Residual Outflow Boundary Impacts on CAPE versus Shear Contributions to Tornadic Supercells: the F-5 Barneveld, Wisconsin Tornado Revisited

Alex Harrington

M.S. Research Assistant, University of Wisconsin – Madison, Cooperative Institute for Meteorological Satellite Studies (CIMSS)

ABSTRACT

The impact remnant outflow boundary over the Upper Midwest from early morning convection on maximized afternoon and evening CAPE values is examined through the use of Geostationary Operational Environmental Satellite (GOES) data and available surface observations. Satellite imagery and surface analyses conveyed that a residuum deformation structure provided the focus for further convective development over southern and eastern Wisconsin. Thus, the prevalence of widespread cloud debris over southern Wisconsin prohibited excessive boundary layer instability from reaching high values during the window of maximum diurnal diabatic heating. The combination of reduced CAPE values and ambient high shear profiles is investigated for priming Barneveld, Wisconsin with low Bulk Richardson Numbers (BRN) conducive for a nocturnal tornadic supercell. Furthermore, it is hypothesized that the presence of the deformation zone itself led to an augmentation of streamwise vorticity, enhancing low-level rotation such that the F-5 Barneveld tornado could materialize.

I. Introduction

While late night tornadoes are not uncommon, violent tornadoes; which make up approximately three percent of all reported tornadoes, are a rare phenomenon. At 0550Z 08 June 1984, an F-5 tornado destroyed the small, southwestern Wisconsin community of Barneveld; killing nine, only ten percent of Barneveld was left habitable. Fig. 1 (top) showed the devastation in the wake of the tornado. Noteworthy was the fact that debris penetrated the reinforced steel of the still-standing water tower in the background (Harrington, 2006).

The supercell which later spawned the tornado was one of many tornadoes which formed in the Upper Midwest on 07-08 June, 1984. Fig. 1 (bottom) depicted the tornado tracks and storm reports from the severe weather outbreak (SPC, 2006). Evident was an extensive, though episodic, tornado track from near Topeka, Kansas, to sixty miles north of Madison, Wisconsin. The existence of severe weather reports between confirmed tornado events was evidence of the pulse nature of a long-lived supercell that lasted over four hours (Bunkers et. al., 2006).

The supercell produced a violent F-4 tornado over south-central and southeastern Iowa; then, after considerable weakening, the cell rapidly regenerated a hundred miles to the northeast over Lafayette and Iowa counties of southwestern Wisconsin. Thirty minutes after its intensification, the supercell fostered a quarter-mile wide F-5 tornado that descended on Barneveld.

The synoptic environment was ideal for convection, including severe multicellular and supercellular storms throughout the 07-08 severe weather outbreak. A Mesoscale Convective Complex (MCC) over southeastern Iowa, northern Illinois, and southern and central Wisconsin, pushed to the northeast during the late morning hours of 07 June. 17Z Geostationary Operational Environmental Satellite (GOES) imagery conveyed a remnant boundary induced by the effects of a southward propagating gust front from the morning MCC, extending from southern Iowa to the Wisconsin/Illinois border. A 12Z mesoscale analysis confirmed the presence of the southward extent of the density current through a surface temperature discontinuity. North of the boundary, widespread cloud debris prevailed; and, by 19Z, it served as a focusing mechanism for thunderstorm development across southern and eastern Wisconsin. While the physics of outflow boundaries remains poorly understood, meteorological consensus regards them as integral features to convective initiation (Browning, 1997). Cloud debris associated with the deformation zone and convective activity precluded Convective Available Potential Energy (CAPE) values across southern Wisconsin from reaching maximized values of 5000 J/kg experienced south of the boundary. Thus, the loss of diabatic heating following sunset limited already reduced CAPE values over southern Wisconsin to the 1500-2000 J/kg range by 06Z 08 June. Sufficiently strong 0-6km shear profiles, coupled with modest CAPE values, fostered an environment primed for strong tornadic development.

Figure 1. Top: Ninety percent of Barneveld was destroyed after the F-5 08 June 1984 tornado (Barneveld Public Library, 1985). Bottom: 07-08 June 1984 archived SPC tornado tracks and storm reports.

Thus, Bulk Richardson Numbers (BRN) of 10-20 were experienced over Lafayette and Iowa counties at the time of the supercell intensification. Furthermore, the imprint of the outflow boundary on the local environment resulted in a fortification in the streamwise vorticity such that low-level rotation of the mesocyclone ensued; likely leading to the formation of the F-5 Barneveld tornado.

II. Data

GOES data primarily served the investigation and placement of the outflow boundary produced by a morning MCC over the Upper Midwest. GOES data was collected from Space Science and Engineering Center GOES archive. 1984 satellite data was devoid of the multiple bands and projection capabilities of present date. GOES Band-1 Visible imagery was only available at 20Z 07 June and after 00Z 08 June. Hence, the lost of solar flux prohibited the use of the more beneficial visible band. Thus, GOES Band-8 thermal IR was accepted for discerning the existence of the deformation zone.

National Weather Service (NWS) surface analyses archived by the University of Wisconsin – Madison (UW-Madison) Atmospheric and Oceanic Sciences (AOS) department were also advantageous in assessment of the vestige boundary. Although the quality of preservation was not pristine; it was however, crucial in discovery of a temperature discontinuity and subtle wind shift associated with presence of the boundary. 12Z 07 June surface temperatures were hand analyzed in conjunction with the previously examined surface plots. NWS 00Z 08 June vertical profile data for Omaha, Nebraska, Peoria, Illinois, and Green Bay, Wisconsin were hand plotted to avoid model smoothing of discrete features.

Three-hourly, 30km resolution, North America Regional Reanalysis (NARR) data, combined with UW-Madison Nonhydrostatic Modeling System (NMS) formulation for key severe weather parameters, was computed by UW-Madison Ph.D. Student, Steven Jaye. Jaye created Vis5d datasets that were exercised in exploration of the atmospheric state of the Upper Midwest at 00Z and 06Z 08 June. Vis5d plots aided assessment of the significance of CAPE versus shear contributions to the severity of the Barneveld supercell.

Using GEMPAK, NARR data was used to recreate the synoptic state at 12Z 07 June and 00Z

08 June. Four-panel plots were fabricated to mirror traditional four-panel synoptic plots used extensively today. Additionally, it facilitated a rudimentary 0-6km shear calculation to show the relationship between the ratio of CAPE versus shear and BRN values that coerced tornadogenesis in southwest Wisconsin.

Crude NWS Doppler Radar imagery, provided by UW-Madison AOS archives, showed the orientation of convection at 03Z 08 June. No radar imagery was available at the time of the tornado. Thus, it should instill appreciation for modern technology readily available to present day meteorologists.

III. 12Z 07 June synoptic situation

A broad surface low pressure existed in the western High Plains at 12Z (Fig. 2. upper-left). Thus, ambient background surface southwest flow channeled warm, moist air from Gulf of Mexico sources, northward into the Upper Midwest. A thermal ridge was evident at 850 hPa (Fig2. upper-right) across Nebraska, extending southeastward across southern Iowa, south along the Mississippi River; east of St. Louis. A shortwave disturbance is subtly depicted by a discontinuity in the 850 hPa heights across southern Iowa. Potential Vorticity Advection (PVA) by the thermal wind was tangible across southern and central Wisconsin, downstream of a positive vorticity anomaly at 500 hPa (Fig. 2. lower-left), centered near Rochester, Minnesota.

