Dianosis of Tornadic Supercell Formation over Southern Wisconsin

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ABSTRACT

On August 18th, 2005 a tornadic outbreak occured in central and southeastern Wisconsin. Prelinimary reports are dominated by tornadoes. There were also a few large hail reports, but these were few and far between, and wind reports were non-existant. Radar from the event showed storms with classic supercell shape and movement. Of particular interest are two heavy precipitating supercells that formed in along and ahead of the cold front in southern Wisconsin. It was found that these storms had a better chance of producing tornadoes because of their low cloud condensation and level of free convection that occured in an environment with high low level shear. These two mesoscale properties of the storms lead to a strong mesocyclone that formed near the surface. With the meso so close to the ground, any vocticity formed below the meso could easily be transformed into a tornado.

1. Introduction

Large tornado outbreaks are rare in Wisconsin. In addition, one rarely gets that many tornadoes when an outbreak does occur. This is evidenced since the record one day total of tornadoes in Wisconsin is 26 tornadoes. This outbreak occurred on the afternoon of August the 18th. In this case, the National Weather Service only issued a slight risk of severe weather. This risk was warranted, but the storms that did form had plenty of low level shear, which could be transformed into a tornado. These tornadoes were not weak also of the 27 tornadoes formed, 16 of them were rated F1 or above by the national weather service. The strongest of which was an F3 that struck Stoughton, WI. Viewing a plot of the paths of the tornadoes, one will notice two principal areas in which the tornadoes formed. Either, the tornado occurred along a line extending from just east of Tomah, WI east northeastward toward Green Bay. Then there is as second line that starts in eastern Vernon county and extends east-southeastward into south west Jefferson county. The southern line of tornadoes had more tornadoes (19) and also had stronger tornadoes (all of the F2 and F3 tornadoes). This difference in strength can be attributed to the type of storms that created the event. The southern track tornadoes were created by a strong supercell that grew out of a convective line. The northern track tornadoes grew out of a vortex that formed on the north side of a squall line.

The supercell that formed the tornadoes in southern Wisconsin formed more and stronger tornadoes, because supercells are more condusive to creating tornadoes. In a typical supercell, vertical shear is tilted in the updraft to produce an updraft that rotates, otherwise known as a mesocyclone, see Figure 1. Many effects result from this rotation. Most importantly is that the rotation of the updraft creates an inertial wall which prevents intrusion of dry air into the updraft. The rotation also spins out heavier particles in the updraft. These particles such as rain, hail and gaupel form in an intense band of precipitation as seen on radar just to the outside of the updraft, see Figure 8. Typically, the heavier particles only get partially wrapped around the mesocyclone and on radar, there appears a hook echo.

The water loading outside of the mesocyclone also helps to facilitate the development of two principal downdrafts. The forward flanking downdraft is formed in association with dry air from the back side of the supercell working its way underneath the cell, and then having rain fall into the dry air cools it off and moistens it. This forces the air to fall to the surface and form a stationary front out in head of the storm. The rear flanking down draft is created by the upper level winds being forced downward when they hit the updraft. Then as they fall, they fall into the rain that has been evacuated from the updraft cooling and moistening the air as it falls. This air too falls to the ground and spreads out forming a rear-flanking outflow. The sometimes on the north side of the rear flanking down draft, there can be cyclonic vorticity that can be kicked up due to horizontal speed shear. If this can become move under the mesocyclone, then this could provide an excellent opportunity for a tornado to develop. Furthermore, this outflow can actually get out ahead of the updraft combining with the forward flanking outflow boundary. This in effect kills the updraft as it is now isolated from the warm moist air that was feeding it.

The life of the storm is renewed by the cyclonic shear though. As the storm occuludes there is two dynamic lows that form to the left and right of the original updraft. One will have cyclonic shear and the other will have anticyclonic shear. Which one is cyclonic and which one anticyclonic depends on the flow in the vertical. The updraft with cyclonic flow will have chance to survive and become the new supercell, while the other will quickly die. The most typical arrangement of cells is to have the cyclonic flow to the right and the anticyclonic flow to the left. This means that most typically the right storm is favored for development, giving the storm in general the appearance of moving right.

