Analysis of the June 11, 2001 Wisconsin Bow Echo and Associated Rear-Inflow Jet & 'Bookend' Vortex

BRIDGETTE A. EAGAN

Department of Atmospheric and Oceanic Sciences; *University of Wisconsin—Madison*

ABSTRACT

Presented is a synoptic and mesoscale analysis of the June 11-12, 2001 bow echo storm event. The storm system originated in southern and central Minnesota during the afternoon hours of June 11, 2001, and spawned several tornadic supercells. The storms moved to the southeast into northwestern Wisconsin where the mesoscale convective system (MCS) gradually developed a line of intense radar reflectivity oriented from the southwest to the northeast. The storm was further enhanced as the MCS outflow became part of a dynamic flywheel associated with a 250 hPa jet located to the northeast of Wisconsin. At approximately 0100 UTC on June 12, 2001, the line of storms began to develop a bowed structure in the radar reflectivity known as a bow echo. Over the next four hours, this bow echo was further enhanced by a strong rear-inflow jet. The intense system-scale downdraft associated with this MCS created a severe straight-line wind storm called a derecho spawning wind gusts in excess of 70mph.

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1. INTRODUCTION

In the evening hours of June 11, 2001, a severe straight-line wind event associated with a radar detected bow echo signature roared through Wisconsin producing wind gusts in excess of 70 mph. The prolonged high level winds extending over a large area caused over twenty-five million dollars in property damage and nearly three-quarters of a million dollars in crop damage across Wisconsin (courtesy of the National Climatic Data Center [NCDC]). The straight-line wind event, or derecho, even induced a storm surge on Lake Butte Des Morts in eastern-central Wisconsin (Marshall et al., 2001).

According to Burke and Schultz (2004), damaging winds of this nature are quite often associated with the aforementioned radar signature know as the bow echo. The bow echo is a convective structure so named for its arched or curved appearance on a radar reflectivity field. An idealized bow echo radar signature typically begins as a strong and large convective cell that may be a remote cell, or may be associated with a larger convective complex. In this developing cell, the storm updraft is initially tilted downshear of the background environmental windshear (see FIG. 1. (a)). As the storm grows, the storm circulation begins to create a cold pool of air at the surface associated with the cool sinking air of the storm downdraft. This cold pool of air develops a circulation due to horizontal buoyancy gradients along the edge in the opposite direction than that of the environmental wind shear balancing this background shear, and allowing the updraft to take on a more vertical nature. The radar reflectivity becomes more narrow and intense as the updraft is oriented more vertically (see FIG. 1. (b)). As the cold pool grows, the circulation of the cold pool becomes stronger and overtakes the ambient wind shear. The updraft then begins to tilt upshear inducing a rear-inflow jet, as the updraft shear couples with the cold pool circulation. This rear-inflow jet causes the storm to take on a bowed shape as it transports momentum to the leading edge of the storm (see FIG. 1. (c)). The shear from the rear-inflow jet and the background environmental wind shear are then able to balance the cold pool circulation, and the system becomes a steady-state system (Weisman, 1993).

The thermal structure of a typical bow echo storm can be seen in FIG. 2. The cold pool can be seen in both potential temperature and equivalent potential temperature structures. The isentropes slope sharply upwards at the discontinuity between the warm moist air and the cold pool. Lines of constant equivalent potential temperature also rise up over the cool dry air of the cold pool.

The derecho, or straight-line winds, form due to the storm circulation. The updraft gets quite strong once the storm reaches its steady state. The updraft may begin to lift the more stable cool air located to the north of the quasi-stationary thermal boundary. As this air is lifted, some of the cooler air falls out of the updraft creating an up-downdraft. This cool air has been lifted above its equilibrium level, thus when the air falls out of the updraft, it overshoots its original position and falls to the surface spilling into the already strong gust front. This can create very high straight-line wind speeds as the air spreads at the surface.

