this section. In the study done by McNulty, as discussed in the section on supercell development, it was concluded that there are three main factors necessary for the development of severe weather systems including convective instability, moisture, and a source of lift. The source of lift on a synoptic scale was discussed in the previous section and the following section will discuss in detail the role convective instability and moisture availability, as well as vertical shear, played in the development of the St. Peter tornado outbreak.

IVb. Moisture

Any storm, synoptic or mesoscale in nature, needs moisture in order to produce any significant precipitation. As air rises in the atmosphere, it cools and is forced to condense out the liquid it contains, forming clouds or precipitation. However, if no moisture is present in the air in the first place, no amount of lifting will be capable of producing any clouds or rain of any significance. As discussed in the study done by McNulty et al, the moisture the central plains receives is the direct result of a low level jet that advects warm, moist air in from the Gulf of Mexico. *Figure 9* shows the progression of such a low level jet, associated with the March 1998 event. Beginning at 12Z on the 29th, the low level jet is fairly strong, but has not quite reached into southern Minnesota. By 00Z on the 30th, the jet is both strong and has traveled into the southern portion of the state, supplying the system with warm, moist air directly from the Gulf. This figure parallels the discussion from the synoptic analysis in reference to the 1000mb temperatures and winds. Winds are clearly flowing from the south, and temperatures on the east side of the cold front in association with the low level jet are extremely warm, near 20C. The counterclockwise rotation of the large low pressure system, aided by the warm air advection forced by the low level jet nicely provide the moisture needed in the supercell development in this case.

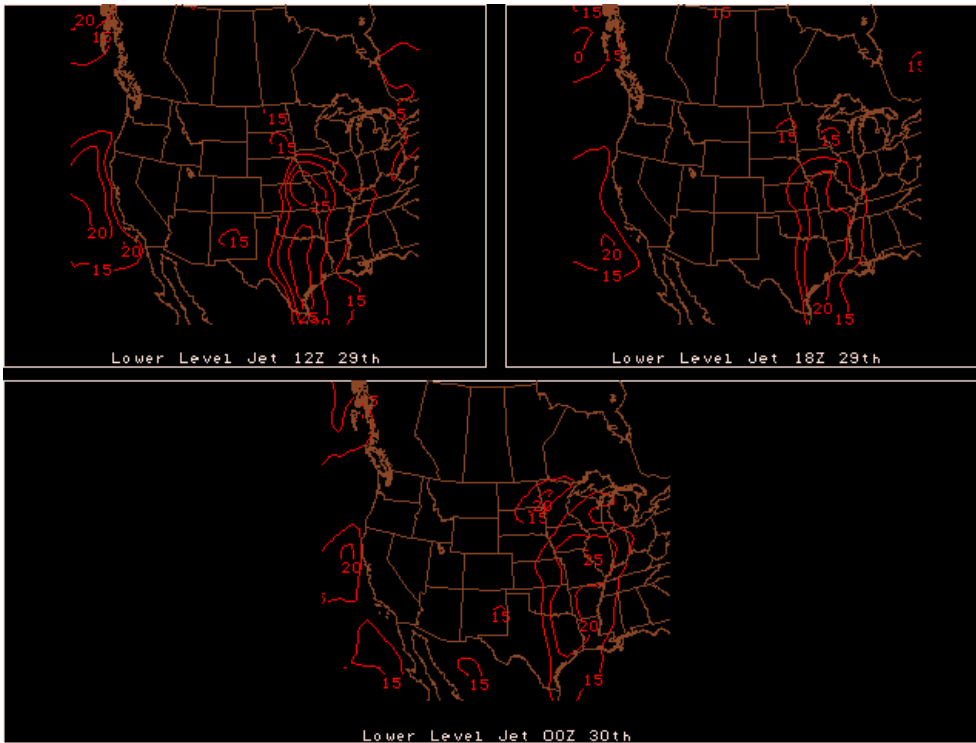


Figure 9: Location of the lower level jet at 12z, 18z on the 29th and 00z on the 30th, indicating the advection of warm, moist air from the Gulf supplying the energy needed in the development of the supercells associated with this case.

