An Unprecedented Wisconsin Tornado Outbreak on 18 August 2005

Zachary P. Uttech
Department of Atmospheric and Oceanic Sciences
University of Wisconsin-Madison
May 5, 2009

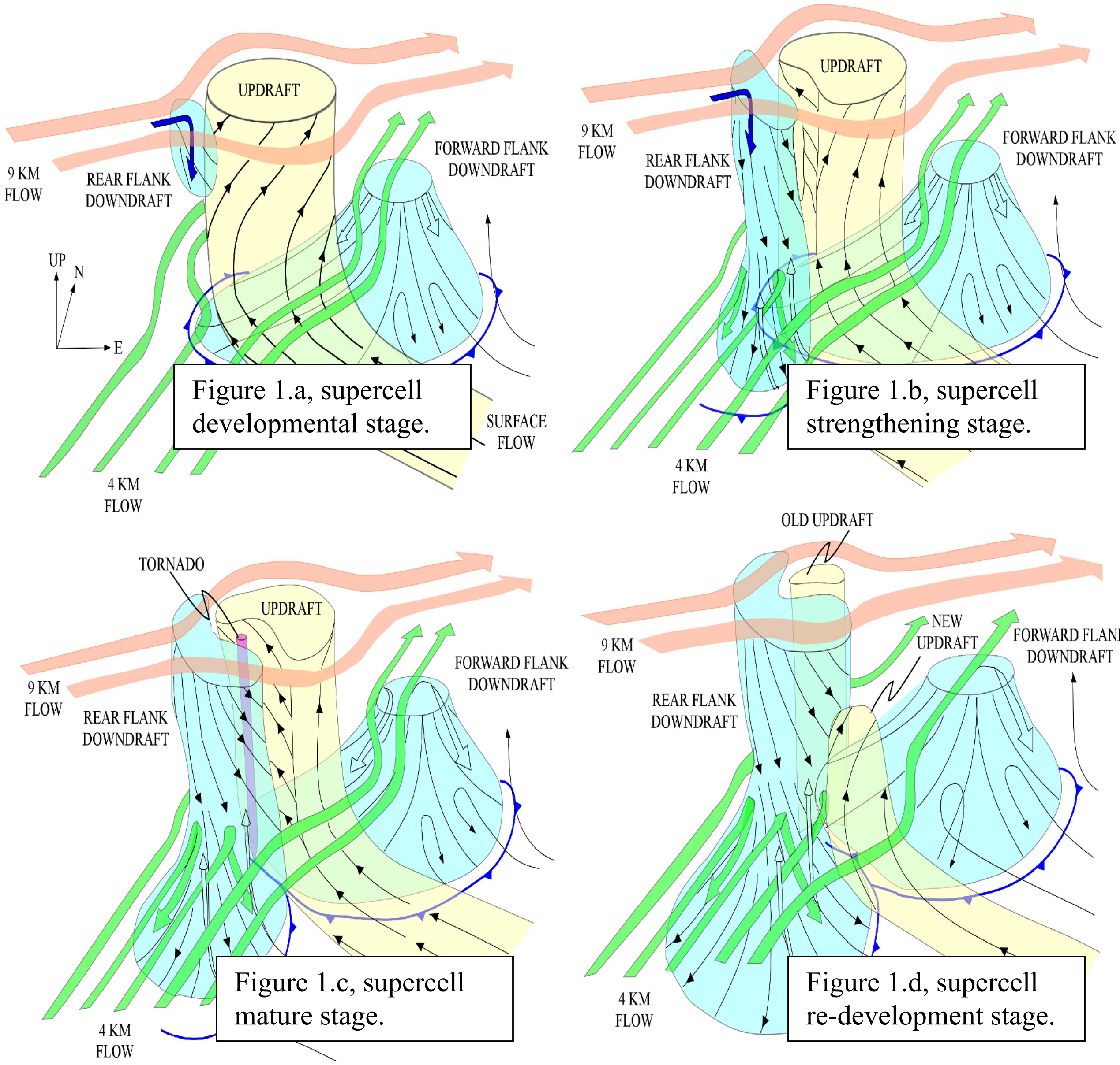
ABSTRACT

On 18 August 2005, a mid-level shortwave trough, most pronounced at 700mb, traversed through central and southern Wisconsin. In tandem with the 700mb shortwave, a weak but cyclonically organized surface low pressure center (of 1003mb) tracked slightly further to the south. Extreme instability developed by 21z, with the combination of mid-level geopotential height falls (7°C/km + mid-level lapse rates) and the cyclonic low-level circulation advecting tropical-like 354 K θ_e values into southern Wisconsin. This instability was manifested as surface based CAPE values of 3,000 J/kg +. Additionally, a veering low-level hodograph, 0 – 6 km bulk shear values as high as 33kts, and 0 – 3 km helicity values approaching 267 m^2/s^2 were sufficient enough to produce two persistent right moving supercells. The potential for instability to increase was made possible by a very dry, mid-level atmosphere around 700mb where 320 K θ_e values were measured. 300mb ageostrophic divergence, a dynamical forcing mechanism for ascent, was the last need ingredient needed for a significant tornado outbreak. The combination of the aforementioned atmospheric ingredients produced a record setting 27 tornadoes. The two supercells to be studied in greater detail went on to generate 14 of the 27 tornadoes. Before this case study, the author hypothesized that vertical directional shear was the most important dynamical parameter driving the tornadic storms.

1. Introduction

On rare occasions, all the needed atmospheric ingredients come together to produce tornadic supercells, as was the case on 18 August 2005 when southern Wisconsin experienced an unprecedented tornado outbreak. (The old record was 24 tornadoes on 8 May 1988). A total of 27 tornadoes touched down in the southern half of the state producing $42.5 million worth of damage. Most of the 27 tornadoes were relatively weak (e.g. 11 were rated F0 and 13 were rated F1). However, there were 3 moderately strong tornadoes (e.g. 2 F2s and 1 F3). According to Dr. Fujita's tornado intensity classifications published in 1971, an F2 and F3 tornado are classified as strong and severe, respectively. The F3 tornado traversed through Stoughton, WI (in southeastern Dane County) with wind speeds between 158 mph and 206 mph on the Fujita scale. An Enhanced-Fujita scale was implemented on February 1, 2007. According to the EF-scale, the Stoughton tornado would have estimated wind speeds between 135 mph – 165 mph. Similar to the F2 and F3 intensity, the EF-2 and EF-3 intensities are considered to be moderate and severe, respectively.

The author's goal for this case study is to diagnose what meteorological conditions were responsible for this unmatched tornado outbreak. This case study is focused on tornadic supercell genesis. A tornadic supercell life-cycle conceptual model will help the reader visualize the typical structure, thermodynamics, and dynamics associated with tornadic supercells (fig. 1). To diagnose large-scale forcings for ascent the discussion will begin with a synoptic overview of the 300mb, 500mb, and 850mb



Courtesy of the American Meteorological Society

Fig 1. Conceptual model of a tornadic supercell life-cycle, the notable features are: the mean updraft (current, old and new), the rear flanking down draft (RFD), the forward flanking downdraft (FFD), the mesocyclone, the tornado, and the 9 km flow and the 4 km flow. (a) the development phase; a supercell develops when a mid-level flow is split by a strong updraft. This produces two mescyclones that rotate in opposite directions, (b) the strengthening phase; a supercell strengthens when the RFD reaches the surface which tends to reinforce the updraft/RFD compensatory circulation, (c) the mature stage; a supercell reaches a mature stage when the RFD and updraft become strong enough to increase the low-level vorticity which can produce tornadoes inside the mesocyclone circulation, (d) the redevelopment stage; a supercell redevelops when the RFD intersects the FFD, essentially cutting-off the updraft from the supercell. However, a new updraft can form at the RFD and FFD intersection leading to new supercellular development. This is why the supercell usually redevelops to the south.

geopotential height patterns at 12z and 00z on 18 August 2005. In addition, the surface pressure analysis will be used to identify low-level fronts (i.e. low-level convergent flows) and regions of cold θ_e (equivalent potential temperature) advection at 700mb. The mesoscale analysis will primarily focus on the thermodynamic and dynamic instabilities of the atmosphere by using several severe weather indices. To examine the mesoscale instability over southern Wisconsin, the following severe weather indices will be used as a guide for tornadic supercell potential including: CAPE (convective available potential energy), CIN (convective inhibition), 0 – 6 km bulk shear, Bulk Richardson Number (BRN), hodographs, 0 – 3 km helicity, and the Severe Weather Index (SWEAT).