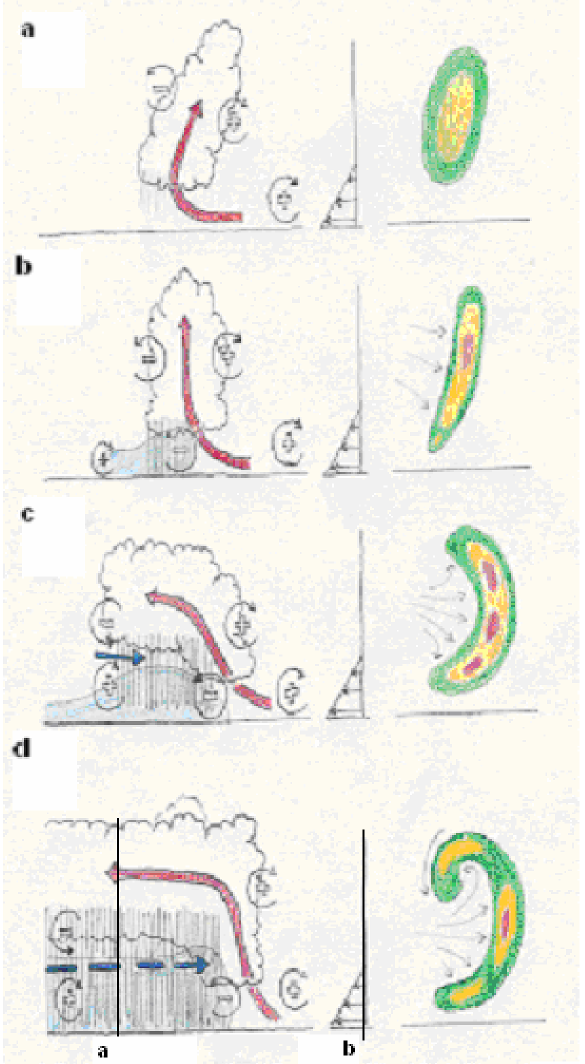

FIG. 1. The left side depicts a vertical cross section of the development of an idealized bow echo. The right side shows the corresponding radar reflectivity field during the bow echo evolution. (a) The initial updraft develops and is tilted downshear due to background atmospheric shear. The right side shows the radar reflectivity indicating light precipitation. (b) The storm generates a cold pool which develops a circulation that balances the background atmospheric wind shear. The updraft is now in an upright position and the radar reflectivity becomes more narrow and intense. (c) The circulation of the cold pool overwhelms the background shear and the updraft tilts upshear, inducing a rear-inflow jet. The radar echo begins to bow. (d) The cold pool circulation is balanced by the background shear and circulation of the rear-inflow jet creating a steady state system intensifying the bow echo (adapted from Weisman 1993). The blue shaded region indicates the cold pool. The thick red arrow is the storm updraft, and the blue dashed arrow is the rear-inflow jet.