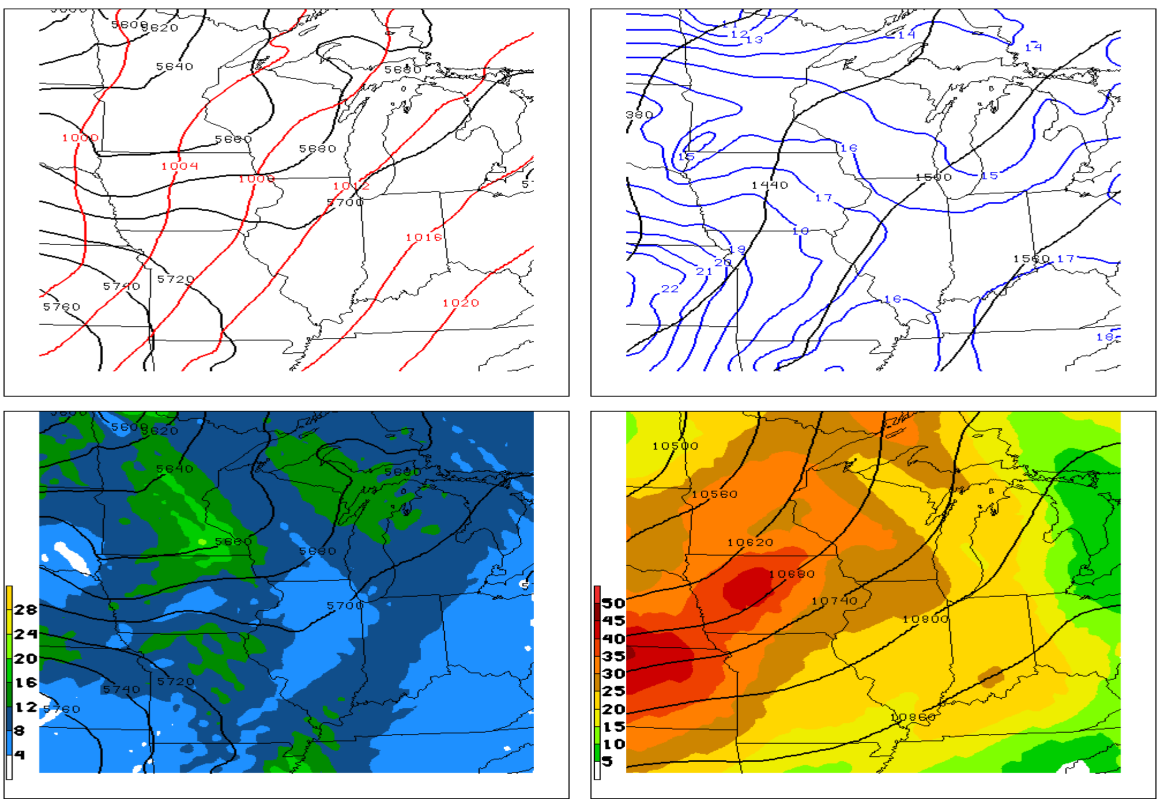


Figure 2. 12Z 07 June 1984 synoptic situation. Upper-left: Surface pressure (red) and 1000-500 hPa thickness (black). Upper-right: 850 hPa isotherms (blue) and heights (black). Lower-left: 500 hPa vorticity (1/s) and 1000-500 hPa thickness (black). Lower-right: 300 hPa wind speed (kts) and heights (black).

A shortwave disturbance was also clear at 300 hPa (Fig. 2. lower-right), extending from near Pierre, South Dakota, south-southeast to just northeast of Kansas City, Missouri. Quasi-geostrophic (OG) theory argued descent across southern Wisconsin due to its position in the right-exit region of a 300 hPa jet to the west and southwest over Iowa, Nebraska, and Kansas (Martin, 2006). Thus, PVA was the primary vertical forcing mechanism for the MCC that progressed across Wisconsin and neighboring states during the morning hours of 07 June.

III. 12Z-00Z 07 June mesoscale situation

Fig. 3, GOES Band-8 IR imagery valid 12Z-1930Z 07 June, showed the presence of a lingering outflow boundary associated with a morning MCC moving north and east across the western Great Lakes Region. Fig. 3 (upper-left) centered the MCC near Dubuque, Iowa at 12Z. The southern peripheral of the MCC exhibited bowing gust front characteristics north and northwest of Quincy, Illinois, and west of Peoria. A hand-analyzed 12Z surface temperature plot (Fig. 4 upper-left) allegorized the existence of a rain-cooled gust front through a temperature discontinuity across northern Illinois.

By 15Z (Fig. 3 upper-right), the MCC had push northeast to northern Wisconsin. The remnants of the southern density current were still evident from west of Davenport, Iowa, east-northeast to the western and northern suburbs of Chicago. Based upon the brightest cloud-top brightness temperatures, it appeared that weak convection was occurring near and east of Davenport.

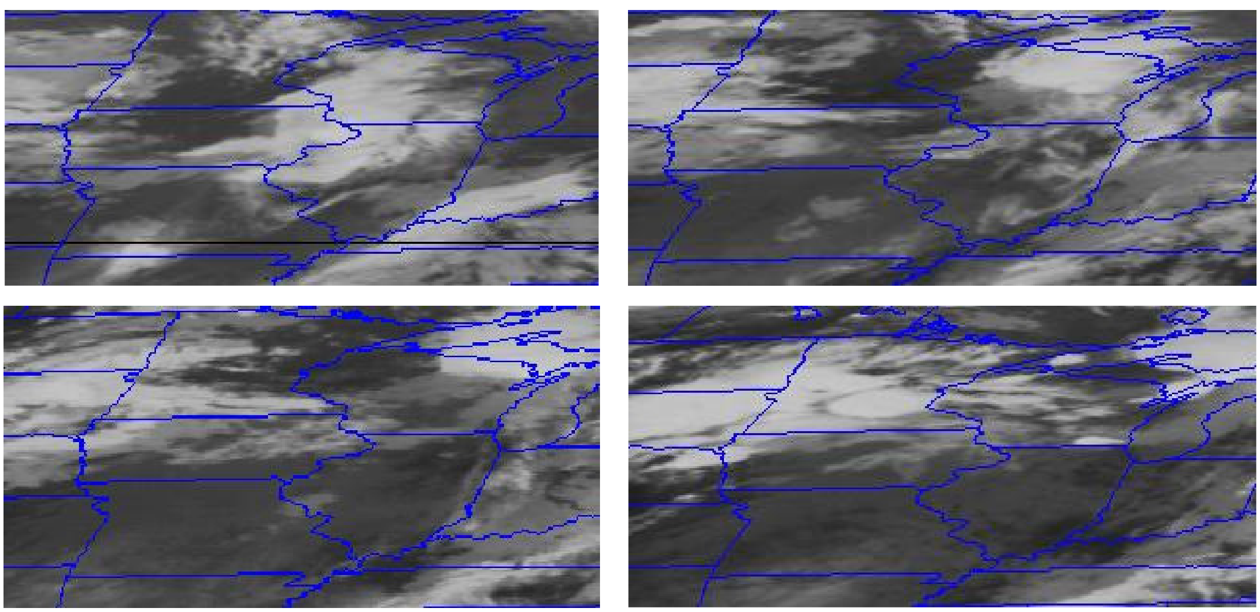
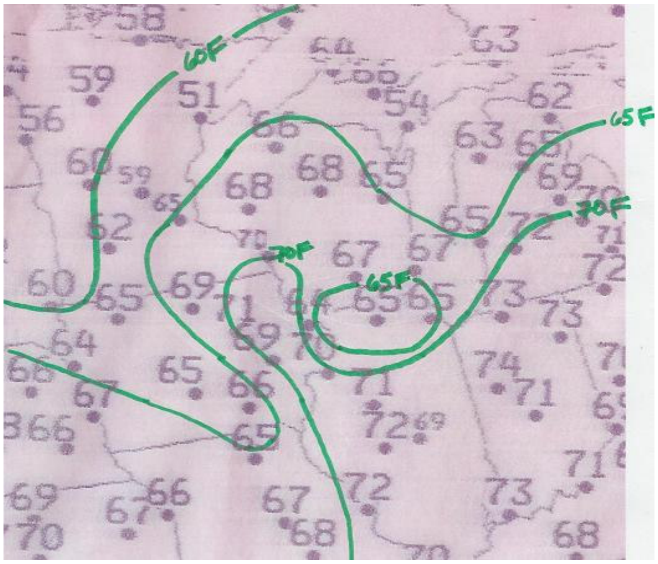
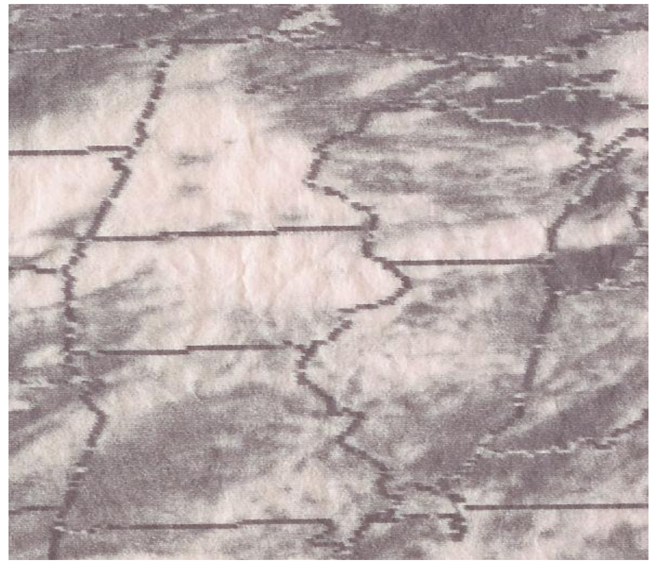