From a mesoscale standpoint, the author believes directional wind shear was the single most important dynamical parameter responsible for this unparalleled tornado outbreak. A surface low tracked eastward across central Wisconsin during the afternoon, concurrently a 500mb vorticity max tracked across northern Wisconsin. This provided more than enough directional wind shear with height and time, which are necessary for tornadic supercells.

2. Data

Data for this case study was acquired from a number of different sources. The Storm Prediction Center (SPC) provided a 12z 700mb upper air map and a 00z Davenport, IA sounding. A 00z Lincoln, IL sounding was obtained from the University of Wyoming upper air archive website. In addition, thermodynamic instability parameters and dynamical values were gathered from both soundings. The Plymouth State University meteorological data archive was used for both 12z and 00z synoptic four-panel plots and a 22z miller diagram state outline background. The unysis weather data archive provided a 12z surface analysis of the contiguous U.S. Also, the National Weather Service (NWS) La Crosse 18 August 2005 severe weather summary provided base radar reflectivity and radial velocity images of the Vernon County supercell at 21:09z. The NWS Sullivan provided base radar reflectivity and radial velocity images of the Dane County supercell at 23:37z. Lastly, a 22z Blue River, WI hodograph profiler was used for helicity values, because the supercells occurred during the 21:00z to 00z time frame and Blue River is only 25 miles southeast of Viola and 70 miles northwest of Stoughton.

3. Synoptic Overview

At 13z, the Storm Prediction Center (SPC) was only forecasting a slight risk for severe thunderstorms in southern Wisconsin. The main synoptic weather player was a mid-level (700mb) trough propagating through the upper Midwest (fig. 2).

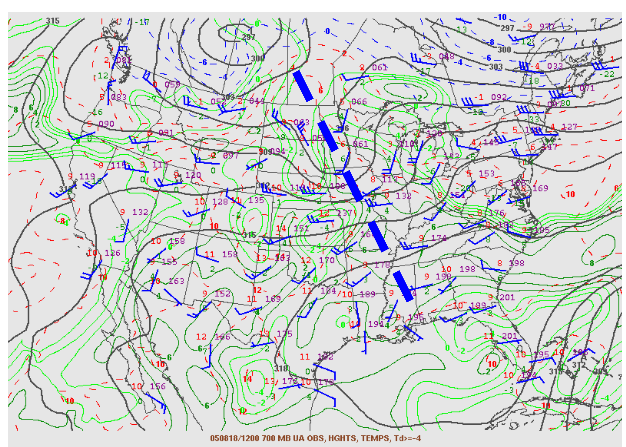


Fig 2. 12z 700mb geopotential heights (black contours), 700mb dew points (green contours), and 700mb trough axis (dashed blue line).

Furthermore, the combination of modest mid-level lapse rates and surface dew points approaching 70° F by the afternoon should produce MLCAPE (ML= mixed-layer) values of 2,000 to 3,000 J/kg. In addition, upper-level westerly flow of 60 to 70 kts and southerly 15 to 25 kt low-level flow will provide sufficient vertical shear for supercells and persistent bowing segments. The SPC forecasted thunderstorms to develop no later than early afternoon near a surface low progged to be in northern Iowa. This convection was then expected to intensify into the evening hours because of the aforementioned instability and shear (speed and directional). Most importantly, tornadoes were forecasted to occur along the warm front where moisture and shear values would be maximized (Thompson and Jewell, SPC). According to the SPC, the atmosphere in southern Wisconsin was primed for supercell development; however southern Wisconsin was only under a slight risk for severe thunderstorms. Further exploration in this case study will uncover the limiting and favorable meteorological factors for severe convection.

a. *12z synoptic analysis*

After diagnosing the dynamical forcings for ascent at 12z, it may be clear what synoptic forcings aided tornadic supercell development by producing large-scale ascent over southern Wisconsin, or by destabilizing the local atmospheric environment. As illustrated in figure 3a*,* there was a west to east zonal 300mb flow at 12z (300mb geopotential heights are in color fills). The lack of curvature in the 300mb flow certainly limited ageostrophic divergence resulting from the gradient wind balance which is maximized in extreme cases of curvature in the geopotential flow. However, there was a 300mb 68 knot jet streak positioned in eastern Nebraska and western Iowa. Based on the zonal 300mb pattern, the jet streak was expected to propagate toward northern Illinois by the afternoon. Downwind of the jet streak, the vertical cross-product antiparallel to the flow results in ageostrophic divergence in the left exit region of the 300mb jet streak. Figure 3b*,* is a plot of 300mb ageostrophic divergence and as expected the ageostrophic divergence plotted is positioned in the left exit region of the 300mb jet streak (pictured in figure 3a*).* Like the 300mb jet streak, the attendant ageostrophic divergence over western Wisconsin and eastern Illinois is expected to propagate toward southern Wisconsin by the early afternoon hours.

The 500mb differential positive vorticity advection by the geostrophic wind (DPVA), plotted in figure 3c*,* is another large-scale negative omega (- ∂p/∂t) forcing mechanism.

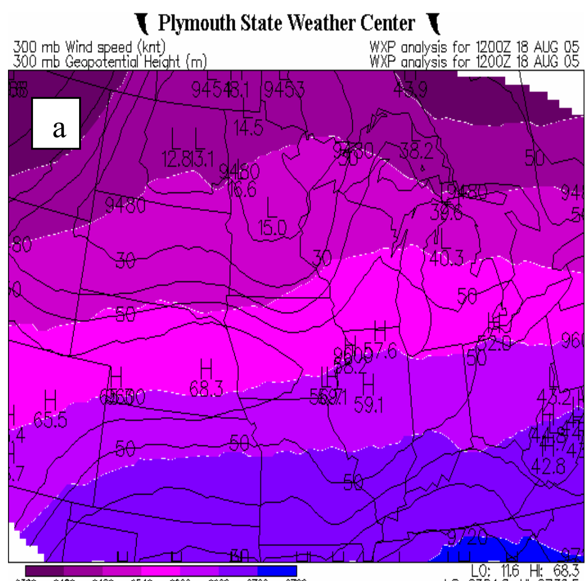


Fig 3. (12z 18 August 2005), (a) 300mb geopotential heights (color fills) contoured every 60 (dm) and isotachs (black contours) contoured every 10 kts. Interestingly, supercells later formed north of the 300mb jet axis where the inertial stability is high. This may have been a limiting factor to overall convective potential.

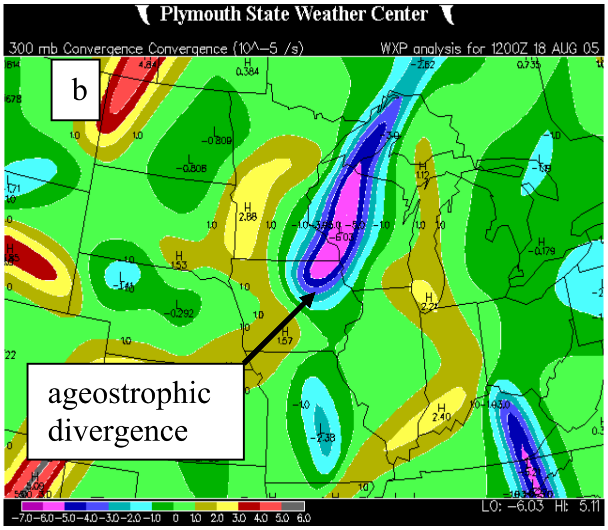


Fig 3. (b) 300mb ageostrophic divergence (blue to purple color fills) and ageostrophic convergence (yellow to red color fills) both are contoured every 1 vorticity unit ($10^{-5} * S^{-1}$).

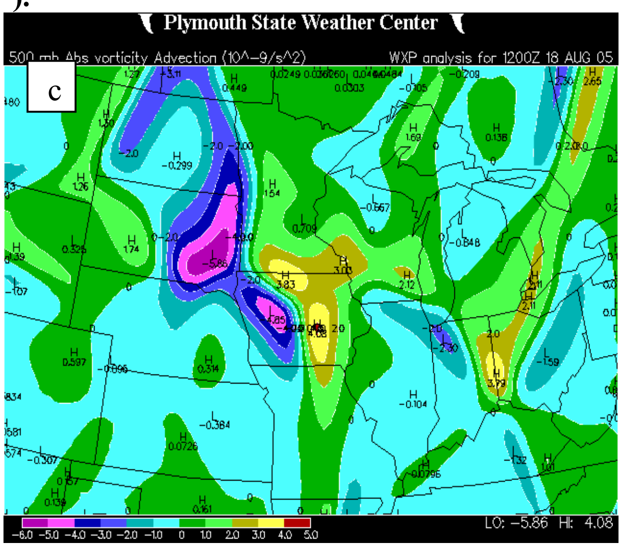


Fig. 3 (c) 500mb differential positive vorticity advection (green to yellow color fills) and differential negative vorticity advection (blue to purple color fills) both contoured every 1 ($10^{-9} * S^{-2}$) unit.