2. Data

Many different media performed the analysis of this storm. For an overview of the meso- and synoptic scales setup, Storms Prediction Center event analysis was used. This included mesoscale discussions that were issued throughout the day, the severe weather outlooks that were updated, and the storm reports. Initial analysis of infrared satellite loops and radar loops was also done, using the Storms Prediction Center website. Through these, a more specific period was found that best correlated with the time that the event was set up and the event occurred, August 18th 12Z to August 19th 04Z. In addition, surface data from weather stations across the United Stated was available hourly and upper air data was available for every 12 hours across the United States. For the times between the sounding 00Z and 12Z hours, i.e. the times soundings were launched, the eta model that was initialized with the sounding and surface observations was used. General Meteorology Package (GeMPak) was used to image model and observed data along with model soundings. In addition, soundings were retrieved from the University of Wyoming achieve. In addition, skew-t and hodograph plots based on the soundings previously mentioned soundings were also retrieved from the University of Wyoming archive. Satellite data was retrieved from GOES-8. The available data was 4km resolution visible (.65 micron) and infrared (10.7 micron) channel images as well as 8 km water vapor channel images (6.5 micron). In addition, Level III radar data from Milwaukee , WI (KMKE), La Crosse, WI (KARX) and Davenport, IA (KDVN) were used to diagnose the evolution of the supercells that affected central and southern Wisconsin. McIDAS-V beta 1 and 2 were both used to visualize radar as well as satellite images. Using most to all of the previously mentioned sources, a hand drawn Miller Diagram was

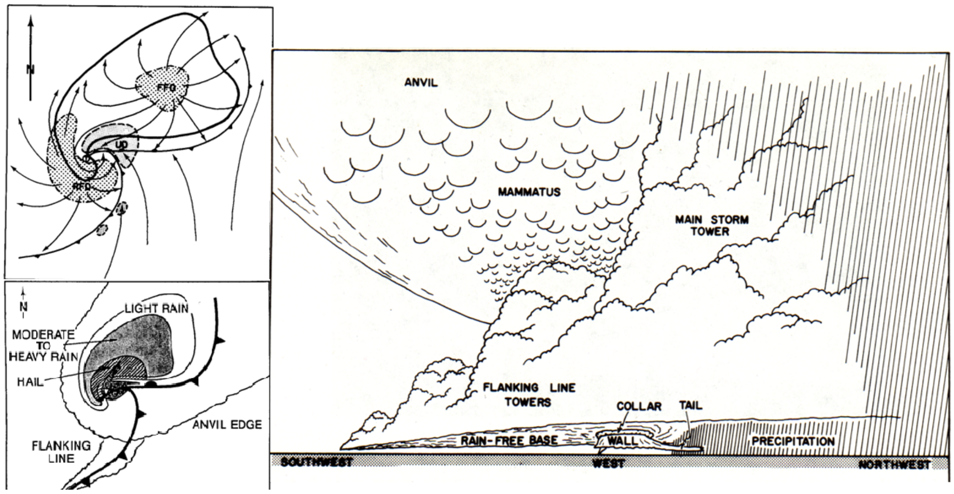

FIG. 1. Conceptual model of a tornadic supercell. The images on the left are veiws from above the storm. The top left image shows the positions of the vertical motions in the storm, and the associated flow at the surface in response to these vertical motions. The bottom left image shows both the clouds and precipitation associated with the supercell. The image on the right shows the vertical structure of the supercell. Of note is the postition of the tornado and wall cloud and the tilted updraft. Images were adapted from Professor Tripo's third lecture.

also created.

3. Synoptic Setup

In the case of the tornadoes spawned on August 18, 2005 in Wisconsin, these storms formed in conjunction with a surface low and an upper level short wave trough. Synoptically, the supercells in Wisconsin were created north of the warm front connected to a surface low over Minnesota. The forcing for convection though was forced by positive vorticity advection at 500 mb and 250 mb upper level jet to the south of Wisconsin.

a. 250mb analysis

At 250 mb, there was a positively tilted trough coming on shore at 12Z on August 18. The jet maximum over the United States was not associated with this trough but was zonal stretching from northern Colorado all the way to eastern Indiana. As the day progresses, the eastern half of the jet maximum is advected to the east over Pennsylvania. Meanwhile the western half strengthens over Colorado and then propagates to the east. Applying the four-quadrant model to these observations, one can surmise that over the area affected by the storms, between 12Z and 18Z on the 18th, the area was under the left entrance region of the eastern jet. This means that there would be sinking motions aloft. Typically sinking aloft would act to create a dry adiabatic lapse rate aloft. This potentially could be fuel for storm development by adding to or creating convective available potential energy (CAPE). CAPE is a useful indicy as it indicates the strength of the updraft. The between 18Z and 12Z, the area becomes coincident with the left exit region. This in effect would create divergence aloft which would lead to upward vertical motions below the divergence aloft. Of note also is that this jet is a subtropical jet, as can be inferred by the 190 mb high tropopause as seen in the 12Z atmospheric sounding from DVN on August 18th.

