Barron County, Wisconsin, Multiple Tornadoes and Hailstorms of 11 September 1990

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ABSTRACT

Four tornadoes, of F1–F2 intensity, occurred over Barron County, Wisconsin, on the evening of 11 September 1990. The tornadoes were associated with a slow-moving thunderstorm cluster that developed along a warm front, and all occurred within 17 km of Rice Lake over a 2-hour and 15-minute period. National Weather Service radar data indicate that the tornadoes probably were associated with mesocyclones. Hail up to 7 cm in diameter and damaging winds also were reported over Barron County and three adjoining counties. Forecasting of slow-moving thunderstorms within an environment capable of producing mesocyclones and tornadoes remains an important forecast problem. Analysis of features that produced quasi-stationary thunderstorms *and* a vertical wind profile sufficient to generate mesocyclones hopefully will improve recognition and forecasting of similar events in the future.

1. Introduction

Tornadic thunderstorms that persist or regenerate over the same area pose a repeated threat to life and property, as well as a difficult forecast problem. On 11 September 1990, four tornadoes occurred over Barron County, Wisconsin, in a 2-hour and 15-minute period (Fig. 1), without appreciable net movement of the regenerating parent mesocyclones. Prediction of the place of development, direction and speed of movement, and character of the thunderstorms all proved particularly challenging to National Weather Service forecasters. The tornadic thunderstorms occurred within a *severe thunderstorm* watch issued over northern Wisconsin. In addition, since the associated thunderstorm cluster remained stationary, the severe weather episode was localized and only a small portion of the watch was affected.

Cases in which very slow moving or regenerative supercell storms produced tornadoes occasionally have been documented in the literature. Tornadoes over Pampa, Texas (Jensen et al. 1983), and Grand Island, Nebraska (Barlow 1983), were associated with strong low-level cyclonic vorticity and supercell thunderstorms that persisted for at least two hours. Fujita (1970) documented two tornadoes over Lubbock, Texas, on 11 May 1970. The Palo Duro Canyon Storm (Belville et al. 1979) produced several tornadoes and particularly devastating flash floods as the parent supercells slowed significantly and turned to the right of the mean wind. Similar events, however, have rarely been documented outside of the western and central plains (from Nebraska to Texas, between the Rocky Mountains and 97° longitude).

Moller (1979) found that multiple occurrences of tornadoes (outbreaks) happened in two well-organized patterns—elongated "corridors" and circular "clusters." The Barron County storms on 11 September 1990 fall into the "clusters" category. An examination of activity charts from the National Severe Storms Forecast Center (NSSFC) and *Storm Data* for 1990 and 1991 indicates that cluster events, as in Moller (1979), were uncommon outside of the western plains. Cases were collected in which three or more tornadoes were clustered over less than 3000 km^2 and the event duration exceeded one hour. At least one of the tornadoes was required to be of F1 intensity or greater. During the two-year period, 24 cases met the criteria. All but four occurred in April, May, and June. Seventy-five percent were in Nebraska, Kansas, Oklahoma, north and west Texas, east Colorado, and southeast Wyoming, and only four (including this case) were east of the Mississippi River. Moller (1979) found that over the southern Plains similarly defined clusters usually occurred west of approximately 97° longitude, with a pronounced activity peak in June. Many of the cluster events examined in this study were embedded within much larger events, while the severe weather reports over and near Barron County were isolated over Wisconsin.

Physical differences between tornado cluster events east of the Mississippi River and those over the western and central plains are likely to be small. Rare occurrences east of the Mississippi, like the four tornadoes

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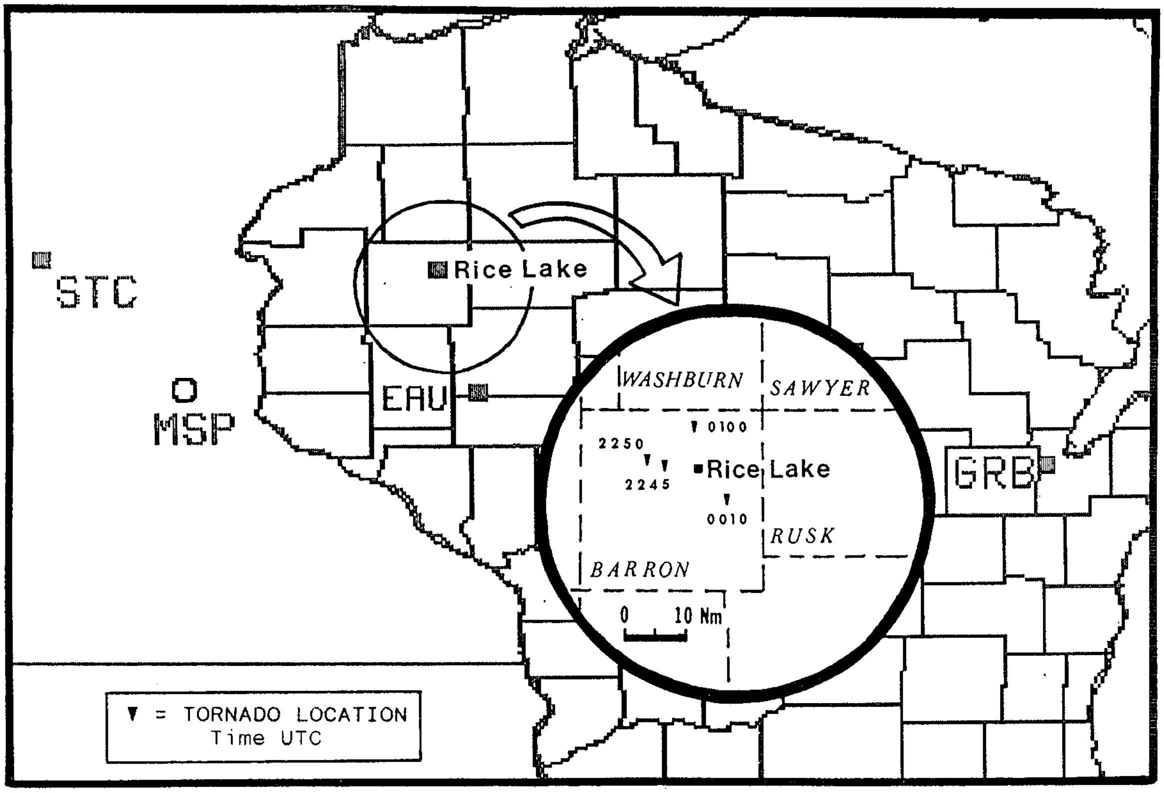

FIG. 1. Regional map. Area of severe weather occurrence is enclosed in bold circle insert. Tornado times are UTC. Upper-air stations: St. Cloud (STC) and Green Bay (GRB). Radar site: Minneapolis (MSP). Eau Claire, Wisconsin, is EAU.

on 11 September 1990, suggest that it is the necessary synoptic conditions that are uncommon. Forecasters need to make quick and accurate diagnoses of similar rare events, however, since the associated weather is often life threatening. The Barron County tornadoes provide an opportunity to study the environmental conditions associated with one such event.

The F2 and F1 tornadoes occurred within 30 km of each other over Barron County. Large hail, up to 7 cm (2.75 in.) in diameter, and damaging winds also occurred over a small area of four counties, including Barron County, between 2245 and 0230 UTC 11–12 September 1990. The city of Rice Lake sustained hail damage at 2258, 2345, and 0100 UTC, and $2 million in crop damage occurred in surrounding Barron County. From the time of initial development around 2215 UTC until 0130 UTC, severe thunderstorms persisted over the northeast half of Barron County. After 0100 UTC 12 September 1990, redevelopment occurred farther northwest, producing large hail over adjoining portions of Rusk, Washburn, and Sawyer counties in the ensuing two hours. At least 7.6 cm (3 in.) of rain fell in Rice Lake.