The vorticity max in western Iowa is the result of sharp curvature in the 500mb geopotential height pattern and a strong across flow speed gradient leading to cyclonic shear north of the 300mb jet streak. As a consequence of the 500mb vorticity max in western Iowa, there is DPVA in central Iowa and attendant upward vertical

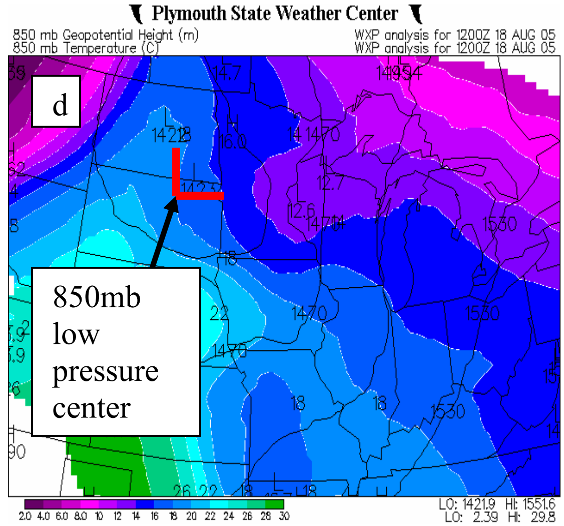


Fig 3. (d) 850mb geopotential heights (black contours) contoured every 30 dm and 850mb temperatures (color fills) contoured every 2°C.

motions at 12z. Most importantly, the region of DPVA is expected to traverse across southern Wisconsin during the afternoon. Overall, the synoptic dynamical forcings for ascent are sufficient for convective initiation to occur in southern Wisconsin during the afternoon. Albeit, the 300mb jet streak and 500mb vorticity max are not exceptionally strong. However, the full convective potential cannot be known without assessing the low-level instability (in terms of temperature and moisture, or θ_e).

Figure 3d, depicts the 850mb geopotential height field (black contours) and the 850mb temperatures (color fills). The warmer and moister the low-level air, the more unstable the atmosphere is because if this air becomes saturated latent heat release is maximized which keeps a rising air parcel warmer than its environment for a longer period of time (i.e. CAPE). Figure 3d, shows an 850mb low centered over the North Dakota, South Dakota border. The cyclonic circulation associated with this 850mb low is advecting warm and moist air into southern Wisconsin. Average 850mb temperatures in southern Wisconsin are around 16°C (61°F) and dew points near 13°C (55°F) which should increase by the afternoon.

Low-level warm advection combined with mid to upper-level geopotential height falls is setting-up an unstable atmosphere. Figure 4 displays, the surface pressure analysis across the conterminous U.S. on 18 August 2005 at 12z. While the surface pressure gradient in the upper mid-west is weak, there is still a notable surface low in northwestern Iowa and an attendant warm front extending from the low center through northern Illinois. This synoptic pattern is poised to head ENE toward southern Wisconsin by the early afternoon.

The mesoscale analysis will further investigate the role this meso-α scale warm front plays in tornadic supercell genesis. Also noted in figure 4 is low-level warm air advection associated with the cyclonic circulation of the surface low pressure. Consequently, the atmosphere is progressively becoming more unstable through this warm and moist advection near the surface.

b. *00z synoptic analysis*

The 00z hour is 2.5 hours after the Viola tornado and 0.23 hours after the Stoughton tornado. Figure 5a shows where the 300mb jet was positioned at 00z and the mean direction of the 300mb flow. The position of the 300mb jet streak is favorable for ageostrophic divergence ($\nabla \cdot V_{ag}$) over eastern Wisconsin, which is plotted in figure 5b. As previously hypothesized, the $\nabla \cdot V_{ag}$ has traversed through Wisconsin, following the mean 300mb flow. As long as the atmosphere is still conditionally unstable, convection is still likely at 00z because $\nabla \cdot V_{ag}$ is a large-scale ascent forcing

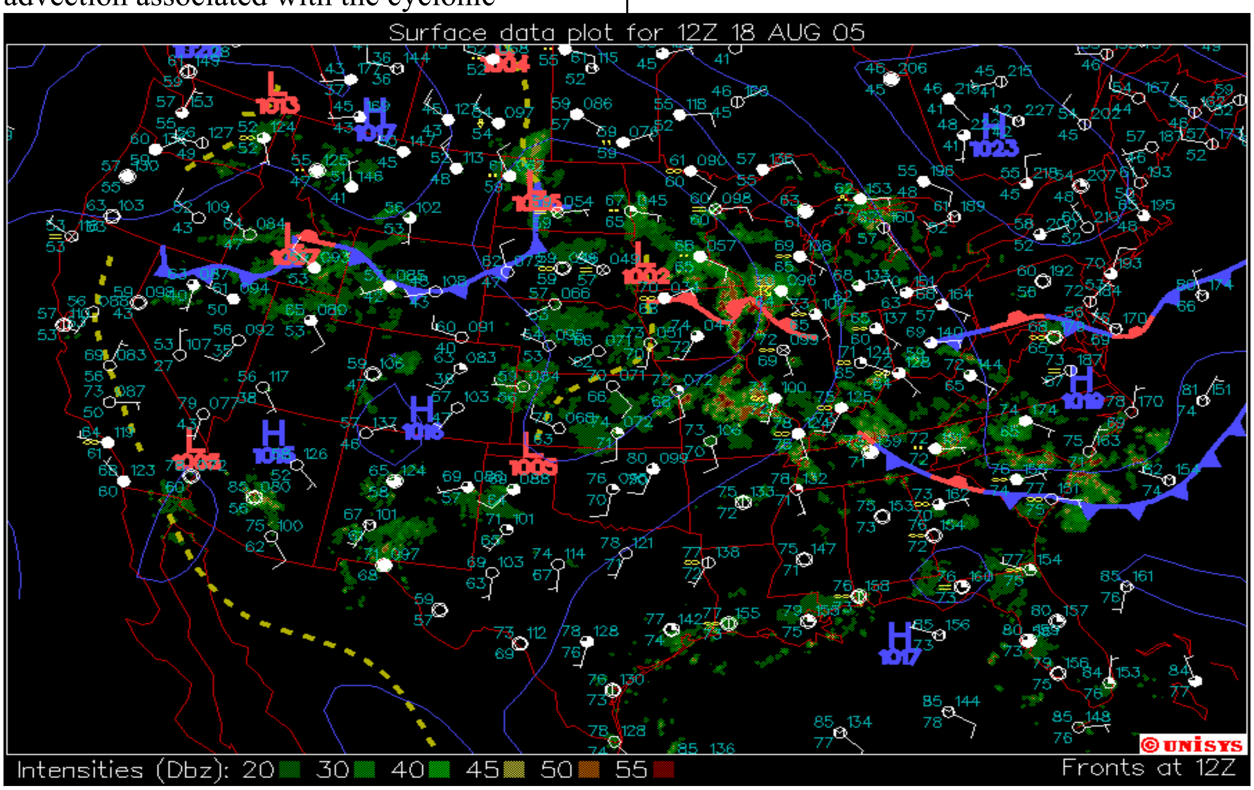


Fig 4. 12 z 18 August 2005 surface pressure analysis of the conterminous U.S.

mechanism. Figure 5c clearly indicates that DPVA by the geostrophic wind is not providing large-scale for ascent over southern Wisconsin at 00z. By 00z the southern Wisconsin 850mb temperatures had increased to 18°C (64°F) and the dew points had decreased to 11°C (52°F) (figure 5d). The dew points may have decreased because moisture may have been exploited by ongoing convection. Furthermore, the geopotential height pattern in southern Wisconsin is consistent with a quasi-convergent flow, with northwesterly winds intersecting southwesterly winds (this quasi-convergent flow is denoted by the green arrows in figure 5d). Conservation of mass requires low-level convergence to be accompanied by upper-level divergence and rising motion in between. To reiterate, $\nabla \cdot V_{ag}$ attendant to the left exit region of the 300mb jet streak along with an 850mb convergent line (cold front or wind shift line) are the two large-scale forcings for ascent at 00z.

