The Wisconsin Derecho Event of 31 May 1998

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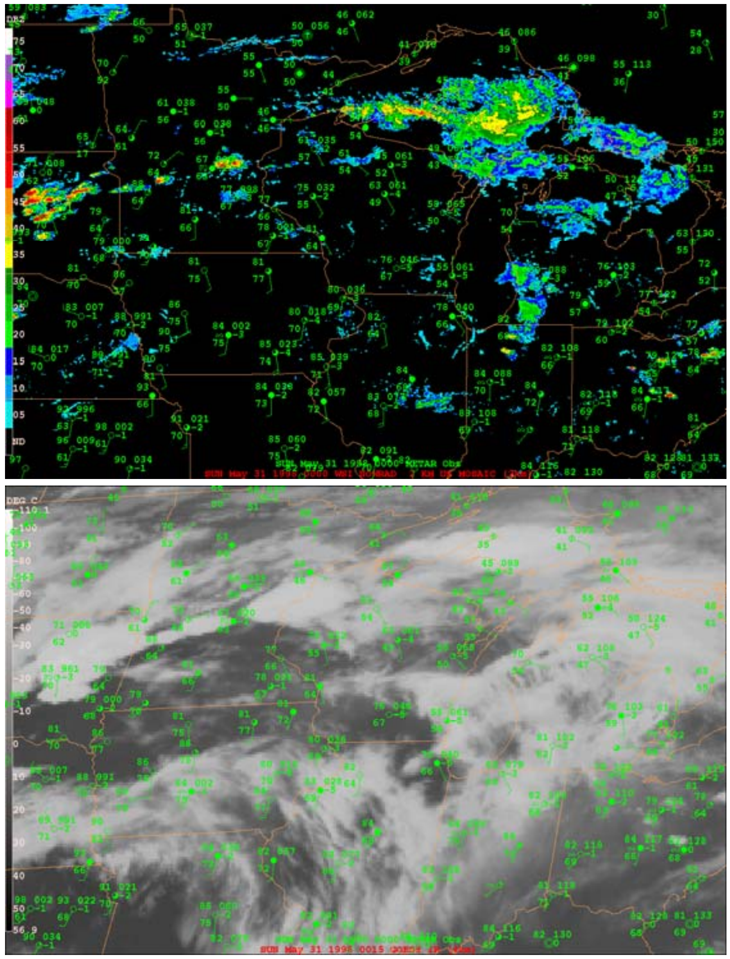
ABSTRACT

A derecho, a family of downburst clusters, passed through the upper Midwest on 30 and 31 May 1998. The squall line intensified as it moved through Wisconsin due to the synoptic and mesoscale conditions of the environment in the region. An extratropical cyclone at the surface propagated directly into the state to support the storm. Two upper jet streaks caused divergence aloft to enhance uplift within the severe thunderstorms. The vorticity field at 500 hPa was aligned to advect positive vorticity and its associated upward vertical motion into Wisconsin. Flows at various elevations brought moist air into the boundary layer and drier air into mid-levels, and past derecho analyses have concluded that these conditions are critical to the maintenance of such a windstorm. Finally, speed and directional wind shear in the vertical profile of the atmosphere supported the development of mesocyclones, some of which produced tornadoes on this day.

1. Introduction

On 31 May 1998, an intense line of severe thunderstorms roared through the state of Wisconsin at an average speed of 60 miles per hour (27 meters per second). Damaging winds and seven tornadoes were reported in Wisconsin between 0600Z and 0900Z (1:00 AM and 4:00 AM local time) that morning, with a peak wind gust of 128 mph (57 m/s) in Dodge county (NWS Milwaukee). The windstorm was one of the most damaging weather events in U.S. history, ranking only behind nine hurricanes (using data up to 2003; Ashley and Mote 2005).

Wisconsin experienced a derecho, which consists of a family of downburst clusters and is often marked by a bow echo signature in radar data. In general, there are two types of derechos: progressive and serial. According to the National Weather Service, a progressive derecho consists of a relatively short line of thunderstorms perpendicular to the mean flow and usually occurs along stationary fronts. Serial derechos are produced by multiple bow echoes within a squall line that extends over hundreds of miles. These windstorms are associated with intense low pressure systems. The derecho on 31 May appeared to be a mixture of these two types. It was similar to a progressive derecho because the squall line was almost perpendicular to the environmental flow. However, progressive derechos are usually smaller in length than observed in this event. The storm also had characteristics of a serial derecho, such as being forced by



(a)

(b)

Fig. 1. 0000Z on 31 May 1998 (a) Composite base radar reflectivity (dBZ) and surface observations, and (b) Infrared satellite imagery (brightness temperature) and surface observations.

an extratropical cyclone moving through the upper Midwest and having a longer squall line. Unlike typical serial derechos, it was not associated with a front or a strong shortwave trough at mid-levels. Overall, the derecho that moved through the region took place due to the surface low pressure system propagating into the area, the correct atmospheric conditions of moist low levels and dry mid-levels with conditional instability, and uplift enhanced by upper divergence and vorticity advection.

This paper examines the environmental conditions at the synoptic- and mesoscales before the derecho took place (0000Z on 31 May) and as the squall line was propagating through Wisconsin (0600Z).