The storms on 11 September 1990 occurred within a synoptic environment and vertical shear profile conducive to severe weather and tornadoes (Weisman and Klemp 1982, 1984; Rotunno and Klemp 1982, 1985). Minneapolis (MSP) WSR-57 radar data suggest that deep, persistent mesocyclones were present (Doswell et al. 1990; Lemon and Doswell 1979). Soundings from St. Cloud, Minnesota (STC), and Green Bay, Wisconsin (GRB), at 0000 UTC 12 September 1990 are used to present characteristics of the vertical wind profile over Barron County. Storm-relative inflow and helicity are computed using actual storm motion from the Minneapolis radar data. Convective available potential energy (CAPE) in the thunderstorm genesis region and the degree of low-level negative buoyancy are examined.

On 11 September 1990, patterns of moisture convergence and low-level winds corresponded to other documented cases of slow-moving intense convection. The relationship of relevant parameters to the quasi-stationary Barron County thunderstorms are discussed.

2. Synoptic-scale features, destabilization, and initiation of convection

a. Quasigeostrophic contribution to vertical motion

A low-amplitude short-wave trough moved into Minnesota by 0000 UTC 12 September 1990 (Fig. 2),

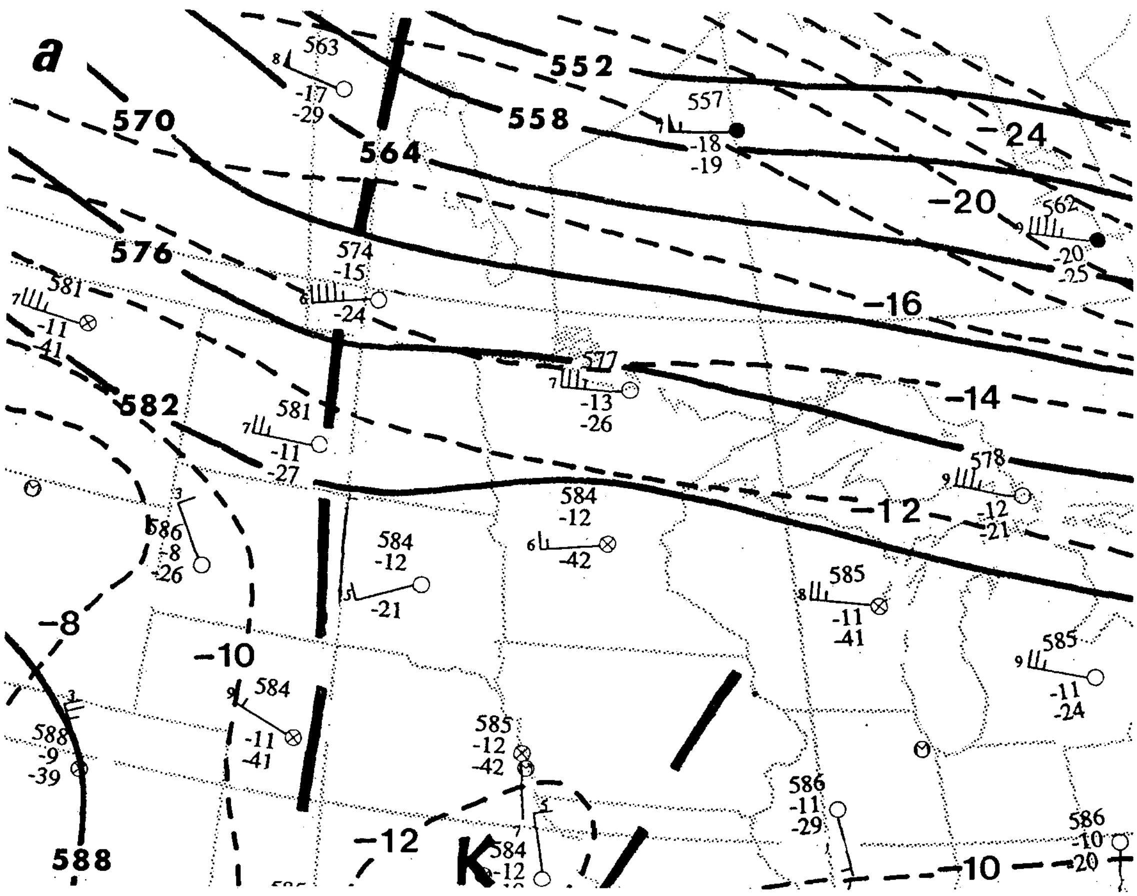

FIG. 2. The 500-mb analyses at (a) 1200 UTC 11 September 1990 and (b) 0000 UTC 12 September 1990. Solid lines are height (30-dam interval), and dashed lines are temperature (every 2°C). For the plot, heights are upper left in decameters, and temperature and dewpoint are left. Full wind barb is 5 m s^{-1}, half-wind barb is 2.5 m s^{-1}, and pendant is 25 m s^{-1}.

and the synoptic-scale environment evolved sufficiently to sustain severe thunderstorms over northwestern Wisconsin. Quasigeostrophic (QG) vertical motion was confined to low and midlevels.

Differential positive vorticity advection (PVA) and warm advection are contributors to QG vertical motion (Holton 1979 p. 136ff.). Differential PVA was weak, as indicated by objective analysis of vorticity advection at 0000 UTC 12 September 1990 (Fig. 3). Upward vertical motion resulting from differential PVA (less than 5 μb per second) was below the 700-mb level. Maxima of warm advection at low levels (Figs. 4 and 5) were closely correlated to the severe thunderstorm area on 11 September 1990. Isentropic analysis (Fig. 6) shows that the warm thermal advection was also occurring throughout a deep layer, roughly from 950 to 750 mb. Warm advection and upward vertical motion are represented by advection of pressure on isentropic surfaces (Moore 1986), although the QG omega equation referenced above is derived in pressure coordinates.

Implied low-level QG lift from warm advection and differential PVA helped initiate thunderstorms over Barron County. Maddox and Doswell (1982) discussed a similar role for warm advection during extended periods of intense convection, especially when midlevel vorticity patterns are weak, as in this study. Surface temperature gradients (Fig. 7a) and the maximum of surface warm advection (Fig. 5) indicate that the strongest warm advection lift was in the vicinity of Barron County at 2100 UTC 11 September 1990, when convection first developed. Davies-Jones (1983) also stressed that low-level warm advection increases wind veering in the boundary layer, which, when combined with destabilization, forms an environment favorable for development of severe convection. Persistent low-level warm advection, as in this case, can produce considerable modification of the vertical wind and temperature profile. Surface data, however, did not reflect this over northwestern Wisconsin on 11 September 1990.