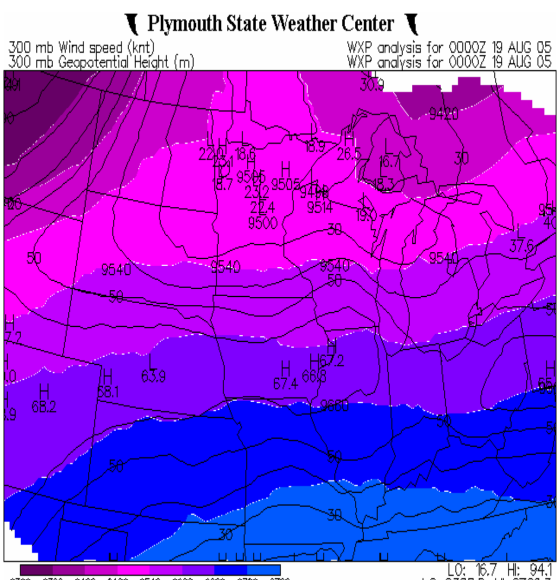


Fig 5. (00z 18 August 2005), (a) 300mb geopotential heights (color fills) contoured every 60 dm and isotachs (black contours) contoured every 10 kts.

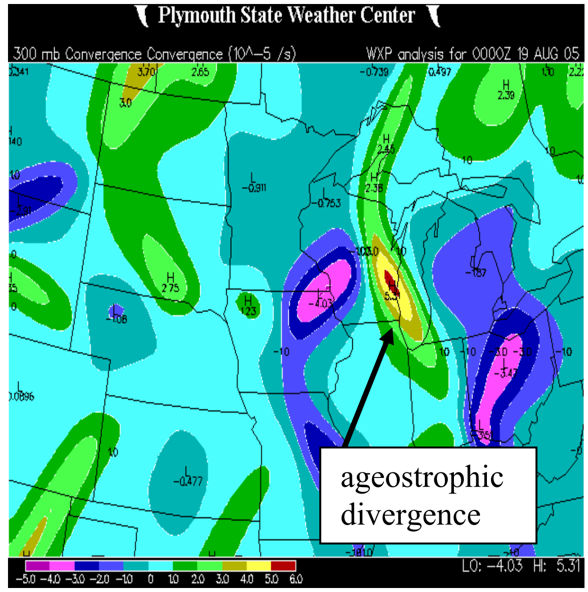


Fig 5. (b) 300mb ageostrophic divergence (blue to purple color fills) and ageostrophic convergence (yellow to red color fills) both are contoured every 1 vorticity unit (10^{-5} * S^{-1})

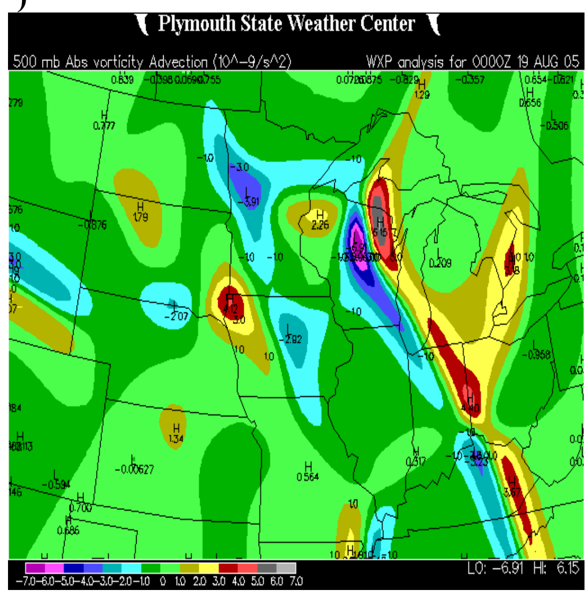


Fig 5. (c) 500mb differential positive vorticity advection (yellow to red color fills) and differential negative vorticity advection (blue to purple color fills) both contoured every 1 (10^{-9} * S^{-2}) unit.

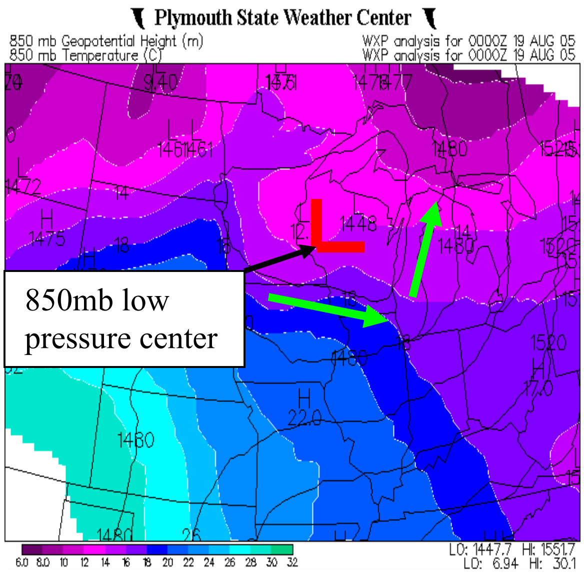


Fig 5. (d) 850mb geopotential heights (black contours) contoured every 20 dm and 850mb temperatures (color fills) contoured every 2°C.

4. Mesoscale Analysis

The atmosphere can only produce supercells when the right meteorological conditions are present in a specific region. Supercell storms are larger, more intense and persistent, and produce more severe weather than other types of thunderstorms. A highly organized internal circulation that reaches a nearly steady state enables the supercell to propagate continuously (Browning and Ludlam, 1962). This internal circulation is called a mesocyclone, which is unique to supercells. This mesoscale discussion will specifically focus on four of the most important ingredients for tornadic supercell development potential:
1) a mesoscale forcing for ascent (surface front or convergence zone) 2) atmospheric instability (specifically CAPE, CIN, LI values, and SWEAT values) 3) vertical speed shear (0 to 6 km bulk shear and BRN values), and 4) vertical directional shear (hodographs and helicity values).

Out of the 27 tornadoes that formed in Wisconsin on 18 August 2005, one was rated an F2 (the Viola, WI tornado) and another was rated an F3 (the Stoughton, WI tornado). The two supercells responsible for these tornadoes will be examined intensively by assessing the four aforementioned atmospheric ingredients needed for tornadic supercell development. The base radar reflectivity and radial velocity images are also studied because the classic "hook echo" supercell structure they show, serves as a visual manifestation of the present dynamic and thermodynamic instabilities in the atmosphere.

a. *Vernon County Supercell*

The Vernon County supercell reached maximum intensity around 21:09z near Viola, WI. At this time, Viola experienced an F2 tornado. Reasons for this tornadic supercell development will now be investigated.

Figure 6*,* is the surface pressure pattern at 18:00z and there is a convergent pattern in southwestern Wisconsin. Conservation of mass ($\nabla \cdot V = 0$) requires surface convergence to be accompanied by upper-level divergence and rising air in between. Therefore, surface frontal boundaries or convergent zones are likely regions for convective initiation. Also, as seen in figure 6*,* the Viola, WI tornado occurs near the triple point of a surface low pressure center, a surface warm front, and a surface cold front. This triple point is characterized by anomalously high low-level positive vorticity values which can strengthen the mesocyclone in a right moving supercell. Usually the triple point of a mid-latitude cyclone is responsible for low-level convergence, convective initiation and a likely region for tornadogenesis. Interestingly, the Vernon County supercell reaches maximum intensity directly underneath the lowest surface pressure. This surface low signifies the area of greatest upper-level divergence and strongest large-scale upward vertical motions. Focusing the upward motion in a small vicinity could be aiding the supercell development and intensity.