Figure 3. GOES Band-8 IR imagery valid 12Z (upper-left), 15Z (upper-right), 17Z (lower-left), and 1930Z 07 June (lower-right).

Synoptic conditions likely facilitated the northward propagation of the remaining deformation zone by 17Z (Fig. 3 lower-left). It was clear that the boundary stretched from just south of Des Moines, Iowa, to south of Janesville, Wisconsin. Fig. 3 (lower-right) illustrated the initiation of convection by 1930Z along the northeastern flank of the boundary, south of Janesville. NWS-Neenah issued multiple severe thunderstorm warnings for southern and eastern Wisconsin from 2030Z through 00Z 08 June for thunderstorms that erupted along the northeastern portion of the boundary (NWS-Neenah, 1984). A single archived GOES Band-1 Visible image (Fig. 4 upper-right) distinctly delineated the extent of convective initiation by





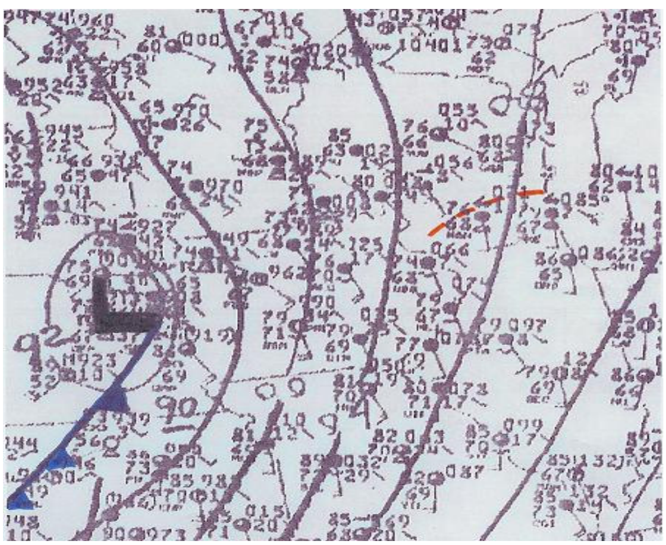


Figure 4. Upper-left: 12Z 07 June surface temperatures showing the existence of a rain-cooled pool over northern Illinois associated with an MCC. Upper-right: 20Z 07 June GOES Visible image indicating convection along a northward propagating outflow boundary from the morning MCC. Lower-left: NWS analyzed 21Z 07 June surface map indicating the subtle existence of a wind shift across southern Wisconsin associated with the remnant deformation zone.

20Z across northeastern Iowa and southern and eastern Wisconsin. Fig. 4 (lower-left) 21Z surface analysis indicated that the characteristics of the outflow boundary had a surface-based component – denoted by a subtle wind shift across southern Wisconsin – with pure southerly flow in Madison, Wisconsin, to east-southeasterly flow in central and eastern Wisconsin. Subsequently, the west-east axis of convection was tied to the subtle wind shift, and was appropriately oriented just north of the 20Z axis of convection denoted in Fig. 4 (upper-right).

IV. 00Z-06Z June synoptic situation

The mode of vertical forcing mechanisms changed from PVA arguments to favorable jet placement such that southern and western Wisconsin was influenced by the near-left-exit region of a strong southwesterly jet at 300 hPa (Fig. 5 lower-right); thus, QG theory would support vertical forcing for ascent. A 500 hPa (Fig. 5 lower-left) plot of vorticity and 1000-500 hPa thickness clarified that vertical forcing by PVA arguments would favor eastern Minnesota and northwestern Wisconsin. At 850 hPa, the thermal ridge pressed northward, situated from Pierre, South Dakota, south to just east of St.

Louis. A surface map displayed a broad, though deepened, surface low situated across the High Plains. Thus, mean surface flow was directed out of the south-southwest, allowing a moist Gulf airmass northward into the Upper Midwest.