b. 500mb analysis

In addition to the jets that could provide mechanisms for vertical motions, there is also evidence of a neutrally tilted shortwave trough over the Dakota/Minnesota boarder. This shortwave becomes negatively tilted over the period of 12Z to 00Z of the 17th and propagates to the east. This means that there must be some positive vorticity advection (PVA) on the east side of the shortwave, which can provide for further ascent below the PVA. This is in conjunction with the upper level divergence mentioned above.

c. 700mb analysis

The 700 mb level shows 30-knot westerly to southwesterly winds over southern and central Wisconsin from 18Z to 00Z period on the 18th. This wind carries with it drier, warmer air out of the west. This is important to the storm development as the warmer, drier air probably has a steeper lapse rate, which could provide for more CAPE values. Higher CAPE means that a stronger updraft would form, which coupled with strong shear would lead to supercells as seen on this day.

d. 850mb analysis

Again, at 850 mb, there is a 25-knot south-southwesterly wind over central and southern Wisconsin. These winds were advecting air with very high mixing ratios out of the Gulf of Mexico and the Southern Plains, across Iowa into southern and central Wisconsin. The mixing ratios over central Arkansas were over 16 g/kg at 12Z on the 18th. This air has not seen the influx of moisture from the boundary layer due to evapotranspiration that would later occur later in the day in response to daytime heating.

e. Surface Analysis

The surface analysis shows a surface low slightly to the east of the aforementioned shortwave at 500mb at 12Z on the 18th. This would indicate that the low could be still strengthening. Along

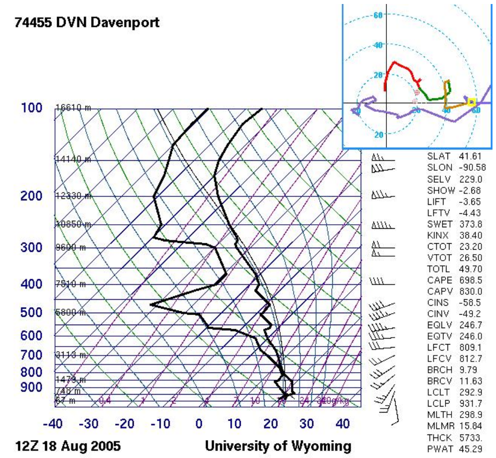

FIG. 3. A vertical sounding taken from 12Z on August 18th. Temperature (black contours), dewpoint (red contour),and windspeed (windbarbs) are ploted on the skew-T log-p diagram with a hodograph that plots the speed and direction of the wind. Of note is the veering profile with strong vertical speed shear near the surface. Also, note the high tropopause.

with that low, a warm front crossed from the center of the low on the Minnesota/Dakotas boarder across southern Minnesota through central and southern Wisconsin. The temperatures north of the front were in the upper 50's in degrees Fahrenheit while temperatures to the south of the front were in the low 70's. By 18Z, the surface low was now to the southwest of Winona, MN. The associated warm front, as diagnosed by the wind change across the front, was now extended into central Wisconsin from just north of Lacrosse, WI to just south of Green Bay. A wind shift was used as there a cold pool of air associated with the outflow boundary left over from morning convection over the eastern Wisconsin and Illinois boarder.

4. Mesoscale Discussion

The mesoscale features that helped to create the storm was due to the synoptic setup but also, the there were some independent mesoscale features that lead to this storm. First, the synop-