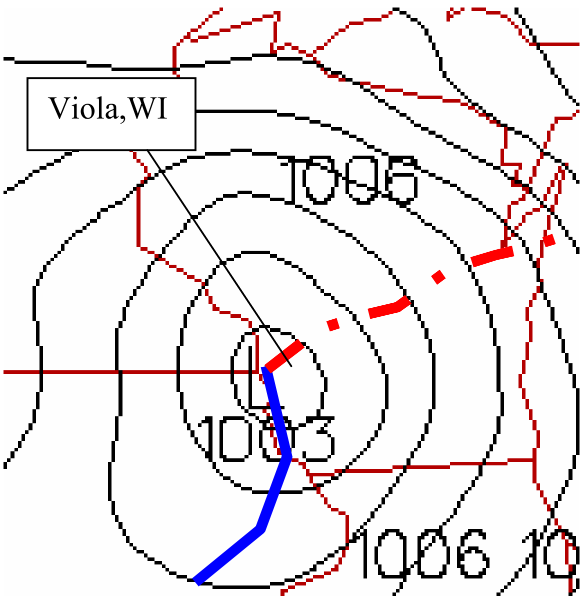


Fig 6. surface pressure analysis at 21:00z, approximate locations of cold front or wind shift (blue line) and warm front (red dashed line). Also, location of maximum tornado strength is indicated by the position of Viola, WI which occurred at 21:09z.

Another important aspect of the atmospheric thermodynamic structure is the vertical moisture stratification. Large amounts of moisture are needed in the boundary layer to support updraft growth, but the absence of moisture above the boundary layer (2-4 km AGL) often enhances storm severity (Fujita, 1981). Dry mid-levels cool at the dry adiabatic lapse rate (9.8°C·km^{-1}) when lifted vertically upward. Therefore, dry mid-level air is an important ingredient for severe weather because it can result in steep environmental lapse rates. Additionally, the combination of a moist boundary layer and steep environmental lapse rates lead to a potential for extreme instability (moist air parcels rising through the dry mid-level air are more buoyant due to the presence of relatively high water vapor concentrations.)

The more CAPE there is in the atmosphere, the higher the potential for strong updrafts and more intense thunderstorms. Conversely, the higher the CIN value the harder it is for air parcels to reach their LFC (level of free convection). However, supercells require a certain amount of CIN because this “cap” on convection allows the low-levels of the atmosphere to reach a maximum destabilized state (or maximum CAPE values). The 00z Davenport, IA sounding (figure 7*)* recorded strong instability which is displayed by several parameters (the 00z Davenport, IA sounding was used because the 12z sounding was contaminated by morning convection). The surfaced based CAPE was near 3,000 J/kg which is favorable for supercell development. Also, CIN values were only around -13 J/kg. As a result, a relatively weak forcing mechanism for ascent is needed for free convection to occur. The LI is another parameter used to assess convective potential. Specifically, the LI is also a measure of instability or the potential for thermal updrafts to freely convect above 500mb. The LI from the 00z Davenport, IA sounding is -9° C, which is an exceptionally low value. This value proves that extremely strong updrafts were likely in the middle troposphere, if a parcel could reach its LFC. More information can be interpreted from the -9°C LI value. Since the LI is equal to the 500mb environmental temperature – 500mb saturated air parcel, a value of -9°C means the low-level moisture is relatively high (i.e. high dew points) and the upper-level temperatures are relatively cold (steep mid to upper-level lapse rates), which is consistent with a eastward propagating low pressure system and attendant geopotential height falls and near surface θ_e advection.

In addition to sufficient thermodynamic instability, supercell storms usually occur in an environment with strong vertical shear, where the wind shear vector turns clockwise (veers) with height below 500mb (Browning and Ludlam, 1962). Strong vertical speed shear allows for mean updraft and downdraft separation within a thunderstorm, producing a persistent convective cell. In other words, moderate to strong vertical shear values produce tilted updrafts and longer lived thunderstorms (i.e. supercells). A significant 0 to 6 km bulk shear value is needed for supercell development. The 0 to 6 km bulk shear is computed by taking the vector difference between the surface wind vector and the wind vector at 6 km. Typical bulk shear
22
values conducive for supercell development are 35 kts or greater. Usually a atmospheric balance of CAPE (1,500 J/kg to 3,000 J/kg) and bulk shear (35 to 60 kts) is favorable for supercell development. However, one parameter can compensate for the other. The bulk Richardson number (BRN) is the ratio of CAPE to 0 to 6 km bulk shear. According to the 00z Davenport sounding (figure 7), the 0 to 6 km bulk shear was 26 kts. This value is marginally sufficient for supercell development. Consequently, supercells that did develop in Wisconsin may have been longer lived, if the bulk shear were greater. The low bulk shear of 26 kts may have been the primary limiting factor for severe thunderstorms in Wisconsin and why the SPC only forecasted a slight risk for severe convection.

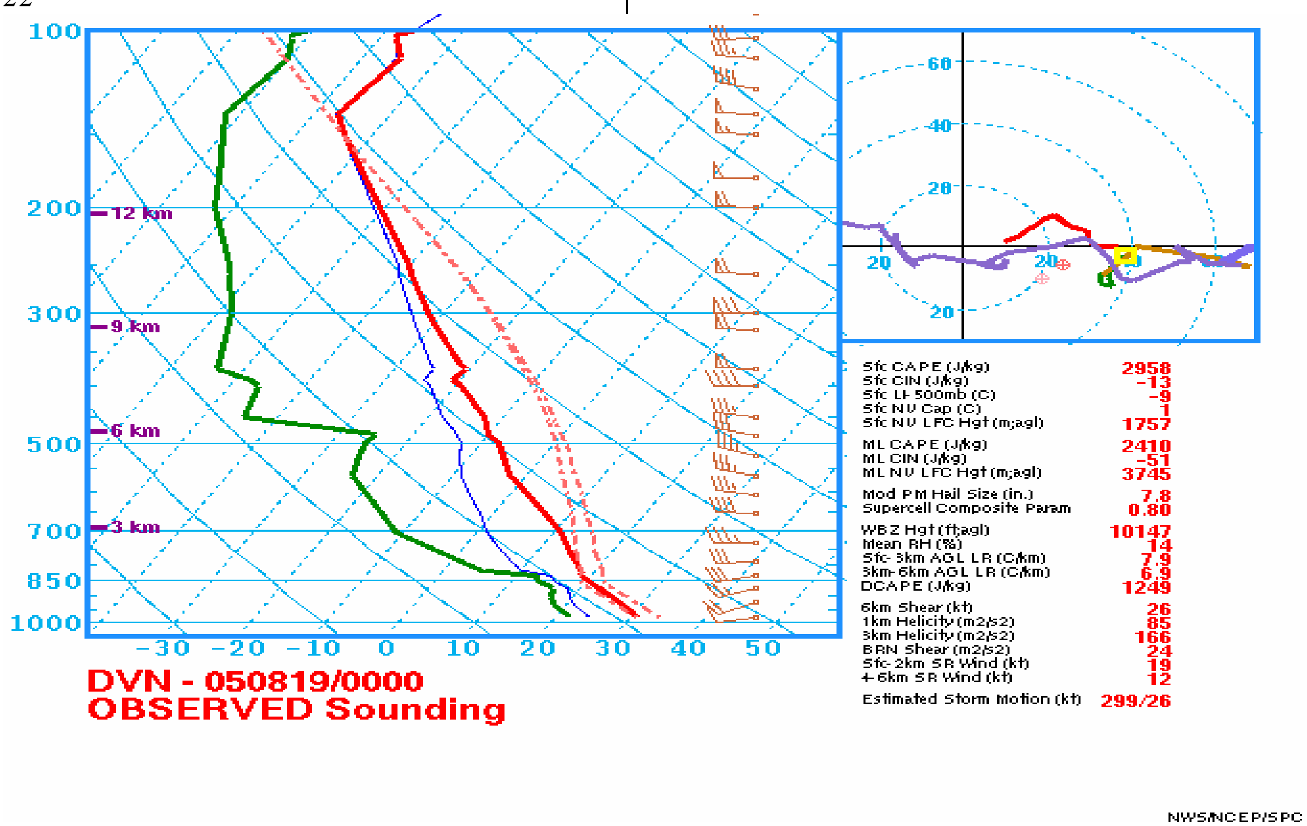


Fig **7. 00z 19 August 2005 Davenport, IA sounding, hodograph, and severe weather indices.**

As previously stated, large CAPE values can compensate for lower bulk shear values. The BRN was 24 m^2/s^2 and values between 15 to 40 m^2/s^2 are favorable for supercell development. SWEAT is the last sever weather index to investigate. A SWEAT value of 248 is also conducive for severe thunderstorms, but tornadic supercells are often associated with SWEAT values of 400 or greater. The wind shear over Wisconsin on 18 August 2005 was moderate in intensity. Consequently, the primary reason this SWEAT value is only moderately high was because the SWEAT parameter incorporates vertical wind shear in the mid-levels of the atmosphere. Even so, right moving supercells did develop in southern Wisconsin.

