AN ANOMALOUS NON-CONVECTIVE HIGH WIND EPISODE OVER UPPER MICHIGAN

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Abstract

Several stations in northwestern Upper Michigan observed wind gusts over 40 kt behind a well-developed low pressure system during the evening and overnight hours of 6-7 April 1997. Observed data and gridded-model output show the strong winds occurred in considerable low-level cold advection along and behind a secondary cold front and beneath a strong inversion that decoupled the lower layers from aloft. A comparison between this event and an episode of high winds observed in Lower Michigan and Wisconsin during the afternoon of 6 April 1997 suggests the conditions supporting the high winds observed over Upper Michigan did not fit an established high wind model.

1. Introduction

One problem faced by operational forecasters is where and when to forecast high winds within the strong gradient flow around a region of well-developed low pressure. Quite often, the highest surface winds occur for only brief periods in the area affected by the storm, and not necessarily where the pressure and thickness gradients are the most significant.

Failure to forecast high winds can have life-threatening consequences as well as severe and negative economic implications. During the winter, high winds can cause dangerously low wind chills and reduced visibility accompanying blowing snow. Drivers not alerted to the potential for blizzard conditions might become stranded along the road and perish in the extreme conditions that result. A major airport affected by unforecasted high winds will experience numerous aircraft delays, and disruptions in the national air traffic control system may result as well.

During the evening and overnight hours of 6-7 April 1997, west winds gusted over 40 kt at some stations in northwestern Upper Michigan along and behind a secondary cold frontal passage in the wake of a deepening low pressure center in Ontario. These strong winds blew down some electrical lines over the Keweenaw Peninsula and caused several power outages. This paper will show that these damaging winds occurred under conditions not normally associated with high wind events. The presence of a sharp inversion around 850 hPa, along with light winds and weak upward motion in the middle troposphere near the closed low pressure system aloft are indicative of the anomalous nature of this event, and suggest other processes contributed to the observed strong surface winds. An analysis of observed and gridded forecast data shows low-level cold air advection (CAA) and a strong isallobaric wind component were the primary catalysts.

2. Background

Kapela et al. (1995) identified the following atmospheric processes as key to the occurrence of high (or strong) winds behind a cold front: 1) a tight pressure gradient and a strong geostrophic wind; 2) a vigorous shortwave moving from northwest to southeast in the region to the northeast of the area of interest; 3) a tight isallobaric gradient between the atmospheric pressure rise and fall maxima; 4) a nearby strong upper-level jet streak; 5) strong subsidence behind the front to transport higher winds aloft closer to the surface; 6) strong CAA to increase subsidence and the isallobaric maximum; 7) steep low-level lapse rates to enhance mixing of strong winds aloft to the surface; 8) the storm's dry slot overhead to signify the proximity of the upper-level jet and increase surface heating/instability; and 9) lack of directional wind shear in the lower troposphere, which indicates considerable downward transport of momentum to the ground.

Niziol and Paone (2000) presented a climatology of high wind events in western New York state. Although they found shortwaves that produce high winds in the eastern Great Lakes area typically move from southwest to northeast in the region to the northwest of western New York, their study otherwise corroborated the findings of Kapela et al. (1995).

When enough of these processes come into phase over a point following a cold frontal passage, the forecaster should anticipate a high wind event. Kapela et al. (1995) defined strong post-cold frontal winds as winds significant enough to cause at least considerable blowing snow such that an advisory or warning would be needed as described by National Weather Service guidelines. The National Weather Service Central Region has defined sustained winds of at least 30 mph (26 kt) for one hour or longer and/or sustained winds or gusts of at least 45 mph (39 kt) for any duration as significant enough to warrant the issuance of a high wind advisory.

3. The 6-7 April 1997 Storm

a. Synoptic overview

Figure 1 shows the presence of a well-developed storm system over the northern plains at 1200 UTC 6 April 1997. Within the storm's dry slot to the southeast of the upper low, Davenport, Iowa (KDVN) reported 500-hPa winds of 105 kt. At this time, a 980-mb surface low pressure center was located near International Falls, Minnesota (KINL). By 0000 UTC 7 April 1997, Figs. 2a and 2b show the occluding storm system had moved to near northern Lake Superior. A water vapor satellite image from 2115 UTC 6 April 1997 (Fig. 3) depicts a well-developed cyclonic circulation centered over western Lake Superior. The storm's dry slot as described in Carlson (1980) is readily apparent on the southern flank of the cyclone center. The drier air noted on the water vapor image in the Red River Valley was associated with subsidence ahead of a trailing shortwave ridge axis.

Although winds aloft over northwestern Upper Michigan were quite light near the closed low center during the evening of 6 April, maximum winds at 500 hPa within the storm's dry slot over Lower Michigan still remained near 100 kt at Detroit, Michigan (KDTX). During the day on 6 April, skies over Wisconsin and Lower Michigan cleared for a time as the dry slot moved overhead. Temperatures rose to around 24°C (75°F) at Detroit before cooling behind the storm's cold front dropped readings into the 40s (°F) after sunset. Surface winds gusted over 45 kt in southeastern Wisconsin and much of Lower Michigan during the afternoon and early evening with several stations in Wisconsin reporting gusts around 70 kt. There were numerous reports of wind-related damage.

The dry slot also cleared skies briefly over southeastern Upper Michigan, and Sault Ste. Marie, Michigan (KANJ) reported a wind gust near 40 kt at 2200 UTC. However, Houghton, Michigan (KCMX), located on the Keweenaw Peninsula, saw little clearing and reported a maximum wind gust of only 26 kt during the early afternoon after the wind had shifted from south to west.

Figure 4 shows a smaller-scale view of the storm system at 0000 UTC 7 April 1997, as well as the winds and temperatures from the 0-h forecast of the 0000 UTC 7 April 1997 Eta model at 15 hPa above the surface. Significant low-level CAA is evident over the entire western Great Lakes

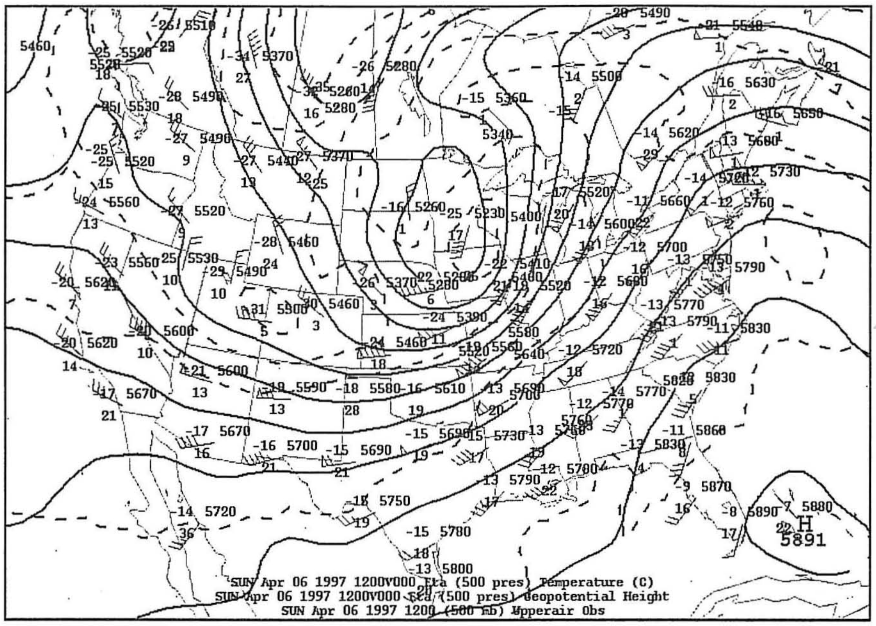

Fig. 1. 500-hPa analysis for 1200 UTC 6 April 1997. Height contours (m, solid) and isotherms (°C, dashed) are from the Eta model 0-h forecast valid at the listed time.