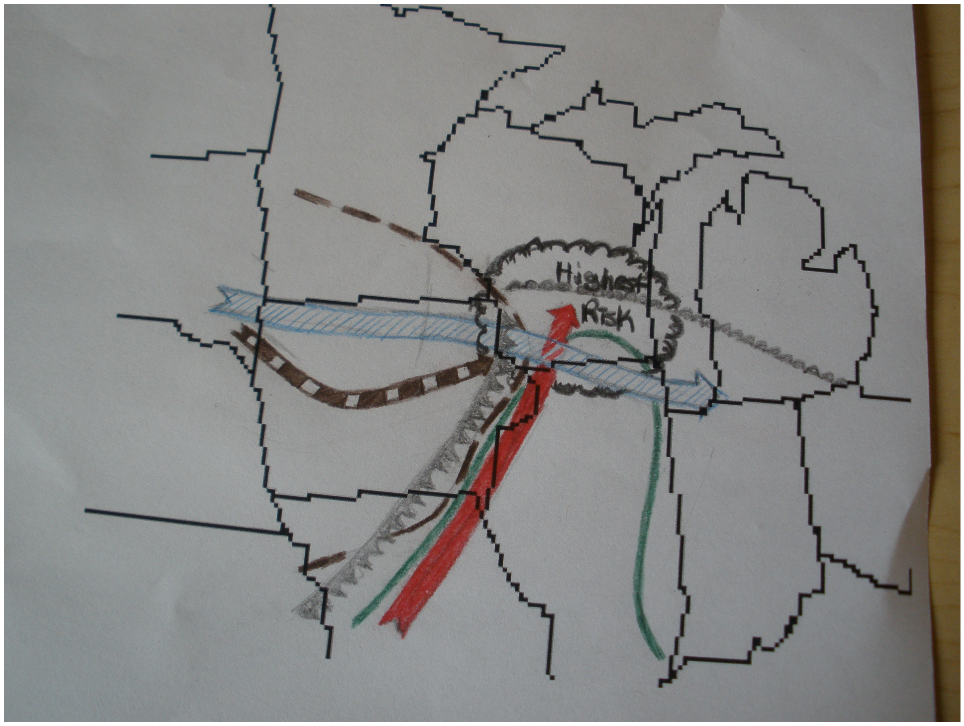

FIG. 2. The miller diagram for the evening of the 18th of August. This shows a veering wind profile with height over northern Illinois and into southern Wisconsin. it also shows a 700 mb dry tounge being advected by the 700 mb jet over the 850 mb moisture tounge. This dry tounge slighly leads the cold front and provides a mechanism for the strengthening of upperlevel cape. The highest risk for thunderstrom development takes place along and south of the surface warm front, and out ahead of the surface cold front. Also, note the 500mb jet that is draped just south of the region providing a mechanism for convection.

tic scale patterns created wind profiles and advected ample moisture into the region. Also, a prior squall line had left a outflow boundary near the warm front, that was conducive to supercell formation. Diurnal moisture from the local vegetation also seemed to play a role in the development of this storm as well.

a. *Synoptically Driven Mesoscale Features*

Shear is important on the synoptic and the meso-scale, but when one examines shear on the synopotic scale, the 500 to surface shear is typically examined in relation to surface low development. In this instance, low level shear is much more important, especially when considering supercell development. One place where low level wind shear can be especially strong is in the vicinity of the warm front. Here, winds at the surface can be from the south with even an easterly tint to them. Above the cold front, winds can veer to a more westerly to a northwesterly direction at the upper levels. This profile does indeed exist. Examining Figure 3 and 2 the wind profile shows the veering profile which is favorable for right moving supercells. This wind profile would be most like what one would see where the supercells developed in southern and central Wisconsin from the 18Z to 00Z hours, see Figure 4. A veering wind with height is favorable, because the shear, in the presence of an updraft can get tilted in such as way as to protect the updraft from dry air entrainment. Protection from dry air entrainment

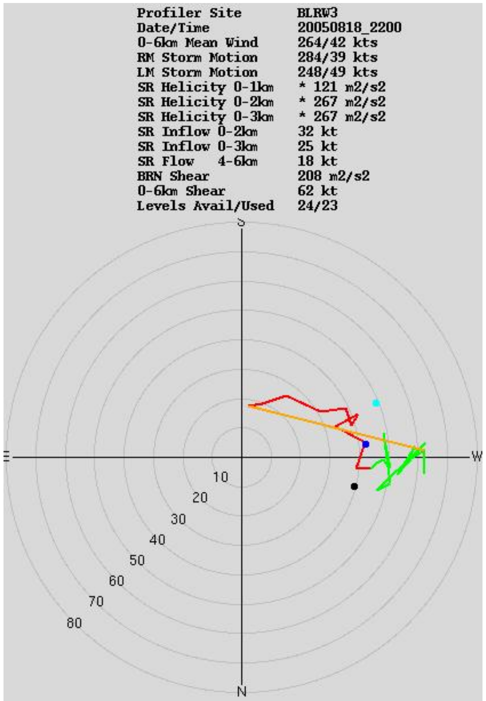

FIG. 4. Wind profiler data from the Blue River station. This wind profile was taken during the event from 5 miles west of the tornado that touched down near Muscada in Grant county and finally lifted near Orion in Richland county. This hodograph of the profile shows the lower level wind speed and direction contoured in red and upper level wind speed and direction countoured in green. Note the strong veering winds at the lower levels, as evidenced by the shear indicies.

is important as dry air entrainment can lead to a quick destruction of the lower level low and leave a storm departed from the moist air that it needs to survive.