The Magnus Force is a deflecting force, arising from Bernoulli effects, that a rotating cylinder experiences when embedded in a moving fluid (Fujita and Grandosa, 1968). The Magnus effect is the dynamical forcing that causes some supercells to move to the right of the mean wind. The southeastern side of the mesocyclone rotates in the same direction of the mean wind, which locally accelerates the flow, simultaneously producing low pressure as Bernoulli's equation requires ($0 = -\nabla ke - \nabla p$, where (ke) represents the wind and (p) is the pressure). Therefore, an increase in (ke) requires a decrease in (p). The end result is a pressure gradient force directed toward the southeastern side of the mesocyclone and a rightward propagating supercell.

Vertical directional shear is paramount for tornadic supercell development. Hodographs that curve to the right are favorable for "right-moving" supercells because these type of hodographs signify a veering wind profile with height (which is consistent with warm air advection at mid and low-levels of the atmosphere). In addition, right curved hodographs are accompanied by higher helicity values. Helicity describes the "corkscrew" nature of the wind profile with height above the surface. The helicity equation can be expressed as: $|\xi|\,|V|\cos(\theta)$; where ξ is the vertical component of vorticity, V is the wind vector, and θ is the angle between ξ and V. The mesocyclone has positive vorticity in a right moving supercell, taking the curl of the vorticity gives a vector parallel to the updraft vector (V) (therefore the helicity is positive). This is one reason the atmosphere commonly favors right moving supercells.

Four hours after the Vernon County supercell occurred, the surface cold front or wind shift line was well to the east of western Wisconsin. Consequently, the vertical directional shear in western Wisconsin was nearly unidirectional with increasing height above the surface. This is why the 00z Davenport sounding (approximately 135 miles south of Viola) recorded a 0 to 3 km helicity value of 166 m^2/s^2, which is relatively low. However, the Blue River, WI profiler sounding (fig. 8) taken at 22:00z (approximately 25 miles to the southeast of Viola), recorded a 0 to 3 km helicity value of 267 m^2/s^2. This helicity value is significantly higher than the Davenport value because Blue River was still relatively close the surface low pressure center, cold front, and warm front triple; where vertical directional shear veers with height. Also noted in figure 8, is the 22:00z right curved low-level hodograph. Right curved hodographs signify warm air advection and warm air advection is often associated with θ_e advection. Warm and moist advection serves as supercell fuel and favors right moving supercells because they receive the θ_e advection before the left moving cell.

The following section takes a detailed look at the structure of a right moving supercell. In strong shear conditions, the pressure forcing now occurs only on the right flank of the original updraft, producing only one quasi-steady cyclonically rotating updraft (Kelmp and Wilhelmson, 1978). If the vertical wind shear extends through the middle levels of the storm (4-6km), the rotation dynamically induces a pressure deficit which is strongest several kilometers above the ground and thus produces a vertical pressure gradient that accelerates surface air upward. This forcings helps both to sustain the updraft and to promote a propagation that deviates from the mean wind. Supercells owe their existence to these dynamically induced pressure forces (Ray, 1986). The mesocyclone initially derives its energy from vertical speed shear, because a horizontally rotating cylinder is tilted vertically by a mean updraft. In 1978, Kelmp and Wilhelmson demonstrated that the hodograph curvature in the lowest 1-2km AGL has the most influence on favoring a particular storm flank for supercell evolution.

Supercells are dynamically different than ordinary convective cells, a supercell usually reaches its mature, quasi-steady phase within 90 min; a hook-like appendage appears on the southwest flank of the storm, a large area of middle-level reflectivity continues to overhang the low-level echo (Chisholm and Renick, 1972). The Vernon County supercell first developed near the Minnesota, Iowa, and Wisconsin tri-state region at 21:30z and reached maximum intensity near Viola, WI at 21:09z.

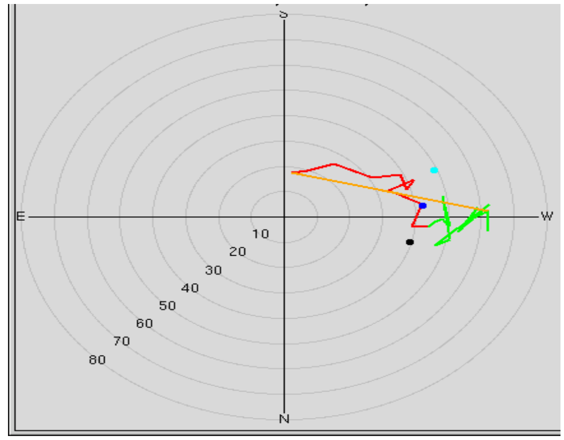


Fig 8. Blue River, WI hodograph taken at 22:00z (approximately 50 minutes after the Viola, WI tornado). This hodograph clearly shows a veering wind profile with height in the lower troposphere.

Figure 9a and 9b clearly show the classic hook echo structure of a supercell. The hook echo is most defined in the radar reflectivity image because the mesocyclone and inflow dictate the spatial distribution of any hydrometeors (i.e., rain and hail), which are detected by the radar beam. In figure 9b (the base radial velocity image), a tornado vortex signature has developed.

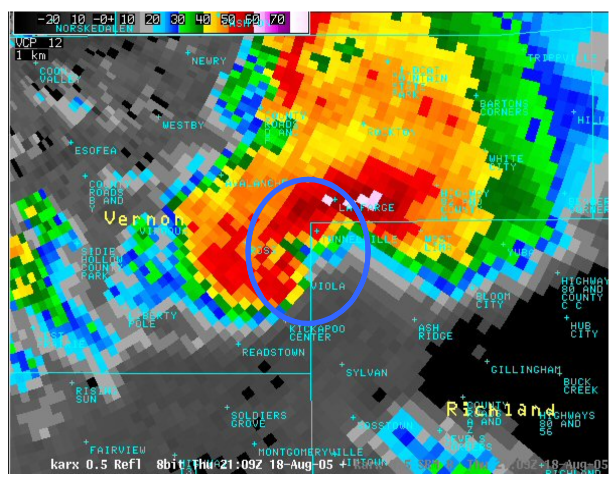


Fig 9. Vernon County supercell at its maximum intensity near Viola, WI; (a) above, 0.5° radar reflectivity factor image, filled every 5 dBZ; blue circle indicates likely area for mesocyclone and tornado.

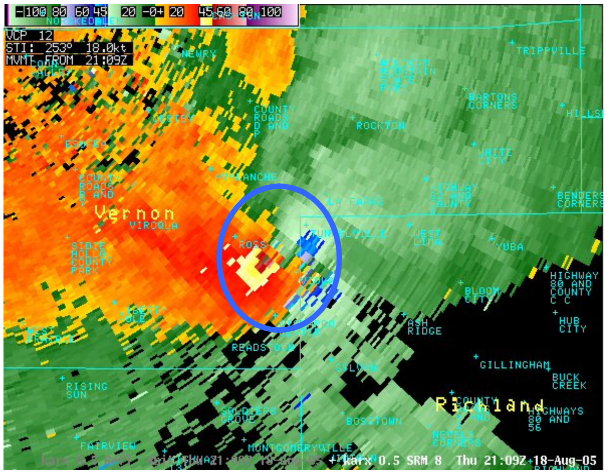


Fig 9. (b) above, 0.5° radial velocity image, both taken at 21:09z; blue circle indicates a TVS and a likely area for tornado development.

A tornado vortex signature (TVS) is an anomalous region of high shear within the mesocyclone (Brown et al., 1978).

b. *Dane County Supercell*

As the Vernon County supercell waned, to the south, a new supercell rapidly developed in Dane County around 23:00z. This supercell reached maximum intensity near Stoughton, WI, when it produced an F3 tornado. Similar to the Vernon County tornado, the Dane County supercell formed and reached maximum intensity near the low pressure center, cold front and warm front intersection. However, as depicted in figure 10, the Dane County supercell developed slightly further south of the surface triple point. This means the Dane County supercell formed and intensified along the surface cold front or wind shift convergence line.

Unfortunately, the 00z Green Bay, WI 19 August 2005 sounding was erroneous. The 00z Lincoln, IL sounding is the next closest sounding that was still entrenched within the warm sector of the mid-latitude cyclone. The 00z Lincoln, IL and Davenport, IA soundings have similar thermodynamics, but their recorded dynamics varied greatly. The Lincoln, IL sounding was slightly more unstable because it was fully immersed within the warm section at this time. The mixed-layer CAPE value was near 3,230 J/kg which is sufficient for supercell development. A mixed layer CIN value of -17 J/kg acted as weak cap on convection. The shear 0 to 6 km bulk shear of 33 kts is also slightly stronger above central Illinois. Being north of the mean jet axis, however, the bulk shear over southern Wisconsin was likely less than 33 kts.