2. Data

All model data was from the Eta model, utilizing the 0 and 6 hours of the 0000Z run on 31 May. The Department of Atmospheric Science at the University of Wyoming created the upper air sounding. WSI NOWrad provided the composite radar data. The National Weather Service office Milwaukee, Wisconsin, provided the single site radar data during the event. Four-kilometer resolution infrared (11

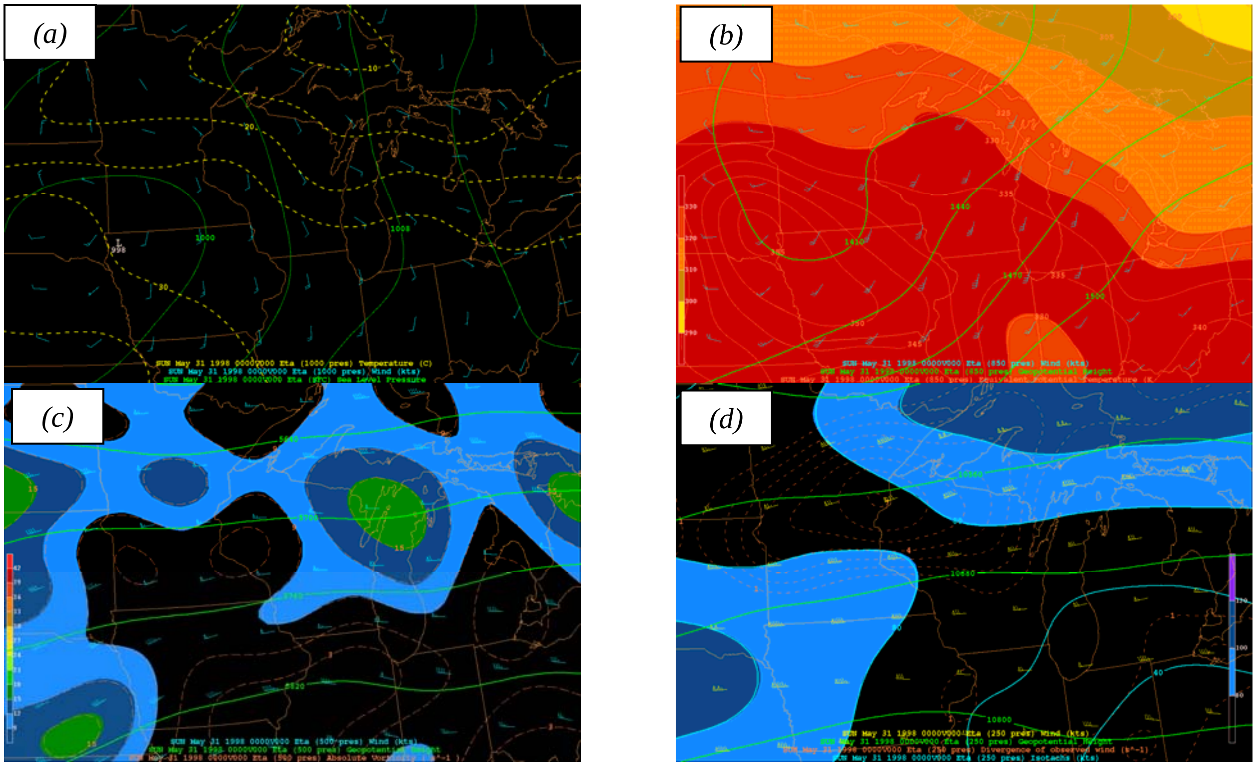


Fig. 2. 0000Z on 31 May, (a) Sea level pressure (hPa, green solid lines), wind (kts, blue barbs), and temperature (°C, yellow dashed line); (b) 850 hPa geopotential height (m, green lines), equivalent potential temperature (K, orange lines), and wind (kts, blue barbs); (c) 500 hPa geopotential height (m, solid green lines), absolute vorticity (s^{-1}, orange dashed lines), and wind (kts, blue barbs); and (d) 250 hPa geopotential height (m, solid green lines), wind (kts, isotachs in blue lines and yellow barbs), and divergence ($* 10^5 s^{-1}$, orange dashed lines).

µm), imagery came from the GOES East satellite. Surface observations were from the National Weather Service METAR stations across the United States. GEMPAK Analysis and Rendering Program (GARP) was used to visualize the data and produce most of the figures in this paper.

3. The Setup: 0000Z

a. Synoptic Overview

The derecho had not yet formed at 0000Z, but there was light, scattered precipitation over the state. The maximum reflectivity of the rainfall was only about 10 to 15 dBZ (Fig. 1a). Areas of clouds had also formed (Fig. 1b) due to a warm front associated with the surface low pressure system centered near southeastern Nebraska, with a minimum pressure of about 998 hPa (Fig. 2a). The circulation it induced caused light winds with varying directions, from east-northeasterly to south-southeasterly, in Wisconsin. Also affecting wind direction was the frontal boundary that was draped zonally across the middle of Wisconsin. However, the temperature gradient was rather weak in the area, so there was only slight warm air advection into the state.

At 850 hPa, the geopotential height minimum was in southwestern Ontario, quite removed from the surface cyclone center (Fig. 2b). This caused a south-southwesterly flow in Wisconsin. There were high values of equivalent potential temperature to the west and southwest of Wisconsin, indicating warm, moist air from southeastern South Dakota to west-central Missouri. The atmospheric flow was bringing this air mass into Wisconsin, thus increasing the moisture at low levels. According to past analyses (Evans and Doswell 2001; Coniglio et al. 2004), this condition is crucial to the intensification of squall lines. The high moisture content in the boundary layer has two main effects on the later development of the windstorm. First, air parcels become more positively buoyant as their temperature and moisture level rise. This enhances convective motions, including strong downdrafts. Second, the moisture advection lowers the level of free convection (LFC), so that less uplift is needed to initiate and maintain convection (Johns and Hirt 1987).