In addition to a warm front extending over central to southeast Wisconsin, there was also an outflow boundary from convection that had rolled through in the morning. This outflow boundary formed in the vicinity of the warm front and was transformed by the warm front to enhance the mesoscale features. These two features alone have been found to be favorable locations for tornadic thunderstorms (Maddux et Al., 1979). The outflow boundary, with its cool air is characterized by strong winds near the surface. The warm front, is associated with strong veering winds near the surface. In this case, these two combined to produce the strong vertical wind shear with height and a strong veering profile, see Figure 3. Which would act to create an even stronger inertial wall, that would protect the updraft.

Vertical differential advection of moisture also played a large role in the development of these storms. As Figure 3, the entire atmosphere was nearly saturated up to 600mb at Davenport, IA. By 00Z on the 18th, significant drying had occurred above 831 mb, see Figure 5. The drying had the effect of increasing the environmental lapse rate, as there was no other deep convection in the area to maintain the moist adiabatic lapse rate of the earlier profile. The decrease in lapse rate helped the CAPE rise from 698 to 1646. By increasing the CAPE in a shear environment favorable for supercells, supercell formation became even more likely as the updraft became even stronger.

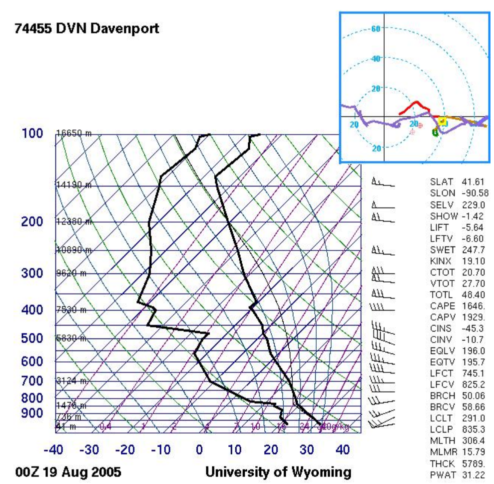

FIG. 5. A vertical sounding taken from 00Z on August 19th. Contours as for Figure 3. Of note is the middle layers drying out and the steeper lapse rate. This is after the 700 mb dry tounge as noted on the Miller Diagram had passed through.

b. Diurnal Moisture and Heat Variation

The daytime heating also played a major role in the development of the storms. To begin with, it destroyed the morning radiation inversion extending from the surface to 942 mb evident in the Devonport sounding, see Figure 3. By 00Z, the mixing of the layer is even evident as a nearly dry adiabatic layer extending all the way up to 831 mb. This conditionally unstable layer had a CIN of 43.7 J/kg, see Figure 5. Further to the north, with better forcing for convection, a cap like this could easily be broken.

Furthermore, the heating of the day really increased the low-level moisture. This could be accomplished by evapotranspiration at the surface. With deep mixing from the surface, this moisture could be mixed all the way to 831 mb. At the surface in Davenport, IA the mixing ratio increased by 2.20 g/kg, and even at 850 mb the mixing ratio had risen by 1.03 g/kg.

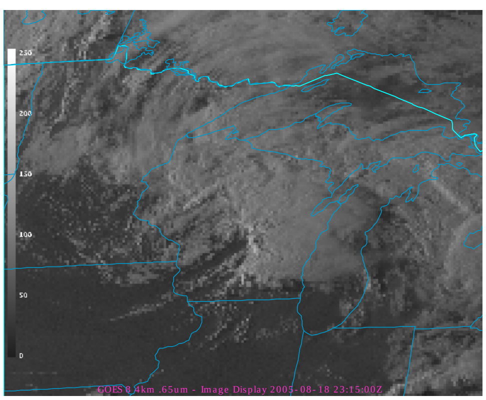

FIG. 6. Visible satellite image taken from GOES-8 centered on central Wisconsin. This image shows the brightness temperatures as per the color bar on the left. Of special not here are the lines of cumulus feeding into the storm.