Table 1. Houghton, Michigan (KCMX) surface METAR observations from 2051 UTC 6 April 1997 through 0851 UTC 7 April 1997.

Date/Time	Observation	CHG T (°C)	CHG P (in.)
062051Z	28009KT 10SM - SN OVC016 30/00 A2907	+1	+.02
062151Z	27011KT 20SM - SN OVC020 03/M02 A2910	0	+.03
062253Z	27011G17KT 1 1/2SM - SN OVC020 02/M03 A2912	-1	+.02
062355Z	28015G25KT 1SM - SN OVC004 00/M02 A2916	-2	+.04
070006Z	28015G25KT 3SM - SN OVC020 00/M02 A2916		
070025Z	28018G30KT 3/4SM - SN OVC011 00/M02 A2918		
070051Z	29018G32KT 7SM BKN011 OVC020 00/M06 A2919	0	+.03
070152Z	27018G38KT 10SM OVC016 M02/M05 A2925 RMK **PRESRR PKWND 27048/20**	-2	**+.06**
070254Z	28020G40KT 10SM OVC017 M04/M07 A2928 RMK **PKWND 27055/50**	-2	+.03
070317Z	27020G40KT 1 1/2SM - SN OVC017 M04/M07 A2928		
070350Z	28020G40KT 1 1/2SM - SN OVC015 M05/M07 A2929 **RMK PKWND 27048/40**	-1	+.01
070413Z	28020G32KT 5SM - SN OVC015 M05/M07 A2931		
070451Z	29020G40KT 5SM - SN OVC015 M06/M10 A2934 **RMK PKWND 29042/35 PRESRR**	-1	+.05
070554Z	28020G30KT 3SM BLSN - SN OVC015 M07/M10 A2938 **RMK PKWND 29046/31**	-1	+.04
070652Z	29020G30KT 1/2SM BLSN - SN OVC015 M08/M09 A2941 **RMK PKWND 30050/14**	-1	+.03
070752Z	29020G30KT 1/2SM BLSN - SN OVC015 M08/M10 A2944 **RMK PKWND 30038/52**	0	+.03
070851Z	29020G30KT 1/4SM BLSN SN VV002 M08/M10 A2947	0	+.03

Secondary Cold FROPA 01-02 UTC 7 April 1997:

1. Initial cooling/pressure rise associated with onset of snow.
2. Sharp pressure rise/cooling and increase in gustiness 00-01 UTC.

region, and the winds were highly subgeostrophic in the cyclonic curvature. Although the analyzed fields indicate the storm's primary cold front had swept well east of Michigan by this time, a tighter packing of the isotherms, a wind shift, and surface observations (not shown) reveal the presence of a secondary cold front stretching from extreme northeastern Minnesota through western Upper Michigan into northeastern Wisconsin. Although the 0000 UTC Eta initialization suggests low-level winds were no higher than 25 to 30 kt over western and central Upper Michigan, Houghton and Marquette, Michigan (KMQT), recorded several wind gusts over 45 kt during the evening and overnight hours as this cold front moved east and the surface pressure rose rapidly. Houghton observed the maximum wind in Upper Michigan as 55 kt at 0250 UTC 7 April 1997.

As the secondary cold front continued east and weakened, peak wind gusts diminished. In fact, no station east of Marquette reported any wind gusts in excess of 35 kt after 0000 UTC 7 April 1997. By 1200 UTC 7 April (not shown), the increasingly occluded storm system had moved northeast to near James Bay.

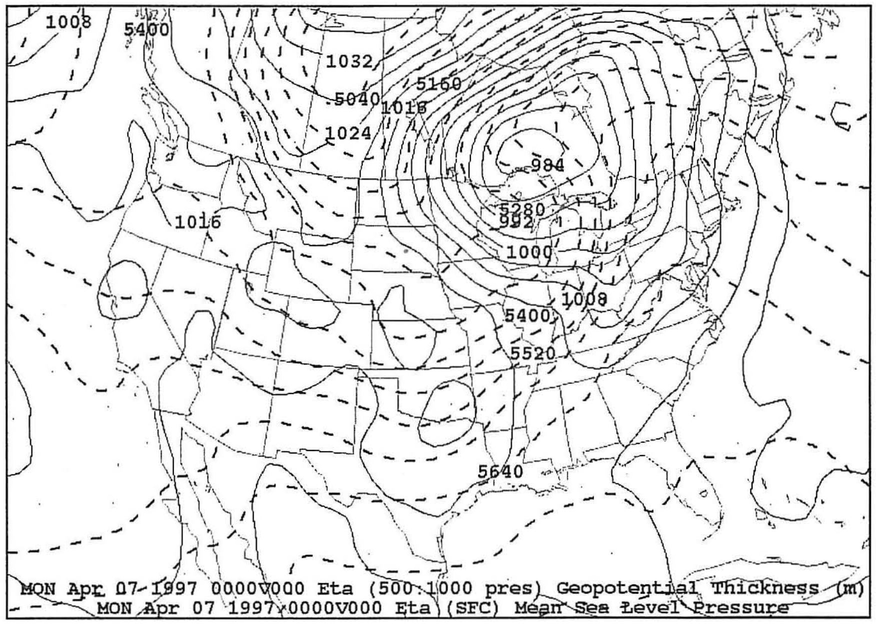

Fig. 2a. 0000 UTC 7 April 1997 Eta model 0-h forecast of mean sea level pressure (hPa, solid) and 1000-500 hPa thickness (m, dashed).