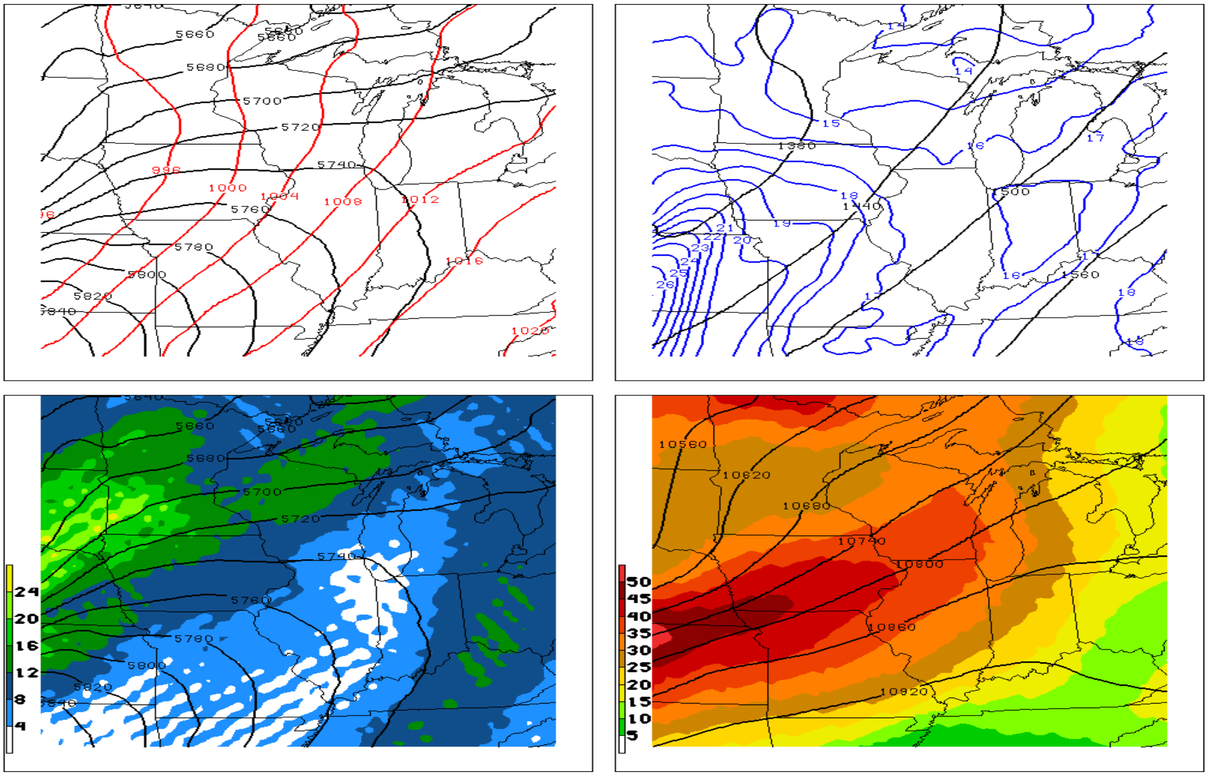


Figure 5. 00Z 08 June four-panel synoptic plot. Upper-left: Surface pressure (red) and 1000-500 hPa thickness (black). Upper-right: 850 hPa isotherms (blue) and heights (black). Lower-left: 500 hPa vorticity (1/s) and 1000-500 hPa thickness (black). Lower-right: 300 hPa wind speed (kts) and heights (black).

V. 00Z-06Z mesoscale situation

a. 00Z

00Z NWS analyzed surface plot (Fig. 6 upper-left) showed that the outflow boundary still illustrated a faint wind shift signal across southern and eastern Wisconsin. Late afternoon convection associated with the deformation zone had moved into eastern and northeastern Wisconsin, with evidence of an overshooting top east of Green Bay, Wisconsin, as shown in GOES Band-1 Visible image, valid 00Z 08 June (Fig. 6 upper-right). Noteworthy is widespread convection over Minnesota and Iowa, with embedded overshooting tops east of Sioux City, Iowa, west of Des Moines, and east of Omaha, Nebraska. Fig. 6 (upper-right) also delineated a supercell with a collapsed overshooting top approximately eighty miles northwest of Macon, Missouri. The collapsed cloud top signified the occlusion process of the supercell, indicative of a possible tornado (Tripoli, 2006). Reference to Fig. 1 (bottom) highlighted a correlation between the collapsed overshooting top and the beginning stages of a long-lived, occasionally violent, tornado that progressed northeastward through southeastern Iowa. NARR Vis5d regenerated plot of CAPE (Fig. 6 lower-left) determined values in the 4000-5000 J/kg range across northern Missouri and southern Iowa; south of the cloud debris associated with the outflow boundary. The ratio of CAPE versus shear was represented in the form of the BRN,

$$BRN = \frac{CAPE}{\frac{1}{2}U^2} \tag{1}$$

where CAPE is defined as the buoyant energy available to a parcel from the surface to the equilibrium level of the atmosphere, i.e.;

$$CAPE = g\int \frac{\theta(z)-\overline{\theta}}{\overline{\theta}} \tag{2}$$

while the denominator (shearing term) considered the effect of 0-6km shearing profile;

$$U = \Delta U = U(6km) - U(0km) \tag{3}$$

therefore, BRN values from 5-40, with 15-20 being optimal, represent an environment primed for supercellular convection (Weisman and Klemp, 1982). Thus, remedial calculations, as well as a NARR reanalysis Vis5d plot (Fig. 6 lower-right), revealed BRN values of 20-30 over south-central and southeast Iowa. Climatological data statistically supports such values as sufficient for strong right-moving supercells and potential tornadic activity (Rasmussen and Blanchard, 1998).

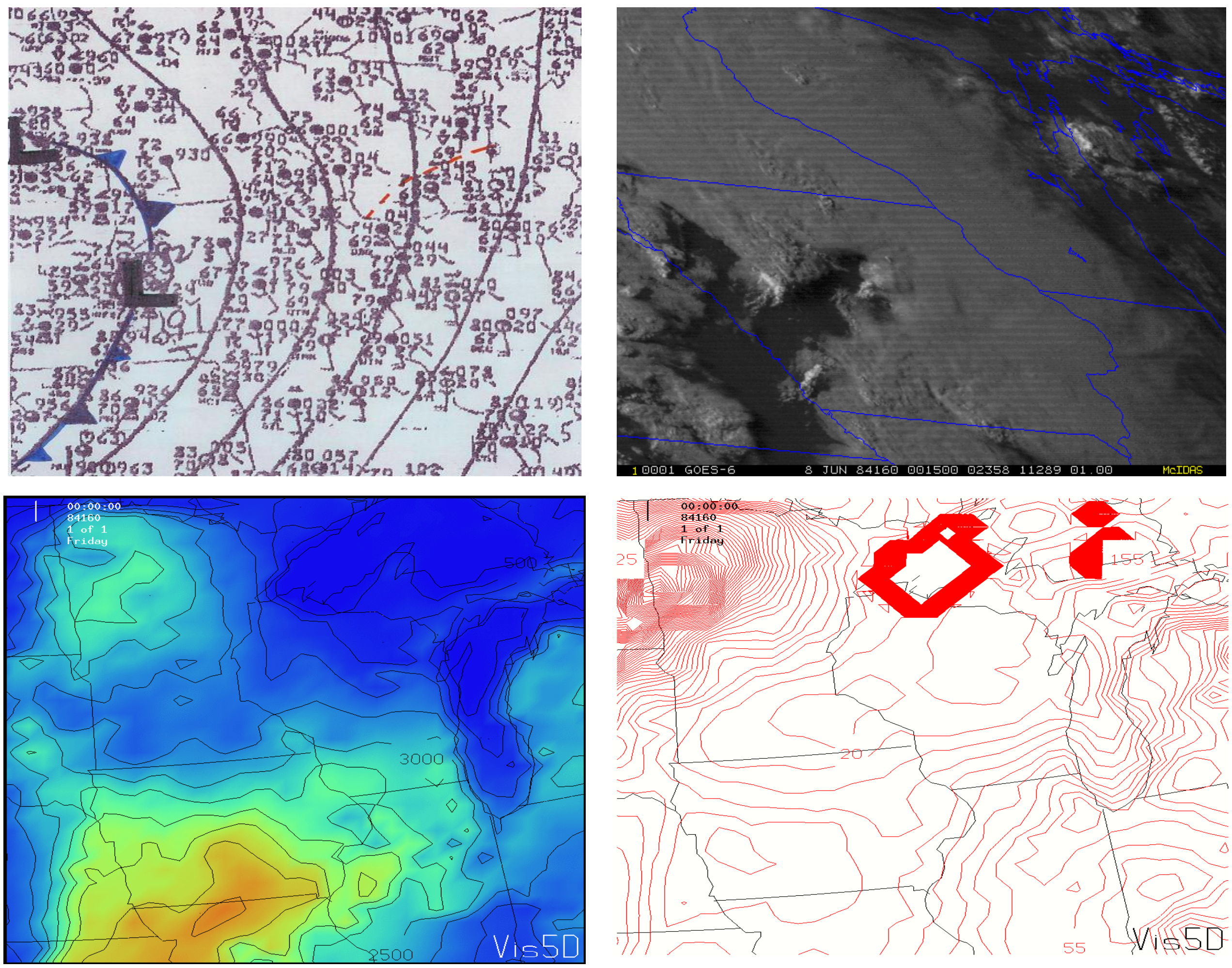


Figure 6. Four-panel plot valid 00Z 08 June. Upper-left: NWS surface analysis. Upper-right: GOES Visible Imagery. Lower-left: NARR regenerated Vis5d plot of CAPE. Lower-right: NARR regenerated Vis5d plot of BRN values.