Further, this moist air was being fed directly into the supercells. Viewing visible satellite photos, Figure 6, one can see a line of cumulus extending from north-west Iowa into the northern storm. This is not the rear flanking line, as it is much too long, but never the less; it follows the northern supercell perfectly, advecting clouds with lots of moisture right into the storm. As a note, this line of cumulus could become the rear flanking down draft closer to the storm, but the resolution of the satellite image is not that good, and upper level clouds obscure the region closest to where one might expect the flanking line to form. One can also see a line of cumulus feeding the southern storm as well. The cumulus line feeding the southern storm is most certainly not the rear flanking line, but never the less it feeds moisture into the updraft.

The low level moisture also provided for low liquid condensation levels (LCL) and level of free convection (LFC). The 18Z sounding out of Lincoln, IL (ILX) shows an 887.7 mb LCL and LFC, see Figure 7. These indicies are really close to the ground, and thus any storm that would form in this environment would have a greater chance to from a tornado, as the distance from the bottom of the meso to the ground would be smaller giving it a greater chance to form up a vortex that could connect with a surface vortex.

c. A Tale of Two Stroms

There were plenty of forcing for convection, and the environment was favorable for supercell development in southern Wisconsin. The Blue River wind profiler shows a Bulk Richardson Number shear of 208 m^2/s^2. Thus any CAPE values from 2000 to 8000 J/kg would be favorable supercell development. The actual formation of convection though started in southeastern Minnesota as a squall line. As the convection moved east of the Mississippi River, it started to get into an environment with more low-level shear, and broke up into discrete supercells. Of special interest is the supercell that moved southeast and the one that moved to the east. These storms both produced many different tornadoes. The most impressive of which was an F-3 that hit Stoughton. This one came out of the southeastward moving supercell. This was a more typical type supercell than was the storm that produced the tornadoes to the

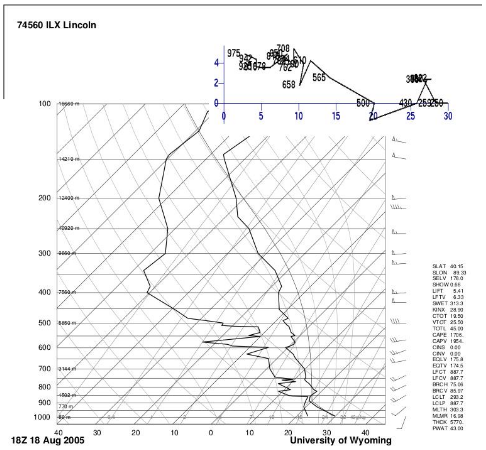

FIG. 7. A vertical sounding taken from 18Z on August 18th. Contours as for Figure 3 but hodograph is the U and V components of the wind vectors. Of note is the low lcl and lfc with the large CAPE values. Also this is the best sounding to evaluate convective indices as it is not affected by local convection, and it shows the effect of diurnal heating.

north.

The southeastward moving supercell formed out of an interaction between the convection occuring in front of a squall line and the squall line itself. These two act to enhance each other, and act to increase the strength of the updraft. This is also the time which it produced the first tornado at in Vernon county. Then it kept moving south and east as part of the convective line in which it formed. As it moved as part of the line, it was supplied with convective cells that were forming out ahead of the line. Eventually though, keeping up with the surface front, it moved out ahead of the line and started absorbing the convective supercells that were forming out ahead of the convective line, see Figure 8. The cells that were forming out ahead of the line were rather strong reaching 50 dbz on the Milwaukee .5 degree radar. Their importance to the continued existence of the supercell would be shown when at 2144Z. At this point the surface front moves out ahead of the convective line and the cells that were forming out ahead of the convective line now form the new convective line. As this happens, another line of convective cells form out in front of the cells feeding the supercell. This line actually acts in collusion with the convective line to amplify their own updrafts. This in effect cuts the supercell off from its moisture source and quickly dies out. While doing so, it then also quits its southeastward movement and starts moving northeastward. This can be attributed to its tendency to move right when it was a supercell.

Further towards evening the low-level jet kicks up at 00Z, see Figure 9. The flow vectors at 925 mb showed strong southwesterly motions pointing directly into the mesocyclone. This acts to enhance convection when one would be expecting convection to be dying down. The dying of convection is evidenced by the lack of convection forming to the southsouthwest of the supercell. Though the supercell still maintains its intensity as it did with the convective cells feeding into the storms and forcings are decreasing.