Figure 10 shows a vertical cross section taking at 00Z on the 30th from Aberdeen, South Dakota, through Chanhassen, Minnesota (just north of St. Peter) ending at Green Bay, Wisconsin. Contours of theta-e have been plotted every 4K and mixing ratio has been plotted every 2 g/kg. In accordance with the idea that the low level jet is responsible for the introduction of

moisture into the system, mixing ratio values at Chanhassen and even at Green Bay are very high, reaching 11.19 g/kg at Chanhassen. Furthermore, the convective plume (shown as theta-e contours) associated with the supercell structure occurs in relation to the maximum in mixing ratio, further illustrating the influence moisture has on the system.

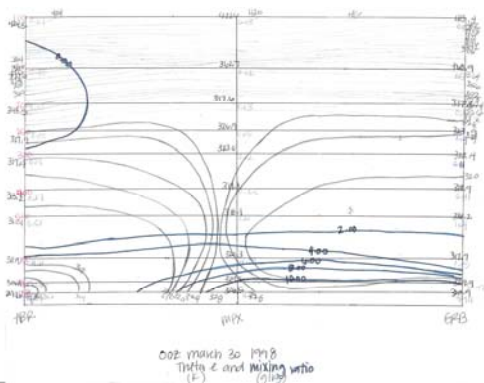


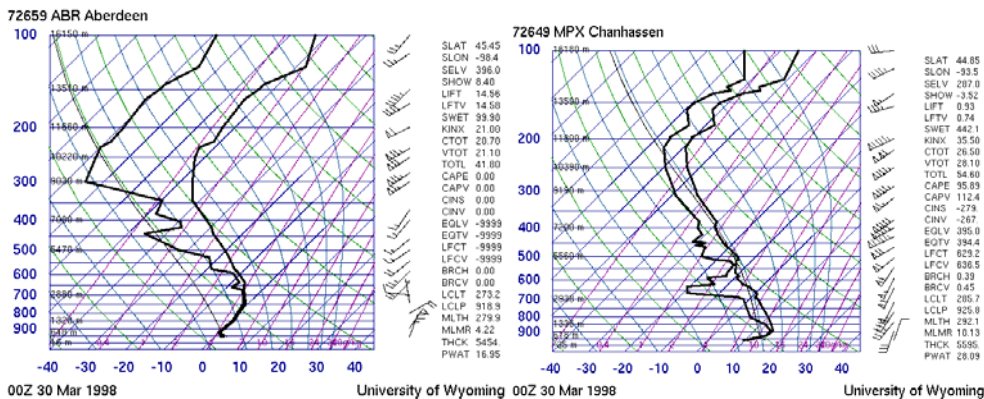
Figure 10: Vertical cross section taken from Aberdeen, SD through Chanhassen, MN and ending at Green Bay, WI. Mixing ratio is plotted in blue in g/kg every 2 g/kg. Note the high levels of

moisture at Chanhassen, consistent with the discussion of moisture availability in the development of supercells. Theta is also plotted, every 4K. The convective plume lines up well with the maximum in mixing ratio.

IVc. Convective Instability

As has been identified several times throughout this case, convective instability refers to the destabilization of air at the surface. This unstable layer is capped, generally by an inversion slightly above the surface, allowing the system to gain energy until the cap is broken so deep convection can occur. Destabilization of the air can occur in any number of ways, the most obvious being either by supplying the layer with moisture or by heating it, or both. Advection of warm, moist air by a low level jet is an ideal situation in which destabilization can occur, especially if an inversion is present. **Figure 11** shows the soundings from the University of Wyoming's Department of Engineering website, depicting a cross section taking at 00Z on the 30th from Aberdeen, through Chanhassen, ending at Green

Bay. The cross section actually cuts just north of St. Peter, which presents an interesting point in the case of the Chanhassen sounding. Nonetheless, in all three soundings, it is immediately obvious that the surface is incredibly moist, no doubt corresponding both to the influx of moisture from the low level jet, as well as to the fact that severe weather and cloud formation are both occurring at this time. The Chanhassen sounding is unique because there is an inversion right at the surface, perhaps in conjunction with the passage of the warm front. Also interesting to note is that the sounding has characteristics reminiscent of a tropical sounding, in that it appears to be almost entirely moist adiabatic. 00Z on the 30th is just near the end of the supercell activity associated with this event, but the soundings nonetheless pose a unique case in terms of convective instability.



