Hurricane Huron

Todd Miner,* Peter J. Sousounis,+ James Wallman,+ and Greg Mann+

ABSTRACT

An intense cutoff low developed over the Great Lakes during the period 11–15 September 1996. As the low deepened, height falls in the lower troposphere exceeded those at upper levels, the cold-core low evolved into a warm core system, and vertical wind (speed and directional) shear decreased dramatically. The low eventually developed an eye and spiral bands of convective showers. In addition, the cyclone briefly produced tropical storm force winds and excessive rain (> 10 cm) that caused flooding. From a satellite perspective, this system bore a striking resemblance to a hurricane. It is believed to be the first time that such a feature has been documented over the Great Lakes.

Because the initially cold-core cyclone moved slowly across the Great Lakes when they were near climatological peak temperature, heat fluxes, particularly latent heat fluxes, were unusually large. For this reason, it is hypothesized that the lakes, especially Lake Huron, played an integral role in the system's development. An analysis of the static stability present during the event suggests that a deep layer of conditional instability allowed lake-modified air parcels to reach altitudes not normally associated with lake-forced convection.

The hypothesis that the heat and moisture fluxes from the Great Lakes played a significant role in the system's development is supported by the following: 1) The cyclone deepened considerably in the presence of very *weak baroclinicity,* with the most substantial height falls occurring *after* the system reached Lake Huron. 2) The combination of surface sensible (F_s) and latent (F_h) heat fluxes exceeded 700 W m^{-2} during the low's development. This value is comparable to flux calculations during wintertime arctic air outbreaks over the Great Lakes as well as for polar low cases and category one hurricanes. 3) The low strengthened considerably more at *lower levels* than at upper levels. 4) The thermal structure of the cyclone appeared to evolve into a warm-core feature from its original cold-core structure, with a significant positive tropospheric thickness anomaly observed over the system's center.

1. Introduction

During the period 11–15 September 1996, a weak synoptic-scale surface low moved from northern Lake Michigan to Lake Huron, where it subsequently stalled and deepened. At the time of maximum surface intensity, the low reached a minimum sea level pressure of 993 hPa and briefly produced tropical storm force winds. The most interesting aspects of the cyclone, however, were not directly related to its magnitude, but rather to its deepening characteristics, and most of all, to its appearance. Figure 1 presents a visible satellite and Doppler radar image of the low over Lake Huron at 1745 UTC 14 September 1996, about the time of maximum surface intensity. A casual observer might classify this system as "tropical," owing to its distinct "eye" and spiral cloud bands surrounding the center. The cyclone did produce tropical storm force winds over Lake Huron and prodigious rainfall with totals exceeding 20 mm over a broad area from northern Michigan to northern Pennsylvania (Fig. 2). The reference to "Hurricane Huron" in the title of this study was in fact inspired by the satellite image and was not meant to imply that the system was of tropical origin or had produced hurricane force winds.

*Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania.
+Atmospheric, Oceanic and Space Sciences Department, University of Michigan, Ann Arbor, Michigan.
Corresponding author address: Todd Miner, Department of Meteorology, The Pennsylvania State University, Walker Building, Room 503, University Park, PA 16802.
E-mail: miner@mail.meteo.psu.edu
In final form 8 June 1999.

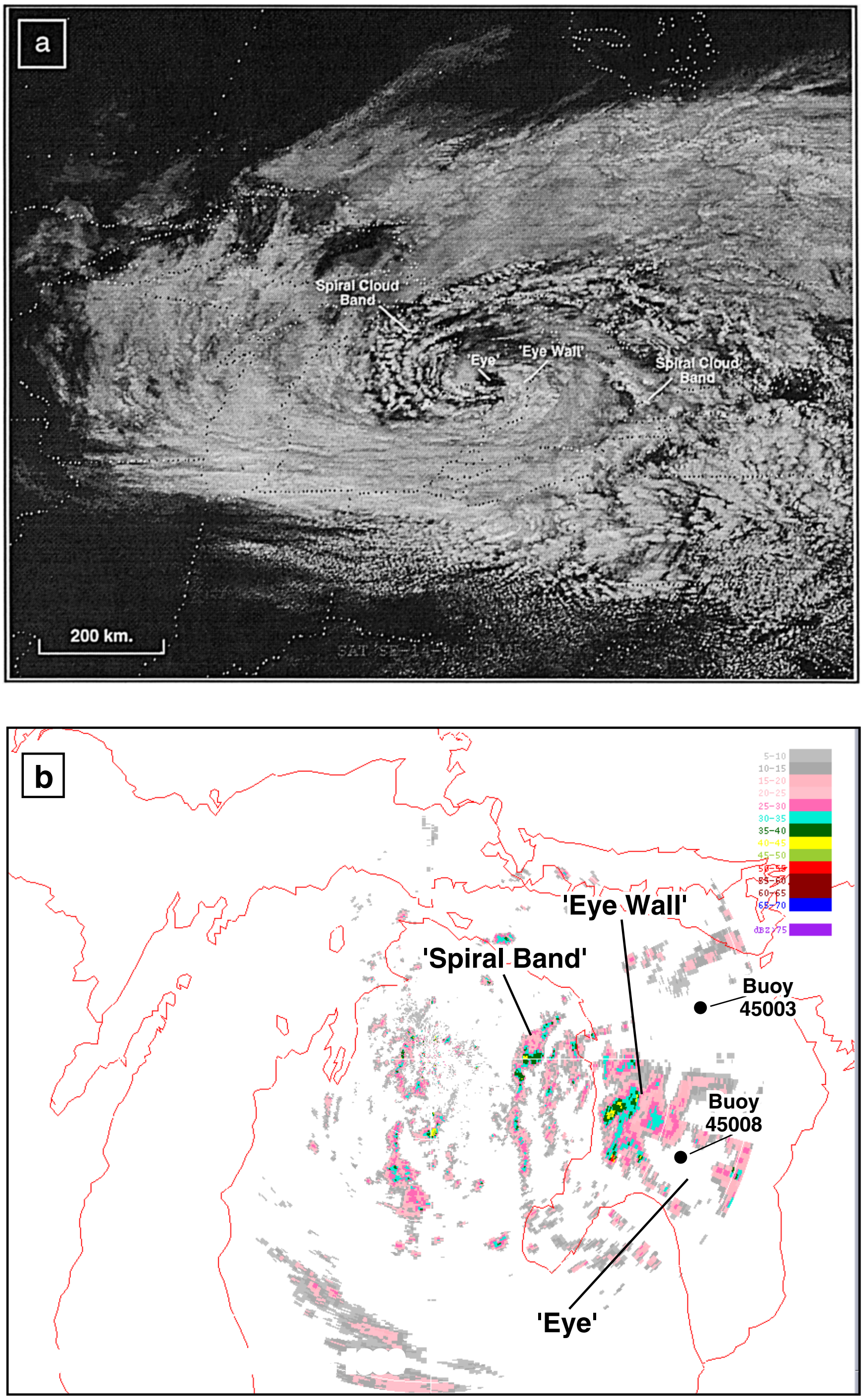

FIG. 1. Satellite and radar characteristics of the vortex near the time of peak surface intensity. (a) Visible satellite image valid 1745 UTC 14 Sep 1996, the time of maximum surface intensity. Note the eye and eye wall-like structure over central Lake Huron and the spiral cloud bands, which extend 500 km outward from the vortex center. (b) Doppler radar image valid 1600 UTC 14 Sep 1996. Note similar features of those in satellite image with the precipitation echoes creating spiral bands and an "eye" over Lake Huron. Location of buoys 45008 and 45003 also shown.

While meso-beta-scale vortices with eyes (Forbes and Merritt 1984) and meso-alpha-scale cyclonic circulations (Agee and Lidrbauch 1989; Sousounis 1997) have been documented over the Great Lakes during wintertime cold air outbreaks, it is believed that this is the first time that a meso-alpha-scale system with an eye and spiral rainbands has been observed over the Great Lakes.

Clear centers and spiral precipitation bands have been noted in other meso-alpha-scale extratropical systems, most notably polar lows. Bussinger and Reed (1989) documented three classes of polar lows with one of the three types developing when old cold-core occluded lows move over large bodies of relatively warm water. This "cold-low" type of polar low can bear a strong resemblance to a tropical cyclone, capable of producing tropical storm and even hurricane force winds (Rasmussen 1989). Studies by Rasmussen (1981), Rasmussen and Zick (1987), Bussinger and Baik (1991), Billing et al. (1983), Ernst and Matson (1983), Mayengon (1984), and Albright et al. (1995) have documented polar lows of the cold-low variety over the Bering Sea, Mediterranean Sea, and Hudson Bay. It is believed that the Huron system was akin to the cold-low class of polar lows. However, in contrast to the typical polar low, this cyclone developed during the *early* meteorological autumn over *interior North America* and subsequently intensified over the waters of the *Great Lakes.*

The temperature difference between the Great Lakes (which were near climatological peak values) and the overlying air during the period suggests that the sensible and latent heat fluxes from the lakes were substantial. These fluxes likely altered the tropospheric static stability significantly and ultimately played a role in the system's development. The objectives of this paper are several-fold. First, the movement and development characteristics of this unique cyclone, including a synopsis of the synoptic environment in which it formed, will be discussed. Second, the impact of the system in terms of the winds and precipitation that it produced will be addressed. Finally, evidence supporting the hypothesis that the Great Lakes (especially Lake Huron) played a significant role in the cyclone's development will be presented.