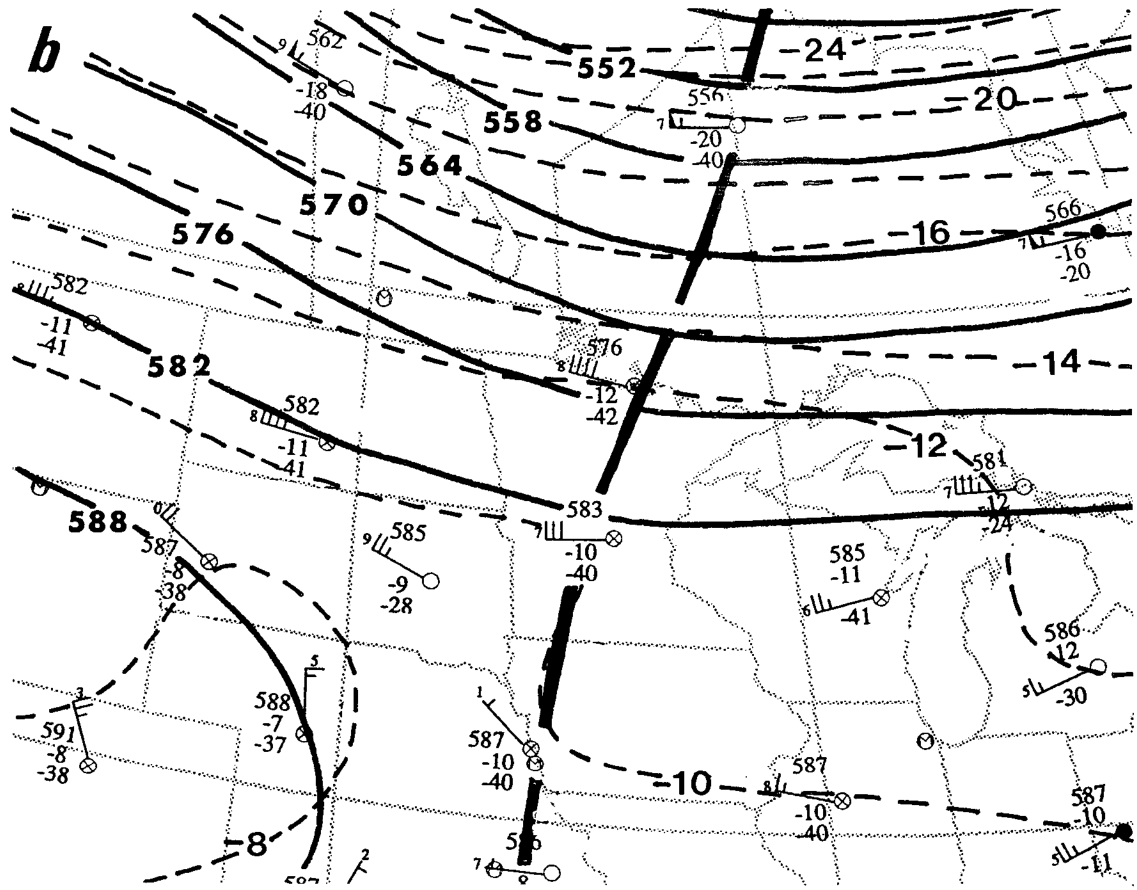

FIG. 2. (*Continued*)

b. Surface patterns, θ_e advection, and results of destabilization

During the morning and early afternoon, solar heating and northeastward transport of warm, moist air resulted in rapid evolution of the thermodynamic characteristics of the boundary layer within the warm sector. The surface warm front then moved only slightly northeastward between 2100 UTC 11 September 1990 (Fig. 7a) and 0000 UTC 12 September 1990 (Fig. 7b) and became the focus of repeated thunderstorm development during the afternoon and evening hours.

To the northwest, southerly flow increased ahead of a surface low (Fig. 7a), and a line of thunderstorms formed rapidly over northwest Minnesota after 2200 UTC 11 September 1990. The evolution is best seen in satellite imagery (Fig. 8). As the line moved east, hail 3 cm in diameter was reported. This line remained separate from the tornadic thunderstorms over Barron County, Wisconsin.

Differential advection of temperature and moisture has long been associated with destabilization and severe weather (Miller 1955; McNulty 1980). South-southwesterly low-level flow resulted in strong positive θ_e advection (Fig. 9) along and northeast of the warm front on 11 September 1990. Above 700 mb, θ_e advection was weak at 1200 and 0000 UTC (not shown). Johns and Sammler (1989) also found that destabilization prior to many tornado outbreaks was the result of increases in low-level temperature and moisture rather than from cooling aloft.

The STC and GRB soundings (Fig. 10) show the effects of destabilization during the day. At STC, moderately unstable conditions were already in place on the morning preceding severe weather occurrence (Fig. 10a), and the temperature and dewpoint profile changed significantly below 3 km by 0000 UTC 12 September 1990. Little change occurred in the temperature and dewpoint traces above 4 km, resulting in very strong instability within the warm sector (as represented by the STC sounding). CAPE computed from the STC sounding was 3480 J kg^{-1}. Considering the west-southwesterly inflow, the STC conditions likely represented the subcloud air that became thunderstorm updrafts over Barron County. The occurrence of 7-

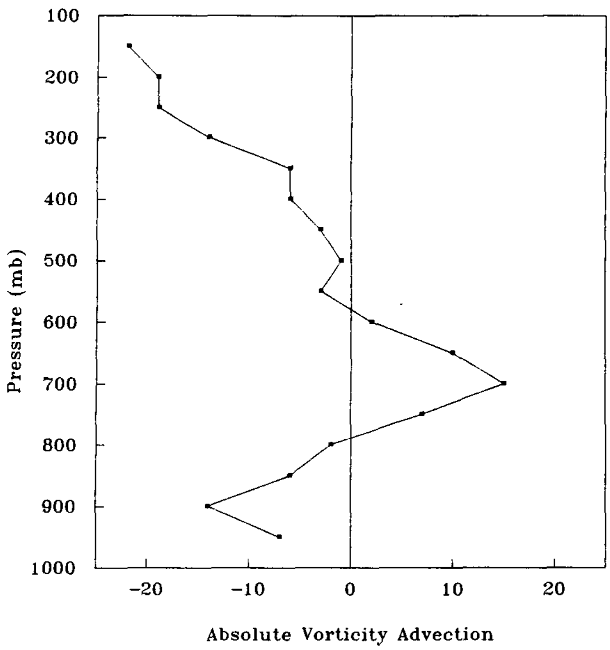

FIG. 3. Vertical profile of absolute vorticity advection (values $\times 10^{-10}$ s^{-2}) over Rice Lake, Wisconsin, at 0000 UTC 12 September 1990.

cm-diameter hail is indirect confirmation of the existence of strong buoyancy and intense updrafts.

The GRB sounding (taken well east of the warm front) is presented for comparison. Available potential buoyant energy associated with parcels in the lowest 2 km was much less than that in the warm sector.

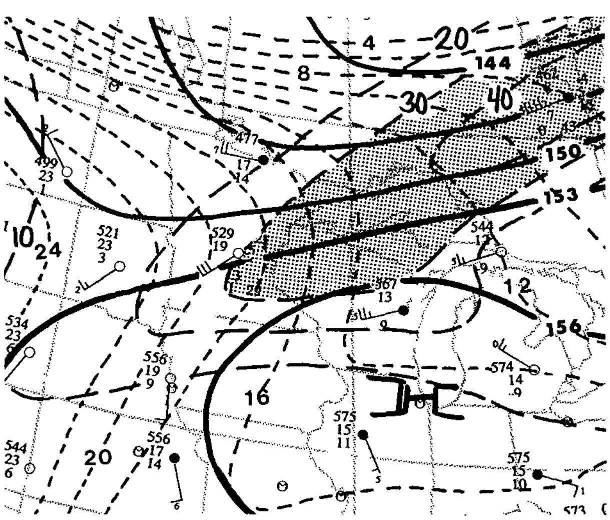

FIG. 4. The 850-mb analysis at 0000 UTC 12 September 1990. Solid lines are height (30-dam interval), and dashed lines are isotachs at 5 m s^{-1} interval (labeled in knots). For the plot, heights are upper left in decameters; temperature and dewpoint in Celsius are left (below heights).

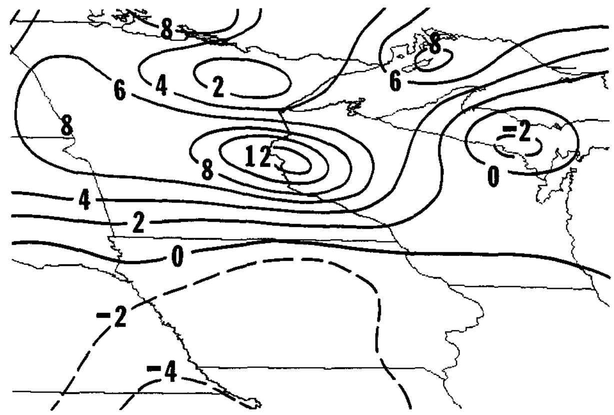

FIG. 5. Surface temperature advection at 2100 UTC 11 September 1990. Contour interval is 2°C h^{-1}.