Cloud debris and convection associated with the influence from the outflow boundary limited diabatic heating and destabilization such that CAPE values over southern Wisconsin struggled to top 3000 J/kg (Fig. 6 lower-left). Additionally, southern Wisconsin was also devoid of maximized 0-6km shear contributions due to strong winds at both 0km and 6km respectively; thus, BRN values of 20-50 prevailed. Had convection ensued at this time over southern and eastern Wisconsin, it would have been biased towards multicellular characteristics due to higher BRN values (Weisman and Klemp, 1982). Furthermore, the lack of dry air aloft, moistened by diurnal convection, would have precluded efficient downdraft production compulsory to expedite a titled, reinforced updraft necessary for a systematic supercellular regime (Bunkers et. al., 2006). Mid-level entrainment of dry associated with the upstream jet structure would foster more robust downdraft capabilities as it advanced northeastward. Affirmation of mid-level dry air was seen in hand-plotted skew-t diagrams (Fig. 7) courtesy of UW-Madison archived NWS profiler data, valid at 00Z. Fig. 7 (upper-left) confirmed a moist tropospheric signal in Green Bay in response to ongoing convection. Positioned in the warm-air-sector, the sounding from Peoria, Illinois (Fig. 7 upper-right) confirmed the presence of a thin layer of dry air between 650-500 hPa. Note this was expected due to the position of the jet core, and subsequent dry air from westerly sources, to the northwest. Not surprisingly, an Omaha sounding provided substantiation of dry air from 550 hPa through the remaining depth of the troposphere. Thus, northeastward evolution of the jet core, dry air, and favorable BRN values would motivate a more conducive environment for pure supercellular convection.

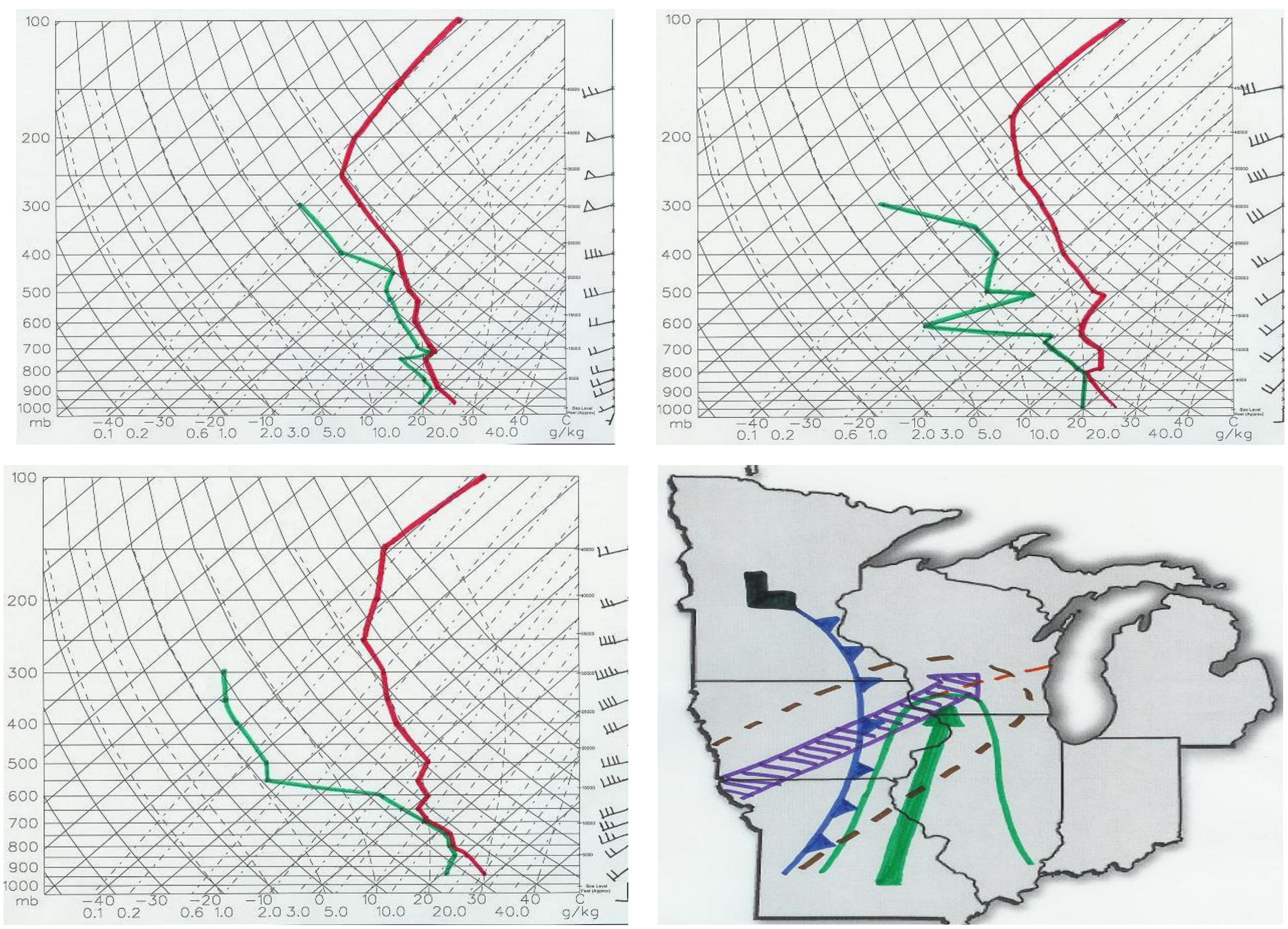


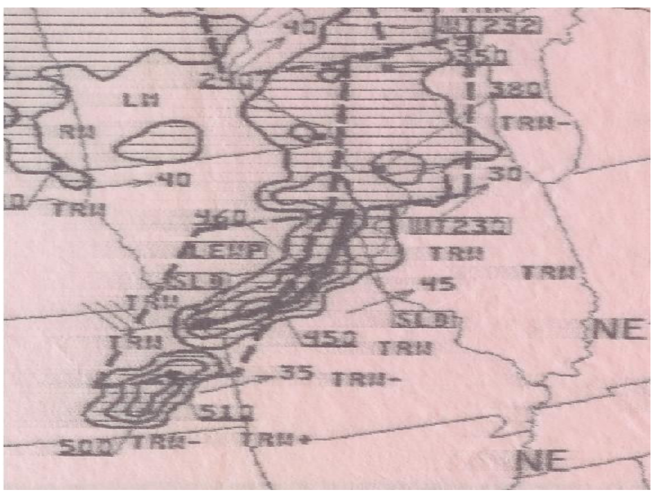
Figure 7 valid 00Z-006Z. Upper-left: Green Bay, Wisconsin sounding. Upper-right: Peoria, Illinois sounding. Lower-left: Omaha, Nebraska sounding. Lower-right: Miller Diagram displaying a Type-B severe weather scenario by 06Z.