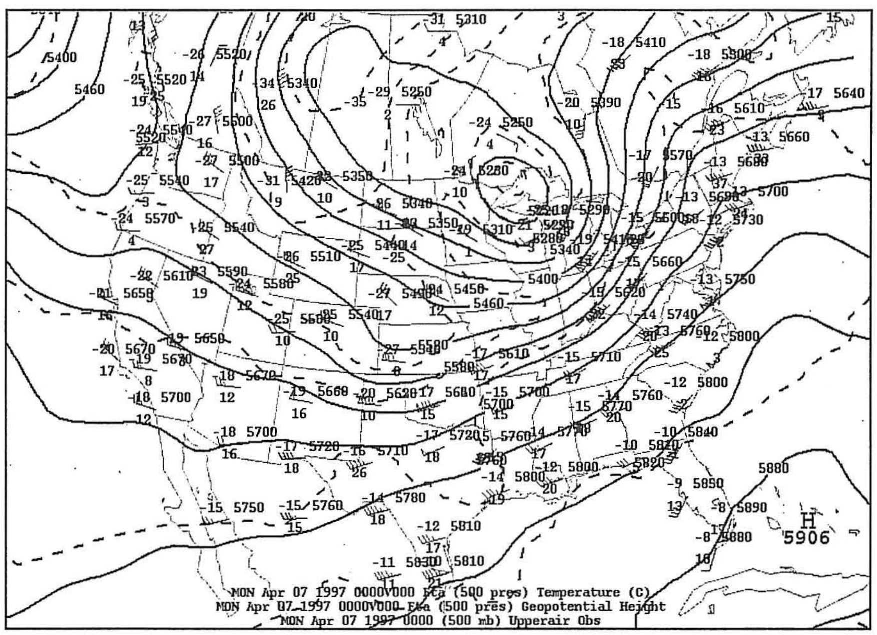

Fig. 2b. As in Fig. 1, except for 0000 UTC 7 April 1997.

b. Discussion

As described above, the storm system of 6-7 April brought two periods of high winds to Michigan. This section will show that the second episode of high winds that affected Upper Michigan occurred under much more anomalous conditions than those which supported the more traditional, widespread first episode of high winds as described by Kapela et al. (1995) that affected mainly Lower Michigan.

Figure 5 shows the 0000 UTC 7 April 1997 Eta 0-h forecast of the dry airstream, described by Carlson (1980) and pictured in Fig. 3, descending over the southern Great Lakes. Wind speeds at 700 hPa within the core of this sinking airstream approached 80 kt near southern Lake Michigan. Note that 0000 UTC 700 hPa winds over northwestern Upper Michigan were only 20 to 25 kt, closer to the upper-level center of low pressure.

The 0000 UTC 7 April 1997 sounding from Detroit (Fig. 6), shows the strong mid-and upper-tropospheric subsidence evident in Fig. 5 created a sharp subsidence inversion over the southern Great Lakes, and transported the higher momentum aloft deep into the lower troposphere with observed winds at 925 hPa exceeding 50 kt at Detroit. Since the high temperature at Detroit on 6 April was 24°C (75°F), an afternoon sounding across southern Lower Michigan would have shown the temperature decreasing at the dry adiabatic lapse rate up to at least 700 hPa. This lapse rate would have enhanced the mixing of the higher momentum air from aloft down to the surface. Although the slight backing of the wind with height in the boundary layer indicates CAA was occurring (see Fig. 4), the considerable mixing appears to have minimized the directional wind shear.

In addition to the tight pressure gradient indicated on Fig. 4 over the southern Great Lakes, a sharp isallobaric gradient existed as well during the late afternoon. The 2100 UTC 6 April 1997 surface observation from Minneapolis, Minnesota (KMSP) indicated pressure rising rapidly with a 3-hour rise of 6.2 hPa. During the same 3-h period, the pressure fell 3.1 hPa at Detroit. The isallobaric wind component likely enhanced the total wind

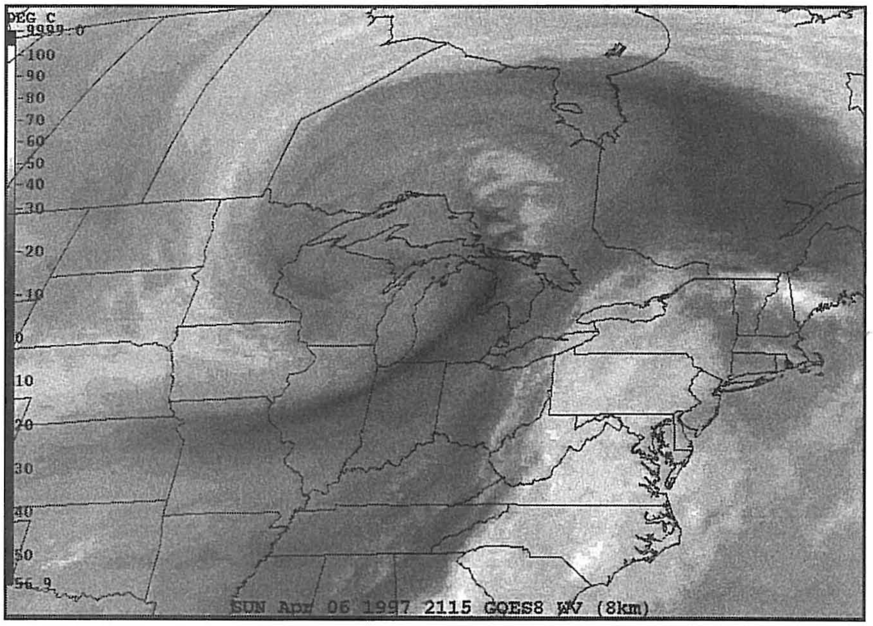

Fig. 3. 2115 UTC 6 April 1997 GOES-8 water vapor (6.7-μm) image.

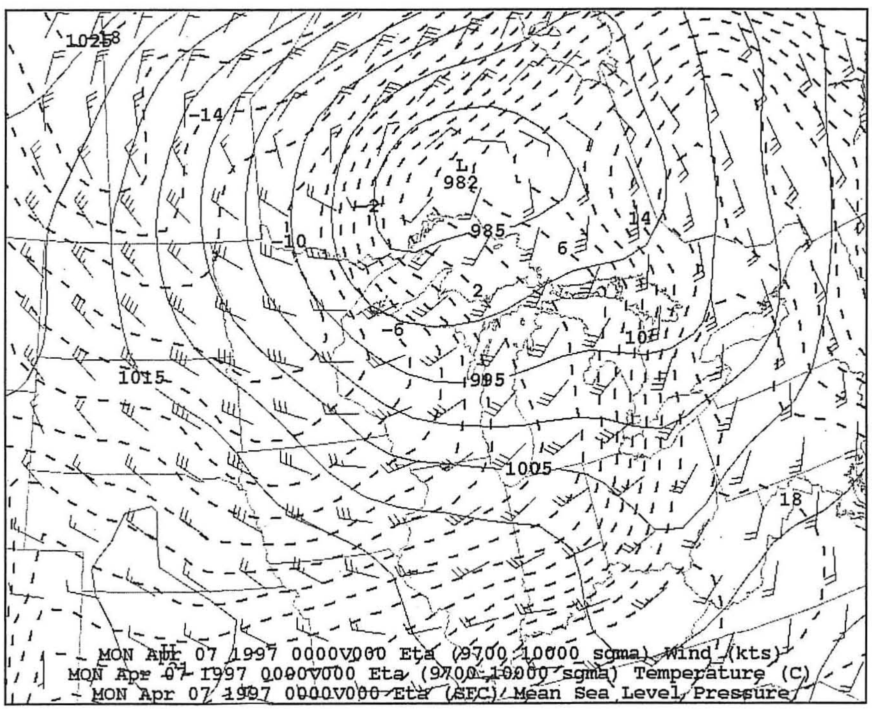

Fig. 4. 0000 UTC 7 April 1997 Eta model 0-h forecast of mean sea level pressure (hPa, solid), boundary layer temperature (°C, dashed) and wind barbs (standard notation).

observed over the southern Great Lakes. So, all nine high wind enhancement factors identified by Kapela et al. (1995) and listed above came into phase over the southern Great Lakes during the afternoon of 6 April. The observed wind gusts up to 70 kt and damage reports verified the significance of this event.