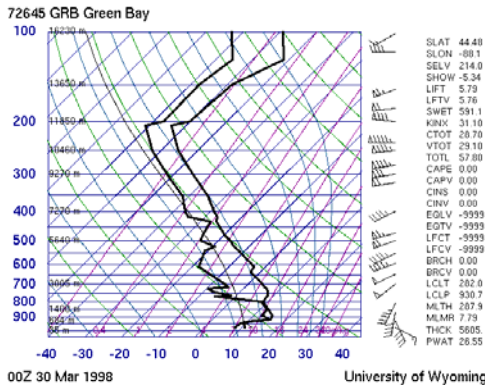


Figure 11: Soundings, all taken at 00Z on the 30th. Top left is Aberdeen, top right is Chanhasseen and the bottom panel is Green Bay.

IVd. Vertical Shear

Referring back to the discussion of supercell development and the need for rotation in the classification of such thunderstorms, a case study on the March 1998 tornado outbreak in Southern Minnesota would not be complete without a discussion on vertical shear. Without vertical shear, rotation would not be induced and therefore supercell development would not occur. McNulty et al concluded that surface flow from the south southeast paired with upper level flow from the west bringing warm dry air in from over the Rocky Mountains was ideal for the development of supercells and this case is a prime example of such a situation. Referring back to **Figure 4**, it is clear that winds at the surface are flowing in directly from the south. The upper level jet, displayed in **Figure 6** clearly shows that flow aloft is traveling in from the west southwest. Upon the interaction between the two air masses, rotation is induced as the winds turn with height, in conjunction with the upward vertical motions and thunderstorm development already occurring in this region.

V. Conclusion

On March 29, 1998 a devastating tornado outbreak occurred in Southern Minnesota, destroying large portions of the small towns of Comfrey and St. Peter resulting in over \$200 million in damages. The outbreak was one of the earliest Minnesota has ever seen, the earliest being only 11 days before it in 1968. A look at the climatology of Minnesota showed that temperatures at the end of March in the southern portion of the state only reach the mid to high 30'sF, much too cold for thunderstorm development. This case was not unique in any of its formation properties except for its premature occurrence. The uncharacteristically warm temperatures responsible for supercell development on this day were the partially due to a strong low pressure system that had developed over South Dakota, with a corresponding warm front extending from South Dakota, through Minnesota, ending over Wisconsin. The following case study has been an attempt to piece together the forcings that resulting in supercell and thus tornadic development on this day. It was discovered that the

synoptic forcings were found to be relatively insignificant alone, but the combination of the mild forcings due to the warm front and thus warm frontogenesis, along with positive vorticity advection by the thermal wind and the presence of the left exit and right entrance regions of an upper level jet all contributed to lifting necessary in this case. On the mesoscale level, the presence of a lower level jet was mainly responsible for the influx of moisture into the system, along with the counterclockwise rotation of the low pressure system which was able to force warm air advection from the Gulf into the southern portion of Minnesota. The influx of moisture beneath a drier layer of air advecting in over the Rockies at upper levels destabilized the air and upon encountering the region of upward vertical motion, convection was able to occur. And finally, the shift in the

winds, from southerly at the surface to westerly aloft, produced vertical shear throughout the atmosphere that allowed for rotation and thus supercell development.

VI. Acknowledgements

The author would like to thank Pete Pokrandt and the UW's Department of Atmospheric and Oceanic Sciences for the data used in the development of this case. She would also like to thank Professor Tripoli for providing the background knowledge necessary for an investigation of this sort. And finally, she would like to thank Holly Hassenzahl for taking the time to meet and discuss this case. Without her, this case could not have been completed to its fullest potential.

VII. References

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