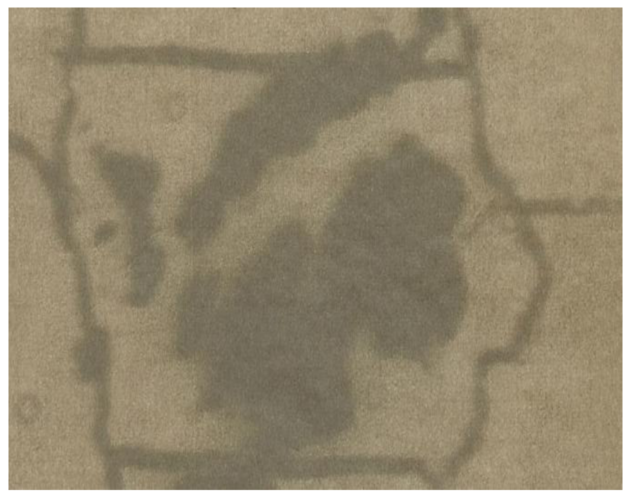
The northeastward expansion of the jet core and re-filtration of mid-level dry air, strong moisture flux from the south-southwest, and the presence of surface convergent boundaries in the form of an eastward propagating cold front and the remains of the outflow boundary, would be necessary to instigate a tornadic state in Barneveld. A Miller Diagram (Fig. 7 lower-right) was constructed to illustrate that by the early morning hours of 08 June, a Type-B scenario would stimulate southwestern Wisconsin for severe weather (Miller, 1972).

b. 03Z

By 03Z, the NWS issued a Tornado Watch for much of east-central Iowa, northwest Illinois, and most of southern and central Wisconsin (Fig. 8 upper-left). A single Doppler Radar image (Fig. 8 upper-right) showed widespread thunderstorm activity over eastern Iowa. The final miles of a long-tracked tornado over southern and eastern Iowa ended at approximately 03Z, roughly sixty miles west of Davenport.

03Z NWS surface analysis (Figure 8. lower-left) showed the cold frontal position elongated from Kansas City, Missouri, northeast to west of Des Moines, to just west of Minneapolis. Although very difficult to interpret, station models still alluded to a weak wind shift oriented from just west of Madison, northeast to south of Manitowoc, Wisconsin. The outflow boundary signature became a crucial factor in the evolution of events that would unfold between 0530-06Z.





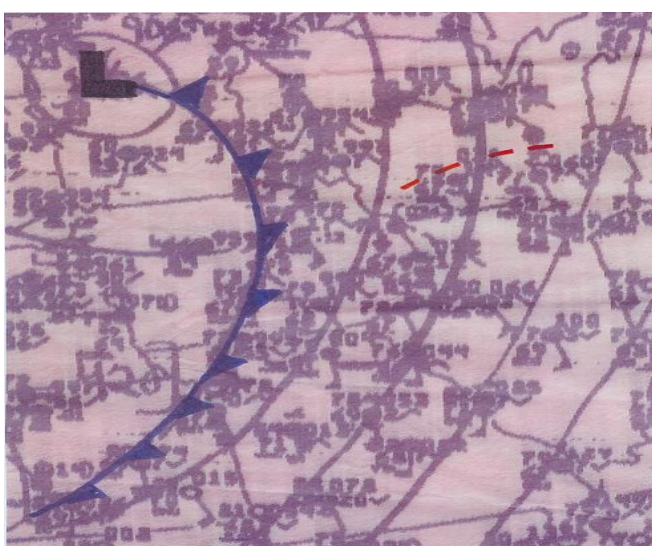


Figure 8. Upper-left: 06Z 08 June severe weather watches and radar composite. Upper-right: 03Z Doppler Radar Image. Lower-left: NWS 03Z surface map indicating the subtle existence of a wind shift across southern Wisconsin associated with the remnant deformation zone.

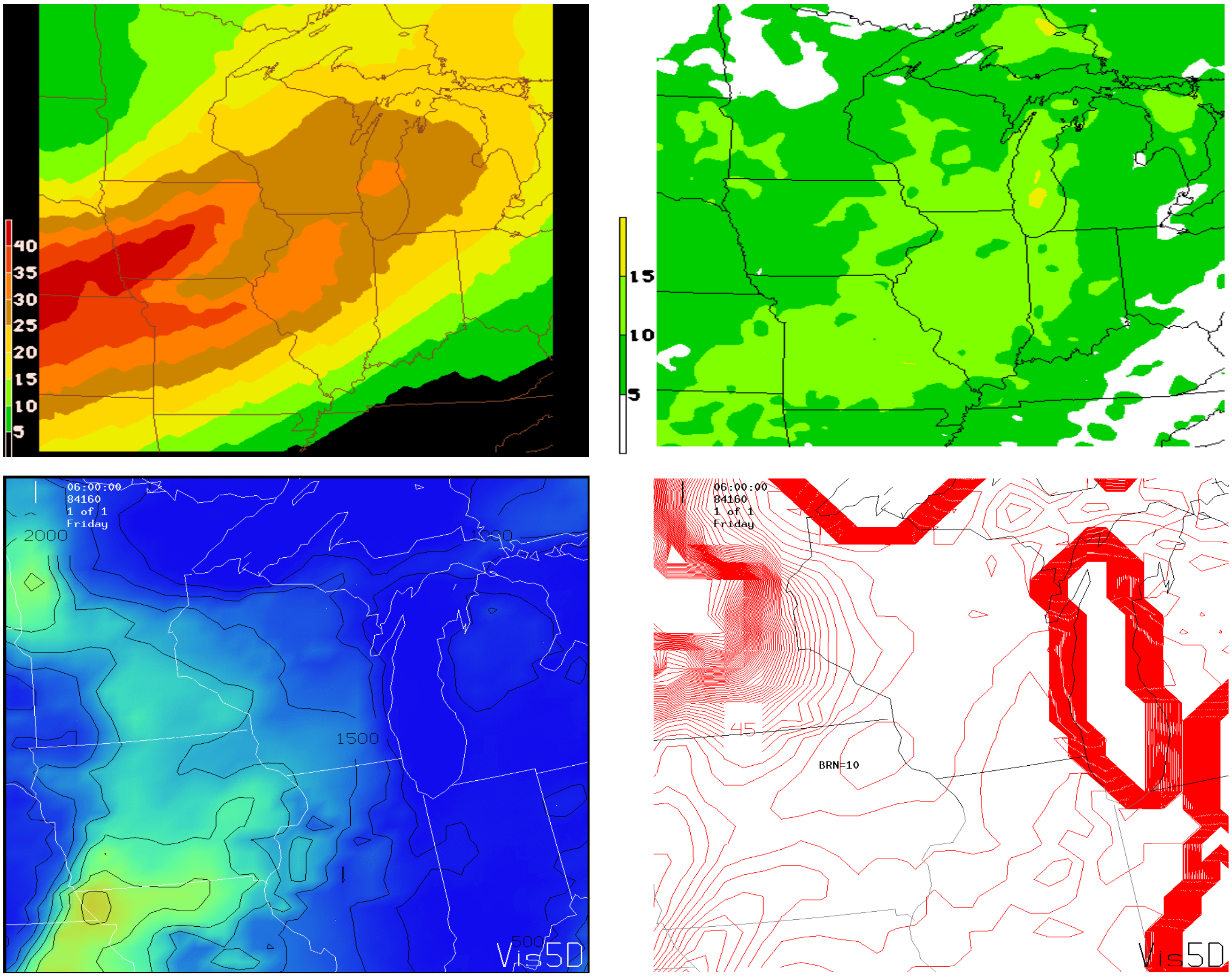


Figure 9 valid 006Z. Upper-left: 6km wind speed (kts). Upper-right: 0km wind speed (kts). Lower-left: NARR regenerated Vis5d plot of CAPE. Lower-right: NARR regenerated Vis5d plot of BRN values.

c. 0530- 06Z

Crude 0-6km ΔU calculations, facilitated by NARR data (Fig. 9 upper-left and right), resulted in values of approximately 20-30 kts. With the loss of daytime heating, CAPE values were reduced to the 1500-2000 J/kg range across southwestern Wisconsin (Fig. 9 lower-left). Climatological work on significant tornadoes and CAPE versus shear contributions, argued these numbers to be ideal for significant tornadoes (Rasmussen and Blanchard, 1998). Furthermore, Rasmussen and Blanchard (1998) climatological work extended Weisman and Klemp 1982 work on BRN values and significant severe weather by associating BRN values of 10-20 as statistically favorable for significant tornadoes. NARR generated Vis5d Plot of BRN values paralleled the rough computation.