The GRB sounding (Fig. 10d) also exhibited a weak inversion from 1 to 2 km at 0000 UTC 12 September 1990, while the STC sounding showed a layer of negative buoyancy but no inversion below 2 km. The 850-mb analysis (Fig. 4) indicated that temperatures over Barron County were 2°–3°C warmer than at GRB, and 2°–3°C cooler than at STC. A comparison was made between surface lifted parcel temperatures (from the warm sector) and environmental temperatures around 850 mb over Barron County. Differences were small, so it appears no appreciable cap or layer of negative buoyancy existed where the thunderstorms developed. West of the front, where the 1–2-km-layer temperatures were higher, observed surface temperatures remained at least 2°C below the convective temperature, and convection was inhibited by the shallow layer of negative buoyancy. Lifting mechanisms were

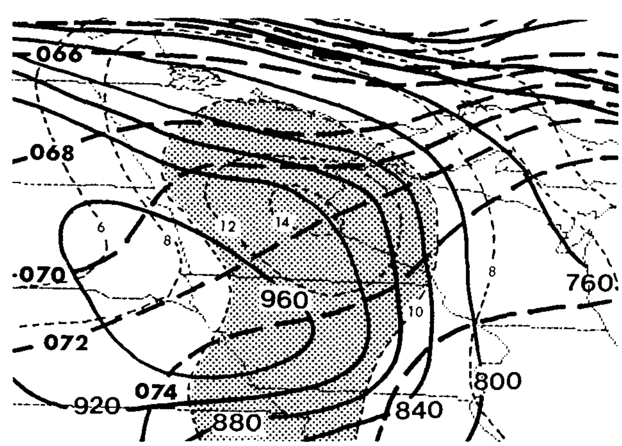

FIG. 6. Isentropic analysis ($\theta = 305$ K) at 0000 UTC 12 September 1990. Heavy dashed lines are Montgomery streamfunction in intervals of 2×10^4 m^2 s^{-2}; solid lines are pressure at intervals of 40 mb; and light dashed lines are mixing ratio at intervals of 2 g kg^{-1}—stippled if greater than 10 g kg^{-1}.

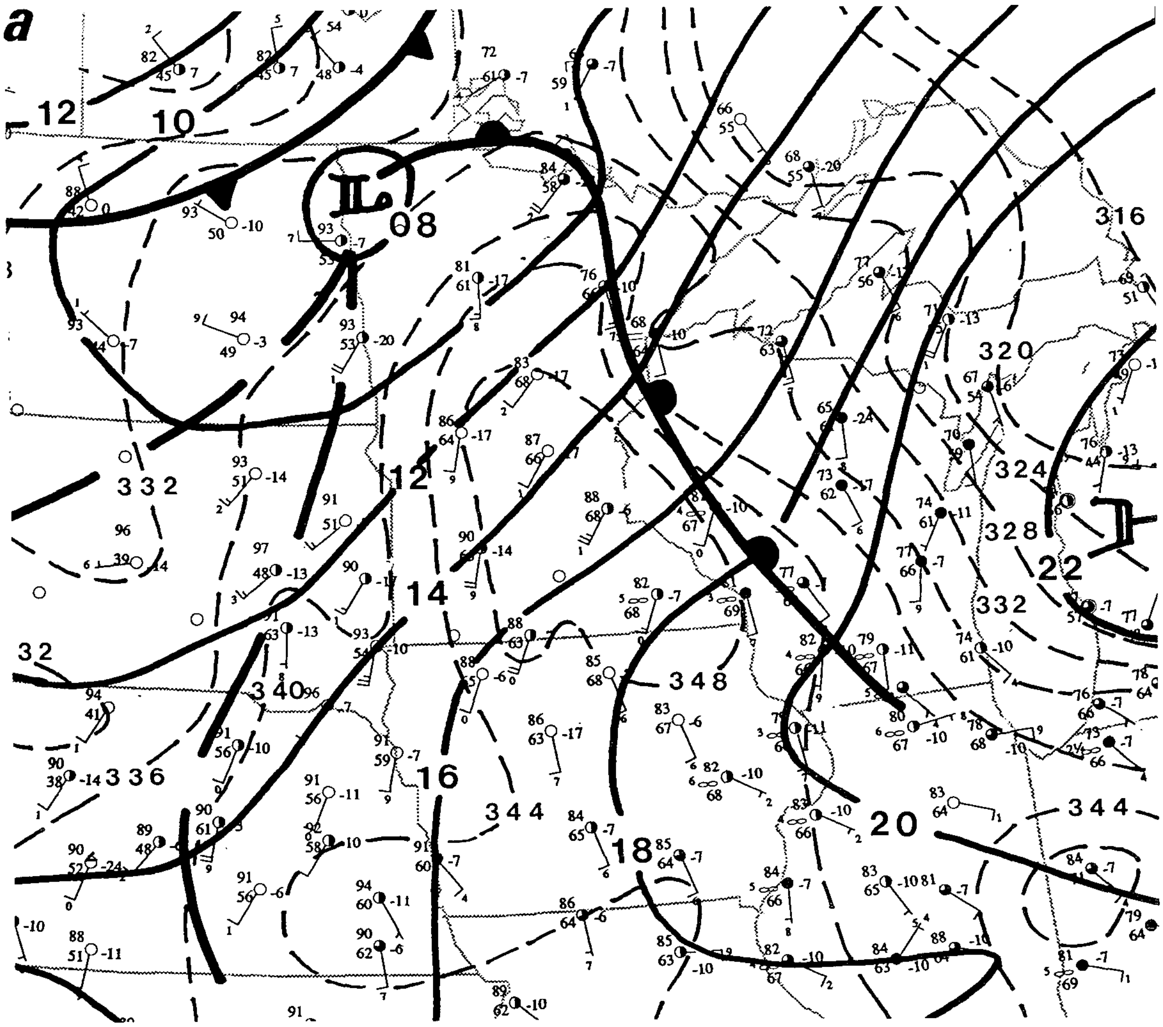

FIG. 7. Regional surface maps at (a) 2100 UTC 11 September 1990 and (b) 0000 UTC 12 September. Standard operational station model plots with pressure omitted—temperature in degrees Fahrenheit. Mean sea level isobars (solid) every 2 mb and θ_e (dashed) every 2 K. Conventional frontal notation is used; surface troughs are indicated by bold dashed lines.

too weak to overcome the low-level negative buoyancy, and skies remained cloud free through most of the warm sector, despite large CAPE. East of the warm front, where surface parcels were cooler, the weak capping inversion prevented convection.

c. Axes of maximum wind and moisture at 850 mb

At 850 mb, increasing winds within the warm advection zone coincided with a tongue of increasing moisture by 0000 UTC 12 September 1990. The low-level wind and instability axes (Figs. 4 and 11) were aligned to maintain an 18 m s^{-1} (35 kt) inflow of very unstable air to the right rear flank of the Barron County storms. Radar data (Fig. 12) show that new cell development was located west-southwest of the Barron County thunderstorm cluster and weak echo regions (reflecting intense updrafts) were in the southwest quadrant of the supercell storms. Coldest tops in the satellite imagery (Fig. 8) were always in the west or northwest quadrant of the Barron County thunderstorm cluster—another indicator that the best inflow was on the back side of the system. Maddox et al. (1979), Chappell (1985), and Merritt and Fritsch (1984) found similar synoptic-scale configurations during extended periods of slow-moving, intense convection.

It is interesting to note, in considering how propagation contributes to storm movement, that the low-level supply of CAPE was at the right *front* flank of thunderstorms that developed over northern Minnesota after 2130 UTC. The strong/severe thunderstorms