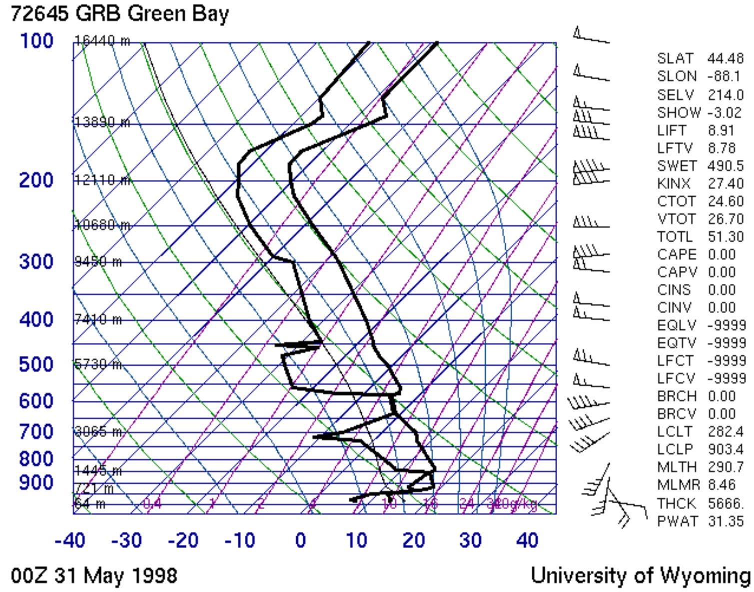


Fig. 3. Upper air sounding over Green Bay, Wisconsin, at 0000Z on 31 May.

The height field at 500 hPa was quite zonal and straight over the upper Midwest at this time (Fig. 2c). The height minimum was in central Ontario. Wisconsin was located in a broad trough with westerly flow, so there was little to no relative vorticity in the area. Furthermore, a drier air mass was being advected into the state from Minnesota at this level. Desiccated air at mid-levels is another critical component for the survival of a long-lived derecho (Evans and Doswell 2001; Coniglio et al. 2004). On the other hand, the lack of a high-amplitude trough or even a shortwave disturbance at this level placed more pressure on other features of the atmosphere to support the derecho.

Wisconsin was in a key position for upward vertical motion with respect to the jet streaks at 250 hPa (Fig. 2d). The state was located beneath the left exit region of one jet to the southwest and beneath the right entrance region of another jet streak to the northeast. Both of these jet quadrants are associated with rising motions because they are areas of mass divergence aloft. The highest values of divergence were centered in east-central Minnesota and northwestern Wisconsin. The upper divergence supported the formation of clouds and precipitation in these regions by boosting uplift (Figs. 1a and 1b).

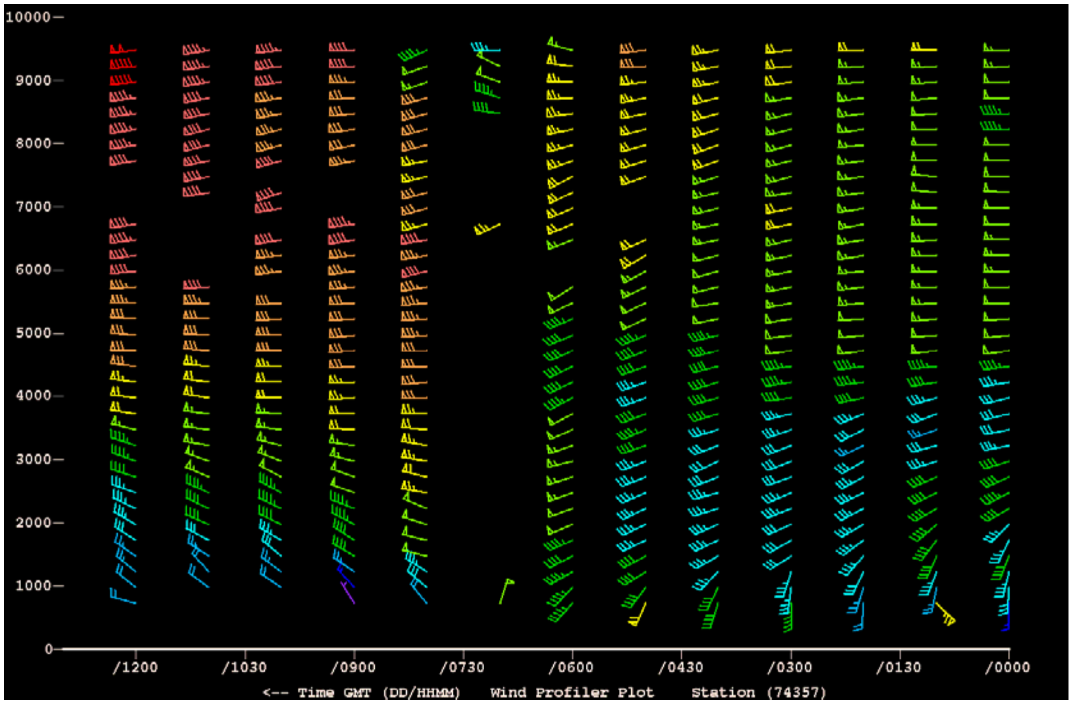
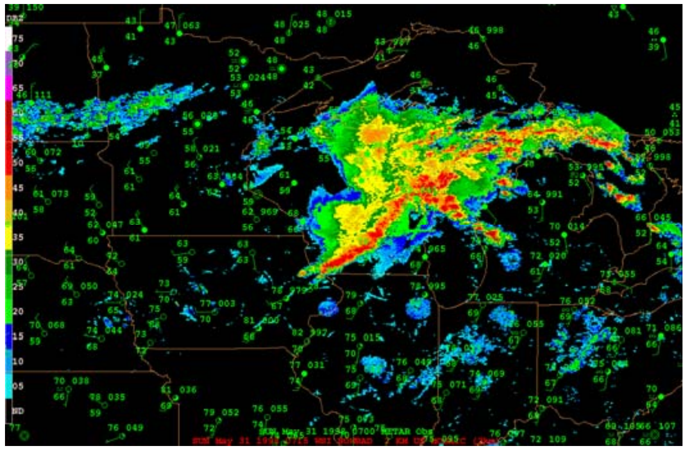