2. Synoptic-scale evolution

The system evolved over a period of several days. Its structure and appearance changed substantially upon crossing, and then returning and stalling, over Lake Huron.

a. Pre–Lake Huron (weak baroclinic) development

1) 1200 UTC 11 September 1996–1200 UTC 12 September 1996

At 1200 UTC 11 September 1996, a weak cyclone was located near Lake Superior. At the surface, a 1012-hPa low was over northern Lake Michigan (Fig. 3a) while aloft, a 500-hPa shortwave was located 500 km northwest of the surface center over Ontario (Fig. 3b). The northwest tilt with height of the low indicated that the cyclone was in its baroclinic development stage. In addition, analysis of the 1200 UTC 11 500-hPa upper-air observations (Fig. 3b) suggested that the cyclone was cold core in the middle troposphere (note the −26°C temperature very near the 500-hPa center). Analyses at 700 and 850 hPa (not shown) also indicated that the system was cold core in the lower troposphere, though admittedly a denser coverage of upper-air observations would be necessary to assess the system's precise thermal structure. Observed wind speeds near the cyclone center during the period increased with height (from about 5 m s^{-1} at the surface to about 30 m s^{-1} at 500 hPa) while a computation of the geostrophic wind also showed that the system became stronger with increasing altitude during this period, an expected characteristic of a baroclinically driven cyclone.[1] Also at this time, the combination of positive vorticity and positive thermal advection was causing a swath of moderate rain north of the surface cyclone in Ontario, Canada, while a broken area of showers and thunderstorms was present in the warm sector ahead of an advancing cold front (Fig. 3a). Farther downstream of the cyclone, fair and seasonably mild conditions covered the central and eastern Great Lakes.

By 1200 UTC 12 September, the cyclone had progressed slowly southeastward so that the surface low was situated over Lake Huron (Fig. 4a), while the upper portions of the cyclone were positioned 200–500 km to the northwest over northern Michigan (Fig. 4b). The surface cyclone deepened 6 hPa (1012 to 1006 hPa) during the 24-h period ending 1200 UTC 12 September while no change in the height field was noted aloft at 500 hPa. According to Hirschberg and

[1]In an attempt to obtain a measure of the system's intensity that was not dependent on the coarse network of upper-air wind observations, a geostrophic wind was computed for the purpose of serving as a proxy for assessing the cyclone's strength using the equation $V_g = g/f\,(dh/ds)$, where ds = 500 km.

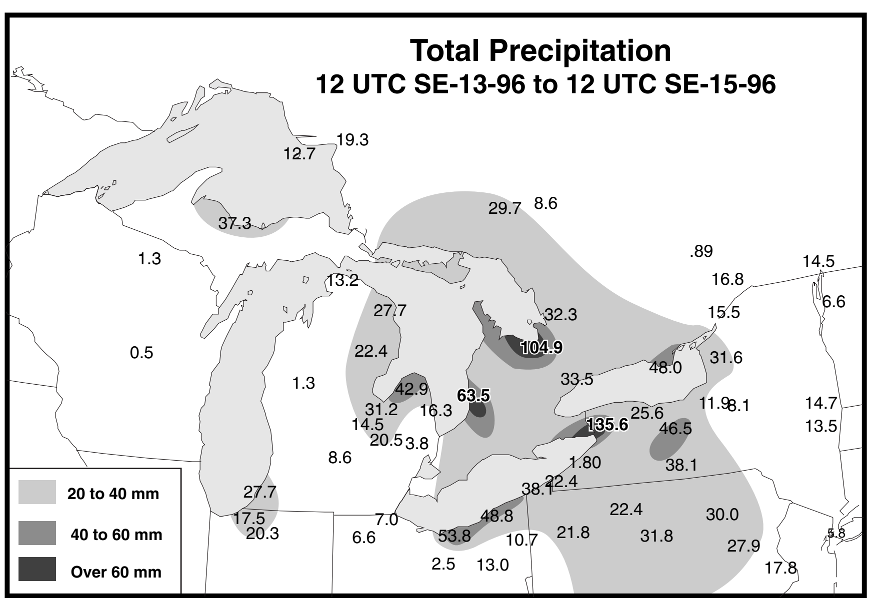

FIG. 2. Total precipitation during the period 1200 UTC 13–15 Sep 1996. Emboldened amounts exceed 60 mm (2.4 in.).

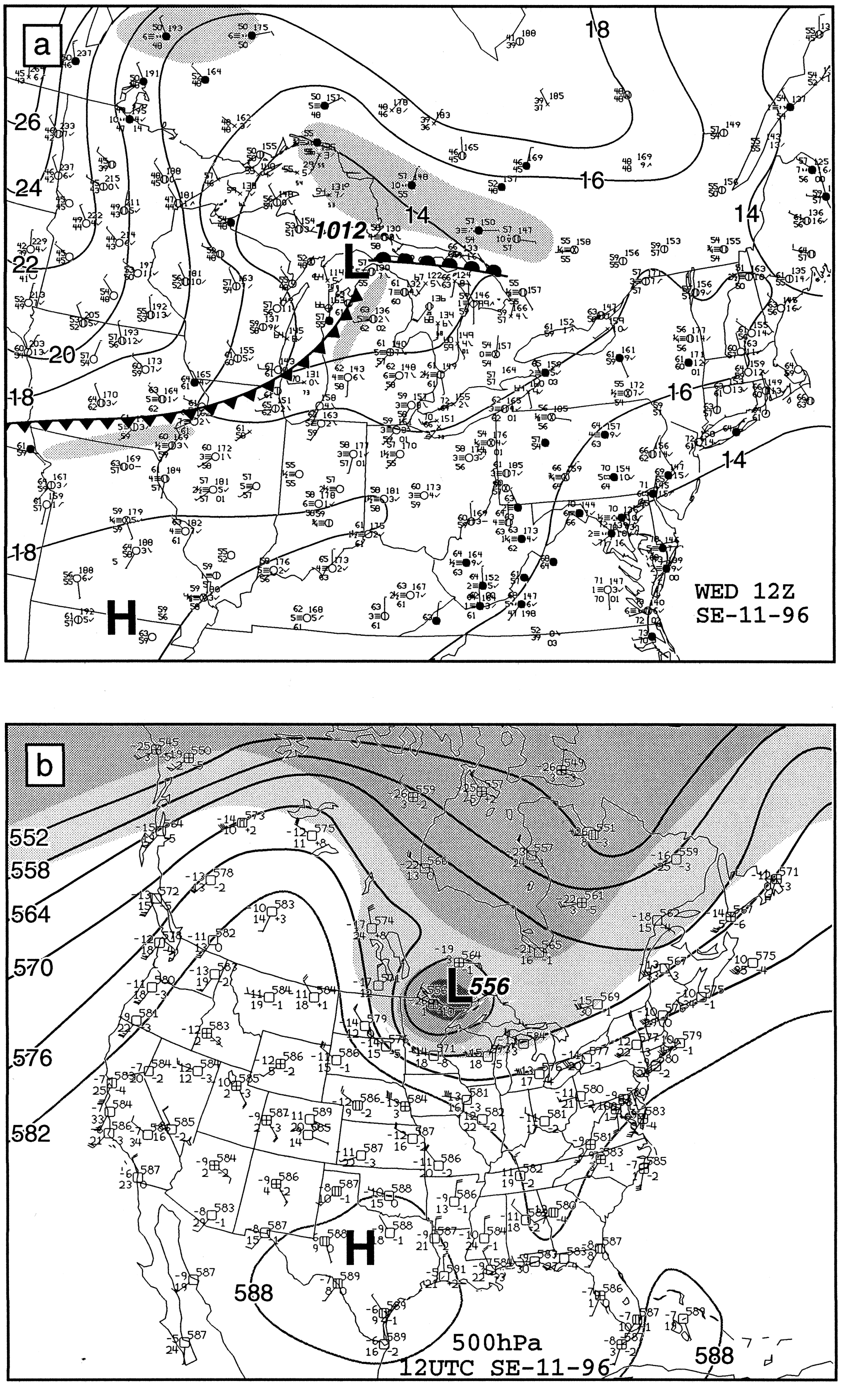

FIG. 3. Subjective analysis of observed conditions valid 1200 UTC 11 Sep 1996. (a) Surface analysis with standard data plotting conventions employed. Solid lines are isobars of mean sea level pressure (hPa, leading 10 omitted). Shading depicts precipitation areas surrounding the cyclone based on surface observations and radar imagery. Note the weak pressure gradient surrounding the center at this time. (b) 500-hPa heights (dm). Light and dark shading shows where temperatures are lower than −15°, −20°, and −25°C, respectively.