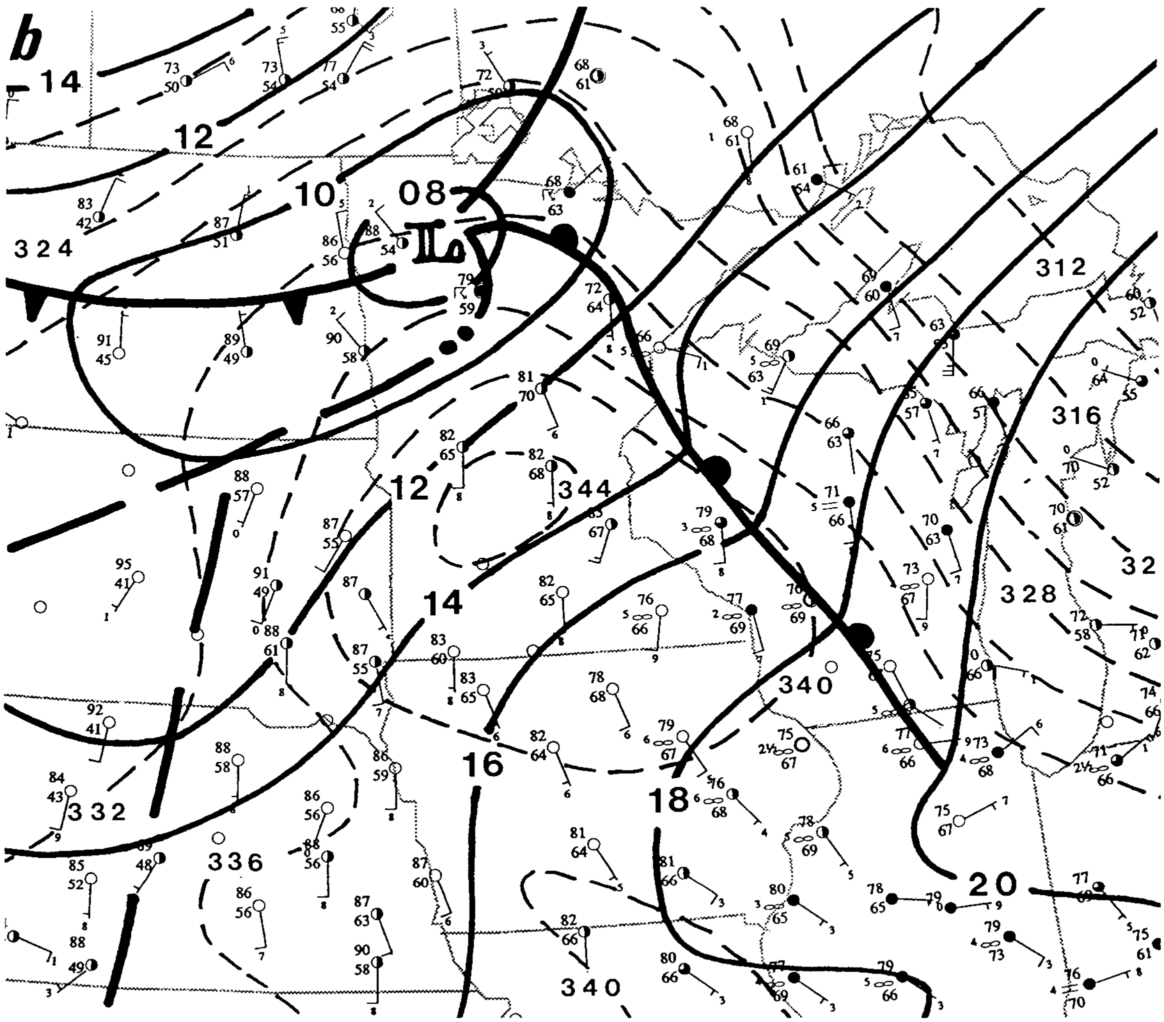

FIG. 7. (*Continued*)

moved east-southeast at 15 m s^{-1} (30 kt), in stark contrast to the quasi-stationary northwestern Wisconsin severe thunderstorms.

d. Moisture flux convergence

The low-level moisture increase shown in the soundings corresponded with persistent moisture flux convergence (Fig. 13), in addition to the θ_e advection. The axis of 20°C (68°F) surface dewpoints (Fig. 7a) was approximately parallel to the warm front and moisture convergence axis and was at a 45° angle to the surface flow. As a result, both the mass convergence and moisture advection terms of moisture flux convergence were aligned in the vicinity of the warm front. Evapotranspiration from vegetation and moist ground also were contributing to high dewpoints, since soil conditions were "favorably to abnormally moist" over much of Wisconsin and southern Minnesota (Le Comte and Lee 1990). Segal et al. (1984) observed a θ_e increase of several degrees in the boundary layer over irrigated, vegetated land.

The Barron County thunderstorms developed west of the persistent moisture convergence maximum and just northeast of a moisture convergence/divergence couplet between southern Minnesota and western Wisconsin (Fig. 13). Development of thunderstorms and severe weather has been noted within the gradient of a divergence/convergence couplet (Bothwell 1988), especially when highest dewpoints were within the gradient, as in this case (Figs. 7 and 13). The higher dewpoints resulted in a lowered level of free convection; thus, less lift was required for convective initiation. Surface convergence often corresponds with low-level lift (providing divergence increases with height), and

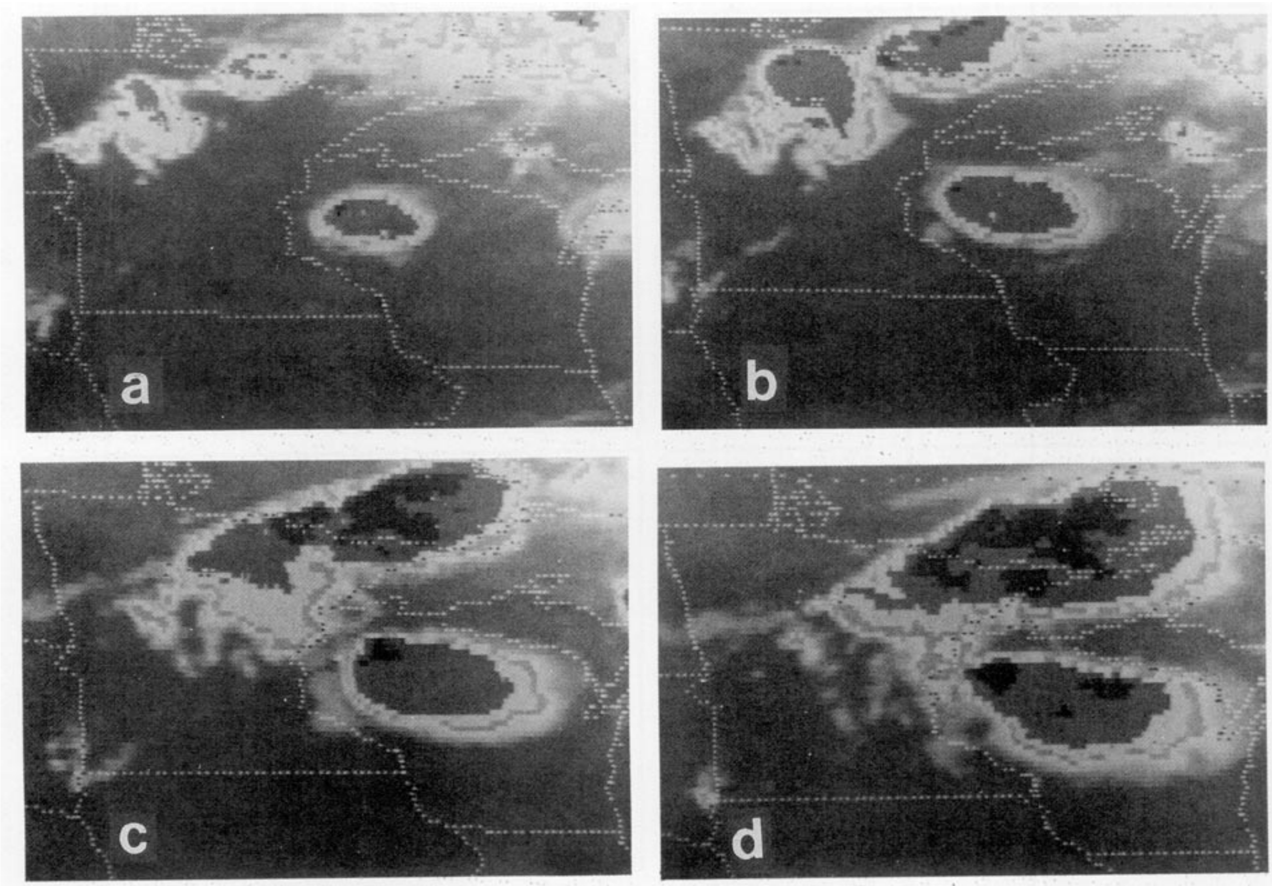

FIG. 8. GOES 4-km resolution IR satellite imagery, with MB enhancement curve from 11–12 September 1990: (a) 2300 UTC, (b) 0000 UTC, (c) 0100 UTC, and (d) 0200 UTC.

developing storms have access to low-level air with the highest CAPE.[1]

Northwestward development of the strongest thunderstorms into Washburn County after 0000 UTC 12 September 1990 corresponded with gradual northward movement of the moisture convergence axis. It is difficult to gauge the strength of the moisture convergence owing to the sparsity of wind data over northwest Wisconsin (Doswell 1982).