Fig. 4. Wind profiler plot (kts) for Blue River, Wisconsin, from 0000Z to 1200Z on 31 May.

b. Mesoscale Analysis

The upper air sounding over Green Bay, Wisconsin, provides a general idea of the vertical profile of the atmosphere over the state at 0000Z on 31 May (Fig. 3). The boundary layer (approximately from the ground to 850 hPa) was quite moist, as the relative humidity levels were about 80 to 90%. It is likely that this air mass was advected into the region by the 850 hPa flow from the south-southwest. It was previously observed that this area contained elevated equivalent potential temperatures. This moisture was trapped near the surface by an inversion at about 950 hPa. Another moist layer, probably due to clouds in the area, occurred between 637 and 578 hPa. Above this level, the air became markedly more arid – the relative humidity dropped to about 20%. The moist air at low levels and dry air at mid-levels increased the probability of the maturation of an intense squall line once it moved into the region (Coniglio et al. 2004).

Some of the calculated stability indices on the sounding supported the chances of a severe weather outbreak, such as the K, Total Totals, SWEAT, and Showalter indices (Fig. 3). All of these values indicated that severe thunderstorms, along with a few tornadoes, were possible. Additionally, the lifted condensation level (LCL) was rather low at 903.4 hPa, which facilitated the development of clouds with little uplift needed. Conversely, the convective available potential energy (CAPE) was 0 J/kg, the lifted index (LIFT) was 8.91°C, and the Bulk Richardson Number (BRCH) was zero. These values pointed toward the unlikelihood of severe weather phenomena. However, some negative buoyancy is important to the development of strong downbursts in derechos (Evans and Doswell 2001). Once an air parcel overshoots its equilibrium level due to its momentum



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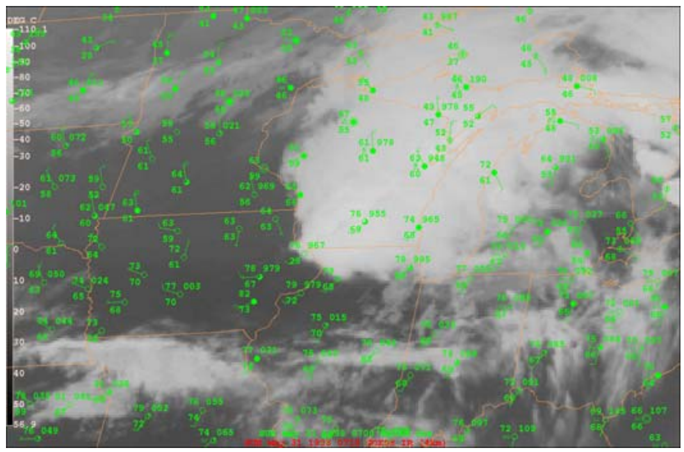

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Fig. 5. About 0700Z on 31 May, (a) Composite base radar reflectivity (dBZ) and surface observations; and (b) Infrared satellite imagery (brightness temperature) and surface observations.

and becomes negatively buoyant, the atmosphere strongly forces it downward. This process produces the downdrafts and outflow necessary for a derecho and for the evolution of its associated bow echo in radar data.

Focusing on wind shear, there was veering with height at low levels at Green Bay (Fig. 3) and at Blue River, which is located in southwestern Wisconsin (Fig. 4). In the mid- to upper levels, there was insignificant directional variation in the wind. At Green Bay, the wind speed increased by 28 knots (14 m/s) from the surface to 700 hPa (about 0 to 3 km) and by 54 knots (28 m/s) from the surface to 500 hPa (roughly 0 to 6 km). The lack of strong shear was reflected in the Bulk Richardson Number of zero, and Coniglio et al. (2004) found that convective systems that produce derechos thrive in environments with deep layer shear. Thus, the atmosphere was not completely conducive to the development of the windstorm in this respect yet.

4. The Derecho: 0600-0700Z

a. Synoptic Overview

By 0700Z, the derecho had formed and stretched from about Cedar Rapids, Iowa, northeastward to Marinette, Wisconsin. (0700Z is used for imagery because there was no satellite data available at 0600Z.) The convective