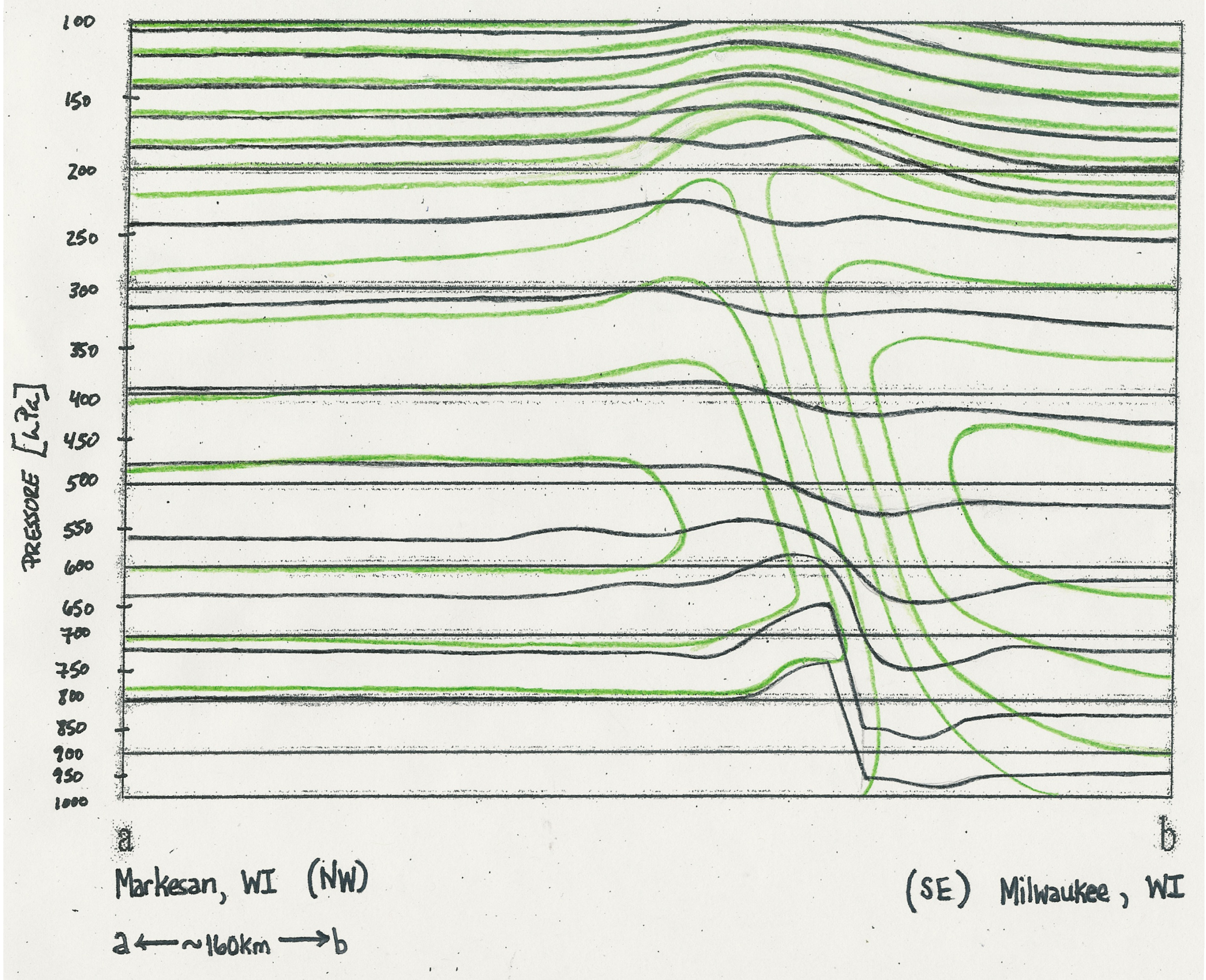

FIG. 2. Vertical Cross Section of potential temperature (heavy black lines) and equivalent potential temperature (green lines). Theta lines rise sharply in the cold pool induced by the storm circulation. The theta lines also dip slightly in the storm updraft indicating the air in the updraft is warm. Equivalent potential temperature also rises up over the cold dry air in the cold pool. The theta-e plume represents the warm moist air rising in the storm updraft. The vertical lines labeled 'a' and 'b' in FIG. 1. (d) indicate the span of this cross section.

There are two types of derechos associated with bow echo signatures. A serial derecho is typically associated with a large squall line in which downburst activity occurs in a series of bow echoes that move along the squall line. A progressive derecho is associated with a short curved squall line which is perpendicular to the mean wind flow. The line bulges in the direction of the mean flow, and downburst activity occurs along this bulge. Progressive derechos typically form along the northern edge of a stationary or quasi-stationary thermal boundary in the lower levels of the atmosphere (Johns and Hirt, 1987). The regions of development are often correlated with high values of Convective Available Potential Energy (CAPE), and strong vertical wind shear in the environment (Weisman, 1993).

The June 11-12, 2001 Wisconsin derecho is a progressive derecho. Convective storms from Minnesota moved along a warm frontal boundary into northwestern Wisconsin. The storm was enhanced as the outflow of the storm was absorbed by the 250 hPa Sawyer-