The 0000 UTC 7 April 1997 sounding from International Falls, Minnesota (KINL; Fig. 7) contrasts sharply with that from Detroit. Although a very strong inversion was also present at International Falls, the base of this inversion near 850 hPa was much lower than at Detroit. While the descending dry airstream on the southern flank of the upper-level low near western Lake Superior caused the inversion at Detroit, International Falls' position just to the northwest of the upper-level low track rules out this mechanism as the cause of the inversion there. Although the mid-level drying over International Falls was probably related to the advection of subsided air behind the upper-level low, the moist inversion there was most likely the frontal inversion above the shallow cold air dome that was observed behind the secondary cold front, as described above. Note the winds throughout the troposphere over International Falls were light.

The Houghton, Michigan (KCMX) observations listed in Table 1 suggest the secondary cold front passed that station around 0100 UTC 7 April 1997. The initial drop in temperature and rise in pressure observed before 0000 UTC were probably related to evaporative cooling accompanying the onset of pre-frontal snow. The increased negative buoyancy associated with evaporative cooling likely mixed higher momentum air parcels from aloft down to near the surface and caused the initial gustiness observed at Houghton. However, the sharp increase in pressure and fall in temperature after 0100 UTC, which was after the snow had ended, strongly suggest a frontal passage. The steep increase in gustiness that reached advisory level at this time also indicates the strong winds were related to the low-level CAA immediately behind the front. The listing of observations from Marquette (not shown) indicates a similar chain of events took place with the frontal passage sometime between 0400 and 0500 UTC. Observations from Green Bay, Wisconsin (not shown) reported a wind gust of 43 kt at 0000 UTC, shortly after cold frontal passage. The 0000 UTC 7 April 1997 Green Bay sounding (not shown but taken near the northern boundary of the descending airstream just before frontal passage) looks similar to the Detroit sounding with a well-mixed layer below a sharp, but moist inversion near 700 hPa. However, boundary layer winds were lighter and ranged from about 30 kt at 925 hPa to 37 kt at 700 hPa.

The 0300 UTC 7 April 1997 surface plot (Fig. 8) suggests the secondary cold front at that time stretched from near Thunder Bay, Ontario to western Lake Michigan. The increasing negative tilt to the storm system and front allowed the colder low-level air to surge eastward faster through Wisconsin than Upper Michigan. In fact, the 0300 UTC geostrophic wind analysis (Fig. 9) shows that the pressure gradient in Wisconsin was considerably tighter than over northwestern Upper Michigan near Houghton, where the geostrophic wind was approximately 35 kt. Maximum wind gusts accompanying the secondary cold front over Upper Michigan exceeded those observed in Wisconsin even though the pressure gradient was weaker, the observed winds aloft were lighter, and the low-level stability was very likely higher.

Note there was a sharp isallobaric maximum (see Fig. 8) observed in northwestern Wisconsin between 0000 and 0300 UTC 7 April 1997 with a 6.2-hPa rise at Hayward, Wisconsin and a 6.6-hPa rise at Ashland, Wisconsin (not shown). The gradient in pressure change across Lake Superior was much larger over northwestern Upper Michigan than farther south. It was about twice as large as over southern Upper Michigan/northern Wisconsin, and three to four times as large as over southern Wisconsin. According to Glickman (2000), the isallobaric wind can be approximated by

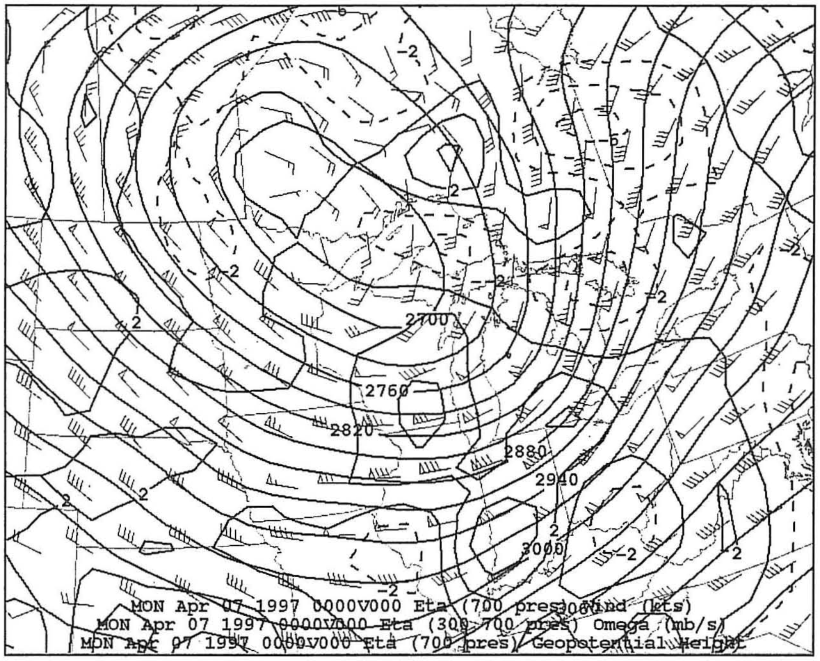

Fig. 5. As in Fig. 4, except for 700-hPa height contours (m, solid) and mean 300-700 hPa omega (μ bs^{-1}; solid > 0, dashed < 0).

$$V_i = \left(\frac{RT}{pf^2}\right)\left(\frac{\Delta\, pressure\ tendency}{\Delta x}\right) \quad (1)$$

where R is the universal gas constant (287 J kg^{-1} K^{-1}), T is temperature (269 K), p is surface pressure (about 950 hPa), f is Coriolis parameter (~10^{-4} s^{-1} at 45°N), and Δx is the horizontal distance along the isallobaric gradient over which the change of pressure tendency is measured. Assuming a 3-h pressure change of 6.5 hPa across Lake Superior (Δx ~ 360 km), the 0300 UTC 7 April 1997 isallobaric wind at Houghton was approximately 26 kt. Since the isallobaric gradient was aligned nearly parallel to the low-level flow, the addition of the isallobaric wind to the gradient flow resulted in a maximized increase in total wind at Houghton. The sharp rise in altimeter setting noted there around 0200 UTC, at the same time the wind gusts increased rapidly (see Table 1), provides supporting evidence that the isallobaric wind was a significant component of the total wind. The magnitude of the isallobaric wind was proportionally diminished farther south where the gradient of pressure change was weaker.

A comparison of the magnitude of the isallobaric wind and the gradient wind reveals just how significant the isallobaric wind component was relative to the total wind at Houghton. According to Dutton (1976), the gradient wind can be approximated by

$$V_{gr} = \frac{V_g}{\left[1 + \left(\frac{V_g}{fR}\right)\right]} \quad (2)$$

where R is the radius of curvature (positive for cyclonic flow) and V_g is the geostrophic wind. For a radius of curvature of 333 km (approximately 3 degrees of latitude from the low-pressure center to the Keweenaw Peninsula) and a geostrophic wind of 35 kt (Fig. 9), the gradient wind was approximately 23 kt. A funneling of air through the nearly west-to-east oriented Portage Canal that bisects the Keweenaw Peninsula and lies just south of Houghton (Fig. 10) very likely enhanced the wind speed observed there through the night, and can explain why the maximum 55-kt wind gust was much higher than observed at other sites and exceeds the 49 kt total wind approximated by the sum of the gradient and isallobaric winds.