Fritsch (1993), this suggests from the hydrostatic approximation that the lower troposphere must have warmed. Also at 1200 UTC 12 September, showers and thunderstorms associated with the cold front attendant to the surface low stretched over southern Ontario and Lake Erie (Fig. 4a). Another area of showers and isolated thunderstorms lay across northern Michigan close to the upper low center, in the area where the cold conveyor belt is typically located (Carlson 1991). As expected, the precipitation pattern surrounding the cyclone closely matched what is observed in the Norwegian cyclone model (Bjerknes and Solberg 1926).

2) 1200 UTC 12 SEPTEMBER 1996–1200 UTC 13 SEPTEMBER 1996

After 1200 UTC 12 September, the midlevel portions of the cyclone (between 850 and 500 hPa) moved east-southeastward to a position over Lake Huron, joining the surface low (that had remained over the lake) and causing the system to become vertically stacked from the surface to 500 hPa (Fig. 5). Farther aloft, the cyclone center at 300 and 200 hPa (not shown) also moved southeastward with the 300-hPa center briefly crossing Lake Huron at 0000 UTC 13 September. Except for the 200-hPa level, the system's heights fell at all mandatory levels during this period with the greatest intensification (height falls) occurring *below* 500 hPa. In addition, the nearly neutral tilt of the cyclone indicated that the system was reaching the occlusion stage of its baroclinic development.

As the system proceeded through its occlusion stage, the cold front attendant to the surface low became an occluded front that extended from Lake Huron to Pennsylvania at 1200 UTC 13 September (Fig. 5a). A 250-km wide swath of showers and thunderstorms was positioned across the occlusion/cold front while an area of showers and thunderstorms lay along a trailing trough, which reached south of the Lake Huron low. Also at this time, a third area of showers was over northern Michigan and Lake Huron near the center of the occluded surface low (Fig. 5a).

b. Lake Huron development

1200 UTC 13 SEPTEMBER 1996–1200 UTC 14 SEPTEMBER 1996

Between 1200 UTC 13 September and 0000 UTC 14 September 1996, a shortwave (noted in Fig. 5b by a vorticity maximum of magnitude 22×10^{-5} s^{-1} at 500 hPa) rotated through the occluded cyclone. The height falls associated with this shortwave apparently caused the middle and upper portions of the system to temporarily shift eastward, so that by 0000 UTC 14 September the 850-, 700-, and 500-hPa centers were located just east of Lake Huron (not shown). During the 12-h period ending 0000 UTC 14 September, the system's heights fell 20 m at 850, 700, and 500 hPa, with lesser height falls (10 m) occurring at 300 hPa. In contrast, height *rises* of 20 m were noted farther aloft at 200 hPa. Between 1200 UTC 13 September and 0000 UTC 14 September, the surface low moved very slowly over Lake Huron and deepened by 5 hPa, falling to a central pressure of 999 hPa. In response to the pressure falls, maximum sustained surface winds also increased.

After 0000 UTC 14 September, the lower and middle tropospheric portions of the cyclone migrated westward so that by 1200 UTC 14 September, the cyclone was vertically stacked through 200 hPa over Lake Huron and cut off from the main flow (Fig. 6a). In contrast to the earlier stages of development, the baroclinicity of the system (as indicated by the temperature gradient within 500 km of the system's center) diminished substantially (cf. Figs. 3b, 6a). Nevertheless, the lower tropospheric portion of the system continued to intensify. In fact, between 0000 UTC and 1200 UTC 14 September the system's surface pressure fell by 6 to 993 hPa while height falls of 40 m occurred at 850 hPa. Deepening was also noted to a lesser extent at 700 hPa (20 m) and 500 hPa (10 m) while no deepening occurred at 300 hPa.

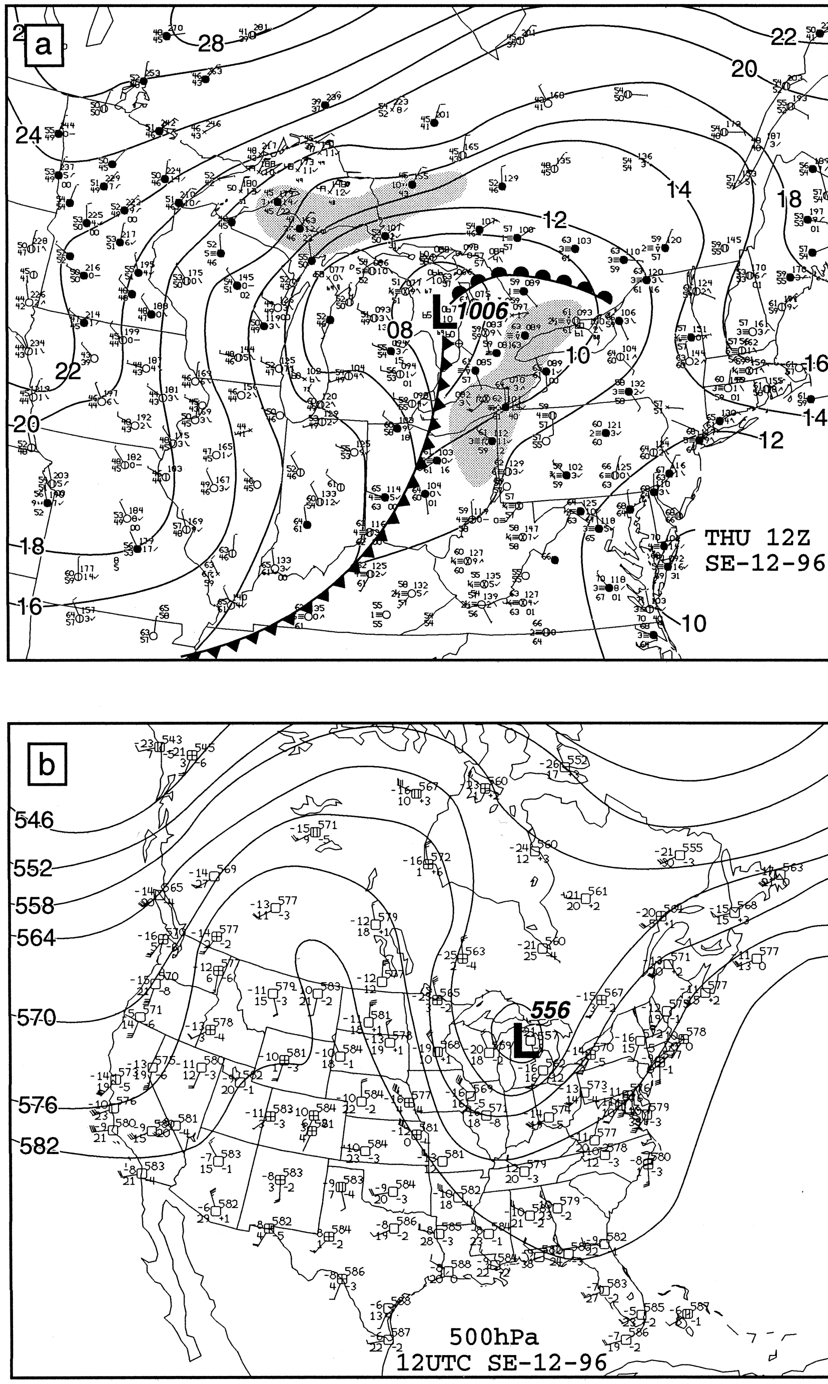

FIG. 4. Subjective analysis of observed conditions valid 1200 UTC 12 Sep 1996. (a) Surface analysis with standard data plotting conventions employed. Solid lines are isobars of mean sea level pressure (hPa, leading 10 omitted). Shading depicts precipitation areas surrounding the cyclone based on surface observations and radar imagery. (b) 500-hPa heights (dm).