Observable was that the jet, although slightly weakened from 00Z, had edged northeast; becoming the only influencing jet structure in the western Great Lakes. Hence, the placement of the jet, with adequate timing, coerced dry air to entrain the middle atmosphere over southwestern Wisconsin once again. Fig. 10 (top) NARR regenerated plot depicted a strong influx of moisture from the southwest, with dewpoints nearing 70 F in Barneveld. With a positive helical background environment (Fig. 10 bottom); caused by strong speed shear with height, the weakened supercell entering northwestern Lafayette county would not have dissipated entirely.

The external outflow boundary, which focused afternoon convection; lessening overall CAPE values such that optimal BRN values eventuated by 06Z, likely augmented the streamwise vorticity near Barneveld. Streamwise vorticity is employed in the formulation for Storm-Relative Helicity (SRH) plotted in Fig. 10 (bottom). SRH is calculated from the vertically integrated effect of the ambient flow within an atmospheric column relative to storm motion (Markowski et al., 1997).

$$SRH = \int_0^z (V - c) \bullet \omega dz \qquad (4)$$

ω represents the streamwise vorticity in equation (4). Sequential increase in the streamwise vorticity expedites an increase in SRH and the veering curvature of the wind profile. Augmentation of the streamwise vorticity signal can mature from any force that changes the magnitude and direction of the u and v components of the wind (Rasmussen, 1998). While the physical entirety may not be well understood, observational analysis of the interaction between existing supercellular structures and external boundaries hypothetically alters the wind such that the local vorticity increases (Jordan et. al., 2000).

Therefore, as the pre-existing supercell updraft intersected the enhanced convergence zone offered by the external deformation zone, it intensified and led to an increased dynamical response within the storm; likely causing another overshooting top. Secondly, the rear and forward-flanking downdraft of the supercell interacted with the increased vorticity signal, stretching and further increasing the rotation; that, when lifted by the occlusion phase of the flanking frontal structures, resulted in the rapid spin-up of the Barneveld tornado by 0550Z (Tripoli, 2006). A conceptual model (Fig. 11 top) is provided for an intuitive illustration.

A hand-drawn cross section (Fig. 11 bottom) of theta and theta-e, as well as a conceptual model was devised to foster a heuristic representation of the evolution of factors that stirred the formation of the Barneveld tornado. The vertical extent of the rain-cooled outflow boundary was over-emphasized to represent the lifting effect of the cold-pool density current. In reality, these features are very shallow, often on the order of tens to several hundred meters (Tripoli, 2006).

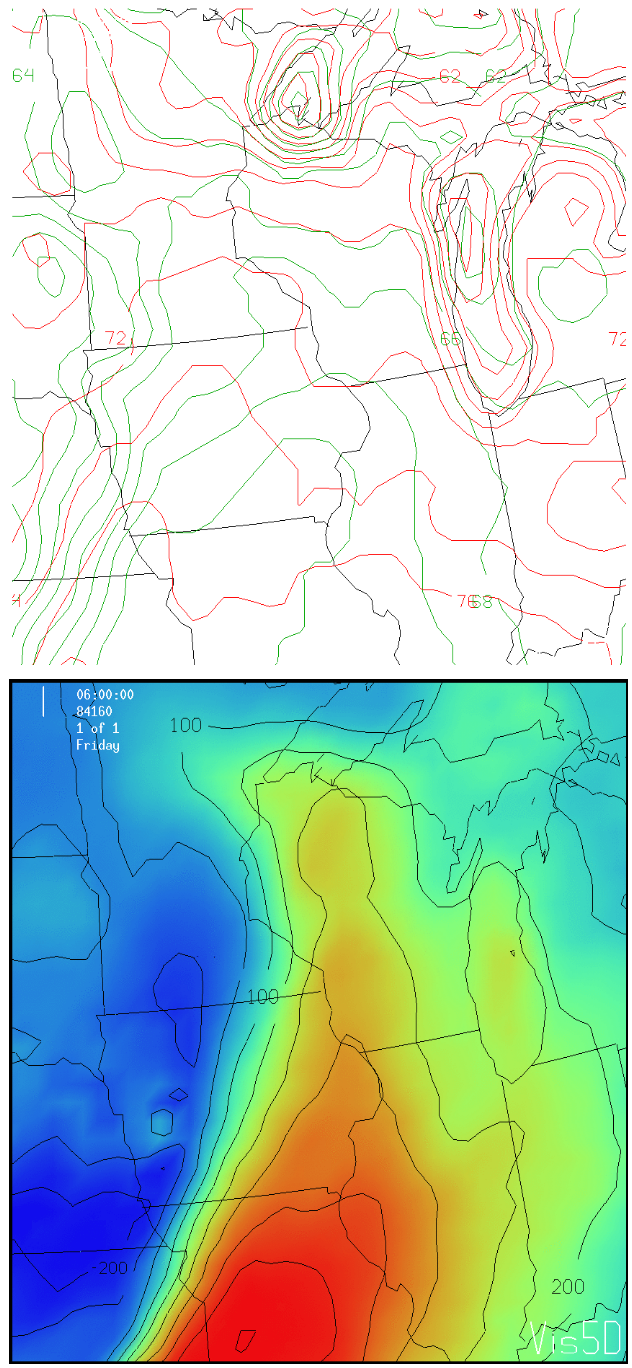


Figure 10. 06Z 08 June NARR regenerated Vis5d plots of temperature and dewpoint (top) and 0-3km Helicity (bottom).