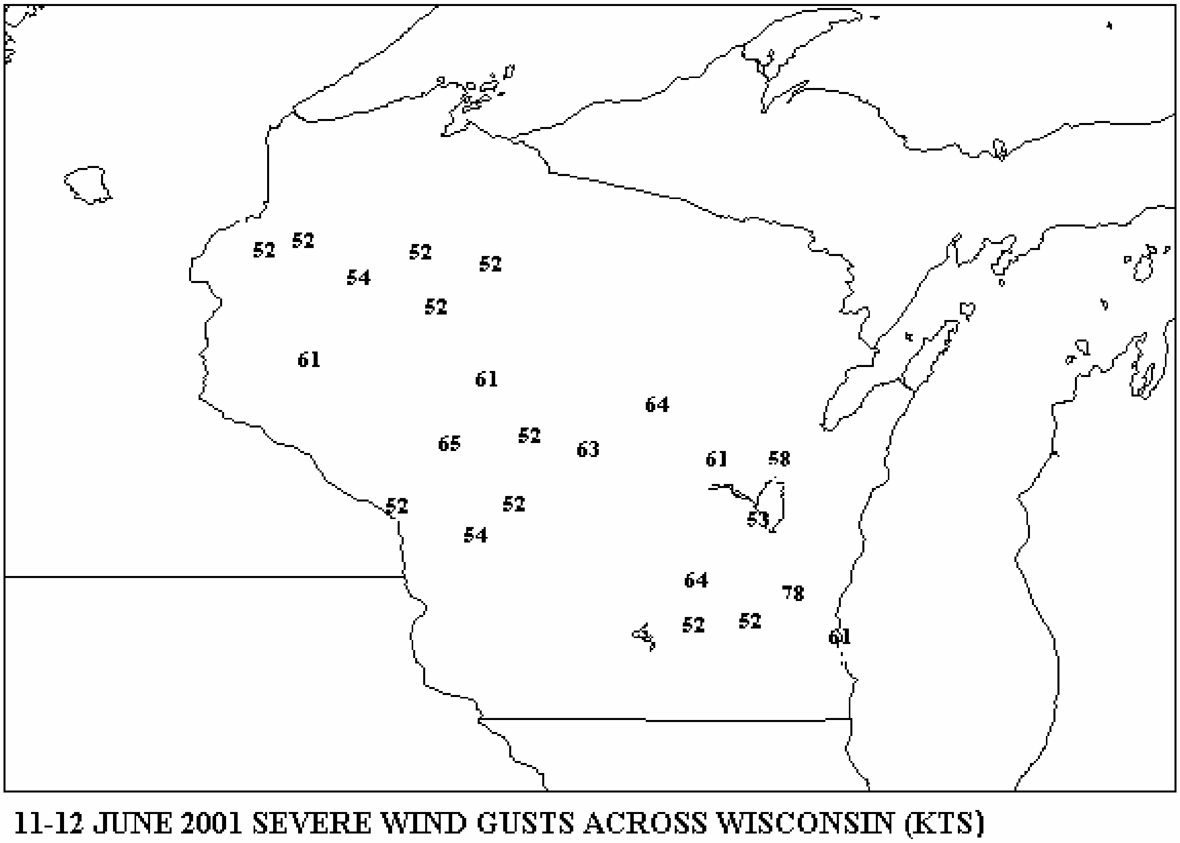

FIG. 3. Progression of severe wind gusts (in knots) across Wisconsin associated with the June 11-12, 2001 derecho (adapted from CIMSS 11/12 June 2001 Wisconsin Derecho Case Study).

Eliassen jet circulation. Thus the storm was able to use available energy to promote growth, rather than using energy to force subsidence of the outflow. These storms gradually developed a linear front edge which began to bow outward in the direction of the mean flow due to the formation of a strong rear-inflow jet. Strong straight-line winds or downbursts occurred along this bulge creating a damage path extending across the entire state of Wisconsin (see FIG. 3. for associated wind gust reports).

2. DATA

The June 11-12, 2001 bow echo storm event is analyzed using several different data sources. The synoptic situation is analyzed using surface observations for pressure

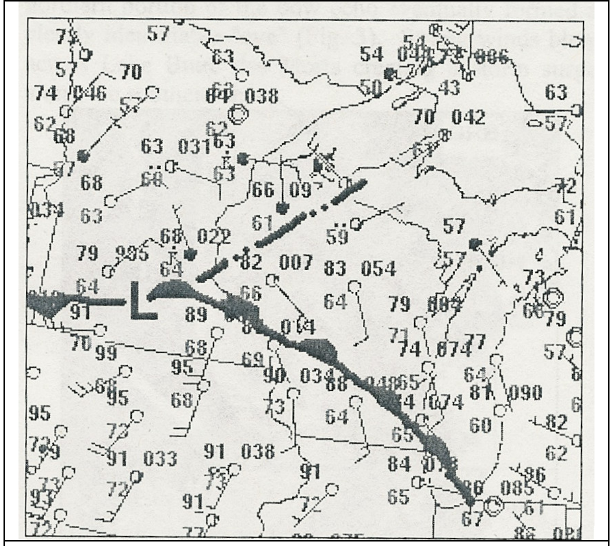

FIG. 4. Surface weather observations and analysis at 2300 UTC on June 11, 2001 Temperatures and dewpoints are in degrees Celsius. The dashed/dotted line indicates the position of the leading edge of the storm (courtesy of Marshall et al. 2001).