3. Radar data and hodographs

a. *Evaluation of thunderstorm structure using radar data*

The structure and evolution of thunderstorms over Barron County was determined by examination of MSP WSR-57 radar data at 5-min or 1-min intervals. The radar data are summarized in Fig. 12, with time intervals selected as close to 15 min as available. Poor quality of the microfilm images prevented direct reproduction, but radar signatures suggested the presence of persistent mesocyclones (supercells) (Doswell et al. 1990; Lemon and Doswell 1979). Weak echo regions coincided with all four tornadoes, and a possible hook echo was associated with the F2 and F1 tornadoes west of Rice Lake at 2245–2250 UTC 11 September 1990 (shown at 2249 UTC in Fig. 12).

It is also clear from the 5-min and 1-min radar data that the tornadic thunderstorms were stationary or moving east at less than 4 m s^{-1} *around the time of tornado occurrence.* Tornadoes were *not* associated with a secondary cell moving east at 15 m s^{-1} into Barron County between 2230 and 2315 UTC 11 September 1990, and no tornadoes occurred with the ensuing merger between 2315 and 0000 UTC 12 September 1990.

The small net thunderstorm movement was the result of nearly orthogonal flow into the stationary moisture-convergence focusing warm front and storm-scale processes. The differing motions between the tornadic

[1] To be entirely correct, CAPE requires consideration of the entire vertical temperature profile in addition to surface potential energy.

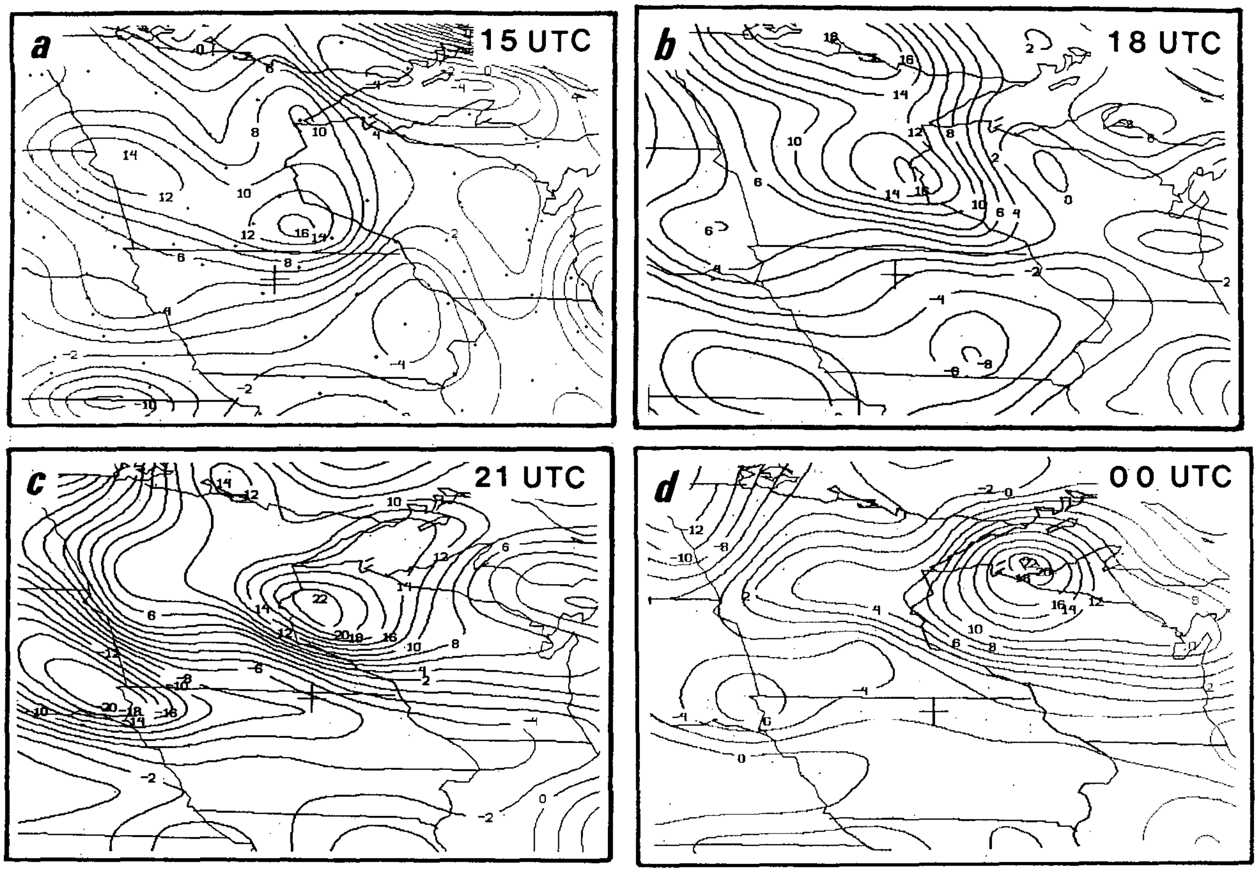

FIG. 9. Surface θ_e advection at (a) 1500 UTC, (b) 1800 UTC, (c) 2100 UTC on 11 September 1990, and at (d) 0000 UTC on 12 September 1990. Contour interval is 2°C h^{-1}.

and nontornadic thunderstorms suggest that storm-scale processes played a large role in storm movement. The near-stationary tornadic storms likely contained mesocyclones that contributed to the intensity and slow movement of the updraft cores. The nontornadic thunderstorms that merged into the stationary cluster did not appear to contain mesocyclones, and they moved east at nearly the speed of the cloud-bearing layer mean wind.

The most damaging F2 tornado caused $1 million damage at Canton, 10 km southeast of Rice Lake, around 0010 UTC 12 September 1990. A weak echo region at the south end of the stationary high-reflectivity core was moving east at less than 4 m s^{-1} when the tornado occurred. Mesocyclone characteristics became less evident as the storms began moving more rapidly eastward after 0100 UTC, and no additional tornadoes were reported.

b. Hodograph analysis: Storm-relative helicity and inflow

Below 4 km at both STC and GRB, winds veered and speeds increased with height, conditions long associated with supercell thunderstorms and tornadoes (Fawbush and Miller 1954). Since the observed storm structure and motion on 11–12 September 1990 was consistent with supercells or storms containing mesocyclones, a discussion of storm-relative (S-R) helicity is relevant. Helicity (Lilly 1986; Lazarus and Droegemeier 1990; Davis-Jones et al. 1990) is related to the rotational potential of the thunderstorm inflow layer. Johns and Doswell (1992), Davies-Jones et al. (1990), and others have shown helicity to be useful in determining an environment favorable for supercell development.

At 0000 UTC 12 September 1990, S-R helicity in the vicinity of the Barron County tornadoes was computed using the STC sounding (Fig. 10c). Surface and 850-mb analyses indicate that STC was representative of the wind flow that supplied warm, moist air to the tornadic thunderstorms. The 0–3-km helicity was chosen for comparison to other studies, although the subcloud inflow layer was around 2 km deep, and over 80% of the S-R helicity was in the 0–2-km layer. Helicity was computed as described by Davies-Jones et al. (1990), with positive and negative layer helicity