Figure 11 shows that the 0000 UTC 7 April 1997 Eta model forecasted a maximum 0000-0600 UTC pressure rise centered over northwestern Wisconsin where Ashland reported a 6.6-hPa rise between 0000 and 0300 UTC. Ashland observed a pressure rise of 10.7 hPa between 0000 and 0600 UTC, which was in excellent agreement with the Eta forecast of nearly 11 hPa. The area of maximum pressure rises correlates well with the area of maximum average near-surface to 850 hPa CAA as depicted by the 0000 UTC 7 April 1997 Eta run, and where the model forecasted this same area at 0600 UTC 7 April (Fig. 12). Recall that CAA maxima imply atmospheric subsidence and pressure rises (Holton 1979; Palmén and Newton 1969).

Recall that the 850-hPa level marked the base of the sharp inversion as depicted on the 0000 UTC 7 April 1997 International Falls sounding (see Fig. 7). In fact, the 0000 UTC 7 April upper-air observations showed (0000 UTC 7 April Eta run forecasted) slight warm air advection (WAA) between 850 and 400 hPa at 0000 (0600) UTC 7 April above the low-level CAA maximum in Upper Michigan. Although CAA developed above 400 hPa after about 0300 UTC, the observed pressure rises line up best with the low-level CAA. This pattern of differential temperature advection likely strengthened and maintained the strong inversion through the night over Upper Michigan, which was coincident with the occurrence of gusty winds at the surface. The 1200 UTC 7 April 1997

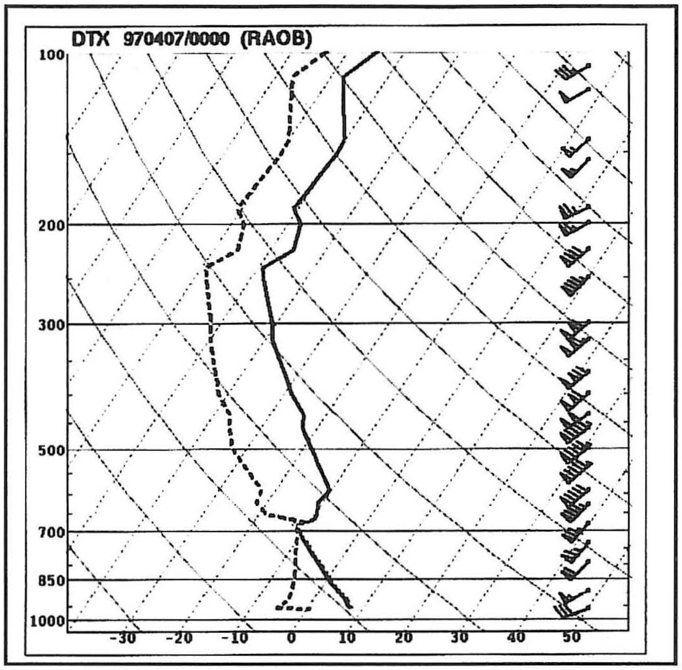

Fig. 6. 0000 UTC 7 April 1997 sounding for Detroit/Pontiac, Michigan (KDTX). Temperature (solid) and dew point (dashed) are in °C. Wind barbs are in standard notation.

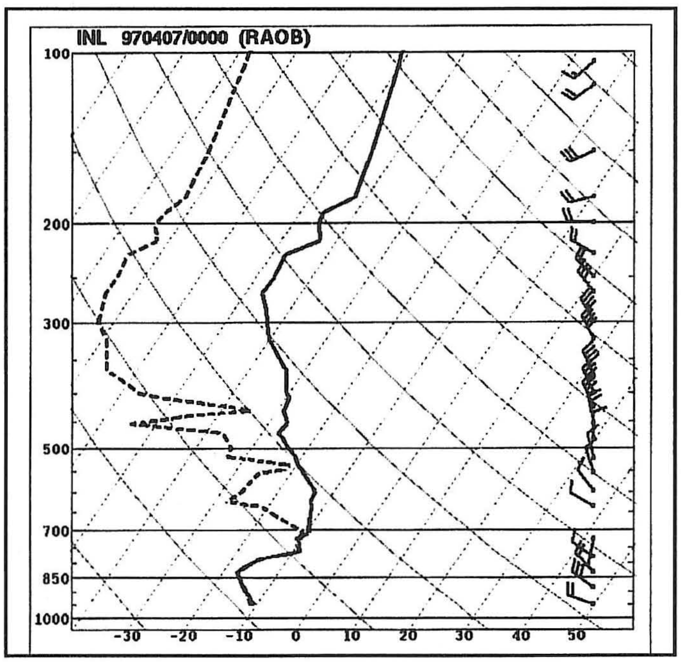

Fig. 7. As in Fig. 6, except for International Falls, Minnesota (KILN).

Green Bay sounding (not shown) indicates a sharp inversion with base near 850 hPa was present overhead. This inversion effectively cut off any mixing down of the limited momentum from the mid-troposphere (see Fig. 5), and rules out this mechanism as a source for the strong surface winds recorded in Upper Michigan that accompanied and followed the secondary cold front.

The surface observations at Houghton (Table 1), at Marquette, and over the rest of Upper Michigan indicate that the maximum wind gusts began to diminish after 0700 UTC 7 April 1997, even though the 0900 UTC geostrophic wind analysis (not shown) indicates the surface pressure gradient had increased or remained constant over Upper Michigan and Lake Superior. Coincidentally, the 0000 UTC 7 April Eta model forecasted the magnitude of the low-level CAA to diminish by 1200 UTC (Fig. 13), and the pressure rises and isallobaric gradient to decrease as well between 0600 and 1200 UTC (Fig. 14). Figure 15 shows the 0900 UTC 7 April 1997 surface plot over the northwestern Great Lakes. The maximum 3-hour pressure rises observed from southern Ontario to Marquette correlate well with where the 0000 UTC 7 April 1997 Eta model run had forecast the greatest pressure increases (see Fig. 14). The isallobaric gradient over eastern Lake Superior and Upper Michigan depicted in Fig. 15 is quite a bit weaker than that observed at 0300 UTC (Fig. 8). A calculation of the isallobaric wind over east-central Upper Michigan using the values in Fig. 15 indicates the magnitude of this flow was about 17 kt, approximately one-third weaker than the value estimated over Houghton at 0300 UTC. Although there were no stations available at the time between Marquette and Sault Ste. Marie (KANJ), the latter station over extreme eastern Upper Michigan never reported a wind gust in excess of 30 kt between 0000 and 1500 UTC 7 April 1997.