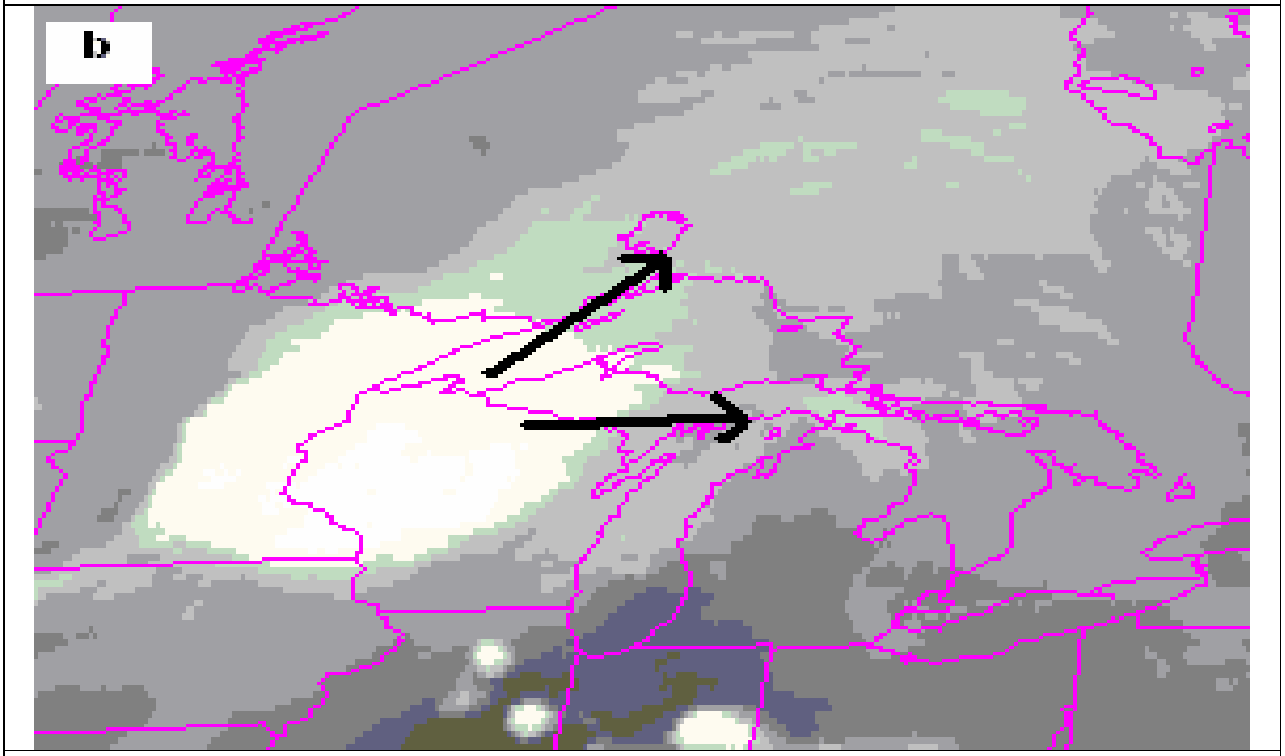

FIG. 5. (a) The 250 hPa jet at 0000 UTC on June 12, 2001. (b) GOES-8 4km water vapor 2345 UTC on June 11, 2001. The storm outflow is flowing towards the 250 hPa jet, where the anticyclonic shear of the jet has locally reduced the inertial stability. The outflow becomes a part of the Sawyer-Eliassen circulation of the jet; it becomes a dynamic flywheel.

center and frontal structure placement. The Geostationary Operational Environmental Satellite-8 (GOES-8 4km Water Vapor) imagery was used to examine the MCS outflow patterns in relation to a 250 hPa jet circulation. The position of this 250 hPa jet was plotted and evaluated in GEMPAK, the General Meteorological Package, using the North American Model (NAM, which was formerly known as the ETA model).

Mesoscale features were analyzed using WSR-88D radar products. The Midwest Base Reflectivity Radar was employed to show the progression of the bow echo. Milwaukee, WI Base Reflectivity Radar and Storm Relative Velocity were used to show the rear-inflow jet. The NAM model was again employed in GEMPAK to plot values of Convective Available Potential Energy (CAPE) in Wisconsin. Wind shear was evaluated using a plotted Skew-T Log-P Diagram from GEMPAK Analysis and Rendering Program (GARP), using the Rapid Update Cycle (RUC) model data. Streamline maps were created using archived surface data from the Plymouth State Weather Center.

3. SYNOPTIC ANALYSIS

Initial storms spawning this system developed in central and southern Minnesota in the afternoon hours. The storms were initiated just northward of a warm frontal boundary associated with a low pressure center located in south-central Minnesota (see FIG. 4.). The warm front extends from the low southeastward into southern Wisconsin. According to Marshall et al. (2001) a shortwave trough moving over northern Minnesota spawned vertical motion while destabilizing the air in the region of storm initiation. The shortwave trough coupled with low level convergence created by an 850 hPa jet located over Iowa which brought very moist air up over the warm front. Storms formed in the afternoon as the very moist unstable air was brought to the north ahead of the shortwave trough into central Minnesota. Many of these storms were supercellular in nature, and several produced tornadoes.