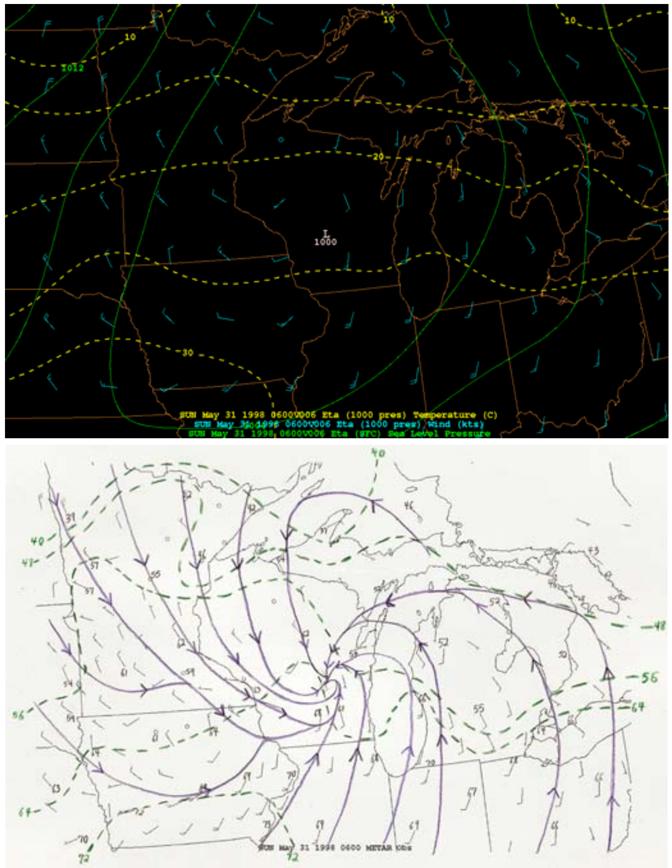

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Fig. 6. 0600Z on 31 May, (a) Same variables shown as Fig. 2a; (b) Surface streamline analysis (solid purple lines) with dewpoint temperatures (°F; green dashed lines).

windstorm was now producing heavy precipitation (Fig. 5a) and cumulus towers (Fig. 5b). During the past several hours, the surface low pressure minimum shifted northeastward into southern Wisconsin (Fig. 6a). The observed sea level pressure in Madison was 995.7 hPa. The fronts associated with the cyclone were not located in the state, thus they did not play a role in the initiation and maintenance of the windstorm. Uplift that would have been caused by a thermal boundary was provided by other mechanisms in this case. Since the low pressure center was in southern Wisconsin, wind directions varied across the state. As a result, there was no significant temperature advection into the area at this level. However, a north-south horizontal temperature gradient could be observed. Madison, Wisconsin, had a temperature of 76°F (24°C), and Ironwood, Michigan, was only 57°F (14°C) (Fig. 5). This gradient was at an angle of about 45° to the squall line. In addition, there was moisture convergence at the surface to support the cloud and precipitation formation (Fig. 6b).

At 0600Z, the geopotential height minimum at 850 hPa was in Ontario, still removed from the surface cyclone center (Fig. 7a). This caused the wind to flow east-northeastward across Wisconsin, which may have caused weak warm air advection from the southwest. The ridge in equivalent potential temperature, with a maximum of about 340 K in far southern Wisconsin, could be a result of such

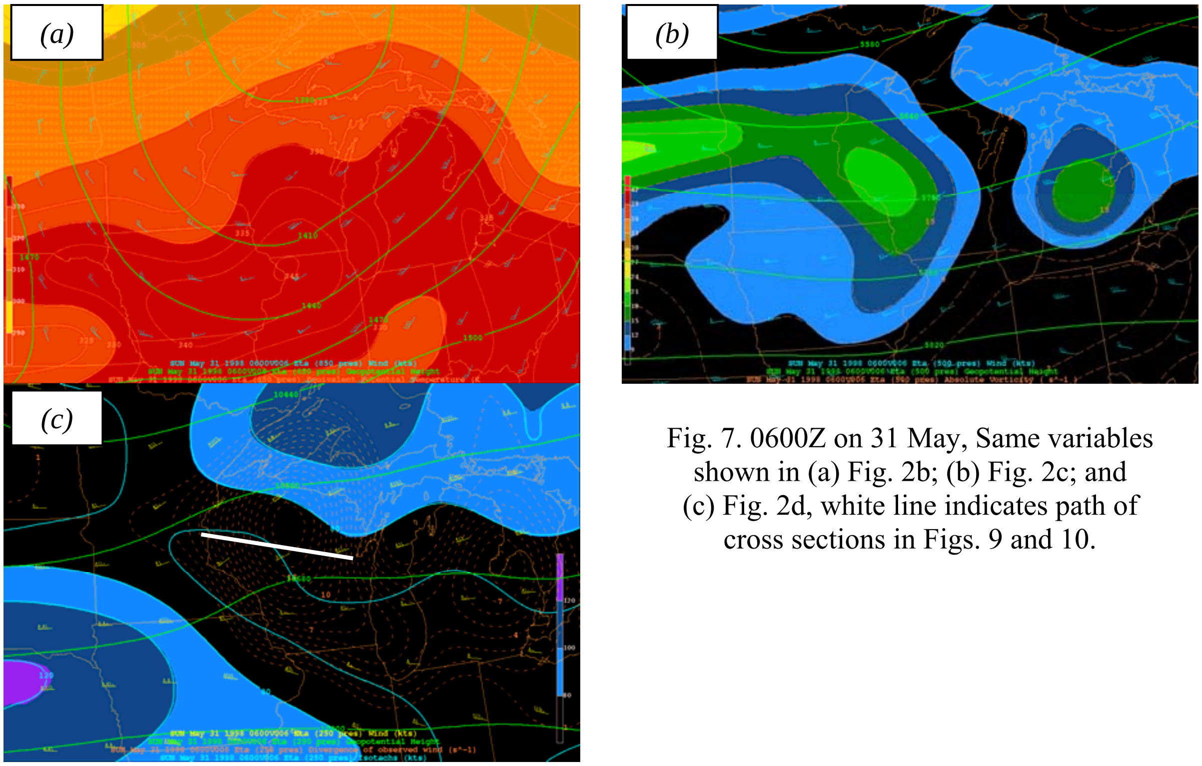

Fig. 7. 0600Z on 31 May, Same variables shown in (a) Fig. 2b; (b) Fig. 2c; and (c) Fig. 2d, white line indicates path of cross sections in Figs. 9 and 10.

advection. This pattern emphasized the warmth and moisture present in the lower levels of the atmosphere to help maintain the squall line as it moved across the area.