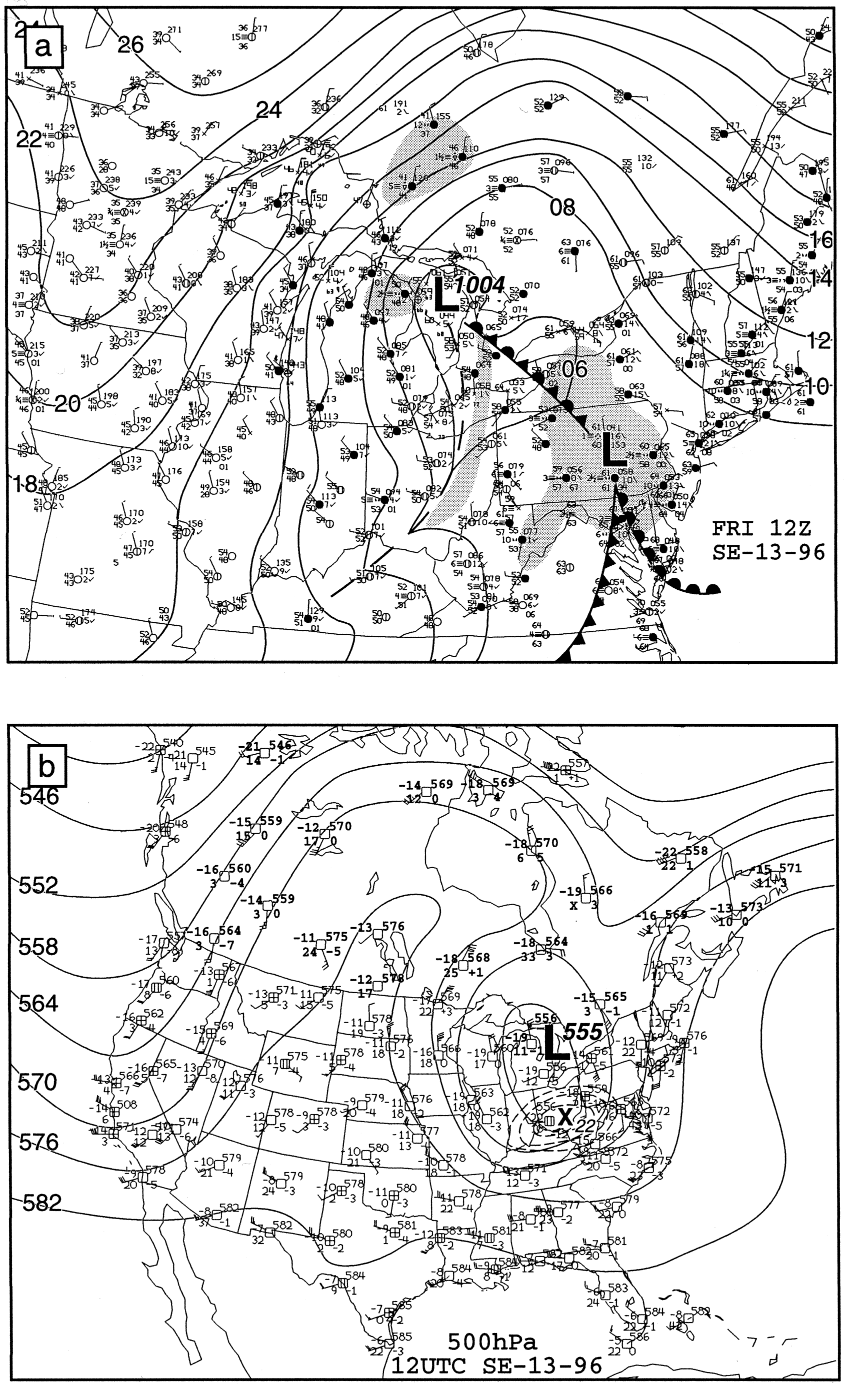

FIG. 5. Subjective analysis of observed conditions valid 1200 UTC 13 Sep 1996. (a) Surface analysis with standard data plotting conventions employed. Solid lines are isobars of mean sea level pressure (hPa, leading 10 omitted). Shading depicts precipitation areas surrounding the cyclone based on surface observations and radar imagery. (b) 500-hPa heights (dm), with vorticity maximum of magnitude 22×10^{-5} s^{-1} depicted.

In concert with the changing height field, the geostrophic wind of the system also changed. During the 24 h ending 1200 UTC 14 September, large geostrophic wind increases occurred in the lower troposphere: +7 m s^{-1} (surface), +10 m s^{-1} (850 hPa), +4 m s^{-1} (700 hPa), and +6 m s^{-1} (500 hPa), while a significant decrease was noted (−14 m s^{-1}) farther aloft at 300 hPa. The reduction of the 300-hPa geostrophic wind during this time suggests that the cyclonic flow at 300 hPa was weakening. This weakening may have been due to the generation of anticyclonic vorticity caused by a net cooling above 300 hPa. This would be true if the cooling from adiabatic ascent exceeded the warming from latent heat release above 300 hPa. In contrast, strong cyclonic intensification was clearly occurring in the lower troposphere (cf. Figs. 5a and 6b).

The lower and middle tropospheric strengthening of the cyclone in an environment of reduced baroclinicity indicated that heat fluxes from Lake Huron and adjacent Great Lakes may have played a role in deepening the system. Figure 7 shows how the weather conditions and surface fluxes at two buoys on Lake Huron (45003, located at 45.32°N, 82.77°W; and 45008, located at 44.26°N, 82.42°W, see Fig. 1b for buoy locations) evolved as the vortex moved slowly across the lake. The data (National Data Buoy Center 1997) from buoy 45008 is particularly revealing because the system center passed almost *directly over* the buoy. Note that the surface wind speed exceeded 15 m s^{-1} around 1200 UTC 14 September 1996. The strong winds combined with relatively large lake–air temperature and moisture differences to generate large surface fluxes. These sensible (F_s) and latent (F_h) fluxes were calculated using the bulk aerodynamic formulas:

$$F_s = \rho C_D C_p |\boldsymbol{V}| (T_{\mathrm{LAKE}} - T_{\mathrm{AIR}}),$$
$$F_h = \rho C_q L_v |\boldsymbol{V}| (q_{\mathrm{LAKE}} - q_{\mathrm{AIR}}), \qquad (1)$$

where ρ is the density, C_D and C_q are drag coefficients for heat and moisture, C_p is the specific heat at constant pressure, L_v is the latent heat of vaporization, $|\boldsymbol{V}|$ is the surface wind speed, T_{LAKE} is the lake temperature, T_{AIR} is the surface air temperature, q_{LAKE} is the saturated specific humidity, and q_{AIR} is the specific humidity of the surface air. Using buoy data for wind, temperature, and dewpoint (where dewpoint is based on an estimated 80% relative humidity over the lake), and a value of 1.5×10^{-3} for C_D and C_q, it is shown in Figs. 7e and 7f that the combination of sensible and latent heat fluxes approached 700 W m^{-2} at buoy 45008 between 1200 UTC 13 September and 1200 UTC 14 September.

Analyses of static stability during this time imply that convective processes would have caused these surface heat fluxes to be distributed over a deep layer of the atmosphere. The differences between the lake and the 850-hPa temperatures at soundings taken near Lakes Huron and Erie exceeded the 13°C criterion noted by Holroyd (1971) to produce lake-effect precipitation. More specifically, a nearly moist adiabatic profile existed beneath 400 hPa (see Fig. 8) with little or no inversion present. In using the nearby lake surface temperature and dewpoint (where dewpoint is based on an estimated 80% relative humidity over the lake) as surface conditions, it is shown that the maximum amount of undiluted convective available potential energy (CAPE) at both 1200 UTC 13 September and 1200 UTC 14 September was quite high. Application of the National Weather Service's SHARP program (Hart and Korotky 1991) to the Gaylord soundings revealed CAPE values between 900 and 1900 J Kg^{-1}. Using the same methodology, calculations of CAPE at a sounding closer to Lake Erie at Buffalo revealed values near 2300 J Kg^{-1}. As a result of the large CAPE values, maximum echo tops in the system's "eyewall" approached 10 km.