4. Summary and Conclusions

Several stations in Upper Michigan recorded surface wind gusts in excess of 40 kt during the evening and overnight hours of 6-7 April 1997 accompanying and following a secondary cold frontal passage in the west flow behind a deep low pressure center over Ontario. Surface and upper-air analyses and forecast fields from the 0000 UTC 7 April 1997 Eta model indicate a good spatial and temporal correlation between the high winds and a strong isallobaric gradient and low-level CAA. However, a sharp inversion and weak midlevel winds and ascent near the closed low pressure center rule out the more traditional downward transport and mixing of momentum as causes of the strong winds. The 55-kt maximum wind gust observed at Houghton was greater than observed at other stations and resulted from a nearly parallel gradient flow and stronger isallobaric wind as well as acceleration of the westerly flow through the nearby Portage Canal. The observed decrease in wind gusts toward dawn on 7 April occurred as the isallobaric gradient and low-level CAA diminished.

This episode of high winds over Upper Michigan contrasted with the occurrence of stronger winds over Wisconsin and Lower Michigan during the daytime hours on 6 April that was associated with the passage of the Ontario cyclone's primary cold front. In that case, all the physical factors identified by Kapela et al. (1995) as conducive to strong winds came into phase. The result was extremely strong winds. The combination of the downward transport of momentum in a subsiding airstream and jet stream that comprised the storm's dry slot, surface thermal instability that mixed the higher winds to the ground, as well as a strong

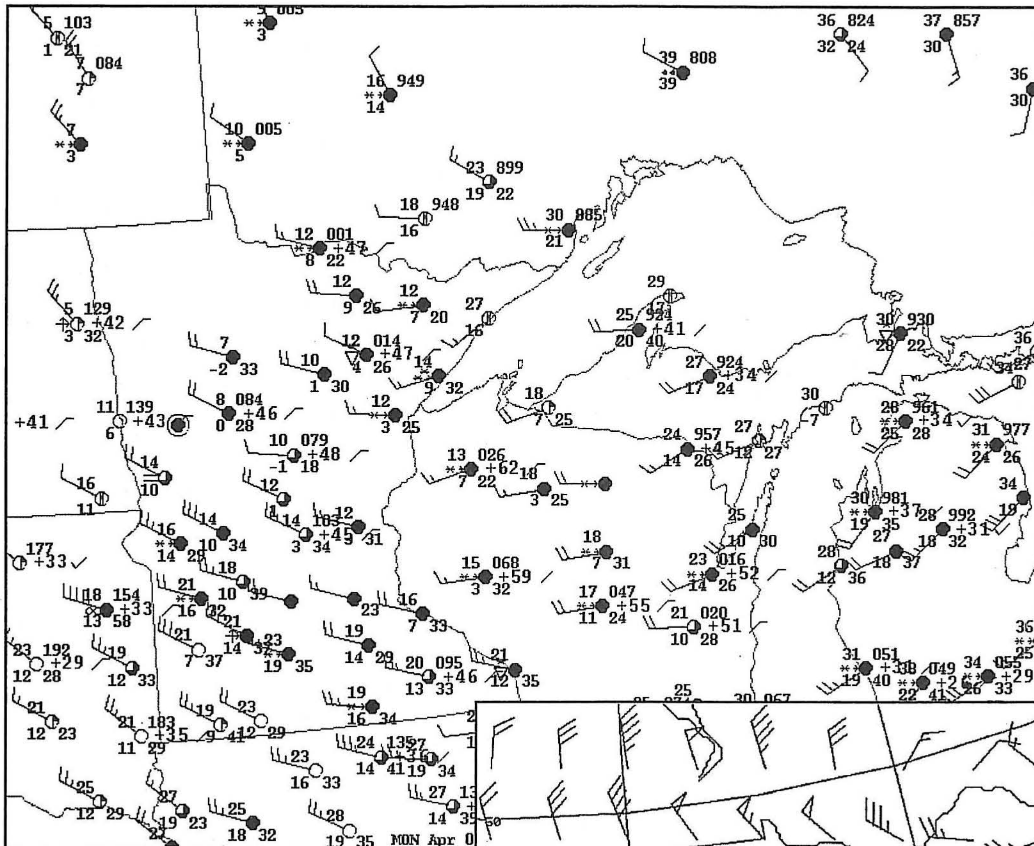

Fig. 8. 0300 UTC 7 April 1997 surface plot. Data are plotted in standard format.

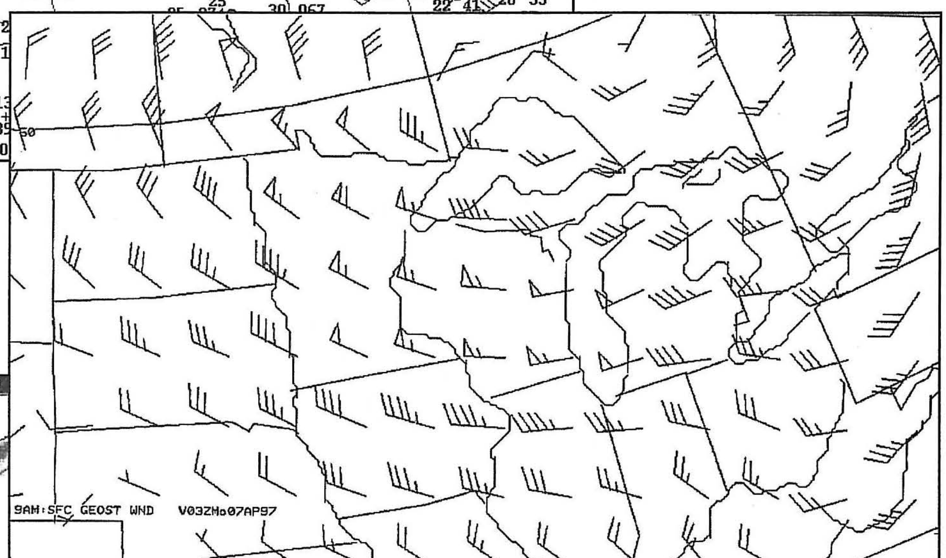

Fig. 9. 0300 UTC 7 April 1997 surface geostrophic wind barbs in standard notation.