The storms moved to the southeast into northwestern Wisconsin along the warm frontal boundary at approximately 0000 UTC. The storm system begins to develop a rear-inflow jet at this time (not shown). The rear-inflow jet converges with the updraft producing a mid-level line vortex, thus decreasing the Rossby radius of deformation within the storm. The line vortex is enhanced as the melting layer heating function is projected onto it, and the vortex balls up creating a circular convective complex (Tripoli, 2006).

At this time, the storm interacts with a 250 hPa jet streak located to the northeast of Wisconsin (see FIG. 5. (a)). The jet displays a strong anti-cyclonic curvature. The jet curvature created anti-cyclonic wind shear to the south of the jet lowering the absolute vorticity in this region. As the vorticity decreases within this region, so does the inertial stability. The outflow from the storms, located just to the south and east of this region, then seeks out the path of least resistance and flows into the area of lowered inertial stability (see FIG. 5. (b)). The outflow of the storm becomes a part of the Sawyer-Eliassen circulation of the 250 hPa jet streak. This quasi-geostrophic circulation stores the “available energy of the storm’s convective latent heating in its mass balanced circulation” (Tripoli, 2006). Thus the storm uses no energy to force subsidence of the outflow; the outflow is absorbed by the ageostrophic jet circulation creating a dynamic flywheel. All of the available energy for the storm can go into the growth and development of the storm.

FIG. 6. Midwest Base reflectivity June 12, 2001 showing the storm progression over a four and a half hour time period. (a) 0000 UTC (b) 0130 UTC (c) 0300 UTC (d) 0430 UTC (courtesy of CIMSS 11/12 June 2001 Wisconsin Derecho Case Study).

4. MESOSCALE ANALYSIS

The storm is enhanced by synoptic features, but the bow echo and enhanced convergence line along the gust front are created by the rear-inflow jet. FIG. 6. (a)-(d) shows the evolution of June 11-12, 2001 storm. At 0000 UTC the storm is beginning to develop a linear line of more intense cells near the leading edge of the storm. At 0130 UTC, the storm begins to arch slightly. By 0300 UTC the bow echo signature is very notable. The bowed structure continues to propagate to the southeast at 0430 UTC.

The formation of the rear-inflow jet was discussed in the introduction through the description of FIG. 1. (a)-(d). The interaction of the buoyant updraft, the