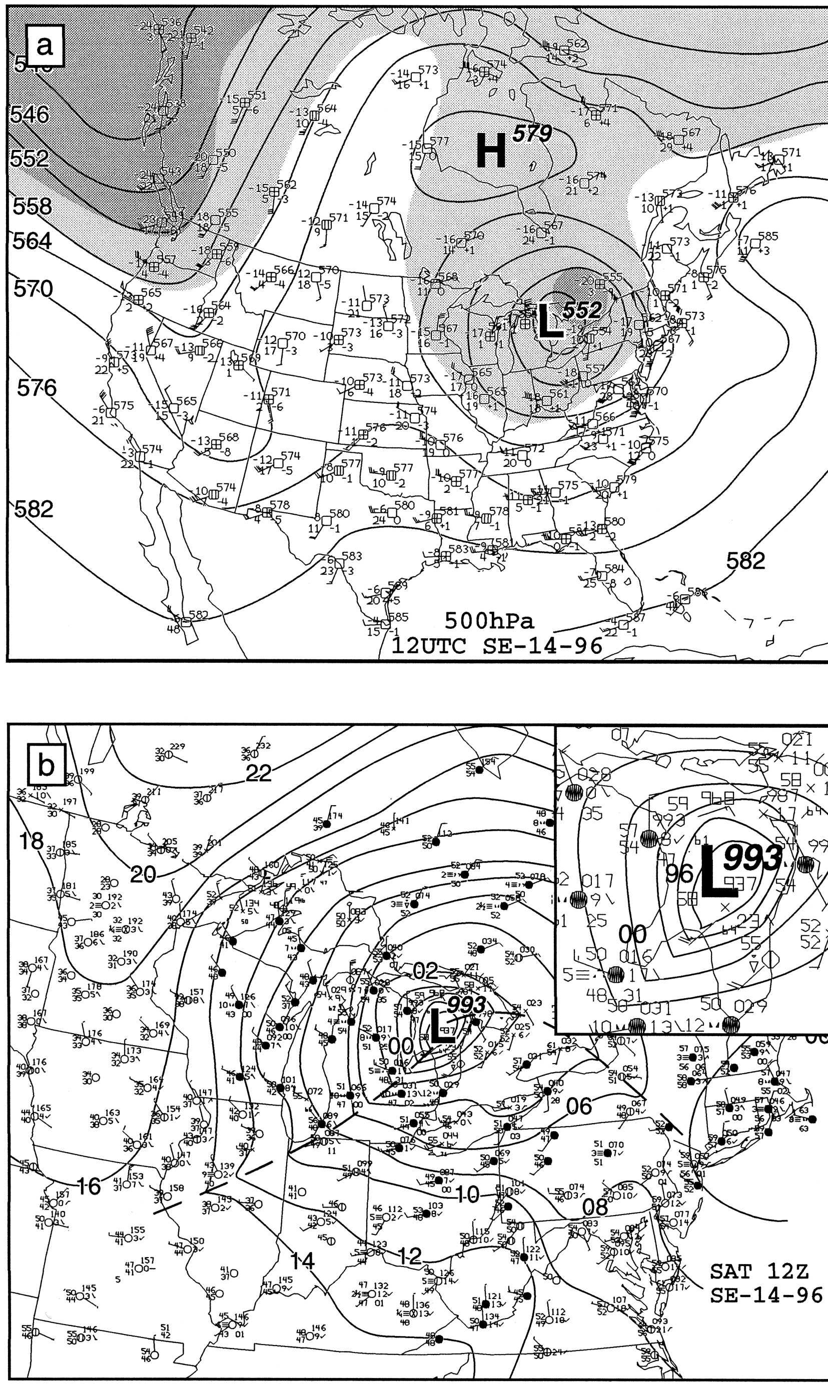

FIG. 6. Subjective analysis of observed conditions valid 1200 UTC 14 Sep 1996. (a) 500-hPa heights (dm). Shading shows where temperatures are less than −15° and −20°C, respectively. (b) Surface analysis with standard data plotting conventions employed. Solid lines are isobars of mean sea level pressure (hPa, leading 10 omitted). Note the strong pressure gradient at the system center. Inset in upper right-hand corner shows close-up of conditions over Lake Huron.

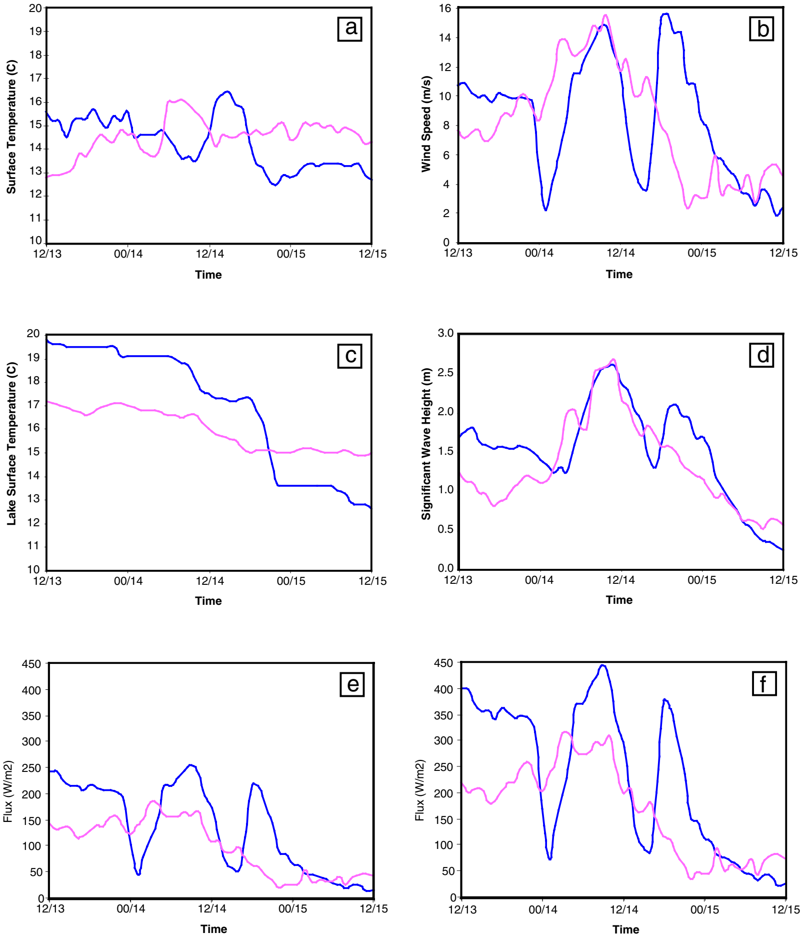

FIG. 7. Time series of observations from 1200 UTC 13–15 Sep 1996 at buoy 45003, located on Lake Huron at 45.32°N, 82.77°W (light curves); and buoy 45008, located on Lake Huron at 44.26°N, 82.42°W (dark curves). See Fig. 1b for buoy locations. (a) Surface air temperature, (b) wind speed, (c) lake surface temperatures, (d) significant wave height, (e) surface sensible heat flux. Values in (e) and (f) computed using Eq. (1) and data from (a)–(d).

Not surprisingly, the diabatic heating from the lakes appeared to be affecting the temperature structure of the system. In contrast to the initial phase of the cyclone, the coldest air at 500 hPa appeared to be displaced away from the cyclone center (cf. Figs. 3b, 6a). Moreover, objective analyses (Barnes 1964) of the 1200 UTC 13 and 14 September observations show a marked increase in the system's tropospheric thickness. Figure 9 clearly illustrates the positive thickness anomaly, which intensified over the system's center. The 50-m thickness increase noted in the 1000–500-hPa layer between 1200 UTC 13 and 1200 UTC 14 September suggests that the diabatic heating from Lake Huron and the other lakes was modifying a deep layer. To further illustrate, an overlay of the 1200 UTC 13 September Gaylord, Michigan, sounding atop the 1200 UTC 14 September sounding (see Fig. 8b) shows a distinct warming of the lower and middle troposphere.

Not surprisingly, as the lower tropospheric portions of the cyclone intensified, the observed surface winds also increased. Between 1200 UTC 13 September and 1200 UTC 14 September, sustained winds at the two buoys over Lake Huron increased from 8 to 15 m s^{-1} and from 11 to 15 m s^{-1}, respectively (Fig. 7b). In addition to the changing mass and wind field, the precipitation structure of the cyclone exhibited a marked change during this period. The area of showers and thunderstorms that previously lay ahead of the occluded/cold front dissipated and a broader area of spiral banded precipitation encircled the cyclone out to a distance of 500 km from the center.

c. Cyclone develops unique features

1200 UTC 14 SEPTEMBER 1996–0000 UTC 15 SEPTEMBER 1996

Between 1200 UTC 14 September and 0000 UTC 15 September, visible satellite images of the vortex revealed a strikingly similar appearance to a tropical cyclone (see Fig. 1a). The center of the cyclone assumed an eyelike feature over Lake Huron with the diameter of the eye measuring 30 km across at 1800 UTC 14 September. In addition, a ring of tall convective clouds surrounded the clear center, resembling an eyewall of a tropical cyclone. Radar echoes within this convective ring exceeded 10 km at 2000 UTC 14 September. Furthermore, spiral cloud bands of convective showers, substantiated by radar, continued to extend outward 500 km from the vortex center.

The movement of the convective ring was clearly evident in the time series from buoy 45008 (Fig. 7). Prior to passage (when the center was north of the buoy), winds were from the west at speeds near 15 m s^{-1} between 0600 and 1100 UTC. As the system center shifted southwestward and passed nearly over the buoy around 1500 UTC 14 September, winds backed to the southeast and diminished to speeds below 5 m s^{-1} (it was at 1500 UTC 14 September that the cyclone's minimum central pressure of 993.5 hPa was reported). Soon after the center passed south of buoy 45008, winds veered to the east-northeast and rapidly increased, briefly achieving tropical storm strength gusts at 1800 UTC. Figure 7a also shows the air temperature at buoy 45008 rising from 13° to 17°C between 1000 and 1500 UTC. It is surmised that the increase occurred as the rain-cooled environment of the southern "eyewall" moved past the buoy and the subsaturated air of the system's center crossed over the buoy, thus allowing the air temperature to approach the 18°C lake temperature. Interestingly, as the rain-cooled environment of the northern "eyewall" moved over the buoy, the air temperature fell back to 13°C at 1900 UTC.