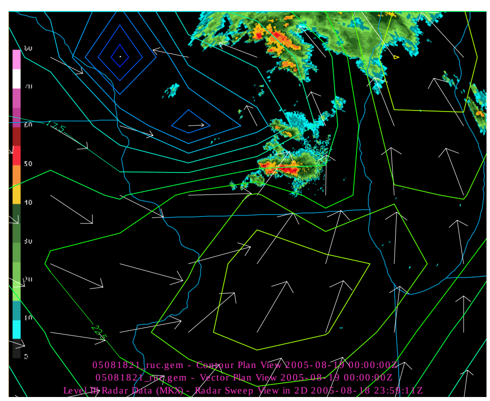

FIG. 9. 00Z RUC analysis at 950mb of the low-level jet. The contours are the windspeed in knots and are contoured every 2.5kts. The vectors are flow vectors, and the .5 degree radar out of MKE is shown. Take note how the flow vector are pointing directly into the mesocyclone of the supercell.

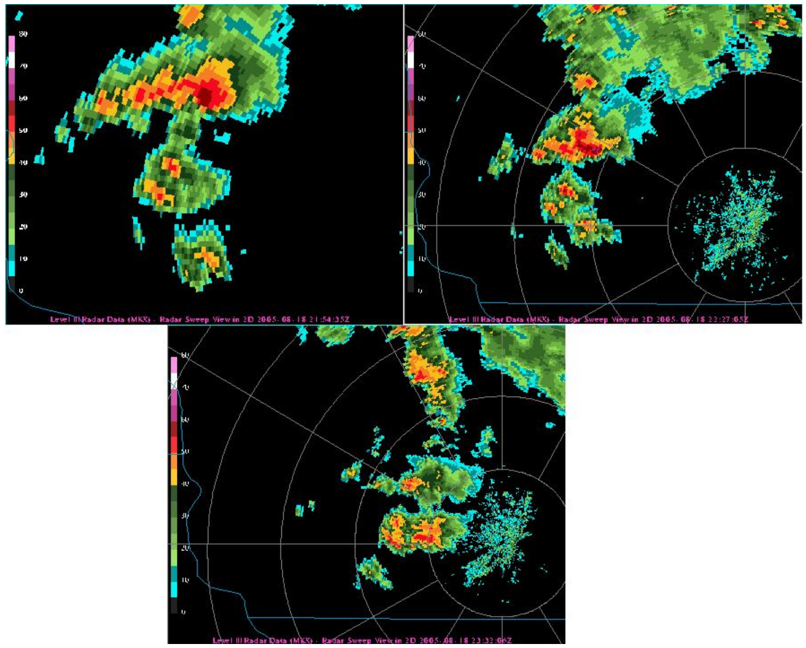

Fig. 8. A time evolution of the radar from KMKX with range rings centered on the radar site plotted on the last two images. Rings are ploted every 50km from the KMKE radar site and radials are plotted every 30 degrees from true north. These three plots show the evolution of the convective line that formed to the south and west of the storm and moved into the storm and the cells that formed out ahead of the storm. The first image on the top right shows the supercell moving out ahead of the convective line that spawned it and the small supercells that were forming out ahead of the convective line. These cells are moving directly into the updraft portion of the supercell. The image on the top left shows a new convective line forming in response to the cold front moving head of the convection trailing the supercell. One can also see convection forming out ahead of the new convective line. The bottom iimage shows convective cells a new super cell forming out ahead of the original supercell to the north. The dying supercell is approximately 60 degrees to the left of north at 65 km from the radar site. The newer supercell is at 90 degrees from north at 50 km from the radar site. All color fills as per the color bar are in dbZ.

d. Tornado Genesis

There were a lot of tornadoes formed from the supercells in southern Wisconsin. These supercells did not produce hail not did they not produce wind. By looking at the severe indicies one sees in the vertical soundings, that low level shear is the most impressive of the indicies. Combine this with the low level (less than 1.5 km level of free convection and liquid condensation level), if the mesocyclone would lower like as typicically does with supercells then one could very well see a mesocyclone getting going all the way down less than 1 km above the surface. Indeed, photos taken from the event shows very low mesocyclone just above the surface. With any sort of vorcitity created near the surface, be it may by differential horizonal wind shear, the vorticity associated with the rear flankind down draft forming a plume as it becomes coincident with the mesocyclone/wall cloud.