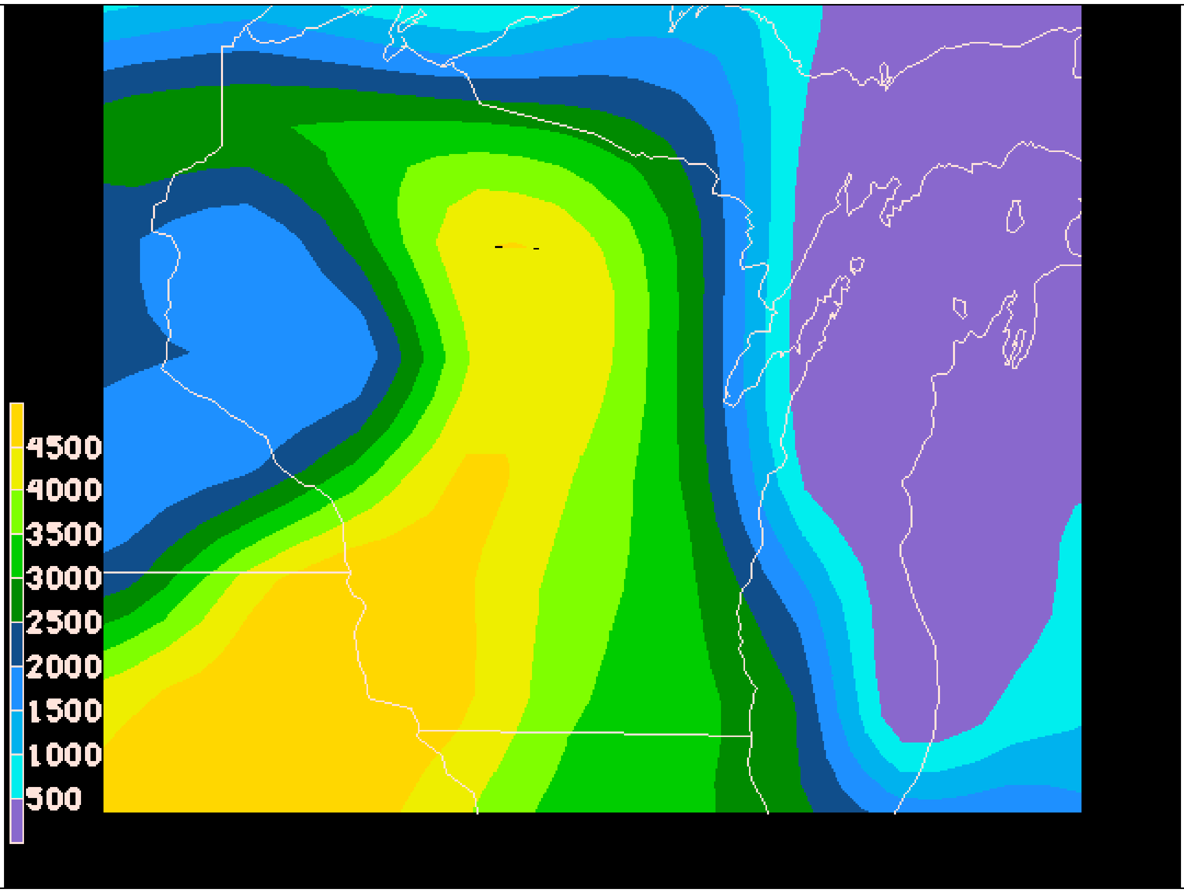

FIG. 7. CAPE (J/kg) plotted at 0000 UTC on June 12, 2001 , using GEMPAK and NAM model data.

environmental wind shear, and the cold pool circulation form the rear-inflow jet. According to Weisman (1993), the strong rear-inflow jets are correlated with high amounts of CAPE and high vertical wind shear. FIG. 7. shows the CAPE values over Wisconsin at 0000 UTC. The CAPE values range from 2500 J/kg to 4500 J/kg in southern and central Wisconsin, thus the CAPE values are fairly significant. FIG. 8. is a Skew-T Log-P Diagram at Oshkosh, WI, at 0000 UTC, created using GARP and RUC model data. The diagram also indicates high levels of CAPE if one traces a parcel trajectory from the surface. The wind barbs along the right edge of the diagram show a high wind shear environment. The winds veer from southeast at the surface to east-northeast at mid levels. The speed shear is also significant ranging from 5

FIG. 8. Skew-T Log-P Diagram at 0000 UTC in Oshkosh, WI created using GARP with the RUC model. Note the strong veering wind profile.

FIG. 9. (a) Milwaukee, WI Base Reflectivity June 11, 2001 at 0229 UTC. Violet and blue colors approaching the yellow and orange colors indicate a rear-inflow jet with a maximum velocity of 64 knots, or approximately 75 miles per hour. (b) Milwaukee, WI Radial Velocity June 11, 2001 at 0234 UTC. The leading edge of the storm is moving at approximately 52 miles per hour.

knots at the surface to 35 knots at approximately 600 hPa.

The rear-inflow jet can be seen in FIG. 9. (a) showing the Milwaukee, WI, radial velocity. The blue and violet colors approaching the yellow and orange colors indicate a jet of air flowing to the southeast at mid-levels. This is the rear-inflow jet, which is flowing at approximately 75 mph. Thus, the high CAPE and shear values are associated with a strong rear-inflow jet. The inflow-jet is approximately 50 km behind the storm, which is moving at 50 mph. The jet forces the storm to arch outwards in the direction of the mean wind creating the bow echo radar signature. FIG. 9. (b) shows the radar reflectivity of the storm at this time, showing the strong bow echo signature. Rear-inflow jets can be enhanced by stratocumulus precipitation falling into the jet. The jet is made up of cool, dry air, thus as the precipitation falls into the jet evaporative cooling enhances the negative buoyancy of the rear-inflow jet. Note the patch of stratocumulus precipitation located directly over the region of violet and blue colors on the radial velocity map. Perhaps this precipitation may be enhancing the rear-inflow jet. There were no other available images of radial velocity showing the rear-inflow jet. Many of the radial velocity images were patchy and had missing data sections, thus this theory could not be further analyzed.

The jet transports momentum to the front edge of the storm causing the bowing and increasing the convergence along the leading edge of the gust front. The top cell of FIG. 10. shows streamlines at 0000 UTC on June 12, 2001. There is a moderate line of convergence along the leading edge of the storm. The bottom cell of FIG. 10. shows the streamlines at 0300 UTC after the development of the rear-inflow jet. Note the enhanced convergence line ahead of the storm. This helps to intensify the storm circulation, thus the storm explodes.