In contrast to the early phase of the cyclone when the mass and wind perturbations were strongest aloft, the latter phase was characterized by a shift in the cyclone's intensity toward the surface. Figure 10 summarizes how the system's amplitude changed with respect to both time and location at the mandatory levels throughout its life cycle. Note the clear tendency for the cyclone's height falls to be greatest in the *lower troposphere* with the greatest deepening occurring at the surface.[2] Total height falls of the system between 1200 UTC 11 September and 1200 UTC 14 September were 143 m (surface), 130 m (850 hPa), 100 m (700 hPa), 40 m (500 hPa) and 30 m (300 hPa). It is interesting to note that height *rises* of 30 m occurred farther aloft at 200 hPa between 1200 UTC 12 September and 1200 UTC 14 September. The pattern of height rises at 200 hPa and height falls below that level are similar to what is observed in tropical cyclones and suggests that the deepening mechanism was not governed by baroclinic processes that normally dominate extratropical cyclogenesis. In this case, the deepening is hypothesized to be mainly a result of sensible and latent heat exchanges from the Great Lakes, especially Lake Huron.

It is also interesting to note that the most rapid intensification occurred when the system became vertically stacked (between 1200 UTC 13 September and 1200 UTC 14 September). It is surmised that the stacking of the closed cyclonic circulation and subsequent reduction of vertical wind shear served to concentrate the sensible and latent heat fluxes thereby aiding the rapid deepening, similar to what is observed in tropical cyclones. Also, note in Fig. 10 how the steady deepening of the cyclone occurred first at the surface and lastly aloft at 500 and 300 hPa. Because the low in its early stages was tilted toward the northwest with height, it is surmised that the surface low deepened first because it came in contact with the diabatic heating source of the Great Lakes prior to the cyclone's upper center.

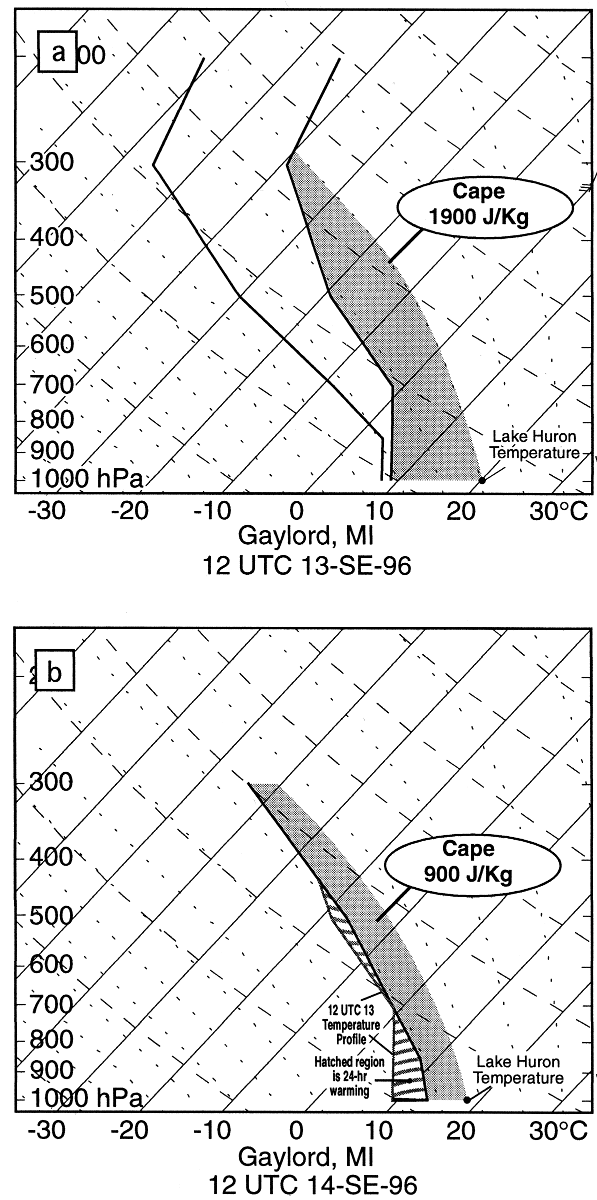

FIG. 8. Upper-air soundings from Gaylord, MI, valid at (a) 1200 UTC 13 Sep 1996 and (b) 1200 UTC 14 Sep 1996. The dewpoint for (b) has been removed so that the temperature trace from the 1200 UTC 13 Sep Gaylord sounding could be shown. Note the tropospheric warming, which occurred during this 24-h period. Nearby lake temperatures are indicated on soundings. Shaded regions indicate maximum amount of undiluted CAPE.

[2]Surface height falls were computed by converting surface sea level pressure to height using the approximation that 8 hPa equals 60 m.

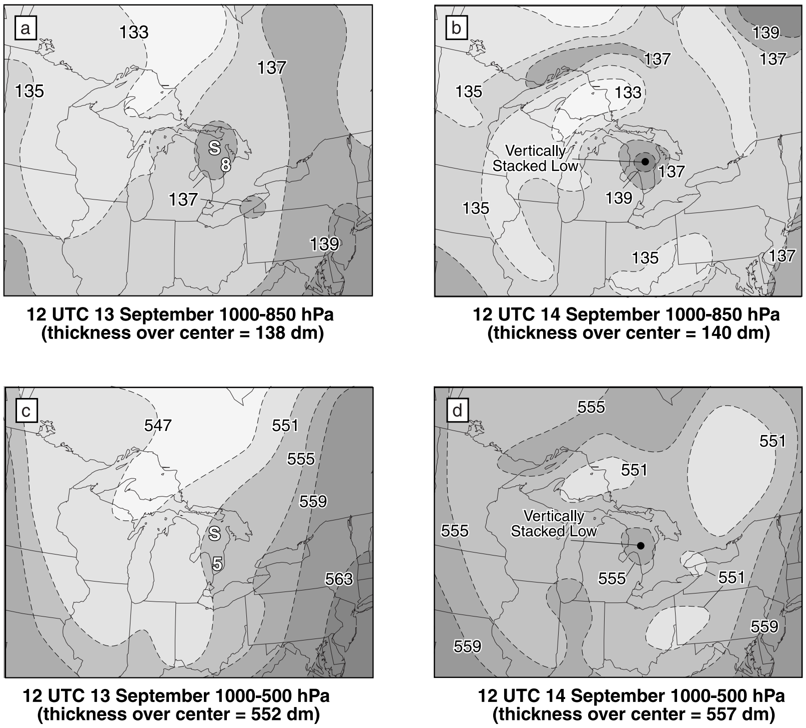

FIG. 9. Objective analysis of thickness (dm) where the positions of the surface 850- and 500-hPa centers are noted by S, 8, and 5, respectively. Note how a positive thickness anomaly develops over the low center, suggesting its change to a warm-core system. (a) 1200 UTC 13 Sep, 1000–850 hPa; (b) 1200 UTC 14 Sep, 1000–850 hPa; (c) 1200 UTC 13 Sep 1000–500 hPa; and (d) 1200 UTC 14 Sep, 1000–500 hPa.

An estimate of the cyclone's geostrophic wind prior to it reaching Lake Huron at 1200 UTC 11 September inditcated the system was weakest at the surface and strongest aloft at 300 hPa (Fig. 10). Upon reaching Lake Huron, the geostrophic wind increased rapidly in the lower troposphere while a weakening occurred above 500 hPa (Fig. 10). Computed geostrophic wind changes during the time of most rapid intensification (from 1200 UTC 13 September to 1200 UTC 14 September) include +7 m s^{-1} (surface), +10 m s^{-1} (850 hPa), +4 m s^{-1} (700 hPa), +6 m s^{-1} (500 hPa), and −14 m s^{-1} (300 hPa). Observationally, low-level increases and upper-level decreases in wind speed during the system's life cycle caused the strong vertical wind shear initially present in the cyclone to diminish. In fact, by 1200 UTC 14 September, similar wind speeds were noted at the surface and 500 hPa.

d. Cyclone weakens
0000 UTC 15 SEPTEMBER 1996–1200 UTC 15 SEPTEMBER 1996

The cyclone drifted slowly eastward so that by 1200 UTC the 500-hPa low was situated just east of Lake Huron (Fig. 11a). Surface analyses indicated that a substantially weaker cyclonic circulation (cf. Figs. 11b and 6b) persisted over the eastern shore (Fig. 11b) of Lake Huron with another center apparently north of Lake Ontario. During this 12-h period, the cyclone weakened significantly, particularly in the lower troposphere. Twelve-hour height rises of the system included +60 m (surface), +20 m (850 hPa), +20 m (700 hPa), +30 m (500 hPa), and +20 m (300 hPa), with no change noted at 200 hPa. Significant decreases in geostrophic wind speeds also occurred below 300 hPa during the 24-h period ending 1200 UTC 15 September (see Fig. 10).

Using these geostrophic wind calculations and height changes as an indicator of the system's strength, the data clearly show a tendency for the cyclone's weakening to be greatest near the surface. It is important to note that the large decreases in surface lake temperature that occurred between 1800 UTC 14 September and 1200 UTC 15 September near the vortex center (Fig. 7c) significantly reduced the sensible and latent heat fluxes from Lake Huron, likely aiding in both the cyclone's decay and departure from its over-lake position. To illustrate, the time series in Figs. 7e and 7f show total heat fluxes decreasing from near 700 W m^{-2} at 1200 UTC 14 September to values less than 100 W m^{-2} by 1200 UTC 15 September at buoy 45008.