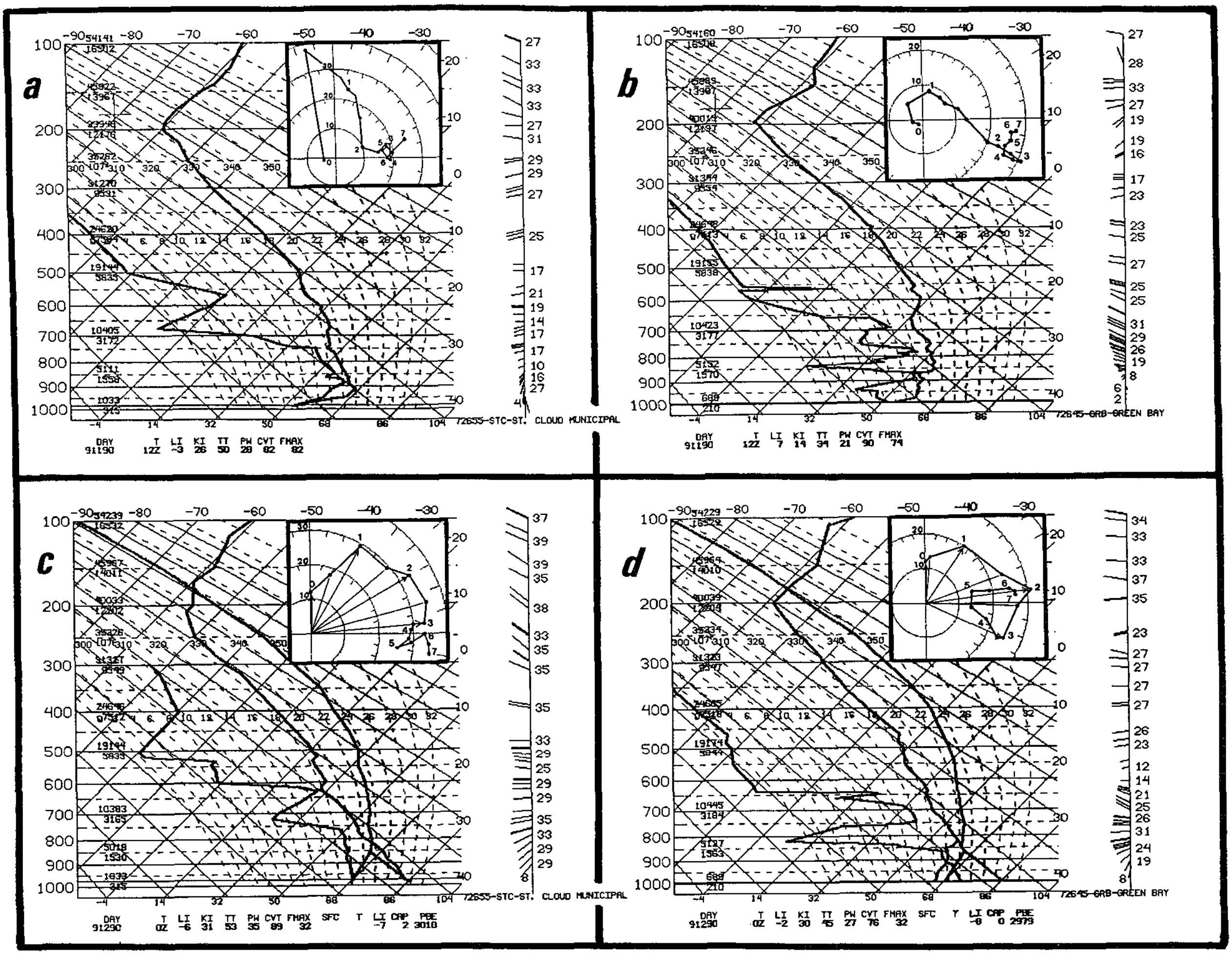

FIG. 10. Soundings in skew T–log$p$ format with hodograph inserts upper right: (a) STC, and (b) GRB, both at 1200 UTC 11 September 1990; (c) STC, and (b) GRB, both at 0000 UTC 12 September 1990. Wind barbs denote direction, with speed in knots (m s^{-1} × 2) immediately right. Right-hand solid line in (c) and (d) is lifted parcel trace approximating the moist adiabat derived from surface temperature and dewpoint of 30° and 20°C (86° and 68°F), respectively. Rings on hodographs are in 5 m s^{-1} increments (labeled in knots). Points on hodographs are in 0.5-km increments with every 1 km labeled. Thin arrows in (c) and (d) are storm-relative inflow vectors up to 3 km using zero storm motion.

summed over the lowest 3 km to arrive at the final 0–3-km S-R helicity. For simplicity, the helicity values were computed using zero storm motion, since radar data indicated very little movement of the tornadic thunderstorm cells.

Storm-relative helicity in the lowest 3 km over Barron County was 265 m^2 s^{-2} at 0000 UTC 12 September 1990. Davies and Johns (1993) computed a mean 0–3-km helicity of 340 m^2 s^{-2} for a large number of strong (F2–F3) tornado cases, and Davies-Jones et al. (1990) arrived at similar values in a smaller study. For cases in which violent (F4–F5) tornadoes occurred, Leftwich (1990) found a wide range of helicity values. Maximum inflow was 15 m s^{-1} (29 kt) in the subcloud layer (0–2 km) at 0000 UTC, owing to the west-southwesterly winds of the same magnitude just below cloud base (Fig. 10c). Mean 0–2-km inflow was 12 m s^{-1}. The aforementioned values, and radar data from the previous section, provide indirect confirmation that the Barron County tornadoes were mesocyclone associated.

Locally enhanced veering of winds on the cool side of the warm front could have increased surface inflow and S-R helicity on 11–12 September 1990. The Barron County storms were very near the warm frontal boundary, but an easterly surface wind component was not evident in sparse surface data after 2100 UTC. Doswell et al. (1990) discussed the role of mesoscale boundaries (often produced by the thunderstorm itself) in augmenting the severe storm environment. Half-hourly satellite images showed cloud development just west of Barron County after 2300 UTC (Fig. 8), which might suggest the presence of an outflow boundary.

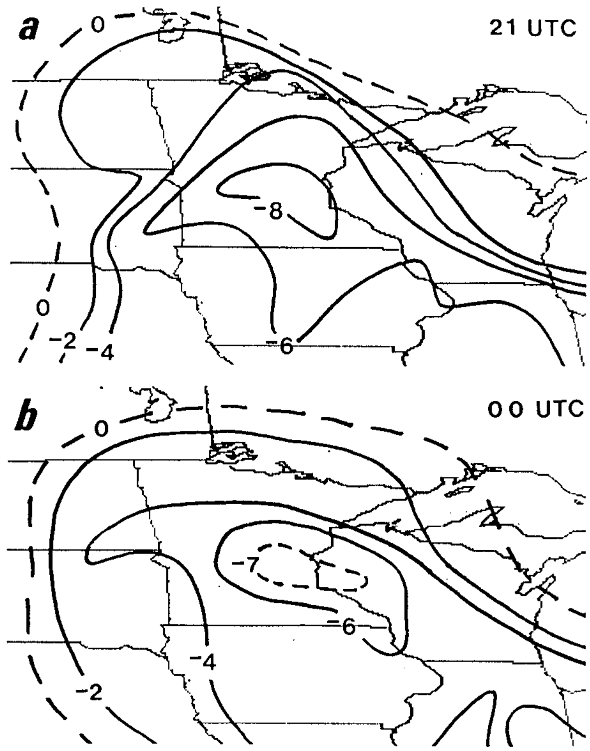

FIG. 11. Surface-based lifted index for (a) 2100 UTC 11 September 1990 and (b) 0000 UTC 12 September 1990. Contours every 2°C.

4. Discussion

Four tornadoes occurred within 17 km of Rice Lake, Wisconsin, between 2245 and 0100 UTC 11–12 September 1990. Similar tornado cluster events are climatologically uncommon outside of the western Plains, and the events of 11–12 September 1990 proved to be a challenging forecast problem.

Minneapolis WSR-57 radar data on 11–12 September 1990 showed mesocyclonic thunderstorm signatures. The mesocyclones developed in an environment where synoptic-scale processes produced strong instability over a large area. Subsynoptic maxima of moisture convergence and low-level warm advection persisted throughout the day near the slow-moving warm front over western Wisconsin. The associated implied lift eventually initiated and sustained thunderstorms in the vicinity of Barron County. It appears that the low-level supply of high CAPE to the right rear flank of the thunderstorm complex (Chappell 1985; Maddox et al. 1979) contributed to its slow movement. The thunderstorms also became stationary or slowed significantly as they developed supercellular characteristics. Dynamically induced vertical pressure gradients (Rotunno and Klemp 1982, 1985), which result from rotating updrafts in a sheared environment, may have been located at the right *rear* flank of the tornadic storms in a position to slow their forward motion. The combined result was a near-stationary cluster of damaging tornadic storms that persisted for over two hours.