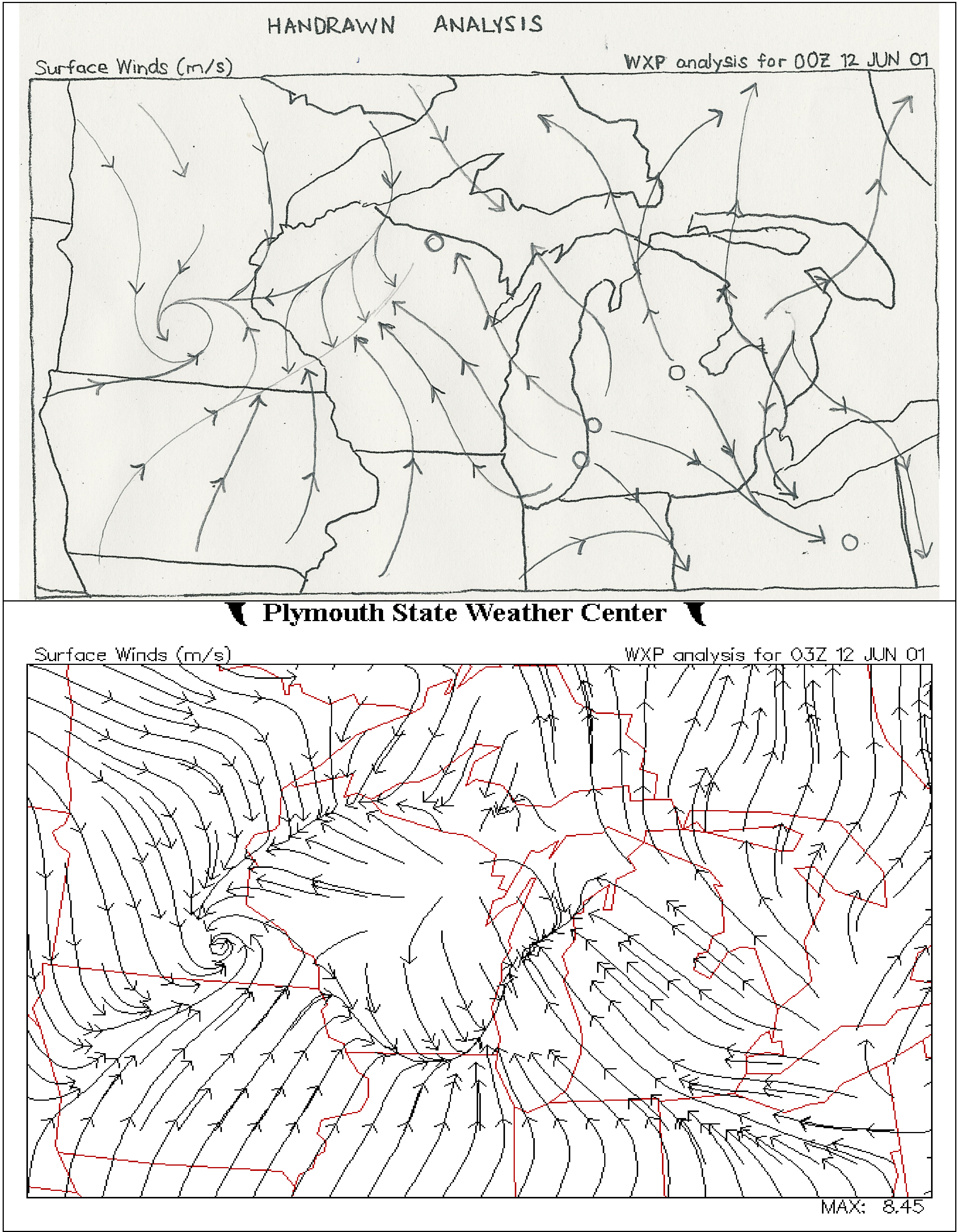

FIG. 10. The top image shows streamlines at 0000 UTC. The bottom image is streamlines at 0300 UTC.

5. CONCLUSION

The storms developed over central Minnesota north of a warm frontal structure associated with a Low pressure center spawning several tornadic supercells. The storms propagated to the southeast into northwestern Wisconsin. At 0000 UTC the storm outflow is absorbed by the Sawyer-Eliassen circulation of the 250 hPa jet located to the northeast of Wisconsin. The storm is thus capable of using all of its available energy to enhance the growth of the storm. At this time, the leading edge of the storm begins to organize into a more linear structure. In between 0000 UTC and 0300 UTC a strong rear-inflow jet develops creating the bowed radar signature as the jet transports momentum to the leading edge of the storm, and thus enhances the surface convergence along the gust front. This ultimately strengthens the storm circulation which in turn creates an intense derecho that roars across Wisconsin in the evening hours of June 11, 2001.

6. ACKNOWLEDGMENTS

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