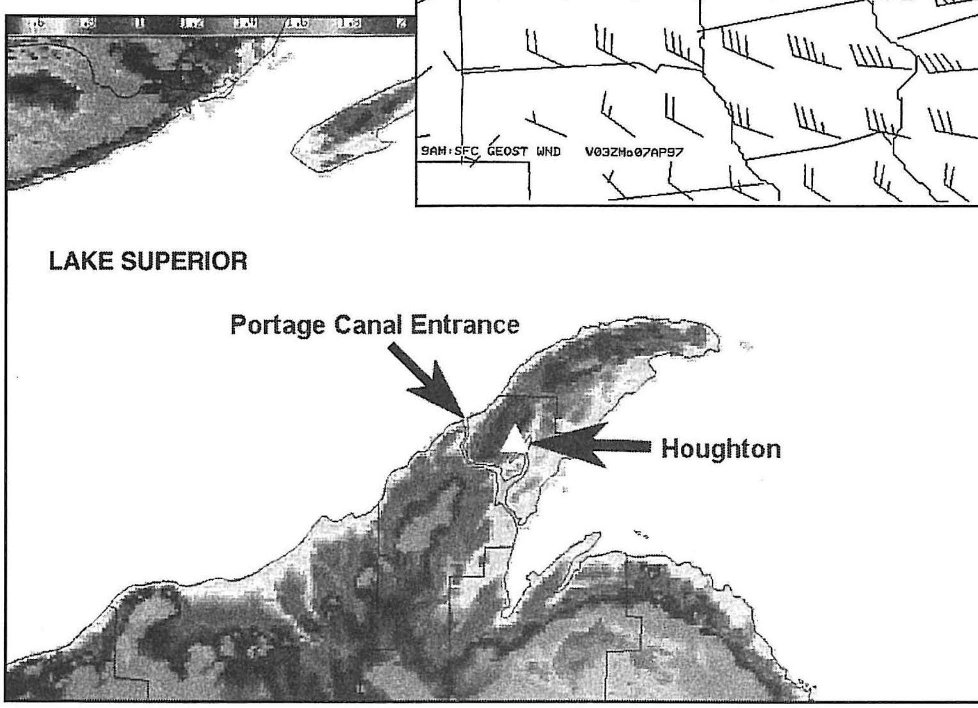

Fig. 10. Map shows the portage canal bisects the Keweenaw Peninsula of upper Michigan. Location of Houghton, Michigan is also shown.

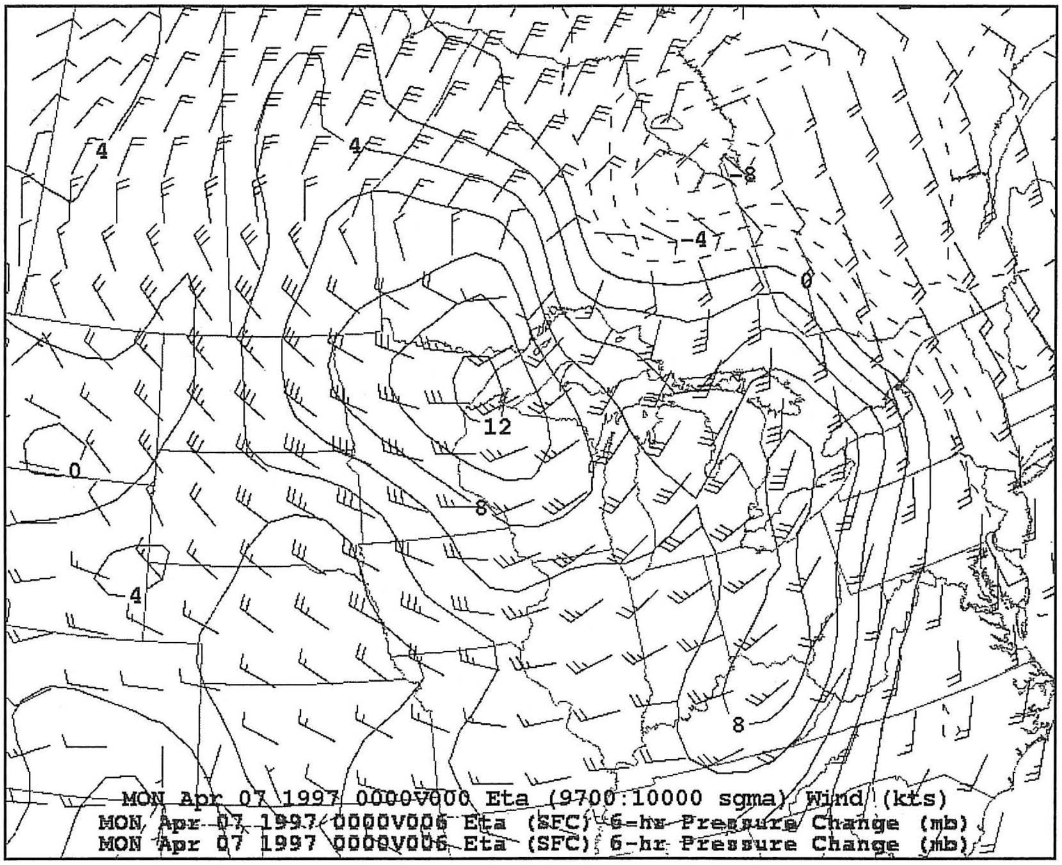

Fig. 11. 0000 UTC 7 April 1997 Eta 0-h forecast of boundary layer wind barbs (standard notation) and 6-h forecast pressure change (hPa; solid ≥ 0, dashed < 0). Note that the pressure change is valid for the period ending at 0600 UTC 7 April 1997.

pressure and isallobaric gradient and CAA caused surface winds to gust up to 70 kt during the late afternoon.

The results from this case study show that the analysis of gridded model data can help greatly to evaluate the potential for high winds in the mesoscale. The most effective tools to diagnose the threat of winds that were related to the physical mechanisms responsible for the Upper Michigan case are a display of forecasted 6-h pressure change and low-level layer-average temperature advection at the appropriate forecast hour.

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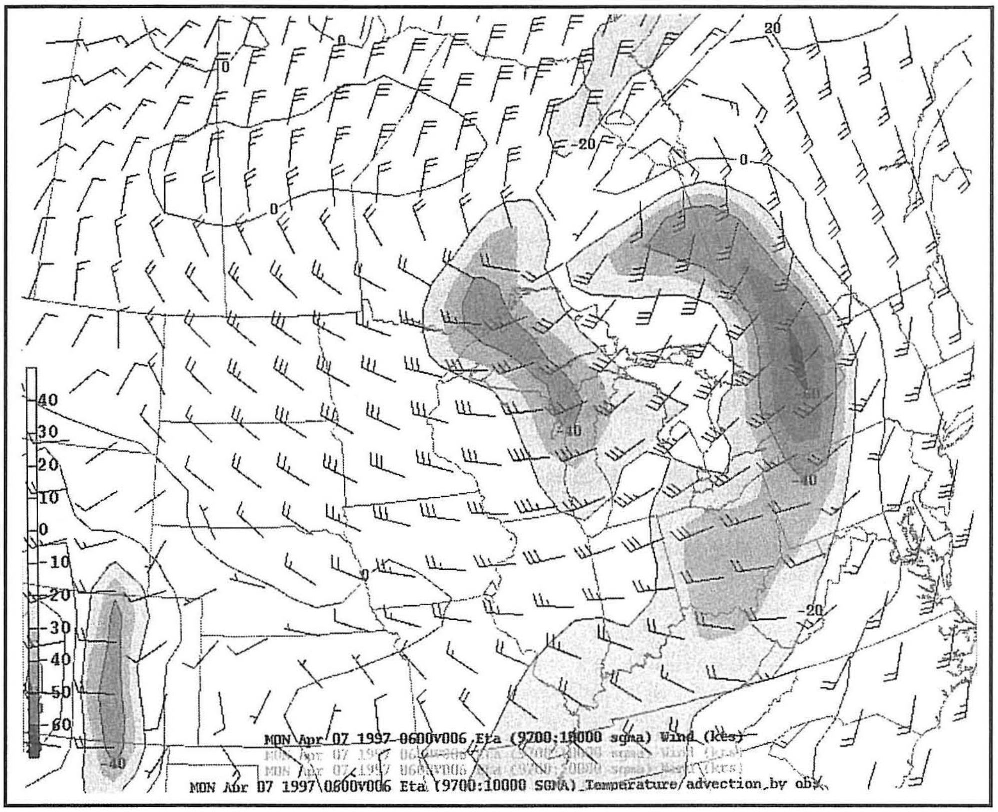

Fig. 12. 0000 UTC 7 April 1997 Eta 6-h forecast boundary layer wind (kt) and average boundary layer-850 hPa temperature advection (10^{-5} °C s^{-1}, solid; shaded < -20), valid at 0600 UTC 7 April 1997.