An interesting news headline the next day was the items that fell out of the storm the next day. Some reports had paper falling out of the air in Milwaukee, when the storms that were pulling up

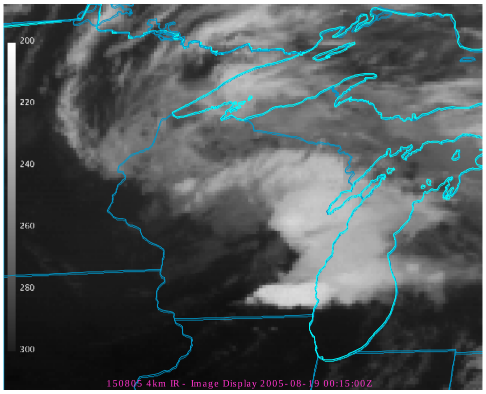

FIG. 10. This plot shows the 10.7 micron infrared image centered over central Wisconsin. All color fills as per the color bar are in Kelvin. Of special note, especially the high cloud tops, in this image is the supercell over southeastern Wisconsin.

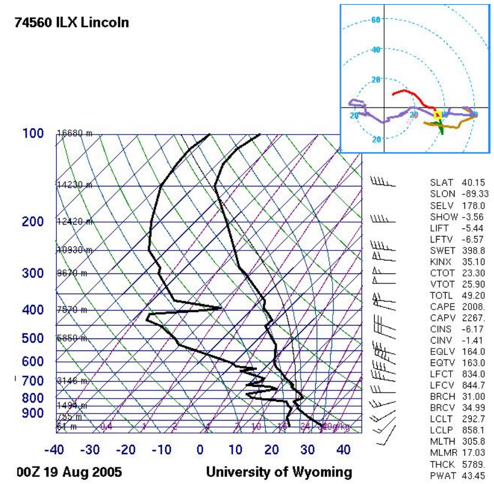

FIG. 11. A vertical sounding from KILX at 00Z on the 19th. Contours as for Figure 3. Of note is the high tropopause and the environmental temperatures at the upper levels.

this trash were near Dane county. This is attributed to one, the strong winds above the storm, and two, and the strength of the updraft. At the time, the upperlevel winds were quite strong. Analysis of the infrared image at 0015Z showed that cloud top temperatures from the blow off ranged near 216K, see Figure 10. Assuming this temperature to be near the environmental temperature at ILX at 00Z, this would mean that the blow off was up near 175 mb. At this level, the winds were 45 knots with the strongest winds lower in the atmosphere at 65 knots, see Figure 11. The depth of the convection would mean that the updraft would have to be strong enough to lift a piece of paper from the surface all the way up to that level, if not higher. Maintaining an updraft that strong over such a deep layer would be incredibly hard, and goes to show that there were strong dynamics at play in the maintenance of the storm.

5. Conclusion

The synoptic pattern did provide for convection later in the day. A subtropical jet lying to the south and a 500 mb short wave trough helped to spur convection over southern and central Wisconsin. Mid-level dry air advection over low level moisture advection, provided for sufficient lift to create supercells. The fronts associated with the surface low helped to spur low level lift as well. The outflow boundary left over from morning convection was also pertantent to enhancing the fronts. The low level speed shear associated with the outflow boundary combined with the directional shear of the warm front to provide for enhanced near surface shear. Later in the day,

Even though this storm had marginal forcings for convection, low level shear and aided the storm in the development of low-level convection with strong rotation. This made it easier for vortices to connect to the ground leading to the formation of many tornadoes over southeast Wisconsin. One can even see where the tornadoes had formed in bunches, as the supercell cycled through stages of splitting. Other than tornadoes, there were few other types of severe weather reported that day. Though the tornadoes themselves were destructive enough.

Unfortunately, some towns were hit by the strongest tornadoes to come out of this event. All told there were 24 injuries and 1 death were recorded.

Stoughton also 80 to 90 homes to the F3 that tore through the town. Consequently, this is where most of the injuries and deaths occurred. This was probably not predicted as for the previous few hours the original supercell was not dying. It was not until 30 minutes before the tornado developed that the rotation couplet appeared on radar. Such quick and unexpected storm development out ahead of the established line would most certainly cause headaches for any forecaster.

To the north, these storms were weaker and did not produce as strong of tornadoes or as many. This could probably be attributed to weaker dynamics and a different mechanism for the development of tornadoes.

Acknowledgments.

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