3. Closing remarks

An intense cutoff low developed over the Great Lakes during the period 11–15 September 1996. The low began as a cold-core baroclinic system embedded within an unseasonably cool air mass in central Canada. The surface low moved slowly southeastward from northern Lake Michigan to Lake Huron where the center stalled during a time at which the Great Lakes were near climatological peak temperature. Aloft, the low followed a similar trajectory except that for a brief period between 1200 UTC 13 September and 0000 UTC 14 September the cyclone moved east of the lake. As the cyclone matured, eastward progression slowed, sea level pressure fell, and deepening occurred more at the surface than at upper levels. The low generated sustained winds of 18 m s^{-1}, wind gusts of 23 m s^{-1}, and waves on the Great Lakes near 3 m. Heavy rain, which exceeded 100 cm in a few locations, produced flooding on the northeast side of Lake Erie near Buffalo, New York, and also to the east of Lake Huron over Ontario, Canada (Fig. 2). The low eventually developed an eye, spiral rainbands, and a warm core. From a satellite perspective, this system resembled a hurricane. It is thought to be the first time that such a low has been observed over the Great Lakes.

The Great Lakes, in particular, Lake Huron, are hypothesized to have played a significant role in the system's development. Several aspects of the system's evolution support this notion. The first aspect is that the low slowed its progression as it moved toward the eastern Great Lakes while deepening from 1000 to 993 hPa. Studies (e.g., Cox 1917; Danard and Rao 1972; Boudra 1981; Sousounis and Fritsch 1994) have documented how the Great Lakes can attract and deepen synoptic-scale lows during the winter. These effects are caused by strong heat and moisture fluxes that can warm low levels of the atmosphere and account for a 6–7-hPa drop in sea level pressure (Petterssen and Calabrese 1959).

The second aspect is that the large contrast in temperature between the lakes and the overlying air caused substantial sensible and latent heat fluxes over portions of the cyclone's horizontal domain throughout its life cycle. At times, combined surface sensible and latent heat fluxes approached values comparable to those that occur during strong wintertime cold air outbreaks over the Great Lakes, as well as to those for polar lows and category one hurricanes. The 11–15 September case differed considerably from the typical wintertime case in several important aspects, however. In contrast to the typical winter lake-effect case, latent heat fluxes were considerably higher than sensible fluxes. In addition, static stability analyses depicted a deep layer of conditionally unstable air over the lakes that extended to the tropopause. This large layer of conditional instability ultimately assured that convective

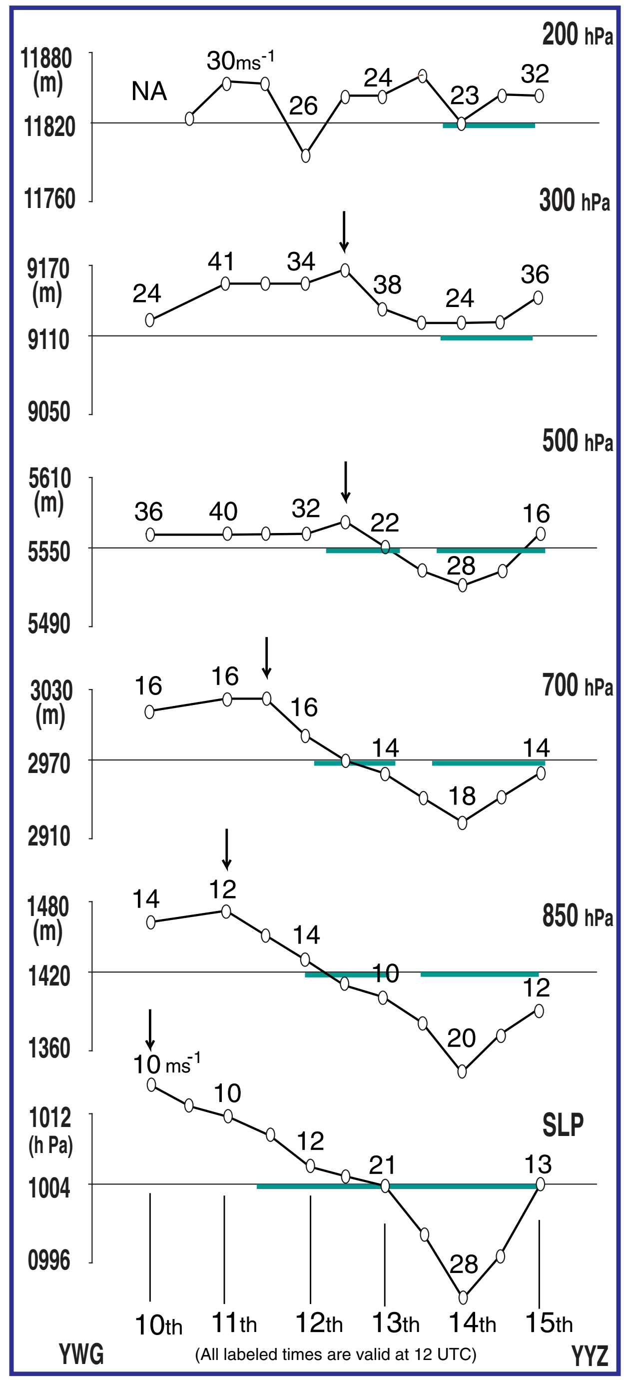

FIG. 10. Positions and heights of the cyclone at the mandatory pressure levels (open circles) every 12 h from 1200 UTC 10 Sep to 1200 UTC 15 Sep along a cross section from Winnipeg, MB (YWG), to Toronto, ON (YYZ). Numbers above the open circles indicate the estimated geostrophic wind speed. Vertical scales show heights in meters on the pressure levels. Lowest vertical scale shows sea level pressure in hPa but scaled so that 8 hPa equals 60 m. Heavy lines at bottom indicate when each center was over the waters of Lake Huron. Note the tendency for rapid deepening between 1200 UTC 13 Sep and 1200 UTC 14 Sep as the system became vertically stacked over Lake Huron. Intensification (height falls) is most pronounced in the lower troposphere with actual height rises occurring aloft at 200 hPa. Arrows mark the time of steady deepening at each mandatory level.

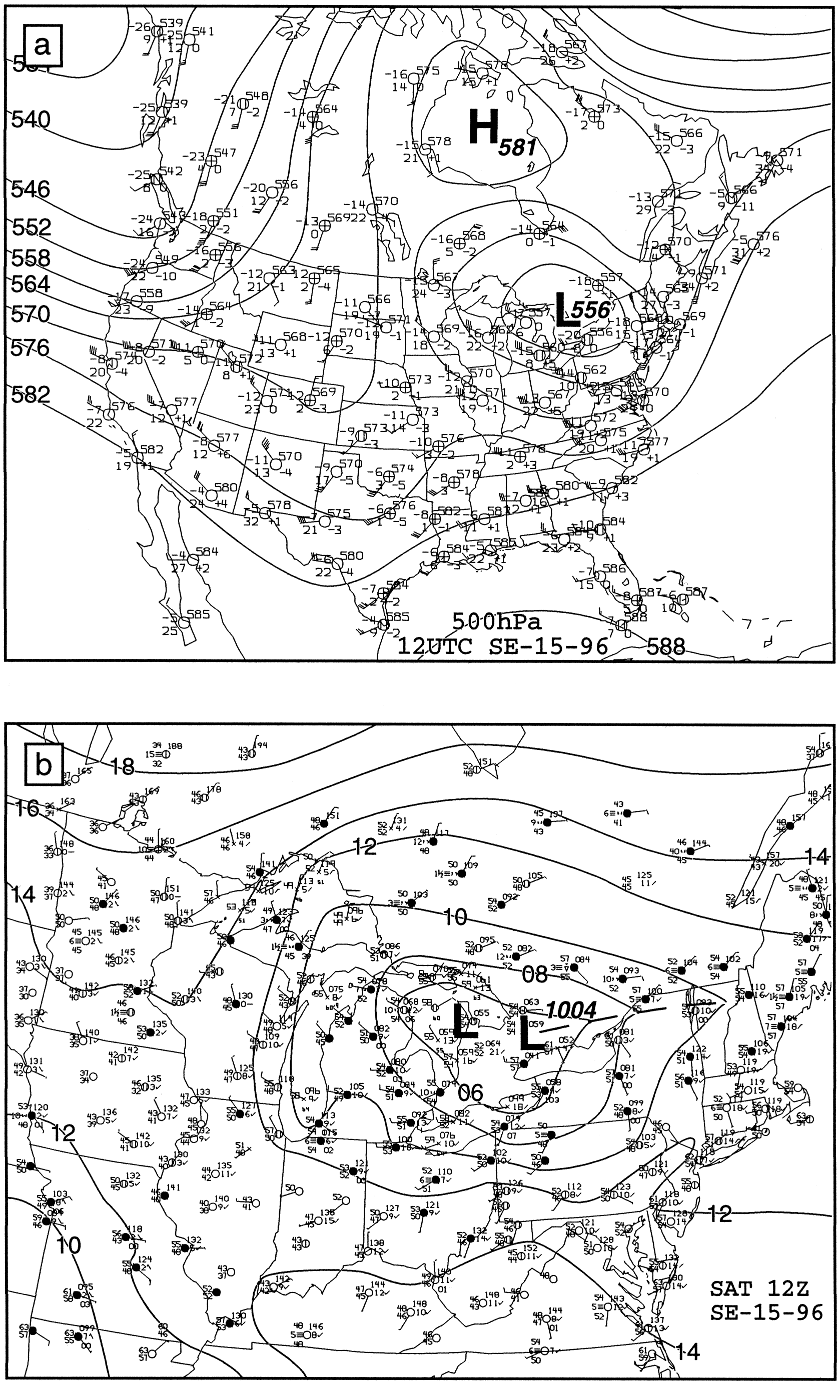

FIG. 11. Subjective analysis of observed conditions valid 1200 UTC 15 Sep 1996. (a) 500-hPa heights (dm). (b) Mean sea level pressure (hPa, leading 10 omitted) with surface observations included.

processes would extend the lakes' diabatic heating throughout the troposphere.