Although there was a bit more curvature in the 500-hPa height field at 0600Z, the flow remained fairly zonal in the Great Lakes region (Fig. 7b). Wisconsin was located downstream of a broad trough axis, and winds were from the west-southwest at this level. The increased curvature in the flow created a vorticity maximum in west-central Wisconsin, causing positive vorticity advection into eastern Wisconsin. This pattern enhanced uplift in the area to support the convective storms as they rushed through the state.

Wisconsin was in a broad geopotential height trough at 250 hPa, causing a westerly flow (Fig. 7c). The positions of the jet streaks at this level continued to support upward vertical motion to aid convection over the state. Wisconsin, especially its northern half, was still located beneath both the left exit region of one jet streak and in the right entrance region of another. This pattern, along with slightly diffluent flow, initiated strong upper divergence in the area, peaking at about 16 * 10^{-5} s^{-1} in north-central Wisconsin. This divergent flow induced rising motions to lift air parcels above the lifting condensation level for cloud development, as can be seen in the infrared satellite imagery at 0715Z (Fig. 5b). The uplift also maintained and even strengthened the derecho as it passed through the area. In addition, the outflow aloft from the squall line may have fed energy into the jet streak to the northeast of Wisconsin. The jet streak could have stored this energy for later convection, which did take place later in the day over areas to the east of the state.

The positions of the jets were not the only influence on the squall line in the

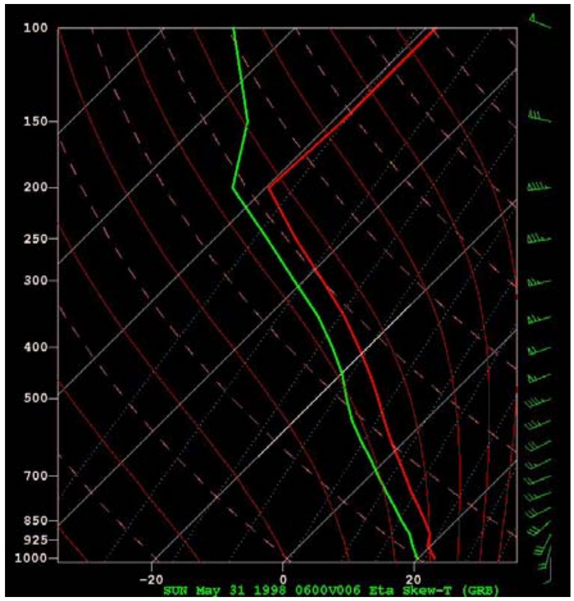

Fig. 8. Forecasted vertical profile over Green Bay, Wisconsin, at 0600Z on 31 May.

upper Midwest at 250 hPa (Fig. 7c). There was also a small shortwave disturbance in the height field, which can be seen as a slight ridge in the isohypses. Such a perturbation probably induced upward vertical motion downstream, once again enhancing uplift in Wisconsin.

b. Mesoscale Analysis

Unfortunately, there was no upper air sounding at 0600Z in Green Bay. Thus, the 6-hour Eta forecast for the vertical atmospheric profile is used instead (Fig. 8). The atmosphere was conditionally unstable and quite moist over much of its depth, most likely because of the storms over the city at this time (Fig. 5a). These characteristics are both signatures of deep convection, especially the nearly pseudoadiabtic temperature profile within the troposphere.

The wind direction veered with height in the forecasted profile at Green Bay and in the observed profile at Blue River (Fig. 4). Such a wind shift supported rotation in the squall line's updraft for the formation of mesocyclones. However, the veering was stronger in both locations at 0000Z than at this time (Figs. 3 and 4). Another important feature of the wind profile for Blue River was the layer of elevated wind speeds from about 2000 to 4000 meters above the surface. These strong mid-tropospheric flows fed into the rear-inflow jet of the derecho to enhance its downdrafts (Johns and Hirt 1987).

Another interesting pattern emerges in the cross section of isotachs between Minneapolis, Minnesota (MPX), and Green Bay (GRB) at 0600Z on 31 May (Fig. 9) Green Bay reached a higher wind speed at a lower level than Minneapolis did. Therefore, there was a larger vertical gradient in horizontal wind speed over Green Bay, an area that the squall line had just reached at 0600Z. Between 750 hPa and 200 hPa, Minneapolis's wind speed increased from 30 to 65 knots (15 to 33 m/s), while it increased from 25 to 80 knots (13 to 41 m/s) over Green Bay. This