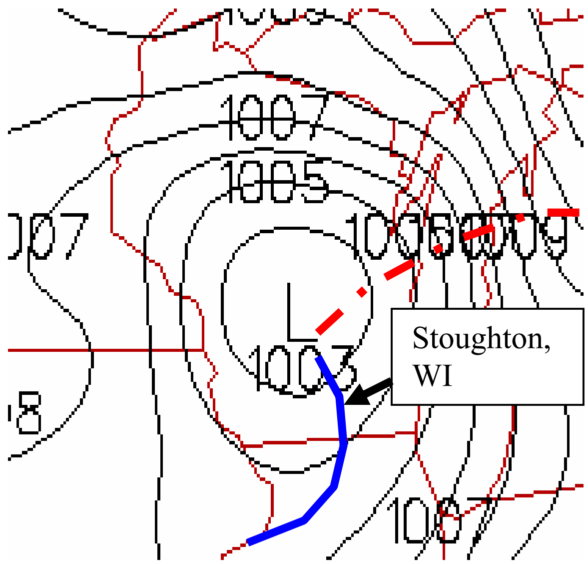


Fig 10. Surface pressure analysis at 00z, approximate locations of cold front or wind shift (blue line) and warm front (red dashed line). Also, location of maximum tornado strength is indicated by the position of Stoughton, WI which occurred at 23:37z.

The BRN, the ratio of CAPE to 3 – 6 km shear, is a dimensionless value. The 00z Lincoln sounding recorded a BRN of 49 m^2/s^2 , which means the warm sector atmosphere has a higher CAPE to 3 – 6 km shear ratio than the atmosphere behind the cold front. Lower level winds often increase behind cold fronts due to increased horizontal pressure gradients, making the

BRN smaller. A BRN of 49 m^2/s^2 actually favors multicellular convection more than supercellular convection. Interestingly, there was a multicellular convective complex over eastern Wisconsin at 00z. Being an isolated right moving supercell, the Dane County supercell was an exception. A third parameter that helps assess the potential for convection is the LI. An LI of -5.5°C was extrapolated from the 00z Lincoln Sounding. This is 3.5°C warmer than the Davenport, IL value because, Lincoln (along with Stoughton) has yet to experience significant geopotential height falls.

Vertical speed shear, strongly influences the form that convection might take (i.e. whether the convection evolves as short-lived cells, multicells, or supercells (Ray, 1986). As the vertical wind shear becomes stronger, the interaction of the updraft with the sheared flow becomes an important contributor to the organization and sustenance of the convection. The essential physical mechanism responsible for this is the development of rotation on the flank of the updraft (Rotunno and Klemp, 1985). This rotation originates through the tilting of horizontal vorticity inherent in the vertically sheared flow (Rotunno, 1981).

As previously discussed, the 0 to 6 km bulk shear from the 00z Lincoln sounding was 33 kts, which is sufficient for supercell development. However, the bulk shear value over southern Wisconsin may be slightly weaker because the strongest jet core at 00z was located over northern and central Illinois. According to Byers and Braham, the magnitude of the vertical wind shear over the lowest 6 km (AGL) increases as the type of convection progresses from short-live storms to supercells. The increased bulk shear from western Wisconsin to southcentral Wisconsin may have allowed the Dane County Supercell to become stronger. Strong bulk shear values allow for a quasi-balance supercell storm structure. Mesocyclone develop as a result of vertical speed shear. In the presence of sufficient vertical speed shear the mean updraft associated with a fully developed mesocyclone separates from the forward flanking and rear flanking downdrafts (FFD and RFD, respectively).

The 22:00z Blue River, WI profiler can still be used for the Dane County supercell analysis because it is only 70 miles northwest of Stoughton, WI. Therefore, the hodograph is likely a good representation of the 0 to 3 km wind shear near Dane County. As stated earlier, figure 8 shows a curved veering hodograph in the lower troposphere, which is conducive for right moving supercells. In convective storms, gust front convergence and dynamic pressure forcing work together to produce the observed storm characteristics, dependent on vertical wind shear profiles (Weisman and Klemp, 1982). The gust fronts that develop with the supercell focus vertical motion along flanking lines. Furthermore, the dynamic low pressure associated with the cyclonically rotating (in right moving supercells) mesocyclone can strengthen the mean draft. The combination of these two negative omega forcing mechanisms, help to drive the supercell.

Figure 11 shows that the Dane County supercell had a classic hook echo structure (and a TVS encircled in fig. when it produced an F3 tornado near Stoughton, WI at 23:37z While the hook echo and TVS are clearly identified in figure 11, the most unique characteristic of this thunderstorm is its size, spanning a width of nearly 40 miles. Interestingly, low-level moisture may have been another reason the Dane County supercell was stronger than the Vernon County supercell. The Janesville, WI (south of the Dane County supercell) dew point at 23z was 23°C (73.4°F), and the Boscobel, WI (south of the Vernon County supercell) dew point was 22°C (71.6°F) at 21z. Evapotranspiration from the plethora of corn fields in southcentral Wisconsin may have contributed to the increased surface dew points south of Dane County. Increased water vapor concentrations, strengthen thunderstorm updrafts by releasing more latent heat and lower LCLs, which make tornadic development more likely. Amazingly, the local environmental vegetation can play an important role on the thermodynamics of the atmosphere.

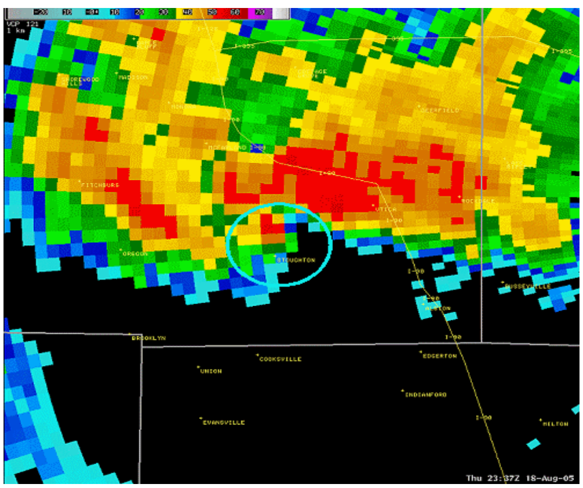


Fig 11. Dane County supercell at is maximum intensity near Stoughton, WI; (a) 0.5° radar reflectivity factor image, filled in every 5 dBZ; blue circle indicates likely area for mesocyclone and tornado.

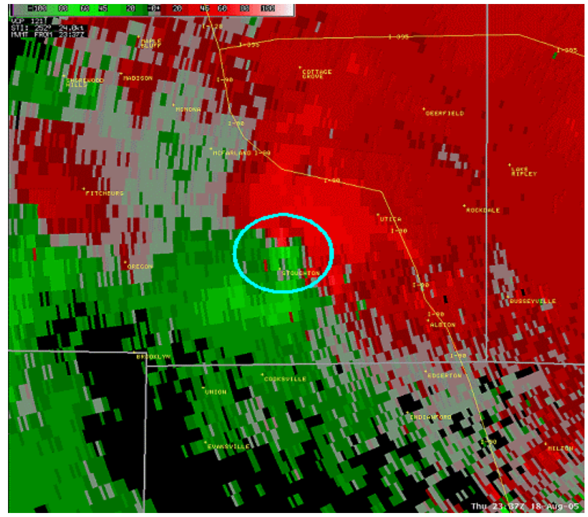


Fig 11. (b) 0.5° radial velocity image, both taken at 00z; a TVS is visible inside the light blue circle (green colors signify air are moving towards the east and red values signify air moving toward the west).

c. 22z Miller Diagram

Although there were some thermodynamic and dynamic differences in their local environments, the two supercells studied essentially fed off of the same environmental forcings and ingredients. Figure 12 is a 22z miller diagram that has plots of some of the most important meteorological features favorable for supercellular convection. The 12z miller diagram points out that the main synoptic forcings were a 500mb trough with attendant height falls, 300mb $\nabla \cdot V_{ag}$ contributing to large-scale ascent, and dry 700mb air (a local minimum θ_e value of 320 K). The mesoscale parameters depicted on the miller diagram are the southerly advection of higher θ_e values near the surface, concurrently 500mb wind are from the southwest leading to a veering wind profile with height. Lastly, a region of 3,000 J/kg + of surface based CAPE is plotted over southern Wisconsin and northern Illinois.