The vertical stacking of the cyclone, the reduced wind shear environment, and the low's slow movement served to concentrate the sensible and latent heat fluxes near the system's center for a long duration. Not surprisingly, tropospheric thickness analyses show that the system evolved from a cold-core to a warm-core system as evidenced by increases in the 1000–850- and 1000–500-hPa thicknesses near the center. Hydrostatically, these heat fluxes integrated over the life cycle of the cyclone contributed significantly to the system's height/pressure falls and likely resulted in the cyclone's tendency to strengthen much more at lower levels than at upper levels.

The third aspect is evident in the cyclone's marked weakening, which occurred in concert with the large (5°C) drop in water temperature over much of Lake Huron. The lower water temperatures helped to greatly reduce the heat fluxes over Lake Huron from near 700 W m^{-2} at peak intensity time at 1200 UTC 14 September to less than 100 W m^{-2} by 1200 UTC 15 September.

Another interesting aspect of this system concerned its development and rapid intensification over a unique topographical region. Near the time of peak intensity, roughly one-half of the vortex circulation lay over water while the other half was over land. More specifically, the system's core ("eye," "eyewall," and inner spiral bands) was over Lake Huron while the outer portions of the vortex lay over land. However, it is importnat to note that the outer bands of the system did occasionally rotate over the other four Great Lakes, gaining further heat and moisture fluxes upon crossing them. In fact, the excessive rainfall northeast of Lake Erie (> 100 mm) can be attributed to these outer bands. In contrast, the time of most rapid intensification for most tropical systems occurs when the *entire* system lies over water. The present case seems to illustrate that surface-driven vortex intensification may occur when only a *portion* of the system is receiving an input of sensible and latent heat flux from the water. This may be especially true when the overwater heat flux is quite large and located about the system's center. Also interesting is the potential that the overland spiral bands may have been intensified during the day, since satellite imagery revealed breaks in the cloud cover across the surrounding land. The solar heating over the land and subsequent radiative heat flux may have strengthened the overland outer bands, potentially having a dynamical effect on the vortex core.

A more quantitative thermodynamic analysis may reveal other physical processes besides the diabatic heating from the Great Lakes that could have caused the system's deepening. Hirschberg and Fritsch (1993) noted that positive thermal advections in both the troposphere and stratosphere can cause a cyclone's heights to lower. In this case, however, the time of maximum intensification below 200 hPa occurred when the cyclone was vertically stacked from the surface through 200 hPa, suggesting that thermal advections would be negligible. In addition, cyclone intensification can also be connected to stratospheric warming from high-level subsidence. Hydrostatically, one would expect to observe 200-hPa height *falls* in a case of stratospheric compressional warming. In this case, however, 200-hPa heights actually *rose* during the cyclone's intensification, suggesting that stratospheric compressional warming was not contributing to the cyclone's deepening.

Given the spatial and temporal limitations of the observations, it is realized by the authors that it is impossible to precisely quantify the impact that Lake Huron and the other four Great Lakes had on the cyclone's development. However, the evidence presented in this study strongly suggests a link between the system's intensification and the Great Lakes. In order to provide additional insight, a companion study by Sousounis et al. (1999, manuscript submitted to *Bull. Amer. Meteor. Soc.*) uses numerical simulations to examine more quantitatively the impact that the heat and moisture fluxes from the Great Lakes had on the system's development.

Acknowledgments. Thanks are extended to the Meteorology Department at The Pennsylvania State University, especially the Weather Communications Group whose generous use of computing facilities helped to make the project possible. Thanks are also extended to Bob Hart and Mike Fritsch for their keen incite and technical support at various points during the project. This project was supported in part by NSF Grant ATM-9502009.

References

Agee, M., and J. J. Lidrbauch, 1989: An observational case study of a continental mesoscale vortex. *Tellus,* **41A,** 222–245.

Albright, M. D., R. J. Reed, and D. W. Owens, 1995: *Tellus,* **47A,** 834–848.

Barnes, S. L., 1964: A technique for maximizing detail in numerical weather map analysis. *J. Appl. Meteor.,* **3,** 396–409.

Billing, H., I. Haupt, and W. Tonn, 1983: Evolution of a hurricane-like cyclone in the Mediterranean Sea. *Beitr. Phys. Atmos.,* **56,** 508–510.

Bjerknes, J., and H. Solberg, 1926: The evolution of cyclones. *Geofys. Publ.,* **3,** 1–14.

Boudra, D. B., 1981: A study of the early winter effects of the Great Lakes, Part I: Comparison of very fine scale numerical simulations with observed data. *Mon. Wea. Rev.,* **109,** 2507–2526.

Bussinger, S., and R. J. Reed, 1989: Polar lows. *Polar and Arctic Lows,* P. F. Twitchell, E. A. Rasmussen, and K. L. Davidson, Eds., A. Deepak Publishing, 3–45.

——, and J. J. Baik, 1991: An arctic hurricane over the Bering Sea. *Mon. Wea. Rev.,* **119,** 2293–2322.

Carlson, T. N., 1991: *Mid Latitude Weather Systems.* Harper Collins Academic, 507 pp.

Cox, H. J., 1917: Influence of the Great Lakes upon movement of high and low pressure areas. *Proc. Second Pan Amer. Sci. Congr.,* **2** (2), 432–459.

Danard, M. B., and G. V. Rao, 1972: Numerical study of the effects of the Great Lakes on a winter cyclone. *Mon. Wea. Rev.,* **100,** 374–382.

Ernst, J. A., and M. Matson, 1983: A Mediterranean tropical storm? *Weather,* **38,** 332–337.

Forbes, G. S., and J. H. Merritt, 1984: Mesoscale vortices over the Great Lakes in wintertime. *Mon. Wea. Rev.,* **112,** 377–381.

Hirschberg, P. A., and J. M. Fritsch, 1993: A study of the development of extratropical cyclones with an analytic model. Part I: The effects of stratospheric structure. *J. Atmos. Sci.,* **50,** 311–327.

Holroyd, E. W., 1971: Lake effect cloud bands as seen from weather satellites. *J. Atmos. Sci.,* **28,** 1165–1170.

Mayengon, R., 1984: Warm core cyclones in the Mediterranean. *Mar. Wea. Log,* **28,** 6–9.

National Data Buoy Center, 1997: NDBC data availability summary. NOAA Tech. Document 96-03, National Data Buoy Center, 82 pp. [Available from National Data Buoy Center, Stennis Space Center, MS 39529–6000.]

Petterssen, S., and P. A. Calabrese, 1959: On some weather influences due to warming of the air by the Great Lakes in winter. *J. Meteor.,* **16,** 646–652.

Rasmussen, E., 1981: An investigation of a polar low with a spiral cloud structure. *J. Atmos. Sci.,* **38,** 1785–1792.

——, 1989: A comparative study of tropical cyclones and polar lows. *Polar and Arctic Lows,* P. F. Twitchell, E. A. Rasmussen, and K. L. Davidson, Eds., A Deepak Publishing, 47–80.

——, and C. Zick, 1987: A subsynoptic vortex over the Mediterranean with some resemblance to polar lows. *Tellus,* **39A,** 408–425.

Shewchuck, J. D., 1997: *The Complete RAwinsonde OBservation Program.* User's Guide. Environmental Research Services, 39 pp. [Available from Environmental Research Services, 1134 Delaware Dr., Matamoras, PA 18336.]

Sousounis, P. J., 1997: Lake aggregate mesoscale disturbances, Part III: Description of a mesoscale aggregate vortex. *Mon. Wea. Rev.,* **125,** 1111–1134.

——, and J. M. Fritsch, 1994: Lake aggregate mesoscale disturbances. Part II: A case study of the effects on regional and synoptic-scale weather systems. *Bull. Amer. Meteor. Soc.,* **75,** 1793–1811.