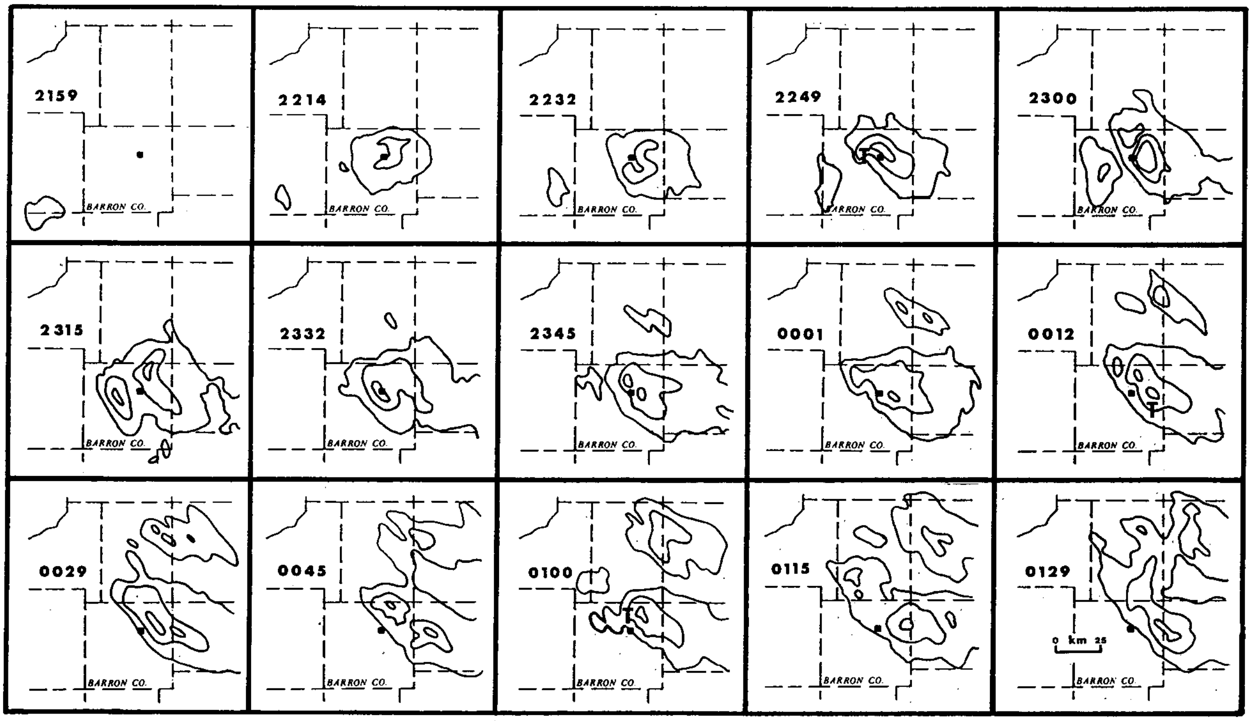

FIG. 12. Minneapolis (MSP) radar reflectivity contours for times as labeled (UTC) on 11–12 September 1990. Contours are for DVIP levels 1, 3, and 5. The capital "T" indicates tornado reports at 2249, 0012, and 0100 UTC. The small square denotes the location of Rice Lake, Wisconsin.

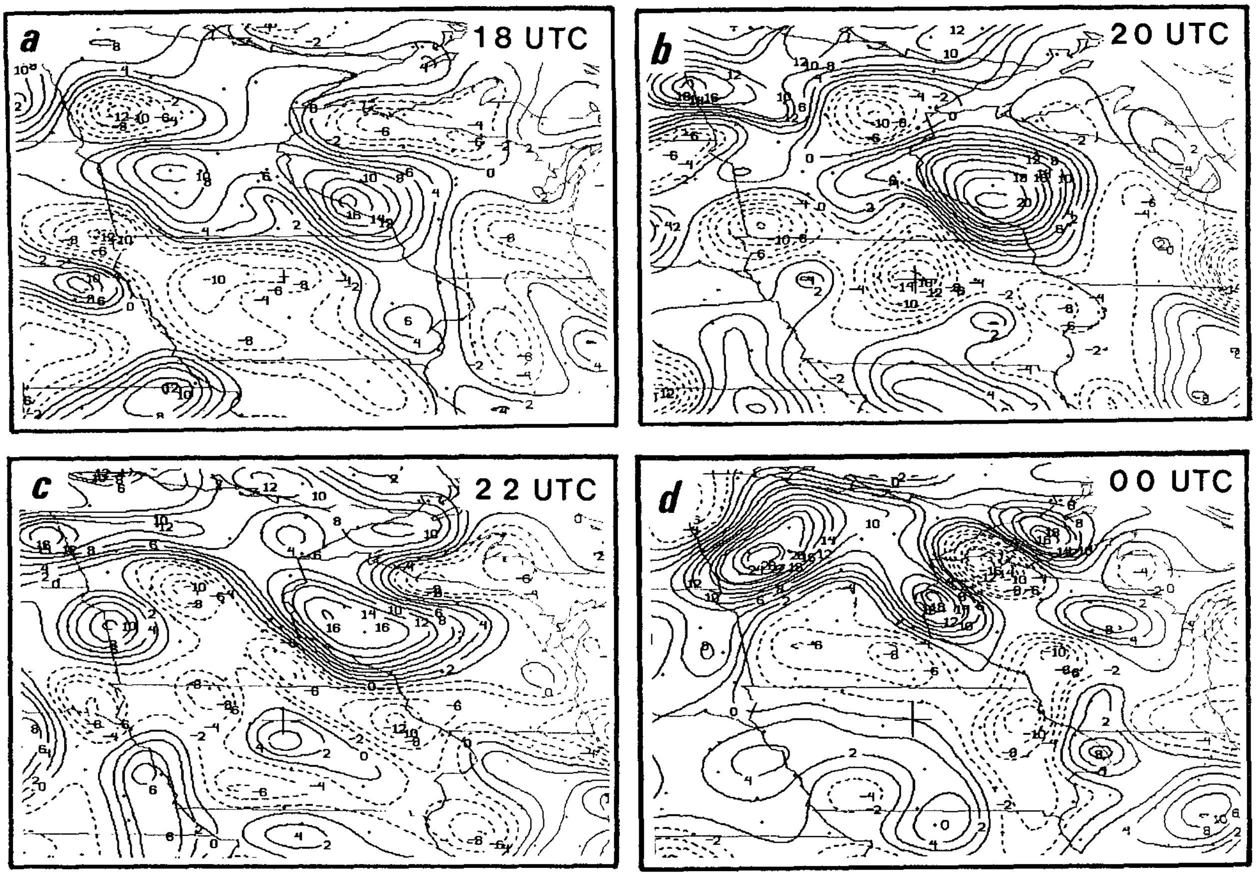

FIG. 13. Surface moisture flux convergence at (a) 1800 UTC, (b) 2000 UTC, and (c) 2200 UTC on 11 September 1990, and at (d) 0000 UTC on 12 September 1990. Contour interval is 2 g $kg^{-1}h^{-1} \times 10$.

Results of observational and numerical modeling studies (Lazarus and Droegemeier 1990) indicate that the storm-relative helicity and inflow values on 11 September 1990 were sufficient to produce supercells, with virtually no storm motion. Forecasters expect that thunderstorms deviating to the right and moving slower than the mean wind experience enhanced S-R helicity and inflow, but stationary thunderstorms usually are not included in that group. With particular hodographs, however, stationary thunderstorms can result in increased helicity (compared with thunderstorms moving with the mean wind), as shown in this study. Analysis of hodographs should include S-R helicity and inflow for a variety of storm motions, allowing the forecaster to determine which motion(s) will favor mesocyclone development on a given day. The easiest way to do this is to display contours of helicity on the hodograph (as shown in Davies-Jones et al. 1990).

The vertical wind profile on 11 September 1990 may be common to other tornado cluster events and will be the object of further study. Development of a climatology of similar events is also recommended, since the cluster events cited earlier included several F3 and F4 tornadoes and numerous F2 tornadoes, and posed a significant threat to life and property.

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