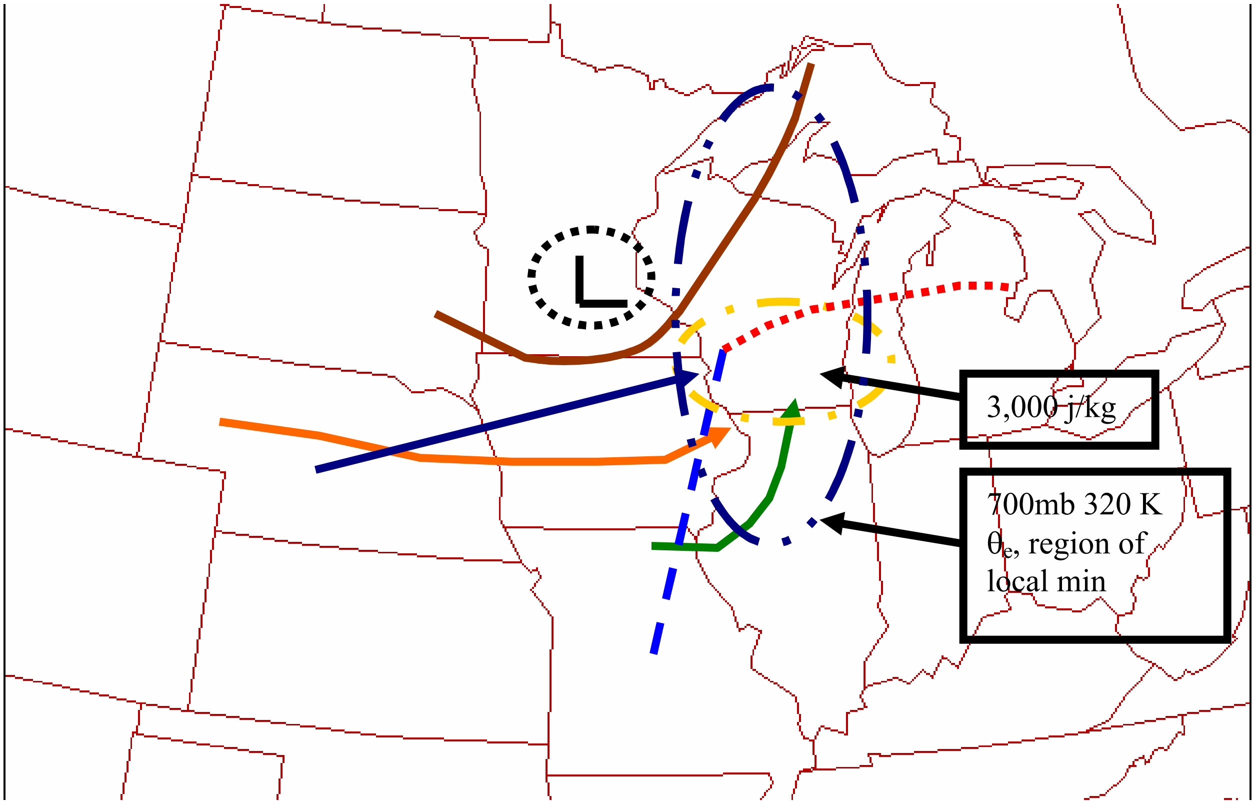


Fig 12. The miller diagram is a clear visual of the meteorological variables present during this tornado outbreak. 22z miller diagram for southern Wisconsin; 500mb low (black L and dotted black circle), 576 (dm) geopotential height isopleth (brown line), 300mb jet (orange arrow), 500mb jet (blue arrow), surface flow (green arrow), cold front (light blue dashed line), warm front (red dashed line), greatest instability of 3,000 J/kg + (inside gold dashed circle), 700mb local dry air region with a dew point depression of 13° C to 15° C (within dark blue dashed circle).

5. Conclusion

The large number of atmospheric ingredients necessary for tornadic supercell development is why record breaking outbreaks are extremely rare. The 18 August 2009 record breaking Wisconsin tornado outbreak resulted from a atmospheric concoction of 300mb $\nabla \cdot V_{ag}$ attendant to the right exit region of a 68 kt 300mb jet streak, a surface low pressure center, warm front and, cold front or wind shift convergent line and the parameters listed in the following table. This table is not exhaustive, but it does include most of the important parameters that together, determined the atmospheric potential for severe thunderstorms.

Atmospheric Parameters (21z to 00z)	Values
Temperature	28 to 29°C
Dew Point	21 to 24°C
CAPE	3,000 + J/kg
CIN	-15 to -20 J/kg
LI	-5 to -9°C
0 – 6 km Bulk Shear	26 to 33 kts
BRN	26 - 49 m^2/s^2
SWEAT	250
0 – 3 km Helicity	270 m^2/s^2
700mn θ_e min (equivalent potential temperature)	320 K

Table 1. 18 August 2005 atmospheric parameters over southern Wisconsin.

The author's hypothesis that vertical directional wind shear took primary responsibility for this unprecedented Wisconsin tornado outbreak was partially true. Some of the severe weather parameter values that are important for violent convection were lower than expected considering the severity of the 18 August 2005 event. Most surprisingly, the 0 to 6 km bulk shear value was only in the 26 to 33 kt range, which is marginally sufficient for supercellular formation and persistence. Not only were the bulk shear values relatively low, the 0 to 3 km helicity of 270 m^2/s^2 are sufficient for tornadic storms, but could be much larger.

Growing up in Wisconsin, a surface based CAPE value of 3,000 J/kg + is rare and should be taken seriously. Consequently, the author believes the CAPE,700mb θ_e min of 320 K, eastward propagating geopotential height falls manifested as LIs of -9°C, and very warm and moist low levels with surface temperatures peaking near 29°C and dew points reaching 24°C (or θ_e values near 354 K). Not only did the 22z Blue River, WI low-level hodograph veer with height, the low-level flow also backed with time both of which are advantageous for right moving supercells.

Of the 27 tornadoes that touched down in Wisconsin, 14 of them can be accounted for by the Vernon County (6 tornadoes) and Dane County (8 tornadoes) supercells. So, the strongest two supercells that were studied in this case study produced more than half of the record breaking 27 tornadoes.

The next phase of discover would look at previous record state tornado outbreaks across the country, to see what parameters are conducive for large number tornado outbreaks vs. few, but strong (EF3 or greater) tornado outbreaks. Do just a few supercells produce the majority of the tornados? Or, are most of the tornadoes produced by multiple convective cells? In situ measurements of dry and wet bulb temperatures (preferably in corn fields were evapotranspiration is maximized) to the south of the supercells may have recorded surprisingly large θ_e values that would act as a local fuel boost to supercells and could explain why stronger tornadoes form sporadically throughout the supercell life-cycle.

Acknowledgements

A special thanks to the NWS La Crosse and NWS Sullivan for their 18 August 2005 severe weather event summary, archived radar reflectivity and radial velocity images, and a map of the 27 tornado tracks.

References

American Meteorological Society

Browning, K. A., and F. H. Ludlam, 1962: Airflow in convective storms. Quart. J. Roy. Meteor. Soc., 88, 117-135.

Brown, R. A., et al., 1978: Tornado detection by pulsed Dopplar radar. Mon. Wea. Rev., 106, 29-38.

Byers, H.R., and R. R. Braham, Jr., 1949: The Thunderstorm. Supt. Of Documents, U.S. Government Printing Office, Washington, D.C., 287 pp.

Fujita, T., and H. Grandosa, 1968: Split of a thunderstorm into anticyclonic and cyclonic storms and their motion as determined from numerical model experiments. J. Atmos. Sci., 25, 416-439.

Fujita, T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. J. Atmos. Sci., 38, 1511-1524.

Klemp, J.B., and R.B. Wilhelmson, 1978b: Simulations of right an left-moving storms produced through storm splitting. J. Atmos. Sci., 35, 1097-1110.

Mesoscale Meteorology and Forecasting, American Meteorological Society.

National Weather Service La Crosse

National Weather Service Sullivan

Plymouth State University Archive

Rotunno, R., 1981: On the evolution of thunderstorm rotation. Mon. Wea. Rev., 110, 136-151.

Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. J. Atmos. Sci., 42, 271-292.

Storm Prediction Center

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy, Mon. Wea. Rev., 110, 504-520.

Unysis Weather Archive