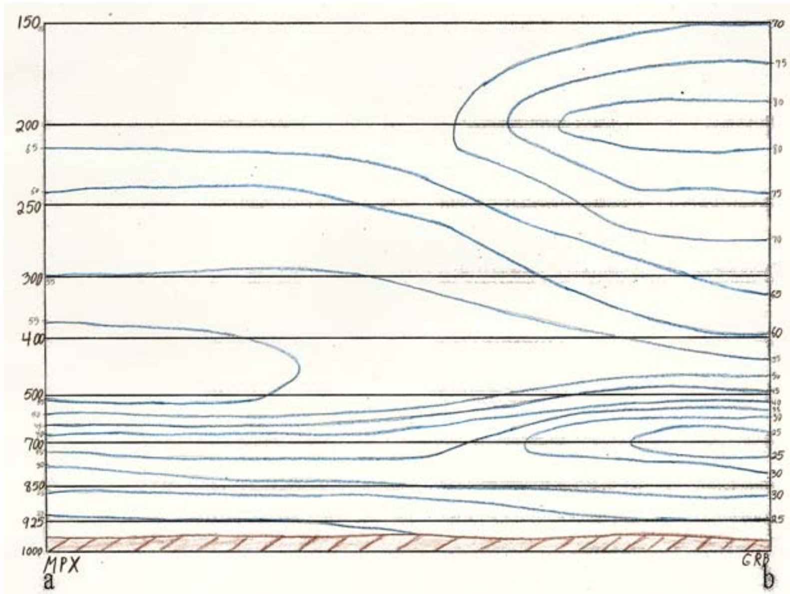

Fig. 9. Hand drawn cross section of isotachs (kts) between Minneapolis, Minnesota (MPX/a), and Green Bay, Wisconsin (GRB/b) at 0600Z on 31 May.

wind shear enhanced the strength of the its structure. The tilt helped to separate the storm's updraft and downdraft regions. The slantwise ascent over the cold pool near the surface on the back edge of the storm caused a large area of stratiform precipitation behind the primary squall line (Fig. 5a).

The cross section of relative humidity, pressure vertical velocity, and circulation between Minneapolis and Green Bay (Fig. 10) matched up quite well with the conceptual model of a derecho (Fig. 11). First, an area of elevated relative humidity reached from the surface to about 280 hPa, using the 70% contour. This indicated the building cumulus tower and its resultant precipitation. Such clouds were observed in the infrared satellite imagery at 0715Z (Fig. 5b).

Second, the relative humidity maximum had a mushroom shape, which highlighted the rear-inflow jet at mid-levels (Fig. 10). The entrainment of drier, cooler air by the jet aided in the creation of strong downdrafts to form a cold pool near the ground in the system. The relatively cool air mass formed a mesohigh, whose circulation created a bulge in the squall line (the bow echo in Fig. 5a). The precipitation within the squall line also strengthened the downdrafts, allowing them to reach severe wind levels (greater than 57 mph or 25 m/s, as defined by the National Weather Service) on this day. As rain fell from the clouds, evaporation of raindrops cooled the air and made it denser, which accelerated the downbursts. Furthermore, the downward movement of cold air added energy to the system. The wind shear also created a vortex of horizontal vorticity, which could be pushed into a vertical position by the updrafts within the squall line to create mesocyclones.

Third, the cross section showed the downdrafts behind the squall line, although the downward motion was only $4 * 10^{-3}$ hPa/s in the forecast (Fig. 10). It may be difficult for the Eta model to resolve small-scale motions

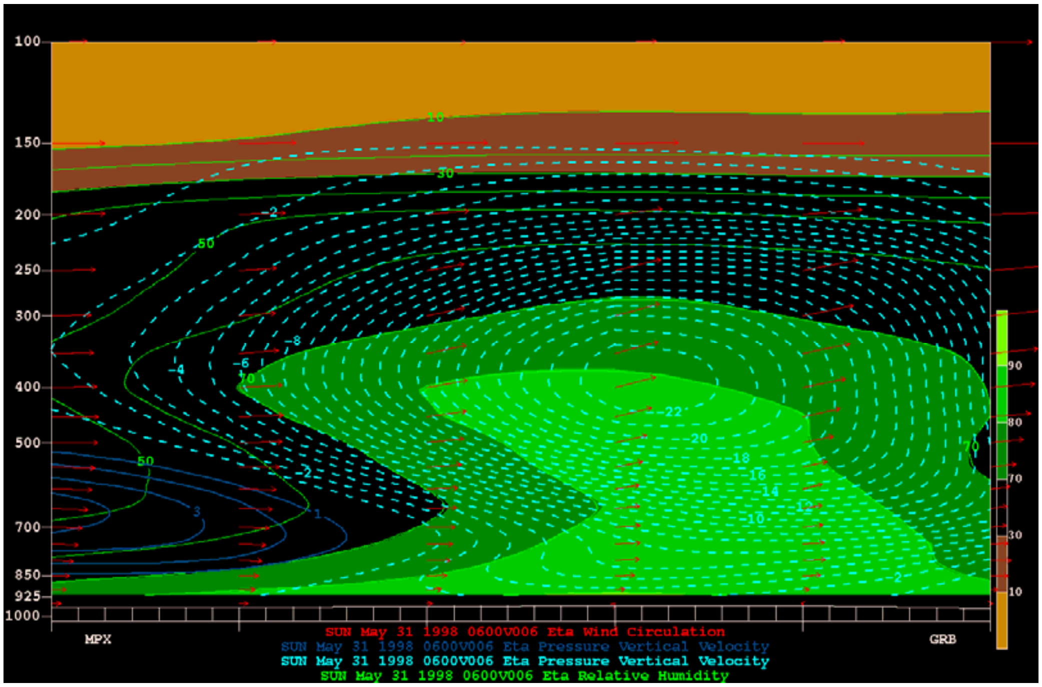

Fig. 10. Cross section of relative humidity (%, green solid lines), pressure vertical velocity (* 10^3 hPa/s, blue dashed and solid lines), and wind circulation (red arrows) between Minneapolis (MPX) and Green Bay (GRB) at 0600Z on 31 May.

like downbursts. However, these downdrafts and their resultant outflows ahead of the derecho could be seen in the storm relative velocity data at Green Bay at 0714Z (Fig. 12). There was a sharp gradient in the direction of the flow along the leading edge of the squall line, especially in northwestern Dodge county. As previously mentioned, the peak wind speed of the entire derecho event took place in this area. In this area, the storm-relative velocity changes from +22 knots (+11 m/s) to -50 knots (-26 m/s). This strong flow, along with the rear-inflow jet, forced the precipitation band to take on its classic bow echo shape (Fig. 5a).