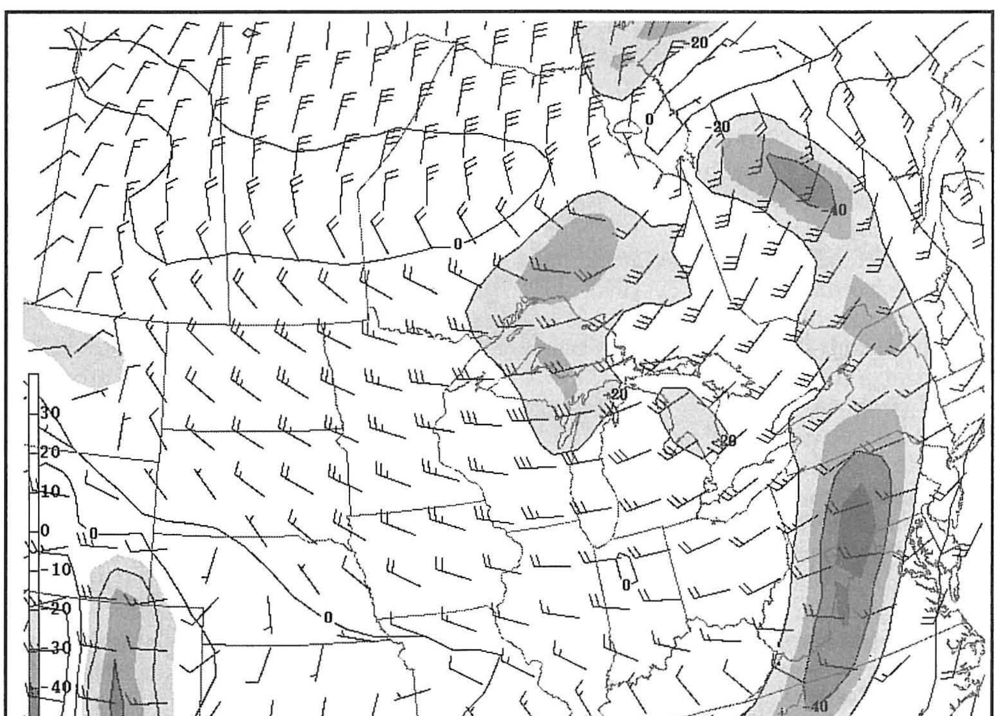

Fig. 13. As in Fig. 12, except 12-h forecast valid at 1200 UTC 7 April 1997.

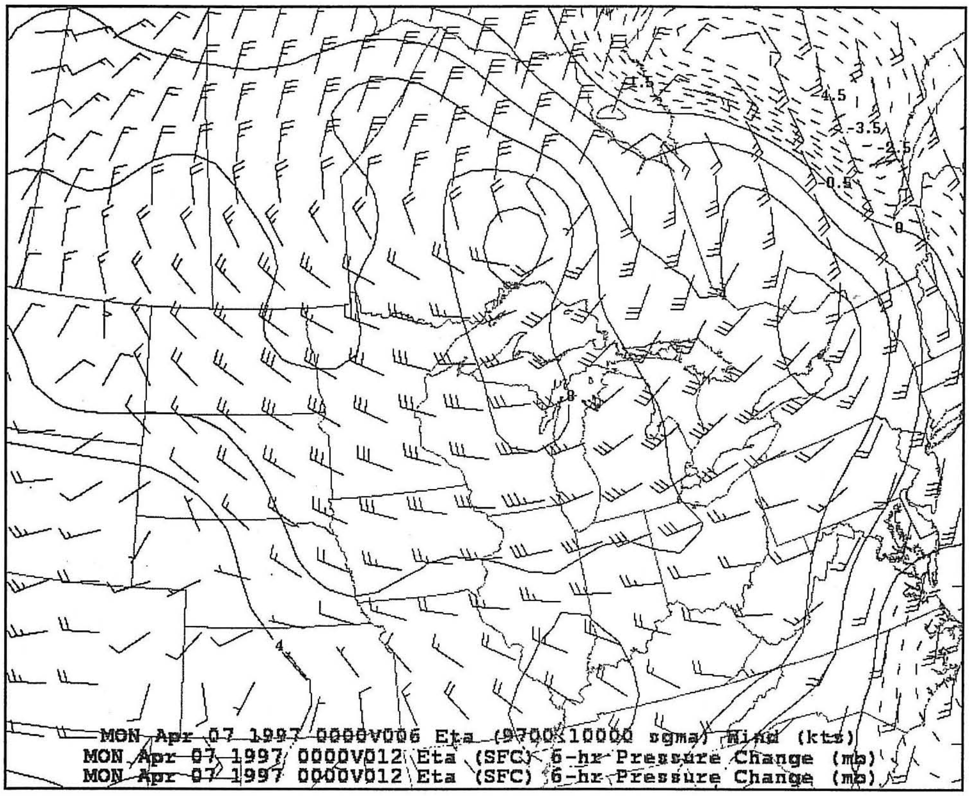

Fig. 14. 0000 UTC 7 April 1997 Eta 6-h forecast of boundary layer wind barbs (standard notation) and 6-h forecast pressure change (hPa; solid ≥ 0, dashed < 0). Note that the pressure change is valid for the 6-h period ending at 1200 UTC 7 April 1997.

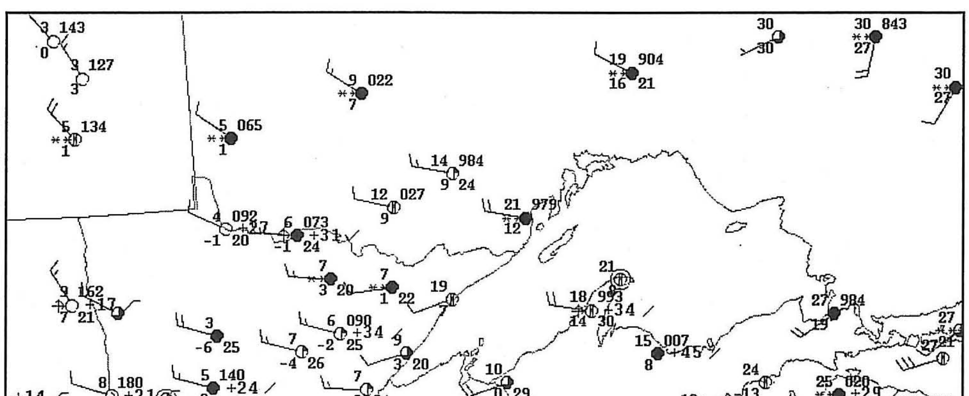

Fig. 15. As in Fig. 8, except for 0900 UTC 7 April 1997.