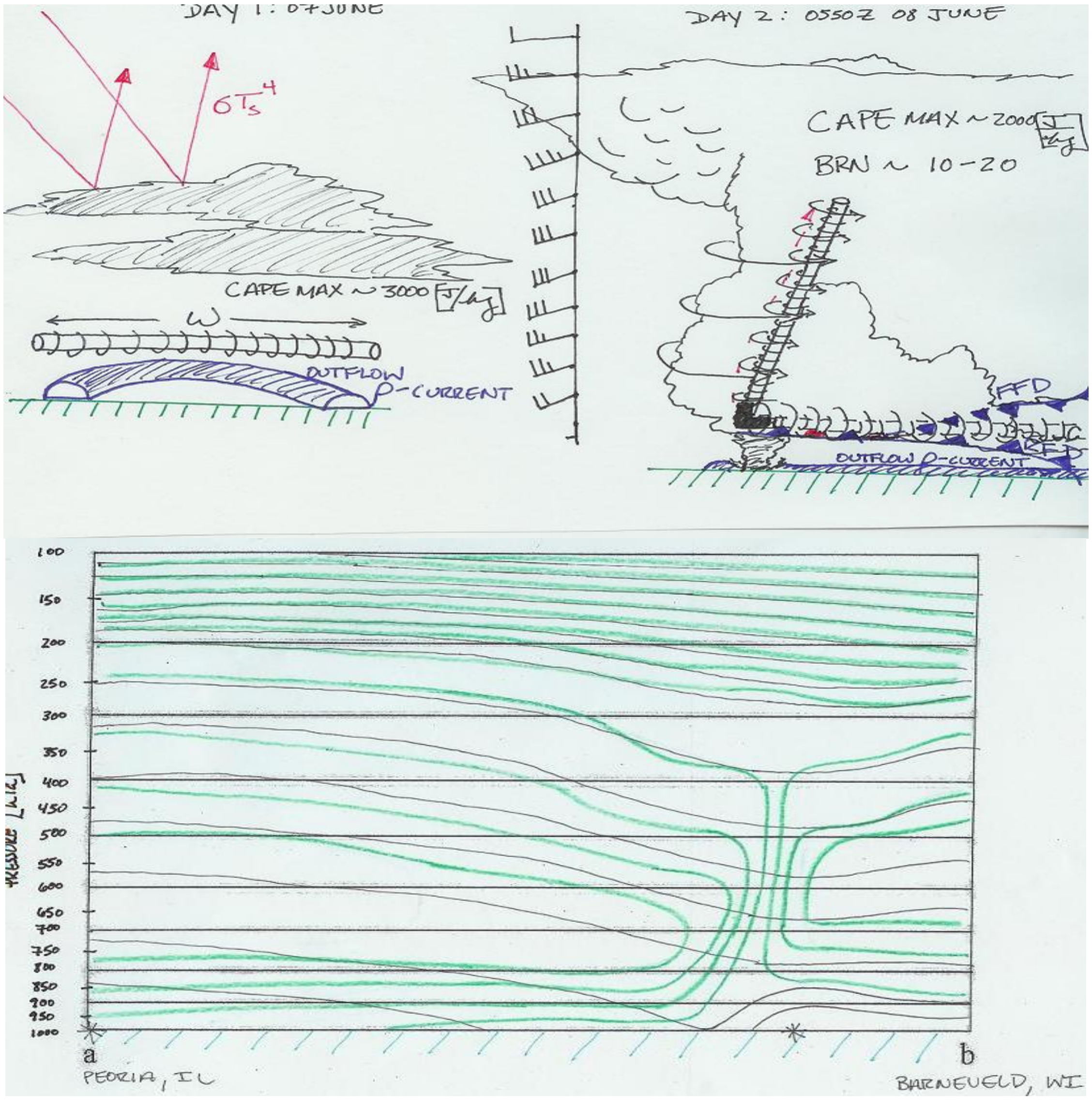


Figure 11. Top: Conceptual model illustrating the evolution of events that predisposed Barneveld for a tornadic event. Bottom: Theta (black) and theta-e (green) cross section indicating the presence of a external rain-cooled outflow boundary (emphasized in the vertical to show cold pool).

VI. Conclusions

The existence of strong diabatic heating to drive high instability was crucial for high CAPE values. While high CAPE values alone can facilitate an explosive thunderstorm development, studies have concluded that in nearly all violent tornadic cases, ambient shear was present in at least modest form. A remnant outflow boundary lingering over southern Wisconsin enabled convection and subsequent cloud debris to negate maximum CAPE values from evolving. Contrarily, this primed Barneveld for BRN values conducive for supercellular convection once a sufficient 0-6km shear profile assembled around 06Z 08 June. The imprint of the external deformation zone served a secondary, perhaps more important, effect by augmenting the streamwise vorticity such that its interaction with the rear and forward flanking downdrafts of a pre-existing supercell fostered increased spin for the descension of the Barneveld F-5 tornado.

Retrospective thoughts included appreciation in advancements of data archiving and preservation, as well as technological progression since the Barneveld disaster. While overwhelming evidence supported the existence of an outflow boundary that was likely integral to the sequence of events that preferentially disposed southwestern Wisconsin for a violent tornadic supercell, there still existed some degree of uncertainty in the specific placement of the boundary due to lack of standard analysis tools, as well as the poor quality of the tools available.

Modern day technology, for example readily available, fine-scale, GOES visible imagery would have better served examination of the boundary. Furthermore, NEXRAD products could have illuminated the boundary had pollutants or insects been caught in the discontinuity. Additionally, detailed GOES and radar imagery could have shown that that perhaps afternoon convection, spawned from the morning MCC density current, left a residual external deformation zone that impacted the 06Z supercell rather than the former boundary.

The use of a fine-mesh numerical model could have helped illustrate the increased rotational impacts of the deformation zone on the pre-existing supercell; perhaps helping to definitively prove the increase in streamwise vorticity. Furthermore, a numerical model could potentially recreate different atmospheric scenarios while modulating the CAPE and shear over southwestern Wisconsin in the presence of the boundary; perhaps leading to a stronger tornado? Conclusively, it might answer whether or not the severity of the Barneveld tornado would have reached F-5 intensity had the outflow boundary been non-existent, yet CAPE and shear values remained the same.

REFERENCES

Barneveld Public Library, 1985. 07 May 2006. http://www.wx-fx.com/barnevld.htm.

Browning, P., J. F. Weaver, B. Connell, 1997: The Moberly, Missouri Tornado of 4 July 1995. Weather and Forecasting., **12**, 915-927.

Bunkers, M. J., J. S. Johnson, L. J. Czepyha, J. M. Grzywacz, B. A. Klimowski, M. R. Hjelmfelt, 2005: An Observational Examination of Long-Lived Supercells. Part II: Environmental Conditions and Forecasting. 8 May 2006. http://www.crh.noaa.gov/images/unr/soo/scm/SC_Longevity_PartII.pdf.

Harrington, Tim. Personal Interview. 27 April 2006.

Jordan, J. K., A. R. Moller, M. D. Vesico, 2000: A Case Study of The Fort Worth and Arlington Tornadic Supercells of 28 March 2000. Texas Tech Atmospheric Science Group, P6.7.

National Weather Service – Neenah. 07 June 1984. 8 May 2006.

Markowski, P. M., J. M. Straka, E. N. Rasmussen, D. O. Blanchard, 1997: Variability of Storm-Relative Helicity during VORTEX. Amer. Meteor. Soc., **126,** 2959-2971.

Martin, J, 2004: Mid-Latitude Atmospheric Dynamics: A First Course. Wiley Publishers., 299-329.

Miller, R., 1972: Notes on Analysis and Severe-Storm Forecasting Procedures of the Air Force Global Weather Central. Air Weather Service (MAC) United States Air Force, **3,** 1-19.

Rasmussen, E., D. O. Blanchard, 1998: A Baseline Climatology of Sounding-Derived Supercell and Tornado Forecast Parameters. Wea. Forecasting, **13**, 1148-1164.

Rasmussen, E., S. Richardson, J. M. Straka, P. M. Markowski, D. O. Blanchard, 1998: The Association of Significant Tornadoes with a Baroclinic Boundary on 2 June 1995. Amer. Meteor. Soc., **128,** 174-191.

Stephen, J., 2006: 30 km Eta Reanalysis. University of Wisconsin – Madison.

Storm Prediction Center (SPC). 2003. 27 April 2006. http://www.spc.noaa.gov.

Thompson, R., R. Edwards, C. M. Mead, 2004: Storm Prediction Center., **2.4**.

Tripoli, Greg. Personal Interview. 6 April 2006.

Weisman, M., J. B. Klemp, 1982: The Dependence of Numerically Simulated Convective Storms on Vertical Wind Shear and Buoyancy. Mon. Wea. Rev., **110**, 504-520.