Fourth, there was strong upward vertical motion within the convective plume, up to about 22 * 10^{-3} hPa/s in the cross section (Fig. 10). The uplift indicated intense convection along the squall line, which was also evident as enhanced reflectivity values in the radar data (Fig. 5a). Not only was the main squall line evident in that image, but there was also convection along the southwestern tip of the line's outflow boundary. The new convective development could also be interpreted as the new cell in front of the squall line in the conceptual model of the derecho (Fig. 11).

5. Conclusion

The derecho event in Wisconsin was a hybrid between the usual progressive and serial derechos. Synoptically, it was mainly forced by a surface low pressure system that propagated into the state on 31 May. The uplift needed for severe thunderstorms was provided by divergence aloft induced by jet streaks at 250 hPa, as well as by a subtle shortwave disturbance at that level.

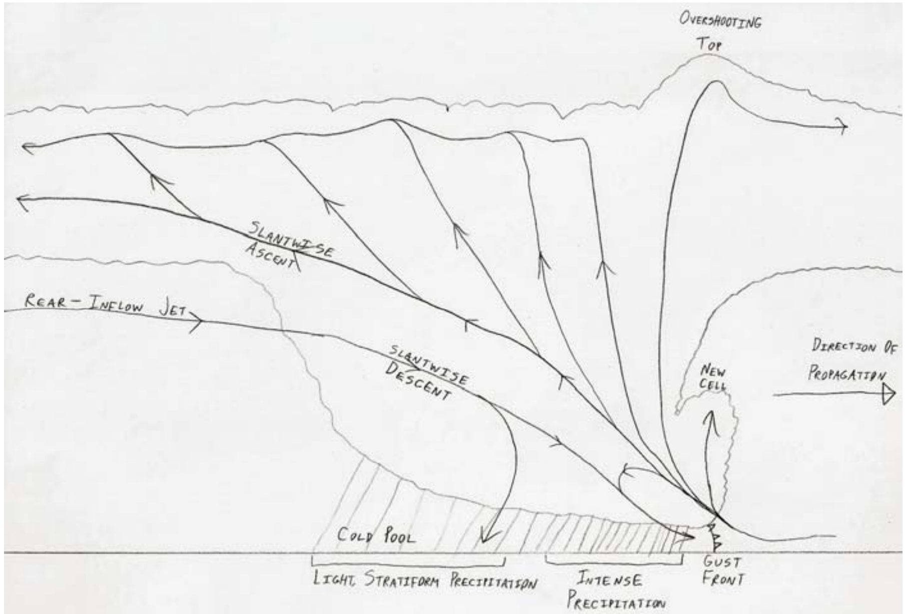

Fig. 11. Hand drawn conceptual model of a serial derecho (After Tripoli 2007).

Upward vertical motions were also enhanced by positive vorticity advection into eastern Wisconsin at 0600Z. Turning to mesoscale features, the combination of moist low levels and dry middle levels aided the development and intensification of the squall line as it moved through the region. Lastly, the mesocyclones that produced tornadoes reported this day were likely initiated by vertical wind shear within the atmosphere. Studying the dynamics of this storm may help meteorologists and the public to be better prepared for similar derecho events in the future. Much research on the crucial ingredients that come together in these convective windstorms may be done to create better forecasts and overall understanding of the atmosphere.

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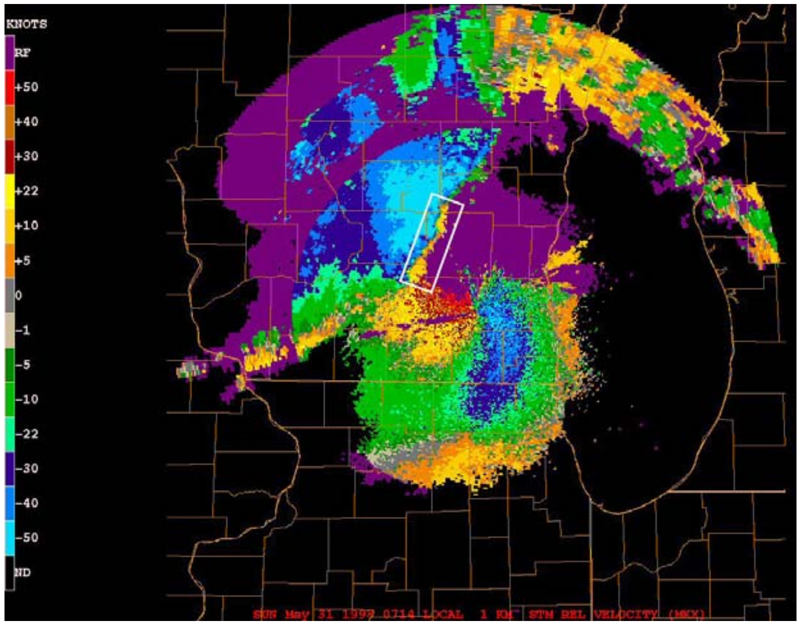

Fig. 12. Storm relative velocity (kts) from the radar site at Milwaukee/Sullivan, Wisconsin, at 0714Z on 31 May. White box indicates the sharp wind directional gradient in western Dodge county.

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